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Ice Storm '98 in Southcentral Canada and Northeastern United States: A Climatological Perspective

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With 13 Figures

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Summary

Dubbed Ice Storm '98, an extreme weather event characterized by two synoptic systems in succession dropped about 70–100 mm (in terms of water equivalent) of freezing precipitation over southeastern Ontario, southwestern Quebec and northeastern New York during a 6-day period from January 5 to 10 in 1998. Individually, the two synoptic systems were not dramatically more extreme in freezing precipitation than other major freezing rain events (4 since 1961) which occurred in the past over the affected area. Some regions in the target area, however, were impacted more by the second system. Based on an analysis of the 500 hPa vorticity field during the '98 event, we suggest that the 1997/98 El Niño had a role in creating a flow environment conducive to the rapid formation of the second synoptic system. In contrast, other major freezing rain events in the last 30 years involved only one synoptic system per event lasting no more than 3 days, and producing 20–50 mm of precipitation.

We have also found that, 3 out of 4 past major freezing rain events since 1958 were associated with the positive phase of the North Atlantic Oscillation (NAO). Consistent with this usual past association between the NAO and a major freezing rain event, Ice Storm '98 also occurred when the phase of the NAO was positive. Analysis of these 3 past and the '98 events also indicates an apparent connection between the positive phase of the NAO and the northern Quebec high pressure system, which is an essential synoptic feature of a major freezing rain occurrence over the southcentral region of Canada. As measured by their respective indices, the maximum positive NAO state leads the maximum northern Quebec high by about 2 days (5 days in the '98 event). There is some suggestive evidence to indicate that the persistence of the northern Quebec high pressure system is connected to the persistence of the positive phase of the NAO.

1. Introduction

During a period lasting from around January 5 to 10, 1998, a combination of various meteorological factors produced a synoptic event which caused freezing rain and drizzle, severely affecting a region stretching from southeastern Ontario to southwestern Quebec, as well as northeastern United States. Because of its severity in terms of economic and ecosystem damage, the synoptic event has been called "Ice Storm '98". See Fig. 1.

Typically, regions in southern Ontario and southern Quebec experience freezing precipitation events slightly greater than 50 hours a year (Stuart and Isaac, 1999). Each event is usually characterized by a line or an area with a spatial dimension on an order of few hundred kilometers associated mostly with the warm front of a synoptic system, and lasting for only a few hours. Comparatively, Ice Storm '98 lasted from January 5 to 10, giving more than a total of 80 hours of freezing rain, drizzle and ice pellets (Milton and Bourque, 1999). Figure 2 (derived from a set of preliminary data from Environment Canada) shows the total amount of freezing precipitation in terms of water equivalent which fell during the event. Although about 70 to 80 mm fell in southeastern Ontario

Fig. 1. A newspaper photograph depicting some aspects of the impact of Ice Storm ’98 on the electrical power delivery system. (*Source*: Canadian Press)

and southwestern Quebec, some areas just to the south in the United States received amounts greater than 100 mm; this is about 10 times more than the climatological amount of precipitation received in any “typical” freezing rain event in these regions. During the maximum intensity of Ice Storm ’98, the affected regions extended from central Ontario, through southern Quebec and into some parts of New Brunswick and Nova Scotia. Northeastern areas of the United States were also severely affected.

Undoubtedly, Ice Storm ’98 was an extreme freezing rain event. However, there have been other major freezing rain events in the recent past. In this study, we will examine both similarities and differences in synoptic characteristics of Ice Storm ’98 compared with the climatological features of the other major freezing rain events. We will discuss Ice Storm ’98 within the context of its relatively unusual duration and precipitation amount, and offer possible reasons for this unusualness within the conceptual framework of El Niño and the North Atlantic Oscillation (NAO). We will present evidence to suggest that a timely combination of two synoptic systems in rapid succession and the persistent NAO-northern Quebec anticyclone association produced the cumulative results of Ice Storm ’98.

2. Data

The meteorological data used for the synoptic analysis of Ice Storm ’98 were obtained from the Atmospheric Environment Service (AES) in Montreal. The precipitation data were extracted from the archived data file in AES. All other meteorological data for the analysis of previous

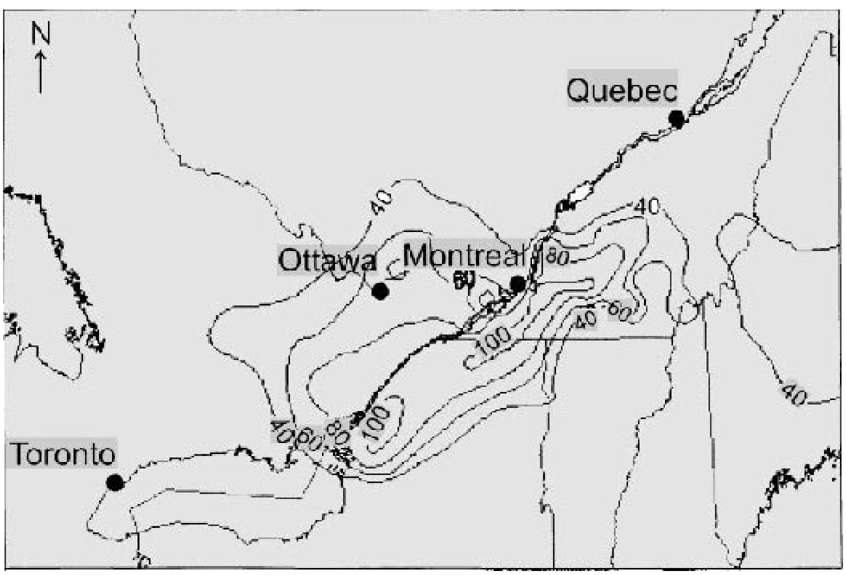


Fig. 2. Distribution of freezing precipitation accumulation over the target area, in terms of water equivalent in mm, between January 5 to 10, 1998

major freezing rain events were obtained from the available re-analyzed NCEP (National Center for Environmental Prediction) data covering the period from 1958 to 1997 (Kalnay et al., 1996). For the purpose of this study, the regions of southeastern Ontario, southwestern Quebec and northeastern New York state will be referred as the target area.

3. Climatological Characterization of the Synoptic Conditions for Freezing Rain

A typical synoptic configuration for a significant freezing precipitation over the target area is given by Koolwine (1975), Stewart and King (1987), and Cantin and Bachand (1990). Briefly, it is characterized by a high pressure system over northern Quebec advecting cold northeasterly air, as a low pressure system moves into the target area from the southwest, allowing southerly intrusion of warm, moist air into a lower tropospheric layer centred around 850 hPa. Cantin and Bachand (1990) found that a vertical atmospheric structure associated with this kind of synoptic pattern is characterized by a warm layer (above 0 °C) centered around 850 hPa, with 700–850 hPa thickness greater than 154 m and 850–1000 hPa thickness somewhere between 129 to 131 m. Ice Storm '98 and other major freezing precipitation events in the recent past over the target area certainly satisfy these meteorological conditions (Milton and Bourque, 1999).

The five major freezing rain events over the target area since 1958 are listed in Table 1 (Milton and Boruque, 1999; Etkin, personal communication). [The year 1958 was the beginning of the re-analysed NCEP data available to the authors in this study.] There have been 4 major freezing rain events over the target area (not counting Ice Storm '98), each lasting 2 to 3 days, and all occurring during non-El Niño winters. A closer examination of these 4 events showed that, with the exception of the 1997 case, each displayed a very similar synoptic evolutionary pattern, each involving a single synoptic system. Therefore, we proceeded to construct composite (average of the first 3 freezing events (1961, 1972, 1983) identified in Table 1) time series of 1000 hPa height and 850–925 hPa moisture flux/divergence fields over a 7-day window surrounding the freezing rain event, with the 5th day denoting the time of maximum

Table 1. *Major Freezing Rain Events over the Target Area since 1958, Provided by Jennifer Milton (Quebec Region, AES). Amount is given in Water Equivalent*

Time	Cumulative Amount
February 23–25, 1961	Ottawa – 32 mm Montreal – 26 mm
March 22–23, 1972	Lower Laurentians – 15 to 40 mm Mix of rain and freezing rain in western Quebec and Montreal
December 12–14, 1983	30 to > 50 mm in Montreal region and Lower Laurentians
January 4–5, 1997	20 to 40 mm Mostly over Laurentians – Three Rivers regions
January 5–10, 1998	70–100 mm over some regions, mostly from the second synoptic system

moisture flux convergence (negative divergence) over the target area.

Because the synoptic evolution which finally led to the freezing precipitation over the target area in January, 1997 is noticeably different, it will be briefly discussed in a separate section (Section 7). We have also constructed and will discuss the behaviour of the composite NAO index associated with a typical major freezing rain event in the target area, and how the positive phase of the NAO becomes associated with the high pressure system over northern Quebec. However, the major freezing event of January 4–5, 1997 (the second last event listed in Table 1) occurred in association with a negative phase of the NAO, even though during the freezing event the NAO index became less negative.

3.1 1000 hPa Height Field

Figure 3 shows a composite daily time series of the 1000 hPa height field from Day 1 to Day 7, with Day 5 corresponding to the time of maximum moisture flux convergence over the target area. (The time of maximum moisture flux convergence over the target area correlates with the time of maximum freezing precipitation.) In Day 1 (Fig. 3a), about 4 days prior to the occurrence of freezing precipitation over the target area, a very broad zone of high pressure system stretched across the mid-latitude North Atlantic,

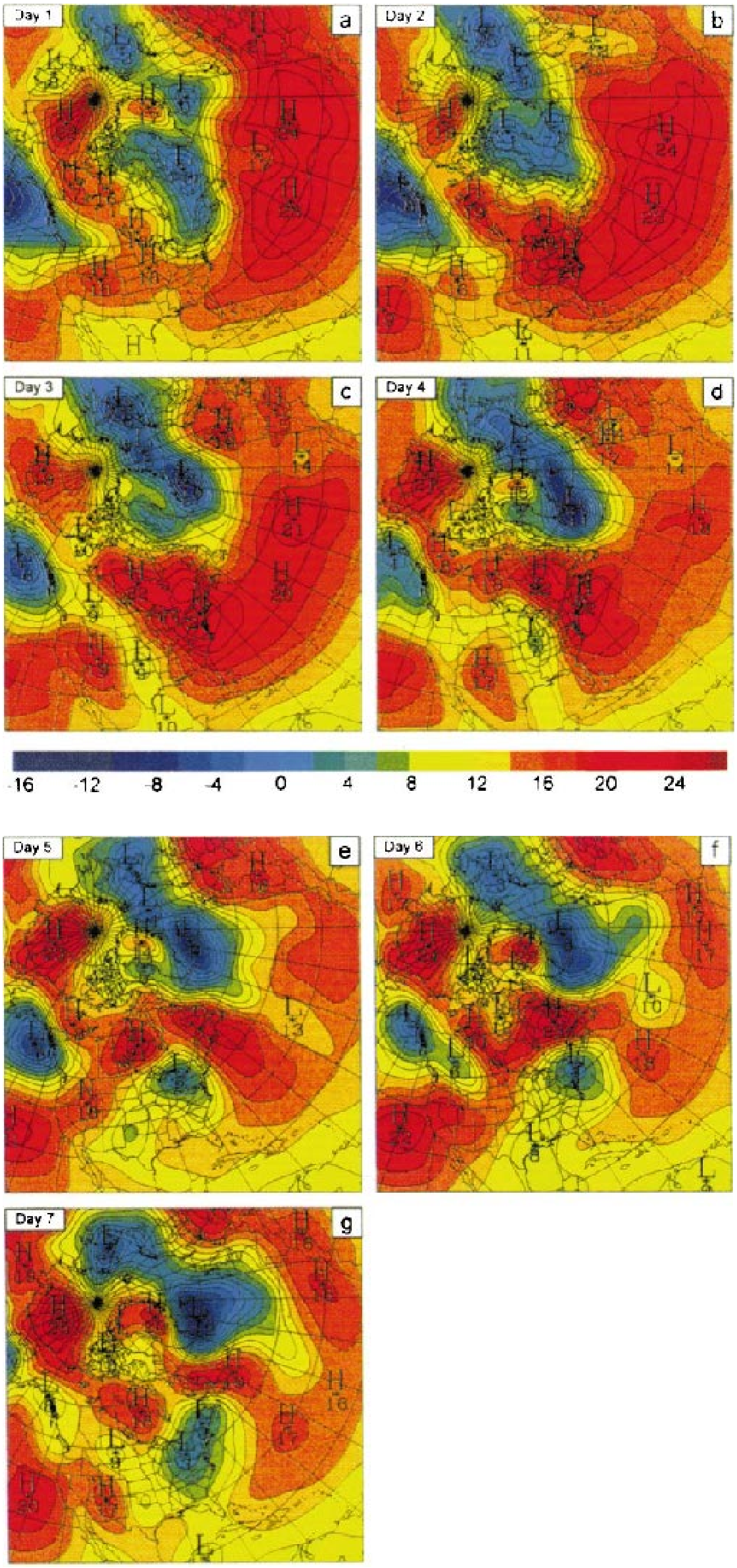


Fig. 3. Composite daily time series of the 1000 hPa height field, obtained by averaging the field associated with 3 major freezing events (1961, 1972, 1983). Day 5 corresponds to the time of maximum moisture flux convergence over the target area. Contour interval is 2 decametres (dams)

particularly between 30° N to 40° N, from North America to Europe. An intense low pressure system, with a trough extending southwestward to the Great Lakes region, was situated over the Labrador Sea. Another trough extended eastward toward the North Sea.

A relatively weak high pressure ridge to the west of the Labrador-Sea low pressure system intensified, spread eastward, and eventually made a direct connection with the mid-latitude North Atlantic high pressure band, as the low pressure system weakened over eastern Canada while expanding eastward to dominate much of the sub-arctic Atlantic Ocean (Fig. 3c, Day 3). In the meantime, a lee cyclogenesis took place in the mid-western United States (Day 3). As this low pressure system intensified, with upper air support, and moved northeastward, the high pressure system which dominated eastern Canada/US on Day 3 began to shrink in size while maintaining its magnitude, but remained connected to the mid-latitude North Atlantic high pressure band (Days 4 and 5).

On Day 5, the synoptic low pressure system reached its maximum intensity as it arrived over the target area. The spatial pattern of the 1000 hPa height field over eastern Canada/US was almost identical to the pattern shown by Koolwine (1975) which was associated with a major freezing rain event over the target area in winter. Cold north-easterly air from the high pressure region over northern Quebec was advected near the surface towards the target area while warm, moist air from the low system was advected northeastward over the surface cold air.

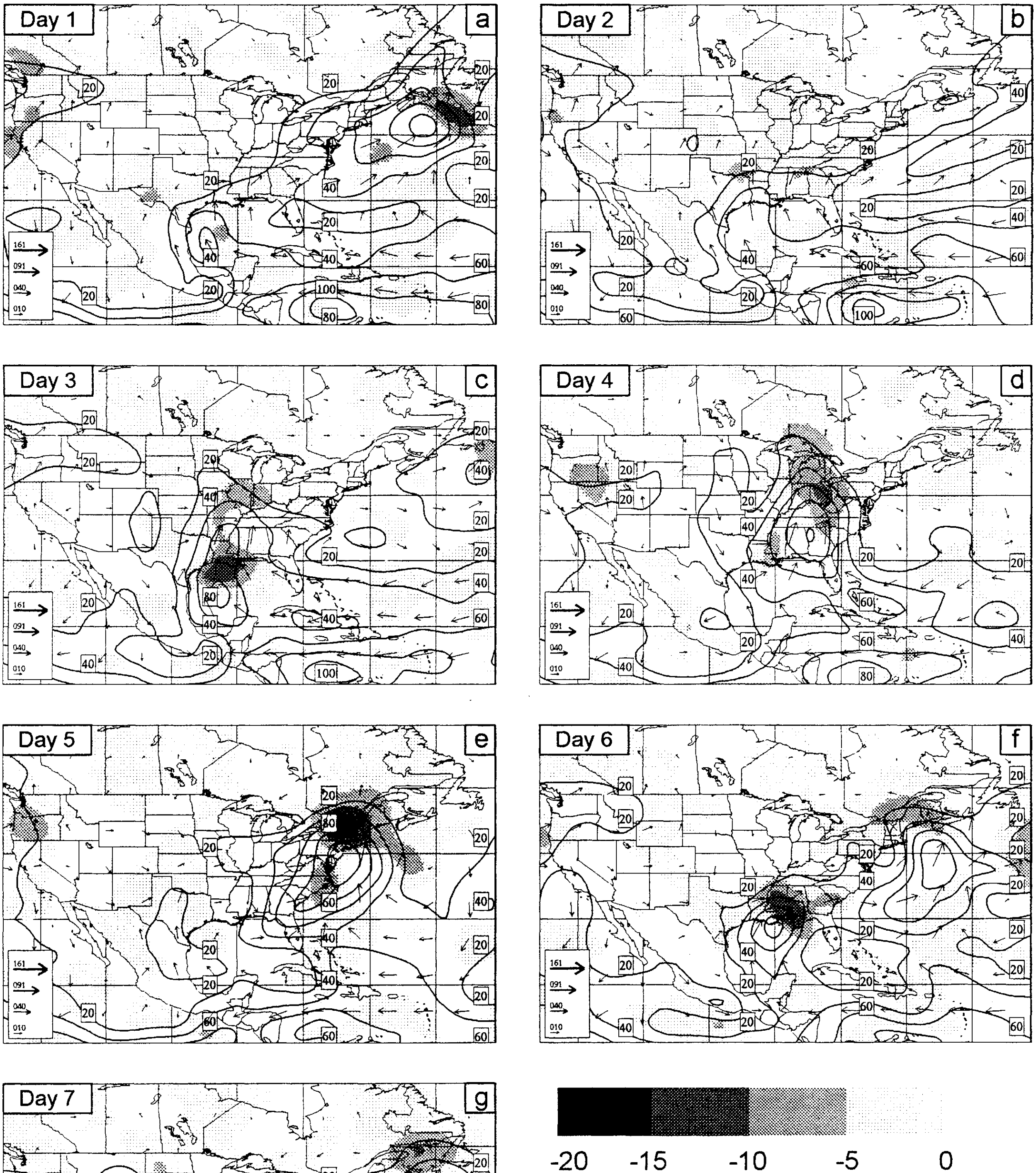
By Day 6 (Fig. 3f), the large low pressure system over the sub-arctic North Atlantic had expanded southward to cover much of the northern portion of the North Atlantic Ocean, pushing the mid-latitude North Atlantic high pressure system southward. This high pressure system was still connected to the northern Quebec high pressure area. However, the synoptic flow configuration for freezing rain in the target area was now gone, as the low pressure area which was situated in the target area moved northeastward, distorting and greatly weakening the ridge between the northern Quebec and the western North Atlantic high pressure systems (Day 7). We also detect, by this time, development of a high pressure system over Greenland which eventually connected with the remnant of the high pressure system over Canada.

3.2 850–925 hPa Moisture Flux and 850 hPa Moisture Flux Divergence

Figure 4 shows a composite daily time series of the 850–925hPa moisture transport and 850 hPa moisture flux divergence fields from Day 1 to Day 7, with, again, Day 5 corresponding to the time of maximum moisture flux convergence over the target area. The moisture transport and flux divergence fields were calculated as

$$\frac{1}{g}\int q\vec{V}\,dp \quad \text{and} \quad \nabla \bullet q\vec{V}\text{, respectively,}$$

where g is the gravitational acceleration, q is the mixing ratio, $\vec{V}$ is the wind vector and p is the pressure. Physically consistent with the 1000 hPa heights, Days 1 and 2 (Fig. 4a and b) show very little sign of any intense moisture transport and moisture flux convergence over eastern half of North America. However, on Day 3 (Fig. 4c), distinct moisture flux convergence occurred over the mid-southern United States, ahead of the southern portion of the low-pressure trough (Fig. 3c). The moisture source for this system appears to be the Gulf of Mexico at this stage in the system evolution. As this low pressure system intensified and moved northeastward, the moisture flux convergence ahead of the system also intensified (Day 4, Fig. 4d) reaching a maximum value over the target area on Day 5 (Fig. 4e). The moisture transport field was an elongated structure located to the east of the main low pressure system stretching along the eastern United States. The source of moisture had now shifted to subtropical western North Atlantic. On Days 6 and 7 (Fig. 4f) and (g), the system moved on to "join" the Icelandic Low. There was a weak but distinguishable area of moisture flux convergence in the southwestern United States on Day 6; this was a "tail" end of the main system which went through the target area on Day 5 and did not affect the target area. Note that prior to Ice Storm '98, the major freezing rain events listed in Table 1 involved only one synoptic system per event which lasted typically for no more than 3 days, and dropped about 20–50 mm of cumulative precipitation.



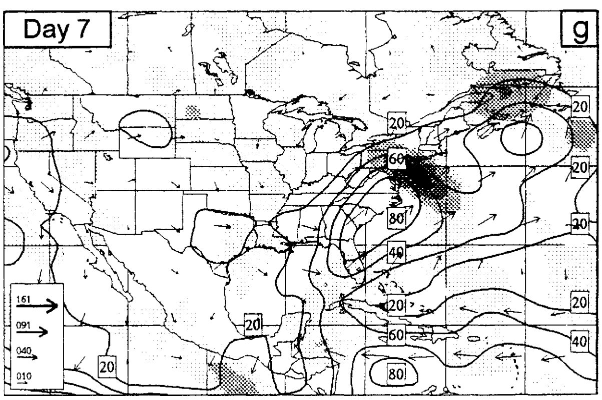


Fig. 4. 850–925 hPa moisture transport (contour lines) and 850 hPa moisture flux convergence (shaded regions). Arrows indicate magnitude and direction of the moisture transport. Units are: kg m^{-2} s^{-1} for the moisture transport, with contour interval of 20 kg m^{-2} s^{-1}, and 10^{-8} s^{-1} for the moisture flux divergence field

3.3 North Atlantic Oscillation Index

The NAO teleconnection pattern is a dominant mode of atmospheric variability in the North Atlantic sector, accounting for more than 30% of the hemispheric variability in the surface pressure data (Cayan, 1992). Although the NAO low frequency variability mode is most pronounced during the winter season, it is identifiable throughout the year. The NAO has a north-south dipole structure with opposite sign in its height and pressure anomaly fields, with the positive phase composed of a negative anomaly centre located over the Greenland region and a positive anomaly area stretching zonally across the mid-latitude North Atlantic between 35° and 40° N from the eastern United States to Europe. The negative phase of the NAO has an opposite anomaly pattern. The NAO index which is designed to capture the salient feature of NAO variability, is usually defined as the difference in the normalized sea level pressures between the Azores and Iceland (Walker and Bliss, 1932; Rogers, 1984). In this study, we used the amplitude of the first rotated winter eigenvector of the 700 hPa height anomaly field as the NAO index (Barnston and Livezey, 1987). This gives a better spatial characterization of the NAO pattern than the surface pressure difference between two geographical locations, although it should be noted that the NAO indices calculated by these two methods are significantly correlated but not exactly alike.

Figure 5 shows a composite time series of an area-averaged (a rectangular area bounded north-south by 60° and 55° N, respectively, and west-east by 75° and 65° W, respectively) 1000 hPa height over northern Quebec, with Day 5 again designating the time of maximum moisture flux convergence over the target area. Hereafter, we will refer to such time series as the Northern Quebec Height Index (NQHI) in decametres. Consistent with the composite 1000 hPa height field evolution described in Section 3.1, NQHI increased quickly from around 4 on Day 1 to about 17 on Day 5. The index value reached a maximum on Day 6, but started to decrease rapidly thereafter, reaching around 10 by Day 7.

Also shown in Fig. 5 is a composite time series of the NAO index. The index became positive on Day 1 and increased over the next few days until it reached a maximum of around 1.4 on Day 3. It started to decrease very rapidly after Day 5 and became negative by Day 6. Note that the gradual degradation of the positive NAO started about a day or two before NQHI began its own decline in

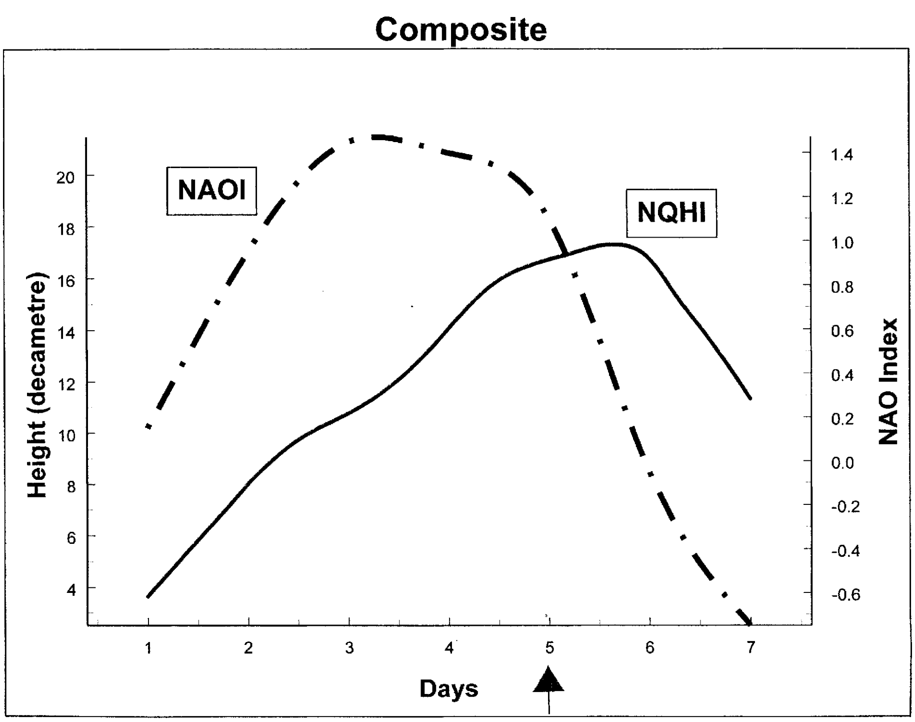


Fig. 5. Composite time series of NQHI (Northern Quebec Height Index), an area-averaged 1000 hPa height over northern Quebec (solid line), with Day 5 corresponding to the time of maximum moisture flux convergence over the target area. The time series of the NAO index over the same time period is indicated by the dot-dashed line. Units of the height field are in decametres (dams)

value. A statistically significant (at the 85% confidence level) maximum correlation of 0.75 between the NAO index and NQHI was obtained with NQHI lagging the NAO index by about two days. We suggest that the positive phase of the NAO and the Quebec high pressure area evolve as different dynamical entities, the southern cell of the former originating as a subtropical warm high pressure area, the latter as a continental Arctic airmass; but once they become synoptically coupled via a blocking pattern, the persistence of the Quebec high pressure area appears to be associated (dynamically linked?) with the mid-latitude North Atlantic Ocean high pressure system (the southern cell of the north-south dipole structure of the positive phase of the NAO).

4. Synoptic Evolution of Ice Storm '98

4.1 1000 hPa Height Field

Figure 6 displays a series of 12:00 UTC snapshots of the 1000 hPa height field from January 3 to 10. In January 3 (Fig. 6a), a weak low pressure system lay over central Ontario, with a trough extending in the northeast-southwest direction. The high pressure system from North America to Europe was a dominant feature. By January 4 (Fig. 6b), the high pressure ridge observed 24 hours ago over western Canada had joined the North Atlantic high pressure system (southern centre of the positive phase of the NAO dipole pattern) to form a high pressure belt stretching southeastward from the Yukon to the southeastern United States. As indicated by the studies already mentioned above, the high pressure region over northern Quebec is an important component of the freezing precipitation occurrence by causing a northeastward flow over the target area, advecting a shallow tongue of cold air below a warm and moist southwesterly flow; this synoptic configuration remained quasi-stationary until its decay around January 10. By January 5, a trough protruded into southern Ontario and Quebec from the mid-western U.S., allowing the first wave of northward flux of warm air and moisture into the target region. On January 7 (not shown), the trough had weakened as the high pressure system observed on January 6, established itself firmly over northern Quebec, ending the first wave of precipitation associated with Ice Storm '98.

The second wave started with a developing low pressure system in the southeastern United States, with a trough extending into the target region (Fig. 6e, January 7). Over the next few days, this low pressure system slowly moved northward, while the northward extending trough shifted slowly eastward (Fig. 6f and g). The zonal high pressure belt over the mid-latitude North Atlantic split into two cells, with the western cell persisting to give a strong southwesterly flow over the eastern seaboard. By January 10 (Fig. 6h), the low pressure centre moved to just south of Hudson Bay, with a trough extending eastward to join a relatively massive low pressure system located over the eastern North Atlantic, stretching from 30° N to the North Sea. By this time, the high pressure ridge with an embedded centre which covered much of northern Quebec a few days earlier weakened and was forced to retreat northward.

4.2 850–925 hPa Moisture Flux and 850 hPa Moisture Flux Divergence

One of the unusual aspects of Ice Storm '98 was that the target area received an excessive cumulative amount of moisture (in the form of freezing rain and drizzle) over the 6-day period. Moisture flux into the target area from January 5 to 10 came in two waves, associated with the two synoptic systems which carried warm and moist air from the Gulf of Mexico and the western tropical Atlantic Ocean.

Figure 7 shows a series of 12:00 UTC snapshots of the 850–925 hPa moisture transport and moisture flux divergence from January 3 to 10. Figure 7a indicates that there was already some moisture advected into the target area on January 3, with moisture convergence taking place just to the south of Lake Erie. The precipitation from this system over the target area was in the form of rain. The northeastward advance of the first wave of the moisture flux toward the target region associated with Ice Storm '98 is evident on January 4 (Fig. 7b). The moisture flux reached about 50 kg m^{-2} s^{-1} over the target area during January 5 and 6 (Fig. 7c and (d). Figure 7e shows a short break after the first wave in freezing precipitation before the approach of the second wave. Unlike the first wave, the moisture flux associated with the second wave moved northeastward, and the target area caught the western edge of the area of moisture

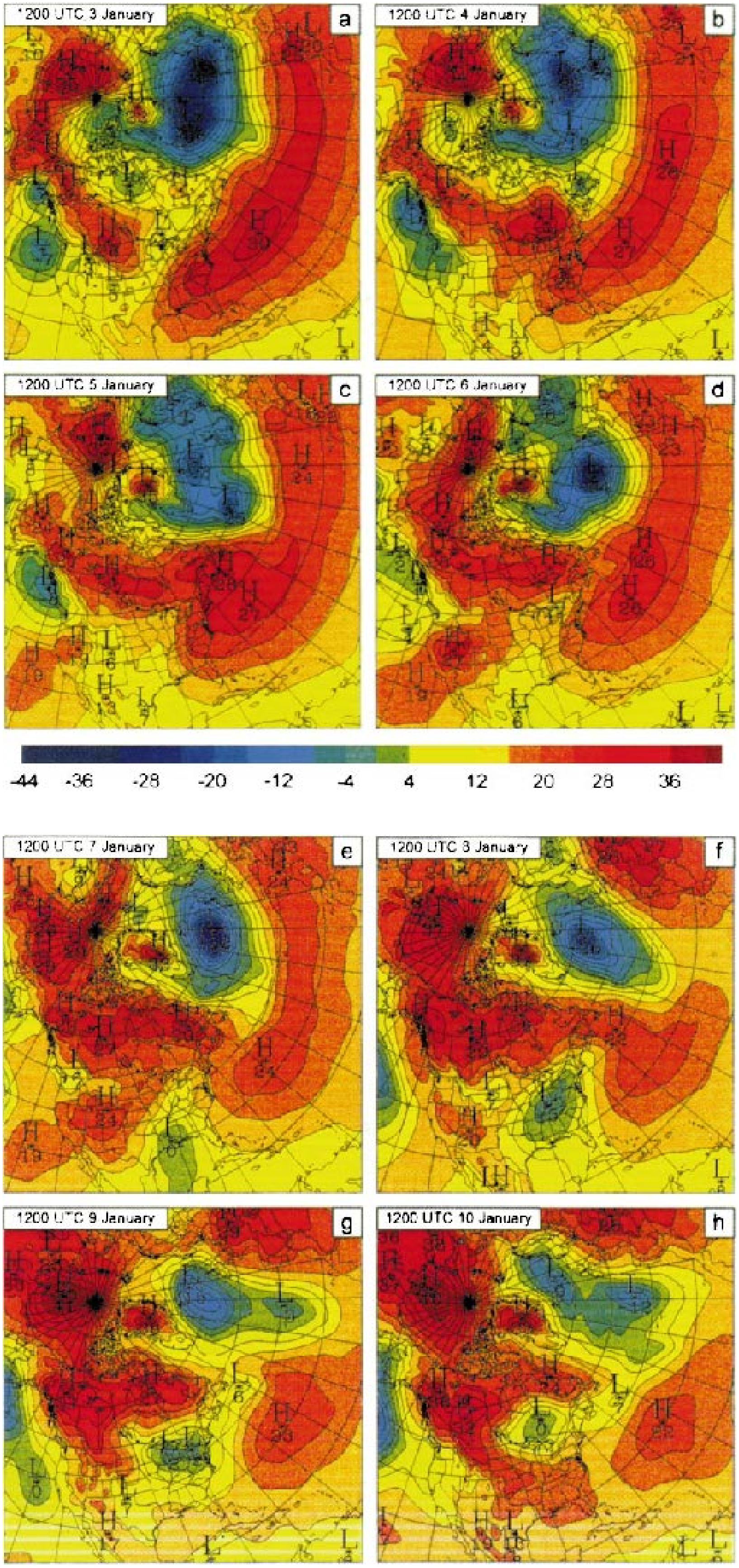


Fig. 6. 1000 hPa height field during Ice Storm '98. Each panel shows observation 24 hours apart from (a) 12:00 UTC, January 3 to (h) 12:00 UTC, January 10, 1998. Contour interval is 4 decametres (dams)

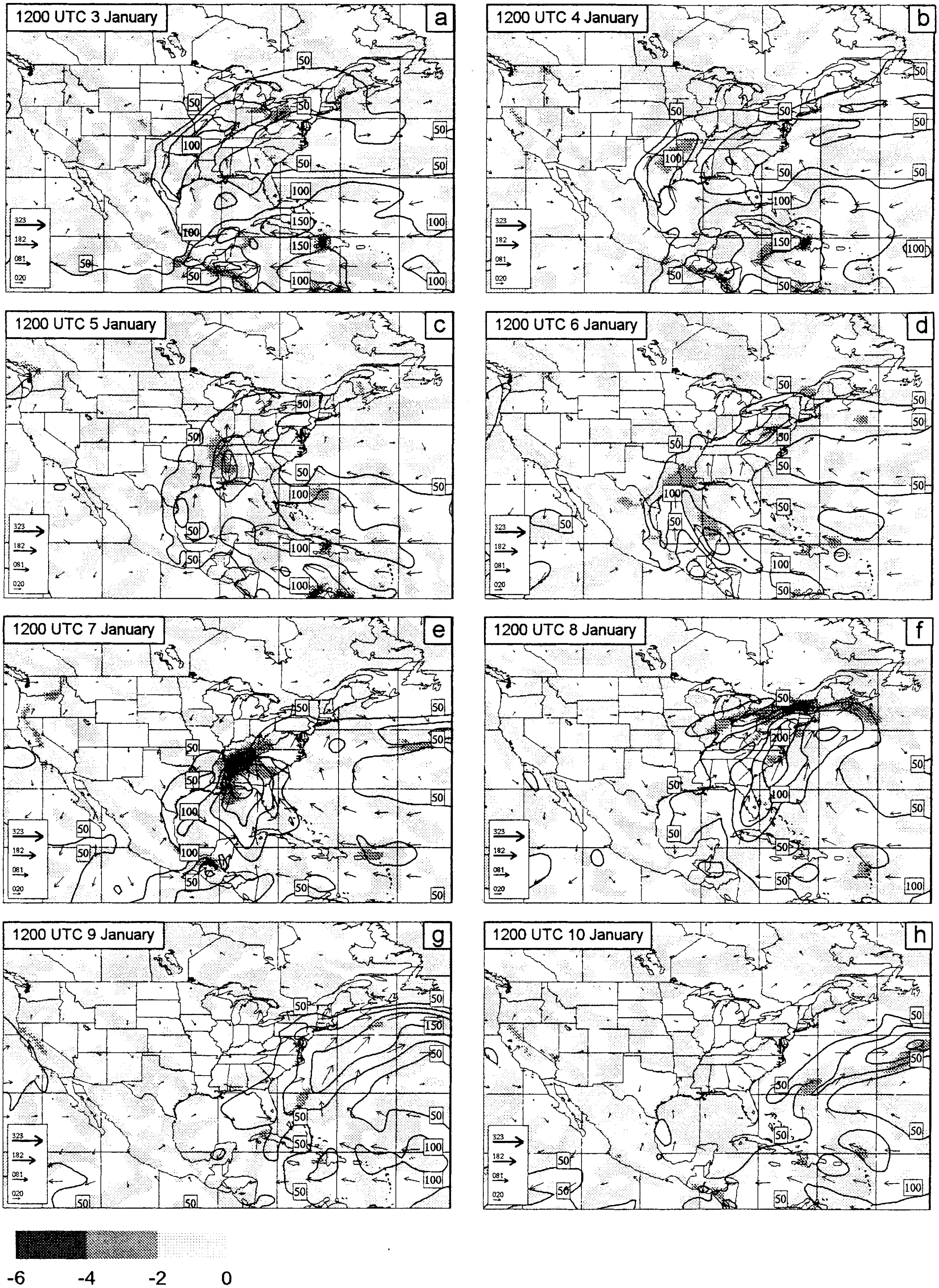


Fig. 7. Same as in Fig. 4, except for the 850–925 hPa moisture transport (contour lines) and 850 hPa moisture flux divergence (shaded regions). Arrows indicate magnitude and direction of the moisture transport. Units are: kg m^{-2} s^{-1} for the moisture transport, with contour interval of 50 kg m^{-2} s^{-1}, and 10^{-7} s^{-1} for the moisture flux divergence field

flux (Fig. 7f and g). A significant area of moisture flux convergence can be seen over the southeastern U.S. on January 7 (Fig. 7e). By January 8, the region of maximum moisture flux convergence was concentrated over northeastern New York state, with a main elongated area of convergence stretching southwestward into southern Ontario (Fig. 7f). The Maritime provinces suffered the brunt of the second wave which dropped much of its precipitation in liquid form, but did cause some minor damage in the form of freezing precipitation in some parts of New Brunswick and Nova Scotia. Much of the freezing precipitation came from the second wave, consistent with the stronger moisture flux convergence. By January 10, the system had moved off the east coast of North America (Fig. 7h).

4.3 NAO and NQHI

In the manner similar to Fig. 5 for the composite case, Fig. 8 shows the NAO and NHQ indices for the period January 1 to 10, 1998. Again, consistent with the discussion of the 1000 hPa height field evolution in Section 4.1, NQHI began with a value of about 6 decametres on January 1. It rose quickly after January 3, reaching a maximum value of about 24 on January 7. The index declined thereafter to about 14 by January 11.

The NAO pattern transformed quickly into the positive phase during the latter part of December, 1997, and by January 1, 1998, the index was close to its maximum value of 3.2, which it reached on January 3. If the NAO index is any indication of its strength, then the positive NAO during Ice Storm '98 was more than twice as intense as those associated with an average major freezing event. The pattern of the positive phase of the NAO started to disintegrate after January 3, reaching an index value of 0 by January 8. A statistically significant (at the 90% confidence level) maximum correlation of 0.82 between the NAO index and NQHI was obtained with NQHI lagging the NAO index by about 5 days. This is longer than the 2-day lag for the composite case.

By the time the first synoptic system associated with Ice Storm '98 hit the target area on January 5, the high pressure system in northern Quebec was already established but was still intensifying. At the same time, the NAO index was declining in value but still showing indication of a very strong positive phase pattern. The second synoptic system entered the target area after January 7, as NQHI reached its maximum value. Over the next few days, the intensity of the northern Quebec high pressure area began to wane as the NAO index rapidly reached 0. Even though the pattern of the positive phase of the NAO, as identified by

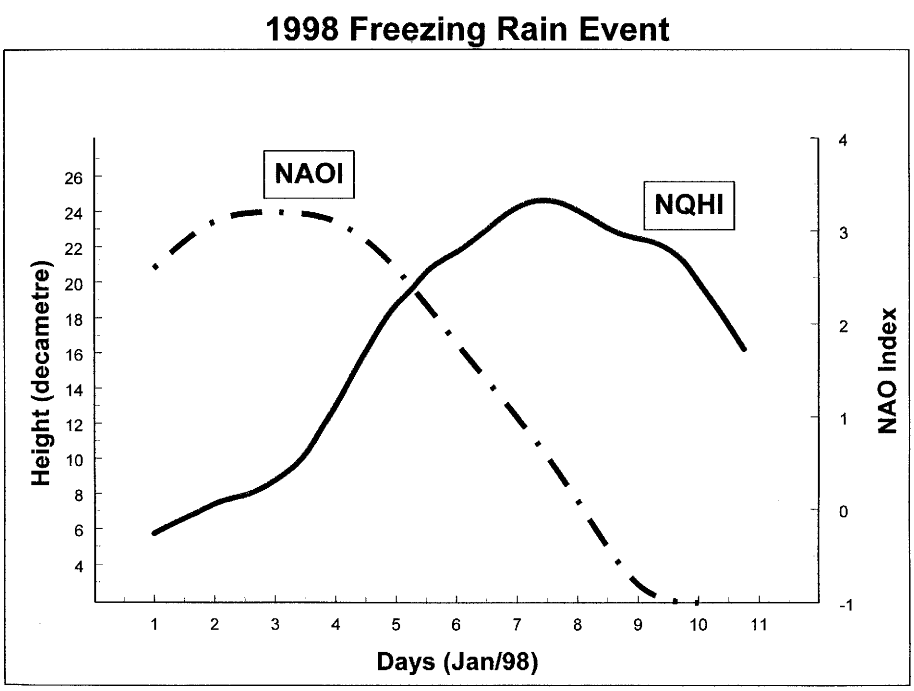


Fig. 8. Same as Fig. 5, except for the period January 1 to 10, 1998

the first EOF (empirical orthogonal function) of the 700 hPa height anomaly field over the North Atlantic Ocean, disintegrated by January 8, the western remnant of the midlatitude North Atlantic high pressure band of the positive NAO persisted during the second synoptic system (Fig. 6f). (It is interesting to note that the pattern in Fig. 6f is similar to the pattern observed during the January 1997 case when a major freezing rain event occurred in association with a negative phase of the NAO. See Section 7.) But this western remnant was also decaying, weakening the connection with the northern Quebec high pressure area. This allowed the severing of the link between the NAO and the northern Quebec high pressure area by the second synoptic system. These final stages of Ice Storm '98 are consistent with the overall decay process of the composite case.

5. Comparison between Ice Storm '98 and Previous Major Freezing Events

5.1 Similarities

(1) Evolution of the high pressure pattern North America and North Atlantic Ocean prior to and after Ice Storm '98 appears similar to that observed in the composite. A high pressure system develops from northwestern Canada and eventually connects with the western side of the already existing high pressure band (southern portion of the positive phase NAO) stretching across the North Atlantic at around 30° to 40° N latitude, thereby establishing a high pressure system over Quebec. After the freezing rain event over the target area, the responsible low pressure system moves northeastward, greatly weakening the synoptic connection between the high over Quebec and the North Atlantic high. Shortly afterwards, we observe weakening and eventual dissipation of the Quebec high, as well as reversion of the phase of the NAO from positive to negative as a high pressure system develops over the Greenland region.

(2) As implied above, there is an apparent association between the positive NAO and the Quebec high pressure area, as indicated in the synoptic evolution of the high pressure system pattern. Dissipation of the anticyclone over Quebec is coincidental with the positive-to-negative phase transition in the NAO.

(3) The NAO phase goes from negative to positive over several days prior to the actual freezing rain event over the target area. The establishment of the positive NAO, with a high pressure band stretching across the midlatitude Atlantic Ocean from North America to Europe (first eigenvector of the 700 hPa height anomaly field), blocks the relatively eastward movement of synoptic low pressure systems, causing them to veer northeastward. (This effect is accentuated more dramatically during Ice Storm '98 than shown in the composite analysis. See later in the paper.) The northeastward movement of low pressure systems, bringing with them warm, moist air, sets up synoptic conditions favourable for freezing rain once the Quebec high pressure system is formed to push cold air southward in the northeasterly flow in the surface layer (Koolwine, 1975).

(4) The NAO remains in the positive phase for about a week. (Previous major freezing rain events occurred in non-El Niño winters while Ice Storm '98 took place during one of the most intensive El Niño winters of recent time.) Following Barnett (1985), who concluded that the NAO-like oscillation over the North Atlantic is due to nonlinear dynamics of the atmosphere and is not wholly dependent on boundary forcing, this is consistent with the idea that a short-term flip-flop in the phase of the NAO is a result of "local" nonlinear dynamical interactions in the atmospheric flow.

(5) Sources of moisture are mainly from the tropical/subtropical western North Atlantic, but there was a significant contribution from the Gulf of Mexico during Ice Storm '98. Total cumulative amount of freezing precipitation from *an individual synoptic system* averages anywhere from 20 to 50 mm.

5.2 Differences

(1) Compared to the composite NAO, the positive phase of the NAO during Ice Storm '98 lasted several days longer, becoming positive about December 29, 1997 and

terminating on January 8, 1998. But much more significant is the fact that the strength of the positive NAO during Ice Storm '98 was much stronger (the NAO index of 3.2 was at its maximum around January 3, 1998) compared to the composite NAO (with its maximum index of around 1.4).

(2) Unlike previous major freezing rain events, Ice Storm '98 was characterized by not just one, but by two successive synoptic waves, dropping a cumulative amount of more than 100 mm water equivalent of freezing rain over some portions of the target area. The second storm entered the target area only one day after the first one. Individually, the two synoptic systems were not significantly more extreme in freezing rain precipitation than other major freezing rain events in the recent past.

(3) Because of the intensity of the NAO-Quebec high pressure area connection during Ice Storm '98, it was not destroyed after the passage of the first synoptic system. The high pressure system over Quebec remained, advecting cold northeasterly air into south-western Quebec as the second system approached the target area from the south-southwest.

(4) For Ice Storm '98, the positive phase of the NAO started about 7 days prior to the first freezing event on January 5, 1998, compared to an average of about 5 days for the composite case. It is interesting to note that the January 5th event took place while the positive phase of the NAO was decaying. In fact, a synoptic system did go through the target area on January 3 when the NAO index was at its positive maximum; this system did not cause freezing precipitation because the Quebec high pressure area was not present at that time.

6. Possible Role of the El Niño in Ice Storm '98

Whereas the previous major freezing rain events occurred in non-El Niño winters, Ice Storm '98 took place during one of the most intensive ENSO winters in recent times. The relation between El Niño and Ice Storm '98 has already been discussed by Barsugli et al. (1999).

A very distinctive Pacific/North American (PNA) low frequency variability mode pattern, with a low pressure anomaly over the northern

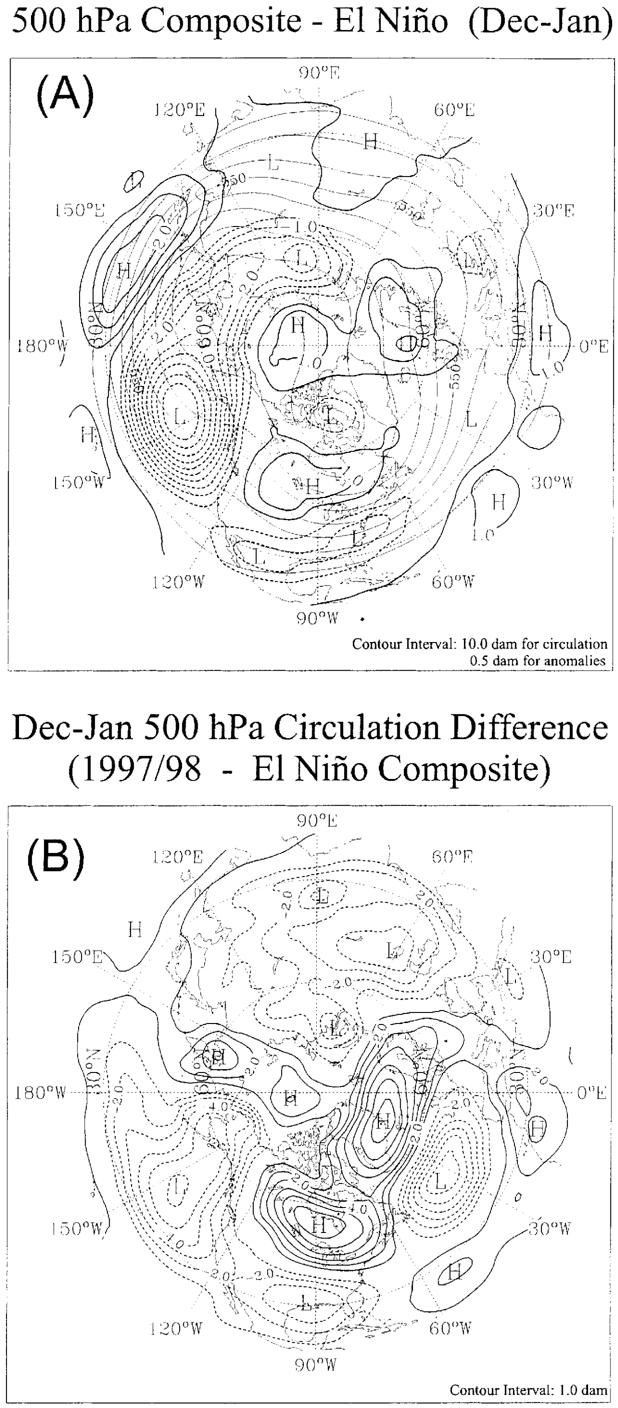


Fig. 9. (A) 500 hPa climatological height and anomaly during moderate to strong El Niño episodes for the December to January period. Contour interval is 10 dams for the height and 0.5 dam for the anomaly. (B) Difference in the 500 hPa height anomaly between 1997–98 and the climatological El Niño for the December to January period. Contour interval is 1.0 dam

North Pacific, followed by a high pressure anomaly over western Canada and a low pressure anomaly over southeastern United States, is

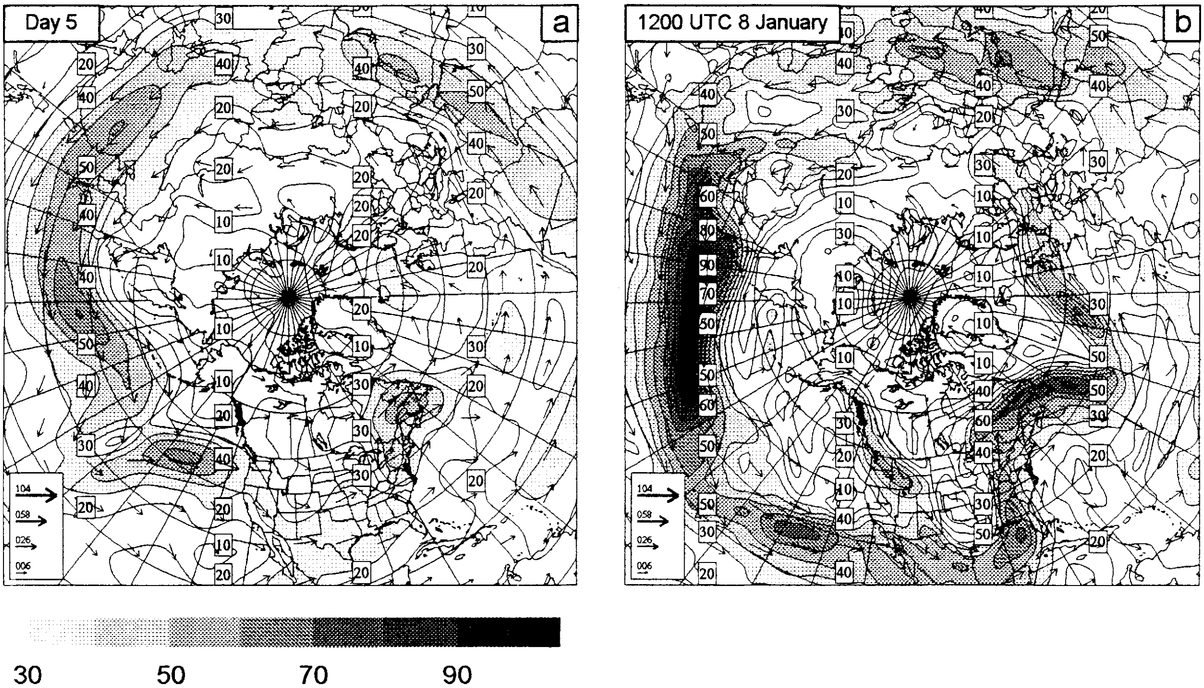


Fig. 10. Wind field (ms^{-1}) at the 250 hPa height level, showing jet streams at (a) Day 5 of the composite average and at (b) 12:00 UTC, January 8, 1998

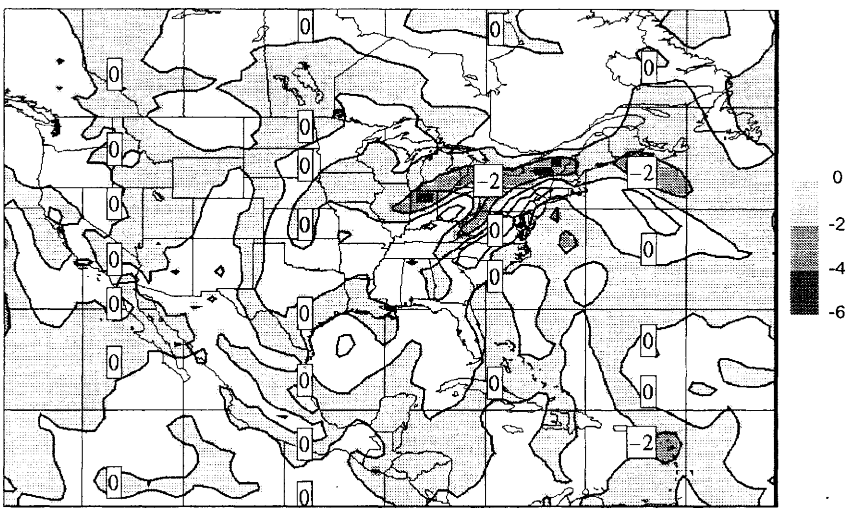


Fig. 11. Difference in the 850 hPa moisture flux divergence field ($10^{-7}\,s^{-1}$) obtained by subtracting the composite Day 5 case from the 12:00 UTC, January 8, 1998 case. Negative areas are shaded

usually associated with a moderate to strong El Niño-Southern Oscillation (ENSO) winter (Wallace and Gutzler, 1981; Horel and Wallace, 1981; Barnston and Livezey, 1987). This pattern is caused by a standing Rossby wave, carrying an ENSO signal northward from the tropical Pacific Ocean and bending eastward with increasing Coriolis force in high latitudes (Hoskins and Karoly, 1981; Lin and Yu, 1990). A climatological 500 hPa composite anomaly field for December/January of an El Niño winter is shown in Fig. 9a. The anomaly field is characterized by an identifiable positive phase of the PNA, with a very deep low anomalous height area located over the Gulf of Alaska area. There is very little difference in the height field over the northern North Atlantic region between the El Niño and the non-El Niño December/January period.

The 1997/98 winter experienced a very strong ENSO event, with magnitude similar to the one in the 1982/83 winter. The difference in the Northern Hemisphere 500 hPa height anomaly between the December/97–January/98 field and the typical December/January El Niño winter one is shown in Fig. 9b. We note that the overall pattern spatial pattern of the 1997/98 El Niño is similar to the climatological El Niño pattern, except for the intensity. Another notable difference is seen over the North Atlantic, where, compared to a typical El Niño winter, a very distinctive negative phase of the NAO is observed. However, beginning late December, 1997 the NAO started to evolve into a positive phase pattern, with its index reaching a maximum greater than 3 on the 3rd of January, 1998. The NAO index stayed positive during much of the time period associated with Ice Storm '98, becoming 0 by January 8 and negative thereafter. The positive phase of the NAO altered the flow pattern of the upper air, blocking the west to east flow of the synoptic systems during the first week in January, and causing them to move towards the target area from the southern United States. Whereas this also characterizes the basic climatology of the synoptic pattern associated with a major freezing event, the occurrence of the positive phase of the NAO within the context of the 1997/98 El Niño resulted in an intensification of Ice Storm '98 compared to climatology in the following aspects: (1) the subtropical jet stream was farther south, (2) there was an increase in the moisture flux and convergence over the target area during the second synoptic system, and (3) the upper air trough over the eastern United States was deeper, giving rise to enhanced vorticity generation.

Figure 10a shows the position of the 250 hPa jet stream over North America on Day 5 of the composite case, which can be compared to the position of the jet stream at the same pressure level on January 8, 1998 (Fig. 10b). During Ice Storm '98, the jet stream flowed over the Gulf of Mexico before it was forced to veer northward toward the target area due to the blocking action of the high pressure system over the midlatitude North Atlantic associated with the southern cell of the bipolar structure of the positive phase of the NAO. Note that the position of the jet stream in the composite case is located farther north, with a shallower trough, before it flows northward. The accentuated trough over the central U.S. on January 8, 1998 is quite obvious in Fig. 10b. The location and intensity of the jet stream during Ice Storm '98 resulted in increased moisture flux into the target area from the Gulf of Mexico and the western tropical Atlantic Ocean (Fig. 11) but not all of it fell as freezing rain, and not all of it fell in the target area. Figure 11 displays the difference in the moisture flux divergence field obtained by subtracting the composite Day 5 divergence field from the 12:00 UTC, January 8, 1998 divergence field. It is interesting to note the similarity in the pattern over the target area with the accumulated freezing precipitation shown in Fig. 1. While Quebec received about 10–40 and 15–50 mm from the first and second synoptic waves, respectively, the target area in Ontario and the United States received much of its freezing precipitation from the second synoptic system (Bourque, personal communication).

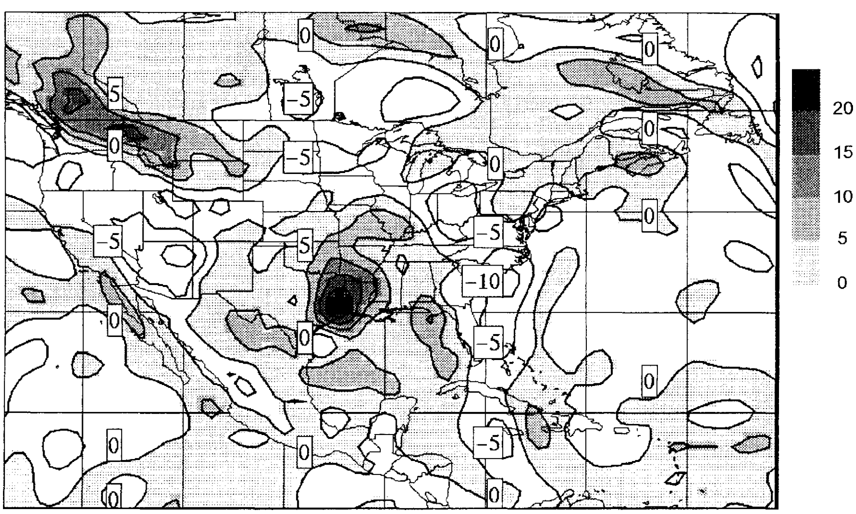


Fig. 12. Same as Fig. 11, except for the vorticity field (10^{-5} s^{-1}). Positive regions are shaded

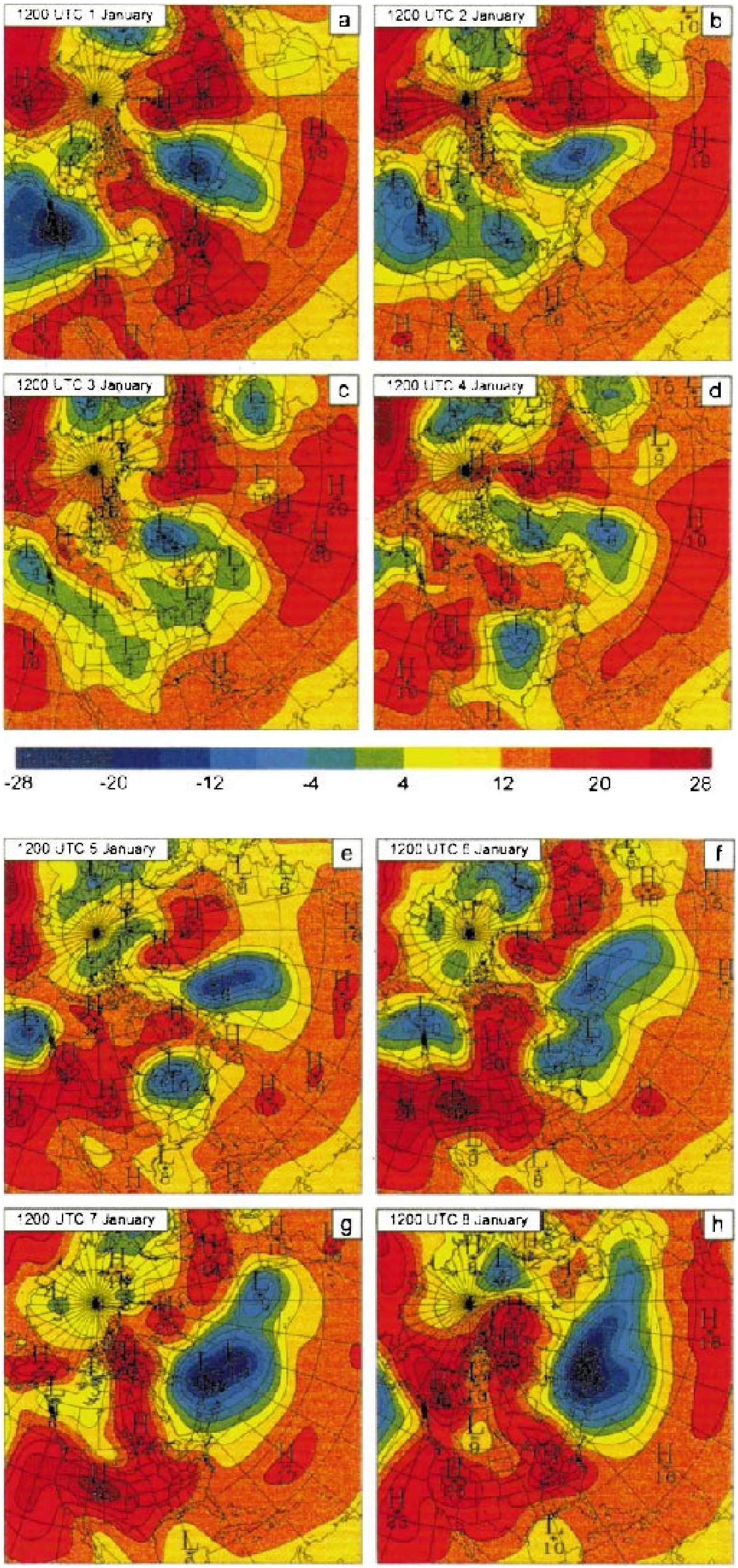


Fig. 13. Evolution of the 1000 hPa height field associated with the major freezing rain event of January 4–5, 1997. Each panel shows observation 24 hours apart, from (a) 12:00 UTC, January 1 to (h) 12:00 UTC, January 8. Contour interval is 4 dams

The presence of the more intense and slow-moving trough over eastern North America during the latter half of Ice Storm '98 also resulted in an enhanced vorticity field, creating potential for generation of more synoptic systems than the dynamical situation of the composite case. Figure 12 shows the difference in the relative vorticity field obtained by subtracting the composite Day 5 vorticity from the 12:00 UTC, January 8, 1998 vorticity. Relative to the composite, there was an enhanced vorticity field located over the southern U.S. during the latter part of Ice Storm '98. It is very likely that the rapid formation of the second synoptic system was due primarily to the enhanced vorticity field.

7. Freezing Rain Storm of January 4–5, 1997

Compared to the events of 1961, 1972, 1983 and 1998, as mentioned earlier, the event of 1997 is quite different in that it occurred during a negative phase of the NAO. Figure 13 shows a series of 12:00 UTC snapshots of the 1000 hPa height field from January 1 to 8, 1997. Much of the freezing precipitation over the target area associated with this event fell on January 5, when the classical synoptic configuration for a freezing rain event described in Section 3 was observed (Fig. 13e).

Consistent with the negative NAO index observed during the first week of January, 1997 (not shown), the midlatitude North Atlantic was dominated by a very prominent low pressure system. On January 4 and 5, however, the NAO became less negative because of the slight northward intrusion of the subtropical high.

A weak low pressure system was observed to move through the target area on January 3, but did not result in freezing precipitation (Fig. 13c). The synoptic system which caused the major freezing rain in the target area developed over the midwestern U.S. on January 3 (Fig. 13c). It intensified and moved quickly to lie just to the southwest of the Great Lakes by January 4 (Fig. 13d). It became a very intensive synoptic system by January 5 as it squeezed the high pressure system toward northern Quebec, thus establishing the typical synoptic situation for a freezing rain event in the target area (Fig. 13e). Twenty-four hours later, the low system moved out of the target area, joining the low over the Atlantic Ocean and setting up a massive low pressure regime stretching across the midlatitude North Atlantic from eastern Canada to Europe (Fig. 13f and h).

An interesting aspect of the 1997 event is that the prominent low pressure system configuration observed over the midlatitude North Atlantic several days *prior* to the January 4–5 freezing event was similar to the pattern seen *at the time* of the freezing rain occurrence in the other 4 cases examined in this study. *After* the freezing event, the evolution of the synoptic pattern over the North Atlantic was almost identical in all the cases, including the 1997 case. It is the persistence of the low pressure system configuration over a significant portion of the midlatitude North Atlantic that resulted in the negative NAO index during the first week of January, 1997. Because of this, the kind of blocking of the general west-to-east movement of synoptic systems observed in other cases was not seen in the 1997 case. Figure 13, therefore, attests to the fact that, at least in one case, it is not necessary to have a positive NAO pattern over the midlatitude North Atlantic to play a part in "pre-conditioning" the synoptic environment to produce conditions conducive to the formation of a major freezing rain event in the target area. Other meteorological mechanisms do contribute to a varying degree to the occurrence of a major freezing precipitation storm, some more significantly in certain cases.

8. Conclusions

Over a 6-day period in early January, 1998, southeastern Ontario, southwestern Quebec, and northeastern New York suffered significant economic and ecological damage from freezing rain, drizzle and ice pellets. Labeled "Ice Storm '98", it started on January 5 and stopped 6 days later, dropping a total cumulative amount of freezing rain of about 70–100 mm water equivalent over some areas in the target area. The Storm was composed of two synoptic systems, the second one coming only 1 day after the first. Comparatively, each of the two synoptic systems was not significantly more extreme in freezing precipitation amount than other major freezing rain events which had occurred in the relatively recent past. In this study we have presented differences, as well as similarities, of Ice Storm '98 compared to the climatology of the synoptic pattern associated with other major freezing events in the target area since 1958.

Five freezing rain events over the target area since 1958 (1961, 1972, 1983, 1997, 1998) have been classified as major events. A typical synoptic configuration for a significant freezing precipitation event over the target area is characterized by a high pressure system over northern Quebec which advects cold air into the target area from the northeast, as a low pressure system moving into the target area from the south transports warm, moist air into a lower tropospheric layer centred around 850 hPa. Also, with the exception of 1997, the major freezing rain events examined in this study have been found to be associated with the positive phase of the NAO. The small sample size of major freezing rain events over the target area since 1958 does not allow us to make a general statistically significant statement about the positive NAO-major freezing rain relationship. However, in order to give more credence to this relationship, we calculated the probability of having the NAO in a positive phase during any particular winter week in the 1964–1996 period to be around 0.4. Comparing this to the fact that 4 out of 5 major freezing rain events since 1958 have been associated with the positive NAO gives us more confidence in the stated relationship.

We have presented evidence to indicate that the formation of the northern Quebec high pressure system and of the positive phase of the NAO appears to be independent; but they do seem to become dynamically connected during the period of freezing rain over the target area. While the northern Quebec anticyclone provides the advection of the necessary cold air into the target area, the positive phase of the NAO forms a midlatitude high pressure band across the North Atlantic, blocking the eastward movement of synoptic systems and forcing them to move northeastward. Usually, a major freezing rain event associated with a single synoptic system lasts for 2 to 3 days, and the synoptic connection between the northern Quebec high pressure area and the midlatitude North Atlantic one associated with the southern cell of the north-south dipole of the positive phase of the NAO is weakened, if not severed, after the passage of the synoptic system through the target area. At this time, the phase of the NAO is already in transition from positive to negative. Shortly afterwards, weakening and displacement, as well as eventual dissipation of the northern Quebec high pressure area is observed, terminating potential synoptic conditions for another freezing precipitation.

In the case of Ice Storm ’98, the magnitudes of the northern Quebec high pressure area and of the NAO were relatively large, and the connection between these two systems remained relatively intact after the passage of the first synoptic system through the target area, even though the positive phase of the NAO was starting to disintegrate. It took another synoptic system to break through the connection, initiating the dissipation of the northern Quebec high pressure area. (It is our opinion that the severance of the connection speeded up the dissipation of the high pressure system which would eventually have occurred as the phase of the NAO transformed from positive to negative.) The passage of the second synoptic system through the target area only 1 day after the first system is an anomaly, compared to the composite case, and is very likely due to the atmospheric condition modulated by the influence of the El Niño.

One of the interesting aspects of Ice Storm ’98 is that, unlike all previous events since 1958, it occurred during an El Niño winter. This had certain repercussions on the nature of Ice Storm ’98 not evident in previous major freezing events. With the subtropical jet stream located farther south than usual over the United States during the 1997/98 winter, synoptic systems were able to access the Gulf of Mexico and the western tropical North Atlantic as significant moisture source. Once the eastward movement of these synoptic systems over southern United States was blocked by the southern high pressure cell of the positive NAO, they were forced to move northeast. The blockage, in addition, caused enhancement of the trough over eastern North America, enhancing the vorticity field and increasing the potential for generating synoptic disturbances. Barsugli et al. (1999) concluded that “El Niño had a strong impact on the location and severity of the ice storm.”

Finally, we wish to emphasize that the role of the NAO in the occurrence of a major freezing rain event over the target area during an El Niño or non-El Niño winter is admittedly speculative at this point, and needs to be explored further. Trained as weather forecasters, the authors (KH and AS) are quite aware of other factors on a more regional scale (meteorological and topographical) which contribute to the formation of freezing precipitation over the target area. For example, the St. Lawrence River Valley quite often provides a channel for cold northeast surface winds blowing up-river into Montreal (Bourque and Munn, personal communication). But based on the evidence presented in this paper we are encouraged that at least some aspects of the synoptic conditions necessary for an occurrence of a major freezing precipitation in the target area may be explained within the framework of an interaction between the positive phase of the NAO and the northern Quebec high pressure system. It is our opinion that the positive phase of the NAO in winter provides a spatial/temporal flow regime environment on a larger scale, increasing the synoptic probability of major freezing precipitation in the target area.

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