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Synoptically classified lake-effect snowfall trends to the lee of Lakes Erie and Ontario

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ABSTRACT: Recent research has indicated that snowfall in portions of the North American Great Lakes region subject to lake-effect snow has undergone a trend reversal, with snowfall declining in recent decades. This study examines the seasonal variability and trends specifically in synoptically classified lake-effect snow across the eastern Great Lakes region, and investigates the mechanisms responsible for observed changes. Using a synoptic climatological approach, days are identified where the synoptic-scale conditions are conducive to lake-effect snowfall and the associated snowfall is analyzed. Seven synoptic types over the November to March snowfall season are identified with characteristics of lake-effect conditions. Snowfall from these 7 lake-effect synoptic types represents between 45 and 53 % of the seasonal snowfall total along the eastern shores of Lakes Erie and Ontario, with snowfall totals being highest during January. Lake-effect snowfall exhibits a 60 yr increasing trend downwind of Lakes Erie and Ontario; however, through examination over shorter 30 yr periods, a change in the trend of snowfall is observed around 1980. While a true trend reversal is not detected, lake-effect snowfall significantly increases from 1950–1979 before exhibiting no significant trend from 1980–2009. The inter-annual variability of seasonal lake-effect snowfall is highly related to the frequency of lake-effect synoptic types where an increase (decrease) in synoptic type occurrence leads to enhanced (diminished) lake-effect snowfall totals. Depending on the period examined, long-term changes in the frequency of lake-effect synoptic types and snowfall rates represent between 89 and 95 % of the observed changes in lake-effect snow.

KEY WORDS: Great Lakes · Synoptic classification · Snowfall variability · Climate change · Lake effect

1. INTRODUCTION

Lake-effect snow (LES) is the enhancement of snowfall downwind of lakes occurring during the late fall and winter months. This is the result of increased convection due, in part, to a heightened temperature gradient between the relatively warm lake surface and overlying cold air masses (Eichenlaub 1970, Niziol et al. 1995, Kristovich et al. 2003). Lake-effect processes can produce twice as much snow in locations downwind of the lakes relative to locations further inland (Norton & Bolsenga 1993); this excessive snow can have substantial negative impacts on the surrounding region, including on transportation, agriculture, economics, and natural habitats (Norton & Bolsenga 1993, Schmidlin 1993, Kunkel et al. 2002, Changnon et al. 2006). Conversely, the additional snowfall can benefit some sectors of the economy, such as recreation and winter-product sales (Schmidlin 1993, Kunkel et al. 2002).

Numerous studies have examined trends in snowfall within the North American Great Lakes region (Leathers et al. 1993, Norton & Bolsenga 1993, Leathers & Ellis 1996, Grover & Sousounis 2002, Burnett et al. 2003, Ellis & Johnson 2004, Kunkel et al. 2009, Bard & Kristovich 2012, Hartnett et al. 2014, Loveless et al. 2014), with some directly investigating LES. While a majority of these studies found increas-

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ing snowfall trends with time, Bard & Kristovich (2012) and Hartnett et al. (2014) respectively found a trend reversal with decreasing trends after the 1970s–1980s downwind of Lake Michigan and in central New York (NY) State. Both studies noted increased air temperature as a possible forcing of declining snowfall.

Typically, LES is defined as snowfall within an 80–100 km lake belt (Eichenlaub 1970, Dewey 1979, Norton & Bolsenga 1993, Scott & Huff 1996). Instead, here LES is defined based on snow falling during lake-effect synoptic patterns (Ellis & Leathers 1996, Leathers & Ellis 1996, Ellis & Johnson 2004, Suriano & Leathers 2017). This allows for the isolation of synoptic-driven LES amounts, not just snowfall that occurs within the lake belts, which could be derived from different systems. Loveless et al. (2014) did in part examine trends in snowfall accumulation from different storm types for Oneonta, NY, utilizing low-pressure storm tracks for differentiation of storms, but only examined 1 observation station.

Synoptic classifications allow for daily weather events to be distinctly categorized, facilitating the evaluation of the atmosphere's influence on the underlying land surface. Techniques include regionalization, circulation pattern classifications, and weather typing (Yarnal 1993, Sheridan & Lee 2014). Synoptic weather typing creates individual synoptic types that represent multiple days with similar atmospheric conditions, permitting researchers to relate synoptic-scale weather patterns to smaller-scale processes and to track the frequency of their occurrence. This synoptic weather typing technique has proven effective in separating snowfall into lake-effect and non-lake-effect types in previous research (Leathers & Ellis 1996, Ellis & Leathers 1996, Karmosky 2007, Suriano & Leathers 2017).

This study utilizes an eigenvector-based synoptic weather typing classification technique (Kalkstein & Corrigan 1986) to generate a daily synoptic calendar for the eastern Great Lakes region. Snowfall events during the November through March snow season are isolated and analyzed based on the synoptic conditions that produced them (Suriano & Leathers 2017). A robust investigation of snowfall forced by lake-effect synoptic conditions, over the entire eastern Great Lakes region will help explain the changing snowfall trends unique to LES. Specifically, this study addresses the role of changing frequency of synoptic types and changing snowfall rates on varying snowfall trends during the 1949/50–2008/09 snowfall seasons. Additionally, while 21st century model projections suggest initial increases in lake-induced snowfall in the region followed by rapid decreases (Suriano & Leathers 2016), exploring the current trends in LES will increase the understanding of potential factors that could drive changes in LES in the future. This information supplements and expands upon the existing literature on LES, details mechanisms responsible for its change, and adds creditability to relationships between the synoptic type and snowfall.

2. METHODS

2.1. Datasets

Snow data come from a dataset (interpolated onto a 1° grid for the period 1950–2009) of daily North American snowfall, snow depth, temperature, and liquid precipitation (Dyer & Mote 2006, Kluver et al. 2016). The dataset for this study has been updated from Dyer & Mote (2006); in the current version, grid cell values are interpolated directly to a 1° lattice, whereas Dyer & Mote (2006) generated one-quarter degree grids before interpolating to a 1° grid. Data originate as cooperative station observations in the US from the TD3200 data from the National Centers for Environmental Information (NCEI, formerly NCDC, US Department of Commerce 2003), and from observations archived in the Meteorological Service of Canada. A quality control method outlined by Robinson (1988) was applied to the station data, which omits unreasonable values and tests the internal consistency of the data. Data that pass the quality control are interpolated onto a 1° × 1° latitude–longitude grid using the Spheremap spatial interpolation procedure from the University of Delaware (Willmott et al. 1984, 1985). Spheremap uses a modified version of Shepard's inverse-distance algorithm of interpolation onto a 2-dimensional Cartesian plane, before projecting onto a spherical lattice. As station density varies with space and time, a variable search radius is used for each grid box (Kluver et al. 2016). Data are presently stored at Rutgers University (http://climate.rutgers.edu/snowcover/noaamelt/). For this study, snowfall observations are clipped to the eastern Great Lakes region, bounded approximately by 40–46° N and 73–85° W, and to 1950–2009.

Kluver et al. (2016) validated the interpolated snowfall dataset to station point observations by comparing it to the Community Collaborative Rain, Hail & Snow Network (CoCoRaHS; Cifelli et al. 2005) stations. Across North America, the interpolated daily snowfall dataset is approximately 2.0 cm lower than the CoCoRaHS observations per event. In some regions within the Great Lakes basin, the interpolated dataset has slightly more negative biases approaching −5.0 cm. The underestimation found by Kluver et al. (2016) is partially attributed to the interpolation method, which smooths higher-frequency signals through averaging of multiple station observations. The study also highlights that differences are additionally due to the inconsistent station locations of the cooperative and CoCoRaHS data.

For the lake-effect criteria (see Section 2.3), 850 hPa temperature and wind data are from the NCEP/NCAR Reanalysis Project, and are acquired from NOAA-ERSL Physical Sciences Division (www.esrl.noaa.gov/psd/; Kalnay et al. 1996). Lake temperature data are obtained from NOAA's Great Lakes Environmental Research Laboratory (GLERL; www.glerl.noaa.gov/) instead of from reanalysis, due its to spatial resolution. The reanalysis surface temperature would include land surface and lake-water temperature into the final product, likely artificially limiting the water–air temperature difference. Lake surface temperatures are modeled from GLERL's Large Lake Thermodynamics model, and are available as monthly averages on a per year basis by lake. GLERL lake surface temperatures agree well with monitored water surface temperatures (Croley & Hunter 1994).

2.2. Synoptic classification

Daily synoptic weather types are developed for Buffalo, NY (Weather Bureau Army Navy station WBAN 14733, 42.941° N, 78.732° W) from 1950–2009 using an eigenvector-based approach similar to that of Kalkstein & Corrigan's (1986) Temporal Synoptic Index (TSI). The TSI procedure has been employed in multiple studies, successfully classifying synoptic-scale weather types for a variety of applications (e.g. Kalkstein et al. 1990, Davis 1991, Ellis & Leathers 1996, Leathers & Ellis 1996, Siegert et al. 2017). Four times daily observations (09:00, 15:00, 21:00, 03:00 h UTC) of meteorological variables are obtained from Kent State University (http://sheridan.geog.kent.edu/ssc.html), with data originating from the National Centers for Environmental Information (NCEI, Surface Data Hourly Global [DS3505]; www.ncdc.noaa.gov). Variables include temperature, dew point, atmospheric pressure, meridional and zonal wind components, and cloud cover.

An unrotated principal components analysis (PCA) is conducted on the meteorological observations to reduce the original 24 variables (6 variables, 4 times daily) into a set of components that are linearly independent and ordered by explained variance (Kalkstein & Corrigan 1986). The PCA is conducted at the seasonal level for winter (DJF), spring (MAM), and autumn (SON). These seasonal classifications are chosen to limit the influence of the annual cycle on the synoptic patterns present within the generally temperate climatic region of the Great Lakes basin. Without the seasonal level analysis, much of the explained variance from the PCA would represent the annual cycle, limiting the effectiveness of the procedure.

Seasonal PCA loadings of all components with eigenvalues >1.0 are retained for further analysis. Five PCs were retained during each of the seasons. Multiplying the eigenvector of each component by the original data generates component scores for each day, indicating the relative importance of each component for a given day. These daily component scores are clustered with an initial 20-cluster solution using within group-average linkage clustering to group days with similar component scores into individual clusters, or synoptic types. Within group-average linkage clustering is generally considered the most appropriate for synoptic weather typing due to its differentiation of extreme and more normal weather days into appropriate clusters (Kalkstein et al. 1987). This clustering method is typically found to minimize within-cluster variance while maximizing between-cluster variance. The entire procedure results in the development of a calendar where each day is categorized as a particular synoptic type.

All days with the same synoptic classifications are composited to produce maps depicting sea level pressure, surface air temperature, and 500 hPa geopotential height for that given synoptic type (NOAA-ESRL PSD, www.esrl.noaa.gov/psd/, Kalnay et al. 1996). If the characteristics of the synoptic types are similar, they are qualitatively combined using knowledge of local weather patterns to fine-tune the clustering's autonomous nature (Siegert et al. 2017). It should be noted that snowfall or other forms of precipitation are not used to define the synoptic type. Furthermore, while synoptic types are generated for 3 meteorological seasons to reduce the impact of the annual cycle, analysis will be further constrained to the November–March snowfall season. Thus synoptic types from the winter (DJF) months are combined with autumn types occurring only in November, and spring types occurring only in March to produce the November–March season. The final result of the TSI is a 60 yr, daily synoptic calendar for the November–March season. Daily snowfall from the 1° × 1° interpolated dataset is combined with the daily synoptic calendar allowing for snowfall to be matched with the synoptic type occurring on the same calendar day. This permits analysis of the spatial relationships between snowfall and each synoptic type.

It should be noted that the TSI is intended to produce classifications that have similar synoptic-scale features such that snowfall at the seasonal level and over larger spatial scales can be analyzed. The procedure is not designed to define micro-scale phenomena such as frictional convergence along the lakeshore or vorticities within the cloud bands associated with LES. These smaller-scale features can influence snowfall at a localized level; however, this study is not focused on these nuances. Due to the focus on the synoptic scale, conditions at Buffalo are sufficient to determine the synoptic-scale situation for the lake-effect regions of the eastern Great Lakes, despite being located within Lake Erie's basin, as opposed to Lake Ontario's.

2.3. Lake-effect classification

Specific emphasis is placed on the snowfall associated with lake-effect synoptic types. A synoptic type is considered lake-effect based on criteria developed by Suriano & Leathers (2017). Lake-effect synoptic conditions are considered as:

(1) wind flow at 850 hPa provides favorable fetch over the lakes (ranging from NNW–SSW flow),

(2) 850 hPa winds surpass 5 m s^{-1} but do not exceed 20 m s^{-1},

(3) directional wind shear between the surface (2 m) and 850 hPa is <30°, and

(4) the temperature difference, or lapse rate, between the lake water and 850 hPa is ≥13°C.

Average conditions for the lakes and synoptic types are used to calculate the lake water to 850 hPa temperature difference. The 850 hPa temperatures within the grid cells directly above the lakes are the reanalysis composite of all snowfall-producing occurrences of each synoptic type. As lake water temperature data are only available monthly, the lake water temperatures are the average conditions for the months and years corresponding to when each individual synoptic type actually occurred. The calculation was initially conducted individually for both Lakes Erie and Ontario; however, in all cases where 1 lake had sufficient instability (≥13°C), the other one did also.

Lake ice has been shown to influence the formation of LES (Burnett et al. 2003, Gerbush et al. 2008, Wang et al. 2012, Vavrus et al. 2013). In this study, the impact of lake ice is indirectly accounted for. Days with substantial lake ice coverage are included in the analysis of snowfall associated with individual synoptic types, as are days without lake ice. Thus total seasonal snowfall and seasonal snowfall rates include days where no, or reduced, LES was observed due to the presence of lake ice.

3. RESULTS AND DISCUSSION

3.1. Seasonal snowfall distribution

The TSI procedure for Buffalo, NY, results in the identification of 43 synoptic types during the 3 seasons (autumn, winter, spring) spanning the November–March snowfall season over 1950–2009. Of these types, 7 met the criteria for LES development, and their sea-level pressure fields are depicted in Fig. 1. Further information on the meteorological characteristics of the 7 synoptic weather types, including temperature, dewpoint temperature, winds, and cloud cover, can be viewed in Table 1. The frequencies of the 7 lake-effect synoptic types are combined into a single grouping that contains all days during November–March when any of the 7 individual synoptic types occurred, corresponding to 2374 total days. On average, lake-effect synoptic types occur on approximately 40 d each season. Of the 2374 lake-effect synoptic type days, 2307 (97%) produced snowfall. For the purposes of this study, the snow produced by these lake-effect synoptic types is considered to be LES, although the limitations discussed in Section 3.4 should be noted.

The average seasonal LES distribution is shown in Fig. 2a. Higher 1950–2009 seasonally averaged LES totals in excess of 185 and 120 cm yr^{-1} exist downwind of Lake Ontario and Lake Erie, respectively (σ = 73.2 and 45.6). The spatial distribution of snowfall per event is similar, with peak snowfall rates downwind of the lakes (not shown). Comparing snowfall totals of the lake-effect types to snowfall from all types, LES comprises 45–53% of the seasonal snowfall total in the grid boxes immediately downwind of the lakes (Fig. 2b). This is similar to Norton & Bolsenga (1993), who found that LES can double the amount of snow received downwind of the lakes over a typical season.

Intra-seasonal LES is additionally inspected. For all 5 months, average LES is greater downwind of Lake Ontario than downwind of Lake Erie, likely due to the orientation of the lakes and to other physical differences highlighted below. By examining the ratio

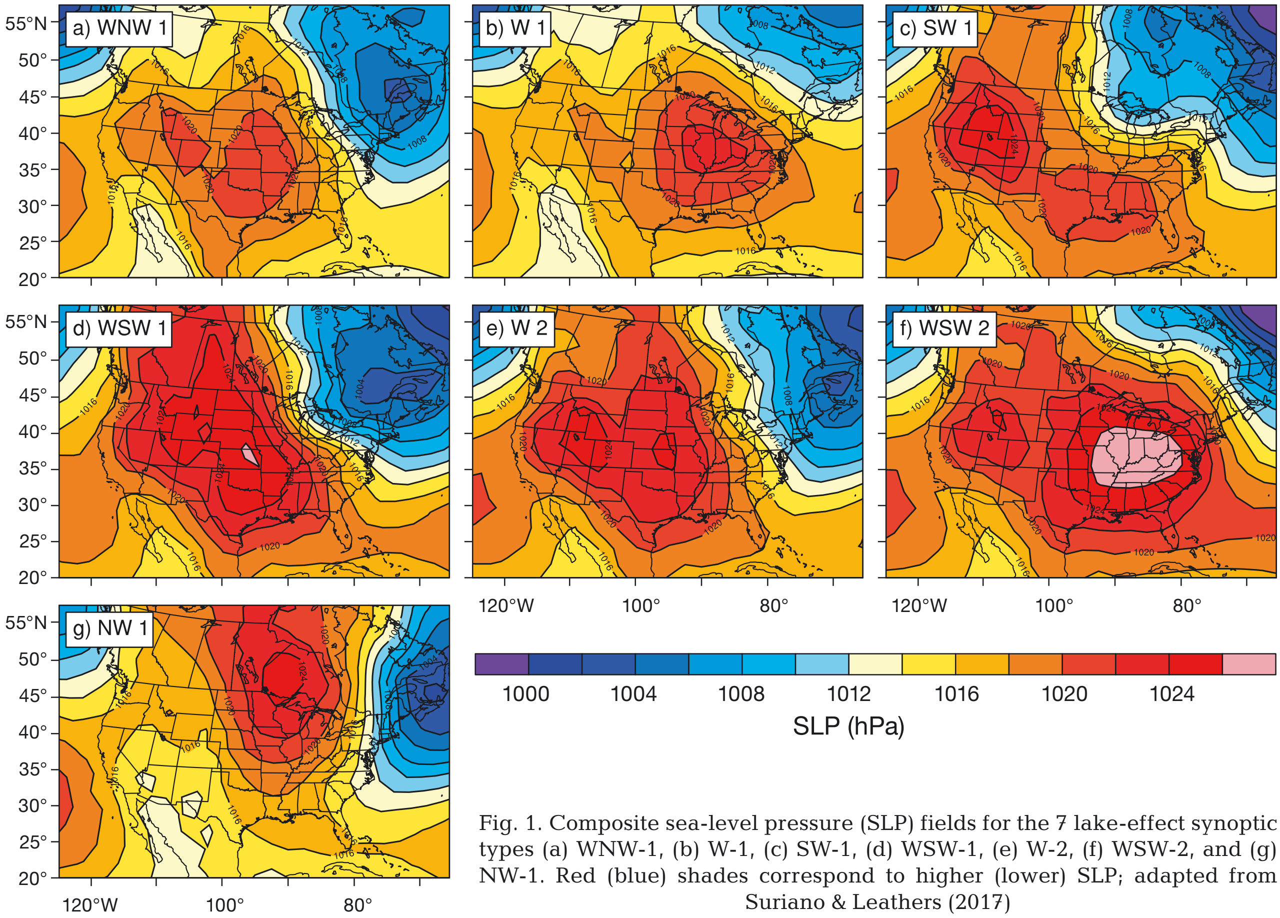

Fig. 1. Composite sea-level pressure (SLP) fields for the 7 lake-effect synoptic types (a) WNW-1, (b) W-1, (c) SW-1, (d) WSW-1, (e) W-2, (f) WSW-2, and (g) NW-1. Red (blue) shades correspond to higher (lower) SLP; adapted from Suriano & Leathers (2017)

of monthly LES to total seasonal LES (Table 2), more information can be gained. For both Lakes Ontario and Erie, a majority of LES downwind of the lakes occurs during the month of January, respectively contributing 36 and 33% of the seasonal LES. Also for both lakes, January is followed by December, February, November, and March in decreasing order of respective amounts of LES produced. During November and December, LES downwind of Lake Erie makes up a higher percentage of the seasonal LES total than for LES associated with Lake Ontario. During January and February, the opposite occurs, such that LES downwind of Lake Erie makes up a smaller percentage of the seasonal LES total than the monthly percentages associated with Lake Ontario. This switch over is likely, in part, due to the temperature of the lakes and the likelihood of lake ice development. During November, Lake Erie is substantially warmer than Lake Ontario due to its shallower depth and lower latitude. This can result in a larger lake-water to 850 hPa temperature difference, and is indicative of stronger convective instability and relatively increased LES. By January and February, Lake Erie is commonly colder than Lake Ontario due to its shallower depth, and typically has a much higher percentage of ice cover (Assel et al. 2003). This increased ice coverage on Lake Erie relative to Lake Ontario lessens the convective instability and can greatly reduce LES (Cordeira & Laird 2008, Gerbush et al. 2008).

3.2. Temporal snowfall trends

To assess 1950–2009 trends in LES associated with Lake Ontario and Lake Erie collectively, LES within the grid cells that most closely align with the lake belts defined in the literature are isolated (Eichenlaub 1970, Dewey 1979, Norton & Bolsenga 1993, Scott & Huff 1996). Grid cells used for this analysis are: 41.5° N, 80.5° W; 42.5° N, 79.5° W; 42.5° N, 78.5° W; 43.5° N, 76.5° W; and 43.5° N, 75.5° W (Fig. 3). The collective LES from both lakes exhibits a long-term increasing trend of 0.81 cm yr^{-1} ($p < 0.05$; Fig. 4a). Leathers & Ellis (1996) found seasonal snowfall increases from November–March of approximately

Table 1. Average surface meteorological characteristics for the 7 lake-effect synoptic weather types at 09:00, 15:00, 21:00, and 03:00 h UTC. Cloud cover is expressed as the fraction of the sky covered by clouds (in tenths)

Synoptic type	Temperature (°C)	Dewpoint (°C)	Sea-level pressure (hPa)	Wind speed (m s^{-1})	Wind direction (°)	Cloud cover (1/10)
09:00 h						
WNW-1	1.4	−1.8	1010	4.6	284	8.7
W-1	2.3	−1.2	1020.3	3.1	266	8.4
SW-1	−9.8	−13.4	1013.8	3.9	220	7.6
WSW-1	−5.9	−8.9	1007.9	8.7	246	9.2
W-2	−6.7	−9.8	1011.4	4.4	271	8.6
WSW-2	−9.1	−12.7	1025.1	4	254	6.8
NW-1	−7	−10.7	1015.9	3.1	329	6.5
15:00 h						
WNW-1	1.4	−2.7	1012.7	5.6	293	8.6
W-1	2.8	−1.7	1023.6	3.9	285	8.2
SW-1	−7.6	−11.6	1012.2	5.9	213	9.1
WSW-1	−6.8	−10	1010.7	9.2	253	9.2
W-2	−7.1	−10.8	1014	5.2	278	8.2
WSW-2	−7.6	−11.9	1027.3	4.3	247	6.7
NW-1	−5.7	−11.5	1018.9	4.2	333	6.3
21:00 h						
WNW-1	1.8	−3.5	1013.6	5.6	292	8.7
W-1	3.6	−2.1	1023.8	4.1	280	7.8
SW-1	−4.8	−8.8	1008.7	7.1	224	9.7
WSW-1	−6.6	−10.6	1012.6	9.8	258	9.1
W-2	−6.6	−11.5	1014.9	5.9	276	7.7
WSW-2	−5	−10.6	1025.9	5	242	7.2
NW-1	−3.5	−11.4	1018.8	4.9	308	5.7
03:00 h						
WNW-1	0	−4.2	1016.2	3.8	290	7.5
W-1	1.2	−2.6	1025.1	1.2	279	6.8
SW-1	−5.2	−8.4	1008.5	6.6	232	9.6
WSW-1	−8.3	−12.1	1016.1	7.7	263	8.8
W-2	−8.5	−12.6	1017.5	4.6	276	7
WSW-2	−6.6	−10.8	1025.6	3.3	226	6.9
NW-1	−6.5	−11.5	1020.5	2.8	296	3.5

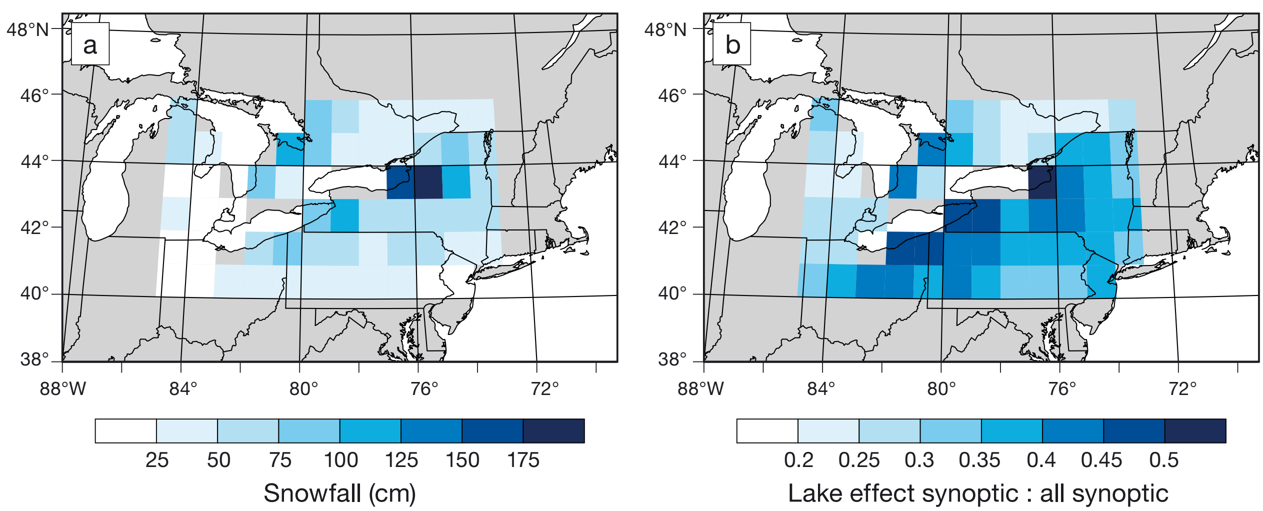

Fig. 2. (a) Average seasonal snowfall (cm) associated with lake-effect synoptic types, and (b) ratio of snowfall associated with lake-effect synoptic types to snowfall from all synoptic types in the eastern Great Lakes region for 1950–2009 winter seasons. Darker (lighter) blues represent higher (lower) values

Table 2. Average monthly lake-effect snow (cm), and ratio of monthly to seasonal lake-effect snowfall total (%) for Lake Erie and Lake Ontario from 1950–2009. These defined regions are shown in Fig. 3

	Lake Erie Snowfall (cm)	Lake Erie % of total	Lake Ontario Snowfall (cm)	Lake Ontario % of total
November	13.1	12.9	16.5	9.4
December	28.0	27.5	43.5	24.8
January	34.2	33.6	64.3	36.7
February	21.9	21.5	44.9	25.6
March	4.5	4.4	6.0	3.4
Season	101.7		175.2	

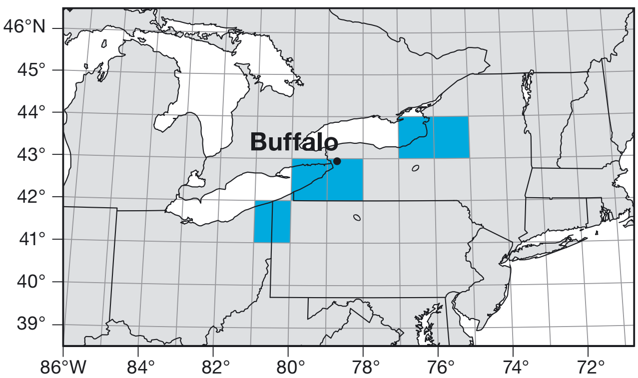

Fig. 3. Study region. The grid cells used for defining Lake Ontario and Lake Erie lake-effect snowfall are shown in blue. Buffalo, NY, is labeled

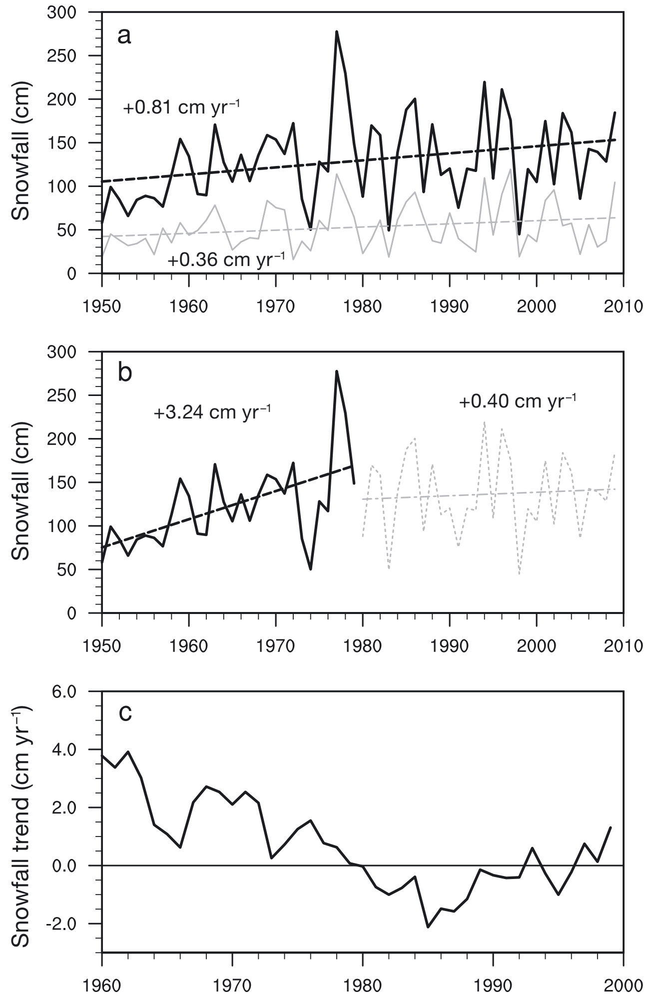

Fig. 4. Lake-effect snowfall and snowfall trends associated with Lakes Ontario and Erie for (a) 1950–2009 using the initial snowfall amounts (black) and snowfall only from stations identified by Kunkel et al. (2009) (grey). (b) Initial snowfall amounts during two 30 yr periods corresponding to 1950–1979 (black) and 1980–2009 (grey dashed). (c) A 21 yr moving trend in initial lake-effect snowfall from 1960–1999 at an interval of 1 yr

0.8–2.0 cm yr^{-1} downwind of Lakes Erie and Ontario from 1931–1990 using individual station data. Burnett et al. (2003) noted a 1.5 cm increase in LES stations across the Great Lakes region compared to non-lake-effect stations from 1931–2001, although this did include lake-effect sites associated with Lakes Michigan and Superior. Kunkel et al. (2009) analyzed snowfall associated with stations deemed homogeneous in the Great Lakes region, finding an increase of 0.6 cm yr^{-1}, but similar to Burnett et al. (2003), trends were examined across all of the lakes. Hartnett et al. (2014) found a 1.16 ± 0.31 cm yr^{-1} increase in snowfall from 1931–2012 in central NY State; however, their study did not distinguish LES from non-lake-effect snow, utilizing stations outside those generally considered lake-effect impacted regions. While trends in our study are broadly similar to those in the literature, it should be noted that the other studies utilized different periods of record and different spatial scales than we did. Using only the stations identified by Kunkel et al. (2009) within the interpolated dataset, the 0.81 cm yr^{-1} increase in LES is reduced to 0.36 cm yr^{-1} ($p = 0.06$). Only 3 stations identified by Kunkel et al. (2009) fall within the grid cells analyzed in our research, and the smaller trend could be a result of the station locations.

Recent research has indicated that snowfall in portions of the Great Lakes region has undergone a trend reversal whereby snowfall steadily increased until the 1970s–1980s before declining thereafter (Bard & Kristovich 2012, Hartnett et al. 2014). In response to these conclusions, trends in LES are additionally examined over 2 equal 30 yr periods (1950–1979, 1980–2009), and by computing a 21 yr moving average of the trend with a 1 yr window. Examining the trend in Lake Ontario and Lake Erie collective LES as 2 distinct periods (grid cells discussed previously, Fig. 3), significant trends cease around 1980 (Fig. 4b). From 1950–1979, LES increases by 3.24 cm yr^{-1} ($p < 0.01$). However, from 1980–2009, LES does not exhibit a significant trend. This is further supported by the 21 yr moving average LES trends calculated for the 1960–1999 seasons (Fig. 4c). Increasing trends are seen during the first 20 seasons through 1979 (1.83 ± 1.17, mean ± SD). In 1980, the 21 yr moving average LES trend becomes negative and stays negative until 1993 (0.81 ± 0.63). During the final 7 seasons (1993–1999), the LES trends hover around 0 but are variable (0.18 ± 0.77). While a true trend reversal is not detected in LES downwind of Lakes Ontario and Erie, LES does appear to be behaving non-linearly over the 60 yr period, with a halt to increasing snowfall trends around 1980.

3.3. Causes of snowfall variability and trends

Air temperatures are related to snowfall trends (e.g. Bard & Kristovich 2012, Hartnett et al. 2014). However, we hypothesize that the frequency of lake-effect synoptic types and the rate of snowfall per day (snowfall intensity) play dominant roles in explaining snowfall variability (Leathers & Ellis 1996, Ellis & Johnson 2004), particularly in explaining the apparent change in LES trend after 1980 (Fig. 3). Examining the time series of the seasonal frequency of lake-effect synoptic types, no long-term trend exists. However, similar to LES, a change in trend is apparent when the long-term trend is examined over 2 equal 30 yr periods (Fig. 5a). From 1950–1979, the frequency of lake-effect synoptic types increased by approximately 0.43 d yr^{-1} ($p < 0.05$). From 1980 onwards, no significant trend in lake-effect synoptic type frequency is detected.

To determine the effect of the frequency of lake-effect synoptic types on LES variability, simple linear regression analysis is conducted. The seasonal frequency of lake-effect synoptic types is significantly correlated to the average LES from Lakes Ontario and Erie ($r = 0.802$, $p < 0.01$; Fig. 5b). A similar relationship is noted when the same analysis is conducted on the 2 time series after they are de-trended ($r = 0.834$, $p < 0.01$). De-trending is conducted by calculating the differences in the original data from the linear regression line. This suggests that the number of lake-effect synoptic types occurring each season can explain a large percentage of the inter-annual

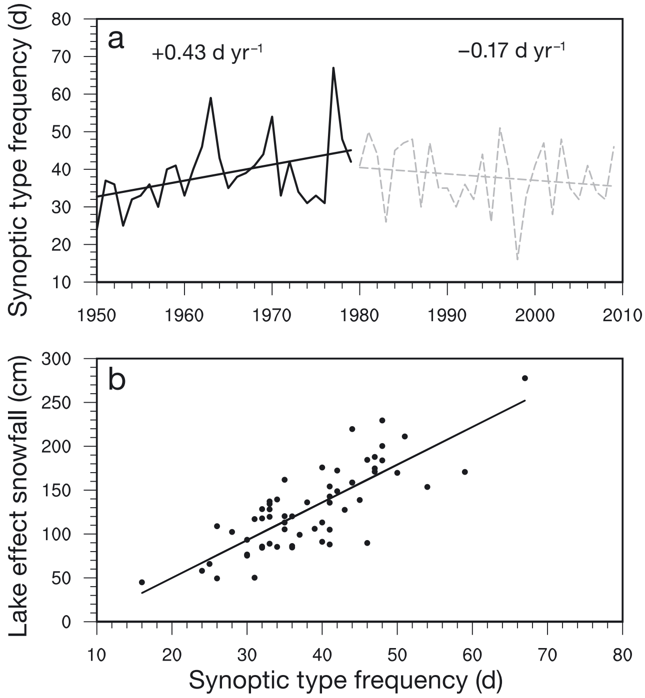

Fig. 5 (a) Lake-effect synoptic type frequency and trend (values at top of panels) during two 30 yr periods: 1950–1979 (black) and 1980–2009 (grey dashed). (b) Lake-effect synoptic type frequency and lake-effect snowfall associated with Lakes Ontario and Erie from 1950–2009

variability of LES associated with Lakes Ontario and Erie, independent of the long-term trend. Changes in the frequency of lake-effect synoptic types are likely the dominant force behind the apparent change in trend of LES.

To understand the magnitude of LES changes caused by lake-effect synoptic type frequency changes, a snowfall term is linearly extrapolated (Eq. 1):

$$SF\_Freq = freq\_trend \times SF \times years \quad (1)$$

where the freq_trend term is the trend in the frequency of lake-effect synoptic types in d yr^{-1}, SF is the average daily LES in cm d^{-1} by grid cell, and years are the number of years in the analyzed period. This calculation is conducted for each cell in the study region. If there is no trend in lake-effect synoptic type frequency, the resulting calculated snowfall value is 0. Fig. 6a shows the calculated snowfall changes due to lake-effect synoptic type frequency changes from 1950–1979. Across the entire region, these frequency changes result in an increase in LES.

The magnitude of LES changes due to the impact of a changing rate of snowfall (snowfall intensity) is also assessed through a similar linearly extrapolated calculated snowfall term (Eq. 2):

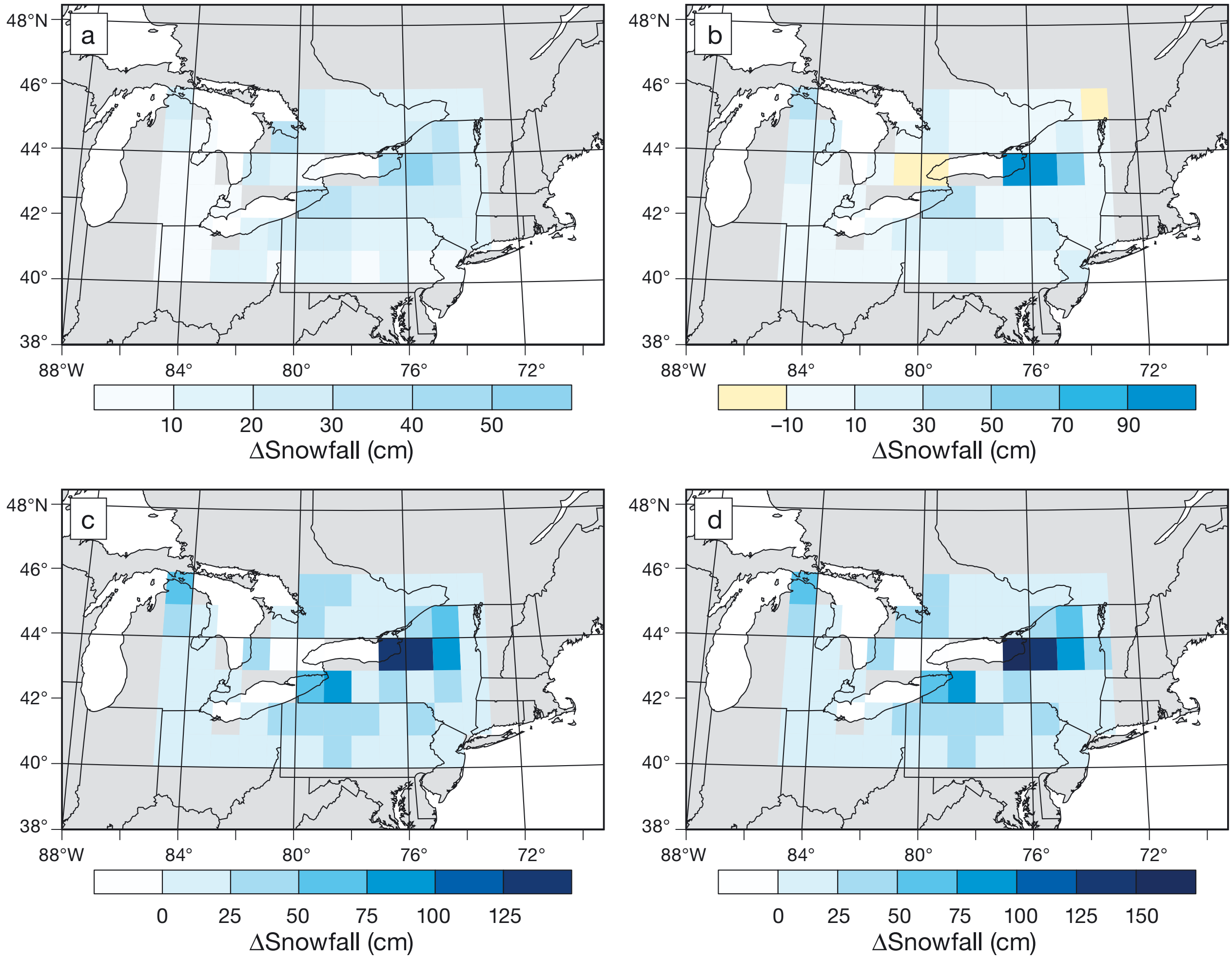

Fig. 6. Linearly extrapolated change in snowfall (cm) during 1950–1979 seasons based on (a) changes in the frequency of lake-effect synoptic types, (b) changes in snowfall rates (snowfall intensity), (c) total changes in snowfall due to frequency and intensity changes (panel a plus panel b), and (d) observed snowfall data. Colors are consistent across all 4 panels and with Fig. 7. Blues (yellows) represent increases (decreases) in snowfall. Darker (lighter) shades correspond to larger (smaller) changes

$$SF\_Int = int\_trend \times freq \times years \quad (2)$$

where the int_trend term is the trend in snowfall intensity in cm d^{-1} yr^{-1} for each grid cell, determined by regressing the average LES d^{-1} against time. Freq is the average number of days of a lake-effect synoptic type, and years are the number of years in the analyzed period. Similar to Eq. (1), if there is no trend in the snowfall intensity, the calculated snowfall value for that grid cell is 0. Fig. 6b depicts the predominately positive calculated snowfall changes due to changes in snowfall intensity during 1950–1979.

The addition of the snowfall changes due to lake-effect synoptic type frequency and snowfall intensity changes account for large snowfall increases of approximately 150 cm to the east of Lake Ontario over the 1950–1979 period (Fig. 6c). In addition, substantial snowfall increases of 60–75 cm are also found along the northeastern shores of Lake Erie over this period. Fig. 6d depicts the linearly extrapolated LES changes observed in the region. The combined changes in snowfall frequency and intensity account for 94.5% of the observed snowfall changes downwind of the lakes.

The same process is conducted for the second time period, 1980–2009. Fig. 7a–d is the same as Fig. 6a–d, but for this later 30 yr period. During this time period, lake-effect synoptic types exhibit a decreasing trend, thus the calculated snowfall changes due to frequency are negative (Fig. 7a). Calculated snowfall changes due to snowfall intensity changes vary by grid cell, with positive and negative changes dispersed across the region (Fig. 7b). Fig. 7c shows the combined calculated snowfall change from lake-effect synoptic

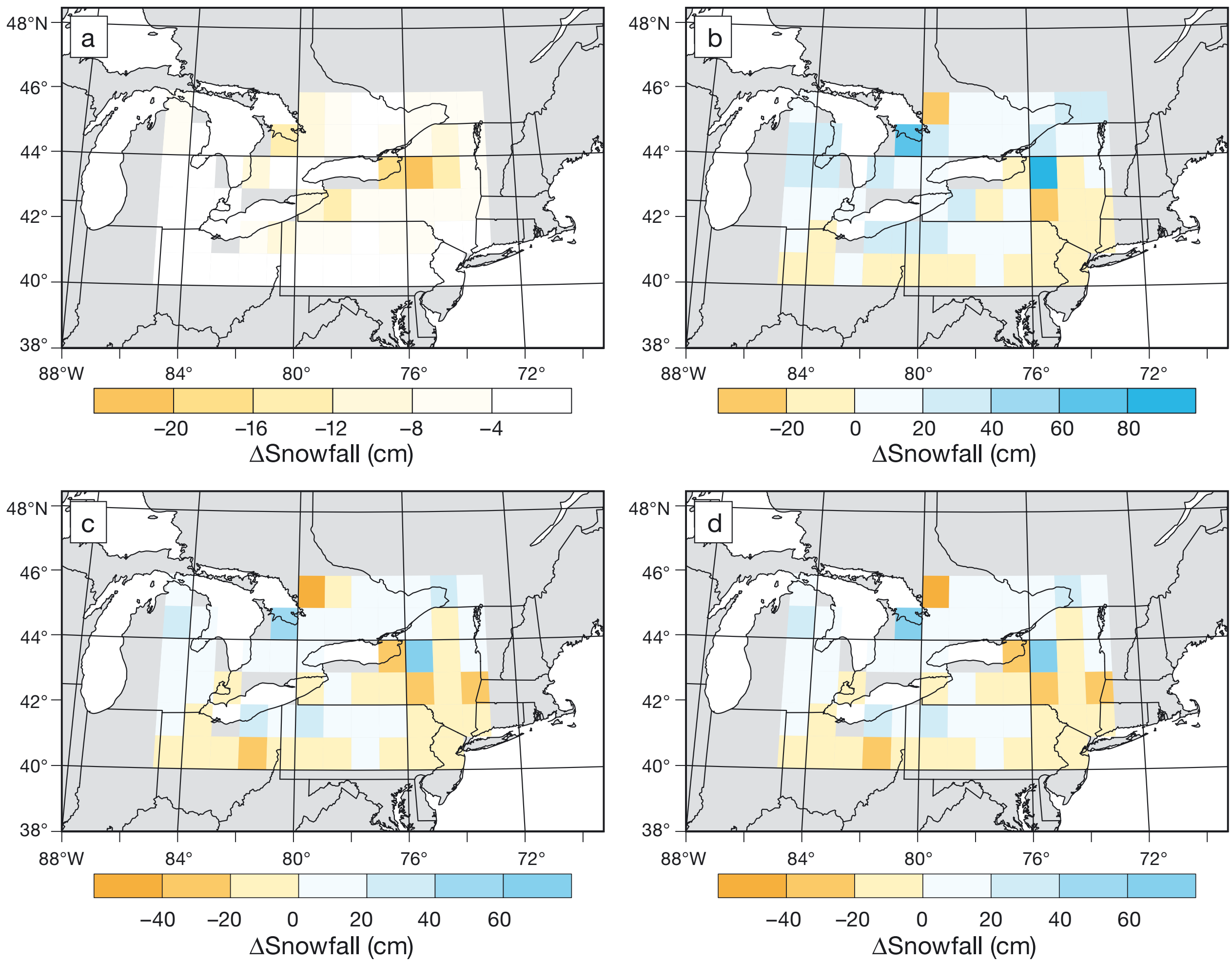

Fig. 7. As in Fig. 6, but for the period 1980–2009

type frequency and snowfall intensity changes. Compared to 1950–1979, these 2 factors collectively result in relatively small increases or decreases in snowfall in 1980–2009. Comparing these changes to the linearly extrapolated observed snowfall change in the region (Fig. 7d), the combined frequency- and intensity-driven snowfall changes account for 89.4 % of the observed snowfall change downwind of the lakes.

During both time periods, calculated snowfall changes are lower than what is observed. This suggests there could be other factors influencing LES trends in the region, with their influence being more apparent during 1980–2009. While synoptic type frequency and snowfall intensity influences appear dominant, other factors such as the effect of air temperature changes (Kunkel et al. 2009, Bard & Kristovich 2012, Hartnett et al. 2014), changes in ice cover (Assel et al. 2003), or intra-synoptic type changes may also be contributing to changes in LES totals.

3.4. Limitations

Beyond the negative bias found in the interpolated snowfall observations (Kluver et al. 2016), 2 other limitations exist that should be considered when examining the results and conclusions of this study. First, LES events are not necessarily confined to a standard 24 h day. It is possible for a single LES event to occur during parts of 2 consecutive days. Second, it is important to note that the interpolated data originate from Cooperative Observer Program (COOP) observations in the US. It is documented in the literature that time of observation by COOP observers has varied during the 20th century and can vary by location (Karl et al. 1986, Kunkel et al. 2007). Stations in close geographic proximity but with different time of observations may cause differences in recorded snowfall. This potential bias could result in a portion of the 'daily' snowfall for certain stations within a grid cell of the interpolated dataset to be assigned to the synoptic type occurring the following day.

Both limitations may cause a dampened LES signal directly downwind of the lakes, and an enhanced LES signal in regions that typically receive small amounts of LES such as those further away from the lakes. This should be considered when examining the spatial distribution of LES. However, despite these limitations, the snowfall from the identified lake-effect synoptic types represents between 45 and 53 % of the total seasonal snowfall directly downwind of the lakes, which is in line with the values seen in the literature (Braham & Dungey 1984, Kelly 1986, Norton & Bolsenga 1993).

4. SUMMARY AND CONCLUSIONS

This study examined the November–March seasonal snowfall associated with lake-effect synoptic types in the eastern Great Lakes region, and the mechanisms responsible for their change during the period 1950–2009. A synoptic climatological approach was used to identify and isolate synoptic-scale weather types consistent with LES patterns that consistently occur in the region (Ellis & Leathers 1996, Leathers & Ellis 1996, Ellis & Johnson 2004, Suriano & Leathers 2017). Of the synoptic types identified, 7 were identified as lake-effect synoptic patterns by their 850 hPa winds, directional wind shear with height, and large 850 hPa to lake-surface temperature lapse rates. Snowfall occurring on days with lake-effect synoptic types is considered LES, and was examined at both seasonal and monthly time scales across the region.

As expected, the spatial distribution of average LES revealed higher totals downwind of both Lakes Ontario and Erie, with lesser totals further inland. Snowfall is most prevalent during the month of January for regions downwind of both lakes, although differences between the lakes in the relative monthly contributions to the seasonal LES total are detected. During the second half of the winter season, the ratio of monthly to total LES is smaller for Lake Erie compared to Lake Ontario, indicating the potential influence of lake ice on snowfall (Cordeira & Laird 2008, Gerbush et al. 2008). A linear trend analysis for the winter seasons 1949–1950 through 2008–2009 revealed that LES increased by 0.81 cm yr^{-1} collectively downwind of Lakes Ontario and Erie. However, breaking the long-term trend into two 30 yr periods reveals a more interesting history. A change in trend of LES is detected downwind of the lakes around 1980. While a true trend reversal is not detected in the region as seen in snowfall in other portions of the Great Lakes region (Bard & Kristovich 2012, Hartnett et al. 2014), LES significantly increased by 3.24 cm yr^{-1} from 1950–1979, before no longer exhibiting a significant trend from 1980–2009.

Changes in the seasonal frequency of lake-effect synoptic types and the rate of snowfall (snowfall intensity) were hypothesized to be the primary drivers for changes in LES (Leathers & Ellis 1996). Similar to LES, the seasonal frequency of lake-effect synoptic types also exhibits a change in trend around 1980. After de-trending both variables, lake-effect synoptic type frequency is strongly correlated to seasonal LES downwind of Lakes Ontario and Erie, explaining over 68 % of the variance in LES. This suggests the frequency of lake-effect synoptic types is likely the dominant force behind the apparent change in trend of LES. The magnitude of the snowfall changes based on synoptic type frequency and snowfall intensity changes are also examined. Over both periods examined (1950–1979, 1980–2009) this calculated snowfall change due to frequency and intensity changes represented 94.5 and 89.4 % of the observed snowfall changes, respectively. This leads to the conclusion that changes in LES over these periods are predominately caused by changes in the frequency of lake-effect synoptic types and snowfall intensity within these types. However, for both periods, calculated snowfall changes are lower than the observed changes, more so during 1980–2009. This suggests there could be additional factors influencing LES trends in the region, with their influence being more pronounced in more recent times. Additional influences could include intra-synoptic type variability, changes in lake ice cover, increasing air temperatures, or other unknown factors.

Comparing some of our results to those of Leathers & Ellis (1996) and Ellis & Leathers (1996), a number of similarities exist. In their studies, 5 synoptic types for Syracuse, NY, were identified as LES producers compared to the 7 found in this study. This difference is likely the result of a larger study period used in our study, and with the meteorological season-based TSI methodology used here, as opposed to the TSI being conducted over a single 5 mo period in Leathers & Ellis (1996) and Ellis & Leathers (1996). Furthermore, during the 1950/51–1981/82 period, Leathers & Ellis (1996) reported that a majority of snowfall changes were due to synoptic type frequency and snowfall intensity changes. Just as in this study, changes in synoptic type frequency and snowfall intensity also accounted for a majority (94.5 %) of observed snowfall changes from 1950–1979. Additionally, the relationship between changing frequency and intensity, and LES persists during times without significant snowfall increases (1980–2009), furthering the novel aspects of the study.

Snowfall is an important component of the hydrologic cycle within the eastern Great Lakes region, influencing water resources, the economy, transportation, winter recreation, and natural habitats. LES plays a pivotal role, resulting in 45–53% of the seasonal snowfall totals downwind of the lakes. The results of this study further the understanding of LES seasonal variability and trends, and what predominately influences LES. Despite LES no longer exhibiting a strong increasing trend in the region, the frequency of lake-effect synoptic types and the rate, or intensity, of snowfall, appear to be the major drivers of LES changes. Future work will expand this analysis, particularly investigating the driving force(s) of LES intensity changes, with an emphasis on intra-synoptic type variability (the changing character of synoptic types), and changing lake surface and 850 hPa air temperature differences.

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