DEVELOPING A CLIMATOLOGY OF SNOWFALL EVENTS IN ONEONTA, NEW YORK

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ABSTRACT: With a cold season average of 172 cm of snowfall since 1981, Oneonta, New York can be significantly impacted by snow events. The geography of upstate New York allows for Oneonta to receive snowfall from a variety of storm types including Coastal Storms, Colorado Lows, and Lake-effect storms. The goal of this research is to gain an improved understanding of snowfall events in Oneonta by identifying storms that produce snow the most often, storms that produce the most intense snowfall, and by describing snowfall patterns in Oneonta through time. Results indicate that snowfall is highly variable from season to season. Lake-effect snow and Alberta Clippers are found to be the most common types of snowfall in Oneonta. Coastal Storms tend to produce the most significant snowfall, despite Oneonta's inland location. Changes in snowfall patterns since 1981 are identified and show that the number of days with measurable snowfall (0.254 cm or greater) tends to be increasing, as has the number of lake-effect snow days. Additionally, the first (last) day of snowfall has been occurring 0.5 (0.3) days earlier, on average, than in previous years. The season's first plowable (6.35 cm or greater) snowfall is found to occur progressively later each season by half a day on average. Analysis of the influence of the NAO and ENSO on snowfall patterns in Oneonta, NY indicate that the NAO is much more influential than ENSO during the winter months. Results also indicate that Oneonta, NY is able to get significant snowfall from both the positive and negative phases of the NAO.

INTRODUCTION

Each winter the Northeast United States is frequently impacted by snowstorms, often resulting in widespread power outages, major disruptions to transportation and numerous snow related injuries and mortalities. Beyond the disruptions to society, snowstorms pose a considerable challenge to forecasters during the winter with so much of snowfall totals depending on the rain/snow line and strong snowfall gradients. Like the entire Northeast region, Oneonta, New York is frequently impacted by snowfall events. Oneonta's situation between the much larger cities of Albany and Binghamton makes it an interesting location to analyze snowfall, especially since daily snow records have been collected for the city by the State University of New York College at Oneonta since 1981. Since long-term, quality controlled records are sparse for locations between major cities, the dataset is an important addition to the geoscience community for use in weather and climate analysis. Given the city's position in central New York, it has the potential to be significantly affected by a variety of snowstorm types, including both Lake-effect snowstorms and Coastal Storms. This makes Oneonta a particularly unique place to study winter season snowfall. Further, the findings of this analysis may be applicable to a wide region beyond city limits that receive similar snowstorms but are without climate records.

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LITERATURE REVIEW

Snowstorms and snowfall patterns in the Northeast have received considerable attention in the scientific literature. Kocin and Uccellini (2004) provide a comprehensive study of the climatology of snowfall in the Northeast, in addition to in-depth case studies of many past major Northeast winter storms. Lake-effect snowfall, in particular, has been extensively researched throughout the greater Great Lakes region. Recently, Wright et al. (2013) observed the sensitivity of Lake-effect snow to lake surface temperature and ice cover using WRF model simulations. Simulations indicated that warmer lake surface temperatures help increase the extent to which a Lake-effect band is able to travel downwind. Meanwhile, ice cover on the lakes can weaken potential Lake-effect bands. The NOAA Coast Watch program has provided daily lake surface temperatures for the Great Lakes since 1995 (NOAA CW/GLERL 2014). These are displayed in **Figure 1** for Lake Ontario which shows increasing lake surface temperatures of 1.97°C between 1995 and 2014. Given the steady rise in lake surface temperatures with time, an increase in Lake-effect snowfall is also within reason, as that identified by Burnett et al. (2003) and Ellis and Leathers (1996). By comparing snowfall trends at locations near the Great Lakes with snowfall trends at locations further inland around the Northeast, Burnett et al. (2003) found a substantial increase in annual snowfall at the near-lake locations, contrasting to no detectable trend in snowfall at inland locations.

Attempts have also been made to link climate change with changes in extreme (high or low) snowfall seasons (Kunkel et al. 2009). Results across the Northeast indicate that there have been increasingly more low-snowfall extreme seasons in the region from 1950–2006, compared to the first half of the twentieth century. Additionally, fewer high-snowfall extremes have been observed in
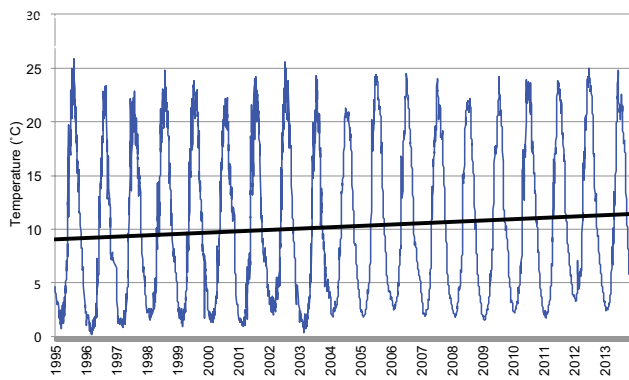
Figure 1. Mean lake surface temperatures for Lake Ontario from 1995 to 2013 (NOAA/GLERL, 2013).

the Northeast for the same time period. However, this study pre-dated the high extreme snowfall seasons of 2009-10 and 2010-11.

Low-frequency climate oscillations have also been linked to impacts on seasonal snowfall patterns in the Northeast, particularly the El Niño/ Southern Oscillation (ENSO) (Mason and Goddard 2001; Smith and O'Brien 2001). Kunkel and Angel (1999) found that the Northeast typically receives less snowfall in both the cold and warm phases of ENSO. Smith and O'Brien (2001) describe an increase in Northeast snowfall during winter months in ENSO warm phases compared to ENSO neutral, while observing a decrease in Northeast snowfall under ENSO cold phases. Patten et al. (2003) observed increased light snow days for the eastern Great Lakes region and New England under cold phase conditions, while warm phase conditions exhibited no change in light snow days for either of those regions relative to ENSO neutral. They additionally detected moderate snow days increasing in both warm and cold phases of ENSO in the eastern Great Lakes region and New England, while decreasing in the Northeast corridor. Only the Northeast corridor was found to have a statistically significant decrease in the amount of heavy snow days, which was observed under cold phase ENSO days.

The North Atlantic Oscillation (NAO) has also been observed to influence Northeast snowfall. Hartley and Keables (1998) make the case that most snowfall in the Northeast tends to occur with a negative NAO. Widen and Coleman (2013) also examined connections between the NAO and snowfall in the Northeast. Results indicate that, in general, the Northeast receives greater snowfall during negative NAO, similar to the findings of Hartley and Keables (1998). However, the Widen and Coleman (2013) study notes that some interior locations, such as central and western New York, are able to receive substantial snowfall in either phase. This can possibly be caused by the effect of the Great Lakes on snowfall patterns in the region.

GOALS

The addition of an analyzed Oneonta snow dataset is valuable in that it allows for the snowfall season at a small city in a sparse data region in central New York to be placed in context with the various findings expressed in the literature on Northeast region snowfall and snowstorms. Therefore, the goal of this research is to examine snowfall events in Oneonta, New York from 1981 to 2013. Events will be classified according to storm type and snowfall intensity.

Additionally, the snow season in Oneonta will be analyzed to determine typical characteristics of the snow season and to identify potential changes over the 32 year study period. Storms capable of producing daily snowfall are manually identified using National Weather Service Weather Prediction Center *Daily Weather Map* archive (http://www.wpc.ncep.noaa.gov/dailywxmap/index.html). Days with measurable snowfall are then classified according to storm type and snowfall intensity. Finally, the influence of the NAO and ENSO is analyzed for both specific storms and general seasonal tendencies.

This research will add new information to the knowledge base used by geoscientists to identify potential changes in the snow season in central New York. It will also help to identify what types of storms most often produce intense snowfall, and which types of storms most frequently produce snowfall in central New York. This information can be used to improve seasonal outlooks, along with both short (up to 3 days) and medium (3 to 7 days) range forecasts for Oneonta and the central New York area. Potential identification of snowfall tendencies that correspond to NAO and ENSO activity in Oneonta can also help further determine the effects of NAO and ENSO on snowfall in the interior Northeast, specifically across New York state. Localized implications could lead to improving snow removal processes in the city of Oneonta and surrounding communities.

Climatological changes in the snow season at Oneonta will also be identified. This will enhance our understanding of the long-term variability in snowfall which may be linked to large scale, global and anthropogenic climate changes. It is likely that any long-term changes in the amount of snow falling or type of snowstorm that produces city snow totals will be representative of conditions occurring throughout the Northeast United States (as these variables are certainly not city-specific). The findings may also serve as in indication of what may be expected in future winter seasons, allowing for better preparedness and resource allocations for the Northeast cold season.
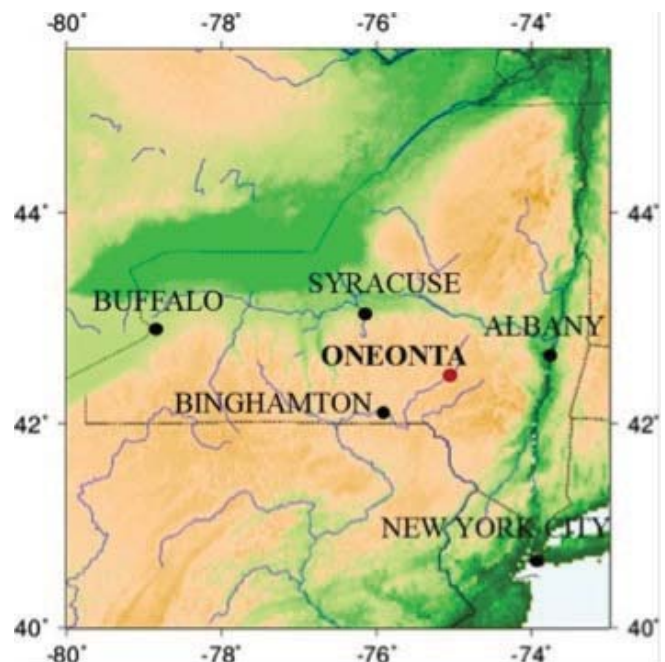

Figure 2. Location of Oneonta, NY relative to major New York state cities (adapted from Woods Hole Coastal and Marine Science Center, USGS 2014)

DATA AND METHODS

Background

The city of Oneonta is located in the northern portion of the Catskill Mountains along the Susquehanna River in central New York, approximately halfway between Binghamton and Albany (**Figure 2**). Snowfall data is collected by the State University of New York (SUNY) College at Oneonta. The data collection process is similar to that of cooperative observing networks, with daily observations taken on a snowboard at 13 UTC. Daily weather observations for the city have been collected at SUNY College at Oneonta since 1981. The existence of a data set of this temporal length outside of a major city is rare for upstate New York. For this study, snowfall from the 1981-82 season through the 2012-13 season are analyzed (SUNY Oneonta 2013).

The geographical position of Oneonta allows for the city to be frequently impacted by snowfall events of a wide variety of sources, including both Lake-effect snow and Coastal lows. Oneonta receives an average of 172 cm of snow and an average of 51 days with measurable snowfall (snow days) each season. However, the snow season can have large variability from season to season (**Figure 3**). This variability is most easily seen from 2010-2012. In the 2010-11 season, Oneonta had the snowiest single season on record with 269 cm (105.9 in) of snow. The 2011-12 season had the least snowiest season on record with only 72.5 cm (28.9 in) of snow recorded. This very high variability is similar to what has been observed over much of the coastal Northeast and the Mid-Atlantic United States (Kocin and Uccellini 2004).

As part of a preliminary analysis to better understand climate variability at Oneonta, the authors examined the long-term Oneonta station temperature records. Over the past three decades, an increase in average temperature is detected with time. An analysis of the smoothed 10-day mean temperature record indicates that the warming observed is occurring at a rate of 0.4°C per decade (**Figure 4**). This is a substantial change for a relatively short climate record and supports the findings of DeGaetano (1996). For rural locations across the Northeast, the author observed that 1959-1993 temperature changes were primarily attributed to higher minimum temperatures. Griffiths and Bradley (2007) found Northeast United States annual temperature (and precipitation) extremes to be increasing since 1926, with most of the increases detected in the past forty years. Malin (2009) linked similar increases in intra-seasonal temperature and precipitation variability to ENSO and NAO. The warming observed at Oneonta will be important to consider alongside general observations of increasing temperature variability throughout the Northeast in recent decades. It is logical to assume that these thermal changes may impact long-term moisture, or snow season, changes.

In order to gain an understanding of the snow season in Oneonta, New York, three analyses are conducted. First, the seasonal snowfall characteristics and variability with time are examined. Second for each storm, the specific cause for its snowfall and intensity is determined on a storm-by-storm basis. Third, climate oscillations, namely NAO and ENSO, are considered on a monthly and daily temporal scale.

Seasonal Characteristics

One of the primary goals of this research is to determine how the overall snow season in Oneonta has changed over the 32 year study period. To achieve that goal, seven parameters are considered:
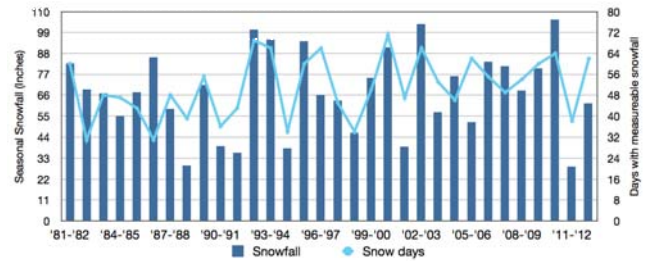

Figure 3. Seasonal totals for snowfall and days with measurable snowfall for each season in Oneonta from 1981 to 2013. Seasonal snowfall is represented by dark blue bars. Total days with measurable snowfall is represented by a light blue line.
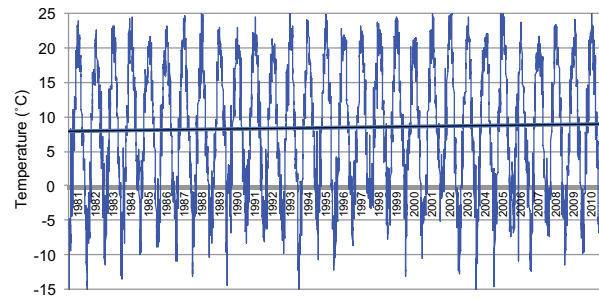

Figure 4. 10-day-mean temperature for Oneonta, NY from 1981 to 2010. The slope of the "best fit" trendline displays an increase of 0.4°C per decade

1) the day of first measurable snowfall (at least 0.254 cm, or 0.1 in); 2) the day of first plowable snowfall (in Oneonta, 6.35 cm, or 2.5 in, is the depth at which snow begins to get plowed); 3) the day of last plowable snowfall; 4) the day of last measurable snowfall; 5) length of the season, indicated by the difference between last and first days of measurable snowfall; 6) total seasonal snowfall; and 7) total number of days with measurable snow (referred to as 'snow days'). Parameters 1 through 5 are measured with respect to 1 October (i,e., 1 October equals day 1). With regard to the first and last dates of plowable snowfall, if a single storm produced snowfall over two consecutive days amounting to 6.35 cm (2.5 in) or more of snow, then it was counted as a single plowable event. In this case, the final day of that event is considered to be the date of the plowable snowfall. This provides a more accurate representation of the date when plowable snowfall is occurring, while avoiding any loss of information if snow begins falling at the end of one day and continues into another day. In short, the weather does not stop at 13 UTC with the completion of the daily observation.

These parameters are identified and plotted for each season and a linear "best fit" trendline is fitted to the data. The statistical certainty of the trends for each of these parameters are calculated using a Student's t-distribution:

$$trend - (\frac{2.042*STDDEV}{\sqrt{S_{xx}}}), \; trend + (\frac{2.042*STDDEV}{\sqrt{S_{xx}}}) \qquad (1)$$

where the trend is the slope of the linear "best fit" line and STDDEV is the standard deviation of the parameter of concern. S_{xx} is calculated by finding the departure from mean for each field for each season, creating an anomaly. The anomaly for each season is then squared. The sum of the anomalies squared for each of the 32 seasons is the S_{xx} value. This statistical test will provide a range of trends that could likely fit the dataset and a measure of certainty

(here, testing at the 95% confidence level) that there is a non-zero relation, and not just a random distribution that resulted in that trend.

These parameters are observed in order to gain an understanding of when the snow season is starting and when the first impactful snows are beginning to take place, and if there have been any changes over the period of record. Additionally, by looking for the occurrence of the last snowfall and the last plowable snowfall, one can discern the date of when impactful snows tend to end and when the snow season in general tends to end. Observing the length of season allows insight about potential increases or decreases in season duration which may be related to the local warm trend observed at Oneonta and/or global climate change. Finally, analysis of seasonal snowfall totals and the seasonal number of snow days adds information about whether or not snowfall tendencies are changing over the 32 years (e.g., Are snowfall patterns changing which may be reflective of storm track changes and/or storm dynamic changes?).

Storm Type Classification

Having determined general seasonal characteristics, more information can be gleaned from analysis of individual snowstorms that have produced snowfall in Oneonta. To do this, a classification scheme is first developed to classify events by storm type and storm intensity. Storm types are determined using surface low pressure tracks. Tracks of typical mid-latitude storms are referenced from various sources (Ahrens 2008; Thomas and Martin 2007) and used to distinguish different storm types. **Figure 5** displays these classifications. As shown, there are several typical mid-latitude storm tracks that can impact the Northeast United States. Any particular snowstorm that produces snowfall in Oneonta is classified as either: 1) Alberta Clipper, 2) Colorado Low, 3) Panhandle Low, 4) Coastal Storm, 5) Lake-effect, or 6) Lake-enhanced. The two storm types that do not require a storm track are Lake-effect and Lake-enhanced snowfall. These two types of snowfall events are mesoscale phenomena that simply require a synoptically forced wind over the Great Lakes. If the cause for snowfall is not obvious, then these events are given an "undetermined" storm type designation.

The Alberta Clipper is defined in a similar way to that of Thomas and Martin (2007). Leeside cyclogenesis occurs to the east of the Canadian Rockies, typically in the Province of Alberta. The low pressure system typically tracks eastward across the northern half of the United States.

The Colorado Low and the Panhandle Low both involve leeside cyclogenesis east of the Colorado Rockies, with tracks defined following Ahrens (2008). The difference between the two storms is that the Colorado Low makes a northeast turn much sooner than the Panhandle Low, which may actually continue dipping south before making a northeast turn much further east. The result tends to be that Oneonta is less likely to be in the warm sector of a Panhandle Low than that of a Colorado Low. Additionally, given a closer track to the Gulf of Mexico, Panhandle Lows may have more moisture associated with them than Colorado Lows. Thus, subtle variations in snowfall patterns at Oneonta may be detected from slight differences between these similar storms. Storms of this track are classified as such despite any coastal redevelopment that may occur (such development happens much farther north than with Coastal Storms, as described next.).

Coastal Storms often (but not always) involve coastal redevelopment along the southeast coast and then move primarily north
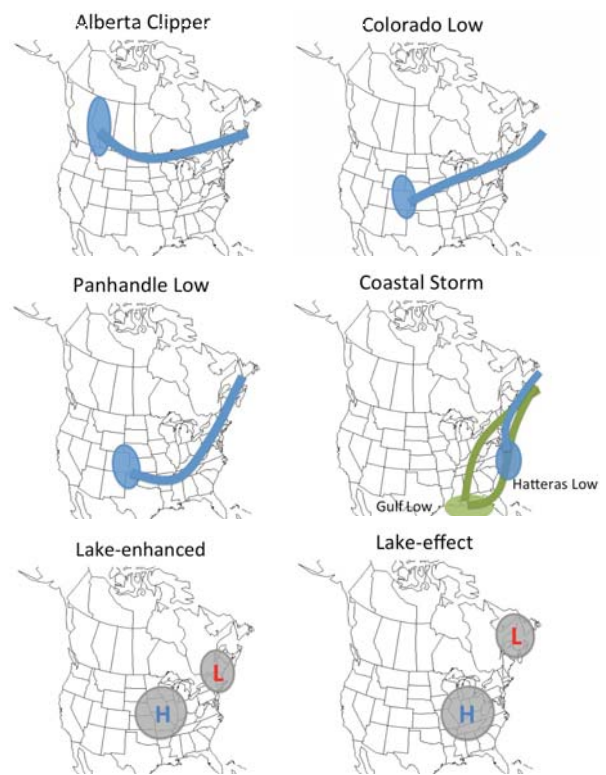

Figure 5. Six snowstorm type designations that impact Oneonta: Alberta Clipper, Coastal Storm, Colorado Low, Panhandle Low, Lake-effect, and Lake-enhanced. Blue shaded areas indicate regions of cyclogenesis. Blue lines indicate typical surface low tracks. Gray shaded regions indicate general locations of high and low pressure systems. For the Coastal Storm, and additional green shaded region and green line are shown to represent the two separate cyclogenesis regions and surface low tracks of both Gulf Lows and Hatteras Lows that can define Coastal Storm type snowstorms.

along the east coast of the United States (Ahrens 2008). Coastal Storms are the typical "Nor'easters" that tend to be the source of most snowfall along the coastal Northeast and have been analyzed in great detail on a case-by-case basis (*e.g.,* Kocin and Uccellini 2004).

Lake-effect and Lake-enhanced systems both produce snowfall in Oneonta due to northwest synoptic flow of very cold air and relatively warm Lake Ontario surface temperatures, combining for a temperature difference around 13°C between the lake surface and the 850 hPa level. The difference in lake surface temperature and lower troposphere temperatures in the atmosphere results in convection over the lakes, which gets carried over land by the northwest winds. For this study, the difference between Lake-effect and Lake-enhanced is determined to be the presence of pressure troughs, convergence lines, and other typical triggers of precipitation. In the case of Lake-enhanced, the low is typically within about 725 km (or, about 450 miles), which is approximately the distance from Oneonta, New York to Caribou, Maine. A pressure trough or cold front may be associated with a departing low pressure that serves as the primary reason for precipitation. The presence of Lake Ontario, as the name implies, enhances precipitation. In the case of Lake-effect snow, the low pressure system is further away from the region and the high pressure system is further eastward than in the lake-enhanced set up. The combination of the two systems continues to synoptically force northwest winds over the lakes. Snowfall is produced primarily because of the instability

generated by cold air moving over the relatively warmer Lake Ontario.

An undetermined category is designated as any situation that produces measurable snowfall without an obvious storm type. These situations tend to be associated with either general warm air advection on the western side of a high pressure or with a very diffuse synoptic set up with no obvious low pressure system being the focus as the cause of precipitation.

Storm tracks are manually traced using the Weather Prediction Center's *Daily Weather Map* archive provided by the NOAA Central Library Data Imaging Project (http://www.wpc.ncep.noaa.gov/dailywxmap/index.html). Each day with measurable snowfall has a storm traced back to a source region, in order to identify and determine storm type. This is also how storms are identified to have produced snowfall on multiple days.

A snowfall intensity scale is also developed and applied to each snowfall event. In this case, five thresholds of storm total snowfall are established to determine the severity and intensity of each snowstorm, as indicated in **Table 1**. This classification system is formed to acquire a typical precipitation distribution and used with the goal of identifying key intensity patterns for each storm type. Inches are the units utilized in the development of this classification system, following NWS standards for reporting snowfall, and to allow for easy societal applications. Level 1 snowfall essentially represents what constitutes a coating of snow. Level 2 spans from a coating to what starts to be interpreted as actual accumulations. Level 3 includes all plowable snowfall events (greater than or equal to 6.35 cm, or 2.5 in). Level 4 and 5 storms represent moderately heavy and excessively heavy snowstorms in the Oneonta area, respectively. Kocin and Uccellini (2004) define moderate and heavy snowfall throughout the entire region with slightly different criteria. The total distribution of snowfall events identified in this study is displayed in **Figure 6**. This creates an expected spread for precipitation events with many low precipitation events and few major precipitation events are shown.

A final additional threshold is applied to each snowfall event, which defines a significant snowfall. In this case, significant snowfall does not have a statistical basis but rather is deemed any "notable" storm with snowfall greater than 10.16 cm. This allows for results to be placed in context with the Kocin and Uccellini (2004) definition of moderate snowfall as 10.16 cm (4 in), and to correspond with their detailed climatology of 10.16 cm or greater snowfall events in the Northeast United States.

Finally, the timing of winter storms is analyzed to determine when Oneonta tends to receive major winter storms. In order to do this, the number of significant storms (10.16 cm or greater snowfall) is counted for 7-day periods beginning with 1 October – 7 October through 22 April – 28 April. This process is repeated for Level 5 (25.4 cm or greater snowfall) storms to better understand the timing of major snowfall events alongside all significant events.

NAO and ENSO Relationship to Snowfall

Monthly and daily indices of the NAO and Oceanic Niño Index (ONI) are acquired from the NOAA Climate Prediction Center to identify the strength of the NAO and ENSO signals, respectively (CPC 2013a; CPC 2013b). NAO index values represent the leading rotated principle component analysis (RPCA) mode of variability in standardized monthly 500mb height anomalies north of 20°N latitude (Barnston and Livezey 1987). The ONI is based on standardized running means of Niño 3.4 region SST anomalies. The
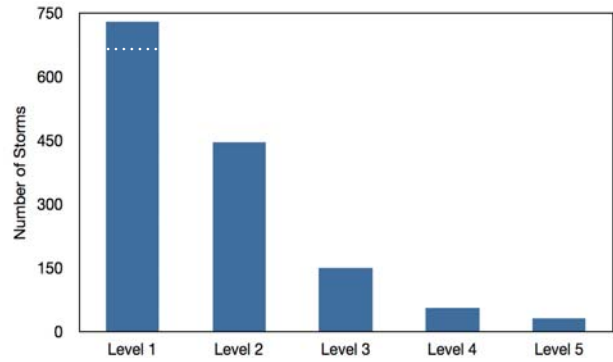

Figure 6. Total number of snowfall events within each classification level at Oneonta.

Snowfall Level	Criteria
1	Trace ≤ Snowfall < 1.27 cm (0.5")
2	1.27 cm (0.5") ≤ Snowfall < 6.35 cm (2.5")
3	6.35 cm (2.5") ≤ Snowfall < 15.24 cm (6")
4	15.24 cm (6") ≤ Snowfall < 25.4 cm (10")
5	25.4 cm (10") ≤ Snowfall

Table 1. Five snowfall level classifications based on total snowfall amounts at Oneonta.

teleconnection patterns are examined alongside monthly and daily snowfall data to establish the basic relationship between low frequency oscillatory climate patterns and snowfall events at Oneonta. An ONI value less than or equal to -0.5 qualifies as a cold phase ENSO, or La Niña. ONI values greater than -0.5 and less than 0.5 qualify as a neutral ENSO. An ONI value greater than or equal to 0.5 qualifies as warm phase ENSO, or El Niño. Similar anomaly distinctions are made with monthly NAO indices to distinguish negative NAO, neutral NAO and positive NAO months. Individual monthly data from November through March are analyzed as the NAO and ENSO signals peak in winter. October and April are omitted from this analysis to focus on the winter phase of each oscillation and avoid the fall and spring patterns. This omits only 5.1% of all the events analyzed in this study. Correlation coefficients are separately calculated for each month's snow totals during NAO and ENSO episodes.

Considering the effect of climate oscillations on a daily time scale, daily NAO values are also paired with daily snowfall records. Negative (positive) NAO phase days are those with an index value less than or equal to -0.5 (greater than or equal to 0.5). Neutral NAO days are characterized with index values between -0.5 and 0.5. The frequency of snow days in each teleconnection phase is calculated, applying the snowfall intensity levels to snow days. This demonstrates the frequency of various snowfall intensities in each phase of the NAO. The analysis is repeated, isolating Level 4 and Level 5 snowfall days within each phase. This is performed to better identify a potential connection between heavy snowfall and the NAO.

RESULTS

Seasonal Characteristics

Seven parameters: 1) the day of first measurable snowfall, 2) the day of first plowable snowfall, 3) the day of last plowable snowfall, 4) the day of last measurable snowfall, 5) the length of the season, 6) the total seasonal snowfall, and 7) the number of snow days, are

Parameter	Trend	P-value
First Measurable Snowfall	**0.5** days earlier per year	0.064
First Plowable Snowfall	**0.5** days later per year	0.35
Last Plowable Snowfall	**0.5** days earlier per year	0.21
Last Measurable Snowfall	0.3 days earlier per year	0.27
Length of Season	0.1 days longer per year	0.73
Seasonal Snowfall	0.2 in. more per year	0.62
Snow Days	**0.4** days more per year	0.055

Table 2. The trend in timing of first measurable snowfall, first plowable snowfall, last plowable snowfall, and last measurable snowfall in Oneonta, along with the changes to the length of season, seasonal snowfall, and snow days from 1981 to 2013. Bolded numbers indicate certainty of non-zero trend via Student's t-distribution.

analyzed in order to identify changes in the snow season over the 32-year study period. A summary of the trends of each parameter are displayed in **Table 2**.

First Snowfall. Results indicate that the day of first measurable snow is occurring earlier in the season. Specifically, these first snows occur 0.5 days earlier each year. Using the Student's t-distribution, the trend in the date of the first measureable snow is known to be non-zero to the 95% confidence level. Combined with a p-value of 0.064, there is high statistical confidence that snowfall is beginning to fall earlier in Oneonta. The earliest initiation of Oneonta measurable snowfall occurred in the 1992-93 season on 30 September while the latest occurred in 1982-83 and 1994-95 seasons on 24 November and 23 November, respectively (**Figure 7**). Thus, the dates for the first snowfall ranged from 30 September to 24 November. The trend for the day of first measurable snow occurring earlier in the season is something that may not generally be expected, given a warming climate (**Figure 4**). Under that type of scenario, the length of the snow season should be decreasing and thus, on average, the first snowfall should occur later into the cold season. However, that is not what is observed in this dataset. The earlier occurrence of snowfall in Oneonta, New York also does not follow what has previously been observed across the Northern Hemisphere by Choi et al. (2010). That work analyzed the first appearance of snow cover, which would be homologous to the first measurable snowfall. It was observed that there was little to no trend in the timing of the first appearance of snow cover. The authors suggest that future work be performed to study the timing of the first snowfall events across the entire Northeast region [for more focused information than that provided by Choi et al. (2010)] to validate the earlier start to the season at locations beyond Oneonta. A more complete understanding of the causes of this phenomenon may be gleaned from such analysis.

Plowable Snowfall. The next set of significant trends observed over the past 32 years is the timing of the first and last plowable snowfall. The timing of the first plowable snowfall has been occurring an average of 0.5 days later per year, with the timing of the last plowable snowfall occurring 0.5 days earlier per year. Both of these trends are known to be non-zero trends as well, using the Student's t-distribution. P-values of 0.35 and 0.21 respectively provide additional statistical confidence for confirming a change in the timing of the first and last plowable snowfall events. The first plowable snowfall dates nearly always arrive later in the season than the timing of first measurable snowfall. The 1988-89 season received the earliest plowable snow on record on 22 October (**Figure 8**). The latest arrival of plowable snowfall occurred in the
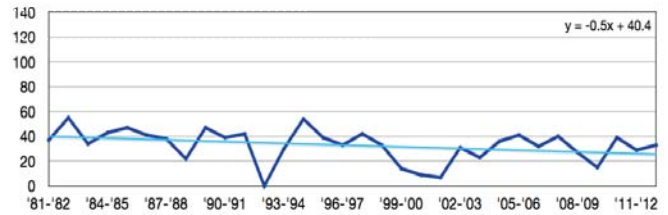

Figure 7. Timing of the first measurable snowfall (at least 0.1 in, or 0.254 cm) over the 32 year period of study at Oneonta. The timing is done with respect to 1 October (1 October equals day 1). A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The day of first measurable snowfall is observed to be occurring 0.5 days earlier each year. Over the 32 year period of study, this amounts to roughly two weeks earlier than at the beginning of the period.
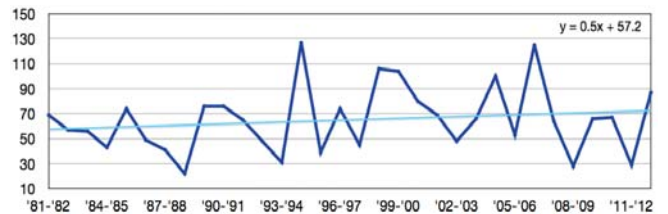

Figure 8. Timing of the first plowable snowfall (at least 2.5 in, or 6.35 cm) over the 32 year period of study at Oneonta. The timing is done with respect to 1 October (1 October equals day 1). A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The day of first plowable snowfall has been observed to be occurring 0.5 days later each year.
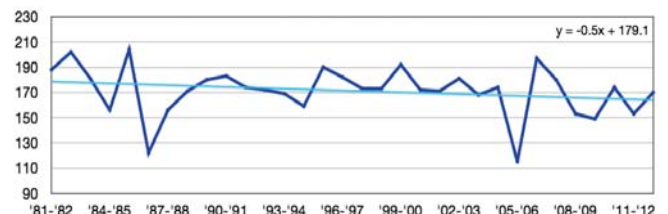

Figure 9. Timing of the last plowable snowfall (at least 2.5 in, or 6.35 cm) over the 32 year period of study at Oneonta. The timing is done with respect to 1 October (1 October equals day 1). A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The day of last plowable snowfall has been observed to be occurring 0.5 days earlier each year.
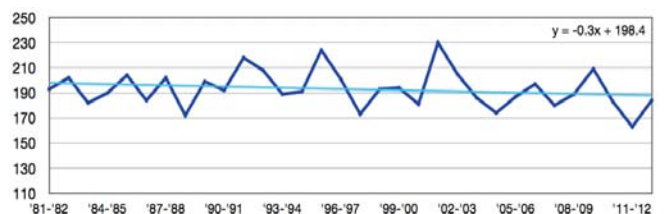

Figure 10. Timing of the last measurable snowfall (at least 0.1 in, or 0.254 cm) over the 32 year period of study at Oneonta. The timing is done with respect to 1 October (1 October equals day 1). A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The day of last measurable snowfall has been observed to be occurring 0.3 days earlier each year.

1994-95 season on 4 February, which was also a season that brought Oneonta a late first measurable snow. Through the years, the dates for the first plows ranged from 22 October to 4 February (**Figure 9**). The earliest final plow date occurred on 23 January, in the 2005-2006 season, while two decades earlier, in 1985-86, the latest final plows took place on 22 April. The timing of the first and last plowable snowfall timing shifting closer together is what would be expected given a warming climate. If so, logic has it that the

length of the season in which 6.35 cm (2.5 in) or greater snowfall occurs should also be decreasing.

Last Snowfall & Season Length. The next two parameters of the snowfall season examined are the timing of last measurable snowfall and the length of the season. While neither of these trends passed the Student's t-distribution test for non-random certainty at the 95% confidence level, they are consistent with other observed changes in the snow season at Oneonta. The trend toward an earlier end to the snow season is supported by the earlier trend in the timing of the last plowable snowfall. The earliest ending to measurable snowfall in Oneonta occurred in one of the most recently assessed seasons (2011-12) on 11 March. The latest timing of measurable snowfall occurred in the 2001-02 season on 18 May (**Figure 10**). Examination of the total length of season shows that very little overall trend is supported. Nevertheless, many of the most recent seasons correspond to the shortest snow seasons on record (**Figure 11**). Furthermore, a p-value of 0.27 exhibits additional confidence in the observed trend in the timing of the last snowfall. The variability in season length has also notably increased since the 1980s with the most dramatic year-to-year variations observed in the late 1990s. Not surprisingly, the longest snow season of 2001-02 also received the latest measurable snow in this period. The fact that the length of the snow season is staying about the same is an interesting result, contradicting expectations of what should happen in a warming climate. Given a p-value of 0.73, there is confidence that the length of the snow season is not seeing any appreciable change in length. It appears that a changing winter climate at Oneonta may be manifesting with greater variability in season length versus simply shorter seasons.

Seasonal Snowfall and Snow Days. Seasonal snowfall and total number of days with measurable snowfall (snow days) are also analyzed and assessed for potential changes over the past 32 years. As seen in **Figure 12**, there is high variability in the total amount of snowfall at Oneonta year-to-year. While the overall trend is indicative of an increase in snowfall over the past three decades, it does not pass the Student's t-distribution for non-zero trend certainty at the 95% confidence level. The p-value of 0.62 shows confidence that climate change is responsible for the trend of seasonal snowfall is weak. If there is a trend, other factors, not considered in this study, could be responsible. The three highest snowfall totals, 255 cm (100.4 in), 263.1 cm (103.6 in), and 269 cm (105.9 in), occurred in rather even intervals across the record, in 1992-93, 2002-03, and 2010-11, respectively. However, each of these seasons is preceded or succeeded by a season with less than 101.6 cm (40 in) of snowfall [91.4 cm (36 in) in 1991-92, 99.1 cm (39 in) in 2001-02, and 73.4 cm (28.9 in) in 2011-12]. This is a difference of more than 150 cm (60 in) of snowfall in these cases. The variability supports the findings of Griffiths and Bradley (2007), though uncertainty remains as to whether the snow season changes are connected to the warming climate. For instance, snowfall is a function of more than just temperature (*e.g.,* total precipitation).

Less variability is detected in the number of snow days each season (**Figure 13**). A trend of an increasing number of snow days is observed each season, with a rate of 0.42 snow days per season. Considering that this trend passes the Student's t-distribution for 95% confidence in a non-zero trend and has a p-value of 0.055, there is high statistical confidence in this observed trend. Similar to seasonal snowfall, many high snow day seasons are followed
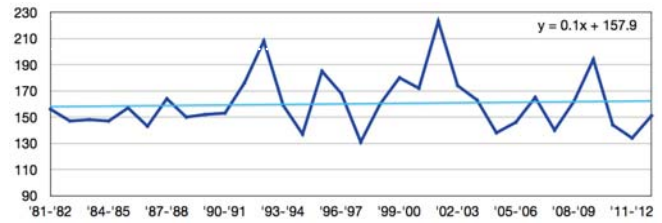

Figure 11. Length of snow season at Oneonta for each season of the 32-year period of study. Length of season is determined by the difference between the first day of measurable snowfall and the last day of measurable snowfall for each season. A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The length of season has been observed to be slightly increasing in length, 0.1 days per year.
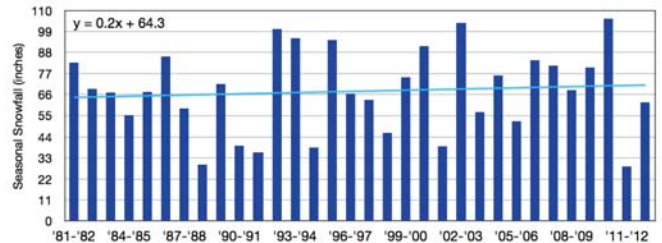

Figure 12. Seasonal snowfall at Oneonta for each season of the 32 year period of study. A linear trendline is fit to the data, with the equation for the "best fit" line displayed. Seasonal snowfall has been observed to be slightly increasing, 0.2 in per year.
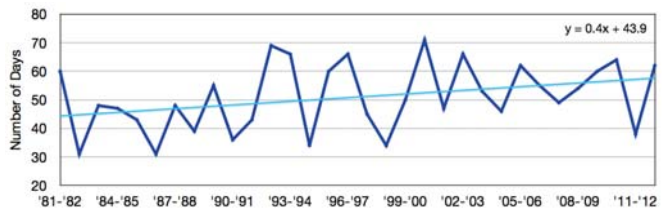

Figure 13. Number of snow days at Oneonta for each season of the 32 year period of study. A linear trendline is fit to the data, with the equation for the "best fit" line displayed. The number of snow days has been observed to be increasing, 0.4 days per year.

immediately by a season with relatively few snow days. This is best observed between the 1993-94 season (66 snow days) and 1994-95 season (34 snow days). An increasing trend in the number of snow days, and the variability identified, may be related by long-term changes in temperature and/or climate oscillations. Regardless, the results demonstrate a long-term change in winter snowfall patterns is occurring in part of the Northeast.

While this analysis used the timing of the first and last measurable snowfall days to determine the length of the snow season, most previous work (e.g., Leathers and Luff 1997 and Choi et al. 2010) analyzed the timing of the first appearance and last disappearance of snow cover to determine length of the snow season. Choi et al. (2010) observed a rate of decrease in the length of the snow season of approximately 5 days per decade, or 0.5 days per year. The decrease in the length of the snow season was found to be caused by shifts in the timing of the last disappearance of snow cover (as mentioned earlier, the time of the first appearance of snow cover, was found to have very little change in their study). This is similar, though not a perfect comparison, to the last measurable snowfall analyzed here for Oneonta, NY. As a whole, Oneonta's decrease in length of time in which impactful snowfall may occur best corresponds to previously identified trends in the snow season and what would be expected in a warming climate. However, it should

again be noted that there is very little trend seen in the length of season, as measured in this study, but rather perhaps an increase in seasonal variability in recent years. Furthermore, the number of snow days is increasing, while seasonal snowfall changes may be masked by the large annual variability. These trends indicate that the changing snow season at Oneonta is dependent on more than just temperature, displaying the complexity of global climate change impacts.

Storm Type Classification

The analysis of all 1,415 snowstorms in the 32 year period by storm type reveals much information about their frequency, intensity and potential impacts in the Oneonta area. With 406 events, Lake-effect snowstorms are clearly the most frequent producer of snowfall in Oneonta (**Figure 14**). 313 Alberta Clipper events are identified, indicating that these storms also tend to produce snowfall in Oneonta quite frequently. Lake-enhanced, Colorado Lows, Panhandle Lows, and Coastal Storms all tend to occur with lower frequencies (173, 162, 146 and 178 events, respectively). A total of 37 storms are classed as undetermined. General warm air advection is deemed to account for 22 of the 37 undetermined days. The undetermined storm type does not contain snowfall greater than Level 2 in the classification system.

Along with understanding the frequency of storm tendencies that produce snowfall in Oneonta, it is important to learn about the storms that produce the most intense city snowfall. **Figure 15** displays the number of events in each storm type by total snowfall classification level. While Lake-effect snow produces measurable snowfall quite often in Oneonta, most of that snowfall tends to be light and rarely produces anything greater than Level 2 snowfall. Four hundred Level 1 and 2 Lake-effect storms are observed, compared to a total of six Level 3 - 5 storms. Thus, these snows tend to fall short of plowable (6.35 cm, or Level 3) snowfall, meaning this storm type has low societal impact. Alberta Clippers occur frequently but tend to be of lower snowfall intensities (277 Level 1 and 2 events). These storms are capable of producing more Level 3 snowfall than Lake-effect. Other storm types, such as Colorado Lows, Panhandle Lows and Coastal Storms, are capable of producing snowfall that can cause significant disruptions to everyday life. Colorado Lows caused 40 Level 3 or greater events, while Panhandle Lows have caused 46 and Coastal Storms have 104 Level 3 or greater events. Of particular interest are the abnormal snowfall characteristics of Coastal Storms. Every other storm type has what constitutes a typical distribution of snowfall, with Level 1 occurring most frequently and each successive snowfall level occurring progressively less frequently. Coastal Storms peak in frequency with Level 2 and Level 3 snowfall, not Level 1.

Lake-enhanced storms tend to occur with similar frequency to the Colorado Lows, Panhandle Lows and Coastal Storms, but produce snows of similar intensities to Lake-effect. Therefore, this variety does not seem to be particularly disruptive, having light snow and occurring less frequently (168 Level 1 and 2 events versus 5 Level 3 or higher).

Further analysis of Lake-effect snowfall over the course of the 32-year study period reveals a distinct increasing trend with time in both the number of Lake-effect snow days, and also the total amount of snowfall caused by Lake-effect events. The number of Lake-effect days has been increasing with time by about 0.21 days per year (**Figure 16**). Lake-effect snowfall has also been increasing by 0.1148 in per year (**Figure 17**). While neither of these trends
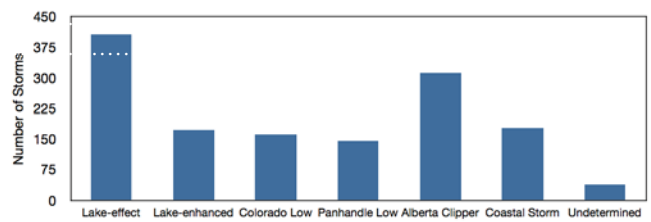

Figure 14. Total number of snowfall events caused by each storm type over the past 32 years at Oneonta.
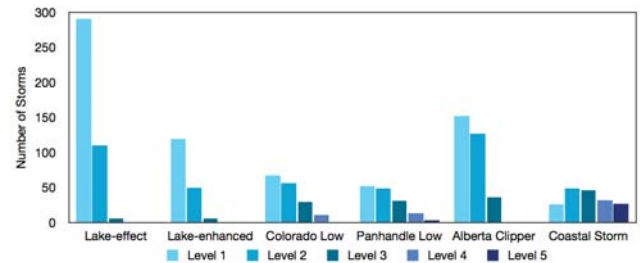

Figure 15. Total number of snowfall events in each storm type that produce Level 1 - 5 snowfall at Oneonta.
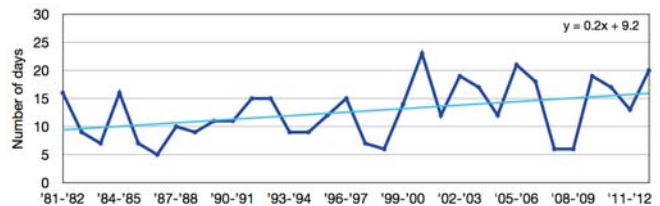

Figure 16. Total number of Lake-effect days per season over the past 32 years at Oneonta. A linear trendline is fit to the data, with the equation for the best fit line displayed.
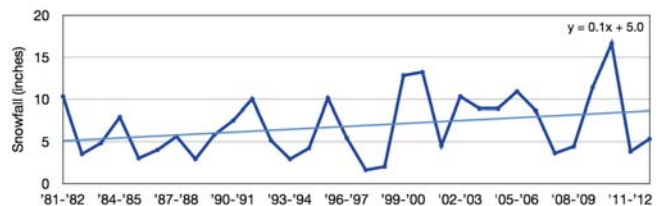

Figure 17. Total accumulation of snowfall from Lake-effect snowstorms per season over the past 32 years at Oneonta. A linear trendline is fit to the data, with the equation for the best fit line displayed.

passed the Student's t-distribution for non-zero trend certainty, they are consistent with what has been previously observed in lake-effect snow trends by Ellis and Leathers (1996) and Burnett et al. (2003). Over the past 32 years, these trends would result in approximately 7 more days of Lake-effect snowfall and nearly 10.2 cm (4 in) of additional snowfall. The increase in Lake-effect snowfall is then one reason for the observed increase in the total number of snow days. These results also make sense with respect to a warming climate where more time before lakes freeze over make Lake-effect, and even Lake-enhanced, snows more probable. Given Oneonta's distance from Lake Ontario, the source of the Lake-effect snowfall, the observed trends are likely suppressed in the Oneonta area, and much more exemplified in the near-lake regions of the state that were studied in previous investigations. Considerable year-to-year variability is detected for both total snowfall and total snow days attributed to Lake-effect events which may make forecasting the impact of Lake-effect snows on the local area more challenging.

Nevertheless, these trends could mean that Lake-effect snows will have increasing influence on the city in the future.

Significant Snowfall and Major Events by Storm Type. **Figure 18** highlights the storm types that produce significant snowfall (greater than 10.16 cm, or 4.0 in) over the 32 years at Oneonta. Having caused 79 significant events, Coastal Storms are by far the primary producer of significant snowfall. This is an interesting result considering that Oneonta is more than 130 mi from the coast, and the Catskill Mountains can create a precipitation shadow in easterly flow. Panhandle Lows and Colorado Lows produce the rest of the majority of significant snowfall events in Oneonta (28 and 22 significant events, respectively). The difference between these two storm type tracks is likely the reason for variations in significant snowfall observed here. The Panhandle low, taking a slightly more southerly track, is less likely to get Oneonta into the warm sector and change precipitation over to rain, as is more possible with the northerly tracking Colorado Low. Also, as a Panhandle Low tracks closer to the Gulf of Mexico more moisture may be added to the system than is possible for the Colorado Low, helping to produce more heavy snowfall events. Alberta Clippers and Lake-effect also produce significant snowfall in Oneonta; but the two events only combine to produce 11 total significant events, compared to the total 140 significant events over the 32 year study period.

The likelihood that a storm may produce significant snowfall is computed by taking the number of significant events produced by a specific storm type and dividing by the total number of snowfall events that specific storms produced in the 32 year study period. **Figure 19** displays these percentages. It shows that 44% of all Coastal Storms with snowfall in Oneonta produce significant snowfall. This is an important and useful finding for forecasters. Based on these results, if a Coastal Storm is forecasted to impact the Oneonta area, forecasters can immediately know that there is over a 40% chance that this storm will produce greater than 4 in of snowfall. This can certainly increase the amount of information available to be communicated to the public 3 to 7 days in advance of a storm, even before forecast models begin to come to an agreement. On the other hand, only 0.739% of all Lake-effect events produce significant snowfall at Oneonta. This should allow forecasters to give very careful consideration to predictions of more than 4 in of snow for Oneonta from a Lake-effect set up.

The maximum snowfall caused by a single event for each storm type is found and displayed in **Table 3**. In 2007, the 13-14 February Panhandle Low snowstorm resulted in 30 in (76.2 cm) of snow at Oneonta, making it the highest snowfall producer of all events. The second highest snowstorm total occurred with a 2002 Coastal Low Christmas event that produced 24.2 in (61.5 cm) of snow. Maximum snowfall from a Lake-effect and Lake-enhanced event is much less, 4.2 in and 3 in respectively. These findings have important implications for short term forecasting as results reveal the typical maximum potential snowfall for each storm type. Future storms

Storm Type	Maximum Snowfall (in)	Date of Snowstorm
Alberta Clipper	8.0	8 – 9 March, 2001
Coastal Low	24.2	24 – 25 December, 2002
Colorado Low	11.6	6 – 8 January, 1994
Lake-effect	4.2	1 February, 2000
Lake-enhanced	3.0	6 December, 2010
Panhandle Low	30.0	13 – 14 February, 2007

Table 3. The timing and amount of maximum snowfall events caused by each storm type over the past 32 years at Oneonta.
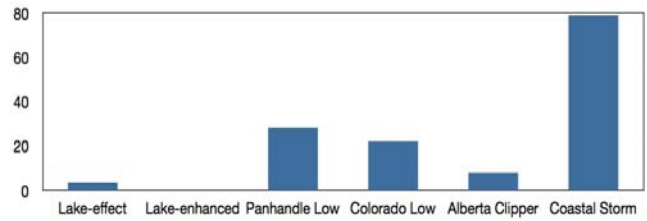

Figure 18. Total number of significant (4 in or greater) events caused by each storm type in Oneonta. 140 significant snowfall events occurred in Oneonta between the 1981-82 and 2012-13 seasons.
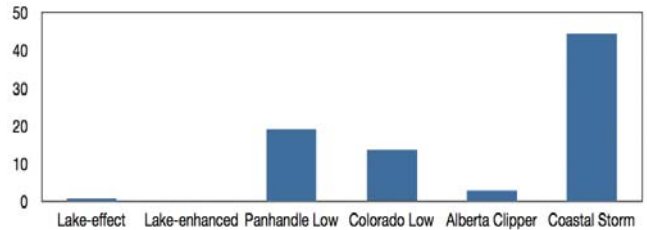

Figure 19. Percentage of each storm type that is a significant event at Oneonta. This information shows the likelihood that each storm type will produce a significant snowfall.
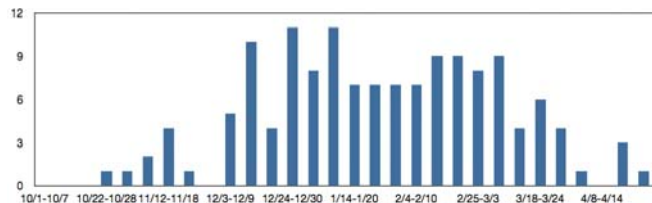

Figure 20. Timing of significant (10.16 cm or greater) storms in Oneonta. The total number of significant storms in a 7-day period, beginning with 1 October to 7 October, is counted for each period through 28 April.
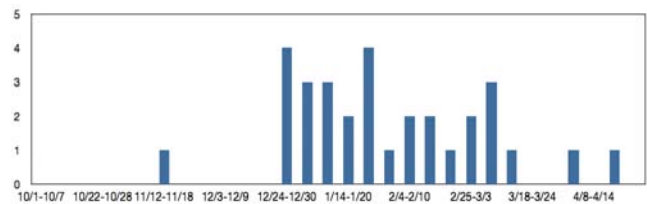

Figure 21. Timing of Level 5 (25.4 cm or greater) storms in Oneonta. The total number of Level 5 storms in a 7-day period, beginning with 1 October to 7 October, is counted for each period through 28 April.

may be placed in context with these historical events to better evaluate impacts and the need for city preparedness with each storm type.

The timing of both significant (10.16 cm, 4 in or greater) and Level 5 storms (25.4 cm, 10 in or greater) is analyzed to determine the typical time of year that Oneonta experiences major winter storms (**Figures 20** and **21**). These times are based on 7-day periods, beginning with 1 October to 7 October through 22 April to 28 April. As would be expected, mid-December to mid-March is when more than 70% of major winter storms occur in Oneonta. Two peaks in the timing of major winter storms can be seen. One occurs in late December and early January. The other, slightly lower, maximum occurs in late February and early March. This could be a product of the method used to identify the timing of winter storms in that the variability through time was not accounted for here. Or, this is an indication that there is a relative lull in storm

activity from mid-January to mid-February. The separate peaks in winter storm activity, at the start and end of the meteorological winter, could mean that the transition from a fall-to-winter pattern, and then a winter-to-spring pattern, produces more storms. This could result in more snowfall and more heavy snowfall if conditions are appropriate. The lull in mid-winter heavy snows could then be explained by the fact that the mean pattern of a long wave trough over the United States has been established, resulting in more southerly and easterly storm tracks. This could produce east coast snowstorms that may primarily impact coastal areas, resulting in either very low snow accumulations or no snowfall at all, in the interior Northeast, including where Oneonta is located.

NAO and ENSO Relationship to Snowfall

Monthly indices of the NAO and ONI are analyzed with respect to monthly snowfall in order to determine the relationship between NAO and ENSO on monthly snowfall patterns. Daily indices of the NAO are also observed with respect to each individual snowfall event in Oneonta, NY to determine how the NAO impacts snowfall patterns on a shorter temporal scale. Furthermore, daily NAO indices are analyzed with respect to Level 4 and Level 5 storms to determine NAO's relationship with the heaviest of snowfall events.

The variances, also known as r-values, obtained using Pearson's correlation coefficient calculation, for NAO and ONI relationships to monthly snowfall are displayed in **Table 4**. The results of both teleconnection analyses indicate that r-values are very low in November. This is likely because neither oscillation has reached its winter phase and is still changing at this time. ENSO has less impact on snowfall in Oneonta than the NAO, with no phase preference. This is particularly exemplified from December to February where the NAO explains 15 - 25% of the variation. The ENSO signal may have more influence on late winter snowfall as peak correlations are at the end of the season. Negative NAO events are more favorable for snowfall than positive phases, as indicated by the negative r-values each month.

Daily NAO analysis of all 1,415 events reveals that most snow falls with neutral NAO conditions (595 events) (**Figure 22**). Positive phase NAO days correspond to more snow (468 events) than negative NAO (310 events). This supports the findings of Widen and Coleman (2013) showing that while most of the Northeast receives snowfall in a Negative NAO, the interior Northeast can receive a significant contribution of snowfall during a Positive NAO. Most events likely occur within a neutral NAO because of the greater number of days that demonstrate this phase, as opposed to a neutral NAO being a more favorable setup for snowfall in Oneonta. **Figure 23** demonstrates that large quantities of snow (over 35% of all Level 4 and 5 events days) occur with the positive phase of the NAO.

Typical upper air patterns of the negative and positive phases of NAO explain why Oneonta receives snowfall, including some heavy events, in both phases. Negative (positive) NAO days occur alongside positive (negative) 500mb height anomalies over Iceland
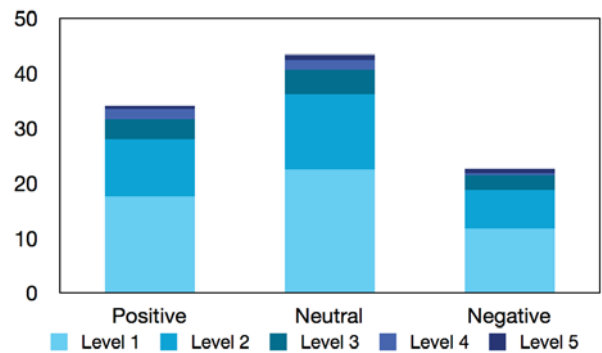

Figure 22. Frequency (%) of Oneonta snow days that are in each snowfall classification level by NAO phase. Daily NAO index values are used.
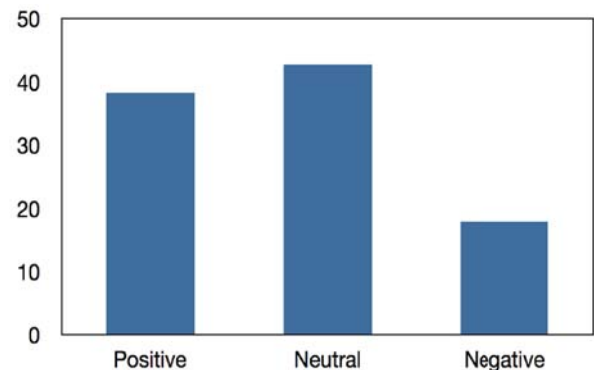

Figure 23. Frequency (%) of Level 4 and Level 5 snow days at Oneonta by NAO phase. Daily NAO index values are used.

and northern Canada and negative (positive) 500mb height anomalies in the western Atlantic (Barnston and Livezey 1987). Negative NAO days are generally associated with coastal snowstorms that impact the coastal regions of the Mid-Atlantic and Northeast (Widen and Coleman 2013). As demonstrated earlier, Coastal Storms produce significant snowfall in the Oneonta area and are the primary source of Oneonta's major winter snowfall (see **Figures 18** and **19**). The positive phase of NAO favors storm tracks similar to that of the Panhandle Low and Colorado Low defined in this study. These storms have also proven to contribute significant snowfall in Oneonta. Therefore, negative NAO Coastal Storms may have more impact on the city of Oneonta but it is clear that this location can receive heavy snowfall in both phases of the NAO.

CONCLUSIONS

This research develops an increased understanding of the snowfall season in Oneonta, New York and how it has changed with time. With respect to changes in long-term climate and the snow season, these findings may be applicable to a larger area throughout the Northeast, particularly other locations in the New York area such as the larger cities of Albany, Binghamton, and Syracuse. It is shown that the length of season in which Oneonta receives plowable snowfall (minimum of 2.5 in or 6.35 cm) is decreasing, while the date of the first measurable snowfall is occurring progressively earlier each year. There are also indications that the timing of the last measurable snowfall is occurring earlier. Although this trend did not pass the t-distribution test, a p-value of 0.27 provides some statistical confidence that there is a non-zero trend. Large annual

Month	NAO	ONI
November	-0.196	0.064
December	-0.543	-0.010
January	-0.297	-0.059
February	-0.334	0.261
March	-0.177	-0.164

Table 4. R-values between monthly snowfall at Oneonta and monthly mean NAO and ENSO (ONI) indices over the past 32 years.

variability in total seasonal snowfall may be masking changes in the snow season that are due to a warming climate. Given the large range in snowfall from season to season, the standard deviation of the dataset would be increased and, as a result, dilute the trend line and decrease confidence in the trend line. Collectively, this could be an indication that the Oneonta snow season is shifting to occur earlier than it did decades ago, rather than increasing or decreasing in length. If so, then it would make sense that the spring season is arriving earlier at Oneonta which follows the findings of Zander et al. (2013). Their research examined springtime air mass changes with time throughout the Northeast United States and found that not only were recent springs receiving more warm air masses, but that those air masses arrived earlier than they did prior to 1975. Here, the length of the Oneonta snow season is also found to exhibit more year-to-year variability than it did in the 1980s. In that decade the season duration was regularly around 150 days but the range is much less consistent in recent decades (**Figure 11**). Despite finding a prominent change in the length of the snow season, the total number of snow days is observed to be increasing which is an important finding that requires verification across the region.

A better understanding of the Oneonta snow season is developed here through examination of the types of snowstorm that most frequently produce city snowfall and those that tend to produce the most intense snowfall. Lake-effect storms are the most frequent producer of snowfall in Oneonta, while Colorado Lows, Panhandle Lows, and, in particular, Coastal Storms tend to produce the heaviest snowfall in Oneonta. Nearly half of all Coastal Storms (44%) with snowfall in Oneonta are observed to produce significant snowfall. The maximum snowfall that has arisen from a single Coastal Storm is over 24 in (61 cm) whereas the maximum Lake-effect snow event is 4 in (10.16 cm) produced by each type of storm. A 2007 Panhandle Low storm produced the most snowfall on record for a single event at Oneonta with 30 in (76.2 cm). These findings have implications for many short term snowfall forecasts in central New York. The National Weather Service Weather Forecast Office in Binghamton and television broadcast centers in Binghamton and Utica are primarily responsible for coverage of Oneonta weather. These forecast and viewing regions can span as far north as Lake Ontario and the Tug Hill plateau where snowfall variability, particularly that from Lake-effect snows and Coastal Storms, can be quite different from Oneonta. Understanding storm variability with these Oneonta data analyses may reduce error in snow forecasts for the far reaches of the forecast region.

The timing of notable snowstorms may also help with city preparedness for winter weather. Most significant storms in Oneonta occur during the meteorological winter, with a peak in activity at the end of December (a very active travel time for residents) and a second peak around the end of February and beginning of March. This finding requires additional research at areas throughout the Northeast and, specifically in central New York, to determine if a pattern of two separate peaks in winter storm activity is present at other locations. Further, comparing the timing of snowstorms in the early and late records may depict a different pattern since the two peaks may be an artifact of a shifting snow season at Oneonta.

Long term and seasonal forecasting for the Oneonta area may benefit from the results relating the NAO to snowfall patterns in Oneonta, though results with implications for short term forecasts are practically more useful. While monthly NAO indices are negatively correlated with monthly snowfall (particularly for the

months of December, January and February), analysis of daily NAO indices indicate that more snowfall occurs in a positive NAO phase. Furthermore, the low correlation coefficients between ONI and monthly snowfall at Oneonta show that there is a very weak signal of ENSO on monthly snowfall patterns. With higher correlation coefficients identified for the NAO, it is clear that the NAO is better related to snowfall patterns in central New York. Future analyses of the effect of climate indices on snowfall patterns in Oneonta should consider additional climate oscillations, like the Arctic Oscillation and Pacific/North American pattern, and should account for the inherent influence of global change on these datasets.

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