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Spatial and Temporal Trends of Snowfall in Central New York - A Lake Effect Dominated Region

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Spatial and Temporal Trends of Snowfall in Central New York -

A Lake Effect Dominated Region

by

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Abstract

Central New York is located in one of the snowiest regions in the United States, with the city of Syracuse, New York the snowiest metropolis in the nation. Snowfall in the region generally begins in mid-November and lasts until late-March. Snow accumulation occurs from a multitude of conditions: frontal systems, mid-latitude cyclones, Nor'easters, and most notably lake-effect storms. Lake effect snowfall (LES) is a difficult parameter to forecast due to the isolated and highly variable nature of the storm. Consequently, studies have attempted to determine changes in snowfall for lake-effect dominated regions. Annual snowfall patterns are of particular concern as seasonal snowfall totals are vital for water resources, winter businesses, agriculture, government and state agencies, and much more.

Through the use of snowfall, temperature, precipitation, and location data from the National Weather Service's Cooperative Observer Program (COOP), spatial and temporal changes in snowfall for Central New York were determined. In order to determine climatic changes in snowfall, statistical analyses were performed (i.e. least squares estimation, correlations, principal component analyses, etc.) and spatial maps analyzed. Once snowfall trends were determined, factors influencing the trends were examined. Long-term snowfall trends for CNY were positive for original stations (~0.46 +/- 0.20 in. yr^{-1}) and homogenously filtered stations (0.23 +/- 0.20 in. yr^{-1}). However, snowfall trends for shorter time-increments within the long-term period were not consistent, as positive, negative, and neutral trends were calculated.

Regional differences in snowfall trends were observed for CNY as typical lake-effect areas (northern counties, the Tug Hill Plateau and the Southern Hills) experienced larger snowfall trends than areas less dominated by LES. Typical lake-effect months (December – February) experienced the greatest snowfall trend in CNY compared to other winter months. The influence of teleconnections on seasonal snowfall in CNY was not pronounced; however, there was a slight significant (5%) correlation (< 0.35) with the Atlantic Multidecadal Oscillation. It was not clear if changes in air temperature or changes in precipitation were the cause of variations in snowfall trends. It was also inconclusive if the elevation or distance from Lake Ontario resulted in increased snowfall trends.

Results from this study will aid in seasonal snowfall forecasts in CNY, which can be used to predict future snowfall. Even though the study area is regionally specific, the methods may be applied to other lake effect dominated areas to determine temporal and spatial variations in snowfall. This study will enhance climatologists and operational forecasters' awareness and understanding of snowfall, especially lake effect snowfall in CNY.

Chapter 1: Introduction

Snowfall (the amount of snow that has fallen during a given time period; usually during 24 hours) variability is an important topic due to the extreme unpredictability that can occur on a temporal and spatial scale, along with the plethora of problems associated with major snowfalls. Seasonal snowfall totals in the United States are exceedingly variable from one location to another, and highly dependent upon latitude (Kocin and Uccellini 2004). However, for the eastern United States, a moderate climate along the Atlantic Ocean causes smaller snowfall changes in latitude compared to regions further inland. In the Northeast, snowfall totals range from as little as 6 in. (15 cm) per year in southeastern Virginia to exceeding 100 in. (250 cm) in central-northern New England, New York, and West Virginia (Kocin and Uccellini 2004). One of the snowiest regions throughout the United States is Central New York (CNY), which can create problems for the region's most populous city of Syracuse (Figure 1). Lake effect snow (LES) tends to dominate this region, and can cause numerous issues when attempting to prepare for and forecast snow events, due to the LES's highly variable and isolated nature. Recent research has been conducted to determine the effects of a changing climate on snowfall in North America; however, there are limited studies observing snowfall climatology throughout CNY.

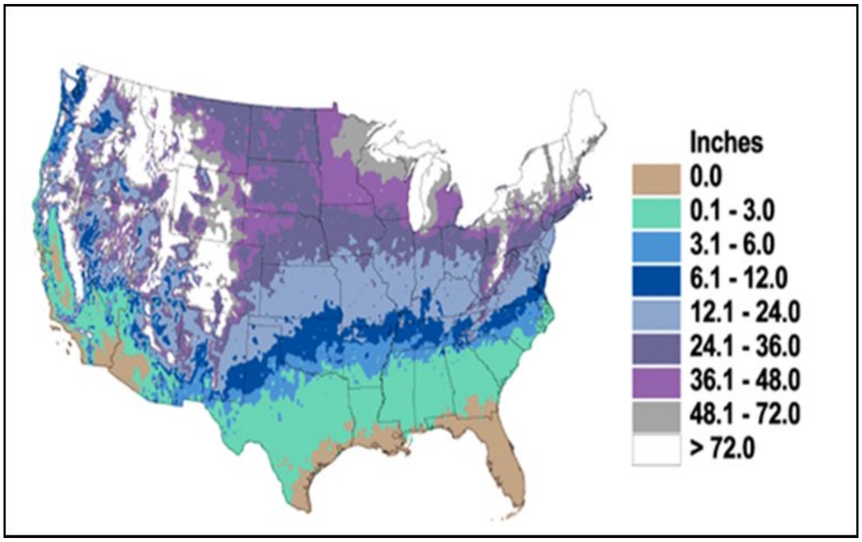


Figure 1. Seasonal Snowfall Averages for the United States (Thompson Higher Education 2011).

The goal of this research is to provide an analysis of long-term temporal and spatial snowfall trends for CNY. This study will determine variations in snowfall at multiple temporal scales (long term, decadal, seasonal, and monthly trends) along with spatial changes in snowfall totals, and possible causalities of any snowfall variations. Results from this study will aid in seasonal snowfall forecasts, especially in lake effect dominated regions. Improving seasonal snowfall forecasts for CNY is especially useful for outdoor winter recreation businesses, water resource management, salt abundance for the Department of Transportation, and more.

1.1 Northeast Snowfall

The Northeast United States is a highly populated region which is regularly impacted by snowstorms during the winter season. Common snowfall occurrences in the Northeast (especially away from the Great Lakes) are due to frontal passages and Nor'easters. Kocin and Uccellini (2004) found that the snowiest seasons in the Northeast generally occurred during the second half of the 20th century. In fact, they found the snowiest season for the majority of all eastern cities was the winter of 1995/96 and the least snow fell during the 1994/95 season. Since the 1990s, interannual variations in snowfall have been increasing; in which there are seasons of extreme snowfall surrounded by seasons with well below normal snowfall (Houghton et al. 2001). Interannual variations in snowfall in the Northeast are inversely related to latitude because snowfall in the southern Northeast is highly dependent on temperature. For example, winter low temperatures in lower-mid latitudes tend to hover around the freezing threshold; therefore, a storm during one season may cause extreme snow totals, but the next season temperatures may increase causing predominately rain to fall (Kocin and Uccellini 2004).

Kocin and Uccellini (2004) also found that variations in yearly snowfall and the frequency of large snowfall seasons are predominantly influenced by large snowfall events. In the Northeast, they found that moderate (4 in. or 10 cm and greater) and heavy (10 in. or 25 cm and greater) snowfall events accounted for 55-65% of snowfall in the second half of the 20th century. Snowfall events greater than 10 in. (25 cm) contributed to 18-24% of the total snowfall and during the 10 snowiest seasons, moderate-heavy snowstorms contributed to 70-86% of the total annual snowfall. Therefore, interannual frequencies are strongly influenced by large snowfall seasons which tend to be dominated by moderate-heavy snow events. However, the relationship between large snow events and interannual snowfall variations closer to the Great Lakes is altered since the major contributor to annual snow totals is LES.

1.2 Lake Effect Snowfall

LES is a term used to describe snow formation that occurs due to a cold polar or Arctic air mass moving over a relatively warm and moist region, usually a lake (Peace and Sykes 1966; Kunkel et al. 2000). The advection of cold air, usually onsetting in the late fall to early winter, causes heat and water to transfer from the lake to the air, as long as the ice cover on the waterbody is not overly prevalent (Norton and Bolsenga 1993). The warm, water destabilizes the cold air, causing relatively low (3000 m cloud tops) stratocumulus clouds to develop through the formation of convective cells (Pease et al. 1988). LES bands tend to form on the leeward side of water bodies, are narrow (typically 5-20 km) and elongated (50-300 km), and can persist over a region for an extended period of time (Niziol 1987). Lake effect (LE) snowstorms are highly variable due to their due to a dependence on: the number of snow bands, the position of the snow band(s), wind direction and speed, fetch, lake-air temperature difference, shape of the shoreline, topography, and convergence (Peace and Sykes 1966). Due to the previous characteristics of LES bands, snow totals can vary greatly between locations, with one area receiving over 40 in. (100 cm) of snow, while a second location, only kilometers away, may barely receive a trace (Niziol 1987; Ellis and Leathers 1996; Ballentine et al. 1998). Hill (1971) found that elevation also has a considerable influence on snow totals; as he discovered a 100 m increase in elevation on the leeward side of a lake can result in an annual snowfall increase of 10-20 in. (25-50 cm).

Regions that tend to experience LES-like events are the Sea of Japan (Tusboki et al. 1989), the Great Salt Lake in Utah (Carpenter 1993), numerous smaller lakes such as the Finger Lakes and Lake Champlain in New York (Sobash et al. 2006; Laird et al.

2009), and the most studied LES region, the Great Lakes. On a yearly average, LE snowstorms account for more than half of the annual snowfall in the Great Lakes basin (Liu and Moore 2004). The Great Lakes provide the heat and moisture needed for LES to form, resulting in average annual snowfall totals exceeding 72 in. (183 cm) per year, rivaling totals experienced on the windward side of the Rocky Mountains (Peace and Sykes 1966; Figure 1).

LE snowstorms that originate over an individual lake can be categorized into four distinct morphological types: parallel bands (widespread coverage), shoreline bands, midlake bands, and mesoscale vortices (boundary cyclonic flow patterns; Niziol et al. 1995; Kristovich et al. 2003; Liu and Moore 2004). Parallel bands are the most common and intense LE bands for the Great Lakes (Niziol et al. 1995). They exist due to a substantial fetch and the transfer of heat and moisture to the air due to winds parallel to the long axis of the lake (Niziol et al. 1995). Niziol (1987) discovered that vertical wind shear has a major role in the formation, or lack thereof, of LES. Wind shear can fragment a strong, single LES band into multiple, weaker bands; shear also tends to spread LES bands out, and if extreme shear is present (>60º), banded structures can dissipate all together (Niziol 1987).

1.2.1 Lake Effect Snowfall Synoptic Conditions

Numerous studies have observed the mesoscale and synoptic conditions observed with LES (e.g. Peace and Sykes 1966; Dewey 1979; Ellis and Leathers 1996; Ballentine et al. 1998; Liu and Moore 2004; Laird and Kristovich 2004). LES events are often triggered by the passage of a synoptic-scale low pressure system (Liu and Moore 2004). For southern Ontario, Canada, intense LES events were most favorable when a low pressure and cold-temperature anomaly was situated over Hudson Bay (Liu and Moore 2004). The authors found the movement of the low pressure system has major implications for LES development. For southern Ontario, a northeastward track of the low produced the most intense snowfall, compared to an eastward track.

Similarly, Ellis and Leathers (1996) found that atmospheric conditions (November-March) conducive for LES development, along the lee of Lakes Erie and Ontario in New York and Pennsylvania, experienced a minimum of less than 1.5 consecutive days in November and March and a maximum of over 2 consecutive days in January and February. They also found the percentage of time a LES event was followed directly by another LES event is dependent on the type of synoptic condition that passes. For example a WNW-W type was rarely (22% of the time) followed by a second synoptic type; however, snowfall fell 75% of the time following a W-S synoptic low.

A study by Peace and Sykes (1966) found that an important characteristic of LES is a narrow confluent-convergent wind shift underneath the snow band. The authors suggested that winds aloft are the dominating factor controlling the location and movement of LE snowbands and not surface conditions. The formation of heavy snowfall rates in such shallow storms is due to the high concentration of moisture in the narrow convergence zone.

The Automation of Field Operations and Services (AFOS) and the National Center for Atmospheric Research Mesoscale Model Version 5 have been used to forecast LES events using mesoscale LES conditions (Dewey 1979; Niziol 1987; Ballentine et al. 1998). An issue with modeling LES is the inability to accurately account for ice-cover on lakes and the snow to liquid equivalent ratio (SLR), defined as the ratio between the initial volume of snow and the volume of melt water (Ballentine et al. 1998; Laird and Kristovich 2004; Ware et al. 2006). Models are constantly being updated, attempting to provide a more accurate forecast for LES; however, due to the complexity and localized nature of LES bands, forecasting remains a difficult task.

1.2.2 Factors Influencing Lake Effect Snow Forecasting

The combination of radar, ground measurements, satellite images, and operational forecast models are used to predict LE events. However, due to the localized nature of LES and the ability to alter its location with a minor shift in the wind, forecasting LES makes for a difficult task. To accurately predict LES bands, forecasters must take into account when the snowbands form, along with the location, duration and movement of the band(s) (Peace and Sykes 1966; Niziol 1987).

The SLR has a major influence on snow accumulation, and can be highly variable from one snowfall to the next (Ware et al. 2006). The average SLR is assumed to be about 10:1, however it can range anywhere from 3:1 to 100:1 (Ware et al. 2006). Differences in SLR occur due to two reasons. The first reason is the variances in the crystal structures of snowflakes. As the snow reaches the ground, the flakes do not perfectly interlock, leaving small air spaces. SLR is also influenced by compaction as the snow settles on the ground. Lower SLRs are caused by greater compaction, resulting from smaller snow depth totals, while larger SLRs are associated with lighter, less dense snow that compacts less, resulting in larger snow depths (Baxter et al. 2005).

LES tends to have a high snow ratio; therefore accumulations tend to be greater than that of other lower SLR snowfalls (Ware et al. 2006). Snow ratios are inversely related to low level temperature and tend to strongly increase as the liquid equivalent decreases (Ware et al. 2006). A study by Baxter et al. (2005) suggested that since many observers apply a SLR of 10 without measuring the snow or the liquid, there is significant error in analyses of SLRs. Instead of the often assumed SLR of 10, the authors found that the optimum mean SLR to use for the majority of the United States is 13, while for areas around the Great Lakes (especially Michigan) and much of the Rocky Mountains it is 15.

1.3 The Influence of Water Bodies on the Central New York Climate

Weather forecasting, especially for LES, can also be complicated due to the interactions of multiple waterbodies, including small and large lakes (Mann and Wagenmaker 2002). Mann and Wagenmaker (2002) found that multiple lake interactions can alter the behavior of a lake disturbance associated with one lake and tends to have a stronger influence when lake disturbances mature. Therefore, it is essential to review the main waterbodies that influence the climate of Central New York.

1.3.1 The Great Lakes

The Great Lakes basin encompasses five of the world's largest freshwater lakes: Lake Erie, Lake Huron, Lake Michigan, Lake Ontario, and Lake Superior (Figure 2). Two countries (the United States and Canada) comprise the basin, with eight different states bordering the lakes (Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin). Water covers approximately 33% of the total Great Lakes basin (Lofgren 2004); which provides vital fresh water resources for the United States, as the basin accounts for approximately 95% of all surface fresh water in the country. The

Great Lakes are immensely important to the United States and Canada as one-eighth of the United States population lives within the lakes' drainage basin while one-third of Canada's population lives within the basin (Wang et al. 2012).

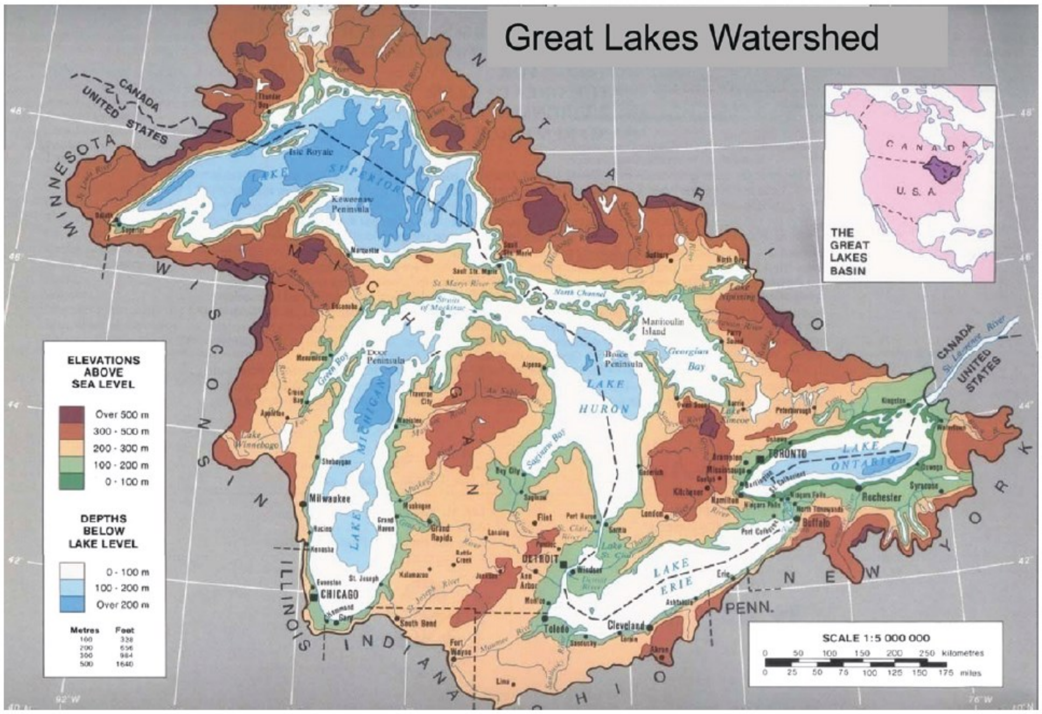


Figure 2. Great Lakes Watershed (Wang et al. 2012).

For all five Great Lakes, initial ice cover typically begins in late November to early December, with an ice onset at week 48 for Lakes Erie and Ontario. Growth of ice cover will then magnify for approximately 14-15 weeks, with maximum ice cover over Lake Ontario occurring early-mid February. Out of all the Great Lakes, Lake Ontario has the smallest proportion of its surface area covered during maximum ice cover. The lower Great Lakes (Erie and Ontario) have an earlier onset of ice breakup, week 7, compared to the three upper Great Lakes (Michigan, Huron, and Superior; Wang et al. 2012). However, studies have found there has been an earlier season migration of ice departures on the Great Lakes since the mid-1950s (Hanson et al. 1992).

Previous studies have documented significant decreases in the Great Lakes' water levels (3-4 ft. or 1-1.3 m), due to decreased ice cover allowing for evaporation throughout the year; most notably during the winter seasons of the 1990s to early 2000s (Trumpickas et al. 2009; Sellinger et al. 2008). The minimum ice coverage from 1973-2010, 11%, for all the Great Lakes occurred in 2002, with the greatest ice coverage, 95%, in 1979. Due to the high importance of the Great Lakes, the general characteristics of the lake (i.e. water temperature, ice cover extent, ice thickness, ice season duration, etc.) have been widely studied.

1.3.1.1 Temporal and Spatial Variations within the Great Lakes

Wang et al. (2012) mentioned that numerous teleconnections have been shown to influence interannual ice cover variability and atmospheric circulation over the Great Lakes: the Pacific-North American pattern (PNA), Tropical-North Hemisphere pattern (TNH), North Atlantic Oscillation (NAO), Artic Oscillation (AO), Polar/Eurasian pattern (POL), and the West Pacific pattern (WP).

A recent study by Wang et al. (2012) found that there are large, natural interannual variations in ice cover over the Great Lakes, which are preventing reliable medium and long range ice predictions. The two most prevalent variations have periods of ~4 years, believed to be associated with ENSO, and ~8 years, which may be related to the AO/NAO. The authors also found that from 1973-2010 there has been a significant decrease in lake ice coverage for all the Great Lakes. Lake Ontario displayed the largest decrease in ice extent at -2.3% yr^{-1}, which translated to an 88% decrease in ice coverage since 1973. The authors also discovered, contrary to what originally may have been thought, ice cover for Lake Ontario behaves most closely to the upper Great Lakes (especially Lake Huron) than the lower Great Lakes.

The interannual variations of ice cover over the Great Lakes are highly dependent on lake characteristic. For example, Lakes Erie and St. Clair (a small lake near Detroit, adjacent to the Great Lakes) are shallow lakes, in which ice extent has nearly covered St. Clair from 1973-2010 except the winters of 1992/93 and 2002/03 and every season for Lake Erie (19 m deep on average) except 1983/84, 1991/92, 1998/99, 2002/03, and 2006/07. Therefore, instead of measuring ice extent, ice thickness is the primary variable used to measure ice on the shallow lakes. On the other hand, deep water lakes such as Lake Ontario (85 m), ice does not cover the surface area of the lake, making ice extent the primary variable observed, rather than ice thickness (Wang et al. 2012). Water depth differences between the lakes causes alterations in ice onset, as the onset of ice on shallower lakes occurs earlier and reaches a maximum sooner than deep water lakes.

1.3.1.2 Lake Effect Snow Development Over Lake Ontario

For Lake Ontario, the temperature difference between the lake and the overlying air mass has major implications on the development of LES (Wilson 1977; Niziol 1987). Holroyd (1971) found that the minimum temperature difference between the lake and the 850 hPa air mass layer to initiate "pure" lake effect snow is 13ºC. Ice cover on the lake reduces the amount of heat, energy, and moisture that can be transferred to the overlying air mass, suppressing LES (Niziol 1987). This contributes to lower snow totals on the leeward side of Lake Erie (due to significant freezing during late-winter to early spring) compared to the leeward side of Lake Ontario (which rarely freezes). Studies have found that frozen and near-frozen lakes are capable of producing lake-breezes (Segal and Kubesh 1996); however, compared to non-frozen lakes, snow accumulation was significantly diminished due to a decreased sensible heat flux.

1.3.2 Lake Effect Snow from Small Lakes in New York State

The Great Lakes are not the only bodies of water that can generate lake-effect precipitation (LEP) in New York State; Sobash et al. (2006) and Laird et al. (2009) have observed the effects of smaller lakes on the creation of LEP. The Finger Lakes, a collection of eleven lakes varying in size and orientation located in Upstate New York, have demonstrated the ability to produce lake-effect circulation and snowfall, as well as the ability to enhance LEP occurring from the Great Lakes (Sobash et al. 2006). Sobash et al. (2006) found 107 LE events associated with the Finger Lakes during a 10 year span (1995-2004), with most events occurring during December and January and forming between 0 and 12Z. The primary factor controlling LEP frequency over the Finger Lakes is lake size and orientation. The larger lakes, Cayuga and Seneca, provide a greater fetch and have the ability to remain relatively warm (taking longer to freeze). The orientations of the lakes are important because a northwest to southeast oriented lake produces considerably more LEP than a north-south oriented lake as air flow is more likely to be sustained from northwest to southeast than north to south (Sobash et al. 2006). The lake-air temperature difference for smaller lakes must be greater than that of larger lakes, such as the Great Lakes; therefore, periods of anomalously warm air temperatures (December 2001) have produced significantly more LEP than anomalously cold periods (January 2002; Sobash et al. 2006). Laird et al. (2009) found similar results for LEP over Lake Champlain, where a 14.4ºC temperature difference between the lake and air, with an

18.2ºC difference between the lake and the 850 hPa layer was needed to produce LEP; which is significantly more than what is believed to onset LEP over the Great Lakes. The authors also found that most of the LES around Lake Champlain occurred when surface air temperatures were at or around 0ºC and typically onset with a surface inversion located outside the Lake Champlain Valley.

1.4 Snowfall Variations

Snowfall is dependent on numerous factors (temperature, wind, moisture, among others), which affect snowfall trends and variations on a decadal, seasonal, and even daily basis. Deviations in snowfall totals at various time scales can provide insight into patterns within snowfall trends, which is an important resource for snow dominated regions.

1.4.1 Snowfall Trends

1.4.1.1 North American Trends

Cities in the eastern urban corridor (New York City, Washington D.C., Baltimore, Philadelphia, etc.) experienced a maximum in snowfall in the 19th century, and generally the later decades of the 20th century experienced diminished snowfall compared to earlier decades (Kocin and Uccellini 2004). However, the 1990s were the snowiest decade of the century, but there was extreme variability between seasons within the decade.

A major breakthrough in snow climatology for the United States was the establishment of the Cooperative Observer Program (COOP) and the use of COOP observations to catalog data since 1892 by the Climate Data Modernization Program (CDMP). The addition of the COOP has greatly increased spatial density of digital data across the United States, for an extended temporal period (Kunkel et al. 2007). However, Kunkel et al. (2007) found that COOP snow data must be analyzed with caution, and the best practice would be to filter for inhomogeneities in the snowfall climate record. Inconsistencies in station practices can lead to biases in the dataset; such inconsistencies include: changes in the observational practices (i.e. use of a snowboard), station relocations, or alterations to station surroundings (i.e. clearing of trees and vegetation increasing the blowing/compaction of the snow; Kunkel et al. 2007, and Doesken and Judson 1996). A particular bias that Kunkel et al. (2007) signifies is the standard use of the 10:1 SLR (Kunkel et al. 2007); when in reality, the SLR is closer to 13:1, nearing 15:1 for LES events (Baxter et al. 2005). Therefore, it is suggested that COOP snowfall data must be scrutinized for each location; resulting in the omission of some stations due to biases. However, not all historical station practices can be determined, therefore trend analyses should err on the side of caution and any uncertain stations should be accompanied with increased error for the trend (Kunkel et al. 2007).

Using the filtered COOP dataset from 1930 – 2004, Kunkel et al. (2007) found increasing trends for high-, relatively no trends for moderate-, and decreasing snowfall trends for stations with low snowfall totals. However, from 1990-2004 all three types of stations experienced anomalously low snowfall totals compared to the long-term snowfall average. Kunkel et al. (2009a) built upon using the quality controlled data suggested by Kunkel et al. (2007) and found that out of the 1110 COOP stations that have reported snowfall from 1930/31 to 2006/07, only 440 were deemed to be homogenous. Using the homogenous stations, it was determined that since the 1920s there has been an upward trend in snowfall leeward of the Rocky Mountains, the Great Lakes – northern Ohio

Valley, and parts of the north-central United States. For the same time period, snowfall has been decreasing in the West and mid-Atlantic coast, with a strong negative trend along the southern-tier, the southern Missouri River basin, and parts of the Northeast.

Using a contemporaneous, homogenous data set of 440 quality-controlled COOP stations throughout the United States, Kunkel et al. (2009c) found that there is no overall trend in extreme snowfall seasons in the United States. However, for certain variables and regions, trends were present in the data. For example, in the east north-central and west north-central regions, there was a statistically significant downward trend in low-extreme snowfall years, with a significant upward trend in the Southeast, Northeast, and Northwest. In general, high-extreme snowfall seasons in the United States are decreasing ($\rho < 0.10$). It should be noted that some of the observed stations around the Great Lakes displayed highly variable differences in extreme snowfall seasons compared to nearby stations further from the lakes. It was hypothesized that lake-effect dominance may have contributed to this difference, as LES behaves differently than typical large-scale synoptic snowstorms (Kunkel et al. 2009c).

The effects of global climate change since the 1960s have impacted the North American climate. Snowfall in North America has been influenced by changes in: air temperatures, the hydrological cycle, aerosol concentrations, and the earth's energy balance (Livezey and Smith 1999; Lau and Weng 1999; Lofgren 2004; Barnett et al. 2005).

Most regions in North America have experienced an overall increase in temperatures over the past century; but within the century, certain regions have experienced an appreciable decrease in air temperatures; such as various areas within the

Great Lakes basin (Norton and Bolsenga 1993; Barnett et al 2005). This is significant because changes in air temperatures can influence seasonal snowfall, since snowfall is highly dependent on freezing temperatures. Brown and Mote (2009) discovered that from 1966 – 2007 a general warming climate has had the largest effect on snow cover in the Northern Hemisphere during the winter in maritime regions. Continental regions dominated by cold, dry winter weather were less affected by changes in temperature. Compared to other atmospheric parameters, such as precipitation, Kunkel et al. (2009c) found that winter air temperatures significantly influence seasonal snowfall extremities. Temperature was found to have a correlation ($\rho < 0.01$) with both high and low extreme snowfall seasons, corresponding to cooler and warmer temperatures respectively, throughout all regions of the United States.

Even though temperature has a greater influence on extreme snowfall seasons, winter precipitation anomalies are also an important factor in annual snowfall totals. Greenhouse warming will increase the energy available for evaporation over the oceans, which will consequently lead to increased precipitation and runoff over the continents (Lofgren 2004; Barnett et al. 2005). Increased precipitation with concurrent freezing temperatures is a driving factor in producing extremely high snowfall seasons (Kunkel et al. 2009c). During the late 19th and early 20th century there was an increase in high precipitation events in the eastern United States, reaching a minimum during the 1920s/30s, followed by an overall increase throughout the 1990s (Kunkel et al. 2003). The authors noted that previous studies found that precipitation events exceeding 2 in. (50.8 mm) during a 24 hour period increased from 9% in the 1910s to approximately 11% in the 1980s/90s. The authors concluded that the frequency and magnitude of 1-day precipitation events from the 1980s/90s were similar to those from 1895-1905. However, 5- and 10- day precipitation events were slightly increased during the 20th century compared to the 1895-1905 period (Kunkel et al. 2003).

The effect of urbanization on snowfall is another widely studied variable. Barnett et al. (2005) found an increase in black carbon, a common aerosol which absorbs sunlight, can decrease surface albedo, resulting in an earlier onset of snowmelt and increased snowmelt ratios. A study by Jones and Jiusto (1980) found that urbanization can impact local weather and climate; for example total annual snowfall has significantly increased since the 1940s in four major metropolitans in New York State (Albany, Buffalo, New York City, and Syracuse). However, the authors attributed much of the increased snowfall in Albany, Buffalo, and Syracuse to natural causes, rather than those of anthropogenic sources. The cold season, in particular, did not demonstrate significant precipitation changes with increased urbanization, while warm season precipitation did show a slight increase with urbanization.

1.4.1.2 Lake Effect Snowfall Trends

Multiple studies have found an upward trend in LES around the Great Lakes during the 20th and early part of the 21st centuries (Norton and Bolsenga 1993; Leathers and Ellis 1996; Burnett et al. 2003; Kunkel et al. 2009b). Compared to non-lake-effect stations, snowfall totals in areas affected by LES have significantly (to the 1% level) increased since 1931 (Burnett et al. 2003). One of the cities studied by Burnett et al. (2003) was Syracuse (NY), which was found to have a similar snowfall trend to that reported by the National Climate and Data Center (NCDC) of 1.9 cm yr^{-1} from 1915-2000. Coincidently the authors discovered a large upward trend in snowfall for LES dominated regions, compared to no significant trend in precipitation in those regions. An increase in snowfall, without an increase in precipitation suggests an increase in SLRs, which is consistent with an increase in LES. The authors do state that it may be possible that an increase in cloud condensation nuclei (CCN) may cause an increase in snowfall; however the influence of CCN is not well understood because the presence of CCN can both enhance and suppress snowfall.

However, Norton and Bolsenga (1993) suggested that the upward trend in snowfall for the Great Lakes basin is not spatially consistent. Similar to Burnett et al. (2003), the authors found an upward trend in decadal snowfall for areas impacted by LES; however LES totals were not consistent for each lake. It was suggested that spatial changes in snowfall for Lakes Superior and Ontario were similar, as snowfall not only increased for lake effect zones, but snowfall for these two basins extended further inland as well. Lake Ontario is unique, in that from 1951 – 1980 areas leeward of the lake experienced the greatest increase in LES snowfall compared to regions adjacent to the other four Great Lakes. However, similar to Burnett et al. (2003) areas much further inland did not demonstrate significant trends in snowfall, compared to regions dominated by LES.

Using the quality controlled data set outlined in Kunkel et al. (2007), Kunkel et al. (2009b) used 19 lake-effect dominated stations, five of which were located in New York State and only three assigned to the Lake Ontario snowbelt, to observe snowfall trends for lake-effect dominated regions in the Great Lakes basin. Kunkel et al. (2009b) found an increase of snowfall in two of the four lake-effect dominated regions from 1925-2007: Lakes Superior and Michigan. Lakes Erie and Ontario demonstrated temporally inconsistent snowfall trends. For the total period of snowfall record (1914-2006), trends for Lake Erie were not statistically significant, but analyzing the period 1925-2006, snowfall around Lake Erie has increased at the 1% significance. In contrast, Lake Ontario demonstrated a statistically significant increase (at the 5% level) in snowfall for the period of record (1893-2006), but from 1925-2007 there was no statistically significant trend. It was hypothesized that the upward snowfall trend around Lakes Superior and Michigan can be explained by an upward trend in liquid water equivalent, but such a trend is not present in Lakes Erie nor Ontario. Compared to the other Great Lakes, Lake Ontario is unique in that seasonal snowfall variability was most pronounced; as described by the authors, there were occasional years of extremely high seasonal snowfalls. However, even though Kunkel et al. (200b) found an increase in LES, compared to Burnett et al. (2003), the snowfall trend is much smaller (0.6 standardized units, compared to over 1 standardized unit).

Possible variables which have increased LES have been observed, especially air temperatures. Similar to other regions in North America, observed air temperatures have increased ($r = 0.403$) around the Great Lakes from 1901 – 1987 (Bolsenga and Norton 1993). However with further analysis, the authors discovered that secondary air temperature trends were present within the study period. They found that from 1900-1950 temperatures in the Great Lakes basin substantially increased, but from the mid-1950s to 1970s air temperatures resembled previous decades. Then from the late 1970s to early 1980s, temperatures rapidly decreased, followed by an abrupt increase. Decreased air temperatures during the winter and spring season during the latter half of the 20th century were suspected to be the cause of increased LES snowfall (December –

March) around the Laurentian Great Lakes (Norton and Bolsenga 1993). This led the authors to conclude that cooler air temperatures and not moisture changes were the primary factor for increased snowfall. However after using a longer time record, Burnett et al. (2003) and Kunkel et al. (2009c) noted that there has not been a significant decrease in temperature, and possibly there may even have been a slight increase. Instead, possible increases in snowfall totals may be due to decreased lake ice and warmer lake surface waters. Therefore, as long as air temperatures remain favorable for snow development, areas downwind of the Great Lakes may continue to experience increased LES (Burnett et al. 2003; Kunkel et al. 2009c).

1.4.2 Snowfall Variations Due to Teleconnections

Some studies have attempted to determine interannual variations in snowfall through the use of teleconnections. Kocin and Uccellini (2004) found that regions in the Northeast displayed nonrandom variations in seasonal snowfall on a 5-12 year cycle. They hypothesized that such variations were driven by atmospheric circulation anomalies associated with the El Niño Southern Oscillation (ENSO). ENSO is classified by the difference in sea level pressure between the Indian Ocean/Western Tropical Pacific and the east-central Tropical Pacific (Bjerknes 1969; Halpert and Bell 1997). There is a significant increase in precipitation in the eastern and southern United States during El Niño phases of ENSO (Kocin and Uccellini 2004). However, the high precipitation totals do not always translate to high seasonal snowfall, due to mild temperatures in the eastern United States during El Niño. Due to mild temperatures and decreased precipitation in some regions, Kunkel et al. (2009c) found a significant increase in the probability of low-extreme snowfall for the United States during El Niño, and in particular the Northeast, Central, west-north Central, and Northwest. However, the authors also found strong multidecadal, large interannual variability, and less pronounced decadal variations in the extreme snowfall seasons. For example, the maximum spatial coverage in the United States for high-extreme snowfall occurred during the 1978/79 season, and only two years later the maximum low-extreme snowfall occurred during the 1980/81 season (Kunkel et al. 2009c). In general during El Niño, snowfall increases in the southwest United States, the mid-Atlantic, and Maine and is decreased over the Rockies and Ohio Valley (Kocin and Uccellini 2004).

The North Atlantic Oscillation (NAO) is a second teleconnection that has been found to influence snowfall totals (Livezey and Smith 1999). The NAO is categorized by pressure differences, which influence circulation over the Atlantic, measured between Iceland and the Azores (Hurrell 1995). During the positive phase of the NAO, pressure is higher over a majority of the Atlantic and lower over the Arctic. This causes enhanced westerlies and mild temperatures in the eastern United States due to predominately southerly winds (Kocin and Uccellini 2004; Ghatak et al. 2010). Therefore, the NAO is highly correlated (-0.64) with increased seasonal snowfall in the eastern United States, especially cities in the mid-Atlantic (Kocin and Uccellini 2004). The NAO can also be highly variable on a daily basis, and storm tracks can be enhanced northward during a weaker NAO (Kocin and Uccellini 2004; Ghatak et al. 2010).

A more recent discovery involving the influence of teleconnections on the North American climate is the impacts of the Atlantic Multidecadal Oscillation (AMO). Schlesinger and Ramankutty (1994) were one of the first to identify a possible periodic variation, approximately equal to 65-70 years, dating back to the 1850s in sea surface temperatures (SSTs) in the North Atlantic Ocean. The authors hypothesized that such a variation most likely arose due to internal variability between the ocean-atmosphere. Kerr (2000) termed this long-term variation in SSTs in the North Atlantic the AMO. The AMO, and the subsequent variations in SSTs in the North Atlantic, are vital as changes can result in alterations in the thermohaline circulation of the oceans which have a major influence on air temperatures, precipitation patterns, and wind patterns in North America (Enfield et al. 2001).

Since the AMO is a relatively newer observed teleconnection, little is known about the parameters influencing the AMO and the possible periodic variation of the oscillation. The long-term record (dating back to the 1850s) has supported a periodic variation between 65-70 years, but during the 20th century the period was much smaller, at an approximate 30 year variation. This is supported by the findings of Enfield et al. (2001) who reported AMO values from 1920-1995 and found lower values from 1920-1930, followed by an increase from 1930-1958, and a decrease from 1965-1994, and became positive again around 1995. It is possible that the change in the periodic variation may be attributed to an influence of climate change, as sea surface temperatures have been shown to directly increase over time due to climate change (Cane et al. 1997). However, little is known about how the AMO will react to warming SSTs due to climate change (Enfield et al. 2001).

There is little to no research that has been conducted analyzing the influence of the AMO on seasonal snowfall totals in the Great Lakes basin, or in general snowfall totals in North America. However, studies have shown that a warming in the AMO can cause changes in precipitation patterns in the United States. For example, Knight et al.

(2006) noted that a positive (or warming) AMO can cause decreased rainfall patterns in the United States, especially noted during the Midwest drought in the 1930s and 1950s. The study also found that rainfall patterns are especially altered due to the AMO phase during the summer season; however, interannual variability in the winter associated with ENSO can be significantly impacted during changes between the AMO phases. Knight et al. (2006) also noted that wide-spread cyclonic pressure anomalies are favored during the positive phase of the AMO, especially over Europe and the Atlantic, and during the winter season.

Studies have also observed the impacts of the East Pacific Oscillation (EP), the Pacific Decadal Oscillation (PDO), the PNA, and the TNH (Serreze et al. 1998; Ge and Gong 2009; and Ghatak et al. 2010). Serreze et al. (1998) concluded that outside of March-April, TNH snowfall signals are fairly weak. They also found that PNA and EP patterns are associated with increased snowfall in the eastern United States. Out of the three teleconnections Serrez et al. (1998) observed, PNA extremes had the greatest impact on precipitation phase. Similarly, Ghatak et al. (2010) found a high index phase of the PNA decreases snowpack, due to negative winter snowfall anomalies across regions of North America. Unlike the NAO, the PNA extends across the whole continent and can create increased temperatures and decreased snowpack in western North America (Ghatak et al. 2010). Similar to the NAO, the PNA also experiences intraseasonal variability on a short time scale, about 10 days (Ghatak et al. 2010).

Ge and Gong (2009) found that snow depth variability has large climatic influences in North America along with the highly observed snowfall and snow extent. The authors found that two major climate modes (PDO and PNA) have a significant influence on North American (especially central and western) snow depth. During the positive phase of the PNA and PDO, multiple atmospheric conditions are aligned so that there is a decrease in moisture and winter precipitation over North America. The decreased moisture results in shallower snowpack during the winter season, and vice versa for the negative phase of PNA and PDO.

1.4.3 Seasonal Variations

Snowfall events during a winter season vary considerably between seasons in the United States, especially in the Northeast urban corridor. Kocin and Uccellini (2004) found that in the Northeast, moderate snowfall events (4-10 in. or 10-25 cm) from 1949/50-1998/99 ranged from less than one per season in southeast Virginia to over six per season in central New England. The majority of moderate snowstorms in the Northeast occurred from December-March. The authors found that during October very few cities experienced moderate snowfall events in the second half of the 20th century and there was a 3-4 year variation in moderate snowfall events during November. Moderate snowstorms in northern regions of the Northeast were more likely to occur in December than March, but for the central Northeast, storms were more common in March than December. Following March in all locations, there is a considerable reduction in snowstorm likelihood. Heavy snowfall events (10+ in. or 25+ cm) are even less likely, with an approximate frequency of once every 12 years in southeast Virginia, once every three to six years in northern Virginia to southern New Jersey, and once every two to three years from southern New Jersey to New England (Kocin and Uccellini 2004). For all of the previous locations there was a significant maximum in heavy snow events during February.

Snow accumulations are also variable based on the time of year they occur, as early and late season accumulations tend to be less due to a relatively warm ground, higher sun angles and a longer length of day (Call 2005). The majority of snow accumulation in LES dominated regions tends to occur during the mid-winter (January and February), with a significant decrease in accumulations during November and March (Ellis and Leathers 1996). Strommen and Harman (1978) found that between November and January, in western Lower Michigan, the heaviest snowfall tended to occur near the lakeshore, then from February to March increased snow totals migrated inland. The authors found that wind patterns (greatest from November to early December, then decreased during mid-winter, and increased again in late February) were positively correlated with the movement of snow bands near the shore or inland and believed this to be the cause of the intraseasonal variation in snowfall.

Air temperatures have also had a major influence on monthly snow totals in North America. Bolsenga and Norton (1993) observed seasonal differences in air temperatures in the Great Lakes from 1901-1987. The authors found an upward trend in spring season air temperatures ($r = 0.614$), an increasing trend during the summer ($r = 0.332$), a weak increase during the fall season ($r = 0.212$), and the lowest positive correlation during the winter ($r = 0.064$). The authors believed that only the spring season trend is truly indicative of an increase in air temperature, while the other three seasons are misleading, due to possible biasing from natural variations in the data.

Increased air temperatures are not only impacting snowfall totals, but snow depth as well. Dyer and Mote (2006) found that from 1960-2000 there has been little to no change in North American snow depth from November through January, but certain regions displayed a decrease in snow depth occurring in late January. A depletion of snow depth is most notable in March and April, implying that the spring melt is occurring earlier due to increased temperatures.

1.4.4 Daily Variations

Diurnal variations in LES were also observed (Kristovich and Spinar 2005). The authors found that in LES snowbelt regions, there is a distinct diurnal pattern in LEP. LEP events were at a maximum from 0300 to 1000 EST and minimum values were much more variable, but mainly occurred after 1500 EST (Kristovich and Spinar 2005). Possible factors for such a diurnal variation in LEP are the magnitude of surface sensible and latent heat fluxes, atmospheric static stability over the lake, height of the lowest inversion, and local uplift from synoptic and mesoscale atmospheric circulation, all of which have diurnal variations (Kristovich and Spinar 2005). The authors found that diurnal variations in surface heat flux were strongly linked to LEP occurrences, and tended to be greater in the morning compared to the evening. Latent heat flux was highest during afternoon hours due to increased wind speeds and dewpoint depression, but due to drier air, LEP was suppressed during the evening (Kristovich and Spinar 2005).

1.5 Impacts of Snowfall

1.5.1 Daily Snowfall Impacts

Moderate and heavy snowfalls tend to be the most detrimental to a city. For example, the nation's road and air traffic systems (including highways, city streets, and local roads) are severely challenged by large snowstorms (McKelvey 1995; Norton and

Bolsenga 1993; Kunkel et al. 2000). From 1995-2001 an average of 85,000 accidents with at least one injury was reported each year during driving conditions where snow, slush, or ice were reported on the road (Kocin and Uccellini 2004). There were 46,000 reports during conditions of falling snow, and from 1994-2001 at least 10,164 accident fatalities reported in the United States may have been caused by snow or ice-covered roads. Snowstorms are also potentially crippling to the economy, in which effects of the storm can be felt well after the storm itself; such was the case during the eastern snowstorms of March 1993 and January 1996 in which economic damages resulted in billions of US dollars (NCDC 2003).

As previously mentioned, LE snowstorms are of special concern because of their persistent nature and ability to create near-zero visibility (Ballentine et al. 1998; Call 2005). For example 102 in. (259 cm) of snow fell on Oswego, New York during a 5-day LE snowstorm in January 1966 and 70 in. (178 cm) of snow was reported in Adams, New York in a 24 h period on 9 January 1976 (Dewey 1979). Therefore strong snowstorms, especially LE storms, can be crippling to a region as they are capable of: negatively impacting transportation, disrupting normal business operations, resulting in property damage and can even cause fatalities through accidents and overexertion (Schmidlin 1993; Ellis and Leathers 1996; Laird and Kristovich 2004; Call 2005).

However, Call (2005) noticed that daily snowfall totals, compared to other snowfall characteristics, are less detrimental to upstate New York cities (Albany, Buffalo, Rochester, and Syracuse). He found that snowfall rates, SLR, air temperature, wind, and storm duration have a more pronounced effect on society than daily snowfall totals. It was noticed that disruption of society is greatest when the storm event occurs during the mid-day, due to an early dismissal of both students and workers, creating a gridlock on roads. However, good forecasting, government cooperation, ample plows and salt trucks, and a tendency of the general public to stay home during large snow events, has created a resilient and prepared city of Syracuse for snow events that would be crippling for any other region (Call 2005).

1.5.2 Annual Snowfall Impacts

Annual snowfall totals have a high importance due to spring runoff, recharge, and water supplies, especially in the northern and western United States. The rate of snowpack melt is vital, especially since rapid and premature melting of snowpack can cause major flooding, specifically in the northern United States and along the Mississippi River (Norton and Bolsenga 1993; Barnett et al. 2005; Kunkel et al. 2007; Kunkel et al. 2009a). Yearly snowfall totals are also significant due to their influence on soil moisture content, as high snowfall can lead to high soil saturation and increased runoff along with cooler ground surfaces due to high evaporative fluxes (Norton and Bolsenga 1993). Along with major flooding that can result from anomalously high snowfall years, low snowfall totals can lead to water shortages come summer and autumn in regions reliant on the spring melt for water (Kunkel et al. 2009c).

Not only do annual snowfall totals have major implications on the hydrology of a region, but the impacts are also vital to agribusiness in the northern latitudes of the United States. Areas surrounding the Great Lakes are core producers of fruit (apples, cherries, pears, berries, etc.), with large farms relying on stable yearly snowfall (Norton and Bolsenga 1993). Low winter snowpack has been shown to negatively impact native vegetation due to the damaging of roots, as winter frosts penetrate deeper into the ground soil, a result of decreased snow cover. Limited snow cover is also crippling to the winter wheat crop allowing winter freezes to damage plants, due to increased exposure (Kunkel et al. 2009c).

1.6 Problem Statement

CNY is a snow dominated region during the winter season; making the area's most populous city, Syracuse, the snowiest metropolis in the United States. CNY is in a unique location in that snowfall is dominated by lake effect events, but other systems (frontal systems, mid-latitude cyclones, Nor-Easters, etc.) contribute to yearly snowfall totals for the region. CNY has been a historically snowy region; therefore businesses, agriculture, government and state agencies, and local individuals are prepared and have a high tolerance for snowfall events. However, alterations in snowfall totals, both random and nonrandom, can disrupt normal snow preparations. Snowfall variations occur at varying temporal scales, each of which have a societal impact. For example, alterations in daily snowfall can cause traffic gridlocks and accidents, the halt of business and government operations, and the potential for hazardous living conditions. Annual snowfall totals are also of concern as increasing yearly snow totals can lead to anomalously high spring flooding, transportation issues (salt deficiencies), and a decline in native wildlife; in contrast, low annual snowfall can create water shortages, crop loss for agribusinesses, and economic hardship for snow dependent businesses (ski resorts, plow/salting companies, etc.). Studies have been conducted to determine historical snowfall trends for the United States, and in particular lake-effect dominated regions, but there has been little research focused on snowfall adjacent to individual Great Lakes.

The purpose of this study was to analyze temporal and spatial changes in snowfall at the regional level to better prepare various facets of society within CNY for snowfall variations.

1.7 Objectives and Research Questions

This study had three main objectives:

1. To determine temporal and spatial changes in snowfall totals for CNY and to determine if possible changes were driven by lake-effect properties.
2. To examine factors which may have influenced seasonal snowfall characteristics in CNY (temperature, precipitation, elevation, or proximity to Lake Ontario).
3. Compare the results to previously studied lake-effect regions to determine how snowfall trends in CNY compared to trends for the whole Great Lakes basin.

This project attempted to address several research questions concerning snowfall in CNY, which were related to the following over-arching objectives:

- How has snowfall changed, at varying temporal scales, since the early 1900s in CNY?
- Were snowfall changes in CNY attributed to alterations in lake-effect storms, and if so did they more closely resemble the finding of Norton and Bolsenga (1993) and Burnett et al. (2003), or Kunkel et al. (2009b)?
- Did the spatial distribution of snowfall alter over time in CNY, or have snowy regions always been located in the same general area? Were they similar to what Norton and Bolsenga (1993) found from 1951-1980?

- Did variations in air temperature, precipitation, elevation, and proximity to Lake Ontario have a significant impact on the temporal and spatial trends of snowfall in CNY? Or were there other variables (such as lake ice dynamics described by Wang et al. (2012)) that had a greater influence on CNY snowfall?

1.8 Hypotheses

1.8.1 Snowfall Trends for Central New York

Norton and Bolsenga (1993) and Burnett et al. (2003) found similar upward trends, ~0.036 standardized units per year, in annual snowfall totals for regions impacted by lake-effect snowfall. However, a recent study by Kunkel et al. (2009b) used homogenous COOP data, and discovered that possible inconsistencies in data records have impacted analyzes, leading to an overestimation of an upward trend in snowfall (actually trend ~0.007 standardized units per year). Since the spatial extent of this study was centralized around CNY, it was anticipated that long-term and shorter-period snowfall trends would behave similar to those found in Burnett et al. (2003), but slightly less since inconsistencies in the dataset were filtered out similar to that of Kunkel et al. (2009b).

It was hypothesized that typical lake-effect snow dominated months (late-November – February) would experience an upward annual trend in snowfall, but months normally dominated by other snowstorms (September – early November and March – May) would display a downward trend in snow. The reasoning for this is because previous studies (Norton and Bolsenga (1993), Burnett et al. (2003), and Kunkel et al. (2009b) have found increased snowfall in LES dominated regions, while snowfall has decreased in areas further from the lake basins.

1.8.2 Spatial Changes of Snowfall in Central New York

As previously mentioned, it was anticipated that snowfall for CNY would exhibit an upward trend. However, it was expected that the spatial distribution of snowfall trends would not be uniform, similar to the findings of Norton and Bolsenga (1993). It was anticipated that there would be regional differences in snowfall between locations. Regional and station 'differences include a greater upward annual snowfall trend for sites strongly dominated by lake-effect snow (those closer to Lake Ontario) compared to sites less dominated by LES (further from Lake Ontario). It was also expected that snowfall trends for a location would be highest with: increased elevation, closer proximity to Lake Ontario, and eastern orientation to Lake Ontario.

1.8.3 Factors Influencing Snowfall Changes in Central New York

Studies have examined the influence of various atmospheric parameters on snowfall in the Great Lakes basin. Norton and Bolsenga (1993) noted that a change in air temperature, instead of moisture and precipitation, is the main factor increasing snowfall in the Great Lakes basin. Kunkel et al. (2009b) found air temperatures for Lakes Superior and Michigan to increase, along with increasing snowfall. Therefore, it was hypothesized that due to an increased air-lake temperature difference, there would be an increase in CNY snowfall associated with a slight increase in air temperatures. Similarly, since air temperatures are expected to increase, precipitation was also expected to increase due to increased evaporation from warmer air temperatures; but the relationship will be less significant than that of snowfall and air temperature.

Chapter 2: Methodology

2.1 Study Area

Central New York (CNY) is the term used to describe twelve counties located in Upstate New York (Figure 3). During winter, each of the twelve counties (Cayuga, Chenango, Cortland, Herkimer, Jefferson, Lewis, Madison, Oneida, Onondaga, Oswego, Otsego, and Tompkins) is located in a snow dominated region. CNY is in a unique location because it is not only affected by LES from the Great Lakes, but snow accumulates due to the passage of fronts, mid-latitude cyclones, and Nor'easters. However, the majority of snow accumulation in the region occurs due to LE snowstorms; Miner and Fritsch (1997) found that in lake effect dominated regions, such as CNY, LEP accounts for approximately one-fifth of annual precipitation days.

Figure 3. Study area. The counties shaded in green are the twelve counties that make up Central New York.

CNY is a highly populated region (over 1 million people) with cities including: Auburn, Cooperstown, Cortland, Ithaca, Oneida, Oswego, Utica, Watertown, and the region's largest city, Syracuse (over 145,000 people; City of Syracuse 2012). Syracuse (43.0°N, -76.1°W), located in Onondaga County, approximately 25 km southeast of Lake Ontario (on the leeward side), experiences snowfall totals exceeding an average of 100 in. (254 cm) per year, making the city the snowiest metropolis throughout the United States (Kunkel et al. 2000; NOAA 2011a).

High annual snowfall totals in CNY have shaped the culture and economics of the region. In particular, the department of transportation has been challenged with keeping the road system serviceable during snowfall; including two major highways, Interstate 81 and Interstate 90, along with two auxiliary interstate highways, Interstate 481 and Interstate 690 (both servicing the Syracuse metropolitan area). An ample amount of salt and plow trucks is necessary for a CNY winter, especially since the road system services two major universities (Syracuse University and Cornell University), dozens of hospitals, 118 public school districts (including over 450 public schools; NYS Education Dept. 2012), thousands of businesses, and millions of citizens and travelers. In addition snowfall impacts other forms of transportation, as CNY harbors multiple railway systems and airports, including Syracuse Hancock International Airport which services seven major airlines and approximately 250 arriving/departing flights per day (City of Syracuse 2012). Also, business and recreational activities have developed as a result of the region experiencing high annual snowfall totals including: multiple ski resorts (i.e. Greek Peek, Labrador Mountain, Four Seasons Ski Resort, and Woods Valley Ski Area), over 16,900 km (10,500 miles) of snowmobile trails in 47 different New York State counties (NYS Snowmobile Association 2012) and the agribusiness sector (apple industry, winter wheat, maple syrup, etc.).

2.1.1 Topography

CNY is characterized as having relatively hilly topography, with the presence of the seven-valleys. The southern counties of CNY extend into the Allegheny Plateau, which is a broad region characterized by high elevations and steep gradients (Figure 4; Figure 5). North of the plateau, including parts of Onondaga, Cayuga, and Oswego counties, the Erie-Ontario Lowlands (a.k.a. northern plains) extend 48-64 km from just north of Syracuse to Lake Ontario. South of the city of Syracuse, elevations quickly rise from approximately 122 m above sea level to 610 m within a 32 km span. While to the southeast of Syracuse, in the Southern Hills, the land rises in irregular hills with numerous valleys providing additional topographic features which increase orographic lifting, and enhances snowfall totals (Clowes 1919). The northern/northeastern region of CNY encompasses the Adirondack Mountains and the Tug Hill Plateau. The Tug Hill, located in the Adirondack Mountains, is not actually a plateau and is instead a mountainous region ranging from 100-600+ m in elevation (Figure 4; Figure 5). The topography of the Tug Hill provides features enhancing orographic lifting of air, making the region the snowiest area in CNY, with some of the largest snowfall totals and rates in the world.

Figure 4. Topography of New York State.

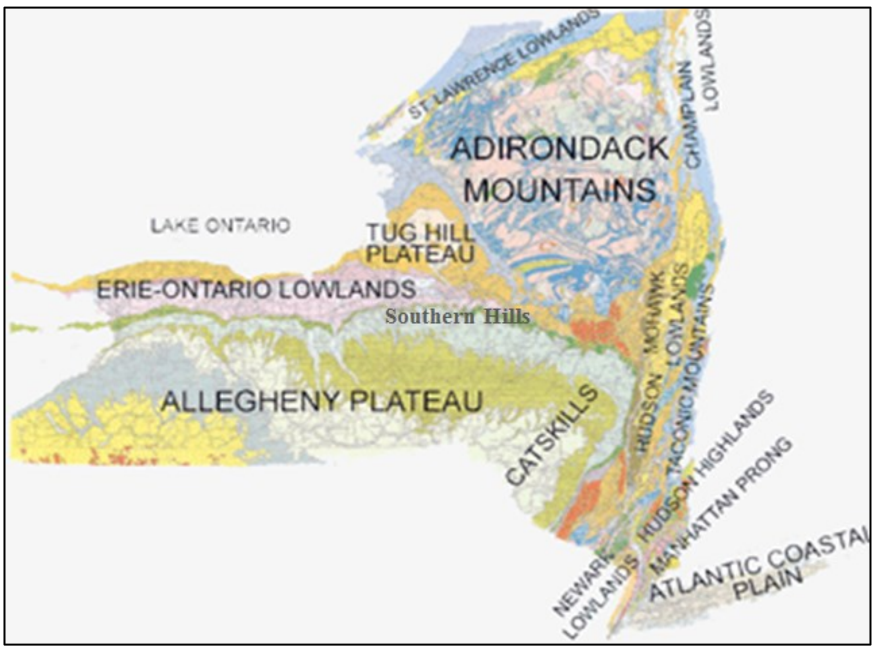


Figure 5. Topographic Regions of New York State (Kluge et al. 2006).

2.1.2 Hydrology

Numerous lakes and rivers are scattered throughout CNY (Figure 6). Some of the smaller lakes around the region are Onondaga Lake (northwest of Syracuse), Oneida Lake (northeast of Syracuse), which is the largest lake encompassed in New York State, and a few of the Finger Lakes. The Tioughnioga River is the main river basin in the region, ultimately draining into the Chesapeake Bay.

The dominating water body influencing CNY is Lake Ontario. Lake Ontario is the smallest of the Great Lakes in surface area. Lake Ontario neighbors CNY to the northwest, directly bordering Cayuga, Oswego, and Jefferson Counties. Lake Ontario is the primary producer of LEP in CNY, which accounts for a large portion of the region's high annual snowfall. Even though Lake Ontario is the smallest Great Lake in surface area, it rarely freezes over during winter (Niziol 1987), allowing the transfer of heat and moisture to overlying colder air masses. Through sensible and latent heat transfers, Lake Ontario provides the heat and moisture needed for LES development in CNY.

Figure 6. Hydrography of New York State.

2.2 Data

Variations in annual snowfall totals will be analyzed for numerous locations around CNY. In order to analyze such changes, snowfall, precipitation, and temperature records for CNY were obtained from the National Weather Service's (NWS) Cooperative

Observer Program (COOP). The COOP, formed in 1890, is an observing network consisting of public volunteers taking weather observations (precipitation, snowfall totals, temperatures, wind speed, etc.) from a variety of locations around the United States (NOAA 2012). Observations are reported on a daily basis, including snowfall measurements (in inches), taken at least once a day up to four times per day (every six hours; NOAA 2011b). Along with weather observations, the latitude, longitude, and elevation of each station are recorded. Daily COOP observations are reported to the nearest NWS; the National Weather Service at Binghamton, New York is the regional forecasting center for CNY. Data is then transferred to the NCDC in Asheville, North Carolina, where historical data records were accessed (NCDCa, 2012). The importance of the COOP is illuminated by NOAA (2012).

2.2.1 Observed Stations

There are 654 reporting COOP stations in the state of New York. Out of the 654 stations, 122 of them are located in a CNY county (Table 1), and were used for this study. The counties with the highest consistency and coverage of COOP observations were Chenango, Jefferson, and Lewis Counties (100%), with Cayuga County having the lowest percentage (71%). Each of the twelve counties, except for Cortland County, currently have reporting COOP stations, with the most recent observation, at the time of data collection, reported on 30 June 2012; Cortland County's last recorded COOP observation was on 30 November 2010. The oldest COOP report for CNY is out of Cortland County, in which a station in the City of Cortland (42.7°N, -76.3°W) began reporting observations in 1892. The oldest station reports for the other twelve counties are as follows: Cayuga (1897), Chenango (1931), Herkimer (1931), Jefferson (1920), Lewis (1920), Madison (1920), Oneida (1931), Onondaga (1893), Oswego (1920), Otsego (1931), and Tompkins (1918).

Table 1. COOP Stations by CNY County.

County	No. of Stations	Start Year	End Year	Length of Record	% Coverage
Cayuga	5	1897	2012	115	71
Chenango	12	1931	2012	81	100
Cortland	9	1892	2010	118	93
Herkimer	16	1931	2012	81	87
Jefferson	9	1920	2012	92	100
Lewis	14	1920	2012	92	100
Madison	5	1920	2012	92	83
Oneida	15	1931	2012	81	85
Onondaga	7	1893	2012	119	89
Oswego	12	1920	2012	92	86
Otsego	14	1931	2012	81	94
Tompkins	4	1918	2012	94	77

The locations of the 122 COOP stations used for this study are displayed in Figure 7. The starting date and reporting length of individual COOP stations was not homogenous throughout CNY, as each station varied from one another. A majority of the CNY stations (61) only had a recording period of 0-25 years, 16 stations covered a 26-50 year period, 41 stations covered 51-100 years, and 4 stations had observations for over 100 years. Until the 1930s, COOP observations in CNY were fairly scarce, and then in 1931 the number and consistency of stations dramatically improved. Therefore, snowfall trends for CNY will be calculated from 1931 – 2012.

The city of Syracuse will be of particular interest during this study, since it is the largest metropolis in the region, and the station reporting is stable for the city (reported from 1 May 1938 to 30 June 2012 at Syracuse Hancock International Airport [SYR]).

Data for Syracuse was obtained from the Past Preliminary Climatology Dataset from the NWS at Binghamton (NOAA 2011c) along with records from NCDC's COOP archive.

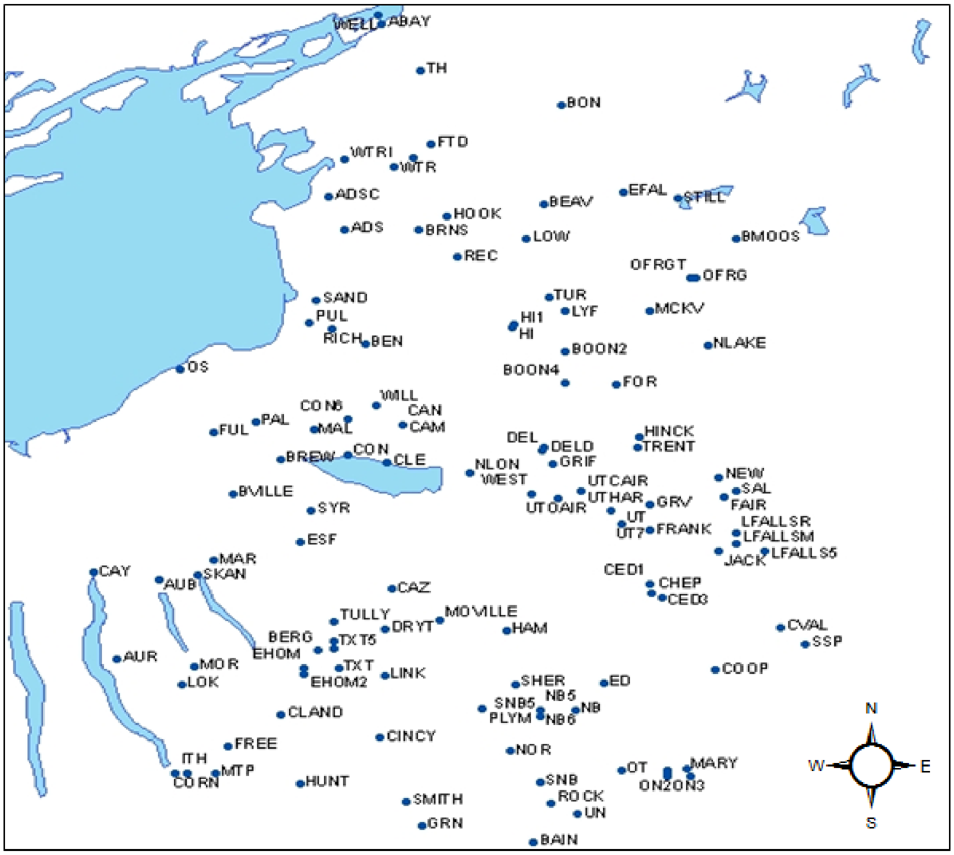


Figure 7. Location of Central New York COOP Stations. See Appendix A for COOP station listing.

2.2.2 Observed Variables and Assumptions

Individual COOP station data obtained for this study included the station's: name, COOP number, elevation (meters), latitude (decimal degrees), longitude, date (month and year), total monthly snowfall (nearest tenth of an inch), total monthly precipitation (nearest hundredth of an inch), and average monthly temperature (ºF). Since observations were reported by month, data was organized into annual snowfall totals, winter precipitation totals, and average winter temperatures for each individual station.

2.2.2.1 Snowfall Data

2.2.2.1.1 Seasonal Snowfall Data

Annual snowfall totals are unique in that yearly (12-month) observations are not recorded for a calendar year (1 January – 31 December); instead observations are reported in "snowfall years" (a.k.a. snowfall season, winter season). A snowfall year is recorded from 1 July – 30 June; therefore, one winter season overlaps between two calendar years (i.e. the 2011/2012 snowfall season encompasses the months from 1 July 2011 – 30 June 2012). As previously mentioned, not all COOP station records had homogenous reporting periods, and in addition some monthly snowfall observations were missing from the record. Therefore, for all missing monthly snowfall data (either omitted from the record, or reported as 9999.0), daily snowfall records were examined for the missing month. Daily snowfall records were obtained from the NCDC using the Global Historical Climatology Network (GHCN). Instead of monthly COOP observations, the GHCN server contains daily snowfall observations for each of the individual COOP stations (NCDCb, 2012).

If at least 85% of the days within the unreported month were observed, then the snowfall total was deemed suitable, and the monthly snowfall total was accounted for. If less than 85% of the days were reported, then the snowfall total for the month was set to 9999.0 (missing value). Therefore, an assumption this study makes is if snowfall totals are recorded for at least 85% of the days within a month, then the summation of the daily snowfall totals is representative of the monthly snowfall.

Annual snowfall totals for a station were only reported if there was consistency in snowfall observations during winter months (November – April). After examining daily snowfall records, if two or more winter months were deemed missing, then the annual snowfall total for that year was not reported. If only one winter month was not reported, then bilinear interpolations were used to estimate the monthly snowfall for that missing month. The monthly snowfall of a station was estimated by interpolating snowfall between the nearest 3 – 4 stations, giving weight to the proximity of each station. Once the missing month was interpolated, the total summation of snowfall for the months November – April was reported as the seasonal (yearly) snowfall total.

2.2.2.1.2 Monthly Snowfall Data

Monthly snowfall totals were obtained from the NCDC for all 122 stations. Snowfall totals were then categorized by month (i.e. all monthly snowfall totals, from 1931 – 2011, for the month of December were categorized into one group, etc.). Monthly snowfall totals were only observed for typical winter months (November – April), and all other months were omitted from the record. Similar to the annual snowfall record, if a monthly snowfall total was missing or omitted from the record, the daily GHNC record was analyzed. Unlike annual snowfall totals, monthly snowfall records were not interpolated for missing values. If a record was missing and at least 85% of the daily snowfall records were not reported, then the monthly snowfall total was deemed missing and set to 9999.0.

2.2.2.2 Temperature and Precipitation Data

2.2.2.2.1 Seasonal Air Temperature and Precipitation Data

Surface air temperature records for COOP stations in CNY were limited compared to snowfall observations. Therefore, only 27 out of the 122 stations were used for analyzing temperature data (Table 2). Monthly air temperature records for the 27 stations were averaged together to produce a single average temperature for each month from July 1931 – June 2012. Temperature records were then filtered to only include months in which snow typically falls in CNY (November – April). The average winter air temperature for CNY was then calculated by averaging the average monthly temperatures from November – April. By averaging air temperatures, the study assumes that air temperatures are comparable throughout CNY (2.95°F average standard deviation). The assumption is made since CNY is a geographically small area, and temperature differences throughout the region are relatively small, and will demonstrate similar trends, unlike the variability in precipitation and snowfall.

Table 2. COOP stations used for air temperature and precipitation data. See Appendix A for abbreviation reference.

Station Abbreviations			
ABAY	CLAND	HINCK	SHER
AUB	COOP	LFALLSR	SKAN
AUR	CORN	LOW	STILL
BAIN	CVAL	MOVILLE	SYR
BERG	FREE	NOR	UT
BMOOS	FUL	OFRG	WTR
BVILLE	HI	OS	

Similar to temperature data, precipitation data was only obtained for the 27 stations listed in Table 2. Unlike snowfall totals, if a precipitation observation was missing, the value was set to 9999.0 and daily totals were not examined nor interpolated. Annual precipitation totals were summed for months November – April, and reported as the winter precipitation total. Since annual temperature and precipitation data are only examined during winter months (November – April), it assumed that little to no appreciable snowfall occurs during months May – October, which would influence annual snowfall totals. Precipitation totals were then averaged by region, classified by principal component analyses later in the study.

2.2.2.2.2 Monthly Air Temperature and Precipitation Data

Monthly air temperature and precipitation records for winter months (November – April) were also used for this study, which were recorded using the COOP and obtained from the NCDC. Similar to annual records, only 27 stations were used for monthly temperature and precipitation data. Monthly air temperature data was again averaged for all 27 stations, and then filtered by month. Monthly precipitation data was also categorized by month, with any missing observations reported as 9999.0.

2.2.3 Teleconnection Data

Three teleconnections were examined in this study, the North Atlantic Oscillation (NAO), the Southern Oscillation Index (SOI) and the Atlantic Multidecadal Oscillation (AMO); as Livezey and Smith (1999) found a relationship between the NAO and snowfall in the Northern Hemisphere and Kocin and Uccellini (2004) found a relationship between eastern United States snowfall and the NAO and ENSO. Data for all three teleconnections was obtained from the NCAR through their climate data guide server (NCAR 2012). Data for the NAO was based on Hurrell (1995), and was calculated by taking the difference of the normalized sea level pressures between Ponta Delgada, Azores and Stykkisholmur/Reykjavik, Iceland. The SOI data contained standardized Tahiti/Standardized Darwin data, and the AMO data considered unsmoothed data from the Kaplan SST V2, and was calculated by NOAA/ESRL/PSD1.

Each teleconnection reported initial data as a monthly value. To analyze the impacts of the teleconnections on seasonal snowfall totals in CNY, data for the teleconnections were limited to winter months; therefore, a single average value was reported for each winter season (November-April). Also, data for the teleconnections dated back further than snowfall records in CNY, consequently the time-series for each teleconnection was reduced from 1931 – 2011.

2.2.4 Homogenous Data

Each COOP station was scrutinized for any inhomogeneities in the station reporting, along with inconsistencies in the frequency of observational reports. Inhomogeneities in the dataset of particular interest were station changes (i.e. station relocations or measurement practices). A majority of the stations reported at least one relocation (either a latitude, longitude, or elevation change). However, some of these relocations were not actual relocations, and instead updated geographic coordinates and elevations. Therefore, a station relocation was considered any change in elevation greater than 10 meters or a change in latitude and/or longitude greater than 0.15°. A select amount of stations, displayed in Table 3, were considered inhomogeneous due to observation changes (i.e. the amount of times snow was measured per day, or the use of a snowboard). The type of observation change and the date which the change occurred, were not reported by the NCDC, only that the station incurred an observation change. Therefore, the whole snowfall record for that station was judged inhomogeneous.

Table 3. Stations with an observation change. See Appendix A for station abbreviations.

Stations		
FUL	HOOK	LOW
HAM	LFALLSR	PUL

Table 4. Homogenous CNY COOP stations by period. See Appendix A for station abbreviations.

1931-2011	1971-2011	1931-1951	1951-1971	1971-1991	1991-2011
BREW	ABAY	ABAY	ABAY	AUR	AUR
BEN	AUB	AUB	AUB	BAIN	BVILLE
BVILLE	BAIN	BAIN	BAIN	BVILLE	BEN
CORN	CAN	CAN	BVILLE	BEAV	BMOOS
GRN	COOP	COOP	BEAV	BEN	BOON4
SHER	CORN	CORN	BEN	BOON4	BREW
SKAN	GRN	CLAND	BMOOS	BREW	CORN
SYR	LFALLSM	HINCK	BOON4	CAM	FREE
WTR	MOVILLE	LFALLSM	BREW	CVAL	GRN
	NB	MOVILLE	CAY	CORN	HI
	OS	NOR	CVAL	CLAND	MOVILLE
	SAL	ON3	CINCY	FRANK	NOR
	SHER	OS	COOP	FREE	OS
		SAL	CLAND	GRIF	SHER
		SHER	DEL	HI	STILL
		SKAN	FOR	LYF	SYR
		WTR	FRANK	SHER	UN
			GRN	SKAN	WTR
			HI	STILL	
			HINCK	SYR	
			LFALLSM	BERG	
			LYF	UT	
			NB	UTOAIR	
			NLON	WTR	
			OS	WTRI	
			ROCK	WELL	
			SHER		
			SKAN		
			STILL		
			SYR		
			UTOAIR		
			WTR		
			WTRI		

Another inconsistency in a station's reporting which resulted in the station being deemed inhomogeneous was missing data. In order for a station to be considered homogenous, at least 85% of the annual observations were reported. The most homogeneous stations occurred during the 1951 – 1971 period (31), while only 9 stations were deemed homogeneous for the long term record (1931 – 2011; Table 4).

2.3 Analyses

2.3.1 Initial Region Classification

CNY COOP stations with a reporting period greater than 5 years were separated into nine regions, and are referred to as wind-direction regions (Figure 8). The regions were based on their directional orientation (Table 5) from a fixed point on the United States-Canadian border located over Lake Ontario (43.6°N, 76.8°W).

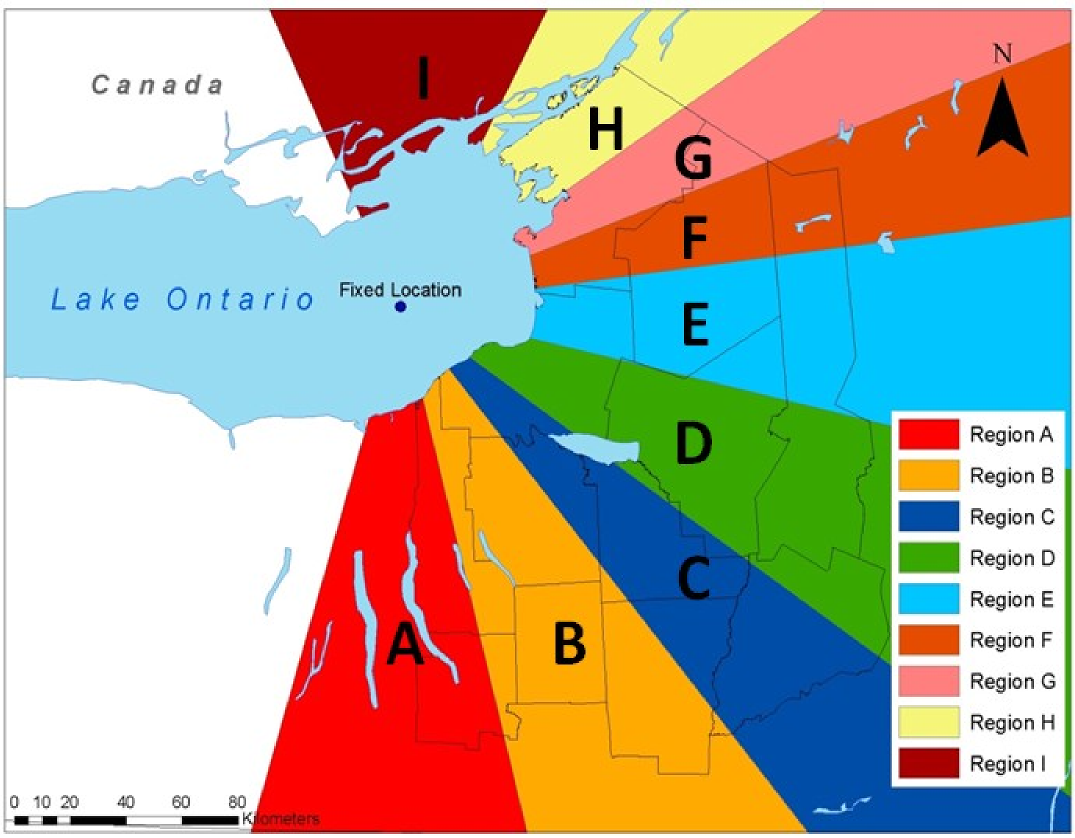


Figure 8. Station regions based on directional orientation to a fixed point. The fixed point (43.6°N, -76.8°W) was located over Lake Ontario on the United States/Canadian border**.**

Table 5. Wind direction classification of regions. 0º and 360º represents due north.

Region	Degrees
A	191.25 - < 168.75
B	168.75 - < 146.25
C	146.25 - < 123.75
D	123.75 - < 101.25
E	101.25 - < 78.75
F	78.75 - < 56.25
G	56.25 - < 33.75
H	33.75 - < 11.25
I	11.25 - < 337.5

Each region was characterized by a dominant wind direction, as Region A corresponded to a northerly wind, Region B corresponded to a north-northwesterly wind, and so on (Figure 9).

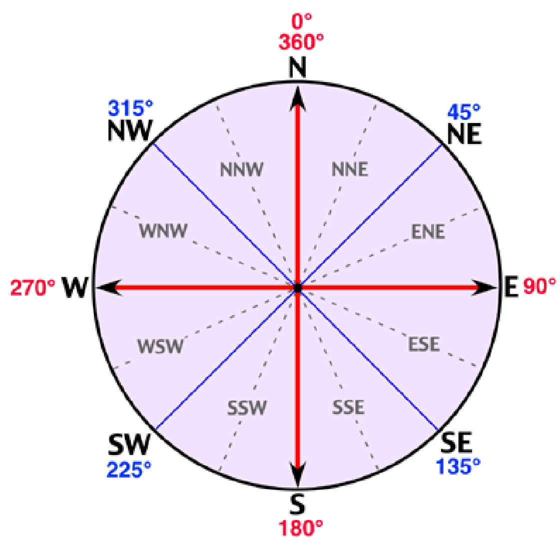


Figure 9. Wind Direction Categories.

In order for a station to be located in an area regularly impacted by Lake Ontario LES, the station must be on the leeward (eastern) side of the lake. Therefore, it should be noted that all COOP stations are located east of the fixed point. Grouping stations into regions based on their directional orientation to a fixed point over Lake Ontario allows for rudimentary wind pattern analyses. A controlling factor of LES is wind direction; therefore, classifying stations into regional categories aided in determining if wind pattern shifts have altered annual snowfall totals in CNY. After grouping each CNY station into a region, the most COOP stations were located in Region D (23), followed by Regions: C (17), B (14), E (13), F (7), A (6), G (3), H (2), and I (0; Table 6).

Table 6. Stations within each region classified by their orientation to Lake Ontario. See Appendix A for station abbreviations.

Region A	Region B	Region C	Region D	Region E	Region F	Region G	Region H
AUR	AUB	BREW	CAM	BEN	BRNS	TH	ABAY
CAY	BAIN	CAN	CHEP	BMOOS	BEAV	WTR	WELL
CORN	BVILLE	DRYT	CVAL	BOON2	BRIV	WTRI	
ITH	CINCY	FUL	CON	BOON4	EFAL		
LOK	CLAND	HAM	COOP	FOR	FTD		
MTP	FREE	SYR	DEL	HI	HOOK		
	GRN	HINCK	DELD	LOW	STILL		
	LINK	MARY	FRANK	LYF			
	SKAN	MOVILLE	GRV	MCKV			
	ESF	NB	GRIF	NLAKE			
	TRX	NOR	JACK	OFRG			
	TULLY	ON3	LFALLS5	PUL			
	BERG	ON3SE	LFALLSR	TUR			
	SUNYO	OS	LFALLSM				
		ROCK	MAL				
		SHER	NLON				
		UN	NEW				
			SAL				
			SSP				
			TRENT				
			UT				
			UTHAR				
			UTOAIR				

2.3.2 *Principal Component Analyses for Regional Classifications*

Principal component analysis (PCA) was used in this study, which is an analysis technique for determining hidden temporal and spatial correlations in the data. In order to do this, the PCA uses a singular value decomposition on a matrix ordered both in time and space. The principal components are determined by calculating the eigenvectors and eigenvalues (or modes) of the data covariance matrix. The first mode explains the greatest variance in the data, followed by the second mode, and so on. For more information on the standard procedures of a PCA see Preisendorfer (1988).

The use of principal component analyses (PCA) for this study was twofold. The first analysis was used to group individual stations by similarities in annual snowfall. A PCA (PCA-a) was conducted on the long-term stations (Table 7) using the program IBM Statistical Package for the Social Sciences (SPSS) 19 (a statistical software program). An initial scree plot was constructed using the 22 COOP stations, and analyzed to determine the numbers of modes present in the data based on Eigenvalues greater than 1. Once determined, the number of modes was input into the dimension reduction, and the fixed number of factors was set equal to the number of modes. A varimax rotation with Kaiser Normalization was used for the analysis of PCA-a, and missing values were excluded listwise for the analysis. A second PCA (PCA-b) analysis was run using the long-term records, but with missing values replaced with the mean.

Table 7. Long-term stations used in PCA-a and PCA-b. See Appendix A for station abbreviations.

Stations		
AUB	GRN	OS
BEN	HI	SHER
BMOOS	HOOK	SKAN
BREW	LFALLSR	STILL
BVILLE	LOW	SYR
CINCY	MOVILLE	TRENT
COOP	NOR	WTR
CORN		

The results of PCA-a and PCA-b were analyzed using the rotated component matrix, and each station was categorized into a mode, based on the previous matrices. The designated mode was based on the absolute value of each factor in the correlation matrix for each PCA. The mode in which a station was categorized was based on the mode which incurred the closest absolute value to 1. If the absolute value of two or more modes of a station were within 0.15 of each other, then the station was categorized into each mode, and region classification was based on proximity to other stations in the correlated modes. The results of each PCA (PCA-a and PCA-b) were compared to determine correlated regions within CNY based on each station's annual snowfall total. The second PCA analysis is outlined later in the study.

2.3.3 Snowfall Trends for Central New York

Snowfall totals were analyzed to determine how snowfall has changed, at various temporal scales (seasonal and monthly) throughout CNY. Snowfall totals for CNY were analyzed through SciLab 5.3.3 (a cross-platform numerical computational software, similar to MATLAB but open source), using a linear least-squares regression to fit a trend to the data.

Prior to calculating any linear trends, an autocorrelation was performed to graph possible correlated signals in the data. If strong correlated signals existed (greater than 0.50), then trend analyses were later recalculated including the modeled correlated signal(s). After autocorrelations were calculated, a manual SciLab algorithm was used based on linear least squares to factor in for missing data and account for the modeling of periodic sinusoids based on the autocorrelation. The intrinsic SciLab code did not handle this, and did not properly calculate uncertainty, therefore it needed to be updated (Appendix C). The least squares regression code accumulates the H-matrix for calculating a trend by looping through the data at partial time intervals. The final product of the least squares regression function returns the best fit of the data, residuals after removing the trend, the trend of the least squares fit, the standard error based on the first standard deviation of the residuals, and the correlation matrix.

Initial trends with only standard error were run for each least squares regression analysis. However, calculating the standard error for a trend is not sufficient, as standard error assumes all points are statistically independent, which is inaccurate due to serial correlations present in the autocorrelation of the residuals. One can calculate the effective degrees of freedom (statistically independent points) based on the lag-1 autocorrelation (Eq. 1) and use this to estimate the 10% significance. According to Eq. 1, DOF_{eff} is the effective degrees of freedom, N is the number of observations, and r is correlation at a 1-point lag.

$$DOF_{eff} = N\,\frac{1-r}{1+r} \qquad \textbf{Eq. 1}$$

When calculating the effective degrees of freedom, one must also account for the number of parameters estimated in the model, for example there are two parameters (bias and trend) accounted for when calculating a trend, four parameters when calculating a trend plus a seasonal fluctuation, etc.

The studies by Burnett et al. (2003) and Kunkel et al. (2009b) observed snowfall trends for locations in the Great Lakes basin, but few stations in CNY were included in their studies. In particular, the spatial extent for the recent study of Kunkel et al. (2009b) was very limited for the whole state of New York (Figure 10). Only three of the locations that met the authors' COOP station requirements were adjacent to the leeward side of Lake Ontario, and only one of the stations was located within CNY (Lowville).

Therefore, the filtering process used for this study was less extensive than that used by Kunkel et al. (2009b), allowing for a larger sample size and greater spatial extent of stations in CNY.

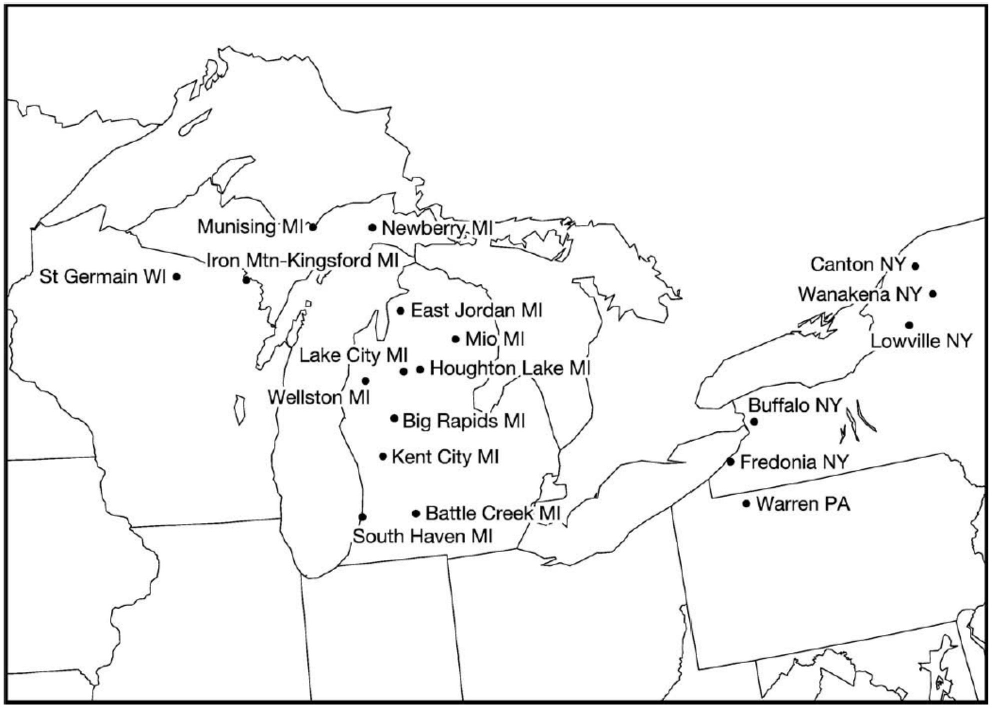


Figure 10. Station locations used by Kunkel et al. (2009b).

2.3.3.1 Central New York Snowfall Trends

Least squares regression was performed for seasonal and monthly snowfall totals, at varying regional and temporal scales. Least squares regression was initially conducted on the average seasonal snowfall totals for the entire CNY region. In order to do this, seasonal snowfall totals for each COOP station were averaged together to get a single snowfall total for each season from 1931/32 – 2011/12. Seasonal snowfall records were then divided into various time periods: long-term, 41-year, and 21-year increments (Table 8). The smaller time periods were chosen as the 41-year increments were half the time period of the long-term record, and 21-year records were half the time period of the 41-year records. For the 41 and 21 year periods, there were overlapping seasons when calculating the trend (i.e. 1991/92 was used for trend calculations from 1971/72 – 1991/92 and 1991/92 – 2011/12). Due to the high variability in snowfall trends, a figure was constructed plotting 21-year snowfall records at 1-year time-step intervals. Along with the trend for each year, associated uncertainty for the trend was also calculated.

Table 8. Time periods used to calculate snowfall trends

Long-term	41-year	21-year
1931/32 - 2011/12	1931/32 - 1971/72	1931/32 - 1951/52
	1971/72 - 2011/12	1951/52 - 1971/72
		1971/72 - 1991/92
		1991/92 - 2011/12

Once initial CNY snowfall trends were calculated, the previous methods were applied to only homogenous COOP stations. Seasonal snowfall totals were averaged between all homogenous snowfall stations producing a single snowfall average for each winter season in CNY from 1931/32 – 2011/12. Trends were recalculated using linear least squares and compared to the initial snowfall trend, which included all available COOP stations.

2.3.3.2 Regional Snowfall Trends

Regional snowfall trends were then calculated based on two regional classifications: wind-direction regions (Table 6) and regions determined by PCA-a and PCA-b. Annual snowfall totals for stations located within the same wind-direction region (Regions A-I), were averaged together to get a single seasonal snowfall total for each year from 1931/32 – 2011/12. Least squares regression was then performed for each region to calculate the snowfall trend for the long-term, 41-year, and 21-year periods (Table 8). After regional snowfall trends were calculated for each wind-direction region, Pearson, two-tailed bivariate correlations were conducted in SPSS. Correlations were run between average annual snowfall totals for each region from 1931/32 – 2011/12. The previous correlation was used to determine regional similarities in high/low snowfall seasons.

Regional snowfall trends were also calculated for the regions determined by PCA-a and PCA-b. Snowfall records for all stations within the same region, identified by PCA-a and PCA-b, were averaged to produce seasonal average snowfalls for each region from 1931/32 – 2011/12. Snowfall trends were then conducted on each region using least squares regressions for three time periods: long-term, 41-years, and 21-years.

2.3.3.3 Station Snowfall Trends

Table 9. Station list by time period. See Appendix A for station abbreviations.

1931-2011	1931-1971	1971-2011	1931-1951	1951-1971	1971-1991	1991-2011
AUB	ABAY	AUB	ABAY	ABAY	AUB	AUB
BEN	AUB	AUR	AUB	AUB	AUR	AUR
BMOOS	BAIN	BEN	BAIN	BAIN	BAIN	BEN
BREW	BEAV	BERG	BREW	BEAV	BEAV	BERG
BVILLE	BMOOS	BMOOS	BVILLE	BEN	BEN	BMOOS
CINCY	BREW	BOON4	CAN	BMOOS	BERG	BOON4
COOP	BVILLE	BREW	CAY	BOON	BMOOS	BREW
CORN	CAN	BVILLE	CLAND	BREW	BOON2	BVILLE
GRN	CAY	CAM	CLE	BVILLE	BREW	CAM
HI	CINCY	CINCY	COOP	CAM	BVILLE	CINCY
HOOK	CLAND	COOP	CORN	CAN	CAM	COOP
LFALLSR	COOP	CORN	DEL	CAY	CAY	CORN
LOW	CORN	CVAL	DRYT	CINCY	CHEP	CVAL
MOVILLE	DEL	FREE	FRANK	CLAND	CINCY	FREE
NOR	DRYT	GRN	FUL	COOP	CLAND	GRN
OS	FRANK	HI	HINCK	CORN	COOP	HI
SHER	FUL	HOOK	JACK	CVAL	CORN	HOOK
SKAN	GRN	LFALLSR	LFALLSM	DEL	CVAL	LOW
STILL	HI	LOW	LFALLSR	DRYT	FRANK	MARY
SYR	HINCK	LYF	LOW	FOR	FREE	MOVILLE
TRENT	HOOK	MOVILLE	MCKV	FRANK	GRIF	NOR
WTR	LFALLSM	NOR	MOVILLE	FREE	GRN	OFRG
	LFALLSR	OFRG	NLON	FUL	HI	OS

Table 9 Continued. Station list by time period.

	LOW	OS	NOR	GRIF	HINCK	SHER
	LYF	SHER	ON3	GRN	HOOK	SKAN
	MOVILLE	SKAN	OS	HI	LFALLSR	STILL
	NB	STILL	SAL	HINCK	LOW	SYR
	NLON	SYR	SHER	HOOK	LYF	TRENT
	NOR	UN	SKAN	LFALLSM	MOVILLE	UN
	OS	WELL	SSP	LFALLSR	NB	WTR
	SAL	WTR	TRENT	LINK	NOR	
	SHER		UTHAR	LOW	OFRG	
	SKAN		WTR	LYF	OS	
	STILL			MOVILLE	SHER	
	TRENT			NB	SKAN	
	WTR			NLON	STILL	
				NOR	SYR	
				OFRG	UT	
				OS	UTOAIR	
				PUL	WELL	
				ROCK	WTR	
				SAL	WTRI	
				SHER		
				SKAN		
				STILL		
				SYR		
				TH		
				TRX		
				UT		
				UTOAIR		
				WTR		
				WTRI		

Snowfall trends for each individual station were also calculated using least squares regression in SciLab. A trend was only calculated for a station if annual snowfall totals were recorded within a certain time frame. For long-term records, station observations must have begun by 1941 and ended no earlier than the 1991/92 season. For the 41-year periods, observations must have occurred prior to 1978 and continued until at least 2004/05. For the 21-year periods, only stations with observations at least 3 years from the start and end year of the record were used. A list of time periods analyzed and the concurrent stations used can be found in Table 9.

2.3.3.4 Monthly Snowfall Trends

Snowfall trends, using least squares regression in SciLab, were also calculated using monthly snowfall data. Monthly snowfall trends were calculated on a regional basis, based on the regional classification from PCA-a and PCA-b. Trends were calculated for winter months (November – April) and only for the long-term and two 41-year periods (Table 8). For each given time period, monthly snowfall trends were calculated at a 10% significance level, similar to previous least squares calculations. Monthly snowfall trends were then compared among winter months to determine if snowfall has been changing consistently throughout CNY for each winter month.

Pearson, two-tailed correlations of monthly snowfall trends for each station from 1931/32 – 2011/12 were also used. Correlations between snowfall trends of each individual month were conducted to determine if snowfall trends for different winter months were highly correlated.

2.3.4 Annual Spatial Snowfall Trends

A second important factor besides temporal changes in snowfall is the spatial change of snowfall in CNY. Therefore, this study examined whether the spatial distribution of snowfall has altered over time in CNY. Annual snowfall totals for each station were converted to an average snowfall total over three different time increments: long-term (1931/31 – 2011/12), 41-year increments (1931/32 – 1971/72 and 1971/72 – 2011/12), and 10-year increments from 1931/32 – 2011/12. It should be noted, that in order for a station to receive an average annual snowfall total, at least 80% of the years for the given time period must have been reported.

Once snowfall averages were constructed, the long-term and 41-year averages were plotted using ArcGIS 10.1, which is a multidimensional geoprocessing software. Spatial maps were created by importing point data into ArcGIS for each available station. Inverse distance weighting (IDW) interpolations were then run in ArcGIS to produce a raster map representing snowfall anomalies for the given time period, for the majority of the CNY region. Each average snowfall map was interpolated using a 10-point interpolation, and plotted at 50 cm intervals from 100 cm – 600+ cm. The maps were analyzed to determine spatial differences of snowfall in CNY. Specifically, this study observed locations of historically high and low snowfall totals, along with differences in snowfall averages for the two 41-year periods.

41-year average snowfall differences were also plotted for CNY using ArcGIS 10.1. The 41-year snowfall differences were calculated by subtracting average snowfall totals for the latter period (1971/72 – 2011/12) by average snowfall totals of the earlier period (1931/32 – 1971/72). Therefore, the 41-year difference figure plotted the difference in snowfall averages between the two periods. 10-year anomaly plots were calculated differently, as snowfall anomalies were determined by taking the long-term (1931/32 – 2011/12) average snowfall total for a station, and subtracting it from the average annual snowfall total for a given decade. The following is an example of a 10-year average snowfall anomaly for the Auburn (AUB) COOP station: (a) Long-term (1931/32 – 2011/12) average annual snowfall (referred to as a) = 232.5 cm; (b) 1930s' average annual snowfall (referred to as b) = 189.9 cm; (c) Snowfall anomaly = b – a; (d) Auburn 1930s' snowfall anomaly = 189.9 cm – 232.5 cm = -42.6 cm.

After snowfall anomalies were constructed, they were plotted using ArcGIS 10.1, similar to the average annual snowfall plots. Spatial snowfall anomaly maps were created using an IDW 10-point interpolation, and plotted at 10 cm intervals from a -75+ cm anomaly to a 75+ cm anomaly. Maps were analyzed to determine decades in which average annual snowfall was anomalously high or low compared to long-term average snowfall totals. 41-year anomaly maps were also used to determine how the latter half of the record compared to the first half of the long-term record.

This study will expand upon the studies of Burnett et al. (2003) and Kunkel et al. (2009b) as temporal and spatial trends in snowfall for a lake effect dominated region will be analyzed. The study by Norton and Bolsenga (1993) attempted to quantify spatiotemporal changes in snowfall for the Great Lakes basin. However, this study will improve upon the spatiotemporal trends found in Norton and Bolsenga (1993), as the data will encompass a longer period of time. Spatial trends in the data will also be mapped using snowfall anomalies based on a 10-year period compared to the long-term mean, instead of using snowfall averages on a 10-year running mean, as the Norton and Bolsenga (1993) did. In addition to the anomaly plots, snowfall difference plots between the later and earlier period were considered.

2.3.5 Principal Component Analyses for Correlated Signals

Along with categorizing stations by regions, PCAs (PCA-c and PCA-d) were run in SciLab to determine common correlated signals in the data. The modes or empirical orthogonal functions (EOFs) determined from the PCAs were used to identify spatial patterns which varied in scale; such as the influence of teleconnections like the NAO, SOI, or AMO. To conduct the PCAs (PCA-c and PCA-d), stations were classified into regions based on the results from the previous PCAs (PCA-a and PCA-b). PCA-c was conducted using the total amount of regions identified in PCA-a and PCA-b, while PCA-d used sub-regions within each region identified by the previous PCAs. It should be noted that observations were expanded to include stations outside the long-term record, and were grouped into a region based on their proximity to the regional classifications extracted from PCA-a and PCA-b. The annual snowfall for each year was then averaged among stations within each region; therefore, a single average snowfall total was reported every year for each of the five regions. Average annual snowfalls for each region were only calculated for years in which there were at least two observations; otherwise that year was removed from the entire record for PCA analysis.

In order to conduct PCA-c and PCA-d, the trend for each station was removed using least squares regression. The subsequent residuals of each region were then used to conduct the PCAs. The computation of the EOFs were done by running the singular value decomposition (SVD) function in SciLab; where M is the transpose matrix of the regions, U is an orthogonal square matrix representing the EOFs, S which is a singular, real diagonal matrix, and V is a singular orthogonal or unitary square matrix (Eq. 2).

$$[U,S,V] = svd(M) \qquad \textbf{Eq. 2}$$

U was analyzed, as each row corresponded to a region, and each column represented a different EOF. The principal components (PCs) were then computed using Eq. 3; where the principal component (PC) is equal to S multiplied by the transpose of V. Once the

PCs were determined, the individual EOFs were calculated for each region (Eq. 4), and plotted compared to the detrended, original annual snowfall data.

PC = S*V' **Eq. 3**

rx_eofy = U (r#,eof#)*pc(eof#,:); **Eq. 4**

Where rx_eofy is the calculated region and EOF, U is the EOF for a given region (r#) and EOF (eof#), and pc is the principal component for a given EOF (eof#). The percent variance was then calculated for each EOF mode and region, by calculating the variance of each individual EOF and dividing it by the variance of the original region data. Bivariate Pearson correlations were then performed in SPSS between the resulting EOFs for both PCAs and the three climate indices (NAO, SOI, and AMO) to determine if the modes may be explained by changes in one of the climate indices.

2.3.6 Factors Influencing Snowfall Changes in Central New York

It is not only imperative to determine trends in annual snowfall for CNY, but possible causes as well. Therefore, possible influences of teleconnections and changes in winter air temperatures and precipitation were analyzed for various regional and temporal scales.

The raw annual normalized value of each climate index (NAO, SOI, and AMO) was plotted using SciLab. Fourier spectral analyses were also constructed (in SciLab) on each index to determine if periodic variations existed in the data. However, due to the lower frequency nature of variations in climate indices, the exact period of the variations cannot be extracted and instead only a possible presence of a periodic variation can be determined. A fit was constructed for each of the three identified modes (NAO, SOI, and

AMO) to the long-term snowfall record for CNY. In order to due this the following equation was solved for and plotted:

$$y(t) = a_o * CI(t) + a_1 * HCI(t) \quad \textbf{Eq. 5}$$

where a_o is the amplitude of the climate index, CI(t) is the time series of the climate index, a_1 is the amplitude of the Hilbert transform of the climate index, and HCI(t) is the Hilbert transform of the climate index. After solving for Eq. 5, the time-series was normalized and plotted along with the normalized long-term snowfall record. Correlations were then conducted between the snowfall record and the normalized time series of each climate index. Correlations were also run based on a time lag between 0-3 years to determine if annual snowfall totals may have lagged behind the seasonal influences of the climate indices.

Linear trends were conducted using least squares regression in SciLab for average winter air temperature throughout CNY and average winter precipitation totals by regions (classified by PCA-a and PCA-b) for the time periods listed in Table 8. Average annual air temperatures for CNY were then normalized by subtracting each value by 32ºF (0ºC). Therefore, negative values represented freezing mean winter temperatures and positive values represented above-freezing average winter temperatures. The normalized mean temperatures were then plotted using a bar chart in Excel, and used to determine if changing temperatures about the freezing threshold are influencing fluctuations in annual snowfall totals.

Long-term CNY annual snowfall, winter air temperature, and winter precipitation data were also normalized by subtracting the mean long-term value from the seasonal value for each year, and then dividing by the standard deviation of the long-term record.

The normalized values were then run through a 1.5-year Gaussian filter in SciLab and plotted to determine any similarities in the filtered time series.

Monthly long-term trends in air temperature and precipitation were also calculated, using least squares regression, for each individual winter month. Precipitation and air temperature trends were compared to annual snowfall trends to determine if either factor influenced the behavior of snowfall trends for each of the time periods.

Finally correlations between a stations' elevation, distance from the fixed point over Lake Ontario (43.6ºN, 76.8ºW), and annual snowfall trend were performed for various time records: long-term, 41-year, and 21-year (Table 8). Correlations were conducted using the Pearson, two-tailed bivariate correlations in SPSS. The previous correlations were used to determine if the annual snowfall trend experienced by a station was correlated with the station's elevation and/or distance from Lake Ontario.

Chapter 3: Results

The findings of this study aim to improve the understanding of the spatial and temporal changes of snowfall in Central New York State. Temporal trends of annual and monthly snowfall in CNY were analyzed at various time intervals. Possible underlying causes of changes in snowfall were also examined through correlations and least squares regression, such as winter air temperatures, winter precipitation totals, elevation of an area, and the distance of a location in respects to Lake Ontario. Spectral analyses and PCAs were used to identify periodic signals in snowfall data, such as the influence of teleconnections. Spatial maps were constructed to provide a visual representation of how average snowfall totals have changed over time, along with visual representations of snowfall anomalies comparing a given time interval to the previous time interval. The understanding of the spatial and temporal trends was then used to determine how snowfall has changed from 1931/32 – 2011/12 in CNY, and if changes in snowfall are driven by lake-effect processes or non-lake-effect processes.

3.1 Principal Component Analyses for Regional Classifications

The results of the rotated component matrices from the PCAs that were computed in SPSS were used to group stations by similarities in annual snowfall totals. The results of the initial PCA (referred to as PCA-a), in which missing values were removed from the record, are outlined in Table 10. Four distinct modes were present in the analysis, with each station categorized into a single mode based on the station’s value in proximity to the absolute value of 1. The mode in which a station was classified is represented as a bold number in Table 10. There were eight stations grouped into Mode 1, seven stations in Mode 2, four stations in Mode 3, and three stations in Mode 4. If a station was not clearly correlated with a single mode (i.e. correlation below 0.50 or a strong correlation between multiple modes within 0.15 of each other), then the station was tentatively categorized into a mode, and further analyses were done.

Table 10. Results of PCA-a. Bold numbers with a *, mean the station was not clearly defined to one mode, and instead may have been correlated with two or more modes. See Appendix A for station abbreviations.

Station	Mode 1	Mode 2	Mode 3	Mode 4
AUB	_	0.35	**0.86**	_
GRN	_	**0.97**	_	_
NOR	_	**0.88**	0.46	_
SHER	0.33	**0.88**	_	_
CINCY	**0.71***	0.57	0.38	_
BMMOS	_	_	_	**0.94**
LFALLSR	**0.84**	_	_	0.45
STILL	**0.91**	_	_	0.35
WTR	**0.98**	_	_	_
HI	**0.78**	_	_	0.60
HOOK	**0.91**	0.32	_	_
LOW	0.54	_	_	**0.83**
MOVILLE	_	_	**0.91**	_
TRENT	**0.92**	_	_	_
BVILLE	-0.38	0.58	**0.72***	_
BREW	0.57	**0.62***	_	0.49
SKAN	_	**0.95**	_	_
SYR	_	**0.73***	0.61	_
BEN	0.36	_	**-0.92**	_
OS	**0.90**	0.33	_	_
COOP	0.53	**0.74**	0.38	_
CORN	-0.47	_	0.54	**-0.67***

A second PCA (a.k.a. PCA-b) was then conducted, in which missing values for each station were replaced with the mean seasonal snowfall. The results for this PCA are displayed in Table 11. Again, four distinct modes were present among the stations, with

Mode 1 representing the greatest amount of stations (8), followed by Mode 2 (7), Mode 3 (4), and Mode 4 (3), with bold numbers representing the corresponding mode for each station. Once again, some stations were not clearly identified with a single mode.

Table 11. Results of PCA-b. Bold numbers with an asterisk mean the station was not clearly defined to one mode, and instead may have been correlated with two or more modes. See Appendix A for station abbreviations.

Station	Mode 1	Mode 2	Mode 3	Mode 4
AUB	**0.82**	_	_	_
GRN	_	_	**0.79**	_
NOR	0.40	_	**0.78**	_
SHER	**0.62***	_	0.59	_
CINCY	**0.52**	_	_	_
BMOOS	_	_	_	**0.85**
LFALLSR	_	_	**0.70**	_
STILL	_	0.33	_	**0.82**
WTR	_	**0.65**	0.31	0.31
HI	_	**0.83**	_	_
HOOK	_	**0.75**	_	0.34
LOW	0.31	**0.56***	_	0.53
MOVILLE	**0.65***	0.45	_	_
TRENT	_	0.47	**0.69**	_
BVILLE	0.46	_	0.31	**0.56***
BREW	**0.50***	0.43	_	0.47
SKAN	**0.62***		0.31	0.49
SYR	**0.77**	0.34	_	_
BEN	_	**0.47***	_	0.41
OS	0.57	**0.61***	_	_
COOP	**0.60***	_	0.50	0.31
CORN	**0.67**	_	0.35	_

The results of the previous PCAs were then compared to determine region classifications within CNY. Comparing the two PCAs, three pairs of modes appeared to be identical to each other: Mode 1 in PCA-a and Mode 2 in PCA-b, Mode 3 in PCA-a and Mode 1 in PCA-b, and Mode 4 in PCA-a and Mode 4 in PCA-b. The final modes (Mode 2 in PCA-a and Mode 3 in PCA-b) had stations in similar locations, but there were noticeable differences between the two modes. For example, stations in Chenango and Otsego counties in Mode 2 of PCA-a, correlated more with stations near Onondaga County; while stations in Chenango and Otsego counties in Mode 3 of PCA-b were highly correlated with stations in Herkimer and Oneida counties. Therefore, the two modes were treated separately.

Five distinct regions were classified for CNY from the resulting modes in PCA-a and PCA-b (Figure 11). The five regions are all located within a general area in CNY: Region 1 corresponds to southwestern CNY including parts of Cayuga, northwestern Chenango, Cortland, western Madison, and Onondaga counties; Region 2 is located in southeast CNY including Chenango, western Madison, Otsego, and southern Herkimer counties; Region 3 is the smallest region located in east-central CNY covering Oneida and southern-central Herkimer counties; Region 4 is elongated and passes over northern Onondaga, Oswego, northern Oneida, northern Herkimer, and eastern Lewis counties; and the final region, Region 5, is concentrated in northwest CNY along Lake Ontario, dispersing over northern Oswego, western Lewis, and Jefferson counties. All snowfall stations with a reliable snowfall record of at least 5-years (93 stations) were then classified into one of the five regions (Table 12).

A second region classification was used to subdivide the five larger regions into 12 distinct smaller regions (Figure 12). As described in this section, the second number attached to the sub-region classification refers to the original larger region (see Figure 11) and the first numbers refers to the specific sub-region within that larger region, so that region 2.1 is the second sub-region of region number 1. In some cases, the sub-region overlapped two main regions, hence for example 3.1/2 is a sub-region, named 3, which has some area in both region 1 and 2. Regions 1.1, 2.1 were subdivisions of Region 1; Region 3.1/2, also a subdivision of Region 1, overlapped partly with Region 2. Apart from Region 3.1/2, Region 2 was divided into two other sub-regions labeled Regions 4.2 and 5.2. Region 6.3 comprised the whole are of Region 3, while Region 7.1/4/5 overlapped with Regions 1 and 4, along with one station from Region 5. Region 8.4/5 overlapped with part of region 4 and also southern areas of Region 5. Region 9.4 comprised the majority of the eastern stations in Region 4, and Region 10.5/4, 11.5, and 12.5 were subsections of Region 5, with the two most northern stations in Region 4 grouped into region 10.4/5.

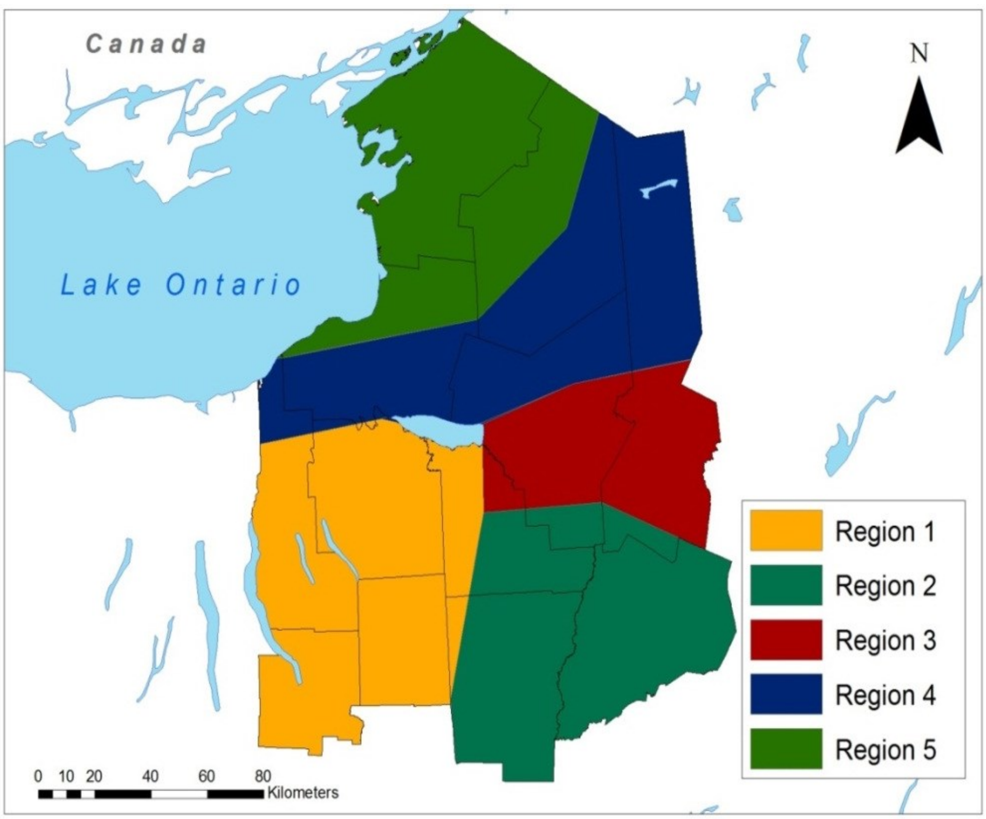


Figure 11. Regions classifications based on PCA-a and PCA-b.

Table 12. Stations listed by regions classified by PCA-a and PCA-b. See Appendix A for station abbreviations.

Region 1	Region 2	Region 3	Region 4	Region 5
AUB	BAIN	FRANK	BMOOS	ADS
AUR	CHEP	GRV	BOON2	ABAY
BVILLE	CVAL	JACK	BOON4	BRNS
CAN	COOP	LFALLS5	BREW	BEAV
CAY	GRN	LFALLSR	CAM	BEN
CINCY	HAM	LFALLSM	CLE	BRIV
CORN	MARY	NEW	CON	BON
CLAND	NB	SAL	CON6	FTD
DRYT	NOR	DEL	EFAL	HOOK
FREE	ON3	DELD	FOR	LOW
SYR	ON3SE	GRIF	FUL	OS
ITH	ROCK	HINCK	HI	PUL
LINK	SSP	TRENT	LYF	REC
LOK	SHER	UTCAIR	MAL	RICH
MOVILLE	SUNYO	UTHAR	MCKV	TH
MTP	UN	UTOAIR	NLAKE	WTR
SKAN		UT	OFRG	WTRI
ESF		WEST	STILL	WELL
TRX		NLON	TUR	
TULLY				
BERG				

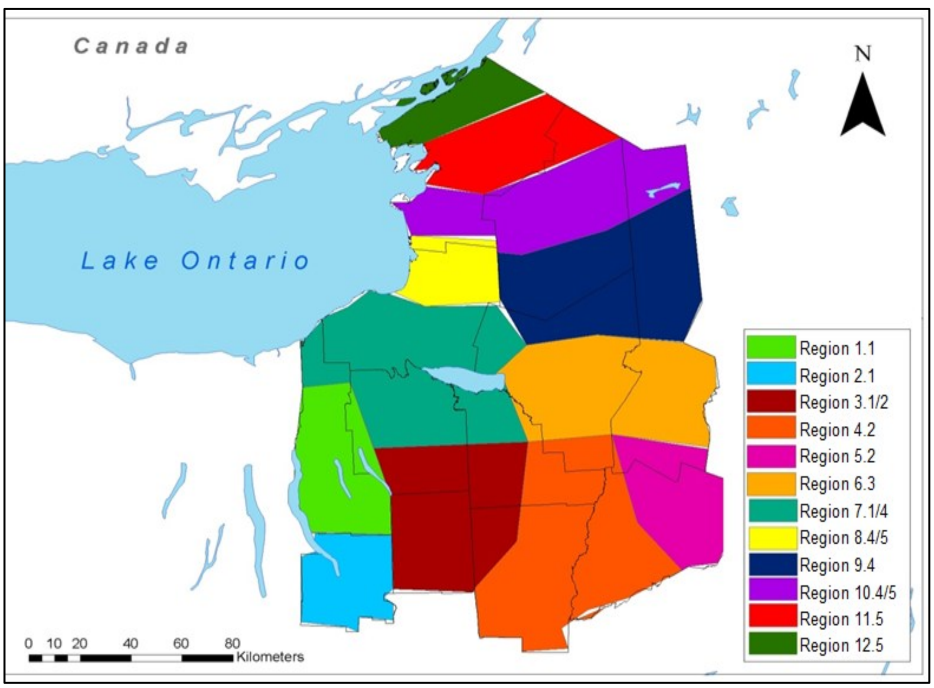


Figure 12. CNY sub-regions classified by PCA-a and PCA-b.

Table 13. Stations listed by sub-regions classified by PCA-a and PCA-b. See Appendix A for station abbreviations.

R1.1	R2.1	R3.1/2	R4.2	R5.2	R6.3	R7.1/4	R8.4/5	R9.4	R10.4/5	R11.5	R12.5
AUB	CORN	CINCY	BAIN	CHEP	DEL	BVILLE	BEN	BMOOS	ADS	BRIV	ABAY
AUR	FREE	CLAND	GRN	CVAL	DELD	BREW	PUL	BOON2	BRNS	BON	TH
CAY	ITH	DRYT	HAM	COOP	FRANK	CAM	RICH	BOON4	BEAV	FTD	WELL
LOK	MTP	LINK	MARY	SSP	GRV	CAN		FOR	EFAL	WTR	
SKAN		MOVILLE	NB		GRIF	CLE		HI	HOOK	WTRI	
		TRX	NOR		HINCK	CON		LYF	LOW		
		TULLY	ON3		JACK	CON6		MCKV	REC		
		BERG	ON3SE		LFALLS5	FUL		NLAKE	STILL		
			ROCK		LFALLSR	SYR		OFRG			
			SHER		LFALLSM	MAL		TUR			
			SUNYO		NLON	OS					
			UN		NEW	ESF					
					SAL						
					TRENT						
					UT						
					UTCAIR						
					UTHAR						
					UTOAIR						
					WEST						

3.1.1 Summary of PCAs for Regional Classifications

Five distinct regions in CNY were determined using the results of PCA-a and PCA-b. Four of the regions (Regions 1, 2, 3, and 5) identified corresponded to a specific region in CNY (e.g. Region 1 covered southwest CNY), while the fifth region (Region 4) covered a long, but narrow stretch of CNY. Twelve sub-regions were then identified, which were based on the previous five regions and correlations between stations.

3.2 Snowfall Trends

As previously mentioned all trends were calculated using the manual least squares algorithm in SciLab, which calculated the bias, trend, and the standard error of the data (one standard deviation away), while periodic signals were not included in initial trend calculations. Using degrees of freedom and the standard error, uncertainty of the trend was calculated at the 10% significance level. Prior to calculating the trend of the data set using least squares regression, the autocorrelation was calculated to determine if there was a strong correlation (> 0.5) in the data, and was again calculated with the residuals after calculating the trend.

3.2.1 Central New York Snowfall Trends

Initial CNY snowfall trends were calculated (Figure 13) using all available stations within CNY. The highest positive snowfall trends for CNY occurred from 1951/52 – 1971/72, 2.26 +/- 1.08 in. yr^{-1} (5.74 +/- 2.74 cm yr^{-1}), with the largest negative trend from 1971/72-1991/92, -2.09 +/- 1.30 in. yr^{-1} (5.31 +/- 3.30 cm yr^{-1}). Snowfall trends from 1931/32 – 2011/12, 1931/32 – 1971/72, and 1931/32 – 1951/52 were all significant (at the 10% level) and ranged from 0.46 – 1.26 in. yr^{-1}. Two time periods (1971/72 – 2011/12 and 1991/92 – 2011/12), did not have statistically significant (to the 10% level) snowfall trends.

After filtering stations for inhomogeneities, the snowfall records of stations deemed homogenous (Table 4) were analyzed. Least squares regression was then used on the homogenous stations to determine trends for multiple time periods: long-term, 41-year, and 21-year increments (Figure 13). Compared to the initial snowfall trend for CNY, three out of the five significant snowfall trends in which only homogenous stations were used, including the long-term trend (0.23 +/- 0.20 in. yr^{-1} [0.59 +/- 0.50 cm yr^{-1}]), were smaller than the initial trend calculated. The two periods (1931/32 – 1951/52 and 1951/52 – 1971/72) in which trends actually increased had contrasting results. The snowfall trend from 1931/32 – 1951/52 both increased in magnitude and decreased in uncertainty after filtering for inhomogeneities in the data; however, both the trend and uncertainty increased for 1951/52 - 1971/72.

An autocorrelation was performed prior to calculating the trend. Since the initial trend calculated only accounted for the bias and trend, the autocorrelation of the residuals was the same as the autocorrelation prior to calculating the trend. An example of the autocorrelation prior to calculating a trend using least squares regression for the long-term period for initial and filtered stations is presented in Figure 14. It should be noted that even though there is no obvious, large correlation in data there are still some smaller residual correlations which may have impacted the trend calculation. For example, around 27.5 years both autocorrelations demonstrate a small correlation peaking at -0.3. The homogenous stations also exemplified a larger correlation (~ 0.2) near the 27 years.

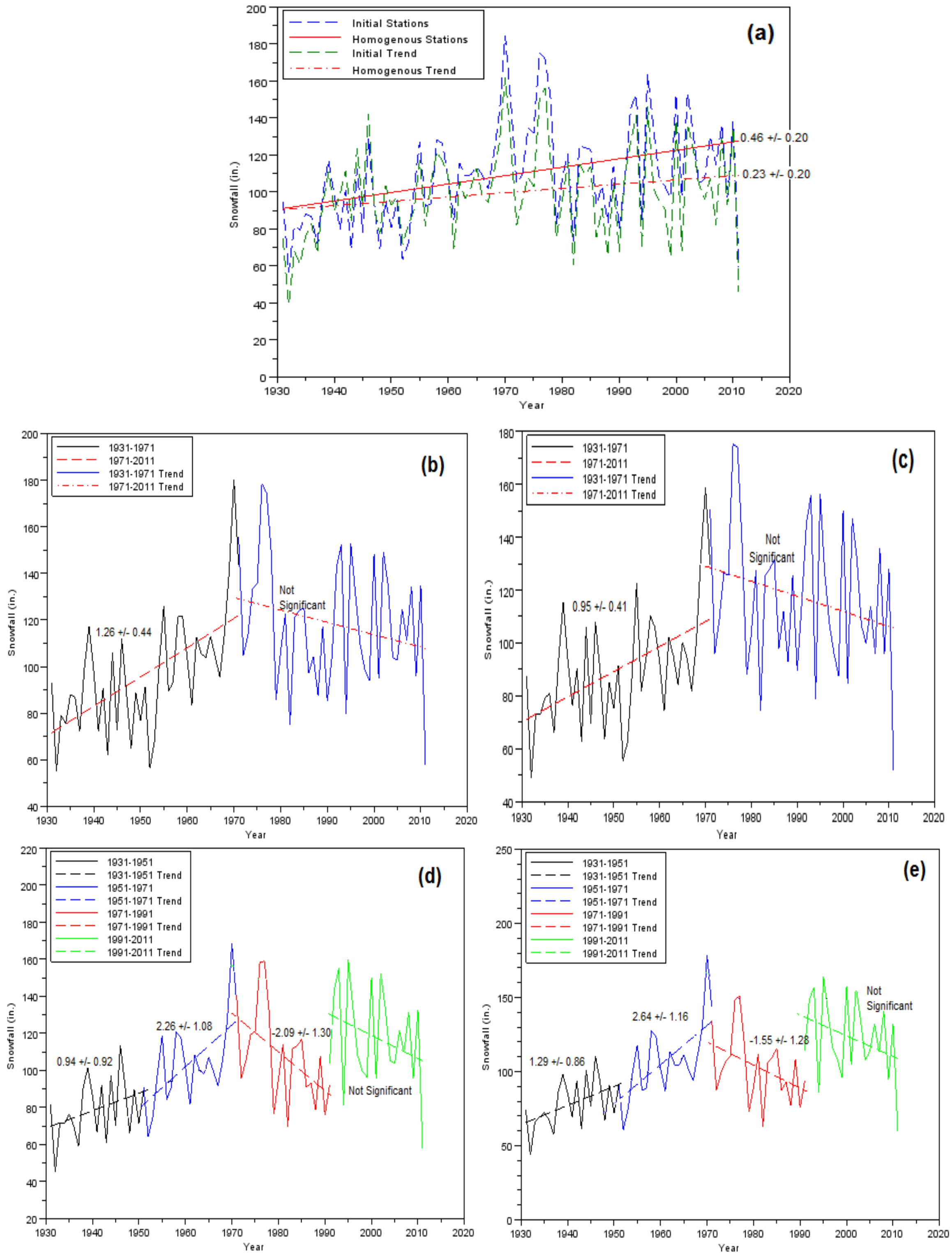


Figure 13. Initial and homogenous snowfall trends for multiple time intervals. Trends are reported at the 10% significance level. Figure 13a is the long-term trend, Figure 13b is the 41-year trends using initial COOP stations. Figure 13c is the 41-year trends using homogenous COOP stations. Figure 13d is the 21-year trends using initial COOP stations. Figure 13e is the 21-year trends using homogenous COOP stations.

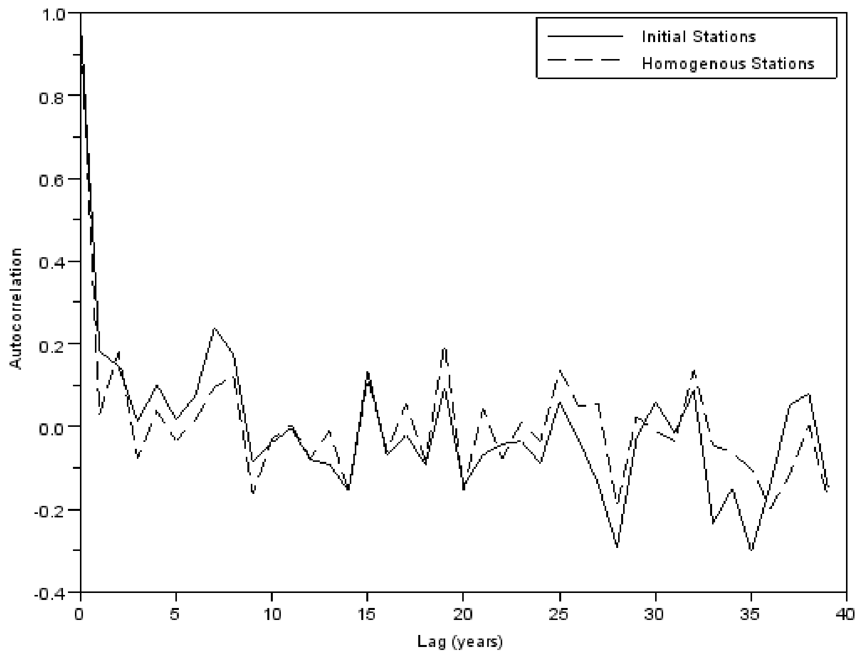


Figure 14. Autocorrelations of average CNY snowfall. The solid line represents that autocorrelation of CNY snowfall using the average snowfall of all available COOP stations, and the dashed line represents that autocorrelation of average CNY snowfall using only station deemed homogenous.

Similar to the calculations of other snowfall trends, Figure 15 demonstrates the high variability in CNY snowfall trends at 21-year time increments. It is apparent that during the early years (i.e. 1940s – 1950s), snowfall trends gradually increased throughout time, reaching a maximum (nearly 3 in. yr^{-1}) during the early and late 1960s. After the peak during the 1960s, snowfall trends decreased substantially into the early 1980s, reaching a minimum (approximately -3 in. yr^{-1}) during the late-1970s/early 1980s. After the minimum in 21-year snowfall trends, trends again generally increased until the early/mid 1990s. However, unlike the early decades, snowfall trend increases were not as high and maximized at approximately 1 in. yr^{-1}. After the second peak in snowfall trends during the mid-1990s, snowfall trends began to decrease again during the late-1990s.

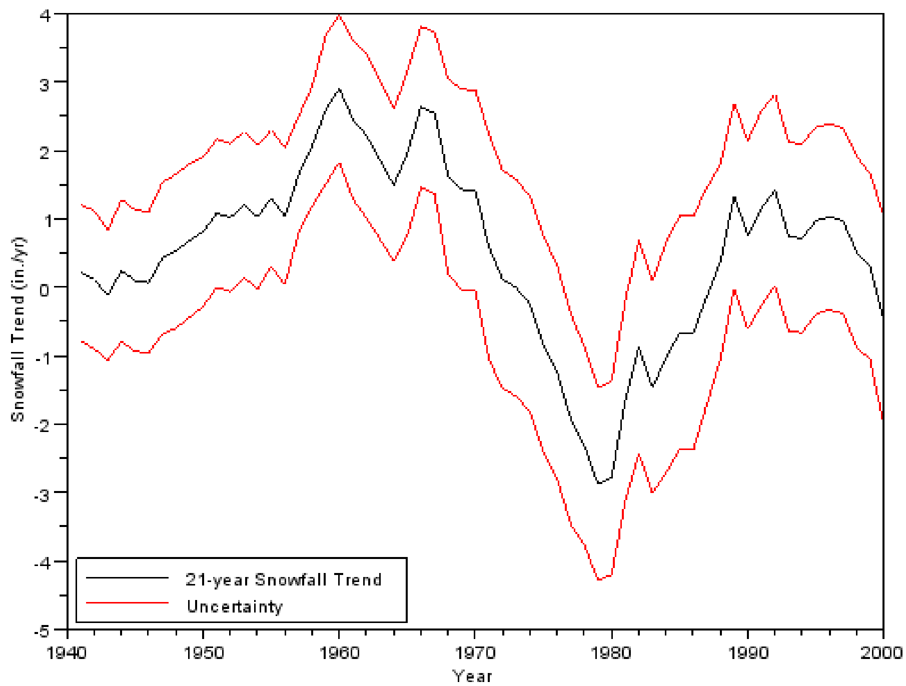


Figure 15. 21-year CNY snowfall trends at 1-year time-step intervals. The black line represents the 21-year snowfall trend for each year from 1942-2000, while the red lines are the associated uncertainty of the trends at a 10% significance.

3.2.1.1 Summary of Central New York Snowfall Trends

The long-term snowfall trend for CNY increased by 0.46 in. yr^{-1} (0.18 cm yr^{-1}), but was lower once inhomogeneous stations were filtered out, 0.23 in. yr^{-1} (0.09 cm yr^{-1}). Significant increases in snowfall were greatest during the earlier periods (i.e. 1931/32 – 1971/72) and were considerably lower and even negative for latter periods (1971/72 – 2011/12). There were considerable periodic variations that were noticed from the autocorrelation of the residuals after calculating the linear trend of CNY snowfall.

3.2.2 Regional Snowfall Trends

3.2.2.1 Wind Direction Regions

Snowfall trends for multiple time increments for the 8 regions identified by their orientation to a fixed location over Lake Ontario are presented in Figure 16. During all three time periods, significant (to the 10% level) snowfall trends for each region were positive. From 1931/32 – 2011/12, the regions furthest east of Lake Ontario (C-F) all had a significant (to the 10% level) increase in snowfall compared to regions with a more southerly and northerly orientation. Regions C, D, and E had very similar snowfall trends from 1931/32 – 2011/12, while Region F had a slightly larger trend, 0.84 +/- 0.29 in. yr^{-1} (2.13 +/- 0.74 cm yr^{-1}). From 1931/32 – 1971/72 snowfall trends were at a maximum for every region, with Region F again having the greatest snowfall trend, 1.51 +/- 0.63 in. yr^{-1} (3.84 +/- 1.60 cm yr^{-1}). Regions A-C all had similar snowfall trends, ranging from 0.63 in. yr^{-1} (1.60 cm yr^{-1}) to 0.89 in. yr^{-1} (2.26 cm yr^{-1}). The initial trends calculated from 1971/72 – 2011/12 were a mix between positive and negative trends, but at a 10% significance, none of the regional trends during this period were significant.

Pearson two-tailed correlations were used to determine correlations between average annual snowfalls between the eight different regions classified by wind direction (Table 14). The significance of the correlations was based on the assumption that all values were independent; therefore, degrees of freedom were not reduced. All of the regions had a significant correlation (at the 1% level) between 0.34 and 0.94. Regions 3 and 4 had the greatest correlation of any two snowfall records (0.94), while Region 1 had two of the lowest correlations between other stations, a 0.34 correlation with Region 7 and a 0.35 correlation with Region 8. A majority of the high correlations were between two adjacent regions; however, Regions 1 and 3 (0.76) and 2 and 4 (0.78) were highly correlated with each other.

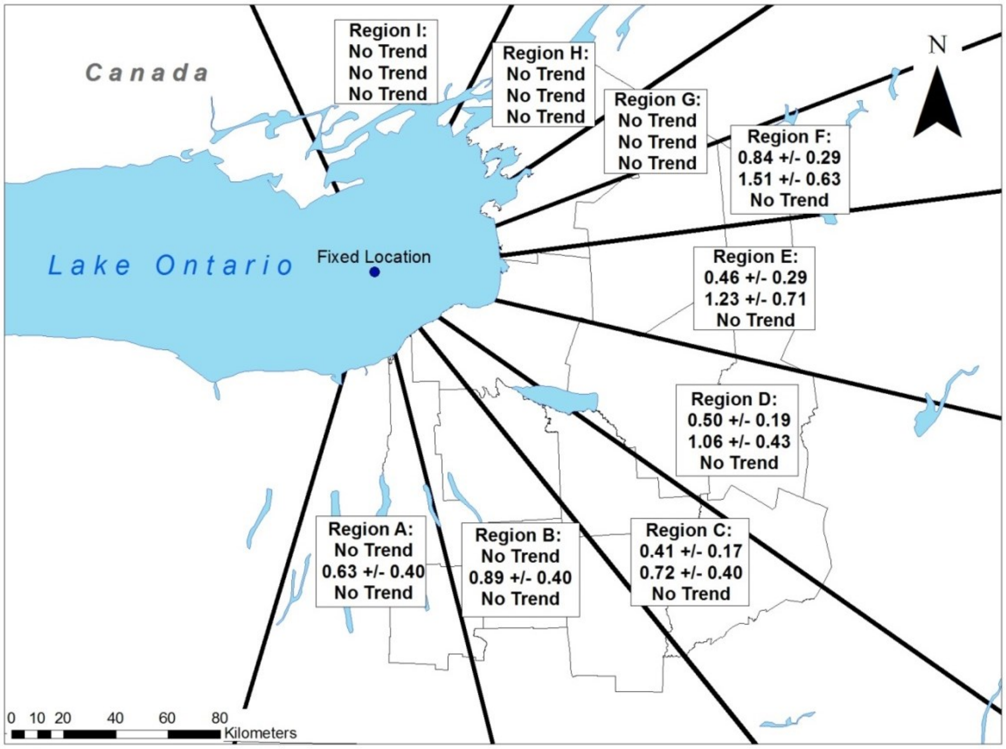


Figure 16. Snowfall trends based on average annual snowfall totals for 8 regions identified by their orientation to a fixed point over Lake Ontario. Trends and uncertainties are reported in in. yr^{-1} and are significant at the 10% level. The trends are ordered from top to bottom: first trend is from 1931/32-2011/12, the second trend is from 1931/32-1971/72, and the third trend is from 1971/72-2011/12.

Table 14. Annual snowfall correlations between regions based on orientation to Lake Ontario. All values are significant at the 1% level. Numbers in bold represent the highest correlation for the regions listed in rows.

Region	1	2	3	4	5	6	7	8
1	_	_	_	_	_	_	_	_
2	0.86	_	_	_	_	_	_	_
3	0.76	0.86	_	_	_	_	_	_
4	0.69	0.78	0.94	_	_	_	_	_
5	0.42	0.57	0.65	0.71	_	_	_	_
6	0.35	0.53	0.66	0.70	0.80	_	_	_
7	0.34	0.40	0.55	0.56	0.60	0.72	_	_
8	0.56	0.52	0.52	0.57	0.56	0.48	0.51	_

3.2.2.2 PCA Regions

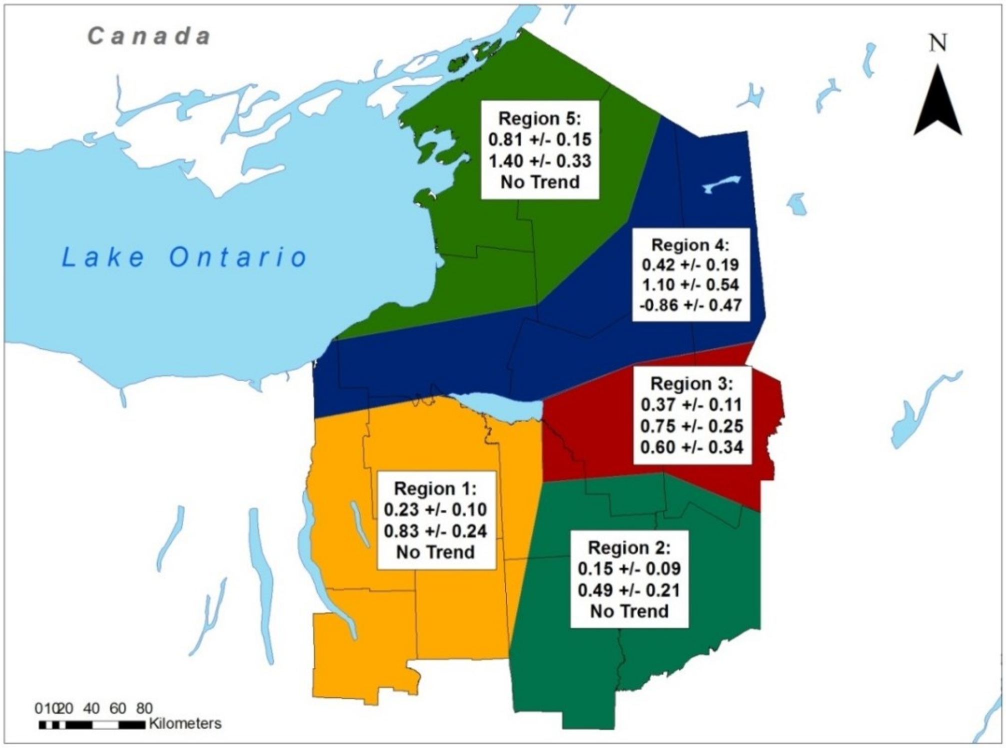


Figure 17. Regional snowfall trends classified by PCA-a and PCA-b for longer time intervals. Trends and uncertainties are reported in in. yr^{-1} and are significant at the 10% level. The trends are ordered from top to bottom: first trend is the long-term trend (1931/32-2011/12), the second trend is from 1931/32-1971/72, and the third trend is from 1971/72-2011/12.

The five regions identified by PCA-a and PCA-b were then used to calculate average annual snowfall trends for multiple time periods. Figure 17 represents the long-term and 41-period trends for each individual region. Positive, significant (at the 10% level) snowfall trends were calculated for all five regions during the 1931/32 – 2011/12 and 1931/32 – 1971/72 time periods. The greatest snowfall trend for both time increments was for Region 5 at 0.81 +/- 0.15 in. yr^{-1} (2.06 +/- 0.38 cm yr^{-1}) and 1.40 +/- 0.33 in. yr^{-1} (3.56 +/- 0.83 cm yr^{-1}), respectively. Snowfall trends for all regions decreased from 1931/32 – 1971/72 to 1971/72 – 2011/12, with Region 4 actually having a negative trend of -0.86 +/- 0.47 in. yr^{-1} (-2.19 +/- 1.18 cm yr^{-1}). From 1971-2011, three regions (Region 1, 2, and 5) did not have a statistically significant (at the 10% level) snowfall trend.

The longer time periods were then divided up into 21-year increments and snowfall trends were calculated for each region (Figure 18). Some commonalities in the trends were that all significant (to the 10% level) snowfall trends from 1931/32 – 1951/52 and 1951/52 – 1971/72 were positive, while trends from 1971/72 – 1991/92 and 1991/92 – 2011/12 were negative. Region 4 had the largest snowfall trends for three of the four time periods (1951/52 – 1971/72, 1971/72 – 1991/92, and 1991/92 – 2011/12), while Region 1 and Region 2 had the smallest trends for each of the time intervals. The largest trend among any period was from 1951/52 – 1971/72, in which Region 4 had a snowfall trend of 4.23 +/- 1.04 in. yr^{-1} (10.7 +/- 2.64 cm yr^{-1}). Only two regions (Region 1 and 4) had a significant (to the 10% level) snowfall trend from 1991/92 – 2011/12, while the other three regions had no discernible trend.

3.2.2.3 Summary of Regional Snowfall Trends

Significant snowfall trends for wind direction regions were concentrated in Regions C-F, while smaller or no snowfall trends were calculated for outer regions (Regions A, B, G, and H). In general, regions adjacent to one another were highly correlated, with a decrease in the correlation the further apart that the regions were. Similar to the CNY trends, PCA regional trends were highest during the earlier decades of the study and lower during the latter decades. Regions 4 and 5 demonstrated the largest snowfall trends in CNY, while Region 2 had the smallest trend.

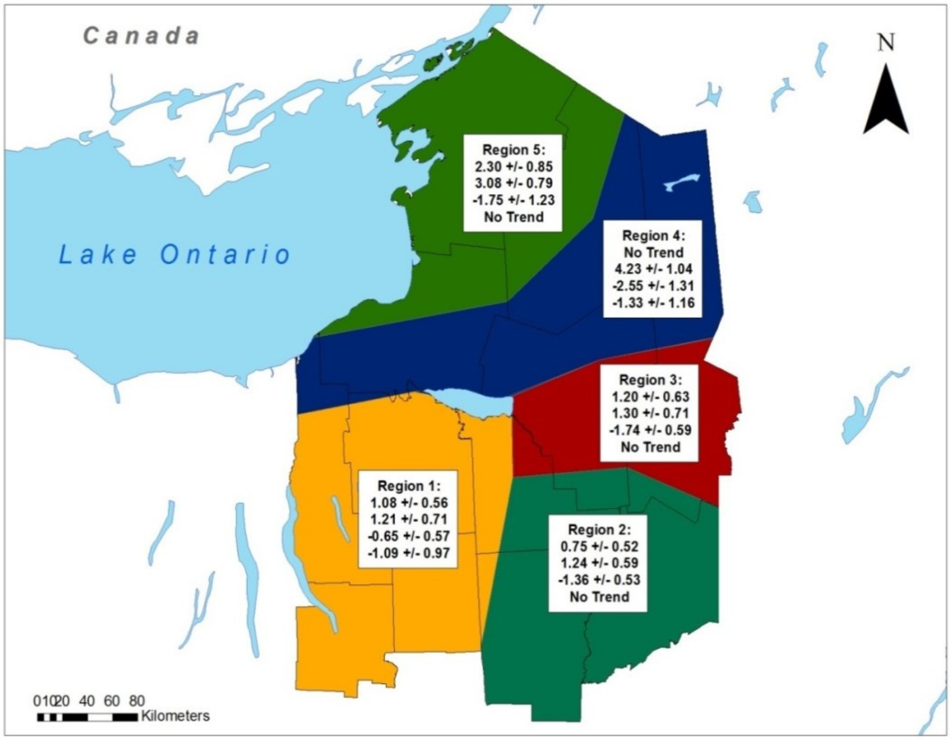


Figure 18. Regional snowfall trends classified by PCA-a and PCA-b for 21-year time intervals. Trends and uncertainties are reported in in. yr^{-1} and are significant at the 10% level. The trends are ordered from top to bottom: first trend is from 1931/32-1951/52, second trend is from 1951/52-1971/72, third trend is from 1971/72-1991/92, and fourth trend is from 1991/92-2011/12.

3.2.3 Station Snowfall Trends

Station snowfall trends for locations around CNY were analyzed using least squares regression (Table 15). The average long-term snowfall trend from 1931/32 – 2011/12 for CNY stations was 0.58 +/- 0.31 in. yr^{-1} (1.5 +/- 0.8 cm yr^{-1}), significant at the 10% level. Comparatively, the average snowfall trend for CNY stations from 1931-1971 was 1.63 +/- 0.74 in. yr^{-1} (4.1 +/- 1.9 cm yr^{-1}) and from 1971/72 – 2011/12 no significant trend was noticed. The majority (10/12) of snowfall trends for individual COOP stations in CNY from 1931-2011 were positive, with the greatest trend (1.53 +/- 0.82 in. yr^{-1} or 3.90 +/- 2.10 cm yr^{-1}) calculated for Hooker 12 NNW (see Appendix A for station listings). Baldwinsville demonstrated the largest negative trend during this period, with annual snowfall totals decreasing by 0.30 +/- 0.27 in. yr^{-1} (0.80 +/- 0.70 cm yr^{-1}). In particular, the long-term snowfall trend for Syracuse (SYR) was 0.56 +/- 0.28 in. yr^{-1} (1.42 +/- 0.71 cm yr^{-1}).

Table 15. Long-term snowfall trends by station. Trends and uncertainties are reported in in. yr^{-1} and are significant at the 10% level. See Appendix A for station abbreviations. Trends with uncertainty less than 75% the value are italicized.

	1931-2011		**1931-1971**		**1971-2011**	
Station	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
AUB	*0.90*	*0.23*	*1.04*	*0.53*	0.97	0.73
GRN	-0.24	0.17	_	_	_	_
NOR	_	_	_	_	_	_
SHER	0.23	0.15	_	_	*0.76*	*0.45*
CINCY	*0.52*	*0.30*	*1.14*	*0.56*	_	_
BERG	_	_	_	_	_	_
BMOOS	_	_	*3.07*	*0.86*	*-2.06*	*1.26*
LFALLSR	_	_	_	_	_	_
OFRG	_	_	_	_	*-4.14*	*1.40*
STILL	_	_	2.40	0.95	*-1.39*	*0.83*
WTR	_	_	_	_	_	_
HI	*1.31*	*0.40*	0.94	0.70	1.21	1.16
HOOK	*1.53*	*0.82*	*3.44*	*1.50*	*-2.78*	*1.61*
LOW	*0.46*	*0.27*	*1.76*	*0.71*	_	_
MOVILLE	*0.71*	*0.25*	_	_	*1.33*	*0.86*
BOON4	_	_	_	_	*-2.40*	*1.06*
CAM	_	_	_	_	_	_
BVILLE	-0.30	0.27	*1.44*	*0.66*	_	_
BREW	_	_	*1.75*	*0.81*	_	_
SKAN	_	_	*1.19*	*0.68*	_	_
SYR	*0.56*	*0.28*	0.92	0.70	0.84	0.79
UN	_	_	_	_	_	_
OS	*1.04*	*0.33*	*2.23*	*0.83*	_	_
COOP	0.26	0.20	*0.89*	*0.48*	_	_
CORN	_	_	*0.63*	*0.36*	7.05	6.84
Average	**0.58**	**0.31**	**1.63**	**0.74**	**-0.06**	**1.55**

From 1931/32 – 1971/72, all fourteen of the significant (to the 10% level) snowfall trends were positive. The highest trend was again located at Hooker 12 NNW, 3.44 +/- 1.50 in. yr^{-1} (8.74 +/- 3.81 cm yr^{-1}), followed by Big Moose 3 SE, 3.07 +/- 0.86

in. yr^{-1} (7.80 +/- 2.18 cm yr^{-1}). Compared to the long-term record, annual snowfall trends also increased for Syracuse (SYR), to 0.92 +/- 0.70 in. yr^{-1} (2.34 +/- 1.78 cm yr^{-1}). Snowfall trends from 1971/72 – 2011/12 were much more inconsistent, with only six out of the eleven reported stations demonstrating a significant (to the 10% level) positive trend, compared to five stations with a negative trend. This caused the average snowfall trend for stations to decrease to -0.06 +/- 1.55 in. yr^{-1} and was not significant (to the 10% level). The snowfall trend calculated for Syracuse (SYR) during this time was still relatively high compared to other regions, 0.84 +/- 0.79 in. yr^{-1} (2.1 +/- 2.0 cm yr^{-1}). There were two large trends noticed from 1971-2011: Cornell (7.05 +/- 6.84 in. yr^{-1}) and Old Forge (-4.14 +/- 1.40 in. yr^{-1}). However, especially for the Cornell trend, the uncertainty was nearly identical to the trend; therefore it is highly plausible that the high trend noticed at Cornell was actually much closer to zero.

The long-term periods previously examined were then subdivided into four 21-year periods, and annual snowfall trends were calculated (Table 16). The first two periods experienced a significant (to the 10% level) increase in snowfall for average station trends, while the final two time periods exemplified a decrease in snowfall over time. The largest snowfall trend occurred from 1951-1971 in which snowfall throughout CNY station increased on average 3.55 +/- 1.93 in. yr^{-1}. (9.1 +/- 4.9 cm yr^{-1}). Only 1 out of the 14 significant snowfall trends determined from 1931-1951 were negative (McKeever), with the highest trend noticed at Salisbury (4.53 +/- 1.24 in. yr^{-1} or 11.5 +/- 3.1 cm yr^{-1}). Similarly, all 21 stations from 1951/52 – 1971/72 with a significant snowfall trend were positive. Extreme snowfall trends were experienced during this time period, as Hooker 12 NNW had a trend between 7 and 13 in. yr^{-1} (18-33 cm yr^{-1}).

Contrary to the 1951/52 – 1971/72 period, all stations with a significant snowfall trend (22) were negative trend. From 1991/92 – 2011/12 only six stations had a significant snowfall trend (at the 10% level), all of which were negative.

Table 16. 21-year annual snowfall trends by station. Trends and uncertainties are reported in in. yr^{-1} and are significant at the 10% level. See Appendix A for station abbreviations. Trends with uncertainty less than 75% the value are italicized.

	1931-1951		1951-1971		1971-1991		1991-2011	
Station	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
AUB	_	_	_	_	_	_	_	_
AUR	_	_	_	_	_	_	*-2.01*	*1.50*
CAY	1.49	1.19	_	_	-0.99	0.76	_	_
BAIN	_	_	_	_	*-3.60*	*1.09*	_	_
GRN	_	_	*1.84*	*1.10*	_	_	_	_
NB	_	_	_	_	-2.23	1.90	_	_
NOR	_	_	_	_	_	_	-1.70	1.41
SHER	_	_	_	_	-0.80	0.71	_	_
CINCY	_	_	*1.94*	*1.34*	_	_	-4.03	4.00
CLAND	*1.80*	*1.02*	_	_	_	_	_	_
TRX	_	_	*2.79*	*1.31*	_	_	_	_
BERG	_	_	_	_	_	_	_	_
BMOOS	_	_	_	_	*-7.29*	*3.47*	_	_
CHEP	_	_	_	_	*-1.59*	*1.01*	_	_
FRANK	_	_	*2.03*	*1.28*	*-2.34*	*0.93*	_	_
JACK	_	_	_	_	_	_	_	_
LFALLSR	_	_	_	_	_	_	_	_
LFALLSM	_	_	_	_	_	_	_	_
OFRG	_	_	6.37	4.98	*-7.28*	*3.94*	_	_
SAL	*4.53*	*1.24*	_	_	_	_	_	_
STILL	_	_	*5.78*	*3.36*	-2.89	2.38	*-3.12*	*2.18*
ABAY	_	_	_	_	_	_	_	_
WTRI	*2.03*	*1.46*	_	_	_	_	_	_
WTR	_	_	1.74	1.62	_	_	_	_
WELL	_	_	_	_	-2.26	2.13	_	_
BEAV	_	_	*4.14*	*2.27*	-2.66	*1.51*	_	_
HI	_	_	_	_	_	_	_	_
HOOK	_	_	*10.50*	*3.10*	_	_	_	_
LOW	*2.27*	*1.39*	_	_	_	_	_	_
MCKV	*-4.17*	*2.14*	_	_	_	_	_	_
CAN	1.22	1.18	_	_	_	_	_	_

Table 16 Continued. 21-year annual snowfall trends by station.

MOVILLE	*2.16*	*1.53*	_	_	*-3.77*	*1.24*	_	_
BOON4	_	_	3.27	2.58	_	_	*-3.46*	*2.44*
CAM	_	_	*2.65*	*1.18*	_	_	_	_
DEL	_	_	2.46	2.01	_	_	_	_
FOR	_	_	_	_	_	_	_	_
GRIF	_	_	_	_	-2.20	1.84	_	_
HINCK	2.17	1.95	_	_	*-2.56*	*1.16*	_	_
NLON	1.85	1.77	_	_	_	_	_	_
UTOAIR	_	_	*3.66*	*1.51*	*-2.98*	*1.31*	_	_
UT	_	_	_	_	*-2.17*	*1.21*	_	_
BVILLE	*2.27*	*1.45*	1.86	1.60	_	_	*-2.50*	*1.93*
BREW	*2.99*	*1.97*	*2.53*	*1.72*	*-3.33*	*2.09*	_	_
SKAN	_	_	*4.40*	*1.48*	-1.49	1.34	_	_
SYR	_	_	_	_	_	_	_	_
BEN	_	_	*4.31*	*2.19*	_	_	_	_
CLE	_	_	_	_	_	_	_	_
FUL	_	_	_	_	_	_	_	_
OS	_	_	*6.88*	*2.21*	-2.94	2.68	_	_
CVAL	_	_	*2.31*	*1.34*	_	_	_	_
COOP	1.36	1.25	*1.83*	*1.36*	*-1.76*	*1.24*	_	_
ROCK	_	_	*1.31*	*0.91*	_	_	_	_
UN	_	_	_	_	_	_	_	_
FREE	_	_	_	_	*-1.82*	*1.17*	_	_
CORN	*1.21*	*0.62*	_	_	-1.17	1.08	_	_
Average	**1.66**	**1.44**	**3.55**	**1.93**	**-2.73**	**1.64**	**-2.80**	**2.24**

3.2.3.1 Summary of Station Snowfall Trends

Syracuse (SYR) had a long-term snowfall trend of 0.56 in. yr^{-1} (1.24 cm yr^{-1}), with a positive snowfall trend for every time period, expect during the 21-year period increments. The highest long-term snowfall trends were located in the Tug Hill (e.g. Hooker 12 NNW). All significant snowfall trends, except for McKeever, were positive for the 21-year periods from 1931/32 – 1971/72 and negative from 1971/72 – 2011/12.

3.2.4 Monthly Snowfall Trends

Monthly snowfall records were also examined using least squares regression to determine how snowfall has changed during winter months in CNY. Monthly trends were examined for three time periods (1931/32 – 2011/12, 1931/32 – 1971/72, and 1971/72 – 2011/12). From 1931/32 – 2011/12, no significant snowfall trends were present for any of the five regions for the months of November, March, and April (Table 17). However, there were significant (to the 10% level) snowfall trends during December, January, and February, especially for Region 5, all of which were positive. The two largest trends were recorded for Regions 4 (0.32 +/- 0.13 in. yr^{-1}) and 5 (0.29 +/- 0.11 in. yr^{-1}) during the months of January and December, respectively.

Table 17. Monthly snowfall trends for each region from 1931/32 – 2011/12. Trends and the associated uncertainty are reported in in. yr^{-1} and are significant at the 10% level. Trends with uncertainty less than 75% the value are italicized.

	November		December		January	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	–	–	–	–
2	–	–	–	–	–	–
3	–	–	–	–	–	–
4	–	–	*0.20*	*0.11*	*0.32*	*0.13*
5	–	–	*0.29*	*0.11*	*0.18*	*0.13*
	February		**March**		**April**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	–	–	–	–
2	–	–	–	–	–	–
3	0.08	0.07	–	–	–	–
4	–	–	–	–	–	–
5	*0.19*	*0.09*	–	–	–	–

Table 18. Monthly snowfall trends for each region from 1931/32 – 1971/72. Trends and the associated uncertainty are reported in in. yr^{-1} and are significant at the 10% level. Trends with uncertainty less than 75% the value are italicized.

	November		**December**		**January**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	7.05	6.71	*0.34*	*0.22*
2	–	–	*0.31*	*0.19*	–	–
3	–	–	–	–	–	–
4	0.29	0.27	*0.59*	*0.26*	*0.51*	*0.27*
5	0.25	0.19	*0.47*	*0.23*	0.33	0.28
	February		**March**		**April**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	0.23	0.21	–	–	–	–
2	–	–	–	–	–	–
3	*0.32*	*0.17*	–	–	–	–
4	–	–	–	–	–	–
5	*0.43*	*0.22*	–	–	–	–

Table 19. Monthly snowfall trends for each region from 1971/72 – 2011/12. Trends and the associated uncertainty are reported in in. yr^{-1} and are significant at the 10% level. Trends with uncertainty less than 75% the value are italicized.

	November		**December**		**January**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	–	–	–	–
2	–	–	–	–	–	–
3	-0.14	0.12	–	–	–	–
4	-0.31	0.24	–	–	–	–
5	–	–	–	–	–	–
	February		**March**		**April**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	–	–	–	–
2	–	–	–	–	-0.12	0.09
3	–	–	–	–	–	–
4	–	–	–	–	*-0.25*	*0.18*
5	–	–	–	–	–	–

Monthly snowfall trends were also broken into two smaller time periods (1931/32 - 1971/72 and 1971/72 – 2011/12) and snowfall trends were calculated for each region (Tables 26 and 27, respectively). There were several significant (to the 10% level) snowfall trends from 1931/32 – 1971/72, especially for Regions 1, 4, and 5 (Table 18).

All snowfall trends from 1931/32 – 1971/72 were positive. December had the most significant snowfall trends since all except Region 3 had a monthly snowfall trend for this month. January and February both had trends in three regions. November only had one region show a trend and March and April did not have significant trends in any regions. From 1971/72 – 2011/12, the only two months to demonstrate a significant snowfall trend were November and April; however, all trends within these months were negative (Table 19). Region 4 had the largest negative trends for both months as the November snowfall trend was -0.31 +/- 0.24 in. yr^{-1} and -0.25 +/- 0.18 in. yr^{-1} during April.

3.2.4.1 Monthly Snowfall Correlations

Table 20. Correlations between monthly snowfall trends. All correlations significant at the 5% level are designated with (*), and those significant at the 1% level are designated with (**).

	November	**December**	**January**	**February**	**March**	**April**
November	_	_	_	_	_	_
December	0.15	_	_	_	_	_
January	0.99**	0.09	_	_	_	_
February	-0.17	0.3	0.89*	_	_	_
March	0.90*	-0.21	0.54	0.98**	_	_
April	0.34	-0.47	-0.51	0.41	.96*	_

After snowfall trends were calculated for each month from 1931/32 – 2011/12, correlations were run to determine if monthly snowfall trends were correlated between winter months. Table 20 lists the correlations between monthly snowfall trends. Six correlations were significant at least to the 5% level with two significant to the 1% level, with the greatest correlation between January and November. Only four of the correlations were negative, while all the significant correlations had a positive relationship. December was the only winter month not to have a significant correlation with another month. In contrast November had the most significant correlations (2) with other months, January and March.

3.2.4.2 Summary of Monthly Snowfall Trends

Significant snowfall trends for the long-term and 1931/32 – 1971/72 periods were concentrated during typical LES months (December – February). The majority of snowfall trends from 1971/72 – 2011/12 were not significant, and the trends that were significant occurred during the early (November) and late (April) winter months and were negative. Snowfall correlations were generally higher for successive months, but there were high correlations in snowfall trends for non-successive months such as January and November.

3.3 Mean Annual Snowfall Maps

3.3.1 Long-term Averages

Examining average snowfall totals for CNY from 1931/32 – 2011/12 (Figure 19), distinct patterns are observed. The highest average snowfall totals per year are located in the Tug Hill Plateau, exceeding 235 in. yr^{-1} (600 cm yr^{-1}) in some locations. On the eastern side of the Tug Hill, average seasonal snowfall totals decrease to approximately 150 in. yr^{-1} (375 cm yr^{-1}). Snowfall totals drop to approximately 110 in. yr^{-1} (275 cm yr^{-1}) on the western side of the Tug Hill, then increase to over 160 in. yr^{-1} (400 cm yr^{-1}) in the Adirondack Mountains. Further south, over the Allegheny Plateau and Erie-Ontario Lowlands, snowfall totals generally decrease with decreasing latitude. There is a pocket of higher average snowfall totals (100 – 120 in. yr^{-1} or 250 – 300 cm yr^{-1}) that extends further south, which is located over southern Onondaga and southwestern Madison counties; while lower annual snowfall totals (60 – 80 in. yr^{-1} or 150 – 200 cm yr^{-1}) creep north over northeastern Chenango, southeastern Madison, and western Otsego counties.

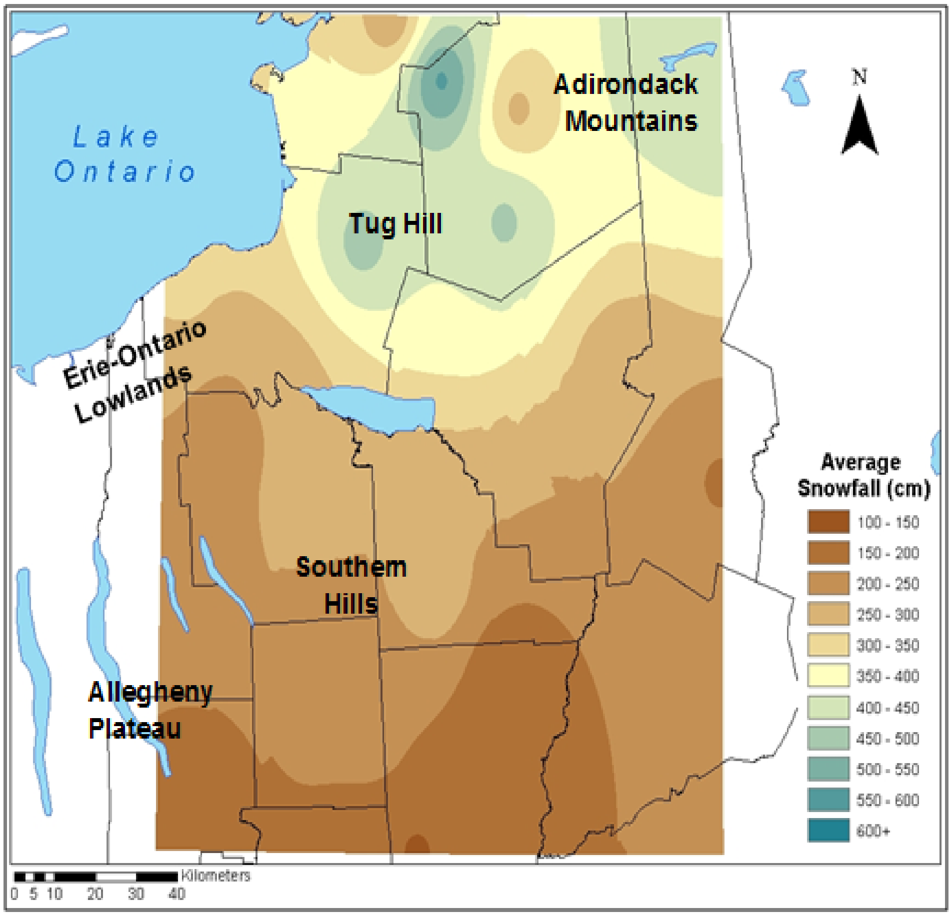


Figure 19. Average annual snowfall in CNY from 1931/32 - 2011/12.

3.3.2 41-year Averages

Figures 20 and 21, represent the long-term average snowfall record divided into two 41-year time periods: 1931/32 – 1971/72 and 1971/72 – 2011/12, respectively. There are visual consistencies between the two 41-year records and the long-term record; such consistencies include maximum snowfall totals over the Tug Hill Plateau, depressed totals to the west and directly east of the Tug Hill, and further south a general decrease in annual snowfall totals.

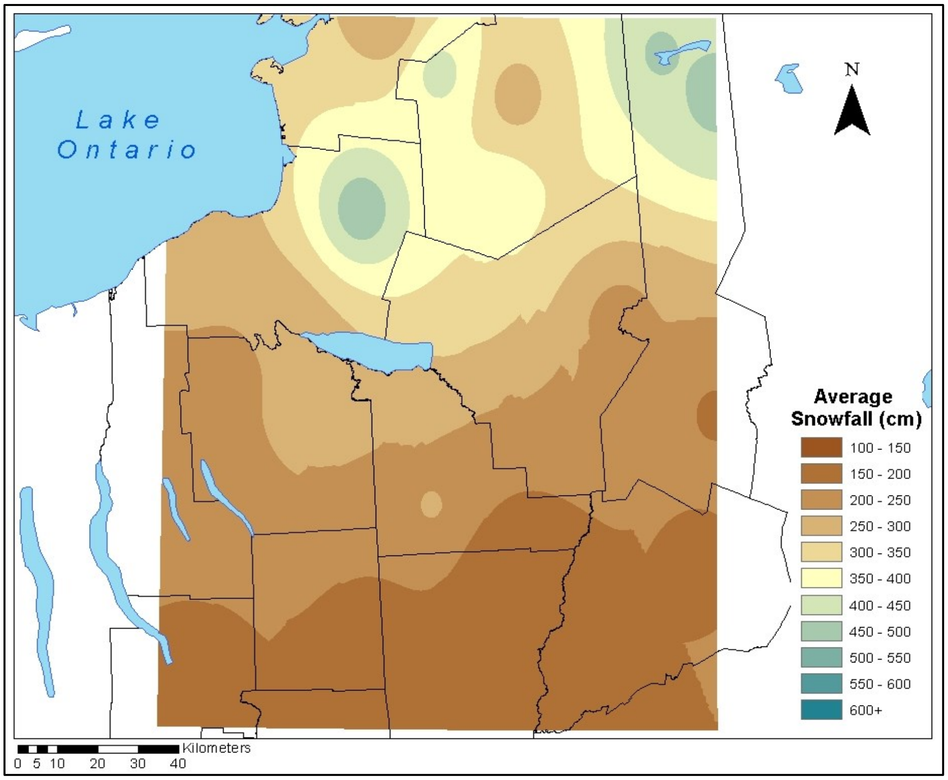


Figure 20. Average annual snowfall in CNY from 1931/32 - 1971/72.

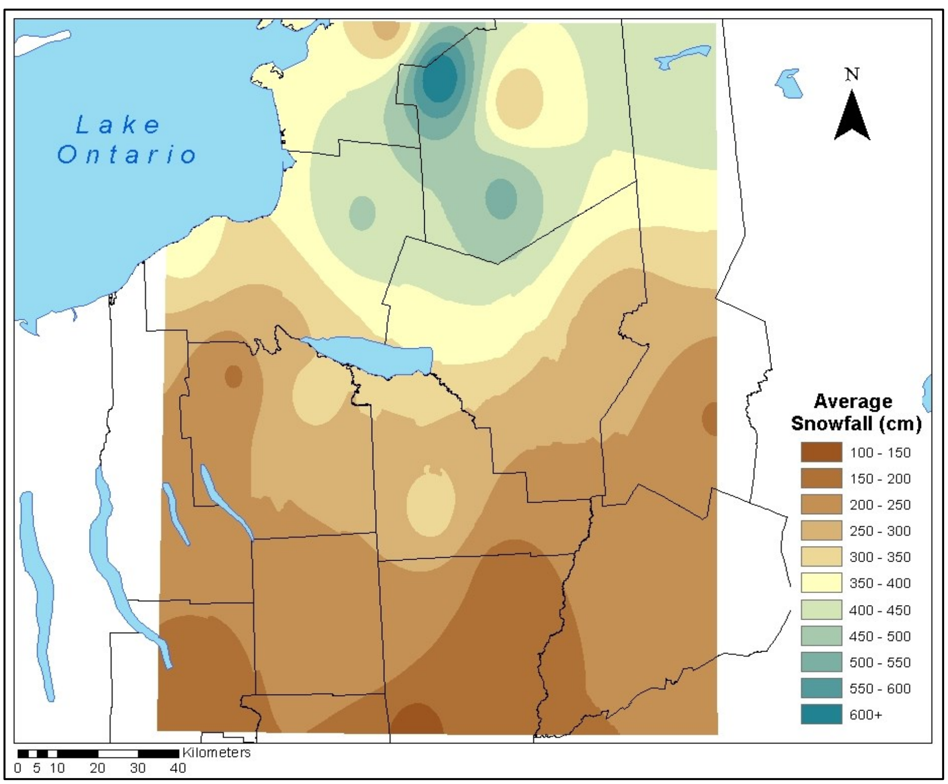


Figure 21. Average annual snowfall in CNY from 1971/72 - 2011/12.

However, there are distinct differences between the two sub-time periods. Comparing the two maps, a major difference is widespread lower snowfall totals from 1931/32 – 1971/72 compared to 1971/72 – 2011/12. For example, from 1931/32 – 1971/72 snowfall totals south of Oneida Lake ranged from 59 – 118 in. yr^{-1} (150 – 300 cm $yr^{-1)}$, with the majority of the area averaging between 59 – 98 in. yr^{-1} (150 – 250 cm yr^{-1}; Figure 20); while from 1971/72 – 2011/12 snowfall totals south of Oneida Lake ranged from 39 – 118 in. yr^{-1} (100 – 350 cm yr^{-1}) with a majority of the region experiencing average annual snowfalls between 79 – 118 in. yr^{-1} (200 – 300 cm yr^{-1}; Figure 21). Likewise, average snowfall totals from 1931/32 – 1971/72 were at a maximum over the Tug Hill and parts of the Adirondack Mountains, reaching 200 in. yr^{-1} (500 cm yr^{-1}); conversely, from 1971/72 – 2011/12 maximum average snowfall totals exceeded 235+ in. yr^{-1} (600+ cm yr^{-1}) over the Tug Hill Plateau. Examining Figures (19-21) it can be deduced that the long-term averages behaved more similar to the 1971/72 – 2011/12 period than the 1931/32 – 1971/72 period. Such similarities include maximum snowfall averages over the northern Tug Hill Plateau, compared to the southern edge of the Tug Hill from 1931/32 – 1971/72. Also, higher annual snowfall totals dip further south (over Onondaga and Madison counties) and low snowfall totals spread further north (into Madison, Chenango, and Otsego counties) from 1971/72 – 2011/12, similar to the long-term record.

3.3.3 Summary of Mean Annual Snowfall Maps

The highest annual snowfall totals in CNY were concentrated in the Tug Hill and western reaches of the Adirondack Mountains. There was also a dip in higher annual snowfall totals to the south located over the Southern Hills, while lower annual snowfall totals extended further north just east of the Southern Hills, over eastern Chenango and Madison counties. In general, average annual snowfall totals during the latter half of the study were considerably higher than the earlier half of the long-term record.

3.4 Mean Annual Snowfall Anomaly Maps

3.4.1 41-year Anomaly

After annual snowfall averages were calculated, the averages were used to calculate snowfall anomalies for multiple time increments. Figure 22 represents snowfall anomalies for CNY comparing annual snowfall averages from 1971/72 – 2011/12 to averages from 1931/32 – 1971/72. Compared to the snowfall averages from 1931/32 – 1971/72, snowfall totals from 1971/72 – 2011/12 were appreciably higher (>30 in. or 75 cm) in northern reaches of the Tug Hill Plateau. Increased snowfall was also present over the Tug Hill (northern Oneida, eastern Lewis, and southeastern Jefferson counties) and eastern Oswego County around the city of Oswego (18-22 in. or 45-55 cm increase). There were a few areas, northwestern Onondaga and northern Herkimer counties, which experienced a decrease in annual snowfall, decreasing by 10 in. (25 cm) in some locations. However, the majority of CNY experienced relatively no change or a slight increase (approximately 2-10 in. or 5-25 cm) in average annual snowfalls.

3.4.2 10-year Anomalies

Snowfall anomalies for each decade from 1931/32 – 2011/12 were plotted (Appendix B), comparing the decadal snowfall to the average annual long-term snowfall. The 1930s (Figure B1) were dominated by negative snowfall anomalies throughout CNY, with a concentration of high negative anomalies (+30 in. or 75+ cm) located directly east of Lake Ontario. The Southern Hills and western extent of the Adirondack Mountains also experienced large negative snowfall anomalies during the 1930s. There were a few areas that did experience a slight positive snowfall anomaly, especially in the southeastern (Chenango and Madison counties) and eastern edges (eastern Oneida and Herkimer counties) of CNY.

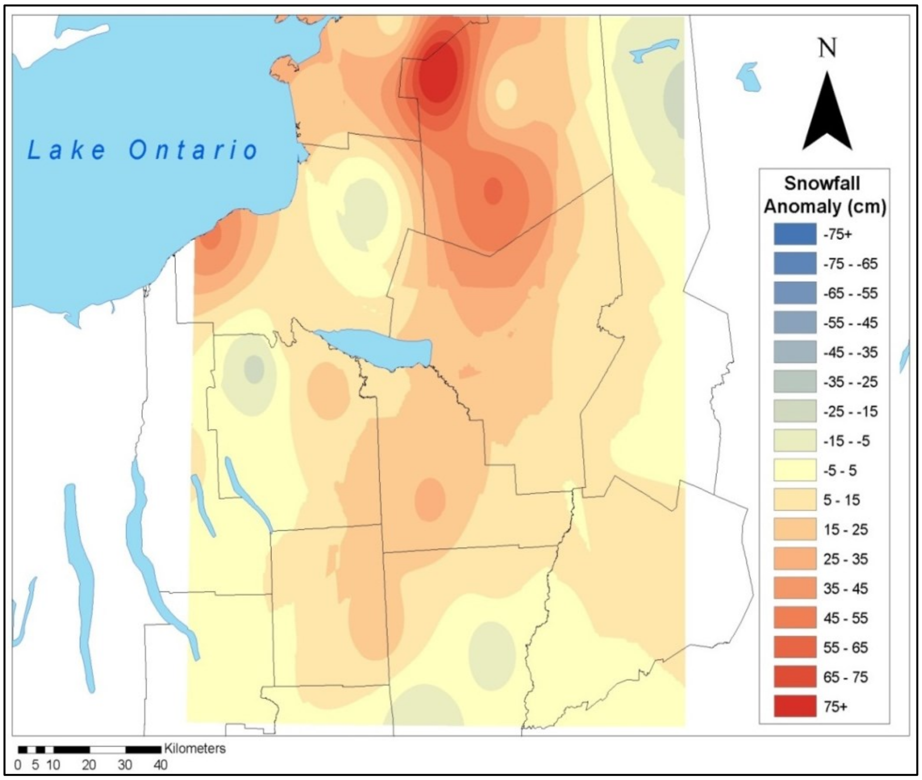


Figure 22. Anomalous mean annual snowfall totals between 1971/72 – 2011/12 and 1931/32 – 1971/72.

Similar to the 1930s, the majority of CNY during the 1940s (Figure B2) either experienced a negative snowfall anomaly or a neutral anomaly in seasonal snowfall totals. The greatest (negative) anomalies were concentrated over the western Adirondack Mountains, especially over northern Herkimer, northeastern Oneida, and eastern Lewis counties. There was also negative snowfall anomalies concentrated over the southwestern counties in CNY (Cayuga, Tompkins, Cortland, Oswego, and Onondaga).

The majority of these negative anomalies were located southwest of Oneida Lake, as well as over the Southern Hills, and the strongest anomaly over western Oswego County.

Positive snowfall anomalies were more persistent during the 1950s (Figure B3) and 1960s (Figure B4). During the 1950s, large positive snowfall anomalies (14-30 in. or 35-75+ cm) were especially present over southwestern CNY counties (Tompkins and Cayuga counties). There were also strong positive anomalies located in central CNY (Madison, southern Oneida, and southwestern Herkimer counties) and the northern reaches of Herkimer County. However, strong negative anomalies (30+ in. or 75+ cm) did cover a large extent of the northern counties, especially Jefferson, Lewis, northwest Oneida, and eastern Oswego. In fact, a negative snowfall anomaly extends in a linear fashion from northern Jefferson County to southeastern Oneida County. The rest of CNY during the 1950s was not covered by a considerable snowfall anomaly.

The 1960s (Figure B4) began to experience higher snowfall anomalies, with large areas covered by strong positive snowfall anomalies (30+ in. or 75+ cm). The greatest extent of large snowfall anomalies occurred in the eastern counties, especially over the western Adirondack Mountains (northern Herkimer and eastern Lewis counties). Along with the strong positive anomalies in the eastern counties, there was also a strong positive anomaly (10-30+ in. or 25-75+ cm) located in the southwestern counties (especially western Onondaga and Cayuga). Negative snowfall anomalies were still persistent during the 1960s; however, the anomalies appeared to be grouped into two linear bands. The first band was located from the St. Lawrence River in northwestern Jefferson County, extending down to southern Lewis County. The second band extended from southwestern Oswego County all the way to southern Otsego County, with the greatest extent of negative anomalies (-10 - -18 in. or -25 - -45 cm) located over the Southern Hills.

The 1970s (Figure B5) was the first decade in which snowfall anomalies were predominately positive. During this period, not only were anomalies generally positive, with a few slight negative anomalies in southeastern CNY, but there were also strong positive anomalies (30+ in. or 75+ cm) covering large portions of CNY. The majority of positive snowfall anomalies during the 1970s were located in areas directly east of Lake Ontario including: Oswego County, the Tug Hill, and the western Adirondack Mountains. There was also higher snowfall totals compared to the long-term mean during the 1970s located over the Southern Hills, with snowfall anomalies ranging between 6 and 26 in. (15-65 cm).

The 1980s (Figure B6) were unique in that snowfall anomalies reverted back to being predominately negative. In fact, all of CNY south of Oneida Lake experienced negative snowfall anomalies between -2 and -22 in. (-5 – -55 cm). There was also a concentration of negative snowfall anomalies over the western Adirondack Mountains, which actually experienced the largest negative snowfall anomaly (-30+ in. or -75+ cm) during the 1980s. However, areas directly east and in close proximity to Lake Ontario did experience large positive snowfall anomalies (30+ in. or 75+ cm), especially over eastern Jefferson and western Lewis counties.

The 1990s (Figure B7) were similar to the 1970s, as positive snowfall anomalies dominated CNY with only a few negative snowfall anomalies present, most notably over northern Herkimer County. In fact, the majority of CNY experienced snowfall anomalies between 6 and 18 in. (15-45 cm). The highest positive snowfall anomalies during this time were located in three main regions: along the eastern shores of Lake Ontario, over north-central CNY (especially over southern Lewis and central Oneida counties), and most notably, directly to the south of Oneida Lake, over the Southern Hills (eastern Onondaga, northeast Cortland, Madison, and northwest Chenango counties).

Large positive anomalies continued to dominate CNY during the 2000s (Figure B8), but were not as wide-spread as the previous decade. Instead, large positive snowfall anomalies (30+ in. or 75+ cm) were located around Oneida Lake, with positive anomalies extending in a linear fashion from the eastern shores of Lake Ontario to southeastern Otsego County. The southwestern counties of CNY (Tompkins, southern Cayuga, Cortland, and southern Onondaga) displayed no discernible snowfall anomalies, with only a few small areas demonstrating negative anomalies. Also, northeastern sections of CNY (especially northern Herkimer County), experienced a strong negative anomaly (-30 in. or -75+ cm) in snowfall. The study also plotted 21st century snowfall anomalies which entailed averaging seasonal snowfall totals from 2001/02 to 2011/12 (Figure B8 and B9). The major difference in the two anomaly plots (Figures B8 and B9) was the magnitude in which positive anomalies persisted. In Figure (B9), snowfall anomalies were not as extreme or extensive, and there were more neutral and negative snowfall anomalies present, especially in southwestern CNY.

3.4.3 Summary of Mean Annual Snowfall Anomaly Maps

The greatest difference in snowfall between the two 41-year periods was located over the Tug Hill and the city of Oswego, in which snowfall totals increased by 30+ in. (75+ cm). Increased snowfall totals also extended into the parts of the southern tier (over the Southern Hills). Snowfall patterns were also observed by comparing the long-term snowfall average for CNY stations to decadal station averages. In general, the earlier decades (1930s-1950s) demonstrated widespread negative snowfall anomalies, while the latter decades (1970s, 1990s and 2000s) had widespread positive snowfall anomalies. There were spatial variations in which snowfall anomalies occurred, as some decades (i.e. 1940s, 1970s, etc.) demonstrated a band-like structure in snowfall anomalies.

3.5 Principal Component Analyses for Correlated Signals

Using the regions and sub-regions identified in Figures 11 and 12, average annual snowfalls were calculated for each region and used to run PCAs to identify any common correlated signals in the data such as periodic variations due to teleconnections. The first PCA, referred to as PCA-c, was run using the five regions previously determined by PCA-a and PCA-b (Table 12); while the second PCA, known as PCA-d, was used running the twelve sub-regions outlined in Table 13. The U matrix for PCA-c is outlined in Table 21, which lists the correlation of each of the five stations within each mode.

Table 21. EOF modes identified by PCA-c.

Region	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1	0.44	**-0.82**	-0.25	**-0.88**	-0.59
2	0.35	**-0.86**	-0.29	-0.05	**1.00**
3	0.50	**-0.81**	-0.01	**1.00**	-0.44
4	**1.00**	**1.00**	-0.55	0.07	0.01
5	0.78	0.09	**1.00**	-0.19	0.14

After the U matrix was examined for PCA-c, the pc-components were constructed and the time series was reconstructed based on each EOF mode. Figure 23 represents the different modes compared to the original time series. Observing the different modes, it is clear that EOF 1 closely resembled the original time series. Mode 2 also accounted for a considerable amount of the original data variance. Modes 3-5 however, accounted for very little of the variance, as the resulting figure was nearly a straight line with only slight variance. Since two modes accounted for the majority of the variance, it may be suggested that the use of the PCA provided no substantial results.

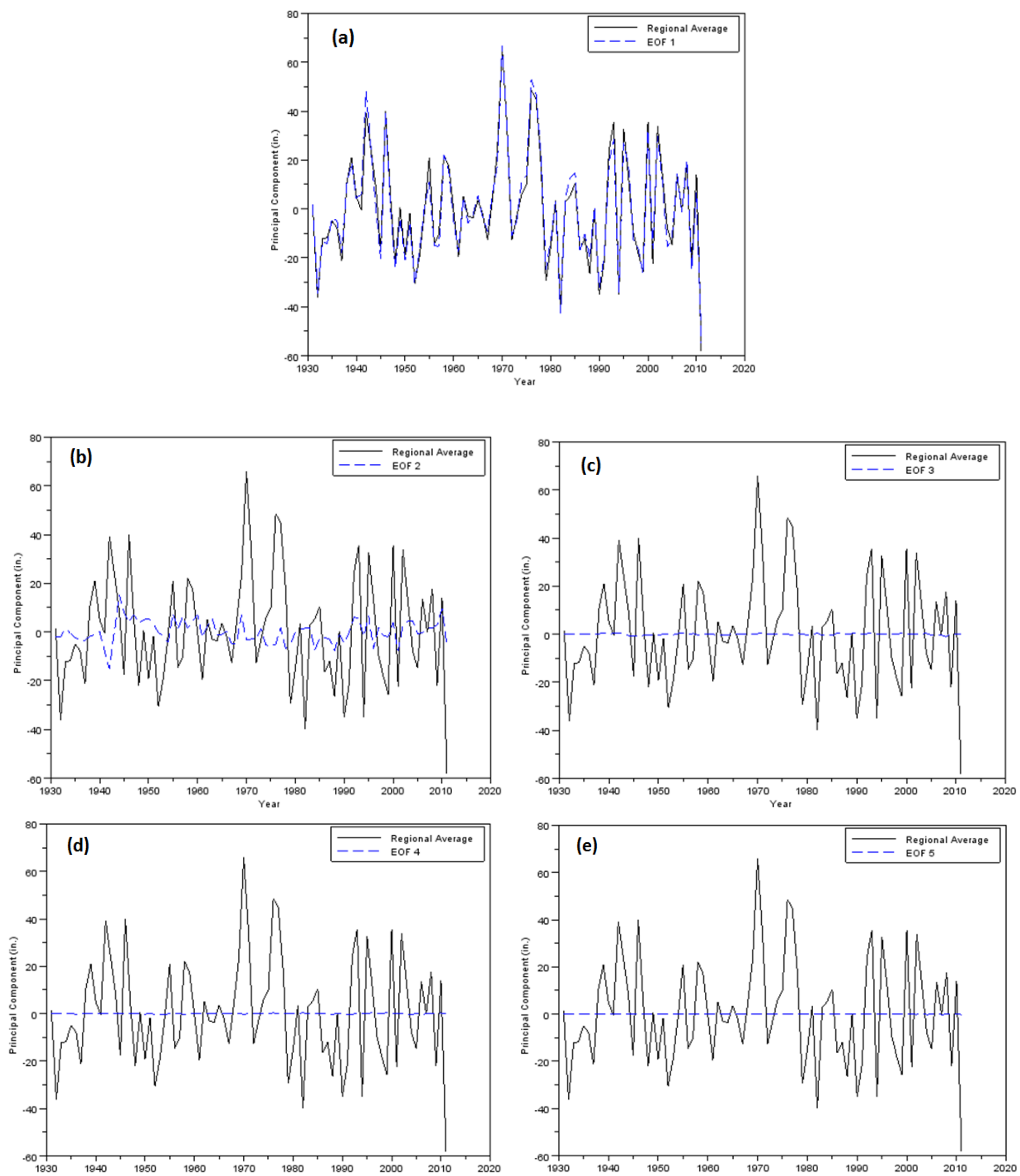


Figure 23. EOF modes and initial data for CNY. Five modes were determined: (a) EOF 1, (b) EOF 2, (c) EOF 3, (d) EOF 4, and (e) EOF 5.

The EOFs for all the regions combined are arranged so Mode 1 explains that greatest variability, followed by Mode 2, etc. Therefore, the greatest percentage of variability explained for all the regions combined was 74.9% for Region 1, 13.8% for Region 2, 5.3% for Region 3, 3.8% for Region 4, and 2.2% for Region 5 (Table 22). The percent variance of each mode, for each region was then calculated (Table 22). EOF 1 (57.6%) explained the greatest variance of the original data for Region 1, followed by EOF 2 (26.7%) and EOF 4 (10.0%). Similarly to Region 1, EOF 1 explained the majority of the percent variance for the remaining four regions: Region 2 (49.1), Region 3 (63.7), Region 4 (84.6), and Region 5 (81.4). EOF 2 also explained the second most variance for Regions 2, 3, and 4, while EOF 3 explained the second most variance for Region 3. Out of the remaining EOFs, over 10% of the variance was explained for a single EOF only for Regions 1, 3, and 4: EOF 4 accounted for 10.2% of the variance for Region 1, EOF 3 accounted for 11.8% of the variance in Region 3, and EOF 3 was attributed to 18.1% of the variance in Region 4.

Table 22. Percent Variance of EOF modes identified in PCA-c.

Region	EOF 1	EOF 2	EOF 3	EOF 4	EOF 5
All	74.9	13.8	5.3	3.8	2.2
1	57.6	26.7	2.6	10.2	2.8
2	49.1	39.9	6.3	2.1	2.2
3	63.7	23.1	0.0	11.8	1.3
4	84.6	11.7	3.6	0.0	0.0
5	81.4	0.2	18.1	0.2	0.1

Each mode was then correlated with the three climate indices examined (NAO, SOI, and AMO) to determine if a mode extracted from the PCA corresponds to a particular climate index (Table 23). Only three of the modes had a significant correlation with a climate index (Modes 1, 2, and 4). However, all three correlations were relatively small (< 0.32), suggesting that random chance did not account for this correlation, but because the value is so small, the two time series differ more often than they agree. It should also be pointed out that the AMO had the greatest amount of significant correlations (2), albeit one a positive correlation and the other a negative correlation, while the NAO did not exemplify any significant correlations.

Table 23. Correlation between the modes extracted from PCA-c and climate indices. Correlations significant at the 5% level are denoted with an (*) and correlations significant at the 1% level are denoted with (**).

Mode	NAO	SOI	AMO
1	-0.18	0.15	*-0.30***
2	-0.15	-0.04	*0.31***
3	-0.01	-0.15	-0.11
4	-0.09	-0.22*	-0.01
5	0.05	0.03	0.14

The U-matrix for the second PCA, PCA-d, using 12 distinct sub-regions are outlined in Table 34. It should be noted that Regions 8.4/5 and Regions 12.5 were omitted from the analyses as average snowfall records for the regions were not consistent, with numerous missing years. Therefore, instead of removing each year from the record, the two regions were omitted to run the PCA. For Mode 1, there is no clear region that is dominating, and instead all 12 regions had comparable normalized correlation between 0.36 and 1.00. Mode 2 is very similar to Mode 1, as there is no definitive region dominating the mode; however instead of all the regions demonstrating a negative correlation, some of the regions were anti-correlated between each other. Mode 3 was the first mode in which a single region was dominant, as Region 1.1 was highly correlated with Mode 3. Modes 4-9 all demonstrated at least one dominating mode, as Region 9.4 and 10.4/5 had a strong anti-correlation (1.00 and -0.99, respectively) in Mode 4. Regions 1.1 (0.83), 5.2 (-0.98), and 7.1/4 (1.00) had the largest correlations within Mode 5, with Regions 1.1 (-0.96) and 7.1/4 (0.93) again having a strong correlation in Mode 6, along with Region 6.3 (1.00). Mode 7 was dominated by Region 3.1/2 (1.00), Region 5.2 (-0.85), and Region 7.1/4 (-0.85), as Regions 1.1 - 3.1/2 and Regions 2.1, 3.1/2, and 6.3 were the governing regions for Modes 8 and 9, respectively. Similar to Mode 3, Mode 10 was dominated by a single region, as Region 4.2 displayed a high positive correlation (1.00) within the mode.

Table 24. EOF modes identified by PCA-d. M is the mode for each EOF.

Region	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10
1.1	0.45	-0.67	-0.10	0.13	0.83	-0.96	0.43	1.00	0.03	-0.02
2.1	0.43	-0.65	-0.16	0.00	0.07	-0.57	-0.35	-0.98	1.00	0.01
3.1/2	0.53	-0.69	0.02	0.29	0.13	0.20	1.00	-0.88	-0.70	-0.23
4.2	0.36	-0.60	0.03	-0.03	-0.67	-0.07	0.11	0.09	-0.20	1.00
5.2	0.55	-0.65	-0.13	-0.04	-0.98	-0.33	-0.85	0.29	-0.48	-0.48
6.3	0.55	-0.44	0.10	0.06	-0.50	1.00	0.59	0.63	0.80	-0.21
7.1/4	0.77	-0.42	-0.07	-0.28	1.00	0.93	-0.85	0.02	-0.23	0.14
9.4	1.00	1.00	-0.29	1.00	-0.06	0.00	-0.19	0.04	0.03	0.10
10.4/5	1.00	0.85	-0.28	-0.99	-0.15	-0.24	0.50	-0.09	-0.03	-0.02
11.5	0.72	0.33	1.00	-0.01	0.04	-0.33	-0.19	-0.07	0.02	-0.03

Again, the total percentage of variance for all the regions combined was displayed in sequential order with Mode 1 explaining the greatest percentage of variance (64.8%), followed by Mode 2 (13.7%), Mode 3 (5.3%), Mode 4 (4.5%), Mode 5 (3.2%), Mode 6 (2.4%), Mode 7 (2.2%), Mode 8 (1.7%), Mode 9 (1.3%), and Mode 10 (1.0%). The percent variance of each mode, within each region is outlined in Table 25. For all 10 regions in PCA-d, Mode 1 accounted for the greatest variance in the data. EOF 2 accounted for the second most variance for all regions except Regions 7.1/4 (EOF 5) and 11.5 (EOF 3). For both regions (7.1/4 and 11.5), EOF 2 accounted for the third most variance. Region 4.2 also behaved differently from the rest as the percent variance accounted for by EOF 1 and EOF 2 were very similar, with only a small difference in percentage points. The most common EOF to account for the third most variance among regions, was EOF 5 (Regions 1.1, 4.2, and 5.2), followed by EOF 4 (Regions 9.4 and 10.4/5).

Table 25. Percent Variance of EOF modes identified in PCA-d.

Region	EOF 1	EOF 2	EOF 3	EOF 4	EOF 5	EOF 6	EOF 7	EOF 8	EOF 9	EOF 10
All	64.8	13.7	5.3	4.6	3.2	2.4	2.2	1.7	1.3	1.0
1.1	46.2	26.1	0.9	0.5	9.4	8.8	1.3	6.7	0.0	0.0
2.1	49.2	29.3	2.7	0.0	0.1	3.6	1.0	7.4	6.7	0.0
3.1/2	57.7	25.3	0.0	2.7	0.2	0.3	6.3	4.5	2.5	0.3
4.2	45.9	34.8	0.1	0.0	9.9	0.1	0.2	0.1	0.4	8.5
5.2	59.1	20.8	1.5	0.1	10.9	0.9	4.2	0.4	1.1	1.0
6.3	66.7	11.3	1.0	0.1	3.3	9.1	2.3	2.5	3.5	0.2
7.1/4	76.4	5.9	0.2	1.5	7.9	4.7	3.0	0.0	0.2	0.1
9.4	71.1	14.8	2.8	11.4	0.0	0.0	0.1	0.0	0.0	0.0
10.4/5	69.7	13.1	2.4	10.1	0.1	0.2	0.5	0.0	0.0	0.0
11.5	42.8	7.0	36.5	0.0	0.0	0.3	0.1	0.0	0.0	0.0

Similar to the correlations for PCA-c, each mode identified in PCA-d was then correlated with the three climate indices examined (NAO, SOI, and AMO) to determine if a mode extracted from the PCA corresponds to a particular climate index (Table 26). Similar to the correlations between the climate indices and the modes extracted from PCA-c, the most significant correlations between the climate indices and the modes extracted from PCA-d occurred between the AMO (Modes 1, 2, and 3). However, once again all significant correlations were relatively small (< 0.35) meaning that they are likely not due to random chance, but are not a strong relationship either. A major difference in the correlation of this PCA to the climate indices compared to the previous PCA (PCA-c) is that the NAO had significant correlations, while the SOI had the least amount (one) of significant correlations.

Table 26. Correlation between the modes extracted from PCA-d and climate indices. Correlations significant at the 5% level are denoted with an (*) and correlations significant at the 1% level are denoted with (**).

Mode	NAO	SOI	AMO
1	-0.21	0.16	*-0.32***
2	-0.22*	-0.15	*0.34***
3	-0.03	-0.09	-0.25*
4	0.15	-0.13	0.18
5	-0.03	-0.09	-0.05
6	-0.14	-0.12	0.11
7	0.14	0.29*	0.16
8	-0.19	-0.05	0.08
9	0.13	0.06	0.07
10	-0.28*	-0.05	0.21

3.5.1 Summary of PCAs for Correlated Signals

Modes 1 and 2 accounted for the majority of snowfall variability within CNY. Mode 4 dominated PCA-c, while no regions dominated Mode 2 in PCA-c or Modes 1 or 2 in PCA-d. All significant correlations between the three distinct climate indices and the different modes extracted were small (< 0.35). For both PCA-c and PCA-d, the climate index with the greatest amount of significant correlations was the AMO.

3.6 Teleconnections

Figure 24 shows the raw data of the three climate indices used in this study from 1931 – 2011. It can be noticed that the NAO has the largest range in values, while the AMO varies the least. However, it appears that the AMO varies at a low-frequency in which there was an approximate maximum in values around the early 1950s, followed by a decrease in values during the mid-1970s, and a subsequent increase reaching a maximum during the mid-2000s.

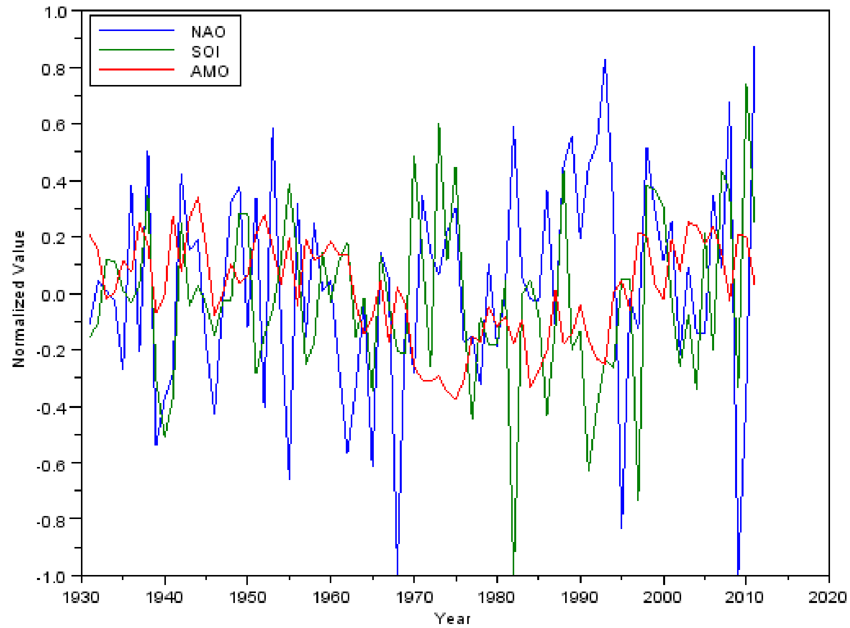


Figure 24. Raw, normalized values of climate indices.

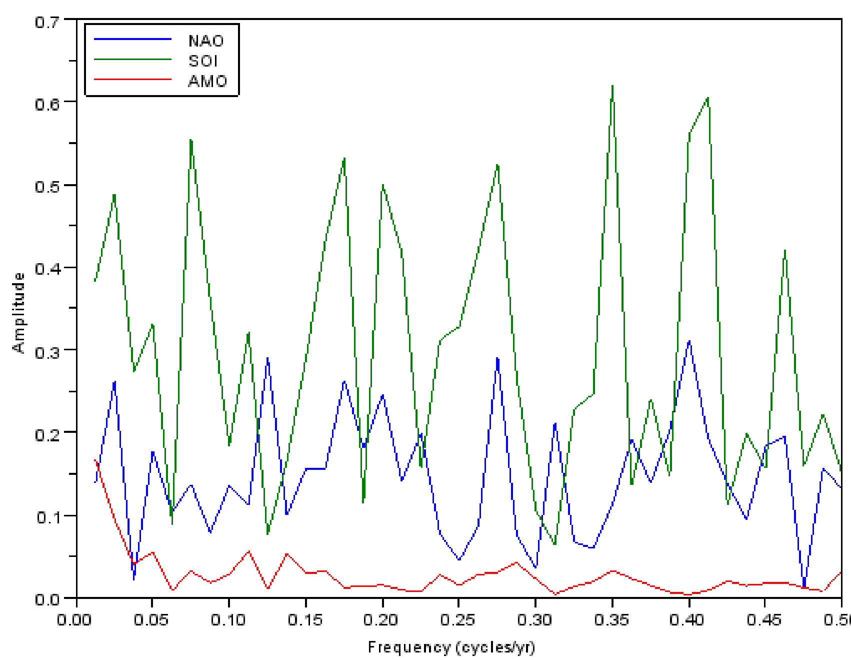
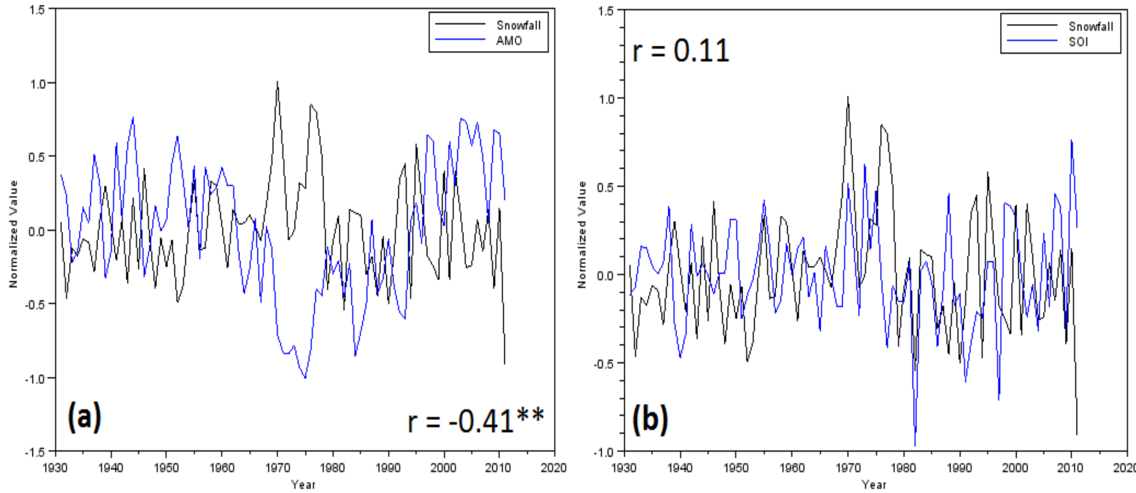
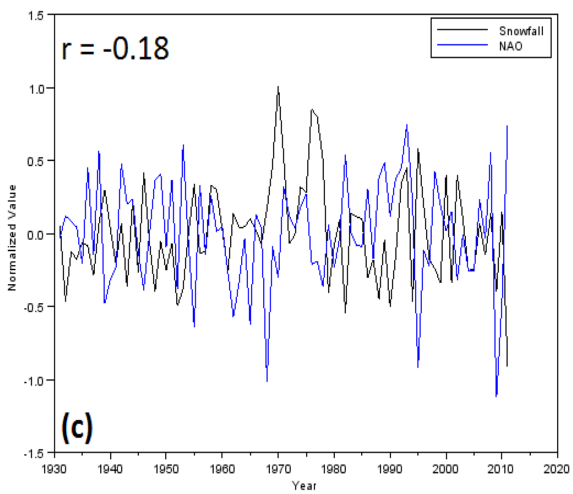


Figure 25. Spectral analyses of climate indices.

Spectral analyses of the climate indices were plotted in Figure 25. No distinct large amplitude frequencies were determined, as in general all three climate indices had a fairly random spectrum. However, there were some variations that were distinctive. For example, the NAO tends to have higher frequency variations than the other two indices, especially between 0.20 and 0.45 cycles/year. Also all three indices, especially the SOI and AMO, exhibit a larger amplitude variation for low-frequency signals (< 0.05). The AMO represents this the best as the largest amplitude throughout the whole record of the AMO occurs for lower frequency signals.

The three climate indices examined in this study (NAO, SOI, and AMO) were all fitted to the long-term snowfall record in CNY (Figure 26). In order to do this a time-series was constructed for each climate index which incorporated the out-of-phase component of the Hilbert transform. Due to the yearly nature of the data, there was not a large shift in the phase after incorporating the Hilbert transform, but a slight phase change. According to Figure 26 it is apparent that only the AMO demonstrated a significant (1% level) relationship with CNY snowfall. As noted by the correlation value (-0.41) and the plotted figure, the AMO and CNY snowfall are negatively correlated but the correlation is not overly dominant. However, one period in which the anti-correlation is noticeable was the 1970s and 1990s when the AMO was considerably lower, while snowfall totals where considerably larger. Very slight correlations can be noticed in the other two figures, for example an anti-correlation existed during the late 1960s between the NAO and snowfall (where it appears snowfall lagged behind the NAO by two years) and a positive correlation between snowfall and the SOI. The chart within Figure 26 represents the correlations between the three teleconnections and average CNY snowfall, at various lags within the data. It can be noticed that the addition of a time lag only improved the correlation of one climate index (the NAO) at a 2-year lag. Therefore the small influence that the NAO did have on CNY snowfall might have been on a 2-year lag compared to the actual phase of the NAO.





	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

Figure 26. Normalized climate indices plotted with normalized CNY snowfall. Figure 26a represents the time-series for the AMO, 26b is the time-series for the SOI, and 26c is the time-series for the NAO. The correlation between the climate index and average annual CNY snowfall with no time lag is reported as the r value. Only one of the values was significant at the 1% level (noted by **). The values within the table represent correlations between average CNY snowfall and the teleconnection at various time lags up to 3 years. Value significant at the 1% are denoted with a (**) and at the 5% level an (*).

3.7 Variables Influencing Snowfall in CNY

3.7.1 Average Winter Air Temperatures

Average monthly and annual air temperatures were analyzed using multiple methods, including linear-regressions, Fourier spectral analyses, and normalizing observations by the freezing threshold. Average annual air temperature trends and the associated uncertainty for the long-term record, two 41-year records, and four 21-year records are presented in Table 27. The majority of air temperature trends (long-term, 1971/72 – 2011/12, 1931/32 – 1951/52, 1971/72 – 1991/92, and 1991/92 – 2011/12) were positive, while the remaining time periods (1931/32 – 1971/72 and 1951/52 – 1971/72) demonstrated a negative temperature trend. Only two of the time periods studied exhibited a significant change in air temperatures at the 10%significance level. One of the significant trends was negative (-0.16 +/- 0.10 ºF yr^{-1}) from 1951/52 – 1971/72, while the second trend from 1991/92 – 2011/12 was positive, 0.16 +/- 0.15 ºF yr^{-1}.

Table 27. Average winter air temperature trends for multiple time periods. Significant values at a 10% significance level are designated with an asterisk. Trends with uncertainty less than 75% the value are italicized.

Record Length	Trend (ºF yr^{-1})	Trend (ºF yr^{-1})
1931-2011	_	_
1931-1971	_	_
1971-2011	_	_
1931-1951	_	_
1951-1971	*-0.16*	*0.10*
1971-1991	_	_
1991-2011	0.16	0.13

Average winter temperatures were then normalized by 32ºF (0ºC), to produce a bar chart representing the average winter temperature in comparison to the freezing threshold (Figure 27). Years in which positive values (red) persisted, average air temperatures were above the freezing threshold; contrastingly, negative values (represented in blue) are years in which average winter temperatures were below the freezing threshold. It is obvious that most years, average winter air temperatures were below 32ºF (0ºC), with the lowest average temperatures (under 27ºF or -2.8ºC) occurring during the 1930s and again in the 1990s. The greatest amount of seasons in which average air temperatures were greater than 32ºF (0ºC) were concentrated in the latter half of the record, especially from 1983/84 – 2011/12. In fact, the warmest average winter air temperatures during a single winter season occurred during the 2011/12 season with average temperatures greater than 34.8ºF (1.6ºC). The longest continuous record in which average air temperatures in CNY did not exceed 32ºF (0ºC) was from the mid-1950s to early 1980s, as a majority of the records averaged between 30-28ºF (-1.1 - -2.2ºC). Observing the bar chart, a possible periodic variation in air temperatures can be noticed, as low average temperatures were at a maximum during the early 1930s, then again during the late 1960s, and again during the early 1990s. Between the low average air temperatures, there were years (early 1950s and late 1980s) where average air temperatures hovered around the freezing threshold. Therefore, it is possible that winter air temperatures in CNY exhibited a 30-year periodic variation in the data. This was further examined by using Fourier spectral analyses on the winter temperature data.

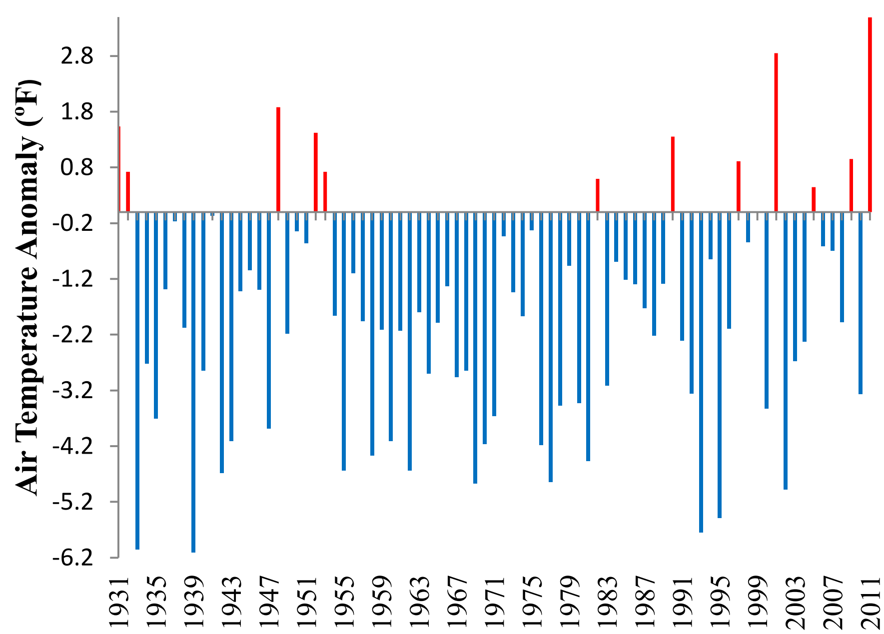


Figure 27. Deviation of average winter air temperatures from the freezing threshold (32°F/0°C).

3.7.2 Monthly Air Temperatures

Monthly average air temperature trends were then calculated using least squares regression, for months November-April (Table 28). It should be noted that monthly snowfall totals were only examined for the long-term record. A majority of the months had a positive trend in air temperatures, with only one month demonstrating a negative trend (March). However, only one of the winter months exhibited an average air temperature trend significant at the 10% level, March (-0.03 +/- 0.02 ºF yr^{-1} and 0.02 +/- 0.02 ºF yr^{-1}, respectively).

Table 28. Long-term monthly air temperature trends. Trends and uncertainty are reported in ºF yr^{-1}. Significant trends (10% level) are designated with an asterisk.

Month	Trend	Uncertainty
November	0.01	0.26
December	0.02	0.04
January	-0.02	0.04
February	0.02	0.04
March	0.02*	0.02
April	0.01	0.02

3.7.3 Summary of Winter Air Temperatures

Overall, CNY air temperature trends were not statistically significant. The most significant trend (-0.16 ºF yr^{-1}) was a negative decrease in air temperatures from 1951/52 – 1971/72. Even though the air temperature trend was not significant, average winter air temperatures appear to be warming as average temperatures have frequently been above the freezing threshold since the 1980s. There also appears to be an approximate 30-year variation in air temperatures, identified in Figure (21).

3.7.3 Winter Precipitation Totals

Table 29. Winter precipitation trends for regions classified by PCA-a and PCA-b. Trends and uncertainty are reported in in. yr^{-1} and are significant at the 10% level. Trends with uncertainty less than 75% the value are italicized.

	1931-2011		1931-1971		1971-2011	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	_	_	_	_	_	_
2	0.03	0.02	_	_	_	_
3	-0.03	0.03	_	_	*-0.15*	*0.10*
4	_	_	_	_	-0.10	0.07
5	*0.07*	*0.02*	_	_	_	_

	1931-1951		1951-1971		1971-1991		1991-2011	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	_	_	_	_	-0.17	0.17	_	_
2	_	_	_	_	_	_	_	_
3	*0.28*	*0.17*	_	_	*-0.32*	*0.19*	_	_
4	*0.65*	*0.39*	-1.17	0.93	_	_	_	_
5	*0.16*	*0.11*	_	_	_	_	_	_

Along with winter air temperatures, winter precipitation totals for seasonal and monthly time periods were analyzed. Precipitation analyses were used on each of the five regions (Table 12). Table 29 represents the results of the least squares regression at multiple time scales for each of the five regions. Two of the regions, 3 and 4, demonstrated a negative precipitation trend from 1931/32 – 2011/12, while Regions 1, 2, and 5 exemplified a positive trend. However, only trends for Regions 2 (0.03 +/- 0.02 in. yr^{-1}), 3 (-0.03 +/- 0.03 in. yr^{-1}), and 5 (0.07 +/- 0.02 in. yr^{-1}) were significant at the 10% significance level. For the two 41-year periods, precipitation trends were only significant for two regions, Regions 3 (-0.15 +/- 0.10 in. yr^{-1}) and 4 (-0.10 +/- 0.07 in. yr^{-1}), both from 1971/72 – 2011/12. From 1931/32 – 1951/52 all the stations demonstrated a positive precipitation trend, with three displaying a significant trend at the 10% level: Region 3 (0.28 +/- 0.17 in. yr^{-1}), Region 4 (0.65 +/- 0.39 in. yr^{-1}), and Region 5 (0.16 +/- 0.11 in. yr^{-1}). A majority of the precipitation trends were negative from 1951/52 –

1971/72 and 1971/72 – 1991/92, with three regions having significant trends (10% level). From 1991/92 – 2011/12, no precipitation trends were significant at the 10% level.

3.7.4 Monthly Precipitation Totals

Table 30. Monthly winter precipitation trends by region. Trends and uncertainty are reported in in. yr^{-1}. Trends are significant at the 10% level.

	November		**December**		**January**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	0.02	0.01	–	–	–	–
2	–	–	–	–	–	–
3	–	–	–	–	–	–
4	–	–	–	–	–	–
5	0.02	0.01	0.02	0.01	0.02	0.01
	February		**March**		**April**	
Region	**Trend**	**Uncert.**	**Trend**	**Uncert.**	**Trend**	**Uncert.**
1	–	–	–	–	0.01	0.01
2	–	–	–	–	–	–
3	–	–	–	–	–	–
4	-0.02	0.01	-0.02	0.01	–	–
5	–	–	0.01	0.01	0.01	0.01

Precipitation trends were also calculated for individual winter months using least squares regression. Similar to monthly air temperature trends, only long-term records were used in the monthly precipitation analyses. Table 30 outlines the long-term precipitation trends for CNY, for trends significant at the 10% level. Significant monthly precipitation trends were greatest for Region 5, as four months (November, December, January, February, March, and April) all displayed a positive snowfall trend. Region 2 was the only region not to exhibit a significant precipitation trend for any of the winter months. A majority of the precipitation trends (6 out of 10) demonstrated a long-term positive trend in precipitation. Significant trends during November, December, and April were all positive, while January and February trends were negative, and March trends were both positive and negative.

3.7.5 Summary of Winter Precipitation Totals

Winter precipitation trends were similar to snowfall trends, as the latter periods experienced predominately negative snowfall trends, while earlier periods experienced positive precipitation trends. For the long-term period, Region 5 experienced the largest precipitation trend. Similar to monthly air temperature trends, no monthly precipitation trends were notably significant.

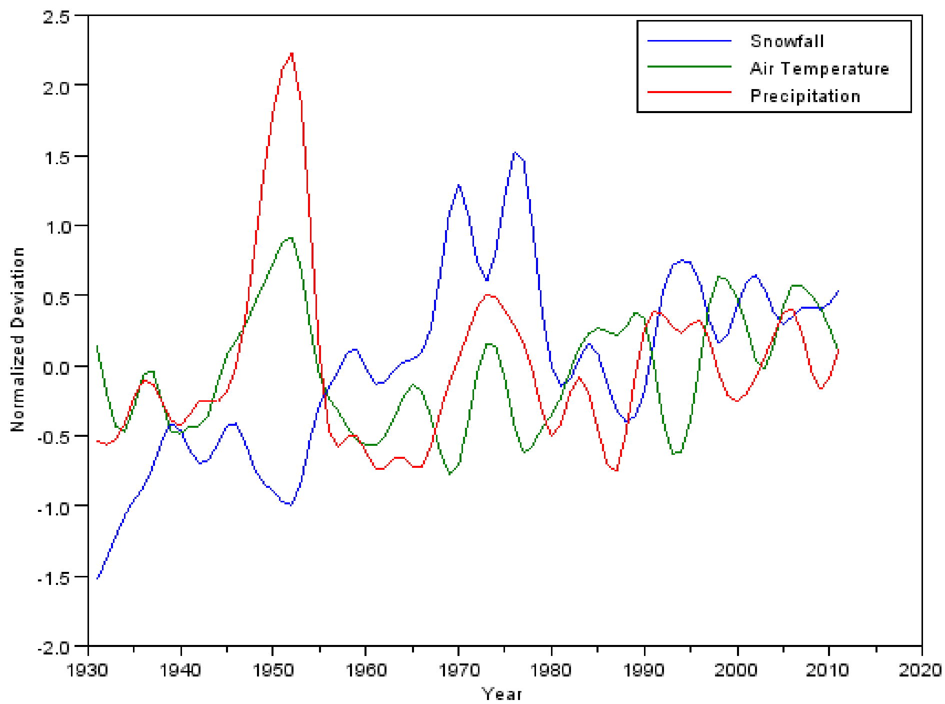


Figure 28. Normalized annual snowfall totals, winter air temperature, and winter precipitation data run through a 1.5-year Gaussian filter.

3.7.5 Snowfall, Air Temperatures, and Precipitation

Annual snowfall, air temperature, and precipitation data was filtered using a 1.5-year Gaussian filter (Figure 28). Each record was normalized using the mean long-term value and standard deviation, and then plotted. Average winter temperatures experienced much less variation compared to winter precipitation and annual snowfall totals. Deviations from the average in precipitation peaked in the 1950s, while snowfall deviations in the 1970s and 1980s were at a maximum. During the early 1950s, snowfall deviations were below average (< 0 normalized deviation); while at the same time precipitation and air temperatures were anomalously above average. During the 1970s and 1980s when snowfall deviations were high, so were precipitation anomalies. Interestingly, two peaks exist in the snowfall record, during the 1970s and 1980s, with a large decrease between the two peaks. During the same time, air temperatures were lower (< -0.5 deviation from the average) and with a peak (> 0 normalized deviation) during the lower snowfall period. Similar relationships were apparent during the early-mid 1990s and early-mid 2000s, in which increases in snowfall occurred during dips in winter air temperatures.

3.7.6 Station Elevation and Distance from Lake Ontario

Significant snowfall trends during multiple time periods were then used to calculate the correlation between a station's snowfall trend, the elevation of the station, and the distance of that station from a fixed point over Lake Ontario. The results of the correlations are presented in Table 31. Only three of the correlations were significant (at the 5% level), all of which related to the correlation between the elevation of a station and the snowfall trend. A majority of the snowfall trend vs. elevation correlations were negative, meaning that as elevation increases for a station in CNY, the snowfall trend is actually decreasing and vice versa. None of the correlations between a station's snowfall trend and the station's distance from Lake Ontario were significant at the 5% or 1% level. However, a majority of the correlations calculated between distance and snowfall trend were inversely related.

Table 31. Correlations of significant snowfall trends (at the 1% level) with the elevation and distance from Lake Ontario of a station. Correlations significant at the 5% level are marked with an asterisk.

Time Period	Elevation	Distance
1931-2011	0.48	-0.41
1971-2011	-0.54	-0.11
1931-1951	-0.23	-0.12
1951-1971	0.46*	-0.34
1971-1991	-0.51*	-0.1
1991-2011	-0.36*	0.04

Chapter 4: Discussion

Observing the spatiotemporal trends of snowfall in Central New York can provide insight concerning long-term variations in snowfall and possibly improve future snowfall predictions for the region. Since CNY is dominated largely by LES, various factors went into the analysis of this study: monthly snowfall totals, winter precipitation, region classifications, among others. This study found that snowfall trends in CNY exhibited a spatial and temporal relationship from 1931/32 – 2011/12.

4.1 Central New York Temporal Snowfall Trends

Previous studies (Norton and Bolsenga 1993; Burnett et al. 2003; and Kunkel et al. 2009b) have determined that LES throughout the Great Lakes basin has increased since the early 20th century. Through the use of greater spatial coverage within CNY and current snowfall records (1931/32 – 2011/12), the long-term trend calculated in this study supports those findings as snowfall in CNY, located within the Lake Ontario snow basin, has increased by 0.46 +/- 0.20 in. yr^{-1} (1.17 +/- 0.51 cm yr^{-1}) which translates to a 1.35 standardized unit increase in snowfall from 1931/32 – 2011/12. Therefore, not only has snowfall increased in CNY, but the increase is comparable but slightly less than that found by Burnett et al. (2003) (1.5-1.8 standardized unit increase). Such a discrepancy in snowfall trends calculated for this study compared to that of Burnett et al. (2003) may be twofold.

One difference was that the study by Burnett et al. (2003) only observed snowfall trends from 1931-2001. This study utilized snowfall records during the 21st century, which may have slightly lowered the snowfall trend. In fact when examining the snowfall record in this study from 1931/32 – 2000/01 the snowfall trend was higher (0.69 in. yr^{-1}) than the trend for the long-term record (0.46 in. yr^{-1}). A decrease in the snowfall trend by including 21st century snowfall totals is highly plausible as Kocin and Uccellini (2004) found that the latter half of the 20th century, especially the 1990s, was an extremely snowy period in the eastern United States. Therefore, snowfall trends from the Burnett et al. (2003) study may have been positively biased due to high snowfall totals during the latter years (1990s) of their study. A second discrepancy was that considerably more stations were used in this study compared to Burnett et al. (2003), which may have resulted in a decreased snowfall trend. By increasing the stations located within CNY, snowfall trends are better representative of the CNY region, and in general the Lake Ontario snow basin.

However, a major difference between this study and previous studies was that snowfall trends were calculated for multiple time increments within the long-term record, and not just for long-term periods (> 50 years). After dividing the long-term record up into multiple time segments (two 41-year periods and four 21-year periods), snowfall trends were not homogenous throughout time. Instead, the first half of the record (1931/32 – 1971/72) exemplified the greatest increase in snowfall (1.26 +/- 0.44 in. yr^{-1} (3.2 +/- 1.1 cm yr^{-1})), especially from 1951/52 – 1971/72 (2.26 in. yr^{-1}); while the second half of the record did not demonstrate any significant snowfall trend, and from 1971/72 – 1991/92 actually displayed a significant decrease in snowfall (-2.09 in. yr^{-1} (-5.3 cm yr^{-1})). The high variability in snowfall trends is also exemplified in the 21-year snowfall trends at a 1-year time step (Figure 15), as trends were highly variable for CNY, ranging from approximately 3 in. yr^{-1} in the early and late 1960s to nearly -3 in. yr^{-1} during the late-1970s/early-1980s. Therefore, the high variability in snowfall trends supports the statement that the long-term snowfall trends calculated in previous studies are not necessarily reflective of how snowfall totals are changing in CNY, and instead snowfall trends are quite fickle.

Thus, snowfall totals were considerably higher in the early 1970s compared to the 1930s and 1950s. However after the 1970s, snowfall trends were negative or not statistically significant suggesting snowfall averages leveled off. This is supported by the decadal anomaly maps (Figure B1 – B9) which show a gradual increase in positive snowfall anomalies throughout CNY as time progresses. In fact, the greatest positive anomalies occurred during the 1970s and 1990s, which would explain why the earlier snowfall trends are much larger than the later trends as snowfall was at a maximum during these two decades. The major difference between the 1970s and the 1990s was that the 1970s experienced more extreme snowfall anomalies (30+ in. or 75+ cm) especially east of Lake Ontario, while the 1990s experienced widespread high (6-18 in. or 15-45 cm) but not extreme snowfall anomalies. Therefore, it is likely that the long-term snowfall trend reported in this study and previous studies for CNY is biased due to snowfall trends from 1931/32 – 1971/72, which resulted from extreme average snowfall during the 1970s. This would propose that snowfall in CNY during the latter half of the full-length record did not actually increase by 0.46 in yr^{-1} (1.2 cm yr^{-1}) and instead experienced little to no change.

This coincides with the findings of Kocin and Uccellini (2004) who reported snowfall during the 1990s was at a maximum for the 20^{th} century over the Northeast

United States (Figure B7), as large positive snowfall anomalies (6-18 in. or 15-45 cm) blanketed CNY. If annual snowfall was greatest during the late-twentieth century, then it might be expected that snowfall totals would naturally decrease or remain constant during the early stages of the 21st century. Because the decadal-scale variability in snowfall is high, evidenced by the highly variable 21-year trends, it is unlikely that the long-term trend is a good predictor of future snowfall. More work is needed to understand the reason for the interannual and decadal variability. However, the length of the snowfall record examined in this study, based on observations provided by COOP stations in CNY, is not substantial enough to infer whether such trends are long-term variations or actual trends. It is possible that annual snowfall in CNY is on a long-term cycle in which annual snowfall totals were at a minimum at/near the 1930s and have crested during the 1990s. Therefore, if such variations exist, it would explain why annual snowfall in CNY has remained relatively constant, with a slight decrease, during the 21st century.

4.1.1 Syracuse Snowfall Trends

Since Syracuse is the largest city in CNY, and is historically the snowiest metropolitan area in the United States, snowfall trends in Syracuse were of particular interest. Long-term snowfall trends for Syracuse (SYR) were comparable to the findings of Burnett et al. (2003) as snowfall increased by 0.56 in. yr^{-1} (1.4 cm yr^{-1}), even though this study examined eleven additional seasons during the 21st century. This has resulted in an increase in snowfall of approximately 45 in. (114 cm) from 1931/32 – 2011/12. This is a substantial increase of 1.36 standardized units, and from other snowfall analyses (other station trends, spatial trends, etc.) was most likely attributed to an increase in LES. Interestingly, when observing snowfall records for Syracuse (SYR) during smaller time periods, snowfall trends were increased for both 1931/32 – 1971/72 (0.92 in. yr^{-1} or 2.34 cm yr^{-1}) and 1971/72 – 2011/12 (0.84 in. yr^{-1} or 2.13 cm yr^{-1}). However, when examining snowfall records during 21-year increments, no discernible trends were present (Table 16). The high variability in snowfall trends may be associated with high seasonal fluctuations in which some years snowfall totals are anomalously high, followed by years of depleted snowfall totals. Although, according to Syracuse (SYR) snowfall trends, snowfall for the region was not increasing as much from 1971/72 – 2011/12 compared to 1931/32 – 1971/72, but compared to the 1971/72 season, 2011/12 averaged over 30 in. (76 cm) of additional snowfall.

4.1.2 Homogenous Station Trends

Kunkel et al. (2007) noted that inhomogeneities in snowfall observations have biased snowfall trend estimations. To counter this over/under estimation of snowfall trends the authors proposed a filtering method which would limit station observations to those which have not experienced a considerable change in measurement practices or relocations.

Even though this study deemed considerably more COOP stations homogenous and examined snowfall for a later time period compared to Kunkel et al. (2009b), this study found that similar to Kunkel et al. (2009b), after filtering for inhomogeneities the long-term trend calculated for CNY decreased to 0.23 in. yr^{-1} (0.58 cm yr^{-1}), which was nearly half the original trend calculated using COOP stations prior to filtering for inhomogeneities. In fact, the recalculated change in snowfall, 0.74 standardized units, was nearly identical to the change observed by Kunkel et al. (2009b). However, it should be noted that when filtering for inhomogeneities, the amount of stations dramatically decreased and snowfall trends may not have accurately represented CNY. For example, from 1931/32 -2011/12 only nine stations were deemed homogenous, with a majority of them located in Onondaga County (Baldwinsville, Brewerton, Skaneateles, and Syracuse Hancock International Airport). Only one of the homogenous stations was located in the Tug Hill, where snowfall trends were generally increased (Table 15). Therefore, this clustering of stations may have caused a decreased snowfall trend and not necessarily the use of homogenous stations. This assumption is further supported by the fact that not all time periods experienced a decrease in the snowfall trend. For example, the use of homogenous stations from 1951/52 – 1971/72 actually increased the snowfall trend, 2.26 in. yr^{-1} (5.7 cm yr^{-1}) to 2.64 in. yr^{-1} (6.7 cm yr^{-1}), and compared to other time periods, 1951/52 – 1971/72, had the greatest amount of homogenous stations (35 stations) available to calculate average snowfall.

The initial and homogenous long-term snowfall trends calculated in this study support the first hypothesis that snowfall totals in CNY have increased since the 1931/32 season. Long-term snowfall trends for CNY were comparable to those found in Burnett et al. (2003) and slightly less once inhomogeneous stations were filtered out similar to the findings of Kunkel et al. (2009b). However, when considering shorter time periods within the long-term record, inconsistencies between the periods result in a rejection of the hypothesis. For example, not all periods experienced a positive increase in snowfall (i.e. 1971/72 – 1991/92) and not all snowfall trends decreased after filtering for inhomogeneities (1951/52 – 1971/72).

4.1.3 Monthly Snowfall Trends

Since prior studies have attributed the increase in snowfall in the Great Lakes basin to LES, some (e.g. Burnett et al. 2003) have suggested that typical LES months (December-February) within the Great Lakes basin have experienced increased snowfall totals since the early 20th century compared to non-typical LES months (October-November and March-April) (Ellis and Leathers 1996). The previous findings were supported in this study as snowfall trends during the long-term period were only significant for typical LES months (December-February); compared to previous studies such findings were determined while using a smaller spatial resolution, increased observations, and a greater time span. In fact, January exhibited the largest snowfall trend, which also coincides with the peak intensity of LES, suggesting that the positive snowfall trends experienced in CNY are due to LES. This is also supported by the fact that the two regions (Region 4 and Region 5) that experienced a large positive, statistically significant long-term trend were both located on the leeward side of Lake Ontario, and in areas generally impacted by LES. Therefore, since long-term snowfall trends were significant during typical LES months, and for LES regions, it may be assumed that snowfall trends in CNY were a direct result of LES.

A unique finding to this study was that long-term monthly snowfall trends were highly correlated between November – January, November – March, January – February, and March – April. Two of the highest correlations were between November – January (0.99) and March – April (0.96). Correlations between March and April are understandable as they are successive months and later in the season. Also, correlations between snowfall trends in January – February and March – November are consistent as the first pair is typical LES months and the last two months are on the ends of the LES season, therefore having increased correlations. However, the high correlation between January and November is unique. January is typically a LES month, while November is only a LES month for some regions. Therefore, it is unclear as to why this relationship exists; but a possible driving force may be related to an oscillation such as the NAO. Further research would have to be explored but it is possible that the atmospheric parameters associated with a particular teleconnection (such as the NAO), typically may be in phase during November and January causing snowfall trends to behave similar during these two months.

Increased snowfall during typical LES months is also supported by snowfall trends calculated from 1931/32 – 1971/72, as positive snowfall trends were recorded for months December-February for Region 1 and November-February for Regions 4 and 5. Region 1 was located in a LES dominated area, especially during northwesterly winds. Therefore, the snowfall increase from December-February is most likely attributed to an increase in LES. Along with typical LES months, snowfall in Regions 4 and 5 increased during November as well. Since Regions 4 and 5 are in higher latitudes and directly leeward of Lake Ontario, LES onset usually begins prior to that of other LES regions (November compared to December). Therefore, since snowfall increases were only significant for typical LES months, the annual snowfall increase experienced from 1931/32 – 1971/72 is most likely attributed to an increase in LES.

4.2 Central New York Spatial Snowfall Trends

Multiple studies have examined the spatial changes of snowfall within the Great Lakes basin, for example how snowfall has changed for the Lake Ontario snow basin compared to the Lake Erie snow basin, but few studies have examined how snowfall has changed within one particular Great Lakes basin. Therefore multiple methods were employed to examine how snowfall has spatially changed throughout CNY, which is located within the Lake Ontario basin, including regional analyses, site specific analyses, and spatial mapping techniques.

Norton and Bolsenga (1993) found that snowfall, and in particular LE-snowfall in the Lake Ontario basin has not increased homogenously, as the long-term basin trends suggest, and instead some areas (regions) have experienced greater trends then others. A particular pattern consistently found in this study was that areas in typical LE-dominated regions in CNY (the Tug Hill Plateau and the Southern Hills) experienced the greatest increase in snowfall. For example, stations within the Tug Hill Plateau on average experienced the largest snowfall trends among all other stations (Table 15). This is also supported by the 41-year snowfall difference map (Figure 22) and regional trends (Figures 16 and Figure 17). Examining Figure 22, it is obvious that snowfall increases were not consistent throughout CNY, and areas adjacent to Lake Ontario, especially those over the Tug Hill Plateau, experienced the greatest snowfall trend. In general, high long-term snowfall anomalies were concentrated in higher elevations in close proximity to Lake Ontario (> 50 km). For example, high snowfall trends also extended into the Southern Hills which provide additional topographic features increasing snowfall totals. This is also supported by station trends, as two of the largest trends based on standardized average snowfall occurred within the Southern Hills, for Auburn (0.033 standardized units yr^{-1}) and Morrisville (0.020 standardized units yr^{-1}). Historically these stations do not experience the extreme snowfall totals that other stations in CNY may undergo (northern counties), but comparatively snowfall in these areas has nearly doubled since 1931. Such increases in higher elevations near Lake Ontario are consistent with an increase in LES as Hill (1971) reported a strong dependence of LES totals on elevation.

The regional trends also coincide with a strong increase in snowfall for typical LES regions. For example, the largest statistically significant snowfall trends for the wind direction classifications were Regions C-F, while little to no discernible trends were extracted for Regions A-B and G-H (Figure 8). It is plausible that trends were not statistically significant for Regions A, B, G, and H due to a lower amount of COOP stations compared to Regions C-F; however, the absence of a palpable trend for Regions A, B, G, and H may actually be because the four regions are on the edges of the Lake Ontario basin. Therefore, LES may be the driving factor in snowfall increases in CNY, since regions within the core of the Lake Ontario snowfall basin (Regions C-F) all experienced a significant increase in snowfall from 1931/32 – 2011/12.

Snowfall trends calculated for regions classified by the principal component analyses also supports the findings that snowfall in CNY is increasing greater for LES regions than non-typical LES regions. All five PCA regions examined in this study were determined to have a statistically positive snowfall trend; therefore, it is suggested that all five regions were located within the Lake Ontario basin as snowfall significantly increased rather than decreased, as previously found by Norton and Bolsenga (1993), Burnett et al. (2003), and Kunkel et al. (2009b). However, even though snowfall trends were significantly (at the 10% level) positive for all five regions, there were considerable differences between the regional trends. For example, the long-term snowfall trend (0.81 in. yr^{-1} (2.06 cm yr^{-1})) for Region 5 was considerably higher than snowfall trends for the other four regions. An explanation for increased snowfall trends in Region 5 is that it encompasses the area most associated with LES: on the leeward side of a LES producing lake, a steep elevation gradient within the region and winter temperatures are regularly below the freezing threshold. Therefore, since snowfall trends are greatest for Region 5 compared to any other region, it can be deduced that LES snow is the dominant contributor to increased snowfall in CNY.

One discrepancy in increased snowfall for areas most associated with LES is Region 4. There was a strong positive increase in snowfall for Region 4 (0.42 in. yr^{-1} (1.07 cm yr^{-1})), but compared to the average amount of snowfall for this region (153.2 in. yr^{-1} or 390 cm yr^{-1}), the standard deviation trend was actually equal to that of Region 1 (0.01 yr^{-1}). Therefore, since Region 4 had extremely high average annual snowfall and covered parts of the Tug Hill Plateau, it was expected that this region would experience one of the largest snowfall increases due to an increase in LES. A possible explanation for a decreased positive trend is that unlike the other four regions, Region 4 covered a long, but narrow stretch of CNY. Therefore, LES bands that influenced one station in Region 4 did not necessarily impact all stations within the region, resulting in variations in the snowfall trends. A second possible cause for the lower snowfall trend for Region 4 was that it extended over the backside of the Tug Hill Plateau. Due to the orographic features and high snowfall totals that occur over the Tug Hill (Figure 19), it would be suggestive that snowfall totals would be depleted on the leeward side of the Tug Hill, resulting in lower snowfall totals. This is also supported by snowfall average maps (Figures 20 and 21) and the 41-year snowfall difference map (Figure 22), as snowfall totals are lessened on the backside of the Tug Hill.

The unequal distribution of snowfall in CNY is not only supported by the findings that snowfall increases were greatest for regions most associated with LES, but snowfall totals and trends for areas commonly outside the extent of LES were lessened. For example, snowfall increases throughout the long-term period were least over the western extent of CNY (except for areas directly bordering Lake Ontario, parts of Oswego County), parts of the southern tier (especially southeast CNY), and the eastern reaches such as southern Herkimer and northern Otsego counties (Figure 22). All three of these regions are in some way not commonly associated with LES due to their orientation and distance to Lake Ontario. Therefore, it is further evidence that snowfall increases in CNY were not evenly distributed and instead were highest over typical LES locations and lowest over edges of the Lake Ontario snow basin.

Decreased snowfall trends in non-typical LES regions are also supported by the regional classifications as not only were seasonal snowfall averages lower for Region 2 compared to the other regions (on average 73 in. yr^{-1} or 185 cm yr^{-1}), but snowfall trends from 1931/32 – 2011/12 (0.15 in. yr^{-1} or 0.38 cm yr^{-1}) and 1931/32 – 1971/72 (0.49 in. yr^{-1} or 1.24 cm yr^{-1}) were considerably smaller in contrast to the other regions. This is supported by the fact that the second region was located in the southeast sector of CNY, furthest away from Lake Ontario. Compared to the other four regions, Region 2 along with Region 3 did not directly border Lake Ontario. Therefore, snowfall trends in Region 2 were considerably lower than the other regions as LES most likely does not dominate this region, and instead other mechanisms, for example Nor'easters, account for a higher percentage of the annual snowfall total. Individual station trends also coincide with a decreased snowfall trend in southeast CNY as long-term snowfall trends for some stations within this region were small (Sherburne) or even negative (Greene).

However, similar to characterizing the Lake Ontario basin as a whole entity, treating each region as a group can cause overgeneralization. Therefore, each individual station was observed to not only represent how snowfall has changed as a whole for CNY, but for site specific areas as well. This is extremely important for LES due to its highly variable nature, which can cause snowfall totals in one region to drastically increase compared to other regions only miles away; which in return may result in snowfall trends within the same region to be highly variable. An example of overgeneralizing the trends is noticed in Region 1, in which the long-term regional trend was considerably lower than the snowfall trend for some of the stations within the region (i.e. Cincinnatus, Syracuse Hancock Internal Airport, and Auburn). The regional trend calculated for Region 1 was 0.23 in yr^{-1} (0.010 standardized units yr^{-1}), while a station such as Auburn experienced a long-term snowfall trend of 0.90 in. yr^{-1} (0.033 standardized units yr^{-1}). These two trends differ greatly in magnitude and over the long-term period may have resulted in a snowfall difference of over 50 in. (127 cm). Therefore, one should always caution when treating a large spatial region as a single entity, and instead should examine the smaller spatial scale, similar to how this study examined CNY (part of the Lake Ontario basin) instead of examining the full extent of the Great Lakes basin as previous studies (Norton and Bolsenga 1993; Burnett et al. 2003; Kunkel et al. 2009b; etc.) have done.

In a certain aspect, the Lake Ontario basin behaves similar to the Great Lakes basin. Similar to the findings of previous studies which used fewer COOP stations and not as current seasonal snowfall totals (Norton and Bolsenga 1993; Burnett et al. 2003; and Kunkel et al. 2009b), typical LES dominated regions have experienced a greater increase in snowfall than areas further inland, and less impacted by LES. This coincides with the hypothesis that snowfall changes in CNY are not spatially homogenous, and that snowfall increases more for stations traditionally in a LES dominated regions (i.e. Region F and Region 5) compared to stations in areas not highly impacted by LES (i.e. Region A and Region 2). The orientation and distance of a station to Lake Ontario appears to have a large influence on not only average annual snowfall totals, but snowfall trends as well.

4.3 Parameters Influencing Snowfall Trends in Central New York

4.3.1 Wind Direction

Since this study classified CNY into wind direction categories, possible long-term wind patterns could be inferred. Each individual snowfall region (A-I) corresponded to a particular wind direction that onsets LES within that region (i.e. Region A is dominated by a northerly wind; Region B is dominated by a north-northwest wind, etc.). Therefore, even though snowfall overall increased in CNY for the long-term record, possible wind patterns in CNY favored the development of LES over stations directly east of Lake Ontario (Regions C-F) compared to stations to the south (Regions A-B) and north (Regions G-H) of the lake. Within the regions east of Lake Ontario (Regions C-F), snowfall trends were highest for Region F (0.84 in. yr^{-1} or 2.1 cm yr^{-1}), equating to 1.85 standardized unit increase in snowfall from 1931/32 – 2011/12. This suggests that long-term wind patterns have not only favored CNY stations directly east of Lake Ontario, but in particular an east-northeast wind pattern may have prevailed; which is supported by the typical LES formation in Ontario, Canada described by Liu and Moore (2004).

However, it should be noted that in addition to eastern regions (C-F), Regions A and B demonstrated a significant (at the 10% level) positive trend from 1931/32 – 1971/72. In general the snowfall trends for Regions A and B during this period were smaller than trends calculated for Regions C-F; however, it is possible that snowfall increases during this time may have been more widespread and no distinct wind pattern was dominant as referenced by the long-term trends.

Correlation patterns between regional snowfall totals also support a wind driven snowfall theory for CNY, as stations adjacent to one another displayed high correlations, with the greatest correlation between Regions C and D. These correlations most likely occurred as LES bands usually form in multiple parallel bands; therefore, a LES storm typically forms over two or more regions, causing snowfall totals to behave similar within those regions. This is also supported by the fact that correlations were decreased the further away two regions were located. For example, correlations between snowfall in Region A and snowfall in other regions decreased further from Region A. However, there were exceptions to this relationship, such as the correlation between Region A and Region H. This may be due to the fact that Region A and Region H are dominated by northerly and southerly wind patterns, respectively. These wind patterns do not historically produce as much LES; therefore, these two regions had a higher correlation because snowfall in these regions is mainly dominated by mechanisms other than LES, which is also supported by the lack of a significant long-term snowfall trend calculated in either region.

An interesting find in this study was that two of the highest correlations were between non-adjacent stations (Regions A and C and Regions B and D). One possible cause for these high correlations is that all four regions are located in the southern half of CNY, and since the regions are further south they are more apt to experience region wide snowfall events (Nor'easters and frontal passages) than other CNY regions. However, a second possible explanation for these high correlations is that there are typical wind patterns that align throughout a day (or multiple days) that favor snowfall over particular regions. Since LES is highly dictated by wind direction, which can shift multiple times within a day, wind patterns in CNY may regularly transition from a northern (Region A) to northwestern (Region C) wind or from a north-northwest wind (Region B) to a west-northwest wind (Region D); which ultimately may cause the high correlations calculated between the two regional pairs.

4.3.2 Extreme Interseasonal Snowfall Variability

Previous studies (Kocin and Uccellini 2004; Kunkel et al. 2009c) have examined, especially for the East Coast and the full extent of the Great Lakes basin, how interseasonal snowfall variations have increased over time, leading to years with high snowfall totals followed by years with extremely low snowfall totals. The extent of this study did not attempt to determine the variability in extreme snowfall seasons in CNY, but the impact of two extreme snowfall seasons (2010/11 and 2011/12) was examined during the 21st century decadal snowfall anomaly plots (Figures B8 and B9). One significant trait about 21st century snowfall was that strong positive anomalies (30+ in. or 75+ cm) were present, but were regionally concentrated similar to the 1940s (Figure B2). For example, it appears that a northwesterly wind was favorable during the 21st century which considerably increased LES snowfall from the eastern shores of Lake Ontario, throughout areas surrounding Oneida Lake and into the majority of Madison County.

However, areas outside of this region (in particular the western Adirondacks and southwestern CNY) snowfall totals were at or below average. Therefore, besides LES formed from a west/northwesterly wind, snowfall during the 21st century was decreased.

This is important because when comparing Figure B8 with Figure B9 it is clear that the addition of the 2011/12 season considerably altered snowfall anomalies. Snowfall anomalies were located in similar locations, but the magnitude of the anomaly was largely influenced. This occurred since the 2011/12 snowfall seasons was vastly different (much lower) than the 2010/11 snowfall season, which supports the findings of Kocin and Uccellini (2004), who found extreme seasonal variations in seasonal snowfall totals since the 1990s. Therefore, it may be anticipated that future years will have high snowfall variability (similar to the 2010/11 and 2011/12 seasons) or even decadal variability (similar to the 1990s compared to the 1980s). It may also be suggested that due to the wide-spread extreme variation in 21st century snowfall, the extreme interseasonal variations may be due to alterations in both LES and other snowfall mechanisms and may be related to a forcing factor such as air temperature.

4.3.3 Small Lake Snowfall Enhancement

Previous studies (i.e. Sobash et al. 2006) have discovered that small lakes can enhance LES in New York State, and even CNY. However, there was no clear increase in snowfall for stations on the leeward sides of smaller lakes (Cayuga Lake and Oneida Lake) in CNY for any of the decades. This suggests that small lake enhancement, described by Sobash et al. (2006), did not significantly increase snowfall totals for stations leeward of smaller lakes. One possible cause for this is that small lakes may enhance snowfall totals during certain days or even months, but over time those totals are averaged out to nearby stations that are not influenced by enhanced small-lake LES. Also, since the lake-air temperature difference is a controlling factor in small-lake enhancement, the temperature difference in the early decades may not have been met. If temperatures continue to increase during the 21st century, small-lake enhancement may occur, but was not in the scope of this study. Another possible factor is that snowfall anomalies are averages and anomalies were plotted based on fixed increments; therefore, if small-lake enhancement only increased snowfall by a few inches or centimeters compared to nearby areas, then that increased signal may not have been extracted.

4.3.4 Periodic Variations and Teleconnections

Numerous studies (Serreze et al. 1998; Livezey and Smith 1999; Kocin and Uccellini 2004; and Kunkel et al. 2009c) have found that teleconnections have a significant role in seasonal snowfall totals, for both the Great Lakes basin and the Northeast United States, both of which CNY is considered to be located in. However, no obvious periodic variations that needed to be accounted for were calculated using autocorrelations for any of the data sets.

The lack of correlation between CNY snowfall and the three teleconnections observed (NAO, SOI, and AMO) is supported by low correlation in Figure 26. In fact, the only teleconnection that demonstrated a significant (1% level) was the AMO. This coincides with the previous findings that the AMO is the only teleconnection observed that may have an influence on CNY snowfall; however, similar to the findings of the PCA, this negative correlation (-0.41) was not large enough to suggest that CNY snowfall totals are always inversely related to the phase of the AMO.

Also, possible low frequency signals (those due to teleconnections) were examined using PCAs. In particular, PCA-c and PCA-d were used to estimate possible causes of variations in snowfall such as the influence of teleconnections through correlations between the modes and the NAO, SOI, and AMO. However, this study found that none of the modes identified in either PCA-c or PCA-d were highly correlated (all less than 0.35) with a climate index, suggesting that alterations in annual snowfall in CNY may not directly be driven by teleconnections, or at least the three examined in this study (NAO, SOI, and AMO).

However, out of the three teleconnections examined, the AMO appeared to have the greatest influence (two significant correlations with modes in PCA-c and three significant correlations with modes in PCA-d). This is unique as the AMO is a low-frequency signal extracted from sea surface temperature records in the North Atlantic Ocean. During the long-term record of this study, the AMO experienced a warm phase from 1930-1960, a cool phase from 1970-1990, and transitioned back into a warm phase during the mid-1990s (Gray et al. 2004). This is supported by Figure 24 as compared to the other climate indices examined the AMO had a low-frequency variation which aligned with the findings in the air temperature record and the snowfall record. All three factors appear to be on a long-term cycle (about 30 years) which coincides with one another. For example, during the 1970s when snowfall is at a maximum, air temperatures are lower than normal, and the AMO is also lower than normal. Similarly, the AMO is higher during the early decades (1930s and 1940s), while air temperatures are slightly warmer, and snowfall totals throughout CNY are decreased. Therefore, one possible driving factor in the snowfall trends experienced in CNY may be due to the influence of the AMO. Therefore, if the signal is real, periodic, and continues then it is possible that snowfall will peak on an approximate 30 year cycle, with the next maximum expected around 2030. However, currently there are few proxies for identifying the frequency of the AMO, and prediction capabilities are sub-par; this ultimately makes predicting snowfall maxima based on changes in the AMO difficult (Gray et al. 2004). Also, it should again be noted that even though there was a significant (at least the 5% significance) correlation with some of the modes and the AMO, the correlation was not high enough to fully suggest that CNY snowfall and the phase of the AMO are negative correlated.

The influence of the AMO is also supported by the findings that not only were the most modes correlated with the AMO, but the modes that explained the greatest variance (Modes 1 and 2) displayed the highest significant correlation with the AMO. In fact, in PCA-c both Modes 1 and 2 had a significant (at the 1% significance) correlation with the AMO (Table 23), while accounting for 88.7% of the variance (74.9% and 13.8%, respectively), while Modes 1, 2, and 3 were significantly (at least at the 5% significance) correlated with the AMO (Table 26) and accounted for 83.8% of the variance (64.8%, 13.7%, and 5.3%, respectively). Therefore not only is the AMO significantly correlated with the most modes in CNY, but it is correlated with the modes that explain a majority of the variance in CNY, Modes 1 and 2.

Interestingly, Region 4 dominated Mode 1 followed closely by Region 5; this suggests that these two regions were most influenced by variations in the AMO. As previously mentioned, these two regions are commonly associated with LES in CNY compared to the other three regions. Therefore, the influence the AMO has on CNY snowfall may be greatest for LES rather than other snowfall mechanisms. For example, snowfall variations forced by the AMO, may have been present due to changes in lake ice formation (Wang et al. 2012), lake-air temperature difference (Peace and Sykes 1966), synoptic movements of low air pressure systems (Liu and Moore 2004), or more.

In the autocorrelations of the snowfall datasets, even though there were no large scale correlations in the data, there were other smaller signals (generally less than 0.30) that may have been due to teleconnections (i.e. Figure 14). However, even though these signals were not strong and therefore not always in sync, it is a possibility that they are slightly alerting snowfall totals in CNY. For example, the correlation in the long-term snowfall trend for CNY (Figure 14) exemplified an autocorrelation of 0.2 every 2-5 years, which may be consistent with the NAO or SOI. Historically, studies (i.e. Kocin and Uccellini 2004) have found eastern snowfall to have a strong negative correlation with the NAO. Therefore, since CNY is further inland compared to typical eastern stations (i.e. New York City, Philadelphia, Boston, etc.) the influence of the NAO may be diminished causing a lower correlation, one that is not as pronounced. Other causes of the small autocorrelation, other than random noise, may be the influence of the PNA as described by Serreze et al. (1998), or even the influence of ENSO on a 5-12 years cycle described by Kocin and Uccellini (2004). Another possible cause for the variation is lake-ice formation, which Wang et al. (2012) found an approximate 4-year variation of Great Lake ice extent most likely due to the SOI. Therefore, all the previous teleconnections may have a slight increase on CNY snowfall, but in term of the NAO, SOI, and AMO, there was not a strong correlation between CNY snowfall and the three climate indices.

4.3.5 Winter Precipitation and Air Temperatures

Previous studies have found that precipitation and air temperatures can have considerable influences on snowfall trends, including areas dominated by LES (Norton and Bolsenga 1993; Burnett et al. 2003, Kunkel et al. 2009c, etc.). Through the use of recent seasonal record (2011/12) and increased station observations, this study found that winter precipitation totals were generally linked to snowfall totals as snowfall is a form of precipitation and significant precipitation trends had a positive relationship with snowfall totals. Therefore, especially from 1931/32 – 1951/52, increased snowfall totals were most likely attributed to increased precipitation during winter months, including LEP. Since precipitation and snowfall increased during these time periods, but air temperatures did not experience any significant change, it can be assumed that the SLR increased during this period, which suggests a possible increase in LES since it is a light-density snow (Burnett et al. 2003; Baxter et al. 2005). This assumption is further supported since snowfall for CNY increased at a higher rate than the precipitation did. It should also be noted that possible discrepancies in the precipitation trends and the snowfall trends was that precipitation totals were examined for fewer COOP stations than snowfall totals.

However, this study also noted that a few regions during various time periods experienced a negative relationship between snowfall trends and precipitation trends, most notably Regions 3 and 4 (especially during January) for the long-term record and Region 4 from 1951/52 – 1971/72 (Table 45). Both of these regions were in the northern areas of CNY and are impacted by LES (especially Region 4). Therefore, winter precipitation in these areas compared to others is generally in the form of snow rather than rain, sleet, freezing rain, etc. A decrease in precipitation and an increase in snowfall during these time periods suggest an increase in LES and subsequent increase in the SLR; this was also supported by the findings of Norton and Bolsenga (1993), Burnett et al. (2003), and Kunkel et al. (2009b), who found a historical increase in LES compared to other snowfall mechanisms (Nor'easters, mid-latitude cyclones, etc.) which have actually experienced a decrease in snowfall totals.

This study found that average air temperature trends were only significant (at the 10% level) for two time periods (1951/52 – 1971/72 and 1991/92 – 2001/02). From 1951/52 – 1971/72 air temperatures decreased by -0.16 +/- 0.10 ºF yr^{-1} (Table 40) while CNY snowfall trends increased 2.26 +/- 1.08 in. yr^{-1} (5.74 +/- 2.74 cm yr^{-1}). However, during the same period precipitation trends were generally not significant, suggesting that snowfall increases were associated with decreased temperatures, resulting in more precipitation falling as snow rather than other precipitation (i.e. rain, sleet, freezing rain, etc.). In contrast, 1991/92 – 2011/12 experienced an increase in air temperatures, 0.16 +/- 0.13 ºF yr^{-1}, while during the same period snowfall did not experience a significant change, and if anything slightly decreased (Figure 13d). Contradictory to the findings of Burnett et al. (2003) and Kunkel et al. (2009c) who examined the Great Lakes basin as a whole, an increase in air temperatures is not necessarily driving increased snowfall totals, as no significant temperature increases have been recorded in CNY other than from 1991/92 – 2011/12. However, increased air temperatures and little to no change in precipitation from 1991/92 – 2011/12, have not increased snowfall totals and possibly even resulted in a decrease in snowfall.

This is supported by Figure 28 as years with normalized average winter air temperature deviations near 0 tended to experience less annual snowfall compared to years where the deviation was much less than 0. However, precipitation deviations did not appear to have as strong of an influence especially since precipitation peaked in the 1950s, while at the same time, snowfall deviations were extremely low (Figure 28). Also, this is possible as Figure 27, shows that the frequency of average winter air temperatures above the freezing threshold (32ºF or 0 ºC) have been more prevalent since the early 1990s. If average winter air temperatures start to increase above the freezing threshold, snowfall is less likely to occur, compared to other forms of precipitation. This will also cause high seasonal snowfall variations outlined by Kocin and Uccellini (2004), similar to the high variability between the 2010/11 and 2011/12 seasons (Figures B8 and B9). Therefore, the initial hypothesis that winter temperature trends in CNY would be a significant factor in changing annual snowfall is rejected as air temperature trends do not firmly support this claim, but Figures 27 and 28 do show a possible strong relationship between snowfall and air temperatures; at the same time, the hypothesis that precipitation would have a small impact on snowfall changes is accepted.

4.3.6 Elevation and Distance from Lake Ontario

As Hill (1971) found, elevation has a significant impact on annual LES, with snowfall totals and elevations positively correlated. Therefore, it was hypothesized that an increase in LES would be best reflected in higher elevations, and that elevations and snowfall trends would be positively correlated. However, four out of the six time periods experienced a negative correlation between snowfall trends and elevation, and only three of which were significant (at the 5% level), all from 1951/52 – 2011/12. The statistically negative correlations might have been a result of negative snowfall trends during the latter decades. The negative snowfall trends were hypothesized to be caused by high snowfall totals during the 1970s which decreased latter decadal trends, especially in northern counties. The greatest elevations in CNY are present in the northern counties (near the Tug Hill and Adirondack Mountains); therefore since negative snowfall trends persisted in these high areas, correlations may have been influenced by this relationship. Correlations between long-term trends and elevations, even though not statistically significant at the 5% level, were positive. Long-term trends were generally positive throughout CNY and believed to be caused by increased LES. Therefore, the long-term correlation supports the hypothesis that higher elevations in CNY experienced a larger, positive snowfall trend.

Similarly, areas closer to Lake Ontario were expected to have higher snowfall trends because those areas would be more likely to receive LES. However, no significant (at the 5% level) correlations were present between distance and snowfall trends. Interestingly, the initial correlation was -0.41, meaning that the two variables were negatively correlated. This rejects the initial hypothesis that stations closer to Lake Ontario would experience higher snowfall trends. One possible cause of this relationship is that distance from Lake Ontario was based on a fixed point over Lake Ontario and not compared to the nearest shoreline. Therefore, it is possible that a positive correlation would exist if distance was measured between the nearest Lake Ontario shoreline. After observing spatial snowfall maps, it is more likely that distance from Lake Ontario has a bell-shaped relationship. This suggests that stations close to Lake Ontario and furthest away experienced the smallest snowfall trends, while stations in central CNY experienced the greatest long-term snowfall trends. This may have occurred because stations close to Lake Ontario have lower elevations, and the further away from the lake, elevations quickly rise (i.e. Tug Hill and Southern Hills). Elevations are high enough that orographic lifting causes LES on the backside of these elevated areas to decrease, resulting in diminished snowfall trends. Therefore, it is possible that distance is an important factor when comparing snowfall trends of central and eastern stations, but when comparing stations in closer proximities to Lake Ontario, elevation is more influential than distance.

Another possible cause of decreased snowfall trends nearer Lake Ontario may be explained by the findings of Jiusto and Kaplan (1972), who noticed that snowfall near the lake shore falls more as graupel (a low SLR snow) then LES. The precipitation of graupel is caused by air convection over the lake, in which warmer waters and higher air temperatures would drive a stronger convection and possibly more graupel. Therefore, if lake temperatures for Lake Ontario are increasing (as referenced by Wang et al. 2012), then the percentage of precipitation falling as graupel and the extent of a moderated climate along the lake shore may have increased causing graupel to fall further inland; which ultimately causes snowfall totals to decrease, resulting in smaller snowfall trends closer to Lake Ontario.

Chapter 5: Conclusion

Central New York State is one of the snowiest regions in the United States. Snowfall in CNY can occur from a multitude of conditions, including fronts, Nor'easters, mid-latitude cyclones, and more; but, CNY is located in one of the Great Lakes basins (Lake Ontario) which causes lake-effect snowfall to account for a majority of snowfall in the region. Recent studies have been conducted to determine how snowfall, in particular LES snowfall, has changed in areas located in the Great Lakes basin. However, very few studies have incorporated both the temporal and spatial aspects associated with snowfall changes in the Great Lakes basin, and no studies have examined how snowfall has changed for one particular Great Lakes basin, such as the Lake Ontario basin in this study.

Annual snowfall totals for CNY increased each season ~0.46 +/- 0.20 in. yr^{-1} (1.17 +/- 0.51 cm yr^{-1}) from 1931/32 – 2011/12. However, after filtering out inhomogeneous COOP stations, the calculated snowfall trend decreased to 0.23 +/- 0.20 in. yr^{-1} (0.58 +/- 0.51 cm yr^{-1}). Therefore, throughout the history of the record, snowfall totals in CNY have increased for the Lake Ontario basin as a whole. Conversely, snowfall trends during smaller time periods were much different than the long-term trend. Snowfall totals in CNY appeared to reach a maximum in the latter decades of the 20th century, especially during the 1970s and 1990s, resulting in snowfall trends after this time that were generally not significant, or slightly negative. This suggests that snowfall in CNY has reached a maximum, and will either remain constant or possibly decrease in future decades.

This study also utilized the spatial aspect of snowfall trends in CNY. Five distinct regions were identified in CNY: southwest (Region 1), southeast (Region 2), east (Region 3), an elongated region stretching from Lake Ontario to the Adirondack Mountains just north of Oneida Lake (Region 4), and northwest (Region 5). Snowfall trends for each of the five regions were used to determine how location affected snowfall trends in CNY. Concurrent with snowfall anomaly maps plotted in ArcGIS, snowfall totals in CNY tended to increase in LES dominated areas, especially Region 4 and 5, along the shores of Lake Ontario, the Tug Hill Plateau, and the Southern Hills. Therefore, it was suggested that snowfall increases in CNY were dominated by increases in LES, and were less influenced by other snowfall mechanisms.

Long-term monthly snowfall trends that were statistically positive were concentrated around typical LES months (December-February). It was inconclusive whether monthly winter air temperatures or precipitation were a driving factor in influencing monthly snowfall trends. Other possible causes in snowfall variations in CNY was the presence of a possible long-term (~30 years) air temperature variation and a slight significant correlation with CNY snowfall totals and the AMO, also on a long-term (about 30 year) variation. Precipitation and air temperature variations were associated with changes in annual snowfall trends, but not on a consistent basis. Similarly, it was statistically inconclusive whether areas with a higher elevation and closer to Lake Ontario experienced an increased snowfall trends compared to areas with lower elevations and at a further distance from Lake Ontario.

The results of this study will aid in the understanding of snowfall trends within CNY, and provide evidence of how climatology of snowfall has changed throughout time and space in CNY. Snowfall patterns determined in this study can be beneficial to various facets of society, as estimations of long-term future snowfall predictions can be made for CNY. Annual snowfall totals in CNY are vital for the region's environs and economy, as stable winter snowfall totals are depended on by: agribusiness, water resources, winter recreational businesses, wildlife, the Department of Transportation, and much more.

5.1 Limitations and Future Work

Even though this study used rigorous, proven methods and provided a solid foundation for understanding the temporal and spatial trends of snowfall in CNY, there were limitations. The most significant limitation was station consistency of COOP observations. The records for each of the 122 stations were not consistent among each other, with varying time spans, reporting frequencies, missing data, and spatial homogeneity throughout CNY. There is a possibility that results may have been skewed toward more complete snowfall records; however, the sample size was large enough where this was most likely not an issue. Also, due to reporting inconsistencies, monthly snowfall totals for some stations were reported with only 85% of the daily record and some months in the seasonal record were interpolated. This was a significant limitation, and may have resulted in possible biasing of trend calculations.

A second limitation was that originally homogenous stations were going to be used for the majority of analyses, per the suggestion of Kunkel et al. (2007). However, due to inconsistencies in the snowfall record (gaps in the data, station relocations, etc.), the limited use of homogenous stations would not have represented the spatial aspect of the study well. Therefore, homogenous stations were used mainly for temporal trends, and not spatial trends which may have created biases due to inconsistencies in station reporting, but still provided an accurate representation of snowfall in CNY.

A third limitation was presented when analyzing air temperature and precipitation data. Since snowfall generally occurs from November – April in CNY, air temperature and precipitation data was limited to these months. Therefore, it was assumed that little to no appreciable snowfall occurred from May – September, which would have a significant bearing on trend analyses. Also, due to the limited availability of air temperature data, temperature records were averaged over all of CNY. Therefore, it was assumed that the average temperature was representative of the whole region, which may not have been the case. A final limitation was that Lake Ontario surface temperatures were initially going to be examined as a possible influence along with air temperature, precipitation, elevation, and distance to Lake Ontario. However, reliable historical lake temperature records for Lake Ontario only date back to the early 1980s and upper level air temperatures to help determine lake surface temperatures were not reliable. This record was not sufficient enough to determine how Lake Ontario water temperatures affected snowfall trends. Since LES has such a high dependence on water temperatures (ice coverage, lake-air temperature difference, etc.), the previous records would have been ideal to determine the possible influence of the lake on LES in CNY. Instead, previous studies on lake ice formation over the Great Lakes were used, but Lake Ontario rarely freezes compared to the other Great Lakes. Therefore, without long-term historical Lake Ontario temperature records, no decisive conclusions could be drawn.

There are numerous research opportunities that can be built off of this study. Since this is the first study to observe the spatiotemporal snowfall trends for a single Great Lakes basin, future studies could apply the same methods for other individual Great Lake basins. Also, Kocin and Uccellini (2004) found that intraseasonal snowfall variability since the 1990s has increased; therefore, there are seasons of extremely high snowfall, followed by years of extremely low snowfall. Therefore, a future study could examine the year-by-year snowfall examining how annual snowfall extremes have altered over time.

Since CNY is highly dependent on annual snowfall, future studies could build upon this study to determine how trends in snowfall totals, or even snowfall depths are impacting various facets of CNY. For example, if snowfall totals in CNY were at a maximum during the 1990s and have leveled out or even decreased during the 21st century, how will those changes influence businesses which are highly dependent on stable annual snowfall totals? Also, agribusiness in CNY is a major industry, and most crops grown in the region rely on sufficient water resources available through snowfall melt or sufficient snowfall cover during cold temperatures. Therefore, future studies could examine how a projected steadying or decrease in annual snowfall totals will impact future agribusiness in the area.

A final study that could be conducted that builds upon the findings of this study, is by using a more direct approach to determine the influence of LES on snowfall trends in CNY. Shorter time periods may have to be used, but reanalysis data could be implemented to determine how many snowfall days were dominated by LES storms, and the percent coverage that each storm entailed. Using the previous method will allow a more complete analysis of snowfall trends, and provide insight into the general extent in which LES occurs over CNY. Also other parameters can be examined which influence LES: the strength of the polar air mass over the lake, lake temperature reanalysis data, wind speeds and fetch over the lake, among others.

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Appendices

Appendix A. Station Listing

Table A1. Station Listing and Abbreviations

Station Abbreviation	Station Name	County	Start Year	End Year	Record Length (yrs.)	% Coverage
ADS	Adams	Jefferson	1965	1972	7	100
ADSC	Adams Center	Jefferson	1947	1950	3	87
ABAY	Alexandria Bay 1 SW	Jefferson	1932	1972	40	99
AUB	Auburn	Cayuga	1897	2012	115	82
AUR	Aurora Research Farm	Cayuga	1956	2012	56	98
BAIN	Bainbridge 2 E	Chenango	1931	1992	61	95
BVILLE	Baldwinsville	Onondaga	1893	2012	119	89
BRNS	Barnes Corners	Lewis	1980	1990	10	91
BEAV	Beaver Falls	Lewis	1934	1996	62	99
BEN	Bennetts Bridge	Oswego	1941	2012	71	98
BMOOS	Big Moose 3 SE	Herkimer	1931	2012	81	97
BRIV	Black River 1 SW	Jefferson	1948	1975	27	100
BON	Bonaparte	Lewis	1934	1943	9	92
BOON2	Boonville 2	Lewis	1933	1966	33	100
BOON4	Boonville 4 SSW	Oneida	1949	2012	63	100
BREW	Brewerton Lock 23	Onondaga	1932	2012	80	98
CAM	Camden	Oneida	1946	2012	66	80
CAN	Canastota	Madison	1932	1983	51	98
CAY	Cayuga Lock Number 1	Cayuga	1927	2012	85	99
CAZ	Cazenovia	Madison	1948	1951	3	83
CED1	Cedarville 1 N	Herkimer	1953	1954	1	94
CED3	Cedarville 3 SE	Otsego	1955	1955	0	99
CHEP	Chepachet	Herkimer	1957	2001	44	100
CVAL	Cherry Valley 2 NNE	Otsego	1949	2010	61	96
CINCY	Cincinnatus	Cortland	1937	2010	73	87
CLE	Cleveland	Oswego	1932	1951	19	92
CON	Constantia	Oswego	1952	1964	12	94
CON6	Constantia 6 N	Oswego	2003	2007	4	98
COOP	Cooperstown	Otsego	1931	2012	81	100
CLAND	Cortland	Cortland	1892	2000	108	98
DRYT	DeRuyter 4 **N**	Madison	1932	1984	52	97
DEL	Delta	Oneida	1931	1976	45	98
DELD	Delta Dam	Oneida	2000	2012	12	80

Table A1 Continued. Station Listing and Abbreviations

EFAL	Eagle Falls	Lewis	1931	1963	32	100
EHOM	East Homer	Cortland	1948	1951	3	78
EHOM2	East Homer 2	Cortland	1949	1969	20	97
ED	Edmeston	Otsego	1948	1951	3	95
FAIR	Fairfield	Herkimer	1979	1981	2	96
FOR	Forestport	Oneida	1934	1978	44	94
FTD	Fort Drum	Jefferson	1975	1985	10	95
FRANK	Frankfort Lock 19	Herkimer	1931	1997	66	95
FREE	Freeville 1 NE	Tompkins	1948	2012	64	93
FUL	Fulton	Oswego	1932	2012	80	55
GRV	Gravesville 2 N	Herkimer	1950	1960	10	100
GRN	Greene	Chenango	1936	2012	76	90
GRIF	Griffiss AFB	Oneida	1948	1995	47	99
HAM	Hamilton	Madison	1937	1963	26	88
HI	Highmarket	Lewis	1931	2012	81	99
HI1	Highmarket 1 SE	Lewis	1948	1951	3	90
HINCK	Hinckley 2 SW	Oneida	1931	1993	62	97
HOOK	Hooker 12 NNW	Lewis	1935	2012	77	91
HUNT	Hunts Corners	Cortland	1948	1951	3	85
ITH	Ithaca	Tompkins	1931	1942	11	100
CORN	Ithaca Cornell University	Tompkins	1918	2012	94	88
JACK	Jacksonburg	Herkimer	1931	1963	32	98
LINK	Lincklaen	Chenango	1953	1979	26	100
LFALLS5	Little Falls 5 E	Herkimer	1960	1973	13	98
LFALLSR	Little Falls City Reservoir	Herkimer	1931	2012	81	94
LFALLSM	Little Falls Mill St.	Herkimer	1931	1994	63	98
LOK	Locke 2	Cayuga	1932	2011	79	98
LOW	Lowville	Lewis	1920	2012	92	100
LYF	Lyons Falls	Lewis	1931	2000	69	98
MAL	Mallory	Oswego	1967	1975	8	100
MAR	Marcellus Soil Conservation Service	Onondaga	1948	1951	3	100
MARY	Maryland 6 SW	Otsego	1984	2012	28	100
MCKV	McKeever	Lewis	1931	1953	22	86
MONT	Montague	Lewis	1998	1999	1	100
MOR	Moravia	Cayuga	1948	1948	0	98
MOVILLE	Morrisville 6 SW	Madison	1920	2012	92	89
MTP	Mount Pleasant Farm	Tompkins	1957	1978	21	100

Table A1 Continued. Station Listing and Abbreviations

NB	New Berlin	Chenango	1936	1997	61	80
NB5	New Berlin 5 WSW	Chenango	1956	1957	1	88
NB6	New Berlin 6 WSW	Chenango	1956	1956	0	100
NLON	New London Lock 22	Oneida	1931	2012	81	96
NEW	Newport 7 NE	Herkimer	1985	1995	10	98
NLAKE	North Lake	Herkimer	1931	1948	17	82
NOR	Norwich	Chenango	1931	2012	81	99
OFRG	Old Forge	Herkimer	1948	1948	0	99
OFRGT	Old Forge Thendara	Herkimer	1948	2012	64	92
ON1	Oneonta 1	Otsego	2010	2012	2	100
ON2	Oneonta 2	Otsego	1956	1958	2	93
ON3	Oneonta 3	Otsego	1931	1956	25	98
ON3SE	Oneonta 3 SE	Otsego	1948	1969	21	95
SUNYO	Oneonta State University	Otsego	1971	1983	12	97
OS	Oswego East	Oswego	1920	2012	92	100
OT	Otego	Otsego	1948	1949	1	100
PAL	Palermo 2 SSE	Oswego	2011	2012	1	100
PLYM	Plymouth	Chenango	1948	1951	3	98
PUL	Pulaski 1 N	Oswego	1948	1990	42	64
REC	Rectors Corners	Lewis	1987	1990	3	100
RICH	Richland	Oswego	1947	1952	5	98
ROCK	Rockdale	Otsego	1943	2007	64	93
SAL	Salisbury	Herkimer	1931	1975	44	97
SAND	Sandy Creek	Oswego	2012	2012	0	100
SSP	Sharon Springs 2 SW	Otsego	1931	1951	20	91
SHER	Sherburne	Chenango	1931	2012	81	99
SKAN	Skaneateles	Onondaga	1900	2012	112	90
SMITH	Smithville Flats	Chenango	1948	1951	3	95
SNB	South New Berlin	Chenango	1948	1951	3	85
SNB5	South New Berlin 5 N	Chenango	1956	1957	1	100
STILL	Stillwater Reservoir	Herkimer	1931	2012	81	98
SYR	Syracuse Hancock International Airport	Onondaga	1948	2012	64	100
ESF	Syracuse SUNY ESF	Onondaga	2001	2012	11	51

Table A1 Continued. Station Listing and Abbreviations

TH	Theresa	Jefferson	1948	1979	31	99
TRENT	Trenton Falls	Oneida	1931	2012	81	93
TRX	Truxton	Cortland	1953	1977	24	94
TRX4	Truxton 4N	Cortland	1948	1949	1	100
TRX5	Truxton 5N	Cortland	1948	1951	3	70
TULLY	Tully 4 NE	Onondaga	1979	1994	15	98
BERG	Tully Heiberg Forest	Cortland	1967	2007	40	99
TUR	Turin 1 N	Lewis	1966	1978	12	97
UN	Unadilla 2 N	Otsego	1978	2012	34	93
UT	Utica	Oneida	1948	1991	43	91
UT7	Utica 7 SSW	Oneida	1992	1994	2	100
UTCAIR	Utica CAA Airport	Oneida	1945	1950	5	95
UTHAR	Utica Harbor Point	Oneida	1931	1948	17	98
UTOAIR	Utica Oneida CO Airport	Oneida	1950	2006	56	98
WTR	Watertown	Jefferson	1920	2012	92	99
WTRI	Watertown International Airport	Jefferson	1949	2012	63	97
WELL	Wellesley Island	Jefferson	1975	2005	30	97
WEST	Westmoreland 4 N	Oneida	2009	2012	3	100
WILL	Williamstown	Oswego	2003	2005	2	92

Appendix B. Decadal Snowfall Anomalies

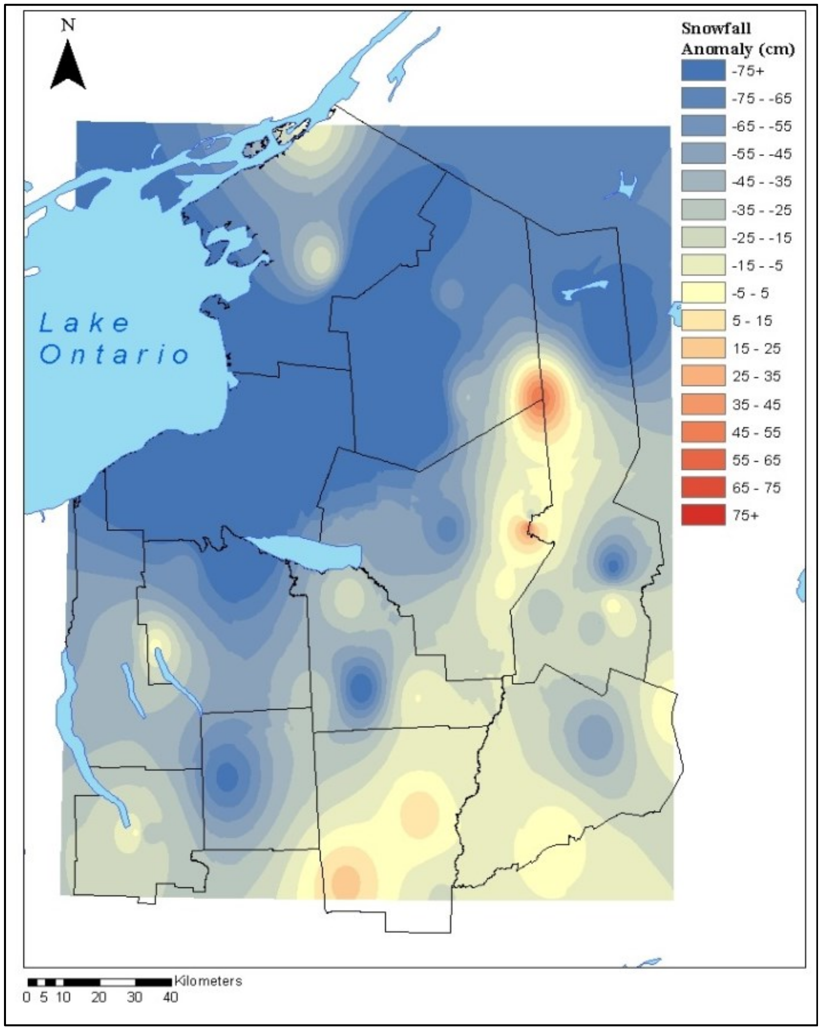

Figure B1. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1931/32 – 1940/41.

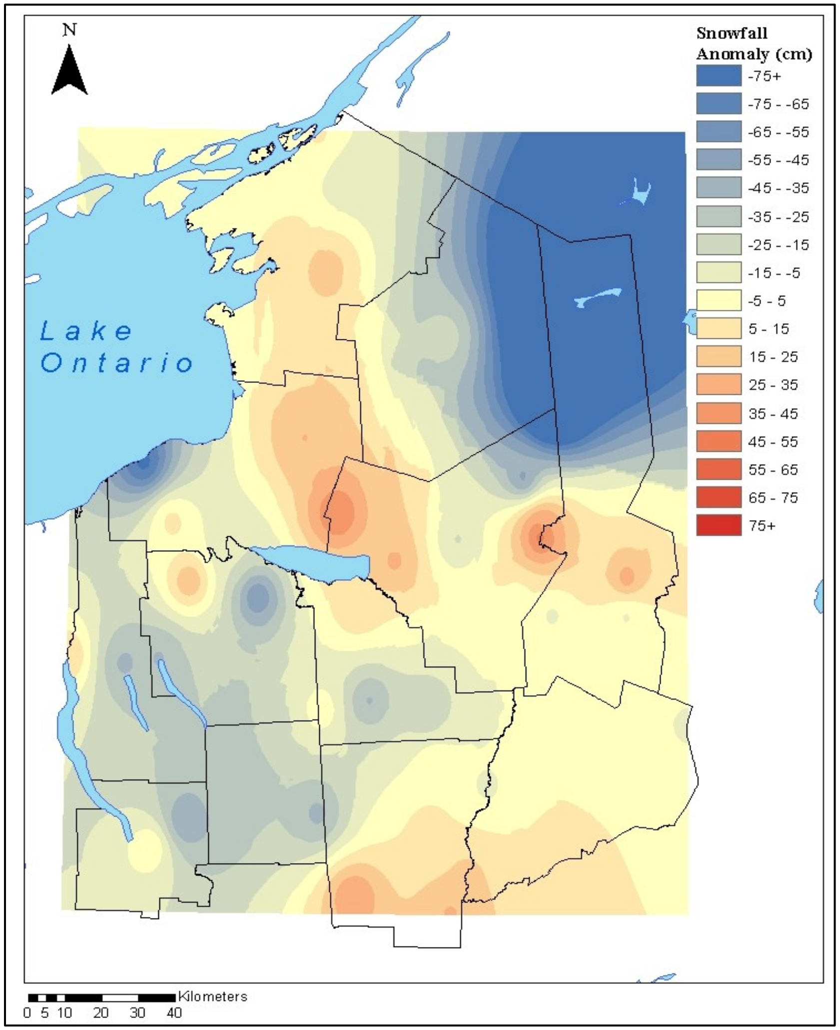

Figure B2. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1941/42 – 1950/51.

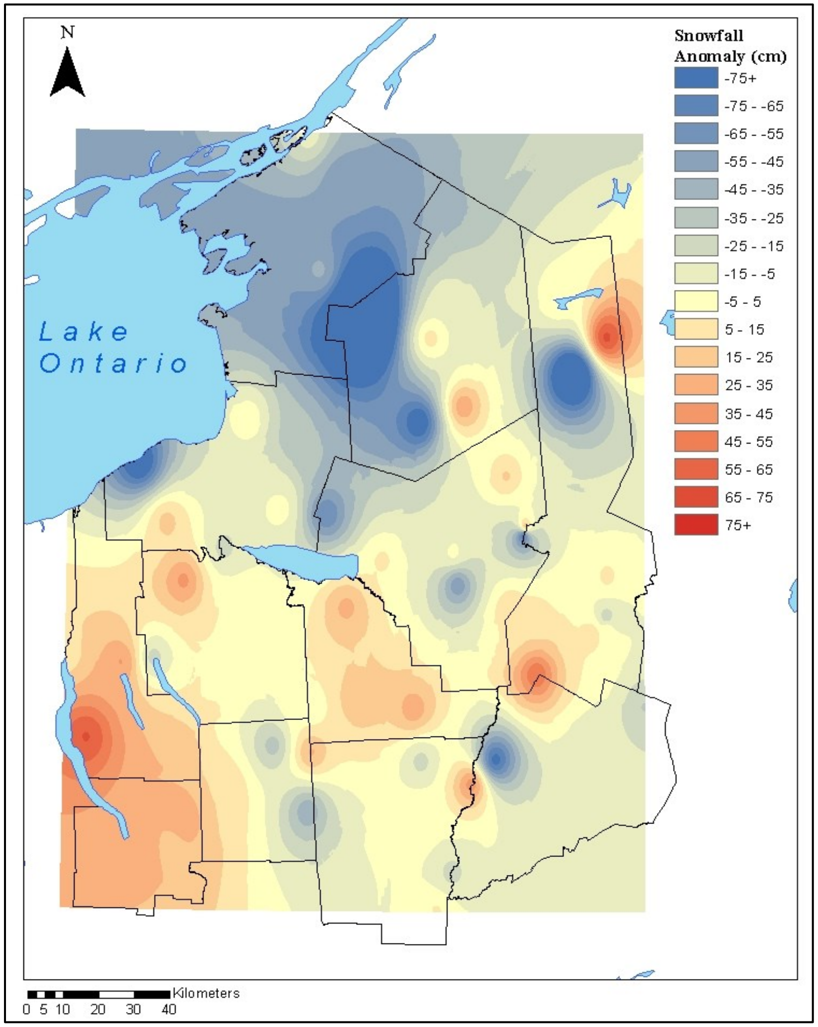

Figure B3. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1951/52 – 1960/61.

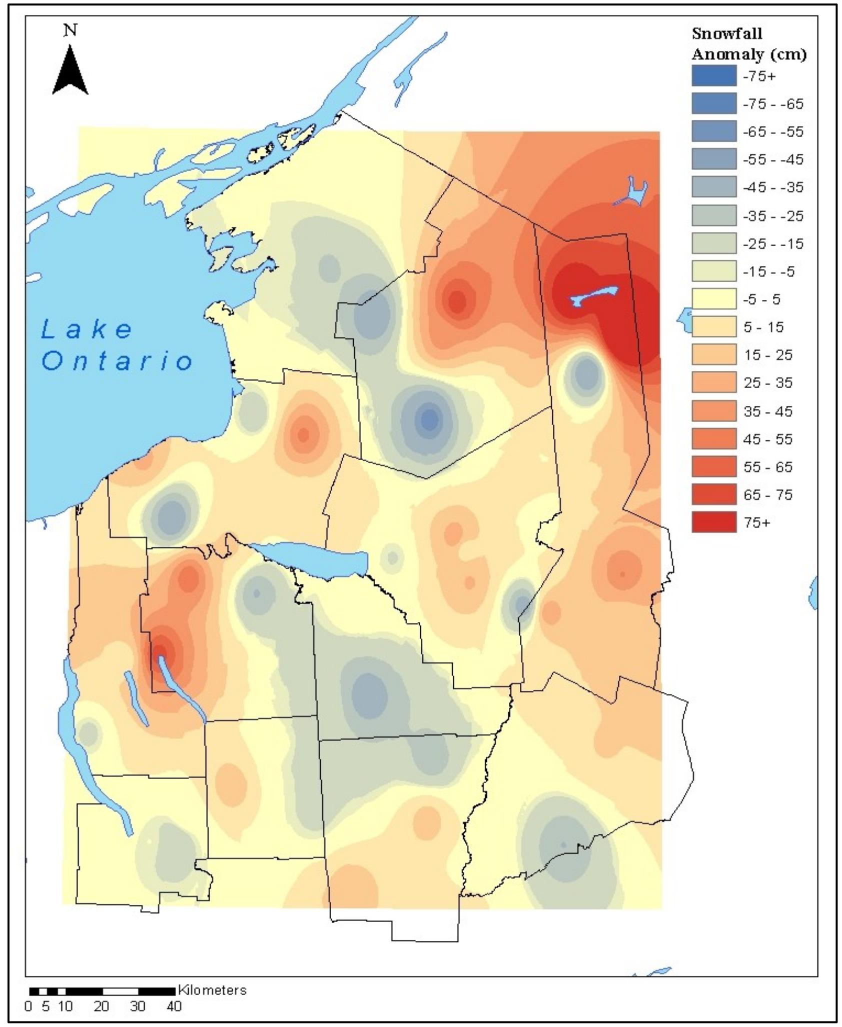

Figure B4. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1961/62 – 1970/71.

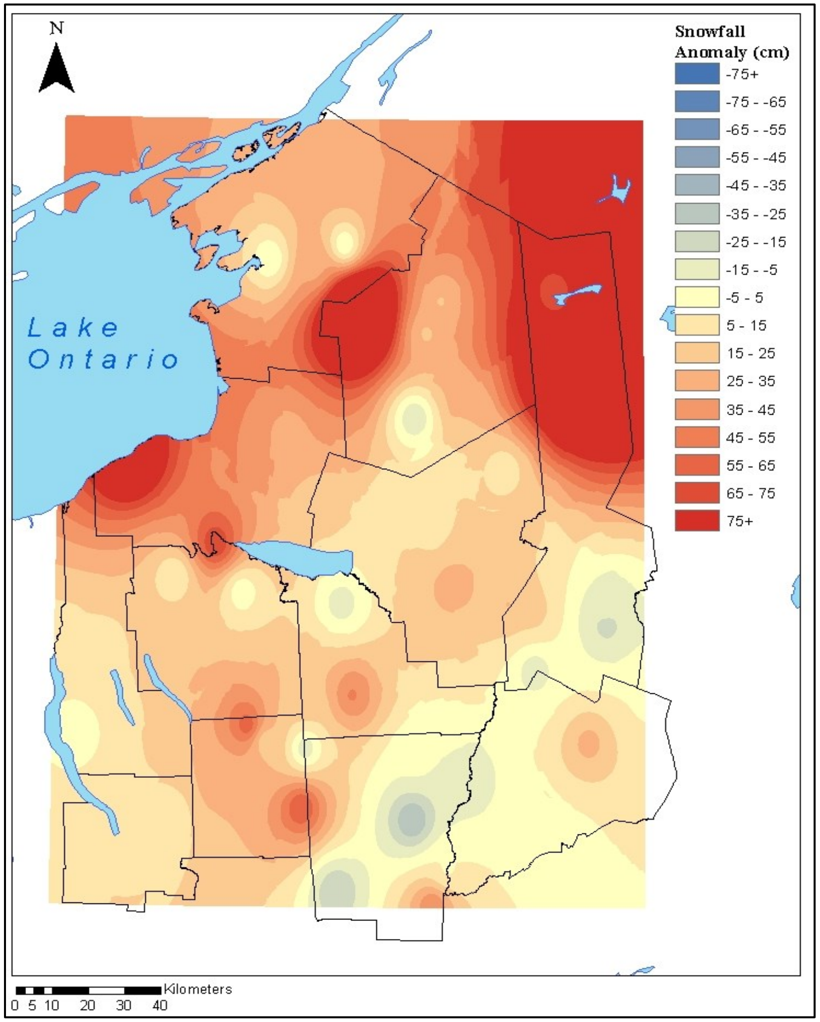

Figure B5. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1971/72 – 1980/81.

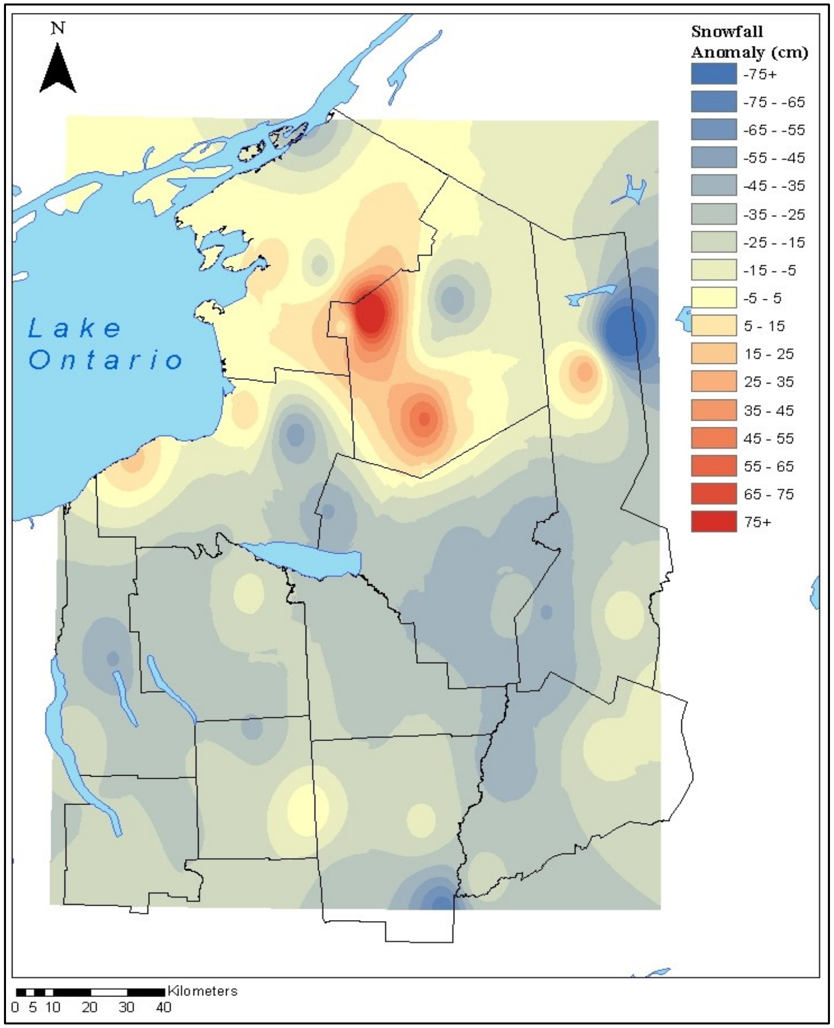

Figure B6. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1981/82 – 1990/91.

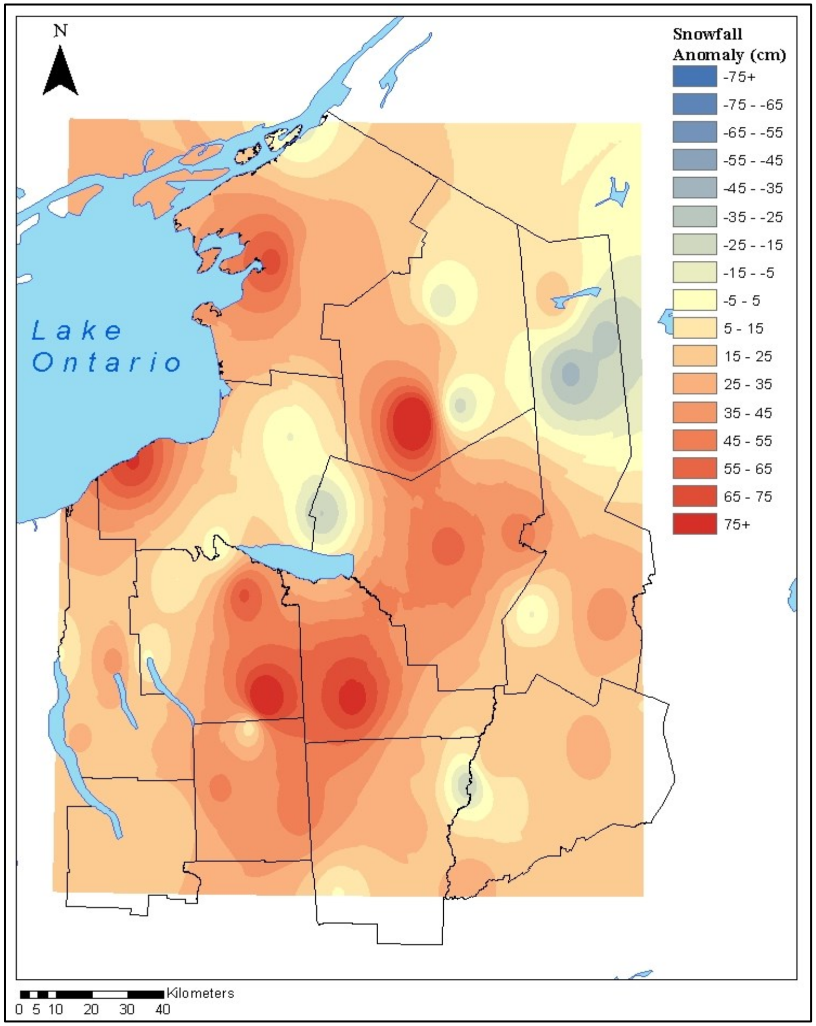

Figure B7. Mean anomalous annual snowfall totals between the long-term average and snowfall from 1991/92 – 2000/01.

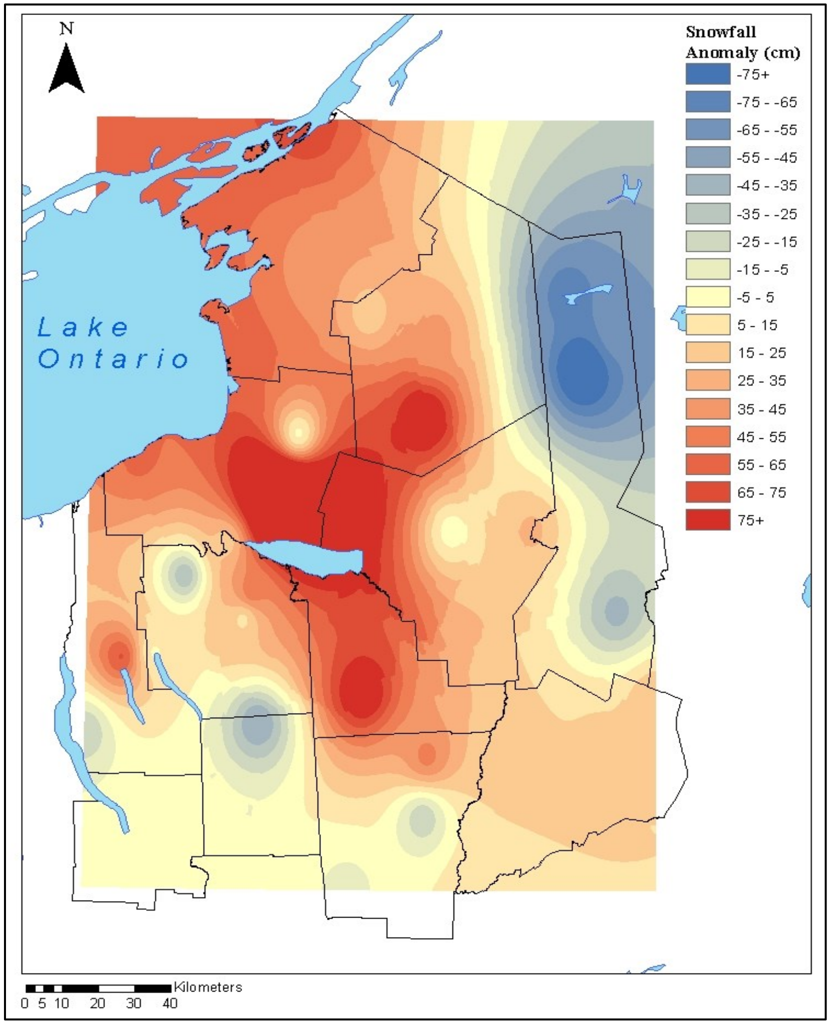

Figure B8. Mean anomalous annual snowfall totals between the long-term average and snowfall from 2001/02 – 2010/11.

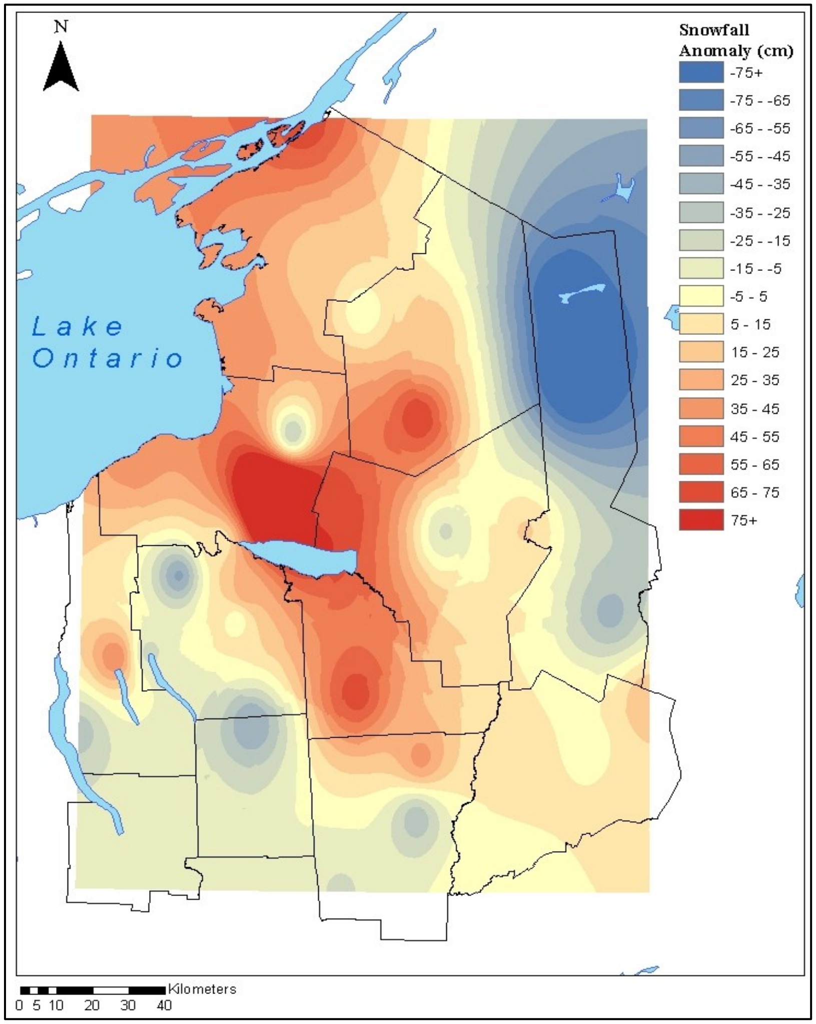

Figure B9. Mean anomalous annual snowfall totals between the long-term average and snowfall from 2001/02 – 2011/12.

Appendix C. Least Squares Regression Code

```
function [yf, yr, x, dev, cormat]=leastsq(t, y, epoch, nper, periods)
a = isnan(y)
n = size(y);
nmax = n(1);
dt = t - epoch;

j = 1
  for i = 1:nmax
  if (~a(i)) then
H(j,1) = 1.0;
H(j,2) = dt(i);
yt(j) = y(i);
nparam = 2
   if (nper >= 1) then
   for k = 1:nper
freqp = 2*%pi/periods(k);
H(j,nparam+1) = cos(freqp*dt(i));
H(j,nparam+2) = sin(freqp*dt(i));
nparam = nparam + 2
    end
    end
j = j+1;
    end
    end

HT = H'
HTy = HT*yt;
HTH = HT*H;
HTHinv = inv(HTH);

x = HTHinv*HTy;
    if (nper == 0) then
yf = x(1) + x(2)*dt;
    end

    if (nper >= 1) then
nparam = 2
yf = x(1) + x(2)*dt
    for k = 1:nper
freqp = 2*%pi/periods(k);
yf = yf + x(nparam+1)*cos(freqp*dt) + x(nparam+2)*sin(freqp*dt);
nparam = nparam + 2
     end
     end
```

```
    for i = 1:nmax
    if (~a(i)) then
yr(i) = y(i) - yf(i)
    else
yr(i) = %nan
    end
    end


sigma = nanstdev(yr)
twoper = nper+2
    for ii = 1:twoper
err(ii) = sqrt(HTHinv(ii,ii))
dev(ii) = sigma*err(ii)
     end

cormat = zeros(twoper,twoper)
     for jj = 1:twoper
     for kk = 1:twoper
cormat(jj,kk) = HTHinv(jj,kk)/(err(jj)*err(kk))
     end
     end

 endfunction
```