A CLASSIFICATION SCHEME FOR IDENTIFYING SNOWSTORMS AFFECTING CENTRAL NEW YORK STATE

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ABSTRACT

The Great Lakes region experiences anomalously high seasonal snowfall totals relative to similar latitudes. Although lake-effect snowstorms are common in this region, snowfall occurs from a variety of storm types. This study examines snowstorms in a subsection of the Lake Ontario basin to develop a classification scheme to categorize the different types of snowstorms affecting the region. From 1985 – 2015, there were eleven different snowstorm types to affect the study area. The classification system was used to assess the frequency of, and snowfall produced by the different storm types within the eastern Great Lakes region.

From the classification, snowstorms were categorized as either non-direct cyclonic storms (NDCS) or direct cyclonic storms (DCS). Lake-effect snowstorms, a type of NDCS, were the most frequent storm (35.1% of all storms) and accounted for approximately 39.4% of the snowfall. Most lake-effect storms (37.7%) produced moderate snowfall totals (10.2 – 25.3 cm), yet heavy snowfall storms (≥ 25.4 cm) contributed significantly ($\rho \leq 0.05$) more to seasonal snowfall totals than lighter snowfall storms. Direct cyclonic clippers forming over high latitudes of northwestern Canada, were the most frequent DCS in Central New York (11.3% of all storms), with nearly three quarters of the storms originating over Alberta. These storms only contributed 9.2% of the seasonal snowfall in the study area, compared to 12.7% from direct cyclonic Nor'easters forming near the east coast of North America. Although Nor'easters occur less frequently than clippers, when they do occur, they tend to produce heavy widespread snowfall across the region. The classification system proposed can be modified to accommodate snow basins across the globe. Classifying snowstorms will help determine the seasonal snowfall contribution from different storms and aid in future climate predictions, as individual snowstorm types may respond differently to a warming global climate.

1.0 INTRODUCTION

Some of the greatest seasonal snowfall totals in North America occur within the Laurentian Great Lakes basin. The Upper Peninsula of Michigan and the Tug Hill Plateau of New York State are two of the most recognizable snowbelts, with seasonal snowfall totals regularly exceeding 508 cm per season (Veals and Steenburgh, 2015). These snowbelts receive anomalously high seasonal totals compared to locations at similar latitudes, largely due to their eastern positions relative to the Great Lakes. From September through March, cold air often advects over the lakes and is altered due to differences in moisture, heat content, and friction between the lake surfaces and the upwind areas (Changnon and Jones, 1972; Scott and Huff, 1996; Vavrus *et al.*, 2013). The relatively warm lake surfaces can destabilize the air column resulting in lake-effect clouds and precipitation (Pease *et al.*, 1988). It is estimated that lake-effect snow accounts for approximately half of the seasonal snowfall in the Great Lakes region (Miner and Fritsch, 1997; Liu and Moore, 2004). Although lake-effect snowstorms may be the dominant contributor to seasonal snowfall totals in this region, snowfall also occurs from extratropical cyclones originating across North America (Karmosky, 2007; Suriano *et al.*, 2019). This study develops a classification scheme capable of identifying the different types of snowstorms that affect the Great Lakes region.

The amount of snowfall from a storm varies across the Great Lakes region. Higher snowfall contributions from lake-effect snow are found in elevated terrain to the lee of the lakes (Hill, 1971). Veals and Steenburgh (2015) estimate that lake-effect snow accounted for 61-76% of the mean cool-season snowfall in the Tug Hill from September 2011 – May 2014. In less prone areas, contributions are lesser, as Eichenlaub (1970) estimates that lake-effect snow contributes slightly over 30% of the seasonal snowfall in parts of the Lower Peninsula of Michigan. Snowfall contributions from cyclonic snowstorms also vary across the region, as eastern locations tend to experience greater contributions from east coast storms due to their proximity to the Atlantic Ocean (Harrington *et al.*, 1987). The ability to classify individual snowstorms influencing the Great Lakes region will help tease out the actual snowfall contributions from the different storm types.

As the climate changes, so too does the interaction of snowstorms with the atmosphere and underlying geography. Snowfall is particularly vulnerable to climatic changes because its occurrence depends on subzero air temperatures (Brown and Mote, 2009). Evidence suggests that snowfall during the 20th century significantly increased in areas dominated by lake-effect snow, but these increases were not observed in non-lake-effect areas (Norton and Bolsenga, 1993; Leathers and Ellis, 1996; Berger *et al.*, 2002; Burnett *et al.*, 2003; Kunkel *et al.*, 2009b, 2009a; Hartnett *et al.*, 2014; Lawrimore *et al.*, 2014). The contrasting trends are linked to synoptic snowstorms, which are the dominant snowstorm type outside of the lake-effect snow basin. These storms decreased in both frequency and snowfall during the 20th century. The updated classification system proposed in this study identifies snowstorms affecting the Great Lakes region and will aid in identifying reasons for discrepancies in snowfall trends and how each individual storm type may respond to a changing climate. Since snowstorms are an integral part of the social, economic, ecological, hydrological and atmospheric processes of the Great Lakes region, a complete climatological analysis of storms is needed to fully understand their importance and how they may change with future climate scenarios.

2.0 Methods and Results

2.1 Snowstorm Identification

Snowstorms affecting central New York State were examined (Figure 1). Located east of Lake Ontario, Central New York is one of the snowiest regions of the Great Lakes basin. Its leeward position to Lake Ontario is not only favorable for the occurrence of lake-effect snow, but the formation of multi-lake snowbands from Lake Huron and to a lesser extent Lakes Michigan, Superior, and Erie (Mann *et al.*, 2002; Rodriguez *et al.*, 2007; Laird *et al.*, 2017; Kristovich *et al.*, 2018; Lang *et al.*, 2018). Lake-effect snow is also common in this region due to Lake Ontario's relatively low annual ice cover (Assel, 2003; Wang *et al.*, 2012) and its east-west axis orientation favoring a longer fetch (Niziol, 1987) . However, Central New York's proximity to the Atlantic Ocean also subjects it to snowstorms not regularly experienced in the western Great Lakes basin. Therefore, Central New York is a prime area to study the types of snowstorms in the Great Lakes region because it experiences many of the synoptic storms that influence the western Great Lakes basin and storms that influence the east coast of the United States.

All snowstorms to affect Central New York were examined from 1 July 1985 to 30 June 2015. Precipitation and snowfall data from the National Weather Service's Cooperative Observer Program (COOP) were accessed from the National Centers for Environmental Information (NCEI) (Table 1). Using the guidance of Perry et al. (2007), a snowstorm was defined as any storm with at least 0.3 cm of daily snowfall recorded for at least two COOP stations in the study area. Stations were only used if daily data were reported for more than 90% of the snowfall season (1 October – 31 May) for at least 25 of the 30 seasons, and after filtering for inhomogeneities in station records identified by Kunkel et al. (2009b). Snowfall was set to zero in instances a station was reporting observations but failed to report a snowfall total because many COOP reporters commonly fail to report days with no snow (Rasmussen *et al.*, 2012). A total of 60 COOP stations were retained for analysis (Table S1; Figure 1).

The use of volunteer-based daily snowfall observations creates additional challenges. Although observers are instructed to measure snowfall at least once every twenty-four hours, they are given flexibility in the timing of their observations (NWS, 2012). This creates challenges when assigning daily snowfall totals to individual snowstorms because snowfall for some stations may reflect same-day snowfall, while totals for other stations represent the previous day's snowfall. Also, since snowfall is measured every twenty-four hours, there is potential for a total to reflect snowfall from more than one storm (Doesken and Robinson, 2009). In these instances, snowfall totals were assigned to one storm depending on the timing of the observation. To prevent deflating snowfall totals for the other storm, observations were treated as missing. Lastly, although flexibility in the timing of observations increases observer participation, it enhances the risk for inaccurate measurements during mixed precipitation events. During rain-on-snow events, rain and above freezing temperatures have the potential to melt any accumulated snow and an observer may miss a snowfall observation altogether.

To improve the temporal resolution of data, hourly surface observations were used from thirteen COOP stations (Table 1; Table S1; Figure 1). These data were used to determine the onset and dissipation of storms (Perry *et al.*, 2007). The onset is the hour any precipitation is reported within the study area. Whereas the dissipation is the last hourly report of precipitation with at least a six-hour gap between the next precipitation event across the thirteen stations (Perry *et al.*, 2007). If the time between precipitation events was less than six hours, then the events were considered a single storm. 2055 snowstorms were identified to influence Central New York from the 1985/86 season to the 2014/15 season.

The hourly data provided the delineation of individual snowstorms that could then be applied to station data from the daily COOP. In some instances, a single storm's snowfall total for a station included the summation of multiple 24-hour totals. To encapsulate the maximum amount of snowfall a storm produced in one area, the station with the greatest snowfall total was identified for each storm and used to classify the magnitude of the storm as either a light (< 10.2 cm), moderate (10.2 cm – 25.3 cm), or heavy-snowfall storm (≥ 25.4 cm) (Kocin and Uccellini, 2004). However, the use of a single station to represent a storm's contribution to seasonal snowfall totals throughout Central New York may bias results and therefore, snowfall contributions for each storm were calculated by averaging the top five snowfall totals for that storm. Averaging across five stations accounts for some of the spatial variability in snowfall across the region. It also prevents biases that occur when averaging across all available COOP stations, especially for snowstorms that produce region-wide snowfall.

2.2 SNOWSTORM CLASSIFICATION

The 2055 snowstorms were classified using the criteria outlined in Table 2. Storms were visually assessed using reanalysis images similar to the procedures used by Clark et al. (2020) and using meteorological reports from Syracuse Hancock International Airport and the methods outlined by Suriano and Leathers (2017a) (Table 1). Archived three-hour *United States (CONUS) Analyses* images were accessed from the Weather Prediction Center (WPC) from 00Z 1 May 2005 to 30 June 2015 (Table 1). These were the primary sources for classifying snowstorms, however CONUS data did not span the entire study period. Therefore, Daily Weather Maps from the National Oceanic and Atmospheric Administration's (NOAA) online archive were accessed for storms prior to the 2005 season (Table 1). NCEP/NCAR Reanalysis 1 were used to inspect upper atmospheric conditions (Table 1) (Kalnay et al. 1996). Reanalysis charts included 200 hPa heights and isotachs; 500 hPa heights and standardized height anomalies; 850 hPa heights, temperatures, and standardized temperature anomalies; and 1000 hPa heights, precipitable water, and standardized precipitable water anomalies. Even though the temporal resolutions of the data differ, it did not impact the analysis of cyclonic storms. The images were examined for the presence or absence of a low pressure within 150 km of Central New York. If a surface low pressure (< 1013 hPa) existed, then the storm was classified as a direct cyclonic snowstorm (DCS), while non-direct cyclonic snowstorms (NDCS) were defined by an absence of a low within the immediate study area (Table 2) (Kelly *et al.*, 2012).

2.2.1 NON-DIRECT CYCLONIC SNOWSTORMS

NDCSs were examined for a freezing surface air temperature; a temperature gradient of at least 13^0C between the lake surface and the 850 hPa layer; a wind direction with a favorable fetch (e.g. westerly wind) over Lake

Ontario; directional shear less than 30° between the surface and 850 hPa winds; and 850 hPa winds between 5 m s^{-1} and 20 m s^{-1} (Table 2) (Niziol *et al.*, 1995; Suriano and Leathers, 2017a, 2017b). For storms that met the previous criteria, NEXRAD data and GOES infrared imagery were obtained from the NCEI (Table 1). For storms occurring between 1994/95 and 2014/15, NEXRAD data were used to identify the presence of a quasi-stationary, coherent precipitation pattern with a notable connection to Lake Ontario or Lake Erie; a distinct mesoscale structure of the precipitation identifiable from other areas of precipitation with cloud heights often below 2 km; and mesoscale precipitation bands that originate over the lake (< 10 km) and increase in strength (i.e. increased reflectivity, depth, or spatial coverage) downwind of the lake (Sobash *et al.*, 2000; Laird *et al.*, 2009a, 2010). For storms prior to 1994/95, GOES infrared imagery were used to determine if the upwind shore of the lake was partially visible and whether the cloud structure was noticeably linked to nearby cloud masses similar to the methods used by Kelly (1986) (Table 2). Although satellite imagery spans the entire study period, the occurrence of clouds does not ensure the production of snow; therefore, NEXRAD data were preferred. The use of two methods to classify lake-effect storms presents a possible bias in the result, notably an undercounting of lake-effect storms prior to the use of NEXRAD data. However, there were no significant ($\rho > 0.05$, two-sample t-test) differences in the frequency of any of the NDCSs before and after the use of NEXRAD data.

If a snowstorm satisfied the above criteria and its precipitation was separated from that of all other snowstorms by at least six hours, then the storm was classified as a 'pure' lake-effect snowstorm (Table 2). There were instances when the above criteria were satisfied, except there was a connection to the lake-effect clouds and a cyclonic storm within 150 km of the study area. This is often referred to as lake-enhanced snow (Owens *et al.*, 2017), and for the purpose of this study was treated as snowfall from the cyclonic storm. If the storm was a NDCS, yet did not satisfy the previous criteria, then surface and upper atmospheric reanalysis charts were examined for the presence of a 500 hPa upper-level disturbance (e.g. low, trough, or ridge) or a frontal system through Central New York and were aptly named either an upper atmospheric disturbance or a frontal storm, respectively (Table 2). 1133 NDCSs affected Central New York during the study period, of which 721 were lake-effect snowstorms, 233 upper-atmospheric disturbances, and 179 frontal storms (Table 3).

NDCSs affecting Central New York were predominately moderate snowfall storms (39.5%; Table 3). Lake-effect snowstorms were the most frequent NDCSs for all three magnitudes, producing mostly moderate (37.7%) or heavy (35.2%) snowfall totals. Of the 322 heavy-snowfall NDCSs, 254 (78.9%) were lake-effect snowstorms, 48 (14.9%) upper atmospheric disturbances, and 20 (6.2%) frontal storms (Table 3). Upper atmospheric disturbances mostly produced moderate snowfall totals, while the majority of frontal storms produced light snowfall totals.

NDCSs contribute approximately 55.4% of the snowfall in Central New York (Table 4). The majority of this snow was from lake-effect snowstorms, which contribute approximately 39.4% of the seasonal snowfall in the study area. The majority (60.5%) of lake-effect snowfall was from heavy-snowfall storms, followed by moderate (30.5%) and light-snowfall storms (9.0%). Upper atmospheric disturbances account for 9.9% of the total snowfall in Central New York. Similar to lake-effect snowstorms, most of this snow is from heavy-snowfall storms (47.6%), followed by moderate (37.6%) and light-snowfall producing storms (14.8%). Of the NDCSs, frontal storms contributed the least to seasonal snowfall totals, accounting for 6.1% of the total seasonal snowfall. The majority (46.5%) of snowfall from frontal storms occurred during moderate-snowfall storms, with heavy (26.9%) and light-snowfall storms (26.6%) accounting for nearly the same amount of snowfall.

2.2.2 Direct Cyclonic Snowstorms

DCSs were classified by their area of cyclogenesis using reanalysis data to trace the movements of the cyclone in the days prior to snowfall in Central New York. Since extratropical cyclones are driven by the transient polar jet stream, their formation varies in time and space (Klein, 1958; Whittaker and Horn, 1981; Jones and Davis, 1995). The location of a cyclone's initial formation can affect its trajectory and internal characteristics. This study defines cyclogenesis as the moment a closed isobar surrounds a surface low pressure center less than 1013 hPa. Since cyclonic storms periodically strengthen and weaken, barring complete cyclolysis, the area of initial formation was used to define the storm.

Areas regularly influenced by the jet stream, with strong baroclinicity are common zones of cyclogenesis (Whittaker and Horn, 1981; Robinson and Henderson-Sellers, 1999). From fall to spring, cyclogenesis over North America is most frequent between 35-40˚N, with a secondary peak from 50-55˚N (Klein, 1958; Whittaker and Horn, 1981). These latitudes correspond to the location of the polar jet stream, which produces extratropical cyclones due to its interaction with permanent and semi-permanent anticyclones centered near 30˚N (Klein, 1958; Whittaker and Horn, 1981). Several zones of cyclogenesis have been identified in North America and have been simplified into six regions: the east coast, coastal Texas, lee of the southern Rocky Mountains, the Great Basin, the Northwest Territories, and Alberta (e.g. Jones and Davis 1995; Klein 1957; Reitan 1974; Whittaker and Horn 1981; Zishka and Smith 1980).

To determine whether the six traditional zones are fully responsible for the development of extratropical cyclones affecting Central New York, the area of cyclogenesis was plotted for the 922 DCSs from 1985/86 – 2014/15. The latitude and longitude of cyclogenesis was plotted for each storm on a 2.5° x 2.5° grid (Figure 2). A Getis Ord Gi* hotspot analysis was performed in ArcGIS. The analysis identified areas of significant geographic clustering of cyclogenesis for storms that produce either heavy (hot spot) or light (cold spot) snowfall totals in Central New York (Figure 3) (Getis and Ord, 1992; Lyza and Knupp, 2018; Saunders *et al.*, 2018). The number of storms forming in each grid cell was then calculated and a Getis Ord Gi* hotspot analysis was again used, this time to determine typical areas of cyclogenesis (Figure 3). Combing the results from the hotspot analyses and the six traditional zones of cyclogenesis, eight primary zones emerged and were assigned a unique storm type: tropical cyclones, Hudson lows, clippers, Nor'easters, Colorado lows, Texas hooks, Oklahoma hooks, and Great Lakes lows (Figure 4).

2.2.2.1 Clippers

Clippers are lows that form to the lee of the Rocky Mountains, often centered near the provinces of Alberta or the Northwest Territories (Figure 4) (Reitan, 1974; Chung *et al.*, 1976; Whittaker and Horn, 1981; Thomas and Martin, 2007). Clippers typically begin as upper-atmospheric troughs in northern latitudes, with cyclogenesis occurring as the trough extends into the northern United States. Originating in northern latitudes, cold air (< 0°C) often accompanies these storms in the winter. They are low-moisture storms due to their inland formation and the depletion of moisture by the Rocky Mountains (Jorgensen, 1963). They are relatively small and fast (> 13 m s^{-1}), with a high central pressure (> 990 mb) compared to other extratropical storms (Thomas and Martin, 2007). Their low moisture content and fast movement typically result in lower snowfall totals and snow water equivalencies compared to other cyclonic storms. However, the cold air advected by these storms often results in greater snowfall totals downwind of the Great Lakes due to the development of lake-effect and lake-enhanced snow (Harms, 1973; Silberberg, 1990; Angel and Isard, 1997; Thomas and Martin, 2007).

Clippers were the most frequent (233 storms) DCS to affect Central New York, and tied for the second most frequent storm overall (Table 3). Most (112) clippers had moderate snowfall totals, followed by light (82) and heavy (39) snowfall totals. Storms forming over Alberta occurred most often (171), most of which were moderate snowfall storms (52.0%). Northwest Territories clippers and northern Rocky clippers only occurred 38 and 24 times, respectively. Storms forming in the northern Rockies favored light snowfall totals (50.0%), while those forming in the Northern Territories often produced moderate (39.5%) or light snowfall (34.2%).

Clippers account for approximately 9.2% of the seasonal snowfall in Central New York, most of which was from storms forming over Alberta (Table 4). Moderate-snowfall Alberta clippers produced the most snow during the study period (919.2 cm), followed by heavy-snowfall Alberta clippers (549.3 cm), and heavy-snowfall Northwest Territories clippers (187.5 cm). Clippers averaged the second least amount of snowfall per storm (16.5 ± 0.9 cm) (Figure 5). Generally, the higher the latitude of cyclogenesis, the more snowfall the clipper produced.

2.2.2.2 Great Lakes Lows

Great Lakes lows form throughout the Great Lakes and upper Midwest of the United States (Figure 4). These storms typically originate to the lee of the Rocky Mountains but undergo complete cyclolysis as they progress to the east. As the storm approaches the Great Lakes, baroclinic conditions enhance the formation or reformation of the cyclone. Since these storms form close to the study area, they are relatively small with a higher central pressure than most snowstorms. In Hirsch et al. (2001)'s classification, the authors did not include these as individual storms most likely because they are often remnants of previous cyclones.

There were 118 Great Lakes lows to affect Central New York during the study period (Table 3). Of these storms, 22 produced heavy snowfall totals, 56 moderate snowfall totals, and 40 light snowfall totals. Great Lakes lows formed in one of three locations: over the Great Lakes, in the Midwest United States, or over the Upper Mississippi River Valley (Figure 4). Storms forming over the Great Lakes were most common (84), 18 of which produced heavy-snowfall totals, 41 moderate-snowfall totals, and 25 light-snowfall totals. Midwest lows produced snowfall in Central New York 22 times, the majority of which were moderate (45.5%) and light (50.0%) snowfall events. Upper Mississippi River Valley lows only occurred 12 times, with a more even distribution of the frequency of different magnitude storms.

Great Lakes lows account for approximately 4.9% of the seasonal snowfall in Central New York, most of which was from storms forming over the Great Lakes (Table 4). For all three storm types, light-snowfall storms accounted for less seasonal snowfall than moderate-snowfall storms. Heavy-snowfall storms forming over the Great Lakes and Upper Mississippi River Valley accounted for the majority of their respective seasonal snowfall totals. Moderate-snowfall Midwest lows were the dominant snowfall contributor (56.8%) for these storms. Great Lakes lows often averaged less snow per storm (17.2 ± 1.3 cm) than other cyclonic snowstorms. There is considerable variation, as storms forming over the Great Lakes average significantly more snowfall (19.0 ± 1.7 cm) than storms forming over the Midwest (11.5 ± 1.5 cm) (Figure 5).

2.2.2.3 HUDSON LOWS

Hudson lows form due to the baroclinicity caused by the Hudson Bay (Figure 4). Since they also tend to form from remnant clippers, they display many of the same characteristics, and were likely not identified as separate storms by Hirsch et al. (2001). Hudson lows are associated with polar or even Arctic air masses and are often accompanied by strong cold fronts extending south from the low well into the United States. There is often a strong contrast between the air masses with differences exceeding 10°C (Curry, 1983).

Central New York was affected by 43 Hudson lows during the study period. Most (55.8%) of those produced moderate snowfall totals and accounted for 46.9% of their snowfall. Hudson lows only accounted for 2.1% of Central New York's snowfall, 90.3% of which was from heavy- and moderate-snowfall storms. Since Hudson lows tend toward heavy and moderate snowfall totals in Central New York, they averaged the fourth most snowfall per storm (19.2 ± 2.1 cm), behind Nor'easters, Texas hooks, and lake-effect snowstorms (Figure 5).

2.2.2.4 NOR'EASTERS

Nor'easters, also known as east coast storms, are low-pressure systems with winds exceeding 10.3 m s^{-1}, that generally track to the north or northeast for at least six hours within the Nor'easter zone of Figure 4 (Hirsch *et al.*, 2001). They are usually widespread storms, bringing heavy snowfall totals with a high moisture content and cold windy conditions throughout the Northeast (Kocin and Uccellini, 2004). The strong baroclinic conditions created by the Appalachian Mountains and Gulf Stream often cause these storms to undergo rapid development and bombogenesis (Sanders and Gyakum, 1980; Zishka and Smith, 1980; Cione *et al.*, 1993; Jacobs *et al.*, 2005). Nor'easters tend to form in three distinct areas: the Gulf of Mexico, the southern east coast, and the northern east coast (Colucci, 1976; Zishka and Smith, 1980; Whittaker and Horn, 1981; Davis and Dolan, 1993; Jones and Davis, 1995; Hirsch *et al.*, 2001; Changnon *et al.*, 2008).

Gulf lows and southern east coast storms form south of 35°N due to humid air and a strong baroclinicity (Jacobs *et al.*, 2005). Gulf lows form between coastal Texas and the Gulf Coast of Florida, while southern east coast storms often form just east of the Gulf Stream temperature axis near the Carolinas, Georgia, or Florida (Figure 4) (Miller, 1946; Changnon *et al.*, 2008). Southern east coast storm cyclogenesis is most frequent to the lee of the Appalachian Mountains around 32°N because the mountains impede the progress of strong cold fronts to the south-southeast (Whittaker and Horn, 1981; Kocin and Uccellini, 1990). Miller (1946) suggests the synoptic conditions include a cold anticyclone over most of the eastern United States flowing off the continent; the advection of warm maritime air from the Gulf or western Atlantic; a distortion of the cold front into a wave-like pattern; and middle cloud and precipitation formation along the distorted portion of the cold front. Although less frequent than northern east coast storms, their southern formation often leads to higher precipitation totals and snow water equivalencies in the northeastern United States (Kocin and Uccellini, 1990; Davis and Dolan, 1993).

Northern east coast storms form north of 35°N between Norfolk, VA and Cape Cod, MA (Miller, 1946; Whittaker and Horn, 1981). These storms often form along the boundary of a remnant cyclone's warm front and are unique to the eastern United States (Miller, 1946). Though less severe than their southern counterpart, they occur more frequently in the Northeast due to their northern and western formation (Miller, 1946; Branick, 1997; Zielinski, 2002; Kocin and Uccellini, 2004; Changnon *et al.*, 2008). Their synoptic conditions often consist of an occluded frontal boundary in the Great Lakes; cold continental air trapped between the Appalachian Mountains and the Gulf Stream; warm maritime air advecting northward into the trapped cold air; cloud and precipitation formation within the trapped cold air; and an area of decreasing pressure dissociated with falling pressure from the primary cyclone center (Miller, 1946).

Nor'easters were the second most frequent (196 storms) DCS to affect Central New York (Table 3). They often produced heavy (36.7%) and moderate (37.8%) snowfall totals. Northern east coast storms were the most common (71 storms), 40.8% of which produced heavy snowfall in Central New York, 36.6% moderate snow, and 22.5% light snowfall. Gulf lows were the next most frequent (65 times) Nor'easter, most of which were moderate (41.5%) or heavy (32.3%) snowfall producing storms. Southern east coast storms influenced the study area 60 times and often produced heavy (36.7%) and moderate snowfall (35.0%) totals as well.

Nor'easters accounted for a greater percentage of snowfall (12.7%) in Central New York than any other DCS storm (Table 4). Most of that snow was from northern east coast storms (37.1%), followed by southern east coast storms (32.0%) and Gulf lows (30.9%). For all three storm types, heavy snowfall storms contributed considerably more (67.2 – 70.0%) to seasonal snowfall totals than moderate (21.9 – 27.6%) and light (4.8 – 8.1%) snowstorms. Northern east coast storms averaged the most snow per storm (26.0 ± 2.6 cm), which was significantly ($\rho \leq 0.05$) more than every snowstorm type except lake-effect snowstorms, Texas Hooks, and other the Nor'easters (Figure 5). Southern east coast storms (24.2 ± 2.6 cm storm^{-1}) and Gulf lows (22.1 ± 2.5 cm storm^{-1}) also produced more snowfall per storm in Central New York than most other snowstorm types.

2.2.2.5 Colorado Lows

Colorado lows form a definite center on the eastern slopes of the Rocky Mountains near Colorado (Figure 4) (Changnon et al. 2008). Cyclogenesis is common over the Great Basin and northeast Pacific, but as the system moves across the Rocky Mountains it often strengthens or reforms over the Colorado front range (Whittaker and Horn, 1981; Changnon and Changnon, 2006). After forming, the low tracks to the northeast crossing the central United States and entering the Great Lakes region (Branick, 1997; Changnon *et al.*, 2008). The combination of highly contrasting air masses (Djurić and Damiani, 1980), their large extent and curved track result in the potential for severe weather across the United States. Though snowfall is common in the northwest sector, sleet, freezing rain, rain, thunderstorms, high winds, and even tornadoes are possible elsewhere (Saylor and Fawcett, 1965; Kreitzberg and Brown, 1970; Galway and Pearson, 1981; Stewart, 1992).

There were 129 Colorado lows that affected Central New York during the study period, 55 of which produced moderate snowfall, 48 light snowfall, and 26 heavy snowfall (Table 3). Approximately three-fourths of the Colorado lows formed over the Colorado front range and produced moderate (43.3%) or light (37.1%) snowfall totals. Storms forming over the Great Basin (25 storms) and Northeast Pacific (7 storms) also tended toward moderate and light snowfall totals.

Colorado lows accounted for approximately 5.4% of Central New York's snowfall, most of which was from storms forming in the Colorado front range, followed by the Great Basin and the northeast Pacific (Table 4).

Heavy-snowfall storms forming over the Colorado front range and the Great Basin produced more seasonal snowfall than their moderate and light-snowfall counterparts. There was no significant ($\rho > 0.05$) difference in the average snowfall per storm between the three types of Colorado lows (Figure 5). Although there was a greater variability in the snowfall from northeast Pacific lows (15.1 ± 4.1 cm) than lows forming over the Colorado front range (16.8 ± 1.9 cm) or Great Basin (16.6 ± 2.3 cm).

2.2.2.6 Oklahoma Hooks

Oklahoma hooks are similar to Colorado lows, but form slightly to the south (Figure 4). These storms are sometimes referred to as Panhandle hooks and are low-pressure systems originating in the panhandles of Oklahoma and Texas. They often form due to a more pronounced trough in the jet stream compared to Colorado lows. This leads to a greater influence from the Gulf of Mexico and a more pronounced curved track towards the upper Midwest and Great Lakes (NWS, 2004). This often results in low surface pressures, strong winds, and high precipitation totals (Bentley and Horstmeyer, 1998; Changnon *et al.*, 2008).

There were 124 Oklahoma hooks in Central New York during the study period (Table 3). These storms mostly produced moderate or light snowfall totals, 47 and 43 storms, respectively, while 34 storms produced at least 25.4 cm of snowfall. Oklahoma hooks accounted for approximately 5.9% of the seasonal snowfall in Central New York, with most (59.0%) of that snow from heavy-snowfall storms (Table 4). During the study period, Oklahoma hooks averaged approximately 18.9 ± 1.5 cm of snowfall per storm in Central New York (Figure 5).

2.2.2.7 Texas Hooks

Cyclogenesis is also common further to the south over the coastal and central plains of Texas (Figure 4). These storms are termed Texas hooks. As they track east, they pass, albeit briefly, over the Gulf of Mexico resulting in an influx of moisture and heat to the overlying air (Businger *et al.*, 1990). This increases the potential for heavier precipitation and more severe weather than Oklahoma hooks and Colorado lows. Texas hooks are distinct from Gulf lows due to their pronounced curved track west of the Appalachian Mountains. This strong curvature causes more intense precipitation over the Great Lakes region than the east coast of the United States.

Texas hooks produced snowfall in Central New York 77 times during the study period (Table 3). Most storms (41.6%) produced moderate snowfall totals, followed by light (36.4%) and heavy (22.1%) snowfall totals. Texas hooks accounted for approximately 4.4% of the seasonal snowfall in Central New York, most (56.4%) of which was from heavy-snowfall storms. Texas hooks averaged (21.4 ± 2.9 cm) significantly ($\rho \leq 0.05$) more snowfall per storm than the northern forming Colorado lows (Figure 5).

2.2.2.8 Tropical Cyclones

Tropical cyclones are the final snowstorm type to affect Central New York during the study period. These are warm-core, non-frontal synoptic-scale cyclones that originate over tropical or subtropical waters, with organized deep convection and a closed surface wind circulation about a well-defined center (NWS, 2004). If these storms produce snowfall it is after they have transitioned into extratropical cyclones, in which case they are cold-core systems forming along an air mass boundary (Hart and Evans, 2001; Evans *et al.*, 2017). Since this classification is based on the area of cyclogenesis, storms originating as tropical cyclones were assigned to a region in the Atlantic Ocean, regardless of where they formed (Figure 4).

There were only two tropical cyclones to affect Central New York during the study period, one with moderate snowfall and the other with light snowfall (Table 3). Due to their infrequency and since air temperatures are often above freezing during these storms, they accounted for less than 0.1% of the seasonal snowfall from 1985/86 – 2014/15 (Table 4).

3.0 Discussion

A new classification scheme is purposed to classify the different snowstorms that affect the eastern Great Lakes region. This study expands upon the classification and analysis of previous research which examined snowfall contributions from three primary snowfall patterns (coastal storms, lake-effect storms, and overrunning storms) in the northeastern United States (Karmosky, 2007; Suriano *et al.*, 2019). Results suggest that there are three types of non-direct cyclonic storms (lake-effect, upper disturbances and frontal systems) and eight direct cyclonic storms (clippers, Colorado lows, Great Lakes lows, Hudson lows, Nor'easters, Oklahoma hooks, Texas hooks and tropical storms) that influence Central New York.

NDCSs occurred approximately 1.2 times more often than DCSs in Central New York from 1985 – 2015 (Table 3). These storms contributed significantly ($\rho \leq 0.05$, t-test) more snowfall in the region, most of which was from lake-effect snowstorms. Lake-effect snowstorms accounted for significantly ($\rho \leq 0.05$, t-tests) more seasonal snowfall (39.4%) than any other snowstorm type. Results are comparable to previous findings that suggest that lake-effect snow contributes approximately half of the seasonal snowfall in the Great Lakes basin (Eichenlaub, 1970; Miner and Fritsch, 1997; Liu and Moore, 2004; Veals and Steenburgh, 2015). However, these results fall short of the estimated 61-76% contribution suggested by Veals and Steenburgh (2015) and surpass the 30% estimate suggested by Eichenlaub (1970). The contrasting results are likely a product of the size and location of the study area. Central New York is located to the lee of Lake Ontario, and although the lake is the smallest of the Laurentian Great Lakes, it is the deepest on average. Therefore, Lake Ontario rarely freezes, providing a greater potential for lake-effect snow throughout the winter (Wright *et al.*, 2013). In addition, Lake Ontario's east-west orientation and position downwind of the other Great Lakes are favorable for the development of lake-effect and lake-enhanced snow over Central New York (Sousounis and Mann, 2000). The lesser contributions found in this study compared to Veals and Steenburgh (2015) are likely due to a larger study area. The Tug Hill is infamously known for its recording-breaking snowfall (Campbell *et al.*, 2016), often generated from lake-effect storms. However, since Central New York is located between the Great Lakes and the Atlantic Ocean, a variety of snowstorm types bring snowfall to the region, especially further south and east of the lake. This mixed variety of snowfall likely lessens the contribution from lake-effect snow for all of Central New York compared to only the Tug Hill Plateau.

Approximately 35% of all snowstorms in Central New York were lake-effect storms. Lake-effect storms occurred three times more than any other snowstorm type. Upper atmospheric disturbances and clippers were the second most frequent storms, both occurring 233 times during the study period. Both of these storm types are often associated with the conditions necessary for the formation of lake-effect snow including the advection of cold air over the Great Lakes, west-northwest winds over Central New York, and a substantial fetch across Lake Ontario (Thomas and Martin, 2007; Metz *et al.*, 2019). Therefore, clippers and upper atmospheric disturbances may often prelude lake-effect snowstorms. Clippers originating further to the north (Northern Territories) averaged more snowfall per storm than those forming to the south (northern Rockies). There is even a significant ($\rho \leq 0.05$) clustering of lower snowfall producing clippers over western Montana and the south-central Northwest Territories (Figure 3). These lighter producing storms need further investigation but are potentially linked to a lack of moisture in the air, as clippers are often fast-moving systems that fill as they move across the country (Thomas and Martin, 2007).

More frequent storms did not always equate to greater snowfall totals, as Nor'easters produced the second most snowfall while being the fourth most frequent storm type. Contributions from Nor'easters (12.7%) were comparable, but less than those found by Suriano *et al.* (2019). This is likely because Central New York is northwest of the Catskill/Delaware Watershed, further from the moisture source of the storms. In addition, elevations in the Catskill Mountains are relatively higher than those throughout Central New York, further enhancing orographic precipitation. Although Nor'easters contribute considerably to seasonal snowfall totals in the area, Karmosky (2007) suggests they are not the leading contributor anywhere throughout the Northeast United States. Nor'easters average some of the greatest snowfall totals per storm (24.2 ± 1.5 cm), with generally more snow produced by northern east coast storms than southern east coast storms and Gulf lows. Suriano *et al.* (2019) found similar results, suggesting that coastal mid-latitude cyclones produce the highest snowfall per event in the Catskill/Delaware Watershed.

Although northern east coast storms are often less intense (e.g. higher pressure, slower winds, less precipitation) than southern east coast storms and Gulf lows (Kocin and Uccellini, 1990; Davis *et al.*, 1993;

Zielinski, 2002), their proximity to Central New York likely accounts for the greater snowfall totals. Forming near the mid-Atlantic, as these storms move north-northeast, their center of low pressure is often closer to Central New York than that of other Nor'easters (Kocin and Uccellini, 2004). This likely leads to greater snowfall totals even though the storm is often weaker. There is a significant ($\rho \leq 0.05$) clustering of heavier snowfall producing northern east coast storms over the Delmarva Peninsula, northern Virginia, and southern New Jersey (Figure 3). Cyclogenesis in this region is likely to produce heavier snowfall in Central New York compared to storms forming off the coast of southern New England or the Outer Banks of North Carolina because the storm's center is closer to the region. In addition, when the storm center passes over southeastern New York State, northwest winds over Lake Ontario often increase the likelihood of lake-effect and lake-enhanced snow (Niziol, 1987). Results suggest that the further west a southern east coast storm forms, the more snow it produces in Central New York (Figure 3). Storms forming further inland are more likely to directly affect Central New York; however, these storms also tend to have a lower moisture content (Jorgensen, 1963; Businger *et al.*, 1990). This suggests that storm track has a greater influence on snowfall totals from southern east coast storms than the moisture content of the storm. Gulf lows average the least amount of snowfall in Central New York of the Nor'easters; however, there is a significant ($\rho \leq 0.01$) clustering of higher snowfall producing storms that form near coastal Texas (Figure 3). The reasons for these storms producing more snowfall in Central New York needs further investigation. Nor'easters likely have a greater influence on seasonal snowfall totals in Central New York compared to other areas within the Great Lakes region because of its proximity to the Atlantic Ocean. Since the greatest snowfall totals following Nor'easters are often concentrated in southeastern Central New York, seasonal snowfall contributions in other parts of the Great Lakes region would likely be lesser, and similar to those found in northern Central New York.

The majority (53.5%) of snowfall in Central New York occurs from storms with at least 25.4 cm of snow. Of the eleven different snowstorm types, heavy-snowfall storms accounted for the majority of the seasonal snowfall for seven storms. In contrast, moderate or light-snowfall storms are the most frequent storm size for all eleven storm types. This suggests that even though lower magnitude storms occur more often, they contribute less to seasonal snowfall totals in Central New York compared to high magnitude storms. As anthropogenic warming continues throughout the 21st century, it is expected that there will be an increase in the frequency of extreme weather events, including snowstorms (Lai and Dzombak, 2019). Nearly 45% of the snow from heavy-snowfall producing storms in Central New York occurs from lake-effect storms. Therefore, future changes to lake-effect storms may have a disproportionate effect on seasonal snowfall totals in Central New York. The general consensus is that snowfall in the Great Lakes region will increase throughout the mid-21st century and then decrease through the late-21st century (Notaro *et al.*, 2015; Suriano and Leathers, 2016). Changes in snowfall may impact winter recreation, agriculture, state revenue, water resources, and the ecology of the region. This study provides a methodology to help understand how snowfall may respond to future changes.

4.0 Conclusions

To determine the different types of snowstorms that affect Central New York, every snowstorm to influence the study area from 1985/86 – 2014/15 was examined. Combining the criteria established from previous studies (Whittaker and Horn, 1981; Jones and Davis, 1995; Niziol *et al.*, 1995; Sobash *et al.*, 2000; Changnon *et al.*, 2008; Laird *et al.*, 2009b, 2010; Kelly *et al.*, 2012; Suriano and Leathers, 2017b, 2017a), a newly developed classification scheme is proposed for storms in the Great Lakes region (Table 2). This if the first comprehensive classification scheme developed for the Great Lakes region and is applicable to other snow basins across the world with modification.

Storms were classified as either direct cyclonic snowstorm or non-direct cyclonic snowstorms using NCEP/NCAR reanalyses. NDCSs occur more frequently, accounting for the majority of the region's snowfall. These storms were further categorized as lake-effect storms, upper atmospheric disturbances, or frontal storms using upper atmospheric charts, NEXRAD data, and infrared satellite images. DCSs were categorized based on their area of cyclogenesis and included clippers, Great Lakes lows, Hudson lows, Nor'easters, Colorado lows, Oklahoma hooks, Texas hooks, and tropical cyclones. Variations within these storms were examined depending on their specific area of formation (Figure 4). Categorizing the different snowstorms to affect an area allows for a determination of their frequency and their seasonal snowfall contributions. Ascertaining the average seasonal snowfall contributions of storms will aid seasonal snowfall predictions because different modes of atmospheric circulation favor certain snowstorm types over others (Grover and Sousounis, 2002). In addition, snow water equivalencies vary considerably between snowstorm types (Baxter *et al.*, 2005); thus, a better understanding of snowfall contributions will benefit water resource managers in snow-influenced areas.

Lake-effect snowstorms are the most frequent snowstorm in Central New York and account for nearly 40% of the seasonal snowfall. Clippers and upper atmospheric disturbances were the second most frequent storms to affect the region; however, Nor'easters contributed a higher percentage of the seasonal snowfall than both of these storms. Nor'easters and lake-effect snowstorms averaged the most snowfall per storm. Generally, Nor'easters that formed further to the north averaged more snowfall in Central New York than those forming further south. Heavy snowfall producing Nor'easters tend to form in one of three hotspots including the Delmarva Peninsula, northern Alabama and Mississippi, and coastal Texas. Heavy-snowfall storms have a disproportionate effect on Central New York snowfall. Even though these storms are the least frequent, they account for over 53% of the seasonal snowfall. Lake-effect snowstorms and Nor'easters are the most frequent heavy snowfall producing storms, accounting for nearly 33% of the seasonal snowfall in Central New York. Previous findings suggest that snowfall from lake-effect and non-lake-effect storms can trend in opposite directions (Norton and Bolsenga, 1993; Leathers and Ellis, 1996; Berger *et al.*, 2002; Burnett *et al.*, 2003; Kunkel *et al.*, 2009b, 2009a; Hartnett *et al.*, 2014; Lawrimore *et al.*, 2014). Since snowstorms are highly vulnerable to climate change, some more than others, the categorization of different snowstorm types and the determination of their seasonal snowfall contributions will aid in the prediction of how snowfall may respond to future climatic changes.

Although this study focuses on a subsection of the Great Lakes region, the general procedures can be applied to other snow basins across the world. Understanding the different types of snowstorms that affect an area, their frequency, and the amount of snowfall they produce will elucidate how snowfall may change in the future. Numerous studies have attempted to quantify how seasonal snowfall totals may change in an area; however, there is often a focus on an individual snowstorm type or the collective snowfall totals. This study improves such projections by providing a detailed analysis of the different snowstorm types that contribute to seasonal snowfall totals. The classification scheme will also help clarify our understanding of the spatial variability of snowfall, as snowfall contributions from different storms can be examined at the local level.

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