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Article

Multivariate Analysis of Lake-Effect Snowstorms in Western New York

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ABSTRACT

The Great Lakes region of the United States is subjected to a wintertime convective phenomenon known as lake-effect snow (LES). These events are capable of producing significant quantities of snow over localized areas by developing elongated bands that tap into heat and moisture exchanges between the warm lake surface and the overlying continental polar air. Several factors are believed to affect the snowfall intensity associated with LES events, including the ice coverage over the lake where the snowbands originate. Improvements in the quality of snowfall forecasts associated with these LES events require an approach that uses a larger number of events than used in previously investigated case studies. The intensity of 91 LES events was assessed using the total volume of snow (snow depth multiplied by snow coverage area) per day in western New York as reported by the National Weather Service in Buffalo, New York, from 1998–2011. These events were cross-referenced against the fetch, capping inversion height, thermodynamic instability, wind speed, and ice coverage over Lake Erie during each event. A multivariate regression revealed that only fetch, inversion height, and ice coverage were statistically significant in determining the intensity of the LES event, with ice coverage having the greatest impact. These parameters accounted for approximately 30% of the overall snowfall volume variability in our LES events. An examination of two events demonstrated that other environmental controls—such as orography and low-level moisture—may have affected the quality of the snowfall predicted by our regression.

1. Introduction

Lake-effect snow (LES) is a type of mesoscale, convective snowfall phenomenon that normally develops in the middle and high latitudes downwind of moisture sources during the winter months. In the United States, this phenomenon frequently is seen from November–April in the Great Lakes region (Niziol et al. 1995). Thermodynamic instability and convection are generated when a continental polar air mass flows from the Canadian Shield over the relatively warm waters of the Great Lakes (Rothrock 1960; Holroyd 1971). The ensuing convection has been shown to be strong enough to produce (1) as much as 2.5 m of snow accumulation from one multi-day storm (Sykes 1966; Niziol 1989) and (2) enough charge separation in LES clouds to yield lightning—a phenomenon that is not commonly observed with snowfall (Niziol 1982; Moore and Orville 1990; Steiger et al. 2009). Not surprisingly, the quantitative forecast of precipitation in LES events remains one of the greatest challenges for operational meteorologists in the Great Lakes region.

The intensity of LES events has been shown to be a function of several environmental conditions, including the temperature difference between the lake and the overlying air, the fetch (i.e., the distance that the air mass travels over the lake), the unstable layer's depth and wind shear, the strength of the capping inversion, and lifting by topography or dynamic mechanisms (Wiggin 1950; Jiusto et al. 1970; Hill 1971; Niziol 1982; Byrd et al. 1991; Hjelmfelt 1992; Reinking et al. 1993; Lackmann 2001; Laird et al 2003; Evans and Murphy 2008). Additionally, sensible and latent heat fluxes have been shown to be related to lake ice cover; and ice thickness plays an important role in these fluxes (Zulauf and Krueger 2003; Cordeira and Laird 2008; Gerbush et al. 2008). The presence of extensive ice cover over the Great Lakes has been indicated as a possible cause for reduced snowfall accumulation in LES events by affecting the

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moisture and heat fluxes between the lake and the overlying air (Saulesleja 1986; Niziol 1987; Niziol et al. 1995; Laird and Kristovich 2004; Rauber and Ralph 2004; Cordeira and Laird 2008). The shallow depth of Lake Erie—which averages only 19 m—allows for the development of substantial ice coverage during the winter season. A first climatology of ice conditions over Lake Erie from 1897–1983 using a statistical ice-cover model was discussed by Assel (1990). In that study, ice coverage was shown to be most extensive in the month of February, when on average 68% of Lake Erie's surface was glaciated.

In order to give meteorologists a better understanding of the LES forecast limitations, it is paramount to pursue a more comprehensive investigation on the impacts of Lake Erie's ice on snowfall totals using a larger number of LES events than those seen in recent case studies. The overarching objective of our research is to quantify how much of the total snowfall volume can be explained by variability in five environmental factors: Lake Erie's ice fraction, thermodynamic instability, inversion height, fetch, and wind speed. We hypothesized that ice fraction would play a major role in controlling snowfall intensity. Thus, we also were interested in quantifying the relative importance of ice fraction and the remaining parameters on the intensity of LES storms in western New York using a multivariate regression approach.

2. Data and methodology

Since the 1998–1999 winter season, the United States National Weather Service (NWS) in Buffalo, New York, has been documenting, analyzing, and naming significant LES events posthumously that occur within their forecast jurisdiction. The naming system adopted by the Buffalo forecast office for these LES events currently remains unofficial, but it is akin to the system used for tropical cyclone naming and it is used primarily for reference and/or simplicity purposes. Between the 1998–1999 and 2010–2011 winter seasons, a total of 129 LES events were documented. The reports generated for each LES event by the Buffalo forecast office contained total snowfall accumulation maps, which were created based on measurements from a network of volunteer observers in the region.

Given that one of the goals of this study was to evaluate potential impacts of ice conditions over Lake Erie—relative to other known environmental parameters—we focused only on the LES events that (1) occurred from December–April of each year (i.e., the lake glaciation period) and (2) produced snowfall with fetches coming into New York State from a south, southwest, or west direction. Moreover, we confined our analysis to snowfall accumulations occurring only in New York State and west of 77.7°W longitude, as illustrated in Fig. 1. Our assessment was that areas east of 77.7°W were normally affected by LES originating over Lake Ontario that, owing to its greater depth, develops little ice cover during winter. Consequently, our ultimate snowfall dataset comprised the 91 LES events that met the aforementioned criteria.

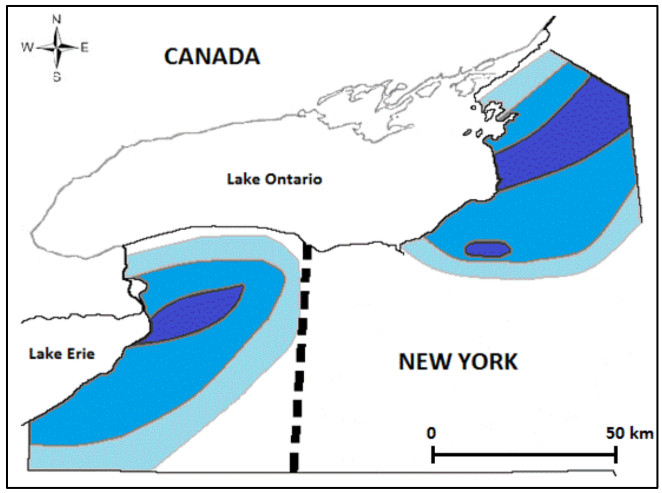

Figure 1. Snowfall accumulation map for lake-effect storm Hognose, which took place from 21–23 December 2008. Dark blue denotes areas with 30 cm of snowfall accumulation; medium blue depicts areas where 15 cm of snow accumulated; light blue indicates areas where snow accumulation was around 7.5 cm. The snowfall-volume results shown in this study were only calculated using data in NY west of 77.7°W longitude, which is illustrated by the thick dashed line. *Click image for an external version; this applies to all figures hereafter*.

Table 1 shows the dates for each of those 91 LES events. A multivariate regression analysis was used to evaluate how much of the total snowfall variability associated with these events can be explained by the remaining environmental variables, as well as their relative contribution. Below we explain how each of these variables was calculated for each event.

a. Snow-volume ratio

LES accumulations at any given point are dependent not only on the actual intensity of snow-bands, but also on the duration these bands remain

Table 1. Dates of the 91 lake-effect snow events examined in this study.

Event #	Date		Event #	Date		Event #	Date
1	Dec 17–18, 1998		**32**	Jan 14–15, 2003		**63**	Jan 23–24, 2007
2	Dec 22–25, 1998		**33**	Jan 20–21, 2003		**64**	Jan 25–26, 2007
3	Dec 31–Jan 1, 1999		**34**	Feb 4–6, 2003		**65**	Jan 29–30, 2007
4	Jan 3–5, 1999		**35**	Feb 9, 2003		**66**	Jan 31, 2007
5	Jan 6–7, 1999		**36**	Feb 12–14, 2003		**67**	Feb 15–16, 2007
6	Jan 10–11, 1999		**37**	Dec 11–12, 2003		**68**	Apr 4–8, 2007
7	Jan 15–16, 1999		**38**	Dec 17–18, 2003		**69**	Jan 14–15, 2008
8	Dec 16–17, 1999		**39**	Dec 19–20,2003		**70**	Jan 19–21, 2008
9	Dec 21–24, 1999		**40**	Dec 25, 2003		**71**	Jan 23–24, 2008
10	Dec 26–27, 1999		**41**	Jan 6–9, 2004		**72**	Jan 25, 2008
11	Jan 25–27, 2000		**42**	Jan 18–21, 2004		**73**	Jan 30–31, 2008
12	Feb 1–2, 2000		**43**	Jan 22–24, 2004		**74**	Feb 10–11, 2008
13	Feb 20, 2000		**44**	Jan 28–31, 2004		**75**	Feb 19–20, 2008
14	Dec 5–7, 2000		**45**	Dec 13–14, 2004		**76**	Dec 1–2, 2008
15	Dec 17–18, 2000		**46**	Dec 24, 2004		**77**	Dec 4–6, 2008
16	Dec 19–20, 2000		**47**	Jan 16–18, 2005		**78**	Dec 21–23, 2008
17	Dec 22–23, 2000		**48**	Feb 17–18, 2005		**79**	Jan 7–9, 2009
18	Dec 24–27, 2000		**49**	Dec 2–3, 2005		**80**	Jan 16–17, 2009
19	Jan 27–28, 2001		**50**	Dec 6–7, 2005		**81**	Jan 24–27, 2009
20	Dec 20–21, 2001		**51**	Dec 12, 2005		**82**	Jan 30–31, 2009
21	Dec 24–Jan 1, 2002		**52**	Dec 19, 2005		**83**	Feb 19–21, 2009
22	Jan 17–18, 2002		**53**	Dec 20, 2005		**84**	Dec 10–12, 2009
23	Mar 3–5, 2002		**54**	Jan 18–19, 2006		**85**	Dec 28–29, 2009
24	Mar 10–11, 2002		**55**	Feb 5–8, 2006		**86**	Jan 27–29, 2010
25	Mar 21–23, 2002		**56**	Feb 13–14, 2006		**87**	Dec 1–3, 2010
26	Dec 1–2, 2002		**57**	Feb 17–21, 2006		**88**	Jan 2–5, 2011
27	Dec 4, 2002		**58**	Mar 18–20, 2006		**89**	Jan 15–16, 2011
28	Dec 6, 2002		**59**	Dec 3–5, 2006		**90**	Jan 21–22, 2011
29	Dec 21, 2002		**60**	Dec 7–8, 2006		**91**	Feb 9–11, 2011
30	Dec 23, 2002		**61**	Jan 8–10, 2007			
31	Jan 10–12, 2003		**62**	Jan 19–20, 2007			

stationary over that same point. Hence, two separate events can potentially generate the same amount of snow, but one event can scatter it over a wider area producing lower localized maxima. Therefore, we chose to assess the overall intensity of each event based not on the maximum reported snowfall depth at a single point within our domain, but rather on the total volume of snow produced in western New York as reported by the NWS in Buffalo for each LES event. Using their maps, as shown in Fig. 1, we calculated the total snowfall volume of each event by multiplying the depth of the snow by the associated area where that snow accumulation was observed. Furthermore, because the length of each event was variable (1–8 days), we obtained the snow volume per day. The duration of each event was determined based on radar reflectivity images from the NWS radar in Buffalo. Last, in order to simplify our analysis discussion, we normalized these results by dividing the aforementioned snow volume per day of each LES event by the overall average value of the same parameter (3.53×10^7 m^3 day^{-1}). As a result, the dependent variable of our regression model will be the snowfall intensities of these LES events in terms of snow-volume ratio (SVR). A SVR value of 1.0 represents an LES event that produced a snowfall equal to the average of all 91 LES cases analyzed in this study—that is, an event of average intensity. Accordingly, ratios >1.0 were associated with LES events that had above-average intensity in terms of snowfall production. The SVR of each event is shown in Table 2.

b. Ice fraction

One of the key datasets used in this study was provided by the Canadian Ice Service (CIS), which produced weekly observations of Lake Erie's ice conditions. This included the fraction of Lake Erie's *surface* that was covered by ice (hereafter referred to as ice fraction), which is derived by the CIS from an array of remote sensing and in situ observational platforms (Meteorological Service of Canada 2005). The CIS ice dataset ranges from December 1998 to

Table 2. Snow-volume ratio (SVR) and snow covered area of each event in Table 1.

Event #	SVR	Area ($\times 10^3$ km^2)	Event #	SVR	Area ($\times 10^3$ km^2)	Event #	SVR	Area ($\times 10^3$ km^2)
1	2.05	4.03	**32**	1.89	9.58	**63**	1.21	5.95
2	0.45	9.70	**33**	0.10	1.40	**64**	1.10	3.54
3	0.98	5.50	**34**	0.29	5.31	**65**	1.76	7.58
4	1.14	9.88	**35**	0.67	2.05	**66**	1.99	5.87
5	1.49	11.4	**36**	0.75	2.98	**67**	0.15	1.36
6	1.26	9.23	**37**	0.67	11.1	**68**	1.15	14.4
7	0.66	2.61	**38**	1.13	8.11	**69**	1.50	5.41
8	1.42	9.93	**39**	0.30	2.52	**70**	0.89	10.6
9	1.07	10.7	**40**	1.45	5.59	**71**	0.91	2.83
10	1.00	10.3	**41**	1.83	11.9	**72**	0.20	0.82
11	0.17	2.33	**42**	0.56	5.87	**73**	0.09	0.88
12	0.06	0.58	**43**	0.16	2.05	**74**	0.94	3.94
13	0.30	4.24	**44**	0.75	9.39	**75**	0.90	6.32
14	1.74	17.0	**45**	1.72	13.0	**76**	1.14	6.12
15	1.35	7.4	**46**	0.71	8.10	**77**	0.71	6.09
16	2.20	11.4	**47**	0.98	6.03	**78**	1.87	15.2
17	2.19	16.9	**48**	1.46	8.82	**79**	2.38	12.3
18	0.08	9.02	**49**	1.44	9.79	**80**	0.75	7.17
19	0.10	0.91	**50**	1.75	9.25	**81**	0.03	0.20
20	3.27	12.4	**51**	0.32	1.09	**82**	0.24	1.87
21	1.09	13.1	**52**	1.64	8.67	**83**	1.04	7.27
22	2.44	12.0	**53**	1.81	7.40	**84**	2.71	17.6
23	1.22	9.88	**54**	0.40	2.24	**85**	1.23	10.2
24	1.61	13.6	**55**	1.80	20.3	**86**	2.16	19.3
25	1.03	9.32	**56**	0.68	4.61	**87**	0.63	3.99
26	2.36	14.3	**57**	0.30	7.46	**88**	0.61	10.5
27	0.47	5.03	**58**	0.18	2.80	**89**	0.17	2.33
28	0.31	3.73	**59**	0.62	9.40	**90**	0.37	3.44
29	1.25	10.0	**60**	0.78	4.91	**91**	0.62	19.0
30	0.61	8.11	**61**	2.52	11.5			
31	2.33	15.9	**62**	2.74	9.09			

April 2011. The CIS IceGraph Tool version 2.0 was used to extract the data in geographic information system format and calculate the surface ice fraction.

Because new ice conditions over Lake Erie are calculated weekly by the CIS, the ice fraction was determined for each of the 91 LES events by using data on the closest date preceding the event (including the date of the event). An event with an ice fraction of 0.50 implies that half of Lake Erie's surface was covered by ice during that specific LES event. The ice fraction of each event is shown in Table 3.

c. Fetch

The fetch over Lake Erie was calculated at 10-degree intervals for wind directions from 180–350°. This fetch is the median length measure over Lake Erie obtained for multiple points along New York's Lake Erie shoreline from Buffalo to the New York–Pennsylvania state border. These possible fetch lengths are shown in Table 4.

Traditionally, the fetch for LES has been calculated using wind direction at 850 hPa (Niziol et al. 1995). However, that information is available only twice daily, and wind direction can change considerably and affect fetch length during the 12-h period between radiosonde launches. A paired *t*-test between median fetch length using 850-hPa winds and median fetch length using surface winds at Buffalo was executed using data every 12 h for all the cases examined in this study. Statistically, we found that these two fetch-length calculations were not significantly different, with a p-value of 0.18. Therefore, in this study the median fetch associated with each event, as shown in Table 3, was determined using hourly surface wind direction at Buffalo.

d. Thermodynamic instability and inversion height

Thermodynamic instability was calculated using 850-hPa temperatures from radiosondes at Buffalo and Lake Erie's water temperature from Buffalo's water

Table 3. Data for the five independent variables of this study: ice fraction (IF, %), fetch (F, km), inversion height (IH, m), temperature difference (T, °C), and wind speed (WS, kt).

Event #	IF (%)	F (km)	IH (m)	T (°C)	WS (kt)
1	0.00	41	2153	16.9	4
2	0.00	251	1822	20.7	10
3	0.00	183	2508	21.7	11
4	0.07	0	1776	18.8	16
5	0.07	251	1829	19.8	14
6	0.32	251	2422	18.5	13
7	0.76	303	981	13.0	15
8	0.00	251	1043	15.8	13
9	0.00	183	1177	20.3	7
10	0.00	130	2438	16.3	13
11	0.31	41	1219	14.7	10
12	0.81	183	1829	17.4	12
13	0.73	303	2134	11.3	12
14	0.00	183	2205	21.3	12
15	0.05	303	1551	14.8	24
16	0.15	183	2591	17.7	8
17	0.15	251	2134	18.0	11
18	0.15	183	1829	16.9	11
19	0.88	130	1420	12.1	13
20	0.00	183	2549	17.2	11
21	0.00	121	2373	16.3	11
22	0.03	251	2241	15.3	13
23	0.00	251	2743	18.9	14
24	0.01	251	4877	14.3	21
25	0.00	251	3360	17.1	16
26	0.00	183	2600	17.9	12
27	0.00	0	716	18.9	5
28	0.00	251	267	16.7	11
29	0.02	303	2618	9.2	20
30	0.02	303	2101	12.9	19
31	0.20	303	2493	15.4	17
32	0.20	251	3271	17.1	13
33	0.41	183	2743	19.5	12
34	0.98	303	2071	14.3	17
35	0.96	121	1970	14.0	16
36	0.96	251	1490	22.1	12
37	0.00	183	2134	17.1	12
38	0.00	251	3430	13.3	14
39	0.01	64	3117	14.6	8
40	0.02	303	1982	13.0	9
41	0.00	251	2134	21.7	14
42	0.23	251	1364	16.0	9
43	0.36	251	2435	21.2	15
44	0.36	121	1530	17.4	17
45	0.00	130	2320	18.3	9
46	0.05	251	1829	21.3	7
47	0.16	64	2460	23.5	10
48	0.65	130	2801	14.1	12
49	0.00	251	2286	19.8	13
50	0.00	183	3015	20.3	12
51	0.14	64	1219	17.0	9
52	0.15	251	736	15.0	15
53	0.15	303	2395	12.8	12
54	0.02	303	1473	9.8	24
55	0.00	251	2278	13.7	19
56	0.06	121	2286	11.6	16
57	0.06	251	1829	16.5	15
58	0.02	130	2129	14.7	11
59	0.00	251	539	20.8	11
60	0.00	76	2743	24.6	12
61	0.00	251	3316	14.5	15
62	0.00	251	2773	18.1	18
63	0.01	303	2015	14.0	14
64	0.01	37	4770	20.5	6
65	0.25	303	1547	16.7	8
66	0.25	251	1801	16.0	20
67	0.97	303	818	14.2	17
68	0.16	303	2282	14.3	14
69	0.01	251	3010	12.5	9
70	0.00	251	1818	22.2	14
71	0.31	183	1899	16.5	9
72	0.31	121	1101	8.9	22
73	0.45	303	1728	13.1	23
74	0.69	251	2134	26.1	24
75	0.69	303	2556	16.9	17
76	0.00	303	3070	16.0	14
77	0.00	251	2743	18.4	11
78	0.07	303	1581	19.9	16
79	0.11	183	1450	15.0	9
80	0.63	251	242	23.5	13
81	0.94	121	721	17.7	9
82	0.91	0	2982	14.1	14
83	0.75	303	2113	14.1	15
84	0.00	183	1524	21.6	20
85	0.03	130	4877	15.2	13
86	0.20	303	2725	12.4	17
87	0.00	0	1256	16.1	10
88	0.21	251	1677	10.1	11
89	0.84	183	1829	15.9	13
90	0.84	183	2928	17.2	16
91	0.96	183	1795	21.3	10

treatment plant. For each event, the median temperature difference was calculated using all the radiosondes that were launched over the duration of the event.

Inversion height also was obtained using radiosonde data from Buffalo. An inversion was deemed to occur anytime the temperature increased between consecutive levels or when the dewpoint temperature decreased ≥5°C, whichever is lower. Table 3 shows the median inversion height and temperature difference obtained for each LES event.

e. Wind speed

For wind speed we used the median hourly surface wind speed at Buffalo. Some of our LES events had short duration and, thus, fewer observations. In those cases, the mean was quite different from the median when there were clear outliers present. Therefore, our choice for median as opposed to mean values (as it was done for fetch and inversion height) was driven by

Table 4. Possible wind fetch lengths in western NY associated with each wind direction.

Wind Direction (degrees)	Fetch Length (km)
175–184	0
185–194	0
195–204	0
205–214	0
215–224	0
225–234	0
235–244	121
245–254	303
255–264	252
265–274	183
275–284	98
285–294	77
295–304	64
305–314	54
315–324	46
325–334	41
335–344	39
345–354	37

the fact that the median is less sensitive to outliers and more representative of the actual conditions. Additionally, a paired *t*-test between surface winds at Buffalo and Dunkirk, New York (which is located further south along the Lake Erie shoreline), yielded a p-value of 0.876, thus indicating that the winds speeds were statistically very similar. Therefore, the median surface wind speeds in Buffalo were accepted as being representative for the region and the value associated with each event is shown in Table 3.

3. Results and analysis

The results are examined in three sections. The first seeks to analyze, individually, LES intensity against Lake Erie's ice fraction, inversion height, thermodynamic instability, and wind speed (fetch is not assessed owing to the discreteness of its numerical values). The second section evaluates the combined effects of all five parameters in the LES intensity. Last, two case studies are examined to understand why the snowfall intensity did not match the expectations.

a. Simple regressions

A scatterplot of the snowfall intensity versus the ice fraction of each event is shown in Fig. 2. The linear trendline in that scatterplot indicates a goodness of fit (R^2) of only about 20%, but the p-value for that regression was <0.001—an indication that, statistically, the parameters are highly related. The relationship evidently is not linear because LES of all intensities occurred when the ice fraction was zero or near zero. Nonetheless, most of the LES events that occurred when Lake Erie exhibited a large degree of glaciation were associated with below-average snowfall intensity. For instance, approximately 89% (16 of 18) of the LES events that developed when Lake Erie's surface was mostly frozen (i.e., ice fraction >0.5) produced SVR values <1.0. Fig. 2 shows that the snowfall intensity remained highly variable among the events that had high ice fractions. Niziol et al. (1995) cited the expected reduction in LES with the onset of Lake Erie's surface freezing and its importance in numerical and operational forecasts, and our results corroborate this idea.

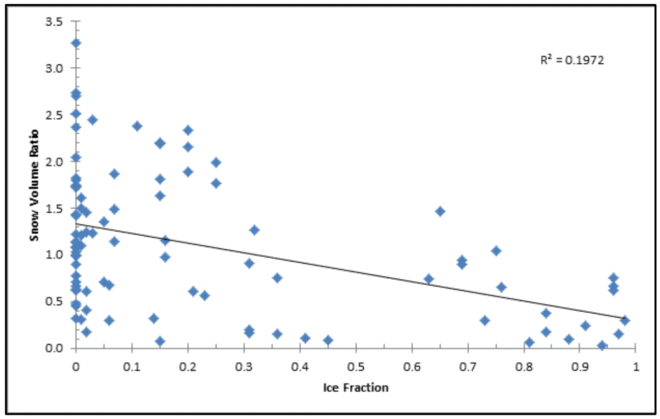

Figure 2. Scatterplot showing the distribution of snow-volume ratio (ordinate) and their associated ice fraction over Lake Erie (abscissa), as well as the best linear fit with its associated goodness of fit (R^2). Snow-volume ratios <1.0 (>1.0) represent lake-effect snow events of below- (above-) average intensity.

Figure 3 shows a scatterplot between the capping inversion height and snowfall intensity data. Although the goodness of fit for a linear relationship for this scatterplot was less than the one obtained for ice fraction in the previous figure, it also is statistically significant with a p-value of only 0.005. Nearly three-quarters of the cases that produced above-average snowfall were associated with inversion heights >2000 m, whereas only one-third of below-average cases surpassed that threshold. This is in agreement with findings from the Lake Ontario Winter Storms Project, which revealed that the height of the capping inversions was a major factor controlling the intensity of LES events (Reinking et al. 1993).

The temperature difference between the surface and 850 hPa is plotted against SVR in Fig. 4. Surprisingly, it shows a widely scattered distribution of points that are not statistically correlated (i.e., yielded a p-value of 0.43). Yet, 88% of the LES events

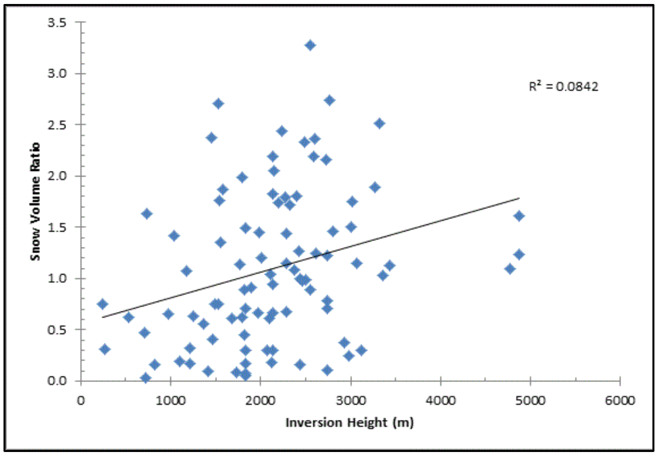

Figure 3. Same as Fig. 2 except for the capping inversion height (m, abscissa).

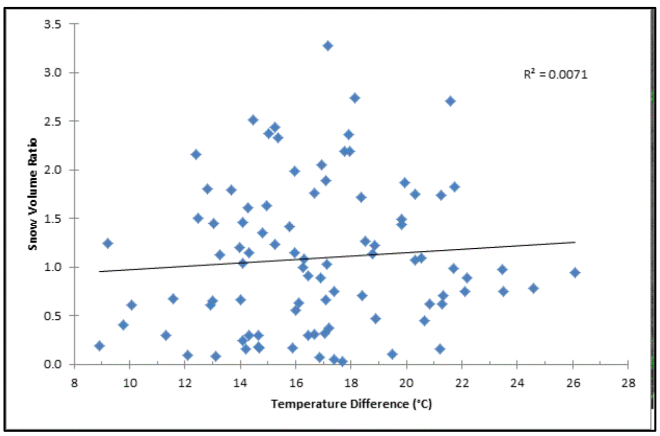

Figure 4. Same as Fig. 2 except for the temperature difference (°C, abscissa).

developed when the aforementioned temperature difference was ≥13°C, which is close to the dry adiabatic lapse rate and suggested as operationally necessary for pure LES (Rothrock 1960; Holroyd 1971). The remaining 12% of cases developed under conditionally unstable thermodynamic conditions (e.g., temperature difference >7°C), which was shown to be sufficient to produce modest increases in precipitation downwind of Lake Ontario (Wilson 1977). Thus, our results indicate that (1) thermodynamic instability is a needed ingredient for the development of LES and (2) a minimum lapse rate threshold is necessary. However, statistically, these data do not lend support to the notion that LES events that occur under greater thermodynamic instability are necessarily tied to a greater amount of total snowfall production over western New York. It is possible, however, that larger lapse rates could play other roles in LES events that are not examined here, but that are of significant importance in operational forecasting, such as how strongly localized the snowbands and associated snowfall areas may be. Additionally, it is possible the thermodynamic profile could be an important factor in modulating the snow microphysics which, in turn, can affect the depth of snowfall accumulation in a given event. LES events that develop under greater thermodynamic instability conceivably could be associated with cloud temperatures outside the Bergeron optimum range where dendrites are favored. In that case, lower accumulations would result in reduced SVR values.

The wind speed data are plotted against their corresponding SVR value in Fig. 5. The widely scattered distribution of points and the linear goodness of fit near zero with a p-value of 0.74 indicated that these two parameters are not linearly correlated. Additional tests using different heights and methods for wind speed (not shown) did not yield different results. Furthermore, to investigate the possible impact of wind speed on transport of snow and its potential scattering over larger areas, we also examined the relationship between wind speed and the snow area data shown in Table 2. Once again, our results were very similar to those of SVR and wind speed, and showed no correlation between these variables. Laird and Kristovich (2004) argued that the ratio between wind speed and fetch is important in determining the morphology of LES bands, but significant snow can occur under calm or strong winds when they are combined with other factors such as large lake–land temperature differences.

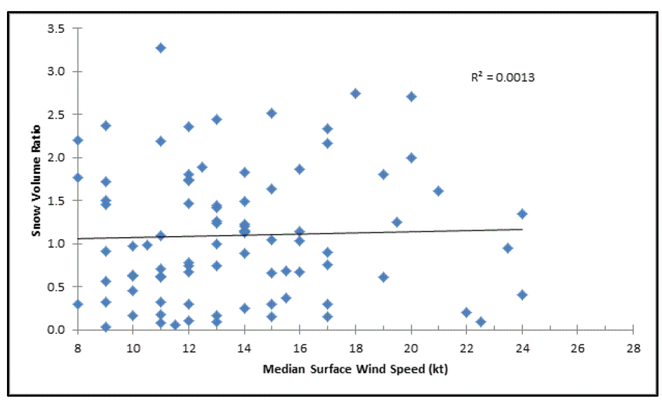

Figure 5. Same as Fig. 2 except for the median surface winds speeds (kt, abscissa).

b. Multivariate regression

Using the data shown in Tables 2 and 3, a multivariate regression yielded the following equation:

$$SVR = 0.0803 - 0.921IF + 0.00204F + 0.000189IH + 0.0229T + 0.00154WS \quad (1)$$

where IF is the ice fraction, F is the median fetch length (km), IH is the inversion height (m), T is the temperature difference between the lake and 850 hPa (°C), and WS is the median surface wind speed (kt). This regression produced a statistically significant function with a p-value <0.001.

Table 5. Multivariate regression results for the statistical significance of each of the five independent variables in explaining the variability in SVR data.

Independent Variable	P-value
Ice Fraction	0.000075
Median Fetch Length	0.023
Capping Inversion Height	0.023
Temperature Difference	0.26
Median Surface Wind Speed	0.93

Using the combined effects of these variables produced a goodness of fit much greater than any generated by the linear regressions shown in the previous section, as Eq. (1) can explain 30% of the SVR variability in our dataset. Furthermore, p-values for each of the five variables, shown in Table 5, indicated that three of them are statistically significant at the $\alpha = 0.05$ level: ice fraction, fetch, and inversion height. Finally, standard partial regression coefficients were calculated for each of these three parameters that demonstrated statistical significance in order to evaluate their relative contribution to SVR in our cases. Table 6 shows that ice fraction had the greatest degree of influence on SVR. The inversion height was only slightly less important than the fetch. Additionally, it also shows that the SVR increases with increasing fetch and inversion height, but it is inversely related to ice fraction.

Table 6. Standardized partial regression coefficients (SPRC) for each of the three statistically significant independent variables.

Independent Variable	SPRC
Ice Fraction	-0.294
Median Fetch Length	0.175
Capping Inversion Height	0.162

c. Case studies

We examined the two LES cases that departed the most in the SVR from the values predicted by Eq. (1). Our first case illustrates a very large snowfall event that took place in December 2001 and was underpredicted by our multiple regression. The second case substantially overpredicted snowfall for a LES event that took place in January 2004.

Lake-effect storm Albatross was the first event of the 2001–2002 season and produced the largest SVR (3.27) in our entire dataset. It developed under favorable conditions for all of the variables we tested in this study, with no ice present over Lake Erie and a slightly above-average inversion height. It produced copious amounts of snowfall downwind of Lake Erie over a large swath of the interior portions of Chautauqua, Cattaraugus, and Allegany Counties, whereas most of the low-lying areas along the shore of Lake Erie received little snowfall. Examination of radar reflectivity images and 850-hPa streamline maps revealed that two elements may explain the intensity and distribution of this event’s snowfall. First, the low-level flow quickly switched from a southwest direction (which commonly promotes the largest possible fetch in our area of study) to a northwest direction as a surface low-pressure area quickly moved from Upper Michigan to Nova Scotia. Occasionally, this flow direction allows for a connection with water bodies upstream of Lake Erie (i.e., Lake Huron and the Georgian Bay) as illustrated by the satellite image shown in Fig. 6. Second, orographic lift seems to have played an important role in snowfall totals as the aforementioned northwest flow was (1) particularly intense, with wind speeds from 18–21 m s^{-1} (35–40 kt) in the 925–700-hPa layer and (2) perpendicular to the predominant orientation of the mountains in the western Allegheny Plateau. Although topographical forcing potentially could be linked to wind speeds, we did not find a correlation between wind speeds and SVR, even when we analyzed a subset of events with the same flow as in this event. Our regression SVR (1.35) was well below the observed SVR (3.27). Outside of these environmental parameters, if snow-to-liquid ratios associated with this event were much higher than normal, this could explain the large snow accumulations observed in this event.

The greatest overprediction generated by Eq. (1) occurred with lake-effect storm Halite from 22–24 January 2004. Our regression model predicted a SVR of 1.23, but this system produced a well below-average SVR of 0.16. Some favorable conditions for snowfall development were present, with an above-average inversion height of 2435 m and a rather large fetch of about 250 km. However, only a small amount of precipitation associated with Lake Erie snowbands was deposited along the southern side of Erie County.

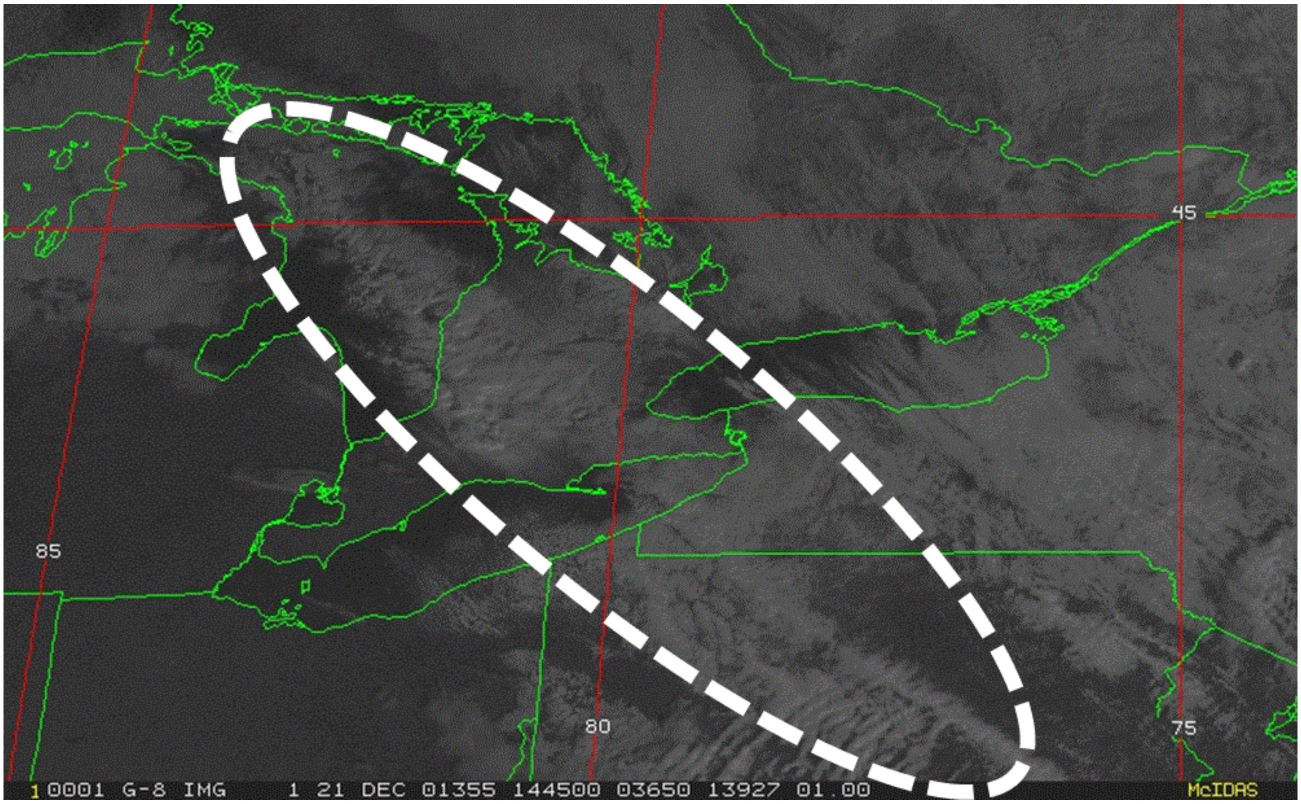

Figure 6. *Geostationary Operational Environmental Satellite-8* visible satellite image of lake-effect storm Albatross showing an upstream connection (white ellipse) with Lake Huron at 1445 UTC 21 December 2001.

One of the unusual features associated with Halite was that Lake Erie underwent a substantial amount of freezing at the same time that the event took place. Ice charts from the CIS showed that on 19 January 2004, the last chart before the event took place, Lake Erie had only 36% of ice coverage, whereas on the next available chart (26 January 2004) Lake Erie was practically frozen completely. Our methodology used the chart prior to the onset of the event, which could have misrepresented the ice conditions with a lower ice fraction for this specific event and, consequently, generated a higher prediction for SVR. Nonetheless, even if we were to use the higher ice fraction of 97% from the 26 January 2004 ice chart for this event, Eq. (1) still would overpredict the snowfall intensity of Halite—albeit by only about half as much as before. Another possible factor, which is not included in our multiple regression, and which could explain the low snowfall intensity of this LES event, was the relatively low amount of moisture at lower levels from Buffalo southward to the Pennsylvania border. Convective condensation levels in that region were typically in the 860–820-hPa range during this event, which would not have yielded the development of substantial vertical cloud growth as the capping inversion was near 760 hPa.

4. Conclusions

This study used a large number of catalogued LES events in western New York to examine how they were affected by five environmental conditions: ice coverage over Lake Erie, fetch length, capping inversion height, thermodynamic instability, and wind speed. The key findings of this study are as follows:

- Ice fraction had the greatest goodness of fit to a linear relationship with snowfall intensity of all simple regressions analyzed in this study. More than 80% of the cases that occurred with high ice fractions (i.e., >0.5) were associated with events of below-average intensity. However, higher capping inversion heights tended to support events of above-average magnitude, as 74% of them developed with heights >2000 m.
- A multivariate regression yielded a statistically significant function, and it revealed that only three of the parameters were statistically significant in determining the SVR of our LES events: the ice

fraction, the fetch, and the inversion height. Yet, the three statistically significant variables were able to predict only 30% of the variability in SVR in our dataset.

- The difference between lake temperature and 850-hPa temperature was not found to be statistically correlated with SVR over western New York in the simple regression as well as in the multiple regression. Further analyses are required to understand the role of lapse rate in the total volume of snowfall production, but it is possible that thermodynamic instability is indirectly related to snow microphysics and, consequently, affects the SVR produced by a LES event.
- Standard partial regression coefficients for each of the three variables indicated that the ice fraction had the strongest influence in predicting the snowfall intensity in LES events in western New York.
- Assessment of two case studies revealed the shortcomings of using only five independent variables in our regression model. Orography, low-level moisture, and the upstream connections to Lake Huron and Georgian Bay may have played a role in causing the regression to either overpredict or underpredict SVRs. Other parameters that have been used in operational forecasting of LES events (Niziol et al. 1995; Evans and Murphy 2008) that could be added to improve this regression model include dynamic/kinematic factors such as low-level convergence and 700-hPa omega.

As we aim to explain a higher percentage of the LES variability in western New York, the future of this work lies on improvements in two aspects of the regression problem. First, we continue to explore the addition of new independent variables that may have a considerable impact in LES snowfall production. Second, there are inherent dataset limitations in our dependent variable (SVR) as we continue to evaluate ways to more accurately gauge the intensity of LES events. The latter remains a much greater challenge because of the high temporal and spatial variability of precipitation, particularly in LES events. The snowfall maps generated by the NWS used in this study to calculate SVR have limitations due to the inequitable geographical distribution of ground observations. However, it is our belief that alternative methods of precipitation retrieval, such as radar-derived products, create their own set of problems (e.g., evaporation/ sublimation losses, large variability of reflectivity–snowfall relationships in this region, etc.) in accurately estimating snowfall totals. An analysis of snow-to-liquid ratios over the United Stated by Baxter et al. (2005) showed that the Buffalo area had the greatest national variability in that parameter, and found that they vary substantially between coastal and inland locations. Thus, our current focus in improvement of the dependent variable is aimed at potential distortions that these high variations in snow-to-liquid ratios can have in the degree of predictability of our multivariate regression model.

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REFERENCES

Assel, R. A., 1990: An ice-cover climatology for Lake Erie and Lake Superior for the winter seasons 1897–98 to 1982–83. *Int. J. Climatol.*, **10,** 731–748.

Baxter, M. A., C. E. Graves, and J. T. Moore, 2005: A climatology of snow-to-liquid ratio for the contiguous United States. *Wea. Forecasting*, **20**, 729–744.

Byrd, G. P., R. A. Anstett, J. E. Heim, and D. M. Usinski, 1991: Mobile sounding observations of lake-effect snowbands in western and central New York. *Mon. Wea. Rev.*, **119,** 2323–2332.

Cordeira, J. M., and N. F. Laird, 2008: The influence of ice cover on two lake-effect snow events over Lake Erie. *Mon. Wea. Rev.*, **136**, 2747–2763.

Evans, M., and R. Murphy, 2008: A proposed methodology for reconciling high-resolution numerical modeling guidance with pattern recognition to predict lake-effect snow. *Electronic J. Operational Meteor.*, **9** (2), 1–55. [Available online at www.nwas.org/ej/pdf/2008-EJ2.pdf.]

Gerbush, M. R., D. A. R. Kristovich, and N. F. Laird, 2008: Mesoscale boundary layer and heat flux variations over pack ice–covered Lake Erie. *J. Appl. Meteor. Climatol.*, **47,** 668–682.

Hill, J. D., 1971: Snow squalls in the lee of Lake Erie and Lake Ontario: A review of the literature. NOAA Tech. Memo., NWS ER-43, 23 pp. [NTIS COM-72-00959.]

Hjelmfelt, M. R., 1992: Orographic effects in simulated lake-effect snowstorms over Lake Michigan. *Mon. Wea. Rev.*, **120**, 373–377.

Holroyd, E. W., III, 1971: Lake-effect cloud bands as seen from weather satellites. *J. Atmos. Sci.*, **28,** 1165–1170.

Jiusto, J. E., D. A. Paine, and M. L. Kaplan, 1970: Great Lakes snowstorms. Part 2: Synoptic and climatological aspects. State University of New York at Albany Report ESSA E22-49-70, 58 pp.

Lackmann, G. M., 2001: Analysis of a surprise western New York snowstorm. *Wea. Forecasting*, **16**, 99–116.

Laird, N. F., and D. A. R. Kristovich, 2004: Comparison of observations with idealized model results for a method to resolve winter lake-effect mesoscale morphology. *Mon. Wea. Rev.*, **132,** 1093–1103.

____, J. E. Walsh, and D. A. R. Kristovich, 2003: Model simulations examining the relationship of lake-effect morphology to lake shape, wind direction, and wind speed. *Mon. Wea. Rev.*, **131**, 2102–2111.

Meteorological Service of Canada, 2005: *MANICE: Manual of Standard Procedures for Observing and Reporting Ice Conditions*, Ninth Edition, Environment Canada, Ottawa, ON, Canada, 146 pp. [Available online at www.ec.gc.ca/glaces-ice/4FF82CBD-6D9E-45CB-8A55-C951F0563C35/MANICE.pdf.]

Moore, P. K., and R. E. Orville, 1990: Lightning characteristics in lake-effect thunderstorms. *Mon. Wea. Rev.*, **118**, 1767–1782.

Niziol, T. A., 1982: A record setting lake effect snowstorm at Buffalo NY. *Natl. Wea. Dig.*, **7** (4), 19–24.

____, 1987: Operational forecasting of lake effect snowfall in western and central New York. *Wea. Forecasting*, **2,** 310–321.

____, 1989: Some synoptic and mesoscale interactions in a lake effect snowstorm. Postprints, *Second National Winter Weather Workshop,* Raleigh, NC, NOAA Tech. Memo. NWS ER-82, 260–269.

____, W. R. Snyder, and J. S. Waldstreicher, 1995: Winter weather forecasting throughout the eastern United States. Part IV: Lake effect snow. *Wea. Forecasting*, **10,** 61–77.

Rauber, R. M., and Coauthors, 2004: An implementation plan for cool season quantitative precipitation forecasting. United States Weather Research Program, 54 pp. [Available online at nldr.library.ucar.edu/repository/assets/technotes/asset-000-000-000-789.pdf.]

Reinking, R. F., and Coauthors, 1993: The Lake Ontario Winter Storms (LOWS) project. *Bull. Amer. Meteor. Soc.*, **74**, 1828–1849.

Rothrock, H. J., 1960: An aid in forecasting significant lake snows. ESSA Tech. Memo. WBTM CR-30, NOAA/NWS, Kansas City, MO, 18 pp.

Saulesleja, A., 1986: Great Lakes climatological reference. Environment Canada, Ottawa, ON, Canada, 145 pp.

Steiger, S. M., R. Hamilton, J. Keeler, and R. E. Orville, 2009: Lake-effect thunderstorms in the lower Great Lakes. *J. Appl. Meteor. Climatol.*, **48**, 889–902.

Sykes, R. B., 1966: The blizzard of '66 in central New York: Legend in its time. *Weatherwise*, **19**, 241–247.

Wilson, J. W., 1977: Effect of Lake Ontario on precipitation. *Mon. Wea. Rev.*, **105**, 207–214.

Wiggin, B. L., 1950: Great snows of the Great Lakes. *Weatherwise*, **3,** 123–126.

Zulauf, M. A., and S. K. Krueger, 2003: Two-dimensional cloud-resolving modeling of the atmospheric effects of Arctic leads based upon midwinter conditions at the surface heat budget of the Arctic Ocean ice camp. *J. Geophys. Res.*, **108,** 4312, doi:10.1029/2002JD002643, D10.