Lake-Effect Snowstorms over Southern Ontario, Canada, and Their Associated Synoptic-Scale Environment

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ABSTRACT

Lake-effect snowstorms are an important source of severe winter weather over the Great Lakes region and are often triggered by the passage of synoptic-scale low pressure systems. In this paper, a climatology of lake-effect snowstorms over southern Ontario, Canada, for the period 1992–99 is developed. The distinguishing characteristics of the synoptic-scale environment associated with intense lake-effect snowstorms in the region are identified through the study of individual events and through composite analysis. In particular, it is found that a low pressure and a cold-temperature anomaly situated over Hudson Bay, north of the Great Lakes, is a favorable environment for the development of intense lake-effect snowstorms over southern Ontario. It is also found that the track of the low pressure system can have a significant impact on the development or lack thereof of lake-effect snowstorms over southern Ontario. It is found that the low pressure systems that trigger intense lake-effect snowstorms tend to have an anomalous northeastward track as compared to the eastward track of most low pressure systems that transit the region.

1. Introduction

Lake-effect snowstorms are common weather phenomena that occur along the lee shores of the Great Lakes during the winter months. These snowstorms typically occur 1–2 days after the passage of a synoptic-scale low pressure system when northwesterly flow is established over the region. As the cold and dry Arctic air flows over the lakes, it is warmed and moistened as a result of the transfer of sensible and latent heat. This transfer can trigger atmospheric convection that is typically organized into long quasi-two-dimensional features known as cloud streets or cloud bands. Figure 1 provides an example of the organization of the convection associated with lake-effect snowstorms into cloud streets. Microphysical and dynamical processes in these clouds often result in intense but highly localized snowstorms that are a hindrance to socioeconomic activity in this densely populated region of North America. Although most of the lake-effect snowstorms are associated with the passage of low pressure systems, anticyclones can also trigger cold-air outbreaks over the region and, in some cases, result in lake-effect snowstorms. Sometimes the lake-effect activity occurs during a synoptic low pressure system and results in additional precipitation, which is called lake-enhanced snowfall (Eichenlaub 1979).

Lake-effect snowstorms contribute more than half of the annual snowfall in the Great Lakes region. Heavy snowfalls, with as much as 150–250 cm falling over a several-day period, are often associated with these weather systems (Nizol 1989). Lake-effect snowstorms also occur downstream of the Great Salt Lake (Carpenter 1993; Steenburgh et al. 2000). Similar phenomena are observed over the high-latitude oceans during cold-air outbreaks (Hartmann et al. 1997; Renfrew and Moore 1999) as well as over the Sea of Japan (Tusboki et al. 1989; Asuma et al. 1997).

Lake-effect snowstorms have been studied through field observations (Reinking et al. 1993; Braham and Dungey 1995; Kristovich et al. 2000), theoretical analysis (Hsu 1987), and numerical models (Sousounis 1993; Ballentine et al. 1998; Cooper et al. 2000). Hjelmfelt (1990) summarized four different classes of cloud bands that occur in lake-effect snowstorms over the Great Lakes region. They are wind parallel bands, shoreline bands, midlake bands, and boundary cyclonic flow pattern bands. Wind parallel bands are the most common, and the most intense lake-effect snowstorms are often associated with such bands. They occur when the wind is parallel to the long axis of a lake, and as a result, there exists a long fetch over water that allows for large transfers of heat and moisture from the lake to the atmosphere (Niziol et al. 1995).

Lavoie (1972) found that the air–lake temperature difference is an important indicator of the intensity of lake-effect snowstorms. Holroyd (1971) argued that a
13°C temperature difference between the lake and the 850-mb-level atmosphere was a necessary condition for lake-effect snowfall. Ellenton and Danard (1979) found that increasing the air–lake temperature difference could result in an increase in snowfall. In the operational forecast package Buffalo’s forecasting toolkit (BUFKIT), developed at the National Weather Service (NWS) office in Buffalo, New York, air–lake temperature difference is one of the most important factors used to predict the intensity and duration of lake-effect snowstorms (Matheny and Niziol 1997). The height and strength of the capping inversion is another major controlling factor in lake-effect snowstorm development (Byrd et al. 1991; Reinking et al. 1993). Furthermore, the intense vertical motion associated with the convection can modify the height of the inversion and intensify cloud growth (Niziol et al. 1995). Recent observations from the Lake-Induced Convection Experiment (Lake-ICE) have confirmed the important role that air–lake fluxes and the vertical structure of the atmosphere play in the development of lake-effect snowstorms (Scott and Sousounis 2001). Additional factors that inhibit the transfer of sensible and latent heat from the lake to the atmosphere, such as lake ice cover, can result in a reduction in lake-effect snowfall (Saulesleja 1986).

The parent synoptic-scale low pressure system also plays an important role in providing conditions preferable for the development of lake-effect snowstorms. In this regard, the location of the Great Lakes along one of the major extratropical storm tracks undoubtedly contributes to the frequency and intensity of lake-effect snowstorms in the region (Blackmon et al. 1977; Hoskins and Hodges 2002). Sousounis and Mann (2000) numerically investigated the interaction between the Great Lakes and synoptic-scale flows and their effect on lake-effect snowstorm development. The impacts that synoptic-scale low pressure system intensity, track, and duration had on the subsequent development of lake-effect snowstorms have been addressed in individual case studies (Ballentine et al. 1998; Schmidlin and Kosarik 1999). Their results showed that for the cases studied, synoptic-scale low pressure systems and the synoptic environment associated with these systems play important roles in modulating the intensity of lake-effect snowstorms. However a comprehensive analysis of typical environmental conditions that give rise to lake-effect snowstorms is not possible from a few case studies.

Composite analysis is a data reduction technique that allows for the objective identification of features com-
com position to a particular population. It therefore provides a basis for interpreting case studies (Carleton 1999). In a synoptic climatological approach to the analysis of lake-effect snowstorms by Ellis and Leathers (1996), composite analysis successfully represented the typical synoptic-scale atmospheric patterns that are favorable for the development of lake-effect snowstorms along the southern and eastern shores of Lakes Erie and Ontario in the northeastern United States. In particular they found that two synoptic patterns, strong westerly wind and strong westerly to northwesterly wind, resulted in large amounts of lake-effect snowfall over the region studied. By using composite analyses and rawinsonde-derived statistics, Steenburgh et al. (2000) described the characteristics of lake-effect snowstorms over the Great Salt Lake. They found the characteristics that resulted in lake-effect snowstorm over the Great Salt Lake include a large temperature difference between the atmosphere and the lake, large fetch, and the absence of a low-level capping inversion. These characteristics are similar to those for lake-effect snowstorms over the Great Lakes. In the above studies, the favorable synoptic-scale pattern for lake-effect snowstorms were identified. However, few attempts have been made to identify the environmental precursors that result in lake-effect snowstorms or the temporal evolution of these weather systems. An exception is the study by Lackmann (2001), who identified the synoptic-scale common denominator prior to and during the lake-effect events through a composite climatological analysis of 32 significant lake-effect events over Rochester, New York. In this study, we will attempt to address these issues over southern Ontario, Canada.

Located downstream of Lake Huron and Georgian Bay, southern Ontario, the most populous region of Canada, experiences intense lake-effect snowstorms almost every winter. However, there has not been a comprehensive investigation of lake-effect snowstorms in the region. In this paper, we use a hierarchical approach to investigate the synoptic-scale environment associated with the intense lake-effect snowstorms over southern Ontario for the period 1992–99. Two specific questions are addressed: 1) Is there a favorable synoptic-scale environment that results in the intense lake-effect snowstorm over southern Ontario? 2) Do the synoptic-scale low pressure systems associated with intense lake-effect snowstorms have different characteristics compared to low pressure systems that do not result in such events? The remainder of the paper is organized as follows. In section 2, we describe the datasets and methods used in this study to develop our climatology of intense lake-effect snowstorms for the period 1992–99. In section 3, we describe the lake-effect snowstorms over southern Ontario during a typical winter in the study period. In section 4, we describe our composite analysis of the synoptic scale environment associated with our identified population of intense lake-effect snowstorms and those associated with a control population. Finally, our results are summarized in section 5.

2. Data and methods

a. Identification of lake-effect events

Daily snowfall data from the Midland, Ontario, weather station site, obtained from the Meteorological Service of Canada (MSC), was used to identify lake-effect snowstorms during the months of October to March for the period 1992–99. We consider those events where the total snow accumulation exceeded 10 cm. The Midland Ontario weather station, shown in Fig. 2, is located in the lee of Lake Huron and Georgian Bay in the center of the region in southern Ontario that is most strongly affected by lake-effect snowstorms. With these data alone, it is difficult to differentiate the snowfall associated with lake-effect snowstorms from that associated with the passage of synoptic-scale low pressure systems. However as compared with the widespread snowfall associated with the passage of synoptic-scale low pressure systems, lake-effect snowstorms are highly localized systems with smaller spatial scales and a unique banded organization to their clouds and snowfall. Therefore radar data can be used to differentiate lake-effect snowstorms from the other snowfall events. For this study, we use the hourly reflectivity data from the MSC’s operational radar at King City, Ontario. This location, also shown in Fig. 2, provides complete coverage of the region of interest. For a snowfall event to be classified as a lake-effect snowstorm, banded-like features as described in the introduction must have been observed for a minimum duration of 6 h in the radar reflectivity data. In addition, during the event, the temperature difference between the lake surface and 850-
TABLE 1. Intense lake-effect snowstorm events over southern Ontario during the winters of 1992–99.

<table>
<thead>
<tr>
<th>Lake-effect snowstorm date</th>
<th>Snow water equivalent (mm)</th>
</tr>
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<tbody>
<tr>
<td>17–19 Oct 1992</td>
<td>15</td>
</tr>
<tr>
<td>6 Dec 1992</td>
<td>12</td>
</tr>
<tr>
<td>18–19 Jan 1993</td>
<td>10</td>
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<tr>
<td>28–30 Jan 1993</td>
<td>30</td>
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<tr>
<td>26–27 Dec 1993</td>
<td>20</td>
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<tr>
<td>6–8 Jan 1993</td>
<td>14</td>
</tr>
<tr>
<td>16–19 Jan 1994</td>
<td>40</td>
</tr>
<tr>
<td>15–17 Mar 1994</td>
<td>13</td>
</tr>
<tr>
<td>21–23 Nov 1994</td>
<td>10</td>
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<tr>
<td>10–11 Dec 1994</td>
<td>15</td>
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<tr>
<td>2–4 Jan 1995</td>
<td>16</td>
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<tr>
<td>11–13 Feb 1995</td>
<td>17</td>
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<tr>
<td>3–4 Nov 1995</td>
<td>15</td>
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<tr>
<td>14–16 Nov 1995</td>
<td>32</td>
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<td>21–23 Nov 1995</td>
<td>22</td>
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<td>14 Dec 1995</td>
<td>19</td>
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<td>1–3 Nov 1996</td>
<td>19</td>
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<td>10–12 Nov 1996</td>
<td>24</td>
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<td>25–26 Dec 1996</td>
<td>11</td>
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<td>11–12 Dec 1997</td>
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<td>15</td>
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<td>20–22 Dec 1998</td>
<td>42</td>
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<tr>
<td>30–31 Dec 1998</td>
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<td>4–7 Jan 1999</td>
<td>27</td>
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<td>20</td>
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<td>27–28 Nov 1999</td>
<td>10</td>
</tr>
<tr>
<td>21–23 Dec 1999</td>
<td>19</td>
</tr>
</tbody>
</table>

mb level must exceed 13°C, which is the threshold temperature difference for the occurrence of lake-effect events (Holroyd 1971). The location (45°N, 80°W) where the temperature difference was calculated is also displayed in Fig. 2. The daily 850-mb temperature at the above location was extracted from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996; Kistler et al. 2001), and the daily lake surface temperature at the above location was from Great Lakes Environmental Research Laboratory (GLERL). Finally, to eliminate the lake-enhanced snowfall events, we required that the low pressure center in the NCEP–NCAR reanalysis sea level pressure field must have been located at least 250 km away from the Midland weather station during the lake-effect event (Lackmann 2001). As a result, 29 events were selected as “pure” lake-effect events during the months of October to March over the period 1992–99. A complete list of these events is provided in Table 1.

b. Identification of non-lake-effect events

As a control population, we require a set of cyclones that passed through southern Ontario but did not trigger lake-effect snowfall. In this section, we outline the steps used to generate this control population. The geopotential height of the 850-mb pressure surface from the NCEP–NCAR reanalysis was used to identify the passage of synoptic-scale low pressure systems through the region. The 850-mb level represents conditions in the lower troposphere, and low pressure features are very easily identified on its geopotential height field (Morrison and Businger 2001). The power spectrum of the 850-mb geopotential height field at a location in southern Ontario (45°N, 80°W) during the winters of 1992–99 (Fig. 3). An assessment of the statistical significance of this peak using a red-noise fit to the spectrum (Mann and Lees 1996) indicates that it is statistically significant at the 99% level. During a typical winter, October to March, one would therefore expect to observe the impact of approximately 30 low pressure systems in southern Ontario. From the above analysis, it is evident that only a small number of these systems resulted in intense lake-effect snowstorms.

The time series of the 850-mb geopotential height at the above location is characterized by an oscillation that represents the passage of synoptic-scale pressure systems. In this study, the day when the minimum geopotential height recorded is defined as day 0, which is the day when the low pressure system reaches the region of interest. For a low pressure system to be considered to be not associated with a lake-effect snowstorm, the system must satisfy at least one of the following constraints during the period from day −2 to day +3: 1) no snowfall was recorded at the Midland weather station, and 2) snowfall was recorded at the Midland station but no lake-effect snowbands were observed in the radar reflectivity data and the temperature difference between the lake surface and 850-mb level was less than 13°C. Of the events that met these criteria, only the 29 stron-
gest events were selected for inclusion in the control population.

c. Composite analysis

Based on the above selection process, two different populations of low pressure systems are available for subsequent analysis. The two populations are the 29 low pressure systems associated with intense lake-effect snowstorms that occurred in southern Ontario between the months of October to March during the period 1992–99, and the 29 most intense low pressure systems that were not associated with lake-effect snowstorms in the same region over the same period of time. Composite techniques were employed to extract information regarding the environmental conditions associated with these two populations of low pressure systems. The composites were constructed with fields contained in the NCEP–NCAR reanalysis dataset. The geopotential height, horizontal wind, and temperature fields on the 850-mb level were used to identify the different dynamic and thermodynamic characteristics of the two populations of low pressure systems. Using this technique, there is concern regarding the significance of the patterns that are obtained, especially if the composite signal is week compared to the magnitude of individual events (Mullen and Baumhefner 1988). To address this issue, resampling techniques were applied to assess the statistical significance of each composite (Gershunov and Barnett 1998). The basic idea behind resampling is to assess the statistical significance of a particular composite through a comparison to the statistics of randomly selected composites of the same size drawn from the same parent population (Moore et al. 2003). The composites will be displayed as anomalies about the corresponding long-term mean. Regions where the composites are statistically significant at the 95% level will be indicated. To gain information of the temporal evolution of these two classes of synoptic-scale low pressure systems, composites were constructed at day $-2$, day $-1$, day 0, day +1, and day +3 for both populations. Lake-effect snowstorms typically occur during the period from day +1 to day +3.

3. 1996–97 winter lake-effect events

a. Overview

Figure 4 shows the histogram of the 24-h snowfall accumulation associated with lake-effect snowstorms during the winter of 1996–97 as observed from the Midland weather station. During this winter, there were 18 lake-effect snowstorms. The figure indicates that more than half of the events gave rise to light flurries (total accumulation < 5 cm), and only three intense events (total accumulation > 10 cm) occurred during that winter. The three intense lake-effect events during this winter were 1–3 November 1996 with 19-cm snowfall accu-

![Figure 4: Histogram of snow accumulation associated with lake-effect snowstorms at the Midland site during the 1996/97 winter.](image-url)

b. Lake-effect snowstorm of 24–26 December 1996

Figure 5 shows the evolution of 850-mb geopotential height, wind, and temperature fields during the event of 24–26 December 1996. Prior to the onset of the event, 23 December, there was a deep synoptic-scale low pressure centered over northern Hudson Bay, with the minimum geopotential height on the 850-mb surface of approximately 1200 m that corresponds to a sea level pressure 998 mb, and a weak mesoalpha-scale low to the southwest of the Great Lakes. The cyclonic flow around this low center resulted in weak warm air advection over the central and southern Great Lakes (Fig. 5a). On 24 December, this low had deepened and moved over the central Great Lakes. There was no significant change in the northern low pressure system (Fig. 5b). On 25 December, the two systems merged into a very deep low centered over northern Quebec, Canada. The location of this low resulted in the establishment of strong northwesterly flow that advected cold and dry Arctic air over the Great Lakes (Fig. 5c). As discussed in the introduction, this orientation of the wind along the long axis of Lake Huron and Georgian Bay, with a maximum fetch over the lake surface, is favorable for triggering intense lake-effect snowfall in the lee of these lakes.
Figure 5. Geopotential height (contours in m), horizontal wind (vectors in m s⁻¹), and temperature (shading in °C) fields on the 850-mb surface for 23–26 Dec 1996 lake-effect snowstorm event: (a) 23 Dec, (b) 24 Dec, (c) 25 Dec, and (d) 26 Dec. All fields are from the NCEP–NCAR reanalysis.

Radar reflectivity data from the King City site at 1900 UTC 25 December shows the presence of several southwestern-to-northeastern-oriented snowbands in the lee of the Lake Huron and Georgian Bay region (Fig. 6). The orientation of the snowbands at this time suggests that there was an accompanying westerly shift in the wind direction that is more favorable for the development of lake-effect snowfalls in the lees of Lake Erie and Lake Ontario (Fig. 5d). On 26 December, the low moved to the Labrador Sea and continued to deepen. The cyclonic flow associated with this system provided a continuous stream of cold and dry polar air over the Great Lakes region. King City radar data on 26 December indicated the presence of intense snowbands over Lake Ontario and in the lee of Lake Erie.

Figure 7 indicates that for this event the Holroyd (1971) criterion for an unstable lapse rate \( T_{850} - T_{\text{lake}} < -13^\circ \text{C} \) was exceeded. The large temperature difference between the cold Arctic air and warm lake surface produced strong thermal instability and intense heat and moisture fluxes from the lake to the air. Also shown in this figure is the 24-h snow accumulation at the Midland station. The large snow accumulation associated with the passage of the parent low can be seen to occur on 23 and 24 December, while the accumulation associated with the lake-effect snowstorm occurred on 25 and 26 December. The period of lake-effect snowfall corresponded to that when the magnitude of the air–lake temperature difference was largest.

The synoptic environment associated with this intense lake-effect snowstorm over southern Ontario had the following characteristics: 1) strong northwesterly flow over Lake Huron and Georgian Bay; 2) a large temperature difference between the lake and the atmosphere; and 3) a low pressure system that moved in a northeasterly direction. The first two criteria, which resulted in a large fetch over water and intense heat and moisture fluxes, are key factors for triggering intense lake-effect snowstorms as described in the introduction. The third characteristic, the northeasterly track of the low pressure system, has not been identified in previous studies. It may nevertheless be important in initiating and maintaining the first two characteristics.

To determine if this is a common track for low pressure systems that result in intense lake-effect snowstorms, we plot the track of the three systems that resulted in intense lake-effect snowstorms during the winter of 1996/97 in Fig. 8. Also shown in Fig. 8 is the
Fig. 6. Radar reflectivity from the King City site on 1900 UTC 25 Dec 1996 showing the banded organization of the convection associated with the lake-effect snowstorm.

Fig. 7. Evolution of the 850-mb and lake surface temperature difference (solid line) and 24-h snowfall accumulation at the Midland weather station (dashed line) during the 23–26 Dec 1996 lake-effect snowstorm events.

Fig. 8. Cyclone tracks of the intense lake-effect events (dotted lines) during the 1996/97 winter. Selected contours of the climatological winter mean (Oct–Mar) 3–10-day bandpass-filtered standard deviation of the 850-mb geopotential height field from the NCEP–NCAR reanalysis are also shown.

winter mean 3–10-day bandpass-filtered standard deviation of the 850-mb height field for the years 1992–99. The maximum of this field provides information of the location of the primary storm track (Blackmon et
al. 1977; Hoskins and Hodges 2002). Figure 8 suggests that a low pressure system with a northeasterly track is more favorable to the development of intense lake-effect snowstorms as compared to the more common easterly track during the winter months. It thus appears that the track of the low pressure system may play an important role in providing a favorable synoptic environment for the triggering and maintenance of intense lake-effect snowstorms over southern Ontario.

4. Synoptic-scale environment climatology of lake-effect and non-lake-effect events

Through the analysis of a single winter’s worth of cases in the previous section, some characteristics of the synoptic environment that is favorable for lake-effect snowstorms over southern Ontario have been described. In this section, we seek to generalize these results by developing a climatology of low pressure systems associated with the intense lake-effect snowstorms during the period 1992–99. As a control, we also develop a similar climatology of low pressure systems that were not associated lake-effect snowstorms.

a. Lake-effect events

In Fig. 9, we show the composites of the 850-mb geopotential height and wind field (Fig. 9a) and the 850-mb temperature field (Fig. 9b) as created from the 29 identified intense lake-effect snowstorms on day −2. Recall that by our definition, the lake-effect snowstorms begin on day 0. The 850-mb geopotential height composite is characterized by the presence of a broad area of anomalously low heights extending from Hudson Bay to northern Mexico. In addition, a region with anomalously high heights is located over the Atlantic Ocean. Associated with this dipolar structure in the height field there was an anomalous cyclonic wind flow. Resampling shows that the low pressure anomaly situated over Hudson Bay and the associated cyclonic flow that was identified in the case study from 1996 (Fig. 5a) are statistically significant. The temperature composite shows a statistically significant cold anomaly over western North America. The presence of a cold anomaly over western North America suggests that the air mass that will subsequently be advected over the Great Lakes region is colder than normal. This may contribute to the intensity of the air–lake interaction during the subsequent lake-effect snowstorm.

The composites on day −1 are shown in Fig. 10. The low pressure anomaly over Hudson Bay present at day −2 remains statistically significant, suggesting that it is a stable precursor to the onset of the lake-effect snowfall. To the west of Hudson Bay there is evidence of a high pressure anomaly that is also statistically significant. To the southwest of the Great Lakes, the weak trough identified at day −2 has evolved into a statistically significant low pressure anomaly. This is the signal of the transient low that will pass by the Great Lakes in the sequential days. The relative weakness of the signal suggests that there is considerable variability in the position and intensity of the transient system. Associated with the intensification of the pressure gradient over northern Canada, there is an increase in the strength of the anomalous northerly wind in this region. Consistent with the wind field, the magnitude of the statistically significant cold anomaly over western North America intensified between day −2 and day −1.

In Fig. 11, we show those same composites on day 0. There is evidence of the northeasterly propagation of the transient low into the Great Lakes region. The stationary low pressure anomaly over Hudson Bay is still present as is the high pressure anomaly to the west. The meridional flow associated with the height anomalies results in the southward advection of cold air from high latitudes, leading to an intensification of the negative
temperature anomaly to the northwest of the Great Lakes region identified on day −1.

The composites on day +1 are shown in Fig. 12. A well-defined and statistically significant pattern extending over much of North America can be seen in the composites. Day +1 is the typical day that intense lake-effect snowstorms over southern Ontario start. The two negative height anomalies have now merged into one, with its center situated to the northeast of the Great Lakes. It is accompanied by very intense northwesterly winds over the Great Lakes. The very intense northwesterly wind provides the maximum fetch over Lake Huron and Georgian Bay. Compared with day 0, there is a broader area where the negative temperature anomaly is less than −6°C. This increase is the result of a more consistent spatial pattern between events as well as the intensification of the cold anomaly; the latter is the result of the cold-air advection associated with the intense northwesterly wind.

The composite fields on day +3 are shown in Fig. 13. The composites maintain a large region of statistical significance and a structure that is favorable for lake-effect snowstorms over southern Ontario. The low-pressure anomaly has continued to move in a northeasterly direction with the center of the composite circulation situated over eastern Hudson Bay and the Ungava Peninsula. The northward movement of the negative height anomaly results in a westerly shift in the direction of the prevailing wind over the Great Lakes. The circulation associated with the low maintains the advection of high-latitude cold air over the Great Lakes region. There is an eastward shift in the negative temperature anomaly, and the Great Lakes region is still under cold anomaly.

b. Non-lake-effect events

We now present the sequence of composites created from the 29 most intense low pressure systems that were not associated with intense lake-effect snowstorms during the winters of 1992–99. These composites show that the evolution of synoptic environment associated with these events is different from that presented above.

In Fig. 14, we show the composite fields on day −2, as created from the 29 non-lake-effect events. In this instance, there is a positive height anomaly on the 850-
mb surface over northern Canada and the Labrador Sea, with negative anomalies over the midwestern United States and over the western Atlantic Ocean. The horizontal wind anomaly associated with these height anomalies is not favorable for the advection of cold air into the Great Lakes region. Indeed, there is no statistically significant signal in the 850-mb temperature field over North America.

The composite analysis on day $-1$ is shown in Fig. 15. At 850 mb, there is evidence of an intensification of the meridional dipole pattern identified at day $-2$. In particular, a large statistically significant low pressure anomaly is present to the southwest of the Great Lakes. As was the case at day $-2$, zonal wind associated with this dipole pattern is not favorable for the advection of high-latitude cold air to the Great Lakes, and there exists no statistically significant signal in the temperature composite.

The composite analysis on day 0 is shown in Fig. 16. The dipole pattern in the height anomaly field identified on day $-2$ has intensified and increased its area of statistical significance. In particular, the center of the low pressure anomaly is now centered over the Great Lakes. The cyclonic circulation anomaly associated with this dipole results in a positive temperature anomaly to the east of the Great Lakes and a negative temperature anomaly to the west. Compared with the composite of lake-effect events at the same time (Fig. 11b), the magnitude of the negative temperature anomaly is considerably weaker. This can be explained by the strong zonal wind to the north of the Great Lakes that prohibits the advection of cold polar air into the region.

The composite fields on day $+1$ are shown in Fig. 17. The general pattern identified earlier is still present. The low pressure anomaly has moved eastward, with its center now over the northeastern United States and maritime Canada. The strong zonal wind to the north continues to inhibit the advection of high-latitude cold air north over the Great Lakes, and as a result the magnitude of the temperature anomaly is smaller than in the corresponding lake-effect composite (Fig. 12b).

The composite fields on day $+3$ are shown in Fig. 18. The positive height anomaly over northern Canada is now diffuse and not statistically significant. The negative height anomaly has continued to move eastward, with its center now over the western North Atlantic. The
temperature anomaly associated with the composite circulation is now situated over the southeastern United States and adjoining areas of the Atlantic Ocean and has no effect on the Great Lakes region. This is in contrast to what occurs in the lake-effect composite where there still exists a significant advection of high-latitude cold air over the Great Lakes region (Figs. 13a,b).

c. Cyclone track analysis

The composite analysis shows clear differences in trajectories between these two classes of low pressure systems. To confirm these differences, a feature-tracking program was used to identify the track of all the cyclones in the two classes (Hodges 1994, 1995, 1999). Compared with the traditional Eulerian method based on bandpass-filtered variance statistics (Blackmon et al. 1977), feature tracking is a Lagrangian technique that provides for the efficient and robust calculation of the statistics on storm tracks (Hoskins and Hodges 2002). In this study, the data used were the 6-hourly NCEP reanalysis 850-mb geopotential data, and the tracking approach of Hoskins and Hodges (2002) was followed.

The original data were bandpass filtered by wave numbers $5 \leq n \leq 42$ in the spatial domain to remove variability associated with planetary wave activity and small-scale features (Hoskins and Hodges 2002). The low pressure systems identified were required to a minimum time of existence of 2 days for their track to be included in the analysis.

The statistic that we will use to identify the storm tracks associated with the two populations is the track density field (Hodges 1994). This field is calculated by using a single point from each track that is closest to the estimation point. The results are presented in Fig. 19 and show a clear difference in the track density field associated with these two classes of low pressure systems. The track density of low pressure systems associated with lake-effect events (Fig. 19a) shows a primarily northeastward propagation from the Great Lakes region toward Hudson Bay and northern Quebec. In contrast, the track density of low pressure systems associated with non-lake-effect events (Fig. 19b) shows an eastward propagation from the Great Lakes region toward the western North Atlantic. These results support the speculation advanced in section 3 (Fig. 8) that most...
of the low pressure systems associated with lake-effect events over southern Ontario have a more northward track as compared to the low pressure systems that were not associated with lake-effect events.

5. Summary

Lake-effect snowstorms are an important source of severe winter weather over southern Ontario. Although these events are typically associated with the transit of low pressure systems through the region, it is evident that not all such systems result in intense lake-effect snowfall. As a result, in this paper we have attempted to identify, through the study of individual cases and composite analysis, the distinguishing characteristics of the temporal evolution of the synoptic-scale environment associated with intense lake-effect snowstorms over southern Ontario.

This was accomplished through the development of a climatology of lake-effect snowstorms over southern Ontario. In particular, we used the historical data and some constraints to identify 29 intense lake-effect snowstorms (accumulation during the event >10 cm) that occurred over southern Ontario during the winters of 1992–99. The characteristics of the synoptic-scale environment that are favorable for lake-effect snowstorms over southern Ontario were studied through the analysis of a typical case and by composite analysis. As a control case, we also performed a composite analysis of the environment associated with the 29 most intense low pressure systems that passed over southern Ontario but did not result in the development of intense lake-effect snowstorms.

We found that the presence of a low pressure and a cold-temperature anomaly situated over Hudson Bay, north of the Great Lakes, is a favorable environment for the development of intense lake-effect snowstorms over southern Ontario. Some of the characteristics that we have identified are consistent with earlier studies (Eichenlaub 1979; Niziol et al. 1995), such as a strong northwesterly wind over Lake Huron and Georgian Bay resulting in a maximum fetch over water, and an intense cold advection of Arctic air resulting in a large temperature difference between the water and the atmosphere.

However, unlike previous studies, we have been able
Fig. 18. Composites of the (a) 850-mb geopotential height (m) and horizontal wind (m s\(^{-1}\)) and (b) 850-mb temperature (°C) for the non-lake-effect events at day +3. Details as in Fig. 9.

Fig. 19. Track density in the 850-mb geopotential height of (a) the 29 low pressure systems associated with intense lake-effect events and (b) the 29 most intense low pressure systems that were not associated with intense lake-effect events. Data are from the NCEP–NCAR reanalysis.

to show that the low pressure systems associated with intense lake-effect snowfall have very different characteristics from those that were not associated with such snowfall. In particular, the low pressure systems that trigger intense lake-effect snowstorms over southern Ontario are characterized by a northeasterly track toward Hudson Bay and northern Quebec (Figs. 9a–13a). In contrast, the low pressure systems that did not trigger lake-effect snowfall tended to move toward the east (Figs. 14a–18a). This latter track is the most common track of winter storms in eastern North America (Fig. 8).

Low pressure systems associated with lake-effect snowstorms act with the background circulation in a different manner compared with low pressure systems that did not result in lake-effect snowstorms. Lake-effect low pressure systems are typically associated with zonally oriented height anomalies that are efficient at advecting cold Arctic air over the region in northwesterly flow (Fig. 12a), a preferred orientation for the development of intense lake-effect snowfall. On the other hand, non-lake-effect low pressure systems are associated with meridionally oriented height anomalies (Fig. 17a). In this synoptic environment, the presence of a positive height anomaly to the north acts as a barrier to the advection of cold Arctic air over the Great Lakes (Fig. 17b). Also, the circulation associated with the low pressure system results in less overlake fetches for the region of interest. With regard to the forecasting of intense lake-effect snowstorms, we have identified statistically significant anomalies in the lower-tropospheric mass and temperature fields 3 days before the onset of the snowstorms. The presence of such anomalies when combined with forecast information on the track of the parent low pressure system may improve the forecasting of the onset of these events (R. Graham 2002, personal communication). In this study, the similarities and differences in the characteristics of these two classes of cyclones can be clearly seen in Fig. 20, in which the evolution of the 850-mb height and temperature fields are shown at the center of circulation in the two composites. Although there is no clear difference in the intensity of these two classes of cyclones (Fig. 20a), the magnitude of the cold anomaly is significantly larger in the lake-effect cyclones as compared to the non-lake-
effect cyclones (Fig. 20b). This is the result of the above-mentioned differences in the synoptic environment and track of the two classes of cyclones. A schematic representation of the environment associated with a lake-effect and a non-lake-effect cyclone is presented in Fig. 21. As Eichenlaub (1979) pointed out, “Usually the incursions of Arctic air necessary for large amounts of snow occur after a strong cyclone has passed through or near the Great Lakes.” The results of this study suggest that the low pressure system track in addition to its intensity plays an important role in triggering the intense lake-effect snowstorm over southern Ontario.

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