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Estimation of Severe Ice Storm Risks for South-Central Canada



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Estimation of Severe Ice Storm Risks for South-Central Canada

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Executive Summary

- Ice Storm '98 was a reminder of just how vulnerable our society has become to severe freezing rain storms. As our population continues to increase and our society becomes even more urbanized, both the size and number of targets impacted by these severe winter storms will increase. Added to this vulnerability will be our continued dependence on electronics and an uninterrupted supply of electricity along with the dependence of our businesses and industries on “just-in-time” delivery. As a result of these shifts, we have collectively become extremely vulnerable to the power of severe ice storms to interrupt our supplies and distribution of electricity, water supplies, and communications and to delay our ground and air-based transportation.
- In order to be better prepared for future severe ice storms, communities need to know current and future risks from severe ice storms of magnitudes approaching those of Ice Storm '98. Better severe ice storm risk information will allow better emergency planning in regions or communities identified as more at risk from this hazard. It will also help communities to identify critical infrastructure and allow improved planning and design of this infrastructure to minimize future risks.
- In the major freezing rain storms that have occurred in Ontario since the 1920s, most of the impacts have occurred as a result of widespread and often long-lasting outages in the communications and power transmission and distribution systems.
- Damage and outages in the power distribution system are often caused by broken or weakened and sagged tree limbs. Under the weight of accumulating ice, tree branches can fall or sag into overhead electrical distribution lines. Accumulations of ice can increase the branch weight of trees by 30 times or greater. Small branches and weak tree limbs break with ice accumulations between $\frac{1}{4}$ and $\frac{1}{2}$ inch (~6–12 mm), while $\frac{1}{2}$ inch to 1 inch (~12–25 mm) accumulations can cause larger branches to break. If high storm winds are combined with the ice loading, the damage to trees and infrastructure will increase, with communications and power distribution outages subsequently becoming more likely. Without the presence of trees, power outages during ice storms occur only at relatively high ice loads.
- The amount of ice accumulation in a storm is normally directly related to the amount of freezing precipitation that has fallen during the storm. Normally, shorter duration events (i.e. 1–2 hours) will have lower ice accumulation amounts than those of longer duration (i.e. 6–12 hours or longer).
- In central Canada, the CSA/CEA freezing rain ice design criteria for high voltage power and transmission lines indicates a design limit for overhead structures of approximately 25 mm of radial ice accretion (not freezing rain totals) on a 1 inch conductor. Therefore, damage to the electrical transmission system normally occurs in the more severe ice storms. However, transmission lines may fail and towers may be damaged in less severe ice storms under the effects of “galloping,” as the conductors and guy wires erratically oscillate and stretch under moderate but steady wind conditions.

- Communication towers are typically designed to withstand higher ice and wind loads than are power or transmission lines. However, communication towers can experience structural damage under heavy ice accretion loads or ice-fall damage from ice shedding (i.e. ice falling from the structure with melting temperatures), and in the most severe ice storms, can collapse.
- The review of the severe ice storm events that have affected southern Ontario over the past century suggests that the risks of major power outages lasting several days and hence, the potential for a community disaster as a result of an ice storm tends to increase when freezing rain amounts exceed approximately 30 mm. Historical evidence indicates that the potential for long power outages and for a community disaster becomes likely when freezing rain totals exceed approximately 40 mm. The current CSA standard for transmission lines (but not necessarily local distribution lines) recommends that structures be designed for 25–30 mm of radial ice accumulation or build-up on power lines in southern Ontario. While radial ice accumulations are not the same as total freezing rain amounts, the historical ice storm evidence would suggest that the ice accumulation amounts used in the CSA standard for design of transmission lines (overhead systems) can handle most of the severe ice storms likely to affect southern Ontario. Eastern Ontario is likely the area most at risk for transmission line failures.

Climatology of Severe Ice Storms

- A variety of methodologies were used in this study to identify areas within southern and eastern Ontario that might be at risk from an increase in freezing rain, and in severe ice storms in particular.
- Since communication towers are normally the last structures to fail in an ice storm, a U.S. Army Cold Regions Research and Engineering Laboratory icing-related communications tower collapse database was used to help identify severe ice storms. An updated version of the database contains information on 205 tower collapses that occurred from 1929–2001. In Ontario, only one communication tower collapse has been recorded in the database over this period and this occurred during Ice Storm '98 (although indications are that as many as five towers may have collapsed in the storm). The linkage between the most severe ice storms and the collapse of communication towers underscores the importance of maintaining high ice loading and wind design criteria for these towers.
- Based on analysis of a variety of data sources, a total of 25 significant ice storms were identified to have impacted southern and eastern Ontario since the mid-1800s (including Ice Storm '98). The most severe Ontario ice storms occurred during the months of November through March, and about half of these typically occurred during the last two weeks of December or the first two weeks of January. The storms generally lasted between 12 hours and one to two days. The most prolonged of these storms (28–30 December 1942) spanned only about half the time period of Ice Storm '98.
- It is worth noting that many of the severe ice storms that impacted southern Ontario brought even greater amounts of freezing rain further south to locations in the northern U.S. Indeed,

some of the most severe ice storms to affect the northern U.S. brought either lower freezing rain amounts or snow to southern and eastern Ontario.

- Most of the significant ice storms that impacted the northern U.S. over the period 1909–2002 also affected southern Ontario, but with lesser freezing rain amounts. For example, of the 22 significant eastern U.S. ice storms assessed for this period, eight storms brought more than 20 mm of freezing rain to southern Ontario but considerably greater amounts to U.S. locations. Of the remaining U.S. storms, five produced less than 20 mm of freezing rain over southern Ontario (amounts ranging from 5–18 mm), another eight brought snow or light rain and one did not impact Ontario. Half of the northern U.S. ice storms investigated impacted New York state more severely than the remaining.
- The majority of the severe ice storms that impacted southern and eastern Ontario and the northern U.S. since 1948 originated in the south central and southeastern U.S. A common ingredient to these severe ice storms was significant moisture from the Gulf of Mexico that was pushed northwards by the storm. Ice storms over Pennsylvania, New York State, New England and eastern Ontario had additional moisture from the Atlantic Ocean, likely explaining the relatively high frequency of freezing rain in these areas. Topographical influences from the Appalachian Mountains and from valleys, including the Ottawa Valley, added to regional risks for severe ice storms. In all cases, an Arctic high pressure area was located to the north of the storms, as would be expected for freezing rain meteorological processes. Most of the ice storms were associated with relatively slow-moving or stalled low pressure systems.
- Meteorological assessment of the most severe ice storms indicated that freezing rain can occur up to 900 km ahead of the storm centre. Almost all of the ice storms that impacted on the northern U.S. had similar points of origin and followed similar tracks to the storms that impacted heavily on southern and eastern Ontario. The main difference was that the U.S. storm centres were located approximately 100–200 km further south at the time of freezing rain occurrence than the storms that impacted southern Ontario. This conclusion would support speculation that should storm tracks shift north under climate change, the frequency of severe ice storms could possibly increase in southern and eastern Ontario given a degree or two of winter warming. However, climate change science and models cannot yet predict how storm tracks will change in a warming climate or whether such changes could potentially lead to regional increases or decreases in ice storms.

Climatology of Average Freezing Rain Conditions

- In terms of freezing rain hours, Ottawa Airport reported by far the highest average number of freezing rain hours of any station assessed, followed by Montreal and Binghamton, New York, and then by London and Sudbury. Ottawa Airport station reported a seasonal average of almost 37 hours of freezing rain or 10 days with some occurrence of freezing rain over the 1953/54 to 2000/01 period. In southern Ontario, London reported the highest seasonal average of hours (24) and days (seven) with freezing rain. It is speculated that the number of freezing rain hours for the Dundalk Highlands of southern Ontario are likely as high or higher than those of London. The

lowest average frequencies of seasonal freezing hours (five to six) and days (two to three) were recorded over northwestern Ontario.

- Observations indicate that the Great Lakes influence the occurrence of freezing rain at western shoreline locations and during some months of the year. The frequency of freezing rain may be decreased on the western and southern shores of Lake Ontario and northern shore of Lake Erie during the fall, early winter and early spring, similar to study results for the western U.S. Great Lakes shoreline locations. The exception to this pattern occurs in areas adjacent to Lake Ontario and eastern Lake Erie, which appear to have a minimal effect in reducing the observed freezing rain frequency for the U.S. northeast states and eastern Ontario. This is consistent with the predominant occurrence of east or northeast surface winds during freezing rain events in this region, which eliminate any thermal input (advection) from the lakes that are located to the west.
- Trend analysis would suggest that the risks of average freezing rain occurrence have remained relatively the same or have been slightly decreasing in northwestern Ontario, southern Ontario and central Ontario during the period 1953–2001. The increasing trends in average conditions over northern Ontario, Ottawa and Montreal (sites away from the influence of the Great Lakes) during the same period are statistically non-significant. Under subtle warming from climate change, changes in the frequency of severe ice storm conditions could differ from changes in the frequency of average conditions.
- An investigation of the relationship between monthly mean temperature and freezing rain events revealed some interesting site-specific results. In particular, on average in January, the monthly total frequency of freezing rain events at Ottawa, Montreal, Sudbury and North Bay increases from the lowest to highest temperature quintiles. Each of these sites is not directly influenced by flows from the Great Lakes and has a high seasonal frequency of occurrence of freezing rain relative to the remaining study locations.
- Based on statistical weather map typing procedures, four weather patterns or types (1–4) were identified to be the most highly associated with freezing rain events at all of the Canadian and U.S. weather stations assessed, while up to two additional weather types were identified at some of the stations. These freezing rain-related categories accounted for 75% to 100% of the freezing rain events that occurred at each location for events lasting ≥ 1 , ≥ 4 and ≥ 6 hours during a day over the entire study period.
- Using the results from the statistical map typing approaches, a trend analysis was performed on the frequencies of the weather patterns most highly associated with freezing rain events to determine whether or not there has been an increase or decrease in these patterns over the past 33 years (1958–2001) at 14 selected stations in Ontario and one in Quebec. While none of the trends in the weather types were found to be statistically significant, the directions of the trends in the freezing rain map types were the same as the trends in the observed freezing rain frequencies at most stations.

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1.0 Introduction

Communities require information on the risks associated with weather hazards, such as severe freezing rain or ice storms, in order to shape their emergency response plans and to take measures to reduce their vulnerabilities to these hazards. Although ice storms of any duration and magnitude can have serious impacts on critical infrastructure and community planning, those associated with severe ice storms such as the January 1998 Ice Storm can be particularly devastating. The purpose of this report is to investigate whether ice storms of magnitudes approaching Ice Storm '98 can be treated as unprecedented or an "Act of God" in Ontario, and whether the risks of such severe ice storms may increase in the near future. The area under consideration is the heavily populated and hence vulnerable area of southern and eastern Ontario which houses approximately 35% of all Canadians.

Although the greater Montreal and eastern Ontario areas were severely impacted by Ice Storm '98, along with some communities in Atlantic Canada, the time frames for this study were not sufficient to allow coordination with meteorological centres for jurisdictions outside of Ontario. This study represents an initial attempt to estimate the repeat risks for and our vulnerabilities to ice storm disaster risks in southern and eastern Ontario. With today's communities becoming increasingly electronic and with industries operating under "just in time" delivery principles, it is important to understand the risks that severe ice storms pose for our communities and their infrastructure, particularly for our electrical distribution and transmission systems and our communications links. Better severe ice storm risk information will allow enhanced emergency planning and disaster prevention in regions or communities identified as more at risk from this hazard. The information will also help communities to identify critical infrastructure and allow better planning and design of this infrastructure to minimize future risks.

In this study, various scientific approaches were used to identify those regions and communities in southern and eastern Ontario which could be at the highest risk from severe ice storms, and to assess whether these risks could be increasing as result of subtle winter climate warming (i.e. 1–2°C). These approaches or studies can be summarized as follows:

1. A comparison of Ice Storm '98 with other significant freezing rain storms that have hit southern and eastern Ontario and the northern U.S. during the past century,
2. An update of the climatology of severe ice storms for the heavily populated regions of southern and eastern Ontario and historical trend analyses for freezing rain storm indicators for Ontario and adjacent U.S. sites,
3. Introduction of a U.S. database on communication tower collapses resulting from severe ice accretion amounts (communications towers are normally more robust to freezing rain storms than other infrastructure),
4. A subjective meteorological analysis and an impact assessment of the most severe ice storms that have affected southern and eastern Ontario and adjacent U.S. regions over the past century (using a team of experienced meteorologists),
5. Application of statistical weather map typing procedures to identify the general weather patterns associated with severe freezing rain events that have affected south-central Canada and the northern U.S. and an assessment of trends in these contributing weather types.

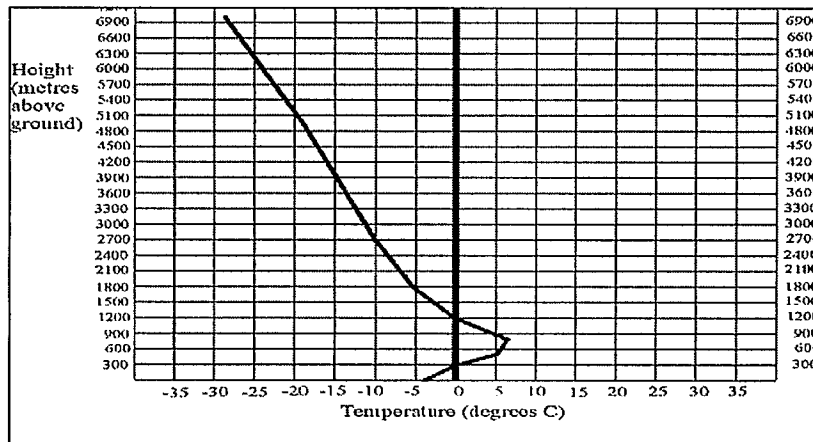
2.0 The Formation of Freezing Rain

Winter storms can often have a variety of precipitation types associated. The temperature profile in the lower atmosphere, below 3000 m, and at the earth's surface primarily determines the form of precipitation that is reported. If there is no above-freezing layer in the lower atmosphere, the precipitation will fall as snow. Similarly, if the snow falls through a shallow above-freezing layer (generally less than 150 metres thick) the snow will have not had sufficient time to melt before reaching the ground. If the depth of the above-freezing layer in the atmosphere is at least 150 metres thick, and temperatures at ground level are also above freezing, the snow will melt as it falls through the layer and typically reach the surface as rain or drizzle.

Freezing rain or ice pellets will form when the snow falls into a layer of above-freezing air deep enough for the snow to melt and then passes through a below-freezing layer of air near and at the surface. The depth of below-freezing layer near the surface is critical in determining the final form of the precipitation. If this layer is too deep (greater than about 500–1000 metres) the rain is more likely to freeze again in this layer and reach the ground as an ice pellet. However, in a shallower below-freezing layer near the surface, the layer is not deep enough to freeze the rain or drizzle droplets. The rain or drizzle cools to a temperature a few tenths of a degree below freezing, but remains as a liquid. These supercooled water droplets freeze on contact with the ground or cold objects near the ground, such as roads, trees, power or telephone wires, or their supporting poles and towers. Although the above description is considered to be the classical process for the formation of freezing rain, there are also cases where there is no melting layer in the atmosphere for the precipitation to fall through. Freezing drizzle and, on some occasions freezing rain droplets, develop and grow by a cloud collision-coalescence mechanism where the clouds, in this case, are composed primarily of liquid water rather than ice.

Figure 1 illustrates a typical example of a vertical atmospheric temperature profile that would be associated with the classical melting process occurrence of freezing rain. The presence of the above-freezing layer in the lower atmospheric levels, as well as the below-freezing layer near the surface, typifies this freezing rain profile.

Figure 1 Typical vertical temperature profile associated with the classical formation of freezing rain.



3.0 Ice Storm 1998

3.1 Introduction to Ice Storm 1998

The January 1998 Ice Storm has been described using many words – freak, unprecedented, “Act of God”, and Storm of the Century. The storm that hit eastern Ontario, southwestern Quebec, parts of the Maritimes and the northeastern U.S. was certainly one of the most significant weather-related news stories in Canada’s history. Lasting for almost a week and extending over parts of four provinces and seven states, the storm was responsible for accumulations of ice hitherto not recorded in central Canada. At the heart of the impacts from the storm was a massive power failure that affected 3.5 million people or more than 10 percent of the entire population of Canada. Extensive community evacuations were organized in an effort to reduce the risks to lives, but despite these efforts, 28 human fatalities in Canada (with an additional 19 deaths in the U.S.) were directly attributed to the storm. Collapses of communication towers, phone lines and other communication infrastructure also hindered emergency response and recovery from the storm. Nearly 16,000 military were deployed in response to the disaster in the largest humanitarian assistance mobilization of Canadian Forces in the history of Canada. Economic losses from the storm totalled in the billions.

The meteorological aspects of Ice Storm ’98 have been well documented in comprehensive reports prepared by Auld et al. (1998) and Milton and Bourque (1999). The Cold Regions Research and Engineering Laboratory in New Hampshire produced a scientific report evaluating the severity of the 1998 ice storm in northern New England and estimating its return period for this region (Jones and Mulherin, 1998). Numerous other scientific publications and journal articles have been written on Ice Storm ’98 and its impacts (i.e. DeGaetano, 2000; Dupigny-Geroux, 2000; Environment Canada, 1998; Higuchi, 2000; Lecomte et al., 1998; Regan, 1998). The following sections provide a description of typical meteorological conditions associated with freezing rain events along with a summary of Ice Storm ’98, its meteorological setup conditions, and its impacts.

3.2 The Meteorological Setup for the Ice Storm

The main weather patterns that led to the setup for the severe icing events over south central Canada and the northeastern United States remained in place during much of the week of 5 January 1998. A succession of low pressure systems that developed in the southern U.S. advected moist, warm air from the Gulf of Mexico into southern Ontario and Quebec at upper levels of the atmosphere. By January 5, a large stationary Arctic high pressure area had become established over central Quebec. The atmospheric circulation associated with this high resulted in very cold air flowing into southwestern Quebec, the Ottawa River Valley and the Maritimes. The warm air at upper levels was unable to dislodge the denser, cold air near the ground and as a result, the storm precipitation fell as freezing rain. A series of low pressure systems moved through the affected areas in quick succession, bringing freezing rain, ice pellets and snow. As temperatures remained below 0°C for most of the event in eastern Ontario and southwestern Quebec, there was little if any thawing of ice between the freezing rain events and the ice continued to accumulate during the week. On 9 January 1998, the persistent upper atmospheric blocking circulation started to change. The freezing rain in eastern Ontario and southwestern Quebec

ended on the 9th, and the storm precipitation finally ended as snow on the 10th. A schematic representation of the weather situation for Ice Storm '98 is provided in Figure 2.

3.3 Precipitation Episodes and Amounts

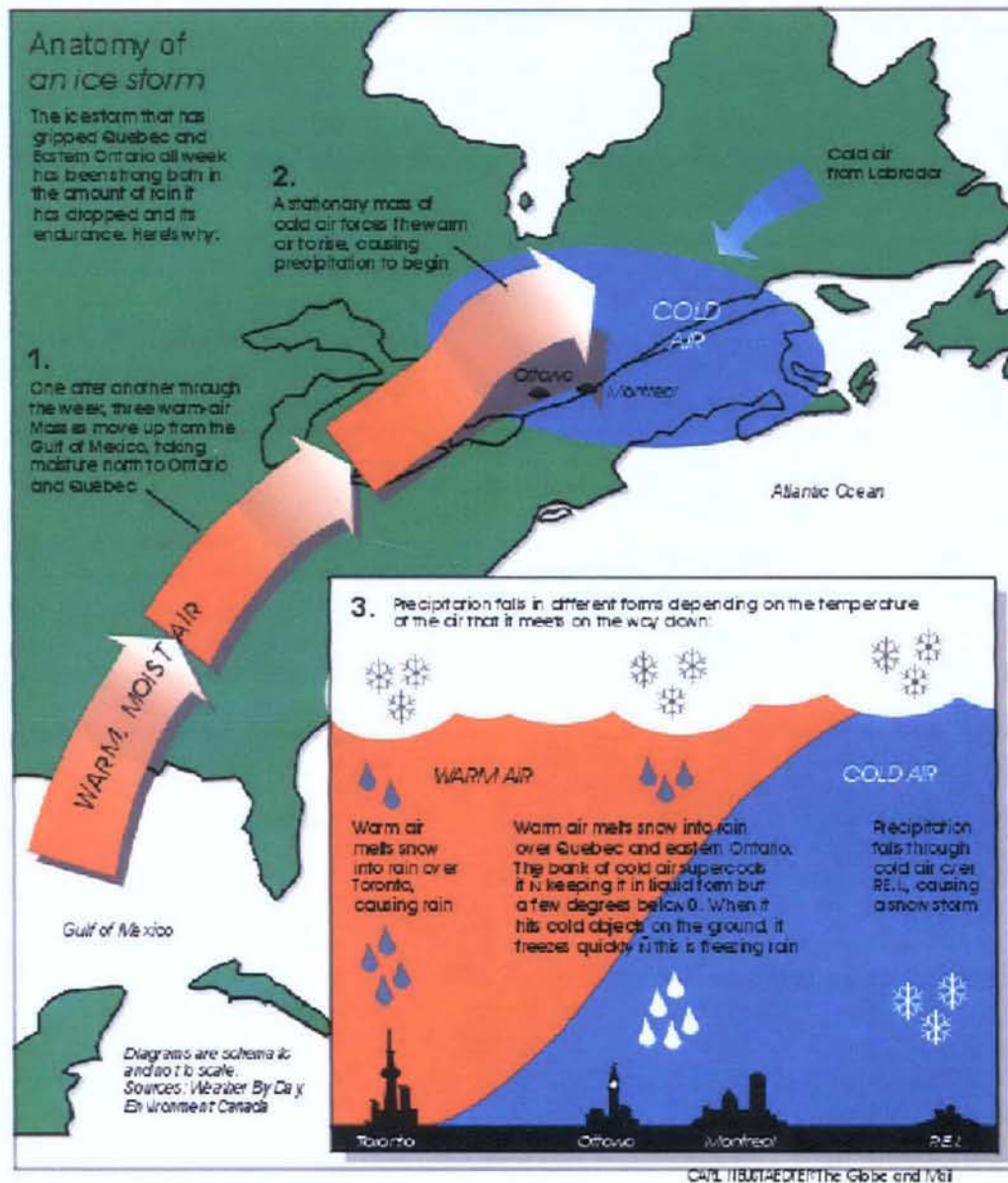
The succession of low pressure systems that were associated with the Ice Storm '98 event resulted in several separate episodes of freezing rain in Ontario. Areas south and southeast of Georgian Bay reported two distinct freezing rain events while eastern Ontario was affected by three main freezing rain events. Freezing drizzle was often observed between each episode, but had no additional significant impact.

The areas to the south and southeast of Georgian Bay were among the first to receive freezing rain during the 1998 ice storm. In the first episode on January 4, the freezing rain lasted only a few hours. Freezing rain amounts ranged from a trace to 15 mm in this event. However temperatures rose above freezing early on January 5. The second episode of freezing rain over the Georgian Bay areas occurred on the 8th and 9th, as colder air began to push southward. As well as the freezing precipitation, snow also fell over the area. As with the first episode, freezing rain amounts were variable, and ranged from a millimetre or two to 20 mm or more.

Although the freezing rain amounts in the Georgian Bay area were significant, they were considerably less than those received in eastern Ontario, where up to 95 mm of freezing rain fell in three major precipitation episodes and the impacts were the most serious.

The first major precipitation episode over eastern Ontario began when an area of snow, ice pellets and freezing rain developed along the north shore of Lake Ontario in the Trenton area in the early afternoon hours of January 4. The precipitation spread eastward, beginning as snow in the Kingston, Massena and Ottawa areas between 3:00 p.m. and 5:00 p.m. (all times are EST). The snow quickly changed to freezing rain in the Kingston area, but in areas to the east it took several hours before the snow ended and freezing rain began.

Figure 2 Schematic representation of the weather situation for Ice Storm '98



Temperatures climbed to above the freezing mark in the Kingston area around 10:00 a.m. on January 5, resulting in the changeover from freezing rain to rain at this point. The rain then continued until 7:00 a.m. EST the next day, and was followed by a few periods of drizzle. At Ottawa and Massena, where temperatures stayed below 0°C, freezing rain continued until daybreak on the 6th. The freezing drizzle continued intermittently through the rest of the day.

The second major precipitation episode in eastern Ontario started on January 7. With temperatures hovering around the freezing mark in the Kingston area on the morning of the 7th, the precipitation began there as rain around 7:00 a.m. Temperatures remained near zero in the Kingston area for the majority of this episode and resulted in the precipitation alternating

between rain and freezing rain until the end of the episode around 9:00 p.m. on January 8. However, both Massena and Ottawa were deeper into the cold air, and as a result the majority of the precipitation fell as either freezing rain or ice pellets. Snow was also occasionally mixed in before the episode finally ended in the Ottawa and Massena areas in the early morning hours of January 9.

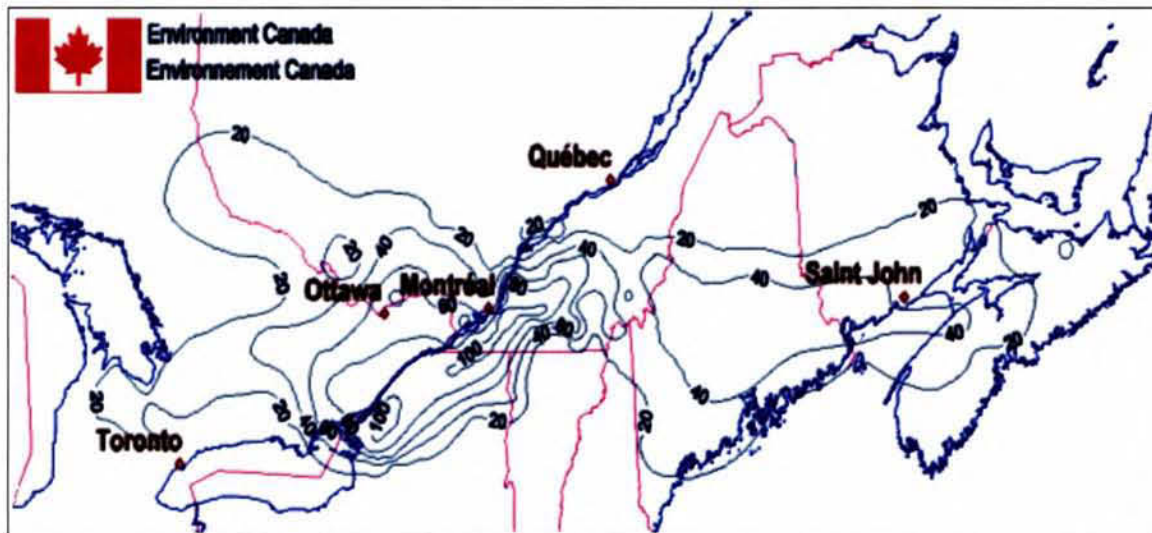
The final episode was the shortest, but consisted of thunderstorms which affected portions of eastern Ontario and southern Quebec. The time interval between the second and last episode was quite brief, only about six to nine hours. By 6:00 a.m. on January 9 a large area of freezing rain was affecting areas just north of Lake Ontario as well as areas near Barrie and the Bruce Peninsula. This freezing rain quickly spread eastward to Kingston and to Ottawa and Massena by 9:00 a.m. Thunderstorms accompanied the freezing rain in a corridor from Kingston to Cornwall to Montreal. The freezing rain over eastern Ontario changed to snow in the early evening hours of January 9 before all precipitation ceased around 10:00 p.m.

Precipitation amounts were spread relatively evenly among the three episodes, although the extent of heavy precipitation was greatest in the first. In general 20 to 40 mm of freezing rain fell during the first episode, 10 to 30 mm in the second, and 10 to 25 in the third. Table 1 provides information on the three main precipitation episodes that occurred in eastern Ontario during Ice Storm '98. An Environment Canada map of the freezing rain amounts that occurred over eastern Canada and the northeastern U.S. during Ice Storm '98 is provided in Figure 3.

Table 1 Eastern Ontario precipitation episodes from 4–9 January 1998.

Episode	Time Period (EST)	Location, Duration, and Type of Precipitation
One	4:00 p.m., Jan 4 to 9:00 a.m., Jan 6	<ul style="list-style-type: none"> • Kingston: 16 hours of freezing rain followed by 20 hours rain with brief break • Massena: 36 hours of freezing rain, ice pellets and snow • Ottawa: 6 hours of snow and 30 hours of freezing rain mixed at times with ice pellets
Two	7:00 a.m., Jan 7 to evening, Jan 8	<ul style="list-style-type: none"> • Kingston: 24 to 30 hours of freezing rain (including some rain) • Massena: 24 to 30 hours of freezing rain and ice pellets • Ottawa: 40 hours of freezing rain, snow and ice pellets
Three	6:00 a.m., Jan 9 to evening, Jan 9	<ul style="list-style-type: none"> • Kingston: 13 hours of freezing rain, snow and ice pellets with brief breaks • Massena and Ottawa: 10 hours of freezing rain, snow and ice pellets, beginning at 9:00 a.m.

Figure 3 Preliminary map of freezing rain accumulations in mm from 4–10 January 1998 (Environment Canada, 1998).



The freezing rain amounts that were recorded in eastern Ontario and southwestern Quebec were unprecedented based on archived weather records from the late 1800s. Auld et al. (1998) used a Chaine ice accretion model to model ice accretion amounts for several locations in Ontario and Quebec. Compared to previous winters from 1953–1997, their study estimated that the return periods associated with Ice Storm '98 at Ottawa International Airport, Montreal-Dorval International Airport, and St. Hubert Airport could be on the order of hundreds of years. Jones and Mulherin (1998) indicated that in New England, the December 1929 ice storm is considered to be of a magnitude comparable to Ice Storm '98. Their study estimated that the ice storm had a return period of 35–85 years for areas of upstate New York and for Vermont and New Hampshire, although other storms since 1929 have generated ice loadings comparable to the 1998 storm, but affected a smaller area. DeGaetano (2000) stated that for the limited number of stations that report hourly meteorological observations, the storm was unprecedented since the beginning of digital records in 1948.

3.4 Impacts of Ice Storm '98

The January 1998 Ice Storm will long be remembered in Canada for the severity of its impacts, particularly in eastern Ontario and southwestern Quebec. Massive power outages during the storm resulted in over 3 million people being left without electricity. Although Quebec was the hardest hit by the power outages, nearly 600,000 people experienced power failures in Ontario. Loss of power for this many people is not unprecedented in Ontario, but never before have so many of Ontario's hydro users been without electricity for so long. As in Quebec, power in some areas was not restored for 3 ½ weeks. Extensive community evacuations were organized in an effort to reduce the risks of lives, but despite these efforts, 28 human fatalities in Canada (with an additional 19 deaths in the U.S.) were directly attributed to the storm. Collapses of communication towers, electrical transmission and distribution systems, phone lines and other communications infrastructure also hindered emergency response and recovery from the storm.

In the Montreal area, five communication towers collapsed and another failed near Kingston. Millions of trees, 120,000 km of power lines and telephone cables, 130 major transmission towers and about 30,000 wooden utility poles were all downed in the storm in Canada (Environment Canada 1998). Nearly 16,000 military were deployed to assist in the evacuation of close to 600,000 people, security, and clean-up.

Although it is difficult to put a price tag on a storm of this magnitude, the economic costs associated with this storm have been estimated to exceed \$5 billion in Canada alone (OCIPEP Canadian Disaster Database). Given these extremely high economic losses, it is not surprising that Ice Storm '98 is ranked as the most expensive climate disaster that Canada has experienced (Environment Canada, 1998). The largest estimated insured losses in Canada's history are associated with Ice Storm '98 (Lecomte et al., 1998).

4.0 Characteristics of Severe Ice Storms

Although freezing rain is a relatively infrequent event during winter storms in Canada, major ice storms are even rarer. Even freezing rain events of short duration and small ice accumulations can produce extremely hazardous conditions for motorists and pedestrians. However, as the duration of the freezing rain and accumulation of ice increases, the significance and severity of the associated impacts increase as well. The most severe events are labelled as ice storms, which are potentially one of the most destructive forms of winter storms.

The severity of an ice storm depends on the accumulation of ice, the duration of the event, and the location and extent of the area affected. The amount of ice accumulation in the storm is normally directly related to the amount of freezing precipitation that has fallen during the storm. Normally, shorter duration events (i.e. 1–2 hours) will have lower ice accumulation amounts than those of longer duration (i.e. 6–12 hours or longer). Highly urbanized communities are particularly vulnerable to ice storms, as utilities, infrastructure and transportations systems are normally concentrated in these areas.

The area impacted by an ice storm can range from a few hundred square kilometres to regions that include several provinces in Canada and/or states in the United States. The 4–10 January 1998 Ice Storm affected eastern Ontario, southern Quebec and New Brunswick as well as a large portion of New England and northern New York State. In the areas of Montreal and Ottawa, the total number of hours of freezing precipitation (freezing rain and freezing drizzle) was in excess of 80, nearly double the normal annual total (Environment Canada, 1998).

The social and economic costs associated with damaging ice storms can be high. Ice storms can cause extensive infrastructure and property damage, human injuries and fatalities, and disruption in surface transportation, communications and electrical power supplies. Heavy ice accumulations can bring down trees, electrical wires, telephone lines and poles, and, in the most severe storms, communication towers. The resulting communications and power outages can be extensive and last for days. During the January 1998 Ice Storm, widespread hydro outages in eastern Ontario and Quebec lasted a week or more, and the longest outages were over three weeks in the Montreal area. Ice storm damage costs in Canada and the U.S. often total in the millions. Robbins et al. (2002) note that in the U.S. statistics compiled by the National Weather Service's Office of Meteorology, ice storms were responsible for 69 fatalities, nearly 3000 injuries, and roughly \$2 billion in damage from 1990–1998. DeGaetano (2000) indicates that 17 of these deaths and damage estimates exceeding \$1 billion occurred during Ice Storm '98. Canadian costs from the January 1998 Ice Storm have been estimated as exceeding \$5 billion with 28 dead and 945 injured (OCIPEP Canadian Disaster Database).

Damage and outages in the power distribution system are often caused by broken or weakened and sagged tree limbs. Under the weight of accumulating ice, these branches can fall or sag into overhead electrical distribution lines. The impacts of ice loading on tree structural damage are discussed in Hauer et al. (1984). Accumulations of ice can increase the branch weight of trees by 30 times or greater. Small branches and weak tree limbs break with ice accumulations between $\frac{1}{4}$ and $\frac{1}{2}$ inch (~6–12 mm), while $\frac{1}{2}$ inch to one inch (~12–25 mm) accumulations can cause larger branches to break. If high storm winds are combined with the ice loading, the damage to trees

and infrastructure will increase, with communications and power distribution outages subsequently becoming more likely.

Without the presence of trees, power outages during ice storms occur only at relatively high ice loads (Jones and Mulherin, 1998). Tree damage to high-voltage transmission wires is less likely during an ice storm, as the wires are normally located on taller poles, away from trees. In central Canada, the CSA/CEA freezing rain ice design criteria for high voltage power and transmission lines indicates a design limit of approximately 25 mm of radial ice accretion on a one inch conductor (CSA 2001a, b). Therefore, damage to the electrical transmission system normally occurs in more severe ice storms. However, transmission lines may fail and towers may be damaged in less severe ice storms under the effects of "galloping," as the conductors and guy wires erratically oscillate and stretch under moderate but steady wind conditions (Jones and Mulherin, 1998). Communication towers are typically designed to withstand higher ice and wind loads than are power or transmission lines. However, communication towers can experience structural damage under heavy ice accretion loads or ice-fall damage from ice shedding (i.e. ice falling from the structure with melting temperatures), and in the most severe ice storms, can collapse. During Ice Storm '98, Environment Canada (1998) reported that 1300 major transmission towers were downed in Canada while Mulherin (2002) listed 13 communication tower collapses in New York and New England and an additional five in Canada.

As described above, damages incurred in ice storms can be extreme. In a report assessing the severity of the January 1998 Ice Storm in New England, Jones and Mulherin (1998) used damage to trees and structures as a qualitative indicator of the severity of freezing rain storms. Damage levels rise with increased ice loads and storm severities. Strong winds accompanying the icing will also increase the level of damage. Table 2 is adapted from the ice load index table produced by Jones and Mulherin (1998).

Table 2 Ice load index as an indicator of ice storm severity. (Adapted from Jones et al., 1998. Note that high winds concurrent with the ice load increases the level of damage/ice storm severity.)

Damage to Trees and Structures (in order of increasing ice load)	Freezing rain severity	
Slippery roads	Hazardous freezing rain episode	
Ice on trees shining in the sun		
Outages in communications and power distribution and transmission systems caused by trees		
Bending birch trees		
Broken branches on susceptible trees (i.e. brittle, old, injured trees)		
Outages to transmission lines caused by galloping		
Broken branches on resistant deciduous trees		
Outages in the distribution system NOT caused by trees		
Broken branches on evergreen trees		
Outages in the transmission system NOT caused by trees		
Communication tower failures	↓	Most severe ice storm

5.0 The Climatology of Average Freezing Rain Conditions in the Great Lakes Region

5.1 Previous Studies

The first published climatology of average freezing precipitation conditions for Canada was published by MacKay and Thompson (1969). A 10-year database (1957–1966) of hourly weather observations was used to calculate the frequency of occurrence of freezing precipitation (freezing rain and freezing drizzle) across Canada. The study determined that during the 10-year period, more than 50 hours of freezing precipitation per year had occurred on average in central and southeastern Ontario, as well as in areas near the Dundalk highlands, north and west of Toronto. Other areas of southern and northwestern Ontario recorded an average of 25 to 50 hours of annual freezing precipitation in this period. Freezing rain hours accounted for 50 to 60 percent of the total freezing precipitation hours in southern, central and eastern Ontario, 30 to 40 percent in northern Ontario and approximately 20 percent in northwestern Ontario. The remaining hours consisted of freezing drizzle events, where the rate of ice accumulation is significantly less than that of freezing rain.

A more extensive national freezing rain, freezing drizzle and freezing precipitation climatology was developed by Stuart (1994) for the 1961–1990 period. The study was based on 140 stations across Canada with 24 hourly weather observations per day. Approximately 20 of these stations were located in Ontario. The results were similar to those of MacKay and Thompson (1969). During the 30-year period, annual freezing rain hours in Ontario were a maximum of 25 hours or greater in the Ottawa River Valley and westward to the Sudbury/North Bay area. An annual average of 10 to 25 hours of freezing rain hours occurred throughout the remainder of southern and eastern Ontario and eastern and northwestern parts of northern Ontario. On average, fewer than 10 hours of freezing rain occurred annually in much of northwestern Ontario.

Recent freezing precipitation studies over the conterminous United States provide information on the occurrence of freezing rain in the states bordering the Great Lakes (i.e. Cortinas et al., 2000; Bernstein, 2000; Robbins et al., 2002). Using data from 1976 to 1990, Robbins and Cortinas (2002) determined that the maximum annual number of freezing rain hours in the U.S. states bordering the Great Lakes is in excess of 25 hours in western Pennsylvania and in northern New York. In a climatological study of freezing rain in the Great Lakes region, Cortinas (2000) used Canadian and U.S. station data from 1976–1990 to examine the spatial and temporal distribution of freezing rain in the area, and the prevalence of synoptic scale features during these events. The study revealed that some storms associated with freezing rain decelerated as they crossed the Great Lakes, which could contribute to some prolonged periods of freezing rain in the central and eastern regions of the Great Lakes. During freezing rain events, a strong surface high pressure area is typically observed over Quebec and Maine with low pressure southwest of the region. As was noted by MacKay and Thompson (1969), Stuart (1994), and Stuart and Isaac (1999), the frequency of freezing rain was found to increase from west to east across the Great Lakes region.

Regional maxima in freezing precipitation can be attributed to major storm tracks, topographic features (i.e. mountains and valleys), and moisture sources such as the Gulf of Mexico and the western tropical North Atlantic (Bernstein, 2000; Higuchi et al., 2000; Rauber, 2001). In the

U.S., the Appalachian Mountains provide upslope conditions for the formation of precipitation and valleys in which cold air with temperatures below 0°C remains trapped for longer periods of time than over the surrounding areas. Similarly, the Ottawa River Valley in Ontario, and the Dundalk highlands northwest of Toronto, experience a relatively higher frequency of occurrence of freezing rain than other regions in southern Ontario. MacIver and Auld (2000) performed a statistical extreme value analysis of historical (20th century) estimated daily freezing rain amounts at climate stations in southern Ontario. The study concluded that topographical and geographical influences in the Dundalk highlands or upland regions northwest of Toronto produce risks of extreme freezing rain amounts that equal those of eastern Ontario, the area in Ontario that was hardest hit by Ice Storm '98. The 25-year return period freezing rain amounts can be expected, on average, to exceed 25 mm, a damaging amount of freezing rain, in both of these areas (MacIver and Auld, 2000).

Observations indicate that the Great Lakes also influence the occurrence of freezing rain at western shoreline locations and during some months of the year (Cortinas, 2000; Robbins and Cortinas, 2002). Cortinas (2000) discussed the influence of the Great Lakes water temperatures on the occurrence of freezing rain at lakeshore versus inland locations in the U.S. Areas immediately to the west of Lake Michigan, Lake Huron, Lake Erie and southwest of Lake Ontario were found to experience a lower frequency of freezing rain than areas further inland. During the fall, early winter and early spring, the temperature of the unfrozen lake increases the low-level temperature of airmasses from just below 0°C to just above 0°C. In freezing rain events when the surface winds are off the lake (the majority of the storms), the precipitation falls as rain near the lakeshore with freezing rain inland away from the lake. However, during mid to late winter, as the temperature of the lakeshore water decreases to near or below 0°C, the water no longer acts to increase the temperature of the lower atmosphere and freezing rain is recorded at both inland and lakeshore locations.

In contrast, Lakes Ontario and eastern Lake Erie appear to have a minimal effect on the freezing rain frequency observed in the U.S. northeast states (Robbins and Cortinas, 2002). This is consistent with the predominant occurrence of east or northeast surface winds during freezing rain events in this region, which eliminate any thermal advection from the lakes that are located to the west (Robbins and Cortinas, 2002).

In southern Ontario, east, northeast or southeast surface winds are most commonly associated with freezing rain events in advance of a surface warm front associated with an advancing storm system or with a quasi stationary surface front. This would suggest that the frequency of freezing rain may be decreased on the western and southern shores of Lake Ontario and northern shore of Lake Erie during the fall, early winter and early spring, as was determined by Cortinas (2000) for the western U.S. Great Lake shore locations.

5.2 Analysis of Freezing Rain Occurrence in Current Study

5.2.1 Data Sources and Treatment

The hourly weather phenomenon indicator and hourly occurrence of freezing rain (yes [1] or no [0]) were retrieved from Environment Canada's Digital Archive of Canadian Climatological Data for 14 stations in Ontario and one station in Montreal, Quebec for the winter months

(November to April) of 1953/54–2000/01. The hourly weather phenomenon indicator and hourly occurrence of freezing rain were also extracted from a U.S. National Climatic Data Center (NCDC) dataset of hourly surface meteorological data for 12 stations in the U.S. Great Lakes region for the period 1973/74–1999/2000. Station information for the selected weather stations is provided in Table 3 and a map showing the selected station locations is provided in Figure 4.

It should be noted that although NCDC provided weather data for the period from 1948–2000, data prior to 1973 had to be excluded from the study. Although the weather phenomenon was observed hourly at the U.S. airport stations during the entire period, the NCDC dataset only includes this information at 3 hourly intervals (i.e. 0000, 0300 GMT, etc.) for the period from the mid 1960s through 1972. The dataset does provide interpolated values of temperature, cloud cover, dewpoint temperature and mean sea level pressure for the intermediate hours (i.e. 0100, 0200, 0400 GMT, etc), giving 24 hourly values of these meteorological variables. However, the occurrence of weather phenomenon, such as freezing rain, can not be interpolated. Therefore, U.S. weather data prior to 1973 was not included in the analyses.

A small percentage of the Canadian and U.S. station data in the study area had missing occurrences of the hourly weather phenomenon, and hence the hourly occurrence of freezing rain was also missing. Automated and subjective techniques were used to assess if freezing rain could have occurred on these “missing” hours.

An automated procedure assumed that no freezing rain occurred on the hour if:

- 1) the surface air temperature was greater than/equal to 1°C at that time, or
- 2) the temperature was less than 1°C and the total cloud cover was less than seven tenths.

For the remaining cases of Canadian station data that were excluded by these screening criteria, a subjective assessment was used to determine if freezing rain could have occurred on the hour. Daily climatological data (daily maximum and minimum temperatures, daily precipitation/rain/snow totals) and hourly weather sequences (including, for example, air temperature, cloud cover, weather phenomenon and visibility) were retrieved from Environment Canada’s Digital Archive of Canadian Climatological Data for the dates and hours of freezing rain occurrence that were in question. A subjective meteorological assessment of the data excluded by automatic screening concluded that no freezing rain occurred on the hour if:

- 1) both maximum and minimum temperatures for the day were >0°C;
- 2) no rainfall was recorded on that day;
- 3) hourly sequences of weather indicated that freezing rain was not likely.

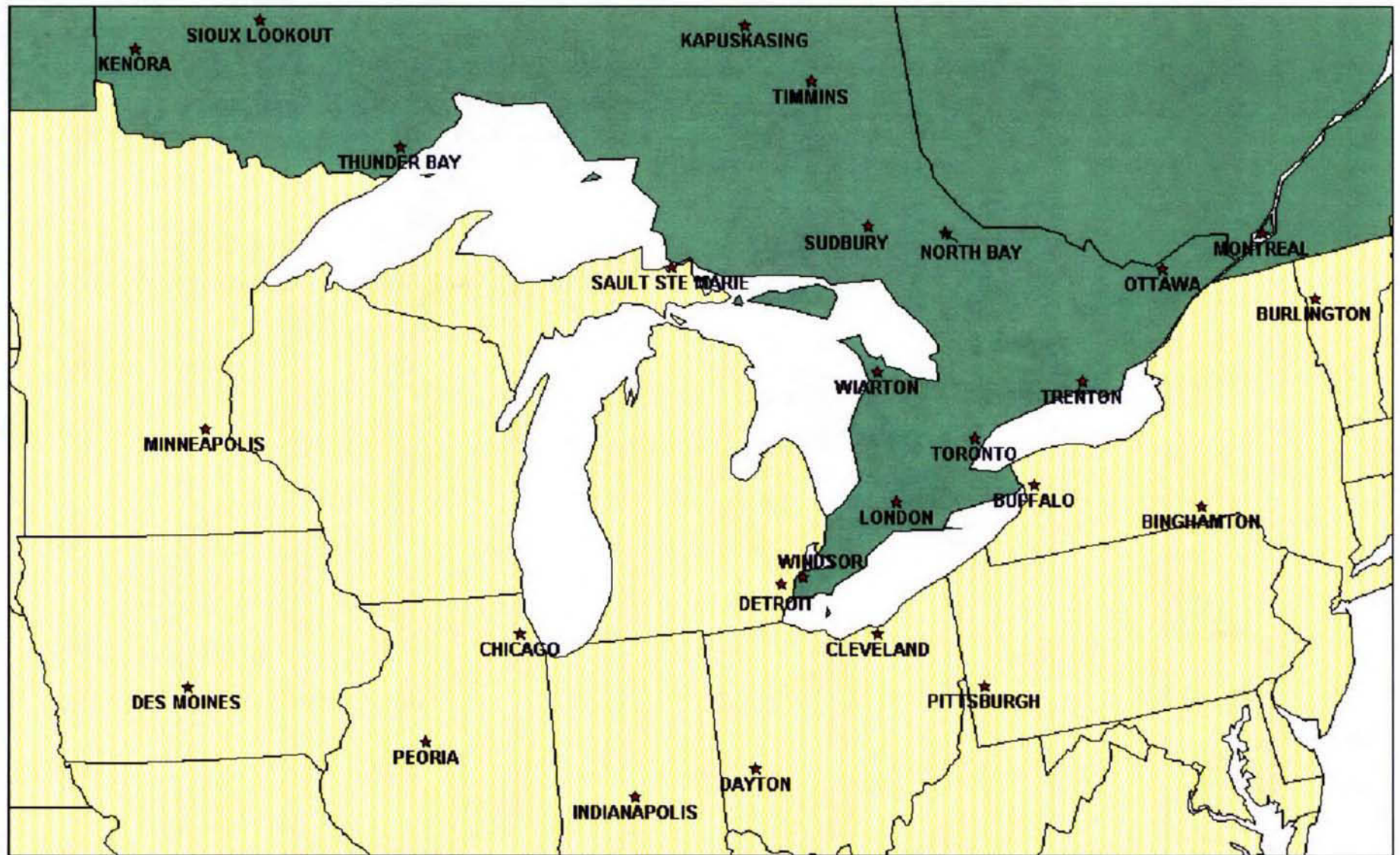
From the missing data assessment, the majority of the missing precipitation type occurrences were determined to be non-occurrences of freezing rain. It was determined that a total of only two hours of missing Canadian station data were likely to have represented freezing rain occurrences. No occurrences of missing U.S. data were flagged as freezing rain occurrences. However, in January 1985, the occurrence of freezing rain was missing at Buffalo, New York and Cleveland, Ohio for part or all of 23 and 27 days, respectively. Given the available data, it was difficult to determine whether or not freezing rain had occurred on these days. The

occurrence of freezing rain remained set to missing on these dates in January, and the entire month of data for the two stations was excluded from further analysis.

Table 3 Location and record information of 24 hourly weather observing stations used in the study.

Station Name	Airport ID	Latitude	Longitude	Elevation (m)	Start Record	End Record
Kapuskasing Airport	YYU	49°25'N	82°28'W	227	Jan-1953	Apr-2001
Kenora Airport	YQK	49°47'N	94°22'W	406	Jan-1953	Apr-2001
London Airport	YXU	43°02'N	81°09'W	278	Jan-1953	Apr-2001
Montreal Dorval Int'l Airport	YUL	45°28'N	73°45'W	36	Jan-1953	Apr-2001
North Bay Airport	YYB	46°22'N	79°25'W	370	Jan-1953	Apr-2001
Ottawa Macdonald-Cartier Int'l Airport	YOW	45°19'N	75°40'W	114	Jan-1953	Apr-2001
Sault Ste Marie Airport	YAM	46°29'N	84°31'W	192	Nov-1961	Apr-2001
Sioux Lookout Airport	YXL	50°07'N	91°54'W	390	Jan-1953	Apr-2001
Sudbury Airport	YSB	46°37'N	80°48'W	348	Feb-1954	Apr-2001
Thunder Bay Airport	YQT	48°22'N	89°20'W	199	Jan-1953	Apr-2001
Timmins Airport	YTS	48°34'N	81°23'W	295	Apr-1955	Apr-2001
Toronto Lester B. Pearson Int'l Airport	YYZ	43°40'N	79°36'W	173	Jan-1953	Apr-2001
Trenton Airport	YTR	44°07'N	77°32'W	86	Jan-1953	Apr-2001
Warton Airport	YVV	44°45'N	81°06'W	222	Jan-1953	Apr-2001
Windsor Airport	YQG	42°16'N	82°58'W	190	Jan-1953	Apr-2001
Binghamton Edwin Airport	BGM	42°13'N	75°59'W	499	Jan-1973	Dec-2000
Buffalo Niagara Int'l Airport	BUF	42°56'N	78°44'W	215	Jan-1973	Dec-2000
Burlington Int'l Airport	BTV	44°28'N	73°09'W	104	Jan-1973	Dec-2000
Chicago O'Hare Int'l Airport	ORD	41°47'N	87°45'W	190	Jan-1973	Dec-2000
Cleveland Hopkins Int'l Airport	CLE	41°24'N	81°51'W	245	Jan-1973	Dec-2000
Dayton Int'l Airport	DAY	39°54'N	84°13'W	306	Jan-1973	Dec-2000
Des Moines Int'l Airport	DSM	41°32'N	93°39'W	294	Jan-1973	Dec-2000
Detroit Metropolitan Airport	DTW	42°25'N	83°01'W	191	Jan-1973	Dec-2000
Indianapolis Int'l Airport	IND	39°44'N	86°17'W	246	Jan-1973	Dec-2000
Minneapolis-St Paul Int'l Airport	MSP	44°53'N	93°13'W	255	Jan-1973	Dec-2000
Peoria Greater Peoria Airport	PIA	40°40'N	89°41'W	199	Jan-1973	Dec-2000
Pittsburgh Int'l Airport	PIT	40°30'N	80°13'W	373	Jan-1973	Dec-2000

Figure 4 Map showing location of the hourly weather stations used in the study (15 stations in Canada and 12 stations in the U.S.).



5.2.2 Frequency of Occurrence of Freezing Rain

The winter seasonal (November to April) average number of days and hours of freezing rain occurrence at the selected Canadian and U.S. study locations is provided in Table 4.

In terms of freezing rain hours, Ottawa Airport reported by far the highest average number of freezing rain hours of any station, followed by Montreal and Binghamton, New York and then by London and Sudbury. Ottawa Airport reported a seasonal average of almost 37 hours of freezing rain and 10 days with some occurrence of freezing rain over the 1953/54 to 2000/01 period. In southern Ontario, London reported the highest seasonal average of hours (24) and days (7) with freezing rain. It is speculated that the number of freezing rain hours for the Dundalk Highlands of southern Ontario are likely as high or higher than those of London. The lowest average frequencies of seasonal freezing hours (five to six) and days (two to three) were recorded over northwestern Ontario. These averages are consistent with the previous freezing rain climatologies of MacKay and Thompson (1969), Stuart (1994), and Stuart and Isaac (1999). In the U.S., Binghamton reported the highest seasonal frequency of freezing rain hours (27) and days (eight). This result is in agreement with Robbins and Cortinas (2002).

The annual time series of the November to April hourly and daily frequency of occurrence of freezing rain at the Canadian locations for the period 1953/54 to 2000/01 are provided in Figures 5 and 6, respectively. Similarly, the time series of the seasonal total number of observed freezing rain hours and days at the U.S. stations are displayed in Figures 7 and 8, respectively. As would be expected, the graphs clearly illustrate the considerable interannual variability that occurs in the frequency of freezing rain. The contribution of Ice Storm '98 to the 1997/98 total freezing rain hours is apparent on the Ottawa time series. In fact, of the 95 hours of freezing rain that Ottawa Airport received that winter, 65 of these hours occurred during the January 1998 Ice Storm. As might be expected, the times series of total days with some freezing rain occurrence at Ottawa clearly are not useful for helping to identify a year, such as 1998, with a significant ice storm.

Table 4 Winter seasonal (November to April) average number of days and hours with freezing rain for selected locations in Canada (1953/54–2000/01) and the U.S. (1973/74–1999/00)

Station	Winter Seasonal (Nov–Apr) Average # of Days with Freezing Rain	Winter Seasonal (Nov–Apr) Average # of Hours with Freezing Rain
Kapuskasing	3.1	8.2
Kenora	2.6	6.2
London	6.7	23.7
Montreal	7.8	27.4
North Bay	7.3	22.4
Ottawa	9.7	36.6
Sault Ste Marie	3.7	10.3
Sioux Lookout	2.3	4.8
Sudbury	7.7	24.4
Thunder Bay	2.1	6.2
Timmins	4.2	11.5
Toronto	5.2	17.1
Trenton	6.8	21.9
Wiarion	5.3	13.9
Windsor	4.9	14.3
Binghamton	8.0	26.6
Buffalo	5.0	15.4
Burlington	5.0	16.9
Chicago	2.6	6.5
Cleveland	4.6	12.3
Dayton	4.7	18.2
Detroit	4.2	12.4
Des Moines	3.6	11.6
Indianapolis	3.8	12.4
Minneapolis	2.9	7.5
Peoria	4.2	14.1
Pittsburgh	4.1	11.7

5.2.3 Trends Analysis of Frequencies of Freezing Rain Events

The frequencies of the seasonal total number of observed freezing rain hours and days were examined to determine whether or not there was an increase or decrease in any of these frequencies over 48 years (November to April, 1953/54–2000/01) at the 15 selected stations in Canada. The trends in the hourly and daily frequency of occurrence of freezing rain are presented graphically in Figures 5 and 6, respectively. All trends were tested at the 5% significance level, using the Student t-test. The linear trend analysis was not performed for the stations in the U.S. The U.S. hourly occurrences of freezing rain are only available since 1973 and this period of record is too short for a trend analysis. However, the time series of the hourly and daily frequency of occurrence of freezing rain for 12 selected U.S. stations are shown in Figures 7 and 8, respectively.

The analysis determined that there are only three statistically significant ($p \leq 0.05$) freezing rain trends at the selected Canadian locations. The results of the trend analysis can be summarized as follows:

- At Wiarton, the seasonal frequency of total freezing rain hours has decreased significantly by approximately eight hours over the 48-year period. A small statistically significant decrease of three days in the number of freezing rain days at Wiarton and London has also occurred over this period.
- Non-significant upward trends in freezing rain hours and days are observed at two northern Ontario stations (Kapuskasing and Timmins), as well as at Ottawa and Montreal.
- All other station trends in freezing rain hours and days were determined to be generally non-existent (stations in northwestern Ontario, central Ontario, Windsor) or decreasing non-significantly (Toronto, London [hours only], Trenton).

The trend analysis would suggest that the risks of freezing rain occurrence have remained relatively the same or have been slightly decreasing in northwestern Ontario, southern Ontario and central Ontario during the period 1953–2001. The increasing trends in northern Ontario, Ottawa and Montreal over the same period are statistically non-significant and hence offer no conclusive evidence of an increased risk of freezing rain occurrence over the period. One of the possible reasons for any changes in freezing rain occurrence could be a subtle change in temperature observed over the same time period. According to a recent study (Zhang et al., 2000), non-statistically significant increases of less than 0.5°C in daily maximum and minimum temperatures were observed in southern Ontario during the period from 1950–1998. Historical observed climate data could be used to investigate potential relationships between trends in air temperature and freezing rain amounts. An assessment of freezing rain risks in a future warming climate could also be undertaken using climate change scenarios derived from Global Climate Model (GCM) output. However, both of these analyses are beyond the scope of the current study.

Even though the majority of the Canadian time-series trends of freezing rain events described above were found to be statistically non-significant, there are still considerable interannual fluctuations in freezing rain occurrence for the period 1953–2001 (Figures 5 and 6). It is hypothesized that these fluctuations are closely associated with monthly mean temperatures. For example, in a warmer January, the boundary area between snow and rain, where freezing rain

would usually occur, could be located further northward than in a colder January. Therefore, under this hypothesis, we might expect that in Ontario, more freezing rain events would occur in a warmer January, with more snow, rather than freezing rain, usually occurring in a colder January.

In order to investigate the relationships between temperature and freezing rain events over the study area, monthly mean temperature and monthly total occurrence frequencies of the freezing rain hours and days were analysed for the months of maximum freezing rain occurrence, December to February. Monthly mean temperatures were sorted in descending order during the period 1953–2001 for the Canadian stations and during the period 1973–2000 for the U.S. stations. The years were then divided into temperature quintiles based on the sorted monthly mean temperatures. Finally, mean frequencies of the freezing rain occurrence for each of the quintiles and the quintile mean temperature were calculated. The results of this analysis are provided in Figures 9 to 11. The first quintile represents the highest monthly mean temperature, the second quintile the second highest, and so on, with the fifth quintile representing the lowest monthly mean temperature.

Three relationship patterns between monthly mean temperature and freezing rain events are apparent from Figures 9 to 11. These patterns can be described as follows:

- First, on average in January, the monthly total frequency of freezing rain events at Ottawa, Montreal, Sudbury and North Bay increases from the lowest to highest temperature quintiles (i.e. as monthly temperatures warm). Each of these sites was noted earlier to observe a higher seasonal frequency of occurrence of freezing rain relative to other Ontario locations (with the exception of London). For example, in Ottawa, on average in January (Figure 10), as the monthly mean temperature increases from -15 to -10°C and to -7°C , the monthly total hours of freezing rain occurrence increase from 5.8 to 8.2 and to 13.3. Similarly, the monthly total number of days with freezing rain events increases from 1.2 to 2.4 and to 2.8. Colder monthly temperatures at these stations likely indicate a significant number of days within the month when Arctic high pressure dominated and synoptic storms moved well south of the area. No clear relationships between monthly temperatures and freezing rain occurrences are evident at the remaining study locations, perhaps in part because freezing rain occurrences may be tempered by the influence of the Great Lakes. Locations well away from the influence of the Great Lakes indicate that freezing rain hours increase as monthly January temperatures warm.
- Second, during the months of December and February, the monthly total frequency of freezing rain events at the selected Canadian locations usually increases from the lowest temperature quintile to a certain quintile, and then decreases from that quintile to the highest temperature quintile. For instance, in Ottawa during the winter shoulder month of December (Figure 9), monthly total hours of freezing rain events increase by 9.5 hours from the lowest temperature quintile (-12°C) to the middle quintile (-7°C); and then slightly decrease by 2.6 hours from the mid-quintile to the highest temperature quintile (-3°C). This pattern might be expected as there could be more liquid or wet snow events in months with warmer mean temperatures.

- Finally, at some of the U.S. stations in the southern region of the study area, there is evidence that the monthly total frequency of freezing rain events decreases from the lowest to highest temperature quintiles. For example, in Dayton during December (Figure 9), as monthly mean temperature increases from the lowest temperature quintile (-5°C) to the highest temperature quintile (3°C), monthly total hours of freezing rain events decrease from 7.2 to 1.3 hours. However, this pattern is not consistent between stations and months. For example, in February, freezing rain hours reach a secondary maxima at the warmest temperature ($>0^{\circ}\text{C}$) quintiles at several of the U.S. stations, including Dayton.

Figure 5 Annual time series of frequency of the winter seasonal (November to April) total freezing rain hours for 15 stations in Canada (1953/54–2000/01)

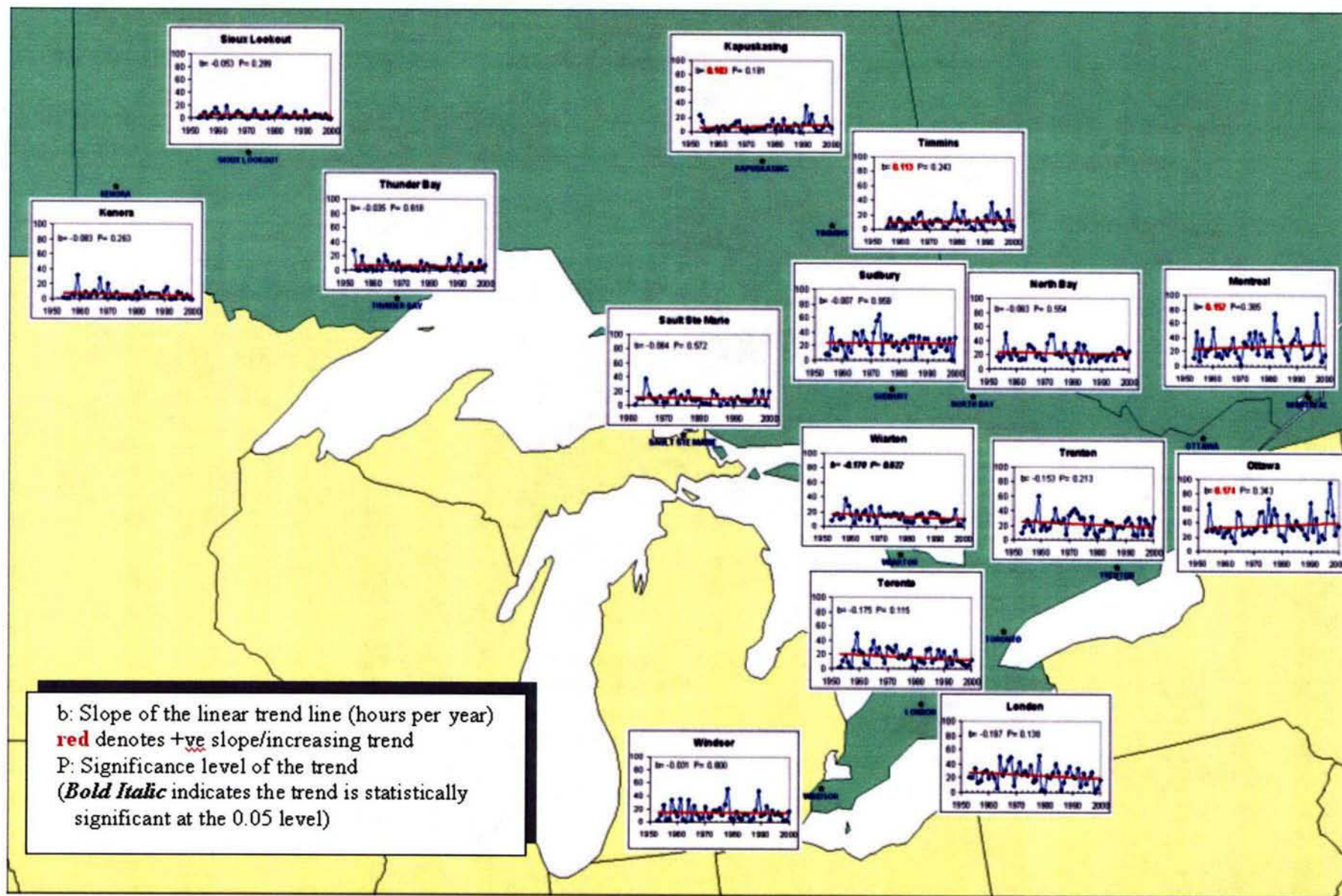


Figure 6 Annual time series of frequency of the winter seasonal (November to April) total freezing rain days for 15 stations in Canada (1953/54–2000/01)

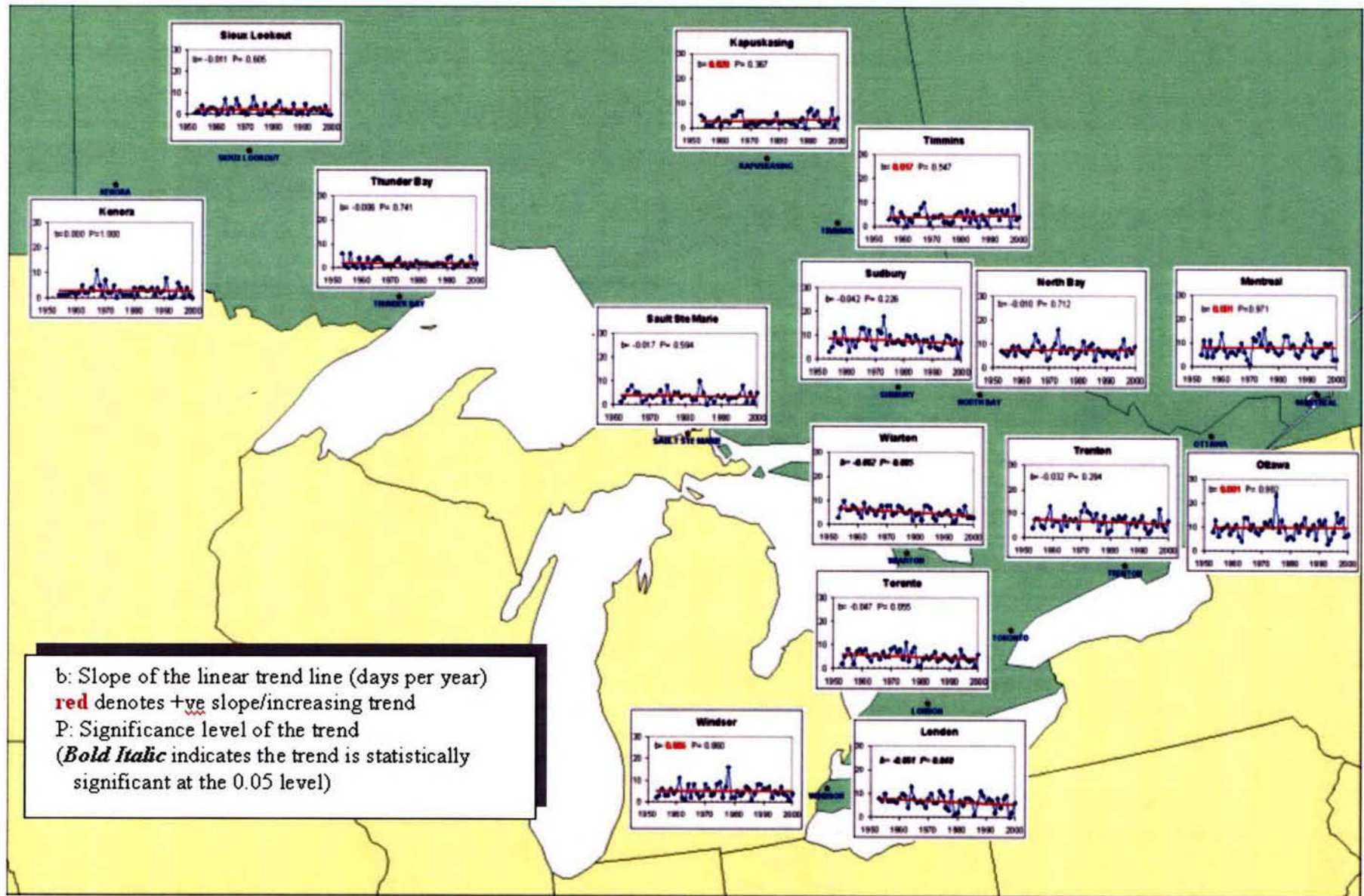


Figure 7 Annual time series of frequency of the winter seasonal (November to April) total freezing rain hours for 12 stations in the U.S. (1973/74–1999/00)

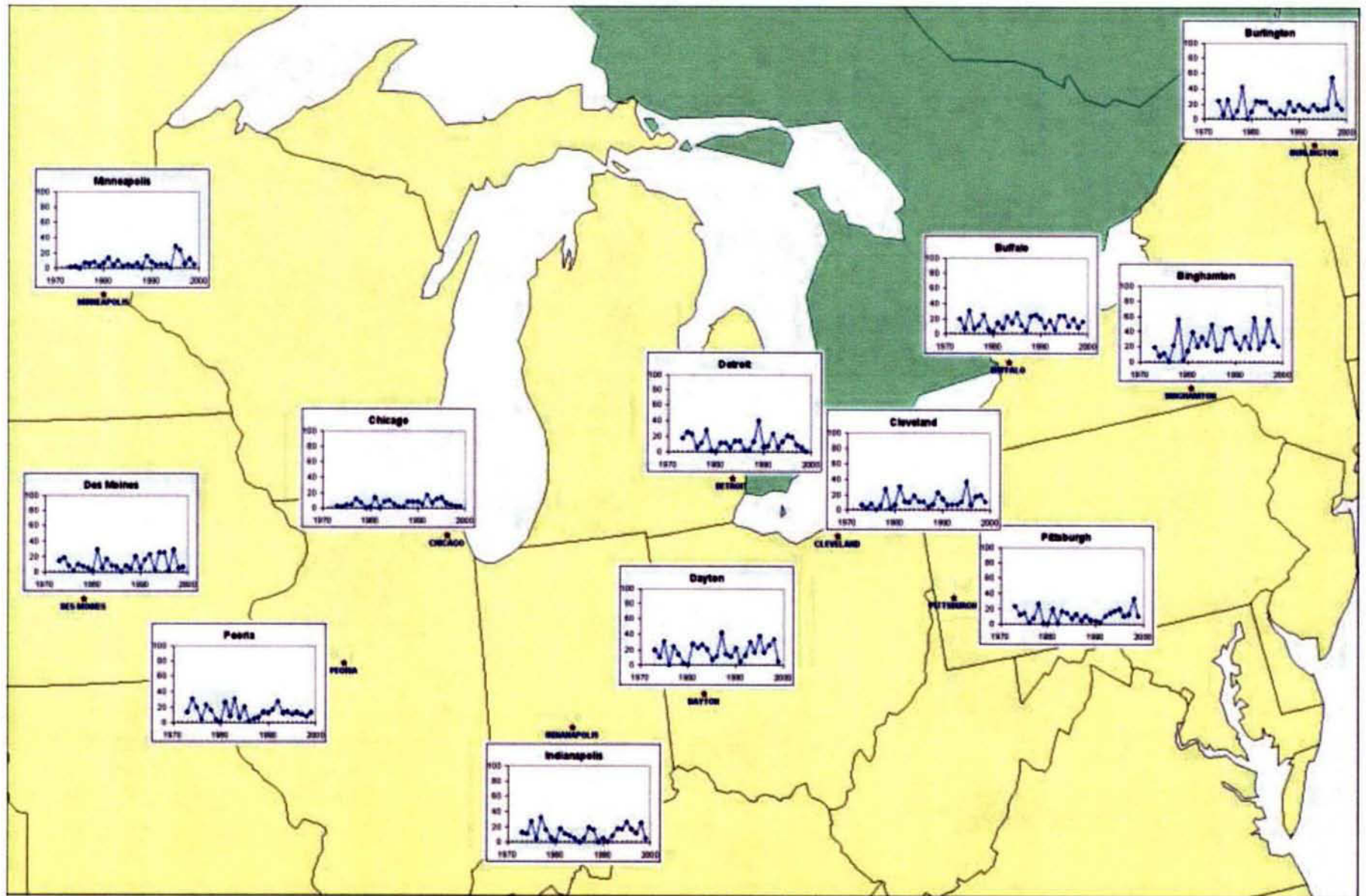


Figure 8 Annual time series of frequency of the winter seasonal (November to April) total freezing rain days for 12 stations in the U.S. (1973/74–1999/00)

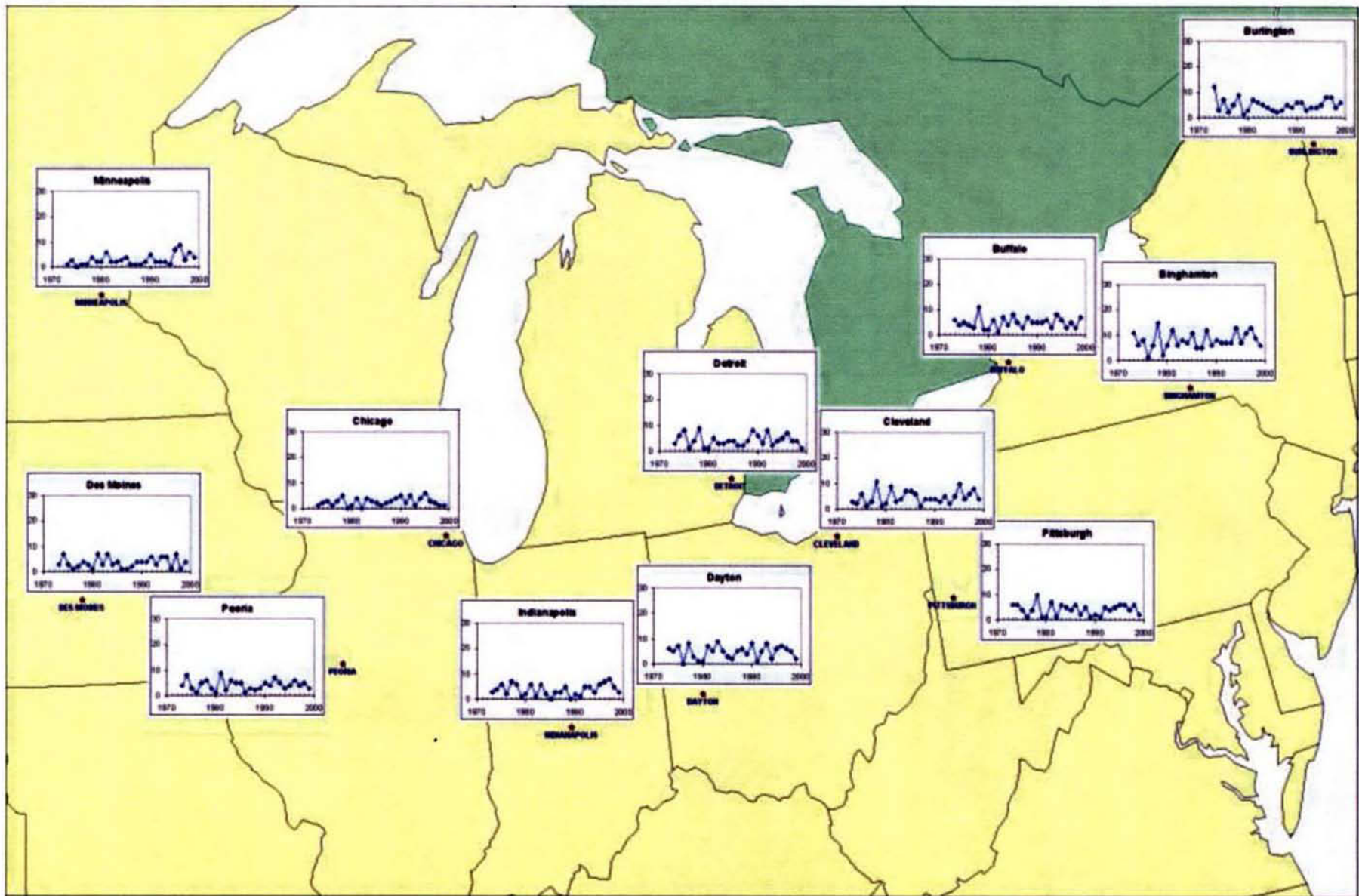


Figure 9 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of monthly mean temperature quintiles in December. The horizontal axis is within-quintile monthly mean temperature ($^{\circ}\text{C}$). (Canadian data: 1953–2000, U.S. data: 1973–1999)

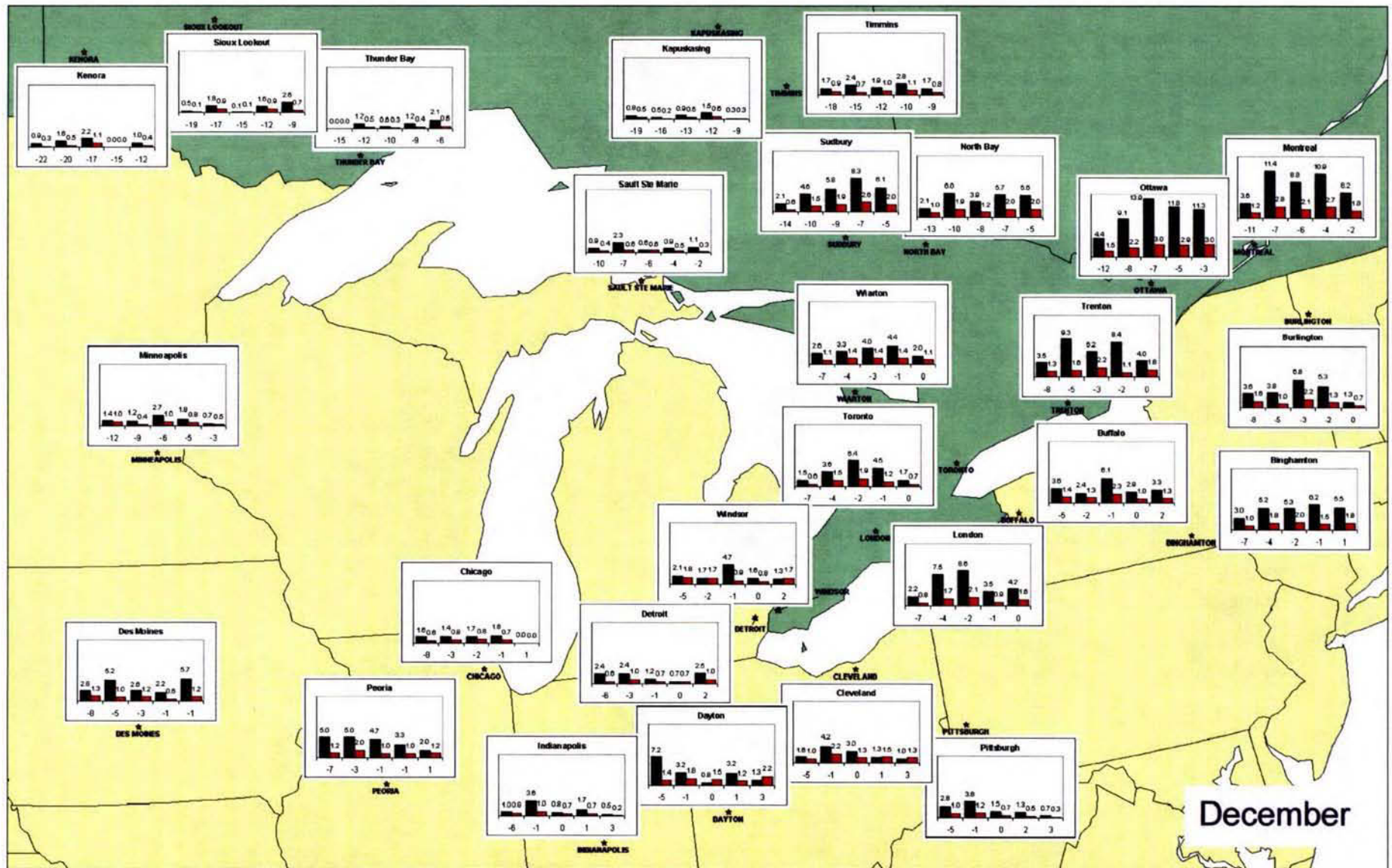


Figure 10 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of monthly mean temperature quintiles in January. The horizontal axis is within-quintile monthly mean temperature ($^{\circ}\text{C}$). (Canadian data: 1954–2001, U.S. data: 1974–2000)

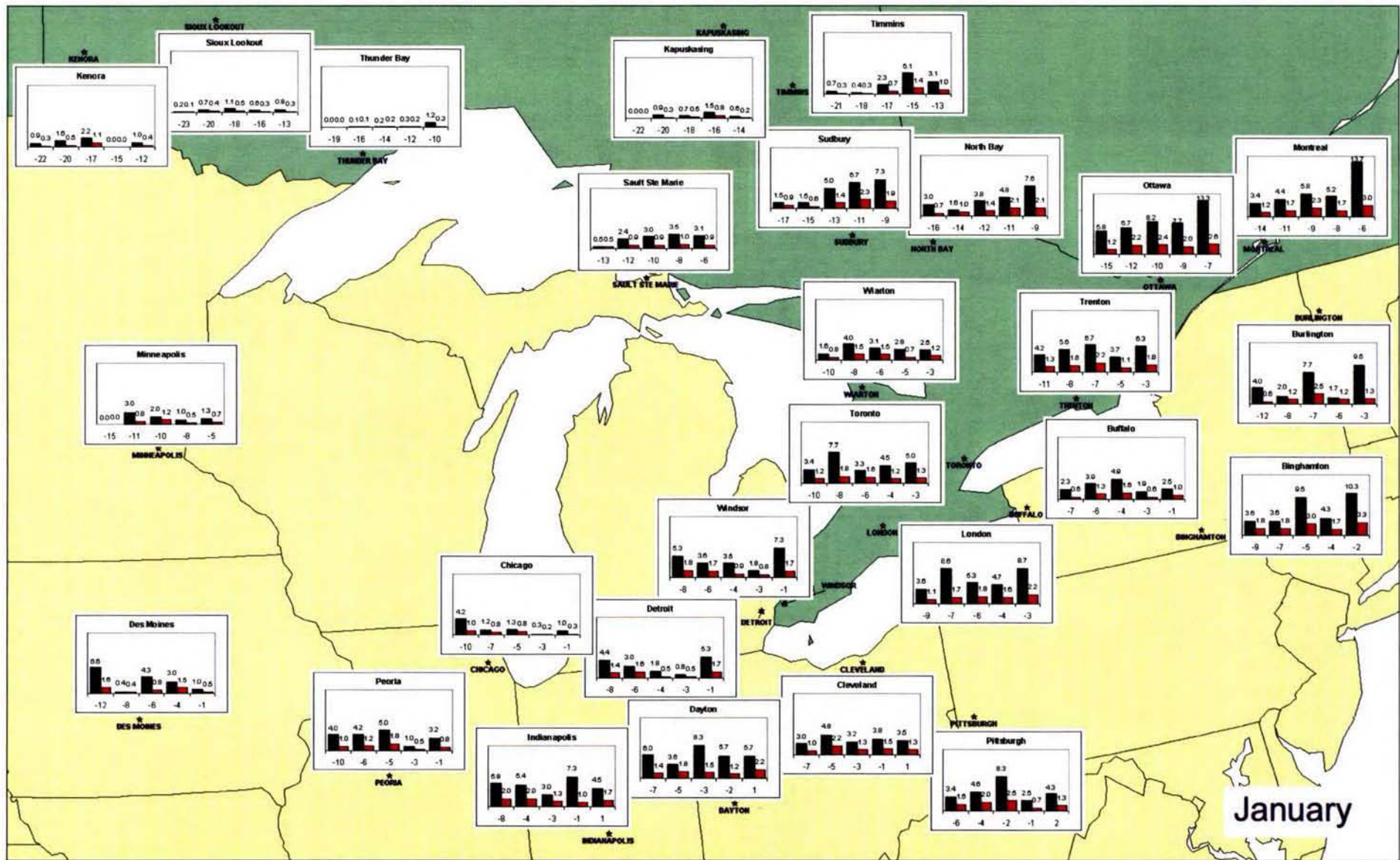
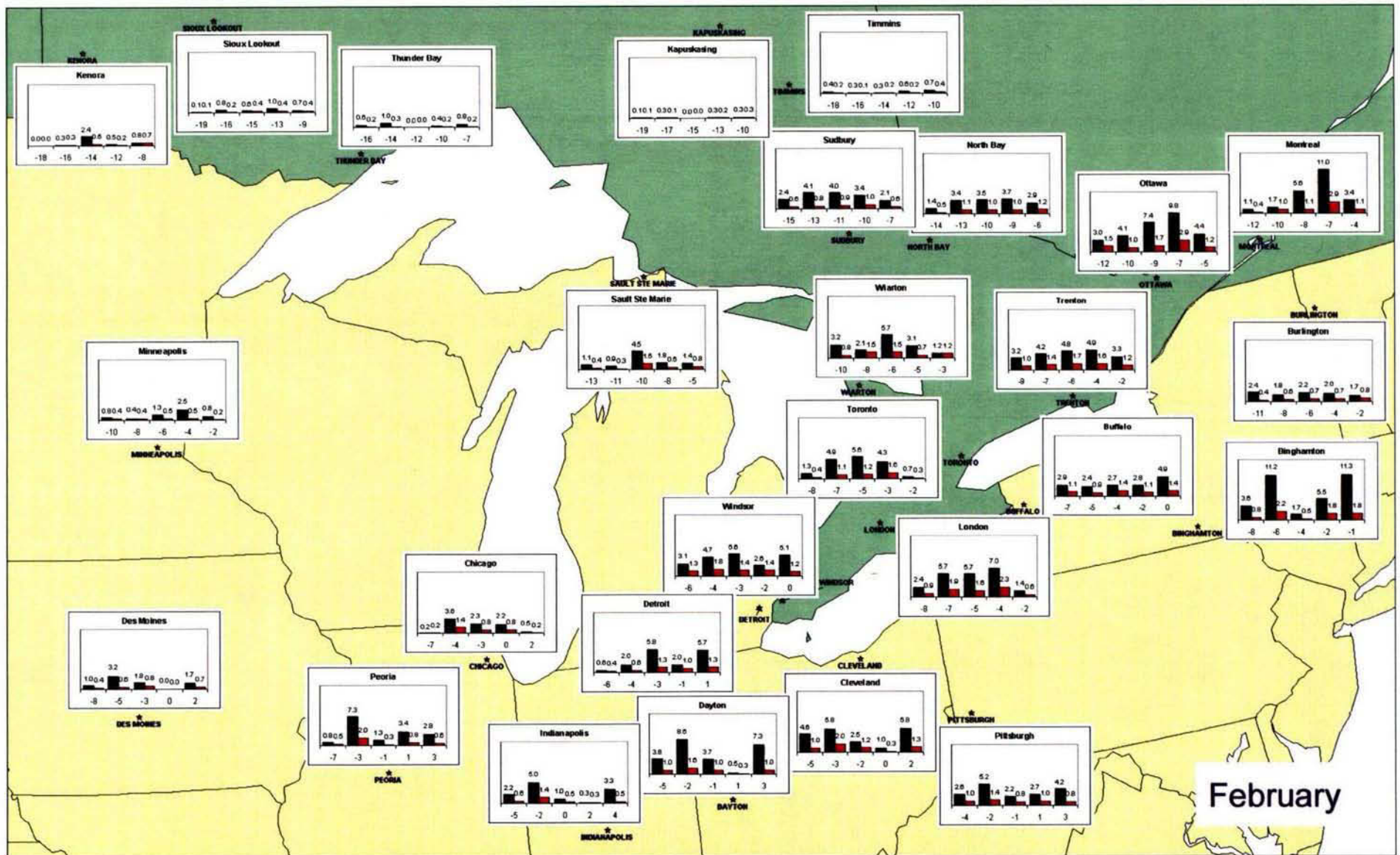


Figure 11 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of monthly mean temperature quintiles in February. The horizontal axis is within-quintile monthly mean temperature ($^{\circ}\text{C}$). (Canadian data: 1954–2001, U.S. data: 1974–2000).



6.0 Climatology of Severe Ice Storms in the Great Lakes Region

A general regional climatology of average freezing rain conditions in the Great Lakes region has previously been described in Section 5.1. The updated analysis of annual occurrences and trends in freezing rain events in Ontario from 1953/54–2000/01 was presented in Section 5.2. The following sections will depart from average conditions and specifically examine the most severe ice storms that have impacted southern and eastern Ontario since the mid-1800s and the northern U.S. since the early 1900s. Because communications tower collapses typically occur under the more severe ice or ice and wind storms, an analysis and discussion will follow on the weather conditions associated with these ice storm related tower collapses.

6.1 Icing Related Communication Tower Collapses

Although communication tower collapses are rare, those that do occur are normally related to severe weather phenomena that include tornadoes, hurricanes, blizzards and ice storms. Due to their more robust design to withstand severe ice and wind loads, communication towers are generally the last structures to fail in a severe ice storm. Therefore, knowledge of icing-related communication tower collapses serves as one means of identifying the most severe ice storms.

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) has established a database of U.S. communication tower collapses that have occurred due to severe atmospheric ice accretion (Mulherin, 1998). The database, as described by Mulherin (1998), lists 140 tower collapses that occurred from 1959–1996, and documents such information as date of the collapse, structural characteristics of the tower, and the tower's geographic location. An updated version of the database lists 205 tower collapses that occurred from 1929–2001. The towers include television, radio (FM, AM, two-way and amateur), Civil Air Patrol, telephone relay and microwave receivers and transmitters, ranging in height from 40 to 2060 feet above ground. Specific information for each of the 205 tower collapses is provided in Table 5, and the location of each of the collapses is shown in Figure 12. The tower collapse information was made available to Environment Canada for use in this study by CRREL (Mulherin, personal communication, 2002). An additional database of 26 Canadian communication tower collapses was also provided by CRREL (Mulherin, personal communication, 2002). These tower collapses occurred during the period 1958–1998. Details of each of these 26 collapses are provided in Table 6, and the collapse locations are also shown in Figure 12.

The communication tower collapse database suggests that severe ice storms and their associated icing-related tower failures are more common in parts of the U.S. than in Canada. The majority of the severe storms and tower failures have occurred in the central, mid-west, southeastern and northeastern U.S. (see Figure 12). Twenty four of the 26 Canadian tower collapses have occurred in the areas immediately bordering the U.S. and over the southern tip of Newfoundland (see Figure 12 and Table 6). The majority of the failures were recorded from December through March, although a few collapses have been reported in April and November. One tower collapsed in October in Newfoundland.

The database indicates that during 1973, 1975, 1983, 1994, 1997 and 1998, severe ice storms caused tower collapses over widespread areas. In 1983, three ice storms were responsible for 29

U.S. and seven Canadian tower collapses. Eighteen U.S. tower failures occurred in one January storm alone. An early March 1983 storm accounted for seven collapses in North Dakota and six in the southern Prairie provinces. A subsequent March storm over the northeastern U.S. and Canada resulted in the failure of the remaining three U.S. tower collapses during this year, as well as one in Newfoundland. All 16 tower collapses in the southeastern U.S. in 1994 occurred as a result of one storm. Power outages were reported over 11 states, and power wasn't restored in some areas for a month (Mulherin, 1996). Northwestern Mississippi was the hardest hit region with 14 towers collapsing. Radial ice thicknesses of four to six inches were reported on these towers (Mulherin, 1996). An early April ice storm in 1997 caused the collapse of 11 towers in North Dakota and Minnesota. Ice Storm 1998 resulted in 13 tower collapses in the northeastern U.S., four in Montreal, and one in Kingston, Ontario. The Kingston tower collapse is one of only two communication tower collapses that have been reported in Ontario since 1958. An icing related tower failure is also listed as having occurred in Essex in April 1970. However, it should be noted that a preliminary weather analysis undertaken in this study could find no evidence that a severe icing event occurred on any day in April 1970. It is possible that this date has been incorrectly registered in the CRREL database or that wind, rather than ice, loading was the determining factor in the tower's collapse.

Figure 12 Location of atmospheric icing related communication tower collapses in the United States (205) during the period 1929–March 2002 and atmospheric icing/wind loading communication tower collapses in Canada (1958–2002) (25 + 1 collapse in northern Labrador which is not shown on this map). Tower collapse database information provided by CRREL (Mulherin, personal communication, 2002).

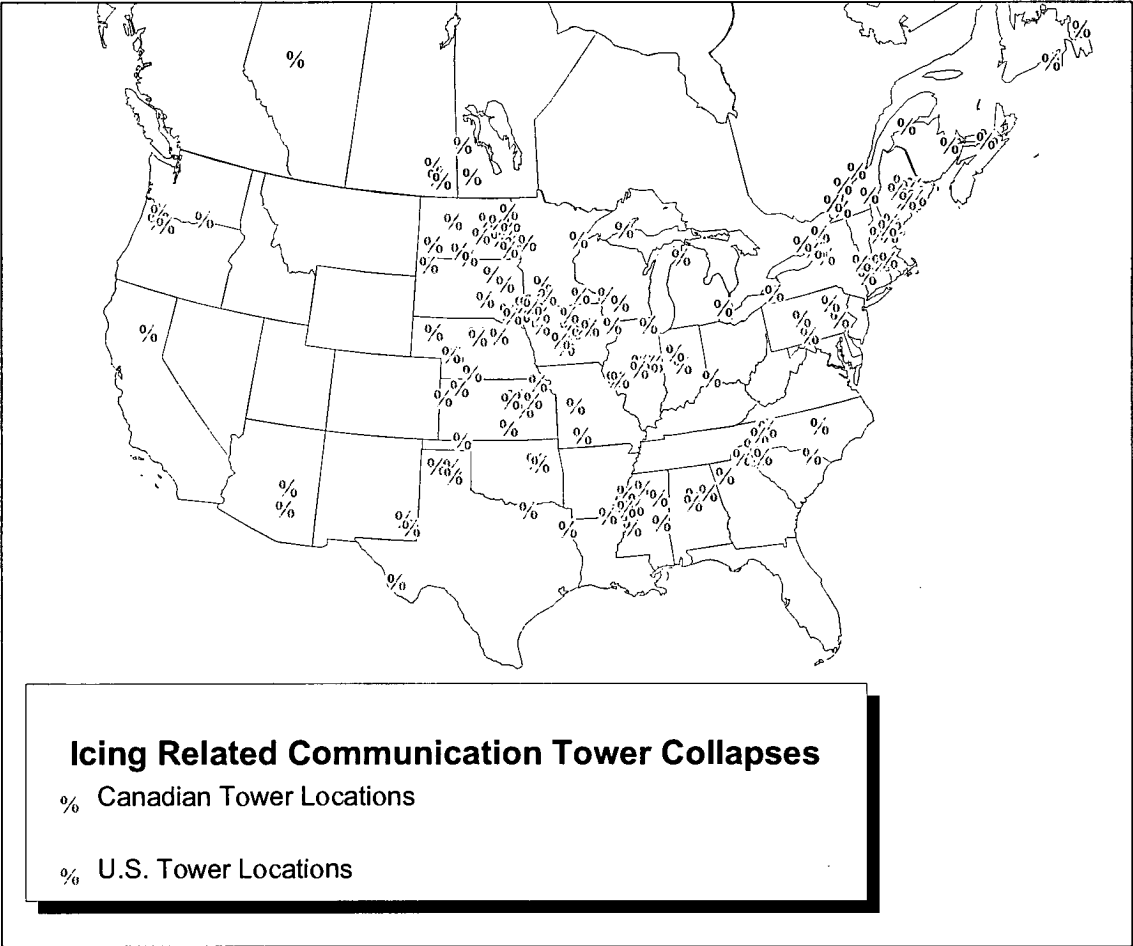


Table 5 Listing of atmospheric icing related communication tower failures in the United States, 1929–2001 (updated to March 2002).
 Provided by CRREL (Mulherin, personal communication, 2002).

No.	Month	Day	Yr	Tower_name	Type	City/Town	State	Height (ft)	No.	Month	Day	Yr	Tower_name	Type	City/Town	State	Height (ft)
1	12	18	29	WCSH		Portland	ME		56	3	27	75	Watowan	CT	Godahl	MN	620
2	1	15	40	WOED	FM	Paxton	MA		57	3	27	75	KXON	TV	Salem	SD	1569
3	1	1	48	WIND	AM	Chicago	IL		58	12	21	75	NE Road Dept	2W	Tryon	NE	300
4	1	1	48	Tower1	AM	Chicago	IL		59	3	4	76	WTMB	FM	Tomah	WI	406
5	1	1	48	Tower2	AM	Chicago	IL		60	11	8	77	KDLO	TV	Garden City	SD	1405
6	1	1	48	Tower3	AM	Chicago	IL		61	11	9	77	KRSW/KLOH	FM	Chandler	MN	700
7	1	1	48	Tower4	AM	Chicago	IL		62	1	15	78	WKOX	FM	Framingham	MA	450
8	1	1	48	Tower5	AM	Chicago	IL		63	2	6	78	KTNE	TV	Alliance	NE	1499
9	1	1	48	Tower6	AM	Chicago	IL		64	2	10	78	KLOE	TV	Goodland	KS	790
10	1	1	48	Tower7	AM	Chicago	IL		65	2	12	78			northern panhandle	TX	
11	1	1	48	Tower8	AM	Chicago	IL		66	2	12	78			northern panhandle	TX	
12	11	28	59	WBRV	AM	Boonville	NY	250	67	3	25	78	WAND	TV	Argenta	IL	1314
13	12	7	60		TV	Marfa	TX		68	3	26	78	WJPT	TV	Bluffs	IL	1588
14	12	8	60	KSWS	TV	CapRock	NM	1610	69	3	26	78	WCIA	TV	Dewitt	IL	303
15	2	26	61	Antenna Systems	CT	Potsdam	NY	400	71	3	26	78	Sammons	CT	Jacksonville	IL	440
16	2	26	61	Canton FD	2W	Canton	NY		70	3		78	WSOY		Decatur	IL	140
17			61	WCDC	TV	Adams	MA		72	12	28	82	Fulda Cable	TV	Fulda	MN	126
18	2	23	62		TV		KY		73	12		82		TV	Elwood	NE	
19	1	1	64	WSPA's old tower	TV	Greenville (Paris Mt)	SC	90	74	1	20	83	East MS Comm	2W	Meridian	MS	300
20	1	2	64	WESC		Greenville	SC	300	75	1	21	83	radio tower	2W	Birmingham	AL	
21	1	16	67	KSDN	AM	Aberdeen	SD	270	76	1	21	83	radio tower #1	2W	Birmingham (Red Mtn)	AL	
22	1	26	67	WICD	TV	Homer	IL	1335	77	1	21	83	radio tower #2	2W	Birmingham (Red Mtn)	AL	
23	1	26	67	Illini Elec	2W	Champaign	IL	310	78	1	21	83	radio tower #3	2W	Birmingham (Red Mtn)	AL	
24	4	30	67	KXMB	TV	St Anthony	ND	882	79	1	21	83	radio tower #1	2W	Birmingham (Dbi Oak Mtn)	AL	
25	4	30	67	KEM Elec Co-op	2W	Linton	ND	370	80	1	21	83	radio tower #2	2W	Birmingham (Dbi Oak Mtn)	AL	
26	2	6	69	NE Road Dept	2W	Flats	NE	300	81	1	21	83	radio tower #3	2W	Birmingham (Dbi Oak Mtn)	AL	
27	2	26	69	KDIX	TV	Dickinson	ND	50	82	1	21	83			Calera	AL	
28	2	26	69	KXMB	TV	St Anthony	ND	876	83	1	21	83	WAGI	FM	Forest City	NC	606
29	2	4	71	WDOE	AM	Dunkirk	NY	194	84	1	21	83	repeater tower	2W	Forest City	NC	300
30	2	23	71	WNPE	TV	Copenhagen	NY	925	85	1	21	83	WQNS	FM	Clyde	NC	150
31	2	28	71	KOIN	TV	Portland	OR	1000	86	1	21	83	WESC	TV	Caesars Head	SC	1284
32	2	28	71	KOIN	FM	Portland	OR	750	87	1	21	83	WMUU#1	FM	Greenville (Paris Mt)	SC	200
33	3	5	71	WBYO		Boyetown	PA	220	88	1	21	83	Two-way tower #1	2W	Greenville (Paris Mt)	SC	-110
34	12	16	72	Civil Defense	2W	Clarks Knob	PA	60	89	1	21	83	Two-way tower #2	2W	Greenville (Paris Mt)	SC	-110
35	1	8	73	Farmers Fertilizer	2W	Lovington	NM		90	1	21	83	Two-way tower #3	2W	Greenville (Paris Mt)	SC	-110
36	12	3	73	MidKansas	CT	Junction City	KS	500	91	1	22	83	WCIQ	TV	Mt Cheaha	AL	578
37	12	3	73	MidKansas	CT	Junction City	KS	500	92	3	4	83	Anderson Comm	2W	Baldwin	ND	500
38	12	3	73	KS Hwy Patrol	2W	Clay Center	KS	245	93	3	4	83	Capital Elec	2W	Baldwin	ND	200
39	12	4	73	Farm Bureau Service	2W	Eldora	IA	230	94	3	5	83	KQDY	FM	Baldwin	ND	919
40	12	4	73	KRNT	TV	Alleman	IA	2000	95	3	5	83	old tower	BK	Baldwin	ND	550
41	12	4	73	KIFG	FM	Iowa Falls	IA	237	96	3	6	83	KXMC	TV	Minot	ND	1053
42	12	4	73	Midwest Elec.	2W	Des Moines	IA	100	97	3	6	83	KSRE	TV	Minot	ND	1031
43	12	4	73	KJCK	FM	Junction City	KS	500	98	3	6	83	Souris Riv Tel	2W	Minot	ND	500
44	12	4	73	KJCK	AM	Junction City	KS	500	99	3	9	83	NW Cblvision	CT	Winchester	CT	
45	12	4	73	KMKF	FM	Manhattan	KS	60	100	3	9	83	WCDC	TV	Mt Greylock	MA	247
46	12	5	73	telephone tower	TL	between Dodge City & Liber	KS		101	3	11	83	WCSH	TV	Sebago	ME	1305
47	12	17	73	WKOX	AM	Framingham	MA	206	102	11	28	83	KWWL	TV	Rowley	IA	2000
48	1	11	75	Renville Cnty	CT	Bird Island	MN	550	103	3	18	84	KFDI	FM	Colwich	KS	1164
49	1	11	75	K & K	CT	Devils Lake	ND	500	104	3	18	84	KLDH	TV	Dover	KS	1230
50	1	11	75	KSFY/KELO	TV	Rowena	SD	1985	105	3	19	84	Council Grove	CT	Council Grove	KS	430
51	3	23	75	KLOH	FM	Jasper	MN	385	106	3	20	84	WVII	TV	E Edgington	ME	700
52	3	27	75	KXEL	FM	Waterloo	IA	600	107	3	20	84	WABI	TV	Dixmont	ME	560
53	3	27	75	IA Safety Dept	2W	Storm Lake	IA	330	108	3	20	84	radio tower	2W	Dixmont	ME	40
54	3	27	75	old tower	2W	Storm Lake	IA	320	161	2	11	94	TN DOT	2W	Camden	TN	
55	3	27	75	KRSW	FM	Chandler	MN	703	162	2		94	WDLJ	FM	Indianola	MS	
111	12	1	86	NE G&P	2W	Bassett	NE	400	163	1	22	95	WHCF	FM	Bangor	ME	
112	12	1	86	Watauga Cty Sheriff	2W	Boone	NC	100	164			95	KCMT	FM	Chester	CA	
113	12	1	86	Watauga Cty Sheriff	2W	Boone	NC	280	165	2	5	96	WMUU#2	FM	Greenville (Paris Mt)	SC	

No.	Month	Day	Yr	Tower_name	Type	City/Town	State	Height (ft)	No.	Month	Day	Yr	Tower_name	Type	City/Town	State	Height (ft)
114	12	1	86	repeater antenna	2W	MI Pisgah	NC		161	2	11	94	TN DOT	2W	Camden	TN	
115	12	2	86	KMNE	TV	Bassett	NE	1524	162	2		94	WDLJ	FM	Indianola	MS	
116	12	2	86	NE Road Dept	2W	Rushville	NE	300	163	1	22	95	WHCF	FM	Bangor	ME	575
117	12	2	86	NE Road Dept	2W	Tryon	NE	270	164			95	KCMT	FM	Chester	CA	
118	3	18	87	State of SD	2W	Miller	SD	250	165	2	5	96	WMUU#2	FM	Greenville (Paris Mt)	SC	200
119	3		87	KXYQ	FM	Portland	OR	300	166	2	5	96	WMUU#3	BK	Greenville (Paris Mt)	SC	
120	12	15	87	WAJC	FM	Indianapolis	IN	200	167	3	4	85	State of SD	2W	Parker	SD	400
121	12	15	87	WWPZ	AM	Petoskey	MI	400	168	3	5	85	SPAT tower	TV	Fostoria	IA	435
122	12	26	87	KTUL	TV	Coweta	OK	1906	169	2	5	96	Two-way tower#4	2W	Greenville (Paris Mt)	SC	120
123	12	27	87	KXYQ	FM	Portland	OR		170	2	5	96	Two-way tower#5	2W	Greenville (Paris Mt)	SC	120
124	12	27	87	KUSO	FM	Tulsa	OK		171	11	22	96	KWOA	FM	Worthington	MN	600
125	1	7	89	WGMR	FM	Phillipsburg	PA	299	172	11		96	KLAK	FM	Denison	TX	500
126	1	8	89	WBRE	TV	Mountaintop	PA	849	173	12	31	96	WOLX	FM	Baraboo	WI	652
127	2	8	89	WSTZ	FM	Raymond	MS	1003	174	1	14	97	Interstate Comms		Pinal Pk	AZ	300
128	3	3	89	KFNF	FM	Oberlin	KS	450	175	1	14	97	Roy Hudgins		Pinal Pk	AZ	
129	3	8	89	WDSC	AM	Dillon	SC	600	176	2	6	97	WBKP	TV	Marquette	MI	600
130	12	10	89	WPTF	TV	Auburn	NC	1929	177	3	12	97	Tulsa PD	2W	Tulsa	OK	
131	12	10	89	WRAL	TV	Auburn	NC	2000	178	4	5	97	KXJB	TV	Galesburg	ND	2060
132	2	15	90	Falcon Cbl	CT	Sedalia	MO	540	179	4	6	97	KFNW	AM	West Fargo	ND	396
133	3	9	90	NE Road Dept	2W	Willowdale	NE	300	180	4	6	97	KJ108	FM	Oslo	MN	500
134	12	21	90	KHCD	TV	Manchester	KS	900	181	4	6	97	Halstad Tel		Halstad	MN	300
135	3	12	91	WSHW	FM	Middle Fork	IN	500	182	4	6	97	KKXL		East Grand Forks	MN	400
136	3	12	91	State of IN	2W	Geetingsville	IN	303	183	4	6	97	Nelson County	2W	Petersburg	ND	400
137	3	23	91	WDIO	TV	Duluth	MN	856	184	4	6	97	Dakota Central Tel	2W	Hawk's Nest	ND	180
138	11	1	91	KIA	FM	Mason City	IA	812	185	4	6	97	Cass County Shop	2W	Casselton	ND	140
139	11	1	91	KCMR	FM	Mason City	IA	445	186	4	6	97	Cass County Shop	2W	West Fargo	ND	180
140	11	1	91	CGordoCty Sheriff	2W	Mason City	IA	250	187	4	6	97	Cass Cty H2O Users	2W	Leonard	ND	150
141	11	1	91	KEZT	FM	Woodward	IA	1026	188	4	6	97		CT	Drayton	ND	400
142	11	1	91	Falcon Cbl	CT	Hiawatha	KS	480	189	1	8	98	Atlantic Comms	2W	Dedham	ME	120
143	11	1	91	KNXR	FM	Rochester	MN	550	190	1	8	98	WCIZ	FM	Watertown	NY	
144	12	28	92	transmitter tower		Pine Log Mt	GA		191	1	8	98	WTNY	AM	Watertown	NY	
145			92	Polk Cty Sheriff	2W	Tryon	NC	50	192	1	8	98	WUZZ	AM	Watertown	NY	
146	3	18	93	Polk Cty Sheriff	2W	Tryon	NC	50	193	1	9	98	WEZQ	FM	East Eddington	ME	140
147	2	10	94	WCLD	FM	Cleveland	MS	338	194	1	9	98	Industrial Comms	2W	Falmouth	ME	~150
148	2	10	94	WAID	FM	Clarksdale	MS		195	1	9	98	Radio Tel of ME	2W	T9 SD	ME	100
149	2	10	94	WDMS	FM	Greenville	MS		196	1	9	98	WLNH	FM	Laconia	NH	245
150	2	10	94	Bolivar Cty FD	2W	Pace	MS		197	1	10	98	WKZS	FM	New Gloucester	ME	500
151	2	10	94	WBAD	FM	Greenville	MS		198	1	10	98	WCDQ	FM	Sanford	ME	240
152	2	10	94	WESY	AM	Greenville	MS		199	1	10	98	Limerick FD	2W	Limerick	ME	130
153	2	10	94	WIQQ	FM	Greenville	MS		200	1	10	98	WBFB	FM	Frankfort	ME	283
154	2	10	94	KUUZ	FM	Greenville	MS		201	1	10	98	Piscotus Cty Sheri	2W	Dover Foxcroft	ME	100
155	2	11	94	Engelkes Farms	2W	Hamburg	AR		202	2	21	98	PCT Comms	2W	Topsfield	ME	90
156	2	11	94	WSUH	AM	Oxford	MS		203	4	4	99	KBJR	TV	Duluth	MN	
157	2	11	94	WMJW	FM	Cleveland	MS		204	12	14	2000	home system	2W	Caddo lake	TX	
158	2	11	94	WYMX	FM	Greenwood	MS		205	1		2001		AR/CAP	Hanford Reservation	WA	90
159	2	11	94	Time Warner	CT	Cleveland	MS										
160	2	11	94	home 2W tower	2W	Clarksdale	MS										

TV = Television
 FM = FM radio
 AM = AM radio
 CT = Cable TV
 2W = Two-way radio
 TL = Telephone relay
 BK = Backup tower
 AR = Amateur radio
 CAP = Civil Air Patrol

Table 6 Listing of atmospheric icing loading related communication tower failures in Canada, 1958–1998 (updated to March 2002). Provided by CRREL (Mulherin, personal communication, 2002).

#	Date	Tower	Location	Province	Height (feet)
1	18 Mar 1958	CBN	St Johns	NL	307
2	1962		Antigonish	NS	300
3	3 Jan 1965	CFXU-TV	Rossfield	NS	450
5	12 Dec 1967	CKTM	Trois-Rivieres	QB	1083
6	23 Mar 1968	CBV-AM	Quebec City	QB	250
7	Apr 1970		Essex	ON	150
8	1972		Mt Megantic	QB	310
9	Nov 1972		Swan Hills	AB	300
10	1976		Grenfield	SK	410
11	1979		Grand Banks	NL	350
12	Jan 1979		Upsolquitch	NB	700
13	Oct 1980		Saglek	NL	303
14	1983		Brandon	MB	1350
15	1983		Mt Scio	NL	950
16	Mar 1983		Warmley	SK	350
17	Mar 1983		Baldy Mtn	MB	508
18	Mar 1983		Baldy Mtn	MB	480
19	Mar 1983		Carlyle	SK	680
20	Mar 1983		Brandon	MB	1400
21	28 Jan 1995	CBC/MITV	Moncton	NB	500
22	9 Jan 1998	CJAD-AM #1	Montreal	QB	675
23	9 Jan 1998	CJAD-AM #2	Montreal	QB	675
24	9 Jan 1998	CJAD-AM #3	Montreal	QB	675
25	9 Jan 1998	CJAD-AM #4	Montreal	QB	675
26	Jan 1998	CFMK-TV/FM	Kingston	ON	?

6.2 Historically Significant Freezing Rain Storms in Southern and Eastern Ontario

A detailed analysis of daily climatological data and hourly weather observations (available after 1953) was undertaken in order to help identify severe ice storms, other than Ice Storm '98, that have impacted southern and eastern Ontario since the mid-1800s. Daily climatological data for the period 1840–2002 were extracted from Environment Canada's Digital Archive of Canadian Climatological Data for climate stations in southern and eastern Ontario. The climate variables included daily maximum and minimum temperatures and daily precipitation, rain (both liquid and freezing) and snow totals. Hourly observed meteorological variables (including air temperature, wind speed and direction and weather phenomena) were also retrieved from the Digital Archive for weather observing stations in southern and eastern Ontario. However, this data is only digitally available from 1953.

The archiving of daily climatological data does not always make it easy or possible to determine days with or amounts of freezing rain. There are certain situations, of course, where it is easy to confirm the occurrence and amount of freezing rain. For example, any observation of rain or drizzle that occurs with a temperature of 0°C can usually be expected to be freezing precipitation. Unfortunately, when only daily maximum and minimum temperature values are available, it is not always possible to be certain that freezing precipitation occurred. If the maximum temperature is at or below 0°C, any rainfall should be considered to be freezing. If the maximum and minimum temperatures are both above 0°C, the rainfall is liquid. However, in cases where the maximum temperature is above 0°C and the minimum temperature is below 0°C, it is not clear if the rain fell as liquid or freezing. Freezing rain often occurs on a day in which the temperature rises above 0°C and then falls below freezing with the onset of precipitation, or the temperature is below freezing when the freezing rain is occurring and then rises above 0°C as the precipitation ends or changes to rain. On such days, it is impossible to know whether freezing rain has occurred and additional proxy information must be investigated to determine the likelihood of freezing rain.

The first step in identifying significant freezing rain events was to search for days in the climate archive record on which freezing rain was a strong possibility. A program was developed that checked each set of daily temperature and precipitation values, and extracted only those days when the maximum temperature was less than 0.7°C and the total rainfall exceeded 5.0 mm. The value of 0.7°C was chosen to include the pre-metric days when temperatures would have just been above freezing and reached 33°F. The 5.0 mm rainfall threshold was arbitrarily used to filter out the insignificant rainfall amounts. The resultant dataset was then sorted and grouped by date to show periods of consecutive days with the possibility of freezing rain. For the period from 1841 to the end of 2002, there were over 9000 favourable freezing rain combinations, comprising over 2000 possible freezing events.

Each combination was then examined to subjectively assess the likelihood of it being a notable freezing event. In general, multiple days, multiple locations, and rainfall amounts greater than 10 mm were required to tag an event as noteworthy. Further investigation of each of the selected events was done to confirm its significance and to examine its impact. This involved examining original climate documents, hourly weather records (available after 1953), Environment Canada paper archived surface weather maps, Environment Canada internal storm summaries, and newspaper accounts (see newspaper reference listings in Appendix A). In a few situations none of these were available. In several others, the extra evidence cast considerable doubt on the

significance of the event or the accuracy of the archival data. A literature search of scientific reports and journal articles provided comprehensive listings and discussions of significant U.S. ice storms for the authors' study areas (Hilberg, 1999; Jones and Mulherin, 1998; DeGaetano, 2000; Nicosia, 2002; Rauber et al., 1994; Van Dyke, 1999). The information served to confirm or add to reports about storms that crossed the U.S. border. Storms that produced 20 mm or more of freezing rain were ultimately selected for this study, with the 20 mm criteria selected as a level at which significant infrastructure damage and societal impacts often start to be reported.

In addition to Ice Storm '98, the above procedures identified 24 significant ice storms that have affected southern and eastern Ontario since the mid-1800s (see Table 7). It should be noted that in the ice storm events that were identified prior to the late 1800s, there is some uncertainty as to the amount of freezing rain that fell, simply because there were no climate stations in the area suspected to be affected. The first climate observations in Canada were recorded in Toronto in 1840. However, the first complete set of climate observations for an Ontario winter was not available until 1848–1849. The second climate station in southern Ontario was only opened in 1865. Although the number of stations had climbed above 50 by 1885, it was almost 70 years later that the 100-station mark was surpassed. One of the implications of this is that, when suggesting that the 1998 storm is unprecedented in Ontario's recorded history, it is only possible to say this with any confidence when comparing it to ice storms that have hit southern Ontario since the late 1800s.

Each of the 24 significant Ontario ice storms was evaluated for the duration, geographical extent and maximum amount of freezing rain. Where available, some information on the societal-economic impacts of the storms was also provided. Table 7 provides the detailed information summaries for the 24 storms.

The most severe Ontario ice storms occurred during the months of November through March, and about half of these typically occurred during the last two weeks of December or the first two weeks of January. The storms generally lasted between 12 hours and one to two days. The most prolonged of these storms (28–30 December 1942) spanned only about half the time period of Ice Storm '98. (Since the intensity of freezing rain is predominantly light over the Great Lakes region [Cortinas, 2000], the duration of the event is usually directly linked to the freezing rain amounts.) In Ice Storm '98, however, three different precipitation episodes over a six-day period resulted in up to 80 hours of freezing rain being reported in eastern Ontario. On the other hand, an ice storm that struck in March 1997 brought intense freezing rain over a relatively short duration to produce a significant freezing rain storm. This storm lasted up to six hours, but during this period, three to five hours of moderate freezing rain resulted in 20–30 mm of ice accumulation in an area from Chatham to London to Hamilton.

The severe ice storms analysed for areas within Ontario varied in size from several regions or counties to the extensive area covered by Ice Storm '98. The impacts of the crippling January 1998 Ice Storm, for example, were felt from southern Lake Huron to the eastern Ontario-Quebec border, an estimated area of approximately 110,000 km².

The amount of freezing rain typically associated with most of the storms was usually not evenly distributed. Freezing rain amounts can vary spatially as a result of local conditions and the fact that freezing rain weather patterns usually move in bands. The maximum amount of freezing rain reported in the Ontario storms ranged on average from 20–40 mm with a few cases of 50–70 mm

of freezing rain. The exception again was the 1998 Ice Storm, with maximum freezing rain accumulations of nearly 95 mm in eastern Ontario. However, four other storms also produced substantial freezing rain amounts. A storm in 1867 likely produced 70–80 mm of freezing rain in southern Ontario in less than one day, while freezing rain accumulations of 65–75 mm were reported over two days in the 1909 storm. The three day storm of 1942 brought at least 55–60 mm of freezing rain to eastern Ontario, followed by snowfalls of up to 40 cm. Ice accretions as “thick as a person’s wrist” were reported on telephone lines in the Ottawa area. The January 1968 Ice Storm in southwestern Ontario also produced significant amounts of freezing rain, 60 mm, over 2 days. However, during the November 1909 ice storm, Brantford reported 74.9 mm of freezing rain on one day (the 23rd). This could be the highest amount of freezing rain ever recorded on one day in Ontario. Despite the significant freezing rain amounts recorded, it should also be noted that significant snowfalls that fell nearby or soon after the ice storms exacerbated the storm impacts. In some cases (such as the storms of December 1959 and January 1968) the event is remembered as much (or more) for its snowfall as its freezing rain.

In the major freezing rain storms that have occurred in Ontario since the 1920s, much of the disruption has been as a result of widespread and often long-lasting outages in the communications and power transmission and distribution systems. The 1922 freezing rain storm was the first to have a widespread impact on provision of hydro-electricity in Ontario. In storms prior to 1922, disruptions in telegraph and telephone communications were notable. Telegraph service had first arrived in Ontario in the mid-1800s, but it wasn’t until the end of the century that telephones became available and not until the early 1900s that long-distance service was feasible. Although generation of electricity from Niagara Falls started in 1896, it was 1910 before transmission over long distances took place, and the widespread electrification of the province began. It’s not surprising then that the storms that have produced major damage and disruption from freezing rain are not found until the early part of this century. With no phones, electricity or motorized vehicles during the 1800s, the potential for major societal impacts was lowered.

In Canada, 28 human fatalities were attributed to Ice Storm ’98. With only one exception, deaths are not a notable part of the story of any of these storms. In one event, December 1959, 11 deaths were recorded. However, the majority of these came as a result of traffic accidents.

The CRREL communications tower collapse database (2002) documented one tower failure in Ontario ice storms since 1950 (see Section 6.1 for comments on the listed 1970 collapse). This collapse occurred in Kingston as a result of severe ice loading during Ice Storm ’98. As indicated in Section 6.1 and in Jones and Mulherin (1998), communication towers are normally the last structures to fail in an ice storm, and are therefore indicative of the most severe ice storms.

Many of these storms have caused considerable damage and have been responsible for major disruptions to travel and society in general. However, it is apparent that, whether comparing cost, damage, areal coverage, freezing rain amounts or duration, none approach the impacts of Ice Storm ’98. Even when adjusted for inflation, the worst of these storms has a price tag in the tens of millions of dollars, well below the billions of dollars that were estimated for Ice Storm ’98. Although the severity of the 1998 storm no doubt helped to contribute to these differences, a large part of the increased damages can also be attributed to our increased reliance on electricity and on instant communications. Studies undertaken by Changnon (1999, 2000) have shown that population growth, which reflects our changing property target, increased value of property

owned and increasing vulnerability to storms can explain a substantial part of significant increases in all storm related damages that have been observed in recent decades.

Notwithstanding the occurrence of the 1998 event, major ice storms have occurred less frequently in Ontario in the past few decades than during the previous hundred years. Although the amount of freezing precipitation that may fall at any one time may have changed very little, the number of such incidents has certainly declined. It is not possible to say whether or not this tendency will continue. However, it is likely that our increasingly electronic society of today has become more vulnerable to freezing rain storms as a result of our increasing reliance on uninterrupted electricity supplies and due to more industries operating under “just in time” delivery principles. The summary in Table 7 of major freezing rain storms affecting southern and eastern Ontario, identified through their impacts, would suggest an increasing frequency of severe ice storm impacts occurring in more recent decades.

It is worth noting that many of the severe ice storms documented for southern Ontario brought even greater amounts of freezing rain to locations in the northern U.S., based on our ancillary information. Indeed, some of the most severe ice storms to affect the northern U.S. brought either lower freezing rain amounts or snow to southern and eastern Ontario, as will be seen in the next section documenting severe northeastern U.S. ice storms.

The review of the severe ice storm events in Table 7 suggests that the risks of major power outages lasting several days and hence, the potential for a community disaster as a result of an ice storm, increases when freezing rain amounts exceed approximately 30 mm. Historical evidence indicates that the potential for long power outages and for a community disaster becomes likely when freezing rain totals exceed approximately 40 mm. The current CSA standard for transmission lines (not necessarily local distribution lines) recommends that structures in southern Ontario be designed for 25–30 mm of radial ice accumulation or build-up on power lines. While radial ice accumulations are not the same as total freezing rain amounts, the evidence from Table 7 would suggest that the ice accumulation amounts used in the CSA standard for design of transmission lines (overhead systems) can handle most of the severe ice storms likely to affect southern Ontario. Eastern Ontario likely is the area most at risk for transmission line failures.

Table 7 Major freezing rain storms over southern and eastern Ontario (1844–2002).

Year	Date	Area Affected	Duration of Freezing Rain	Maximum Amount of Freezing Rain	Remarks
1844	Jan 12	Toronto	1 day	36.1 mm	<ul style="list-style-type: none"> Climate station data is only available for one station, Toronto City.
1867	Dec 21–22	Eastern Lake Erie and western Lake Ontario	1 day	Uncertain, possibly 70–80 mm	
1870	Jan 2–3	Southwestern Ontario, mainly Niagara Peninsula	Less than one day	Unknown, 41.1 mm at Simcoe	
1883	Feb 2–3	Southwestern Ontario	1–2 days	40–45 mm	<ul style="list-style-type: none"> Woodstock – 43.1 mm of freezing rain. Port Dover – 41.2 mm of freezing rain. Storm also brought 10–25 cm of snow.
1887	Feb 6/7/8 or 9?? (Date unconfirmed)	East of southern Lake Huron and east of Georgian Bay	1 day	40–50mm	<ul style="list-style-type: none"> Freezing rain was produced by a major winter storm that tracked through the area during the week. Insufficient station climate data to pinpoint the exact day of the freezing rain event.
1896	Jan 24	Southern Lake Huron to the Kawarthas. Affected mainly Toronto and surrounding areas.	1 day	30 mm in Toronto	<ul style="list-style-type: none"> Telephone poles and wires were downed in Toronto by weight of ice. Disruption in telegraph service.
1908	Jan 12–14	Essex to Kent and Lambton counties	2 days	40–50 mm	<ul style="list-style-type: none"> Chatham reported 51.1 mm of freezing rain over two days.
1909	Nov 22–23	Southern Ontario from Lake Huron to Ottawa River	2 days	65–75 mm	<ul style="list-style-type: none"> Brantford reported 74.9 mm of freezing rain on the 23rd. This could be the highest amount ever recorded on one day in Ontario.

Year	Date	Area Affected	Duration of Freezing Rain	Maximum Amount of Freezing Rain	Remarks
1921	Dec 16-18	West end of Lake Ontario	1-2 days	45 mm	<ul style="list-style-type: none"> • Hamilton and Woodstock each reported 40-45 mm. • The Globe reported that winds of 80-120 km/h over the lower Great Lakes were responsible for most of the damage. • At Buffalo, NY, 12 ships were blown out of their docks.
1922	Mar 30-31	Michigan border to Lake Ontario	1½ days	30-40 mm	<ul style="list-style-type: none"> • 40.4 mm freezing rain reported at Grimsby. First freezing rain storm to have major widespread impact on provision of hydro-electricity in Ontario.
1929	Dec 17-20	Southern Lake Huron to the Niagara Peninsula and the northern states	3-4 days	45-50 mm	<ul style="list-style-type: none"> • Port Dover reported 46 mm freezing rain storm total; 33.3 mm fell on Dec 17-18. • Telegraph, telephone communications and power outages. • Significant damages also reported over Buffalo and western New York state to New England.
1933/ 1934	Dec 31- Jan 01	Eastern Ontario	12-18 hrs	25 mm	<ul style="list-style-type: none"> • Highest freezing rain amounts (to 25 mm) in narrow band from Barrie to Ottawa
1942	Dec 28-30	Eastern Ontario	3 days	55-60 mm, possibly higher	<ul style="list-style-type: none"> • Snow storm followed the ice storm. • Highest amounts near the St. Lawrence River east of Brockville. 57 mm of freezing rain was reported at Morrisburg, then 38 cm of snow. • Greatest damages were reported around Cornwall area. • Power outages up to two weeks. • One of the most severe glaze storms in New York

Year	Date	Area Affected	Duration of Freezing Rain	Maximum Amount of Freezing Rain	Remarks
					State on record from St. Lawrence to Albany. Millions in damage to power and transmission lines. Ice accretions as 'thick as a person's wrist' on telephone lines.
1943	Mar 15-16	From Georgian Bay and Lake Ontario to Ottawa Valley	1 day	Near 50 mm.	<ul style="list-style-type: none"> • 48.8 mm reported at Bancroft.
1948	Jan 1	Essex and Kent counties	1 day	30-35 mm	<ul style="list-style-type: none"> • 32 mm reported at Leamington. • Power outages of over a week and telephone service out for more than a month in some areas. • Hundreds of utility and hydro poles downed. • 100 km/h wind followed the precipitation.
1953	Jan 8-10	Southwestern Ontario	2 days	30-35 mm	<ul style="list-style-type: none"> • 32.5 mm reported at Simcoe. Generally 10-20 mm south of a line from Sarnia to St Catharines. • Much higher amounts reported in PA, NY and NJ with up to 100 mm of ice on trees and power lines. 50,000 people were without power for several days.
1959	Dec 26-28	Western Lake Ontario	3 days	40-45 mm	<ul style="list-style-type: none"> • 41.1 mm at Woodbridge. • Widespread power outages.
1967	Jan 26-27	Southwestern Ontario to northern shores of Lake Ontario	2 days	20 mm	<ul style="list-style-type: none"> • 20.8 mm at London.

Year	Date	Area Affected	Duration of Freezing Rain	Maximum Amount of Freezing Rain	Remarks
1968	Jan 13-15	London, St. Thomas to Toronto	2 days	60-65 mm	<ul style="list-style-type: none"> • 63.6 mm reported at Strathroy and St. Thomas. Freezing rain storm followed by up to 35 cm of heavy snow into southern Ontario. • Widespread power outages up to 5 days in the London area. Collapsed buildings reported.
1971	Feb 4-5	Sarnia	6-12 hours	25 mm	<ul style="list-style-type: none"> • Freezing rain reported throughout southern Ontario with 24.5 mm at Sarnia and 14 mm at Kingston. Elsewhere amounts were in the 5-10 mm range. • Communication tower collapses reported in New York State.
1976	Mar 1-4	Windsor to London	4 days; maximum 2 days at any one location	40 mm	<ul style="list-style-type: none"> • Main brunt of the freezing rain came on the 2nd and 3rd with isolated thunderstorms giving 20-40 mm of freezing rain from Windsor to just west of Hamilton. Power outages in some localities lasted as long as eight days. • Thunderstorms also reported on the 4th at Warton and Muskoka, giving 35 and 25 mm of freezing rain respectively. • Western New York State reported ice accumulations up to 50 mm and power outages up to 10 days.

Year	Date	Area Affected	Duration of Freezing Rain	Maximum Amount of Freezing Rain	Remarks
1986	Dec 24–25	Eastern Ontario	1–2 days	25–30 mm, estimated	<ul style="list-style-type: none"> No clear split in reporting liquid and freezing rain amounts. 70,000 homes, mostly in the Ottawa area were without power for 24–36 hours. Damages well in excess of \$1 million.
1990	Feb 15–16	North shore Lake Erie/Niagara Peninsula to north of Toronto	20–34 hours	20 mm	<ul style="list-style-type: none"> 10–20 mm along and south of a line from Sarnia to the Niagara Peninsula. 5–10 mm along northern shores of Lake Ontario except weather watcher reports of 20 mm locally in York region north of Toronto due to brief thunderstorm with freezing rain.
1997	Mar 14	Chatham to London to Hamilton	3–6 hours	20–30 mm	<ul style="list-style-type: none"> 3–5 hours of moderate freezing rain resulted in 20–30 mm of accumulation. Worst ice storm in Chatham and London area in 20 years (since 1976 storm).
1998	Jan 4–9	Southern Lake Huron to Quebec border	Up to 80 hours of freezing rain over 6 days	95 mm	<ul style="list-style-type: none"> Ice storm of greatest duration, areal extent, ice accumulation and impacts recorded for Ontario.

6.3 Significant Freezing Rain Storms over the Northern U.S.

As indicated in Section 6.1 and in Jones and Mulherin (1998), communication towers are normally the last structures to fail in an ice storm, and are therefore indicative of the most severe ice storms. The CRREL icing-related communication tower collapse database was therefore used to identify the most severe ice storms that have occurred since 1929 in the northern U.S. states bordering Ontario. A literature search of scientific reports and journal articles provided comprehensive listings and discussions of significant 20th and 21st century U.S. ice storms for the authors' study areas (Hilberg, 1999; Jones and Mulherin, 1998; DeGaetano, 2000; Nicosia, 2002; Rauber et al., 1994; Van Dyke, 1999). An extensive search of the Web was also conducted (see miscellaneous U.S. ice storm references in Appendix A). In particular, U.S. National Weather Service Forecast Offices' storm data and the National Climatic Data Center (NCDC) Storm Event Database provided valuable storm information on major ice storm events that have occurred in recent decades. The U.S. National Weather Service describes an ice storm as a storm

that produces a significant accumulation of ice (1/4 inch or more) during a freezing rain event. To produce this amount of ice, the freezing rain usually needs to persist for several hours. Finally, surface weather maps from Environment Canada's Toronto Regional Weather Centre archives were also examined to confirm the presence of winter storms in the areas of ice storm reports and tower collapses.

Using these procedures, a total of 22 major ice storms were identified as having occurred over the northern U.S. states bordering southern and eastern Ontario during the 1909–2002 period. The list is considered to be representative of the majority of the severe ice storms that have impacted on the area. However, given the techniques used for identifying these storms, it should not be considered as all inclusive. A detailed and extensive analysis of U.S. climatological and weather data would be required to identify any additional ice storms that may have impacted on the northern U.S. in the 20th century. However, the most severe ice storms have been documented in this study, as determined from the CRREL communication tower collapse database. The dates and general location of the 22 U.S. ice storms and their impacts on the affected areas in the U.S. and Ontario are summarized in Table 8.

An analysis of the data shows that each of the significant U.S. ice storms affected a large geographical area, generally the size of at least one or two states (see Table 8). Most storms that affected Ohio and New York State also affected southern Ontario to some extent. In particular, 8 of the 22 identified U.S. ice storms during the period 1909–2002 affected southern or eastern Ontario with more than 20 mm of freezing rain. Five of the remaining U.S. storms produced less than 20 mm of freezing rain over southern Ontario with the amounts ranging from 5–18 mm. Eight of the total number of storms affected southern and eastern Ontario with snow or light rain, with five of these storms producing snowfalls in excess of 15 cm. The February 1997 Michigan ice storm had no impact on southern or eastern Ontario, and produced only light snow in northern Ontario. Finally, half of the northern U.S. ice storms that were investigated impacted New York State more severely than the remaining states bordering southern and eastern Ontario (see Table 8).

Table 8 Major freezing rain storms over northern U.S. states bordering southern and eastern Ontario (1909–2002). Bolded Year/Date indicates that the storm was also identified as a major freezing rain storm over southern and eastern Ontario (see Table 7).

Year	Date	U.S. Areas Affected	Impacts on the U.S. States	Impacts on Ontario
1909	Feb 15–17	Ohio, New York State, New England	<ul style="list-style-type: none"> • Described as most severe storm in many years. • Heavy damage to trees and telegraph lines. 	<ul style="list-style-type: none"> • Snow storm over southern and eastern Ontario. • 20 to 33 cm of snow.
1921	Nov 26–29 Dec 01	New York State, New England	<ul style="list-style-type: none"> • The great New England ice storm; damage estimated at \$15 million (1921) 	<ul style="list-style-type: none"> • Light rain and light snow over southern Ontario. 1–2 cm of snow over eastern Ontario.
1929	Dec 17–20	Buffalo and northern New York State, as well as New England	<ul style="list-style-type: none"> • Described at the time as worst in 50 years in Maine and one of worst of record in Buffalo and western NY. 	<ul style="list-style-type: none"> • From southern Lake Huron to the Niagara Peninsula. • Port Dover reported storm freezing rain total of 46 mm; 33.3 mm of the total fell on Dec 17–18.
1942	Dec 28–30	New York state and New England	<ul style="list-style-type: none"> • Described as one of the most severe glaze storms on record in New York State from southern St. Lawrence to Albany. • Ice accretions up to six inches on power lines. 	<ul style="list-style-type: none"> • Eastern Ontario with maximum amount of freezing rain, 57 mm, reported at Morrisburg. • 51.6 mm of the total 57 mm fell on Dec 30. • 30 mm of ice accretion reported over eastern Ontario.
1947/ 1948	Late Dec 1947 /Jan 01/1948	New York state	<ul style="list-style-type: none"> • Two inches of ice accretion. • Several million \$ of damage. 	<ul style="list-style-type: none"> • Affected Essex & Kent Counties with hydro downtime for one week. • Max amount of recorded freezing rain 32.5 mm in Leamington on Jan 1. • Winds to 100 km/h followed freezing rain.
1953	Jan 8–11	New York State, Pennsylvania, New Jersey	<ul style="list-style-type: none"> • Ice accumulation up to four inches on trees and power lines. • 50,000 people without power for several days. 31 deaths in New England. • Millions of \$ in damage. 	<ul style="list-style-type: none"> • Southwestern Ontario. 32.5 mm of freezing rain reported at Simcoe on Jan 10; otherwise 10–20 mm.
1959	Nov 28	Ohio, New York State	<ul style="list-style-type: none"> • Icing related communication tower collapse in Boonville, NY. 	<ul style="list-style-type: none"> • Snow reported over all of southern and eastern Ontario. • Snowfall amounts generally 5–10 cm except 20 cm at Ottawa Int'l Airport.

Year	Date	U.S. Areas Affected	Impacts on the U.S. States	Impacts on Ontario
1961	Feb 26	Ohio, New York State	<ul style="list-style-type: none"> • Icing related communication tower collapses (2) in Potsdam and Canton, NY. 	<ul style="list-style-type: none"> • One of the major ice storms recorded in Canada. • Most severe impacts in Montreal, QC area. • 30 mm of freezing rain in Montreal with damage estimates of \$1.6 billion. • 19.4 mm of freezing rain over 24 hours at Kingston; 17.8 mm over 19 hours at Buttonville Airport (Markham); 12 mm over 13 hours at London.
1964	Dec 3-5	New York State, New England, Ohio	<ul style="list-style-type: none"> • Ice accumulations up to 1.5 inches in New York State. • Power outages for up to two weeks. <p>Duration of freezing rain :</p> <ul style="list-style-type: none"> • 24 hours in Albany, NY; • 14 hours in Buffalo, NY; • 14 hours in Rochester, NY; • 11 hours in Toledo, OH. 	<ul style="list-style-type: none"> • South/southwestern Ontario with 12.7 mm of freezing rain reported at Hamilton Airport; otherwise 2-6 mm.
1971	Feb 4	New York State, Pennsylvania	<ul style="list-style-type: none"> • Icing related communication tower collapse in Dunkirk, NY. <p>Duration of freezing rain:</p> <ul style="list-style-type: none"> • 10 hours in Buffalo, NY and Philadelphia, PA; • 3 hours in Rochester, NY; • 2 hours in Albany, NY. 	<ul style="list-style-type: none"> • Freezing rain over most of southern and eastern Ontario from southern Lake Huron to Ottawa River Valley. • Freezing rain duration: 6-12 hours. • 24.5 mm of freezing rain reported at Sarnia Airport; otherwise 5-12 mm
1971	Feb 23	New York State	<ul style="list-style-type: none"> • Icing related communication tower collapse in Canton, NY. • Only 1-2 hours of freezing rain was recorded at weather stations in Buffalo, Syracuse and Massena, NY and Toledo, OH. 	<ul style="list-style-type: none"> • London to eastern lake Ontario. • 18.5 mm of freezing rain was reported in Kingston otherwise 5-12 mm. • Duration of freezing rain: 7-12 hrs in most areas.
1972	Dec 16	Pennsylvania	<ul style="list-style-type: none"> • Icing related communication tower collapse in Clarks Knob, PA. 	<ul style="list-style-type: none"> • Snowstorm over all of southern, southeastern Ontario. • Snowfall amounts of 15 to 20 cm, except 29.7 cm at Kingston.

Year	Date	U.S. Areas Affected	Impacts on the U.S. States	Impacts on Ontario
1976	Mar 1-5	Mostly western New York State	<ul style="list-style-type: none"> • Up to 50 mm of ice accumulation, with one report of 100 mm. • Power outages lasting for longer than 10 days. • \$86 million in damages. • Six NY counties declared major disaster areas by President. <p>Duration of freezing rain in NY:</p> <ul style="list-style-type: none"> • 28 hours in Buffalo; • 27 hours in Rochester; • 4 hours in Syracuse. 	<ul style="list-style-type: none"> • Windsor to Hamilton. • Freezing rain amounts 20-40 mm.
1989	Jan 7-8	Pennsylvania	<ul style="list-style-type: none"> • Icing related communication tower collapses (2) in Phillipsburg and Mountaintop, PA. • Freezing rain duration of 10 hours at Erie, PA. 	<ul style="list-style-type: none"> • Light snow and rain over southern and eastern Ontario. • Near 2 cm of snow, and 2-8 mm of rain.
1991	Mar 3-6	The "Rochester ice storm." New York State and New England, Ohio and Pennsylvania	<ul style="list-style-type: none"> • Most severe on record in Rochester, NY. • Ice accumulation of 19-25 mm on tree limbs/power lines. • Widespread power outages, lasting up to 13 days. <p>Duration of freezing rain:</p> <ul style="list-style-type: none"> • 22 hours in Rochester, NY; • 15 hours in Erie, PA.; • 14 hours in Massena, NY; • 13 hours in Columbus, OH; • 9 hours in Cleveland, OH. 	<ul style="list-style-type: none"> • Most of southern and eastern Ontario from Windsor through Toronto to the Ottawa Valley. <p>Freezing rain amounts:</p> <ul style="list-style-type: none"> • 17.8 mm at Buttonville Airport in Markham; • 19.4 mm in Kingston • 13.0 mm in Brockville • 12.3 mm in London
1994	Feb 8-9	Ohio	<ul style="list-style-type: none"> • Described as worst in memory. $\frac{3}{4}$ - 2 inches of ice accumulation near Ohio River. • Duration of 9 hours however heavy freezing rain was reported with thunderstorm. • Duration of freezing rain across the state: Columbus 14 hours, Dayton 18 hours. 	<ul style="list-style-type: none"> • Snow storm over southwestern Ontario with amounts of 17 cm in Windsor and Sarnia. • The remaining regions of southern Ontario received 5-9 cm.

Year	Date	U.S. Areas Affected	Impacts on the U.S. States	Impacts on Ontario
1994	Feb 11	Ohio	<ul style="list-style-type: none"> • $\frac{1}{2}$ – 1 $\frac{1}{2}$ inch of ice accumulation after 18 hours of freezing rain. • Within the same week as the Feb 8–9 ice storm. 	<ul style="list-style-type: none"> • Light snow over southern Ontario on Feb 12 with accumulations of 1–4 cm.
1997	Feb 6	Michigan	<ul style="list-style-type: none"> • Icing related communication tower collapse in Marquette, MI. • Heavy snowfall 6–12 inches over lower Michigan. 	<ul style="list-style-type: none"> • 2–5 cm of snow in Sault Ste. Marie, Wawa, Sudbury, North Bay. • No impact on southern or eastern Ontario.
1997	Mar 14	New York State, Ohio, Pennsylvania	<ul style="list-style-type: none"> • Several inches of ice and snow downed trees and power lines in New York State, $\frac{1}{4}$ – $\frac{1}{2}$ inch of ice accumulation in Ohio. 	<ul style="list-style-type: none"> • Also significant ice storm in Ontario. • 20–30 mm of freezing rain over southwestern Ontario. • Duration of freezing rain: 3–5 hours, but freezing rain intensity reported as moderate.
1998	Jan 8–10	New York State and East Coast states	<ul style="list-style-type: none"> • Icing related communication tower collapses (13); three reported in Watertown, NY; nine collapses in ME and one in NH. 	<ul style="list-style-type: none"> • Ice storm of greatest duration, areal extent, ice accumulation and impacts recorded for Ontario. • Maximum amount of freezing rain 95 mm in eastern Ontario.
1999	Jan 2–3	Pennsylvania and New York State	<ul style="list-style-type: none"> • In New York State, 1 inch of ice accumulation after 15 hours of freezing rain. • $\frac{1}{4}$– $\frac{1}{2}$ inch of ice accumulation in Pennsylvania. 	<ul style="list-style-type: none"> • Snowstorm in southern and eastern Ontario. • 25–40 cm of snow; five hours of ice pellets reported near Lake Erie.
2002	Jan 31	New York State, Ohio, Pennsylvania	<ul style="list-style-type: none"> • In New York State, $\frac{1}{2}$ – $\frac{3}{4}$ inch of ice accumulation after 10 hrs of freezing rain, followed by strong winds gusting to 90 km/h. • Ohio had $\frac{1}{2}$ inch of ice accumulation in four counties after 13 hours of freezing rain. • $\frac{1}{4}$ – $\frac{1}{2}$ inch of ice accumulation over northern Ohio counties after 10 hours of freezing rain 	<ul style="list-style-type: none"> • 12–18 mm of freezing rain from Lake St Clair to Niagara Peninsula.

6.4 Tracks of the Major Ice Storms (1948–2002)

The meteorological conditions associated with the most severe Ontario and U.S. ice storms were assessed for commonality in features, contributing meteorological processes and for patterns in storm tracks. Two Environment Canada meteorologists reviewed paper archived surface weather maps dating back to 1948 in order to identify common or consistent synoptic or weather map features associated with these major ice storms and their icing-related communication tower collapses. The storms selected for analysis included all the Ontario and northern U.S. freezing rain events that have occurred since 1948 and are listed in Tables 7 and 8, respectively. Dates of other communication tower collapses that occurred in the northern U.S. since 1948 were also chosen from Table 5. The synoptic weather maps from 1948–2002 were available from the Canadian Meteorological Centre National Archives, Environment Canada's Toronto Regional Weather Centre archives, and the U.S. Daily Weather Map series produced by the National Oceanic and Atmospheric Administration Agency (NOAA). The Canadian maps are available for every six hours on the main synoptic hours (i.e. 0000, 0600 GMT, etc). However, the NOAA Daily Weather Map series provides one detailed surface weather map daily for 1200 GMT, with a more general map from 0000 GMT, 12 hours earlier. The six-hour history of the storm centre movement is shown on the Canadian weather maps and most of the U.S. NOAA maps, where the storm centre is defined as the lowest point of surface pressure in the storm.

The archive map search determined that surface weather maps were missing for some of the selected storm dates. Subsequently, storm tracks were only assessed for 10 of the 11 post-1947 Ontario storms listed in Table 7 and 17 of the 19 post-1947 U.S. storms listed in Table 8. An additional four northern U.S. tower collapse dates were all available from the map archives.

Tracks of the available selected major ice storms which impacted southern and eastern Ontario and the bordering northern U.S. during the period 1948–2002 are provided in Figures 13 and 14, respectively. Three of the 17 U.S. storms were also identified as significant Ontario ice storms, and their storm tracks are provided in both Figures 13 and 14. Ice Storm '98 tracks are provided separately in Figure 15, since five separate low pressure systems comprised this storm event during the period from 4–9 January 1998. Figure 16 shows the tracks of other ice storms that resulted in communication tower collapses in the northern U.S. since 1948. The storm tracks mark the 12 hour movement of the storm centre. Specific storm track date and time information for each of the figures is provided in Tables 9–12, respectively. Locations of communication tower collapses, as identified in the CRREL database (see Tables 5 and 6), are also indicated on the maps.

The storm track analysis for the significant Ontario and northern U.S. ice storms during the period from 1948–2002 identified at least three features common to these storms:

- 1) a warm, moist mid-upper level flow originating in the Gulf of Mexico, and in some cases, an additional moisture source from the Atlantic Ocean;
- 2) presence of a cold Arctic high pressure area to the north of these storms, generally centered over Quebec;
- 3) slow-moving storm systems.

The majority of the ice storms that impacted southern and eastern Ontario and the northern U.S. since 1948 originated in the south central and southeastern U.S. (see Figures 13–16). The counter clockwise atmospheric circulation associated with these types of storms advects moisture from the Gulf of Mexico as they move north-eastward towards the Great Lakes. Storms that move over Pennsylvania, New York State and New England can pick up additional moisture from the Atlantic Ocean. The additional Atlantic moisture is likely partly responsible for the relatively high frequency of freezing rain that has been identified as occurring over these Northeastern U.S. states as well as over the Ottawa River Valley (i.e. Robbins and Cortinas, 2002; MacKay and Thompson, 1969; Stuart and Isaac, 1999). As described in Section 5.1, the topographical effects of the Appalachian Mountains and valleys are considered to be the primary influencing factors in the development and duration of freezing rain in these areas.

For all of the ice storms examined in this study, an area of Arctic high pressure was located to the north of the storms, and was generally centered over Quebec. As explained in Section 2.0, freezing rain forms when precipitation falls through an above-freezing layer of air above the ground, melts to form supercooled water droplets and then freezes on impact with the ground and surfaces that are at temperatures below freezing. As described above, the above-freezing layer of air is provided when warm air is advected into the area from the southern U.S. with the Gulf of Mexico acting as a moisture source. The cold air required for the production and maintenance of freezing rain in the Great Lakes region is then provided by a cold Arctic outflow of below-freezing temperatures in the lowest atmospheric levels and at ground level.

The 12-hour storm centre movement indicates that most of the ice storms were associated with relatively slow-moving or stalled low pressure systems. This allowed freezing rain to endure for an extended period over the storm region, contributing to the severity of the storm. As well, in Ice Storm '98, a quasistationary surface frontal boundary was an important factor in the development and duration of three freezing rain episodes that occurred from January 4–9.

A meteorological assessment of the synoptic and weather situations accompanying the selected ice storms also determined that freezing rain can occur up to 900 km ahead of the storm centre. It is interesting to note that the ice storms that impacted on the northern U.S. (Figure 14) had similar points of origin and followed similar tracks to other storms that impacted heavily on southern and eastern Ontario. However, it appears that in most cases, the northern U.S. storm centres were located approximately 100–200 km further south at the time of freezing rain occurrence. This observation would lead one to speculate that if storm tracks were to shift north under climate change, the frequency of ice storms could possibly increase in southern and eastern Ontario in a future climate. However, climate change science cannot yet predict how storm tracks will change in a warming climate or if such changes could potentially lead to regional increases or decreases in ice storms.

During Ice Storm '98, five separate low pressure systems actually tracked across the northern U.S. and Ontario from January 4–9. These storms were associated with three distinct extended periods of freezing rain occurrence in Ontario that occurred over the six-day period (see Table 11). The initial two storm systems on January 4–6 tracked further north across southern Ontario than the average path of other Ontario ice storms since 1948. However, the final three storm

systems from January 7–9 generally followed the average storm tracks of the historical Ontario ice storms (see Figures 13 and 15).

Figure 13 Storm tracks of the major ice storms which impacted southern and eastern Ontario during the period 1948–2002 (see Figure 15 for Ice Storm '98 storm tracks). The storm centre locations are shown at 12-hour intervals. Specific storm track date and time information is provided in Table 9.

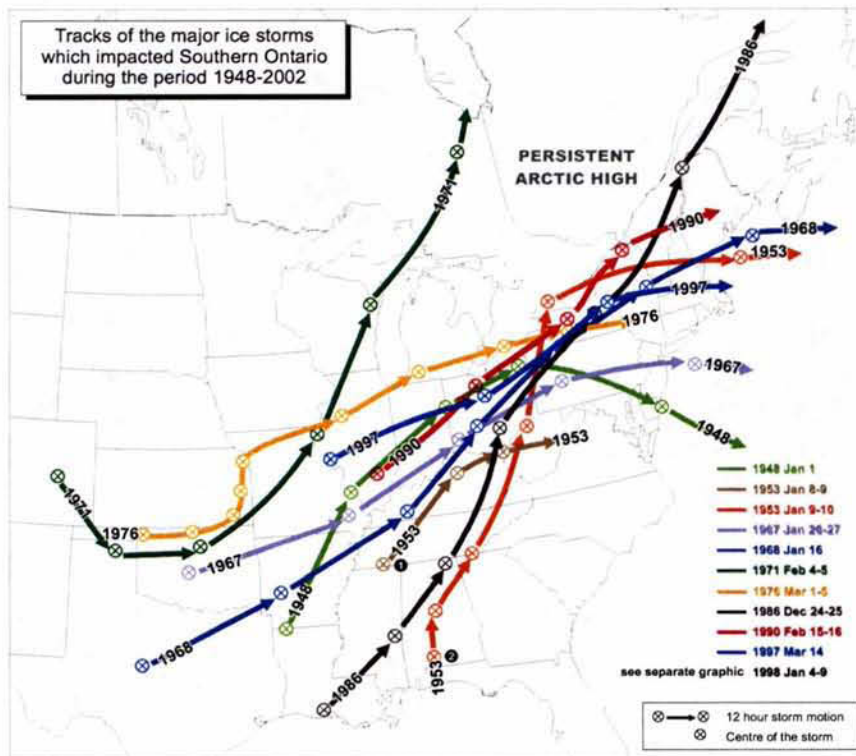


Table 9 Storm track date and time information for ice storms which impacted southern and eastern Ontario (1948–2002). (See Figure 15 and Table 11 for Ice Storm '98 information.)

Year	Ice Storm Track Start Date and Time	Ice Storm Track End Date and Time	Dates of Freezing Rain Occurrence over Ontario
1948	Dec 31, 1947 19:00 EST	Jan 2, 1948 19:00 EST	Jan 1
1953	Storm 1: Jan 8 01:00 EST	Jan 9 01:00 EST	Jan 8–9
	Storm 2: Jan 9 01:00 EST	Jan 11 13:00 EST	Jan 9–10
1967	Jan 26 01:00 EST	Jan 28 01:00 EST	Jan 26–27
1968	Jan 12 13:00 EST	Jan 15 13:00 EST	Jan 13–15
1971	Feb 3 07:00 EST	Feb 5 07:00 EST	Feb 4–5
1976	Feb 29 07:00 EST	Mar 4 07:00 EST & stalled	Mar 1–5
1986	Dec 23 07:00 EST	Dec 25 19:00 EST	Dec 24–25
1990	Feb 15 07:00 EST	Feb 16 19:00 EST	Feb 15–16
1997	Mar 13 19:00 EST	Mar 14 19:00 EST	Mar 14

Figure 14 Storm tracks of the major ice storms which impacted northern U.S. states bordering southern and eastern Ontario (1948–2002) (see Figure 15 for Ice Storm '98 storm tracks). The storm centre locations are shown at 12 hour intervals. Specific storm track date and time information is provided in Table 10.

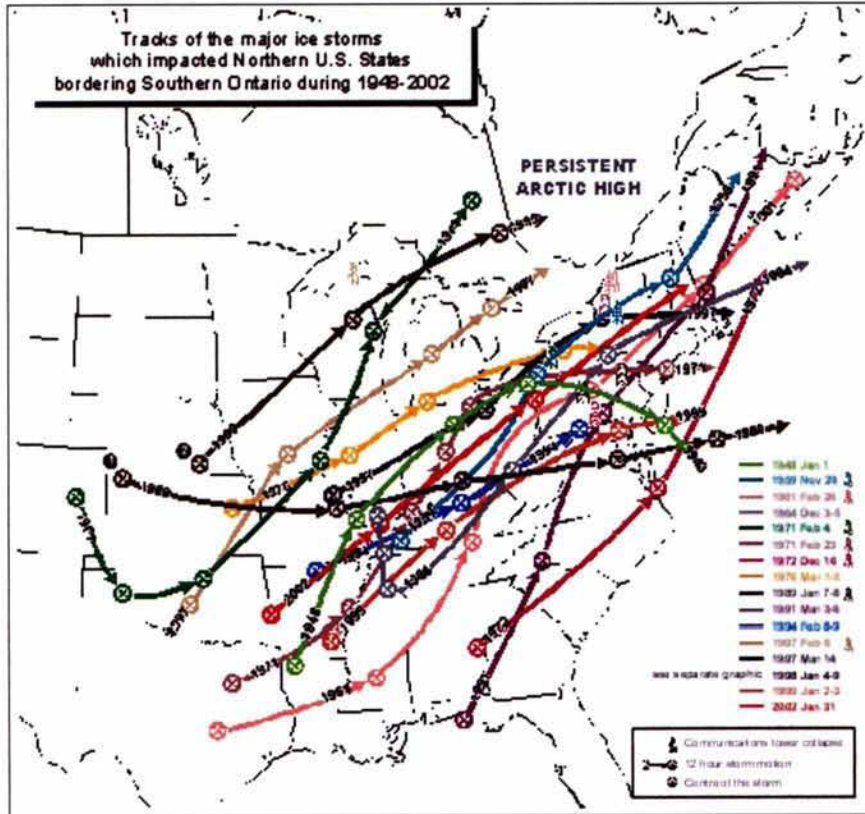


Table 10 Storm track date and time information for ice storms which impacted northern U.S. states bordering southern and eastern Ontario (1948–2002) (see Figure 15 and Table 11 for Ice Storm '98).

Year	Ice Storm Track Start Date and Time		Ice Storm Track End Date and Time		Dates of Freezing Rain Occurrence
1948	Dec 31, 1947	07:00 EST	Jan 2	19:00 EST	Jan 1
1959	Nov 26	19:00 EST	Nov 27	19:00 EST	Nov 28
1961	Feb 24	07:00 EST	Feb 26	19:00 EST	Feb 26
1964	Dec 3	01:00 EST	Dec 5	01:00 EST	Dec 3–5
1971	Feb 3	07:00 EST	Feb 5	19:00 EST	Feb 4
1971	Feb 21	07:00 EST	Feb 23	07:00 EST	Feb 23
1972	Dec 15	07:00 EST	Dec 15	19:00 EST	Dec 16
1976	Mar 2	07:00 EST	Mar 3	19:00 EST and stalled	Mar 1–5
1989	Storm 1: Jan 5	07:00 EST	Jan 7	07:00 EST	Jan 7–8
	Storm 2: Jan 7	07:00 EST	Jan 8	07:00 EST	
1991	Mar 3	07:00 EST	Mar 4	19:00 EST	Mar 3–6
1994	Feb 8	07:00 EST	Feb 9	07:00 EST	Feb 8–9
1997	Feb 3	07:00 EST	Feb 4	19: 00 EST	Feb 6
1997	Mar 13	19:00 EST	Mar 14	19:00 EST	Mar 14
1999	Jan 2	07:00 EST	Jan 3	07:00 EST	Jan 2–3
2002	Jan 30	19:00 EST	Jan 31	19:00 EST	Jan 31

Figure 15 Storm tracks of the three major eastern Ontario/southern Quebec freezing rain episodes during the 4–9 January 1998 Ice Storm. The storm centre locations are shown at 12-hour intervals. Specific storm track date and time information is provided in Table 11. Storm tracks are labelled by end date.

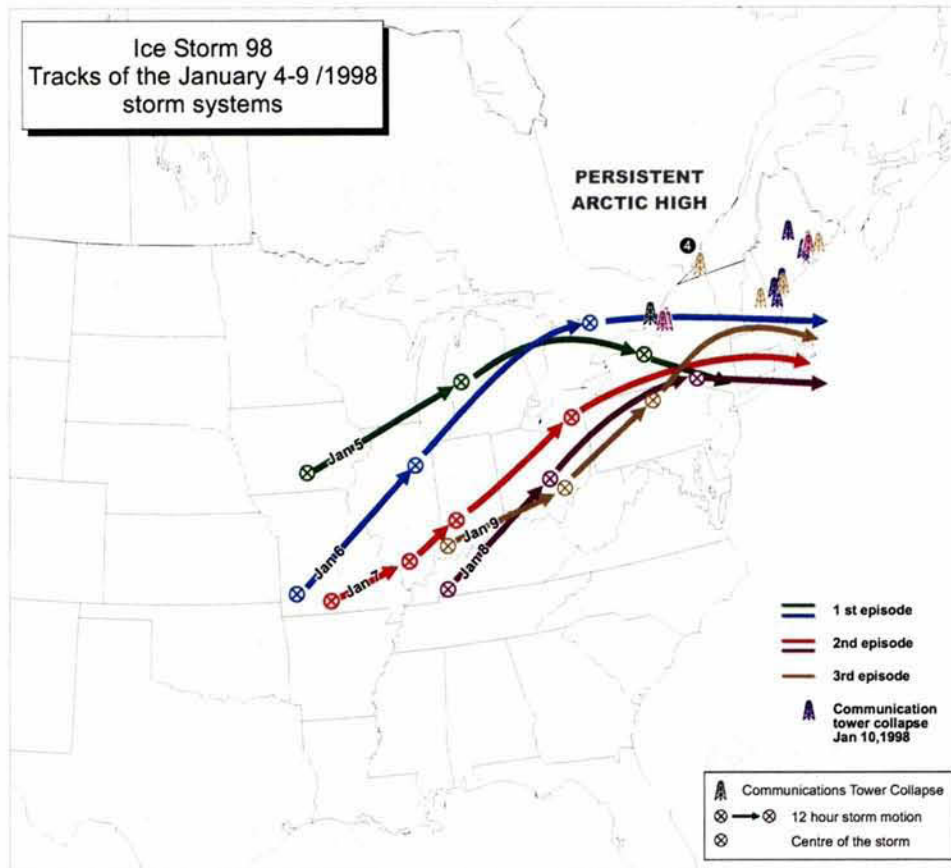


Table 11 Storm track date and time information for the 4–9 January 1998 Ice Storm (see Figure 15 for storm tracks).

Precipitation Episode Number	Ice Storm Track Start Date and Time	Ice Storm Track End Date and Time	Dates of Freezing Rain Occurrence over Ontario
1	Storm 1: Jan 4 19:00 EST Storm 2: Jan 5 07:00 EST	Jan 5 19:00 EST Jan 6 07:00 EST	Jan 4 16:00 EST to Jan 6 09:00 EST
2	Storm 3: Jan 6 01:00 EST Storm 4: Jan 7 19:00 EST	Jan 7 13:00 EST Jan 8 19:00 EST	Jan 7 07:00 EST to Jan 8 evening
3	Storm 5: Jan 8 07:00 EST	Jan 9 07:00 EST and stalled	Jan 9 06:00 EST to Jan 9 evening

Figure 16 Storm tracks of other major ice storms that caused communication tower collapses in the northern U.S. (1948–2002) (see Table 5). The storm centre locations are shown at 12-hour intervals. Specific storm track date and time information is provided in Table 12.

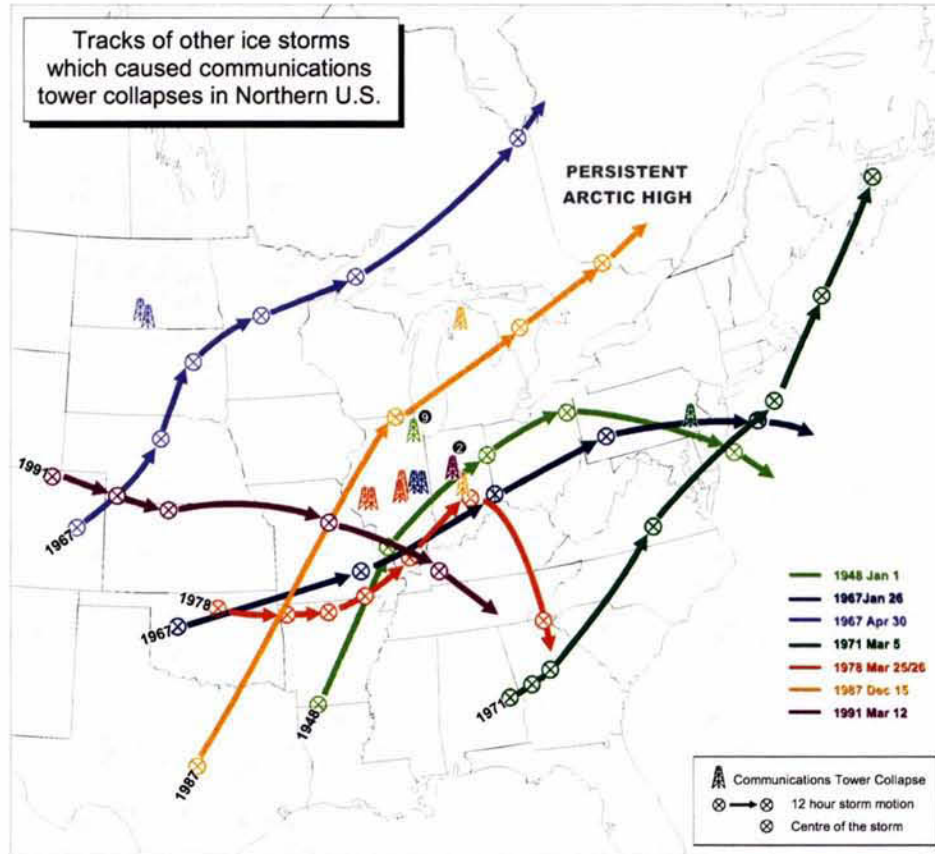


Table 12 Storm track date and time information for other major ice storms which resulted in communication tower collapses in the northern U.S. (1948–2002) (see Table 5).

Year	Ice Storm Track Start Date and Time	Ice Storm Track End Date and Time	Dates of Tower Collapses
1948	Dec 31, 1947 07:00 EST	Jan 2 19:00 EST	Jan 1
1967	Jan 26 01:00 EST	Jan 28 01:00 EST	Jan 26
1967	Apr 30 01:00 EST	Mar 2 13:00 EST	Apr 30
1971	Mar 2 07:00 EST	Mar 5 07:00 EST	Mar 5
1978	Mar 23 07:00 EST	Mar 26 07:00 EST	Mar 25–26
1987	Dec 14 19:00 EST	Dec 16 07:00 EST	Dec 15
1991	Mar 11 07:00 EST	Mar 13 07:00 EST	Mar 12

7.0 Synoptic Classification Approach

7.1 Introduction

Synoptic climatological classification approaches have become popular in evaluating the impact of the climate on a variety of environmental problems. Synoptic classification refers to a process of assessing a series of weather maps for common patterns. This process can be completed manually, as was described in Section 6.3, or can be completed objectively or statistically. Whatever the process, the net result of synoptic classification is an ability to categorize a complex set of meteorological variables as a coherent index (Yarnal, 1993; Cheng and Kalkstein, 1997). Synoptic categorization accentuates homogeneity in weather type or air mass and facilitates analyses of climatic impact on environmental factors such as regional climate variation, air pollution concentration, and human health (i.e. Cheng and Kalkstein, 1993; Kalkstein et al., 1997; Cheng and Lam, 2000). The statistical synoptic map typing methodologies that were modified for this study have also been adapted to develop international heat-health watch/warning systems that have been successfully implemented in Philadelphia, Cincinnati, Rome, Shanghai and Toronto for the United Nations Showcase Project. Dr. Cheng, the principal investigator for this portion of the project, developed much of the methodology and software that is being used in these heat-health warning systems.

7.2 Data Sources and Treatment

Hourly surface meteorological data were retrieved from Environment Canada's Digital Archive of Canadian Climatological Data for 14 stations in Ontario and one station in Montreal, Quebec for the winter months (November–April) of 1953/54–2000/01. The U.S. National Climatic Data Center (NCDC) provided hourly surface meteorological data for 12 stations in the U.S. Great Lakes region for the period 1973/74–1999/2000. Station information for the selected weather stations is provided in Table 3 and a map showing the selected station locations is provided in Figure 4. As discussed in Section 5.2.1, the weather phenomena for the U.S. sites were only available at three hourly intervals for much of the period from the mid-1960s through 1972. Therefore, data prior to 1973 had to be excluded from the study.

The meteorological data used in this part of the study included hourly weather station observations of air temperature ($^{\circ}\text{C}$), dew point temperature ($^{\circ}\text{C}$), sea-level air pressure (hPa), total cloud cover (tenths of sky cover), wind speed (m s^{-1}), wind direction (degrees), and occurrence of freezing rain as described in Section 5.2.1. Sine-cosine transformation was used to convert wind speed and direction into southerly and westerly scalar velocities. With the exception of the occurrence of freezing rain, missing data was interpolated using a temporal linear method when the data was missing for three consecutive hours or less; otherwise, days with missing data for four or more consecutive hours were excluded from the analysis. The interpolation was required for only a small number of days in the Canadian dataset, and a somewhat higher percentage in the U.S. dataset. After interpolation, Canadian station data was complete for >99.5% of the days in the November–April period of 1958–2001. Notably, at Ottawa International Airport, only 0.04% of the total hours required missing data interpolation and the dataset was 100% complete after interpolation. Interpolation of the U.S. hourly meteorological data resulted in a 96% to >99.5% complete dataset.

The six-hourly upper-air reanalysis weather data was retrieved from the National Centers for Environmental Prediction (NCEP) Web site. The re-analysis data was available daily for 1:00 a.m., 7:00 a.m., 1:00 p.m., and 7:00 p.m. EST for the period 1958–2001 and included a variety of meteorological variables on a $2.5^\circ \times 2.5^\circ$ latitude-longitude grid at 17 standard upper-air pressure levels: air temperature ($^\circ\text{C}$), relative humidity (%), west-east and south-north wind velocity (ms^{-1}). Data from the lowest six pressure levels: 1000, 925, 850, 700, 600 and 500 hPa were used in this study since the atmospheric parameters needed to determine both production and phase of precipitation are primarily confined to levels below 500 hPa. Although the NCEP-NCAR reanalysis data was available for an entire 50-year period (1948–2001), only the data for the period 1958–2001 was used in this study. Prior to 1958 there were fewer upper-air observations and the reanalysis data is considered less reliable (Kistler et al., 2001).

For this study, the NCEP-NCAR re-analysis relative humidity data was converted into dew point temperature based on Tetens' equation (Berry et al., 1945). Dew point temperature is preferred over relative humidity since it is highly conservative on a diurnal level and moderately conservative among various micro-environments (Kalkstein and Corrigan 1986). In order to combine the gridded re-analysis data with the surface weather data, the re-analysis data was interpolated to each of the selected weather stations using the inverse-distance method. Although there is no missing data within the reanalysis dataset, there are a few cases where relative humidity values are identically zero, even in the lower levels. These values are not physically realistic and are excluded from the analysis. The number of days on which this occurred was small; for example, at Ottawa, this resulted in the exclusion of only five days of re-analysis data during the entire data record.

7.3 Analysis Techniques

7.3.1 Automated synoptic classification

An automated or statistical synoptic classification procedure, based primarily on air mass differentiation, was used to assign every day of the dataset to a distinctive weather category during the winter season (November–April) from 1958 to 2001 for the Canadian stations and from 1973 to 2000 for the U.S. stations. The entire suite of 240 weather variables was used in the classification, including: 144 hourly surface weather observations of air temperature, dew point temperature, sea-level air pressure, total cloud cover, south-north and west-east scalar wind velocities, as well as 96 upper-air NCEP reanalysis variables at six-hour intervals and six atmospheric levels, including: air temperature, dew point temperature and south-north and west-east scalar wind velocities. In order to directly compare station weather types identified by the clustering procedure, weather data from the 15 Canadian stations was included within one data matrix and the weather type classification was then performed. A similar procedure was used for the 12 selected U.S. stations.

The synoptic classification scheme produces a temporal synoptic index using principal components analysis (PCA) and a hierarchical agglomerative clustering procedure. Since the number of weather types was not predetermined, a hierarchical agglomerative clustering procedure was suitable for this study (Kalkstein et al., 1996a, 1996b; Cheng and Kalkstein, 1997; Cheng and Lam, 2000). The PCA was performed to reduce the 240 intercorrelated weather variables into a small number of linearly independent component variables, which explain much

of the variance within the original dataset. Component loadings were calculated, which express the correlation between the original weather variables and the newly formed components. The number of principal components, of which the eigenvalue was greater than one, was retained to calculate component scores. Days with similar meteorological situations tend to exhibit approximately similar component scores. The average linkage clustering procedure generated statistical diagnostics to produce an appropriate number of clusters (see Section 7.3.2 for details), and then classified those days with similar component scores into one of the meteorologically homogenous groups. Determination of the cluster number to retain was achieved through a variety of statistical tests, which tried to minimize within-cluster variances and maximize between-cluster variances (Boyce, 1996; Cheng and Lam, 2000). In addition to a calendar of daily weather types created by the clustering procedure, the average values and standard deviations were calculated for the various meteorological variables for all days within each category.

7.3.2 Identification of the Weather Types Most Highly Associated with Freezing Rain Events

The occurrence of freezing rain was used in the identification of the synoptic categories which were most highly associated with freezing rain events. The occurrence frequency of freezing rain for each category was then determined to ascertain whether the frequency of freezing rain within a particular category was distinctively high or low. In addition, a ratio of the category's occurrence of freezing rain events (actual frequency) to the occurrence of the category in the entire record (expected frequency) determined whether any of the categories were over-represented for freezing rain events. Categories with ratios significantly greater than 1.0 clearly have a greater proportion of days with freezing rain events than would be expected based only on the frequency of the weather type category. The statistical χ^2 -test was employed to determine whether the theoretical frequency among the freezing rain events was significantly higher than the expected frequency. This method was then applied to different number of hours during a day (0:00–23:00 EST) when freezing rain phenomenon was observed, such as ≥ 1 hour, ≥ 4 hours and ≥ 6 hours.

7.4 Results

7.4.1 Identification of Synoptic Categories Associated with Freezing Rain

The PCA was applied to the 240 weather variables for all days within the winter season from 1958/59 to 2000/01 for 15 Canadian and 12 U.S. stations, producing an 18-component solution that explains 91% of the total variance in the original dataset. The remainder of the components with eigenvalues less than one were discarded. The thermal and moisture variables, air temperature and dew point temperature, load highly on Component 1, explaining over 36% of the total variance. Sea-level pressure, total cloud cover and south-north wind velocity aloft also contribute to this component. The loadings for Component 2, which explain an additional 13% of the total variance, are dominated by west-east wind velocity and sea-level pressure. South-north surface wind velocity and winds aloft have the largest loadings in Component 3 (nearly 11% of the variance). Sea-level pressure and total cloud cover are important in Component 4 (over 9%). The remaining Components (5–18) explain over 20% of the total variance and are largely comprised of terms which explain the diurnal changes of the variables.

The average linkage clustering procedure was employed to produce categories that possess similar large-scale synoptic characteristics in terms of the daily 18-component scores. Determination of the cluster number to retain was achieved through a variety of statistical tests which included: the semipartial R^2 , pseudo-F, pseudo- t^2 , and explained variance R^2 . The semipartial R^2 is the ratio of the increased within-cluster variance after joining two clusters to the variance for the entire dataset. The pseudo-F is the ratio of between-cluster to within-cluster variances. The pseudo- t^2 is the ratio of the increased within-category variance after joining two clusters to the variance within each of two clusters (SAS Institute Inc., 1999; Eder et al., 1994). The judgment of number of clusters to retain was made by observing the largest decrease in R^2 , the largest increase in both the semipartial R^2 and pseudo- t^2 after joining two clusters and a local maximum in the pseudo-F.

Using the above procedures, 18 major synoptic types, based primarily on their meteorological differentiation, were identified for the selected 27 stations in Canada and the U.S. for the winter months (November–April). These 18 major synoptic types represented about 97% of the total number of days during the period. The smaller clusters, which comprised the remaining 3% of the days, were deleted from the analysis. These smaller clusters were largely made up of days which were rarely associated with freezing rain occurrence since the 18 major synoptic types captured over 95% of the total freezing rain days during the period.

As each of the categories displays a distinctive air mass and synoptic signature, a specific regime of freezing rain should be related to each. The number of freezing rain days varied considerably among the synoptic types. While some categories had no days with freezing rain occurrence, others were comprised of many days with freezing rain events. For example, at most of the selected stations, approximately 30% and 50% of the freezing rain events occurring ≥ 1 hour and ≥ 6 hours during a day were observed in weather Type 2 (Table 13).

Besides examining the reasonable number of freezing rain cases, a category frequency ratio was calculated to identify the synoptic types most highly associated with freezing rain. This ratio compared the percentage frequency of days with freezing rain events (actual frequency) to the percentage frequency of the weather type (expected frequency). The resulting ratios are provided in Table 13. For example, for Synoptic Type 2 at Sioux Lookout the frequency of freezing rain events would be expected to be 5.5%, or the expected frequency of the weather type within the entire record. However, the actual frequency of freezing rain events ≥ 1 hour during a day was closer to 32%, or nearly six times what we might expect. A χ^2 -test was employed to ascertain that the observed frequencies of freezing rain cases were significantly different from their expected occurrences (χ^2 -test significance level of 0.001). If a category possessed a reasonable number of freezing rain cases (greater than the number of the cases within each of the remaining non-freezing rain categories) and the frequency ratio > 1.0 , it was selected as a freezing rain category. Based on these two criteria, four to six synoptic types were identified as the primary freezing rain categories for the study area.

Four weather types (1–4) were most highly associated with freezing rain events at all 27 selected stations, while up to two additional weather types were identified at some of the stations. For instance, the weather Type 6 was identified as a freezing rain category for Kapuskasing, Sault Ste Marie and Windsor; the weather Type 8 for Kapuskasing, Montreal, North Bay, Sudbury and

Timmins; and the weather Type 7 for Sioux Lookout and Cleveland. These freezing rain-related categories accounted for 75% to 100% of the freezing rain events that occurred on ≥ 1 , ≥ 4 and ≥ 6 hours during a day over the entire study period. Table 14 shows the within-type mean values of the meteorological variables at 7:00 a.m. for the four weather types identified as being most highly associated with freezing rain events across the entire study area.

7.4.2 Trends Analysis of Frequencies of Weather Types Associated with Freezing Rain Events

A trend analysis was performed on the frequencies of the weather types most highly associated with freezing rain events to determine whether or not there has been an increase or decrease in these frequencies over the past 33 years (1958–2001) at the 15 selected stations in Canada. The trends in the Canadian freezing rain related weather types are presented graphically in Figure 17. All trends were tested at the 5% significance level, using the Student t-test. None of the trends of the freezing rain-related weather types were found to be statistically significant, although the directions (upward or downward) of the trends are the same as the freezing rain frequency trends at most of the selected stations (see Figure 4). The trends could not be calculated for the U.S. weather types, as the available data period from 1973 is too short for a trend analysis. However, the time series of the frequencies of the weather types for 12 selected U.S. stations are shown in Figure 18.

Besides the possibility of relating to monthly mean temperature, it would also be expected that the year-to-year fluctuations of freezing rain occurrences are closely associated with occurrence frequencies of the freezing rain-related weather types. In order to investigate this relationship, quintile methods were used, similar to those used in the monthly mean temperature analysis described in Section 5.2.3. Monthly total occurrence frequencies of the freezing rain-related weather types were sorted in descending order for the Canadian and U.S. stations during the periods 1958–2001 and 1973–2000, respectively. The years with the sorted monthly weather type frequencies were then divided into three groups based on a 1/3 interval of the difference between the highest and lowest monthly frequencies. The within-group mean frequencies of the freezing rain occurrence and the freezing rain-related weather types were calculated and the results for the months of December–February are shown in Figures 19–21, respectively. In general, the monthly total frequency of freezing rain dramatically increases from the lowest to highest frequencies of the weather types. For example, in Ottawa, on average in December (Figure 19), as the monthly total weather type occurrence frequency increases from eight to 12 and to 17, the monthly total hours of freezing rain occurrence increase from 4.6 to 9.4 and to 17.2; and the monthly total number of days with freezing rain events increases from 1.4 to 2.4 and to 3.7.

The results of this work indicate that the synoptic map typing approach is successful in identifying the weather types that are most highly associated with freezing rain in south-central Canada. This approach could be extended to include GCM output, rather than historical archived weather data, for the Great Lakes region. This could then provide a methodology to investigate if freezing rain related weather types and subsequently the occurrence of freezing rain could potentially increase within Ontario in a warming 21st century climate.

Table 13 Frequency of freezing rain events within the related weather types for 15 Canadian stations (Nov.–Apr., 1958/59–2000/01) and 12 U.S. stations (Nov.–Apr., 1973/74–1999/2000).

Synoptic Type			Freezing Rain Events								
			≥1 hour			≥4 hours			≥6 hours		
Type	Days	Freq.(%) ¹ (a)	Days	Freq.(%) ² (b)	Ratio ³ (b)/(a)	Days	Freq.(%) ² (c)	Ratio ³ (c)/(a)	Days	Freq.(%) ² (d)	Ratio ³ (d)/(a)
<i>Ottawa</i>											
1	975	12.33	114	26.89	2.18	43	24.86	2.02	20	21.98	1.78
2	721	9.12	119	28.07	3.08	62	35.84	3.93	38	41.76	4.58
3	721	9.12	117	27.59	3.03	48	27.75	3.04	24	26.37	2.89
4	217	2.74	23	5.42	1.98	11	6.36	2.32	5	5.49	2.00
Total ⁴	2634	33.30	373	87.97	2.64	164	94.80	2.85	87	95.60	2.87
<i>Kapuskasing</i>											
1	878	11.24	45	32.61	2.90	10	30.30	2.70	2	16.67	1.48
2	423	5.42	34	24.64	4.55	8	24.24	4.48	6	50.00	9.23
3	610	7.81	17	12.32	1.58	6	18.18	2.33	2	16.67	2.13
4	240	3.07	8	5.80	1.89	4	12.12	3.94	1	8.33	2.71
6	85	1.09	6	4.35	3.99	2	6.06	5.57	0	0.00	0.00
8	188	2.41	7	5.07	2.11	2	6.06	2.52	1	8.33	3.46
Total ⁴	2424	31.04	117	84.79	17.02	32	96.96	21.54	12	100.00	19.01
<i>Kenora</i>											
1	1005	12.76	50	42.02	3.29	9	42.86	3.36	4	44.44	3.48
2	482	6.12	23	19.33	3.16	8	38.10	6.23	2	22.22	3.63
3	696	8.83	16	13.45	1.52	0	0.00	0.00	0	0.00	0.00
4	166	2.11	3	2.52	1.20	1	4.76	2.26	0	0.00	0.00
Total ⁴	2349	29.82	92	77.32	9.17	18	85.72	11.85	6	66.66	7.11
<i>London</i>											
1	1139	14.50	84	29.27	2.02	30	25.86	1.78	13	23.21	1.60
2	687	8.75	101	35.19	4.02	54	46.55	5.32	28	50.00	5.72
3	450	5.73	55	19.16	3.34	23	19.83	3.46	11	19.64	3.43
4	155	1.97	11	3.83	1.94	5	4.31	2.18	3	5.36	2.71
Total ⁴	2431	30.95	251	87.45	11.32	112	96.55	12.74	55	98.21	13.46
<i>Montreal</i>											
1	949	12.06	89	26.18	2.17	26	19.12	1.59	7	11.48	0.95
2	751	9.54	97	28.53	2.99	52	38.24	4.01	28	45.90	4.81
3	687	8.73	85	25.00	2.86	37	27.21	3.12	16	26.23	3.00
4	222	2.82	16	4.71	1.67	6	4.41	1.56	4	6.56	2.32
8	395	5.02	12	3.53	0.70	7	5.15	1.03	5	8.20	1.63
Total ⁴	3004	38.17	299	87.95	10.39	128	94.13	11.31	60	98.37	12.71
<i>North Bay</i>											
1	1059	13.42	105	32.61	2.43	27	28.12	2.10	9	20.93	1.56
2	658	8.34	99	30.75	3.69	45	46.88	5.62	22	51.16	6.13
3	692	8.77	51	15.84	1.81	15	15.62	1.78	10	23.26	2.65
4	229	2.90	15	4.66	1.61	4	4.17	1.44	1	2.33	0.80
8	363	4.60	16	4.97	1.08	3	3.12	0.68	1	2.33	0.51
Total ⁴	3001	38.03	286	88.83	10.62	94	97.91	11.62	43	100.00	11.65

¹ Represents percentage frequency of the weather type.

² Represents percentage frequency of the days with 1 hr, 4 hrs, or 6 hrs and longer freezing rain events occurring during a day within a particular weather type.

³ Ratio of percentage frequency of the days with freezing rain events over the percentage frequency of the weather type. A number greater than one indicates that a larger proportion of days in the weather type possess freezing rain events than be expected based on the frequency of the weather type.

⁴ Represents the sum of the weather types identified as being most highly associated with freezing rain events.

Table 13 (Continued)

Synoptic Type			Freezing Rain Events								
			≥1 hour			≥4 hours			≥6 hours		
Type	Days	Freq.(%) ¹ (a)	Days	Freq.(%) ² (b)	Ratio ³ (b)/(a)	Days	Freq.(%) ² (c)	Ratio ³ (c)/(a)	Days	Freq.(%) ² (d)	Ratio ³ (d)/(a)
Sault Ste Marie											
1	988	13.67	55	37.16	2.72	14	33.33	2.44	5	31.25	2.29
2	607	8.40	45	30.41	3.62	20	47.62	5.67	9	56.25	6.70
3	577	7.99	24	16.22	2.03	6	14.29	1.79	1	6.25	0.78
4	202	2.80	6	4.05	1.45	1	2.38	0.85	0	0.00	0.00
6	112	1.55	3	2.03	1.31	1	2.38	1.54	1	6.25	4.03
Total ⁴	2486	34.41	133	89.87	11.13	42	100.00	12.29	16	100.00	13.80
Sioux Lookout											
1	898	11.44	27	25.96	2.27	3	23.08	2.02	1	50.00	4.37
2	435	5.54	33	31.73	5.73	8	61.54	11.11	1	50.00	9.02
3	598	7.62	14	13.46	1.77	0	0.00	0.00	0	0.00	0.00
4	155	1.97	3	2.88	1.46	0	0.00	0.00	0	0.00	0.00
7	148	1.89	6	5.77	3.06	1	7.69	4.08	0	0.00	0.00
Total ⁴	2234	28.46	83	79.80	14.29	12	92.31	17.21	2	100.00	13.39
Sudbury											
1	1039	13.22	109	32.54	2.46	23	21.50	1.63	13	25.49	1.93
2	669	8.51	91	27.16	3.19	42	39.25	4.61	23	45.10	5.30
3	645	8.21	47	14.03	1.71	16	14.95	1.82	7	13.73	1.67
4	289	3.68	22	6.57	1.79	9	8.41	2.29	3	5.88	1.60
8	331	4.21	20	5.97	1.42	10	9.35	2.22	3	5.88	1.40
Total ⁴	2973	37.83	289	86.27	10.57	100	93.46	12.57	49	96.08	11.90
Thunder Bay											
1	840	10.71	25	29.07	2.71	3	17.65	1.65	2	16.67	1.56
2	649	8.27	35	40.70	4.92	10	58.82	7.11	8	66.67	8.06
3	524	6.68	8	9.30	1.39	1	5.88	0.88	0	0.00	0.00
4	188	2.40	4	4.65	1.94	1	5.88	2.45	1	8.33	3.48
Total ⁴	2201	28.06	72	83.72	10.96	15	88.23	12.09	11	91.67	13.10
Timmins											
1	894	11.46	54	30.51	2.66	15	34.09	2.97	5	25.00	2.18
2	435	5.58	46	25.99	4.66	18	40.91	7.34	11	55.00	9.86
3	615	7.88	33	18.64	2.36	6	13.64	1.73	3	15.00	1.90
4	235	3.01	11	6.21	2.06	2	4.55	1.51	1	5.00	1.66
8	194	2.49	7	3.95	1.59	0	0.00	0.00	0	0.00	0.00
Total ⁴	2373	30.42	151	85.30	13.33	41	93.19	13.55	20	100.00	15.60
Toronto											
1	1164	14.72	69	30.26	2.06	25	28.41	1.93	10	25.00	1.70
2	627	7.93	58	25.44	3.21	31	35.23	4.44	15	37.50	4.73
3	522	6.60	52	22.81	3.46	22	25.00	3.79	11	27.50	4.17
4	190	2.40	21	9.21	3.83	7	7.95	3.31	3	7.50	3.12
Total ⁴	2503	31.65	200	87.72	12.56	85	96.59	13.47	39	97.50	13.72
Trenton											
1	1081	13.67	86	28.67	2.10	30	29.70	2.17	14	28.00	2.05
2	648	8.19	82	27.33	3.34	41	40.59	4.95	25	50.00	6.10
3	579	7.32	66	22.00	3.01	18	17.82	2.43	6	12.00	1.64
4	173	2.19	15	5.00	2.29	6	5.94	2.72	2	4.00	1.83
Total ⁴	2481	31.37	249	83.00	10.74	95	94.05	12.27	47	94.00	11.62

¹ Represents percentage frequency of the weather type.

² Represents percentage frequency of the days with 1 hr, 4 hrs, or 6 hrs and longer freezing rain events occurring during a day within a particular weather type.

³ Ratio of percentage frequency of the days with freezing rain events over the percentage frequency of the weather type. A number greater than one indicates that a larger proportion of days in the weather type possess freezing rain events than be expected based on the frequency of the weather type.

⁴ Represents the sum of the weather types identified as being most highly associated with freezing rain events.

Table 13 (Continued)

Synoptic Type			Freezing Rain Events								
			≥1 hour			≥4 hours			≥6 hours		
Type	Days	Freq.(%) ¹ (a)	Days	Freq.(%) ² (b)	Ratio ³ (b)/(a)	Days	Freq.(%) ² (c)	Ratio ³ (c)/(a)	Days	Freq.(%) ² (d)	Ratio ³ (d)/(a)
<i>Wiarton</i>											
1	1249	15.95	65	29.15	1.83	16	26.23	1.64	8	36.36	2.28
2	607	7.75	73	32.74	4.22	22	36.07	4.65	7	31.82	4.10
3	478	6.10	36	16.14	2.64	13	21.31	3.49	4	18.18	2.98
4	166	2.12	14	6.28	2.96	4	6.56	3.09	1	4.55	2.14
Total ⁴	2500	31.92	188	84.31	11.65	55	90.17	12.87	20	90.91	11.50
<i>Windsor</i>											
1	1075	13.59	69	31.51	2.32	18	30.51	2.24	7	24.14	1.78
2	715	9.04	66	30.14	3.33	29	49.15	5.44	16	55.17	6.10
3	362	4.58	38	17.35	3.79	6	10.17	2.22	4	13.79	3.01
4	157	1.98	12	5.48	2.76	2	3.39	1.71	1	3.45	1.74
6	175	2.21	10	4.57	2.06	1	1.69	0.77	0	0.00	0.00
Total ⁴	2484	31.40	195	89.05	14.26	56	94.91	12.38	28	96.55	12.63
<i>Binghamton</i>											
1	436	8.86	55	25.70	2.90	24	30.38	3.43	10	25.00	2.82
2	477	9.70	78	36.45	3.76	34	43.04	4.44	21	52.50	5.42
3	553	11.24	39	18.22	1.62	15	18.99	1.69	7	17.50	1.56
4	208	4.23	11	5.14	1.22	2	2.53	0.60	1	2.50	0.59
Total ⁴	1674	34.02	183	85.51	2.51	75	94.94	2.79	39	97.50	2.87
<i>Buffalo</i>											
1	311	6.29	18	13.64	2.17	4	9.76	1.55	3	15.00	2.38
2	533	10.78	53	40.15	3.72	22	53.66	4.98	13	65.00	6.03
3	552	11.17	15	11.36	1.02	3	7.32	0.66	1	5.00	0.45
4	201	4.07	18	13.64	3.35	6	14.63	3.60	2	10.00	2.46
Total ⁴	1597	32.31	104	78.79	2.44	35	85.37	2.64	19	95.00	2.94
<i>Burlington</i>											
1	366	7.35	29	21.32	2.90	15	32.61	4.44	5	19.23	2.62
2	476	9.55	39	28.68	3.00	17	36.96	3.87	11	42.31	4.43
3	632	12.69	27	19.85	1.56	3	6.52	0.51	2	7.69	0.61
4	191	3.83	16	11.76	3.07	7	15.22	3.97	6	23.08	6.02
Total ⁴	1665	33.42	111	81.62	2.44	42	91.30	2.73	24	92.31	2.76
<i>Chicago</i>											
1	294	5.93	12	16.67	2.81	3	16.67	2.81	1	20.00	3.37
2	701	14.13	33	45.83	3.24	10	55.56	3.93	3	60.00	4.25
3	453	9.13	5	6.94	0.76	0	0.00	0.00	0	0.00	0.00
4	184	3.71	9	12.50	3.37	3	16.67	4.49	1	20.00	5.39
Total ⁴	1632	32.90	59	81.94	2.49	16	88.89	2.70	5	100.00	3.04
<i>Cleveland</i>											
1	329	6.62	15	12.50	1.89	5	21.74	3.28	0	0.00	0.00
2	575	11.57	37	30.83	2.67	9	39.13	3.38	7	58.33	5.04
3	565	11.37	17	14.17	1.25	3	13.04	1.15	2	16.67	1.47
4	205	4.12	14	11.67	2.83	3	13.04	3.16	1	8.33	2.02
7	368	7.40	10	8.33	1.13	3	13.04	1.76	2	16.67	2.25
Total ⁴	2042	41.08	93	77.50	9.77	23	99.99	12.73	12	100.00	10.78

¹ Represents percentage frequency of the weather type.

² Represents percentage frequency of the days with 1 hr, 4 hrs, or 6 hrs and longer freezing rain events occurring during a day within a particular weather type.

³ Ratio of percentage frequency of the days with freezing rain events over the percentage frequency of the weather type. A number greater than one indicates that a larger proportion of days in the weather type possess freezing rain events than be expected based on the frequency of the weather type.

⁴ Represents the sum of the weather types identified as being most highly associated with freezing rain events.

Table 13 (Continued)

Synoptic Type			Freezing Rain Events								
			≥1 hour			≥4 hours			≥6 hours		
Type	Days	Freq.(%) ¹ (a)	Days	Freq.(%) ² (b)	Ratio ³ (b)/(a)	Days	Freq.(%) ² (c)	Ratio ³ (c)/(a)	Days	Freq.(%) ² (d)	Ratio ³ (d)/(a)
Dayton											
1	334	6.79	18	13.85	2.04	7	12.96	1.91	2	7.14	1.05
2	577	11.73	57	43.85	3.74	29	53.70	4.58	15	53.57	4.57
3	510	10.37	18	13.85	1.33	8	14.81	1.43	4	14.29	1.38
4	232	4.72	11	8.46	1.79	6	11.11	2.35	4	14.29	3.03
Total ⁴	1653	33.62	104	80.00	2.38	50	92.59	2.75	25	89.29	2.66
Des Moines											
1	311	6.32	13	13.54	2.14	4	16.00	2.53	1	9.09	1.44
2	715	14.53	45	46.88	3.23	15	60.00	4.13	7	63.64	4.38
3	351	7.13	11	11.46	1.61	1	4.00	0.56	0	0.00	0.00
4	170	3.45	8	8.33	2.41	3	12.00	3.47	1	9.09	2.63
Total ⁴	1547	31.43	77	80.21	2.55	23	92.00	2.93	9	81.82	2.60
Detroit											
1	293	5.97	12	10.71	1.79	2	6.90	1.15	0	0.00	0.00
2	665	13.55	58	51.79	3.82	21	72.41	5.34	12	92.31	6.81
3	518	10.56	16	14.29	1.35	4	13.79	1.31	1	7.69	0.73
4	176	3.59	8	7.14	1.99	1	3.45	0.96	0	0.00	0.00
Total ⁴	1652	33.67	94	83.93	2.49	28	96.55	2.87	13	100.00	2.97
Indianapolis											
1	334	6.75	20	20.00	2.96	3	10.34	1.53	2	11.76	1.74
2	647	13.07	36	36.00	2.75	20	68.97	5.28	13	76.47	5.85
3	475	9.59	16	16.00	1.67	1	3.45	0.36	0	0.00	0.00
4	228	4.61	8	8.00	1.74	3	10.34	2.25	2	11.76	2.55
Total ⁴	1684	34.01	80	80.00	2.35	27	93.10	2.74	17	100.00	2.94
Minneapolis											
1	262	5.20	6	7.69	1.48	0	0.00	0.00	0	0.00	0.00
2	687	13.64	32	41.03	3.01	11	73.33	5.38	10	90.91	6.66
3	433	8.60	14	17.95	2.09	1	6.67	0.78	1	9.09	1.06
4	159	3.16	8	10.26	3.25	3	20.00	6.33	0	0.00	0.00
Total ⁴	1541	30.60	60	76.92	2.51	15	100.00	3.27	11	100.00	3.27
Peoria											
1	293	6.03	17	15.04	2.49	5	12.82	2.12	3	13.64	2.26
2	646	13.30	62	54.87	4.12	26	66.67	5.01	15	68.18	5.13
3	402	8.28	12	10.62	1.28	1	2.56	0.31	0	0.00	0.00
4	176	3.62	9	7.96	2.20	4	10.26	2.83	4	18.18	5.02
Total ⁴	1517	31.24	100	88.50	2.83	36	92.31	2.95	22	100.00	3.20
Pittsburgh											
1	323	6.45	17	15.45	2.40	5	16.67	2.58	3	20.00	3.10
2	590	11.78	39	35.45	3.01	12	40.00	3.39	8	53.33	4.53
3	526	10.51	20	18.18	1.73	4	13.33	1.27	1	6.67	0.63
4	220	4.39	7	6.36	1.45	4	13.33	3.03	1	6.67	1.52
Total ⁴	1659	33.13	83	75.45	2.28	25	83.33	2.52	13	86.67	2.62

¹ Represents percentage frequency of the weather type.

² Represents percentage frequency of the days with 1 hr, 4 hrs, or 6 hrs and longer freezing rain events occurring during a day within a particular weather type.

³ Ratio of percentage frequency of the days with freezing rain events over the percentage frequency of the weather type. A number greater than one indicates that a larger proportion of days in the weather type possess freezing rain events than be expected based on the frequency of the weather type.

⁴ Represents the sum of the weather types identified as being most highly associated with freezing rain events.

Table 14 Mean values of meteorological variables at 7:00 AM within the 4 freezing rain-related weather types for 15 Canadian stations (Nov.–Apr., 1958/59–2000/01) and 12 U.S. stations (Nov.–Apr., 1973/74–1999/2000). (The standard deviations are in parentheses.)

Type	Days (% frequency)	Surface						700 hPa			
		Ta (°C) ^a	Td (°C) ^b	Pressure (hPa)	U-wind ^c (ms-1)	V-wind ^d (ms-1)	Cloud Cover (10 ^{ths})	Ta (°C) ^a	Td (°C) ^b	U-wind ^c (ms-1)	V-wind ^d (ms-1)
<i>Ottawa</i>											
1	975 (12.33)	-1.7 (3.6)	-4.5 (3.8)	1020.5 (5.8)	-1.6 (2.3)	-0.4 (1.6)	8.4 (2.6)	-6.8 (4.2)	-16.7 (7.6)	13.2 (5.1)	2.5 (6.3)
2	721 (9.12)	-0.7 (5.3)	-3.6 (6.1)	1013.0 (8.7)	-4.4 (3.0)	-1.5 (2.1)	9.4 (1.8)	-6.2 (4.0)	-12.5 (7.1)	4.0 (8.4)	5.9 (6.9)
3	721 (9.12)	-4.7 (3.3)	-7.2 (4.0)	1012.5 (5.3)	1.2 (2.9)	-2.6 (2.3)	9.8 (0.8)	-11.0 (3.5)	-15.9 (5.6)	17.4 (5.3)	6.0 (5.3)
4	217 (2.74)	4.1 (5.2)	2.5 (5.2)	1001.7 (8.2)	-2.1 (5.6)	3.2 (3.1)	9.5 (1.5)	-3.3 (3.9)	-5.3 (4.5)	13.2 (9.3)	21.7 (7.1)
<i>Kapuskasing</i>											
1	878 (11.24)	-3.1 (4.1)	-5.8 (4.3)	1018.4 (6.0)	-1.2 (1.9)	-2.7 (1.9)	8.3 (2.9)	-8.2 (3.9)	-17.5 (7.5)	10.6 (4.9)	2.2 (6.0)
2	423 (5.42)	-4.3 (6.2)	-6.6 (6.5)	1013.2 (9.0)	-2.2 (2.1)	-1.2 (2.7)	9.2 (2.0)	-7.6 (4.4)	-14.9 (8.1)	0.7 (7.8)	4.4 (6.5)
3	610 (7.81)	-7.0 (3.9)	-9.3 (4.1)	1014.4 (4.9)	1.0 (1.9)	-4.4 (1.8)	9.9 (0.3)	-10.7 (3.8)	-15.3 (4.6)	12.7 (5.4)	2.3 (6.4)
4	240 (3.07)	0.0 (4.2)	1.8 (4.5)	1005.4 (8.3)	-0.2 (5.7)	5.8 (3.3)	9.7 (1.3)	-6.9 (8.1)	-9.4 (9.9)	14.2 (7.8)	22.4 (4.1)
<i>Kenora</i>											
1	1005 (12.76)	-3.7 (4.8)	-7.0 (4.8)	1017.7 (6.4)	-1.1 (1.7)	3.3 (2.2)	7.4 (3.2)	-8.0 (3.9)	-18.9 (7.3)	8.7 (4.7)	1.3 (6.3)
2	482 (6.12)	-1.6 (5.8)	-5.0 (5.9)	1013.0 (7.9)	-3.4 (2.3)	-1.3 (2.8)	8.9 (2.3)	-7.1 (4.2)	-14.2 (7.5)	-0.4 (7.3)	3.3 (6.3)
3	696 (8.83)	-5.5 (3.1)	-7.7 (3.6)	1011.5 (4.7)	1.6 (2.1)	-2.9 (3.1)	9.2 (1.6)	-9.8 (2.3)	-14.5 (3.7)	12.6 (5.9)	0.2 (6.8)
4	166 (2.11)	-0.8 (11.5)	-2.3 (13.3)	1004.0 (9.4)	0.3 (6.8)	3.5 (1.2)	9.6 (1.2)	-5.1 (9.4)	-9.3 (4.8)	7.6 (0.8)	10.5 (4.4)
<i>London</i>											
1	1139 (14.5)	-1.6 (3.5)	-3.6 (3.7)	1021.3 (5.8)	-1.5 (2.7)	-1.2 (1.8)	8.0 (2.9)	-6.7 (3.8)	-17.1 (7.7)	12.8 (4.8)	1.7 (6.4)
2	687 (8.75)	-0.7 (3.9)	-1.6 (4.6)	1014.6 (8.3)	-5.5 (3.6)	-0.8 (2.1)	8.9 (2.4)	-5.1 (3.7)	-12.7 (7.9)	4.5 (7.6)	3.7 (6.2)
3	450 (5.73)	-3.5 (3.3)	-5.4 (3.6)	1014.9 (5.7)	0.8 (2.0)	-3.7 (2.4)	9.4 (1.7)	-11.1 (3.7)	-16.0 (5.0)	16.7 (5.2)	2.5 (6.0)
4	155 (1.97)	2.9 (3.9)	1.9 (3.8)	1003.2 (8.3)	0.0 (6.2)	5.5 (3.2)	9.2 (2.2)	-4.8 (4.3)	-8.4 (5.5)	15.3 (8.6)	21.2 (5.8)
<i>Montreal</i>											
1	949 (12.06)	-0.7 (3.7)	-3.9 (3.8)	1021.0 (5.9)	-0.9 (2.0)	0.4 (2.4)	8.2 (2.7)	-7.3 (4.1)	-17.1 (7.8)	13.4 (5.2)	1.8 (6.6)
2	751 (9.54)	-0.1 (5.6)	-3.1 (5.9)	1013.0 (8.5)	-3.4 (2.4)	-3.3 (3.0)	9.2 (2.1)	-6.3 (4.0)	-12.9 (7.4)	3.7 (8.8)	5.1 (7.5)
3	687 (8.73)	-4.6 (3.5)	-6.7 (3.7)	1011.8 (5.3)	-0.8 (1.9)	-3.2 (2.4)	9.9 (0.2)	-9.8 (3.3)	-13.8 (5.2)	17.3 (5.5)	7.7 (4.9)
4	222 (2.82)	4.0 (6.1)	1.9 (6.2)	1000.6 (8.7)	-0.7 (5.3)	3.4 (5.4)	9.6 (1.2)	-4.1 (5.0)	-6.7 (5.3)	13.8 (9.7)	21.4 (6.4)

^a Air temperature

^b Dew point temperature

^c Positive value is for westerly wind

^d Positive value is for southerly wind

Table 14 (Continued)

Type	Days (% frequency)	Surface						700 hPa			
		Ta (°C) ^a	Td (°C) ^b	Pressure (hPa)	U-wind ^c (ms ⁻¹)	V-wind ^d (ms ⁻¹)	Cloud Cover (10 ^{ths})	Ta (°C) ^a	Td (°C) ^b	U-wind ^c (ms ⁻¹)	V-wind ^d (ms ⁻¹)
<i>North Bay</i>											
1	1059 (13.42)	-2.3 (3.7)	-5.1 (4.1)	1020.4 (5.9)	-1.6 (2.2)	1.8 (1.9)	8.6 (2.6)	-7.5 (4.0)	-17.6 (7.6)	11.9 (4.9)	1.8 (6.1)
2	658 (8.34)	-1.8 (5.7)	-4.9 (6.4)	1013.0 (8.9)	-4.5 (2.7)	-1.5 (2.8)	9.0 (2.3)	-6.7 (4.1)	-13.9 (7.6)	3.2 (7.8)	4.0 (6.6)
3	692 (8.77)	-4.4 (4.3)	-6.3 (4.8)	1013.0 (5.2)	0.0 (2.2)	-2.3 (2.9)	9.6 (1.2)	-10.1 (4.4)	-16.1 (6.3)	16.7 (5.8)	3.2 (5.2)
4	229 (2.90)	3.6 (3.4)	2.2 (2.7)	1001.0 (8.5)	-1.6 (6.0)	4.5 (2.6)	9.6 (1.2)	-3.2 (3.4)	-5.9 (3.8)	12.5 (7.7)	21.7 (5.2)
<i>Sault Ste Marie</i>											
1	988 (13.67)	-1.3 (3.6)	-3.3 (3.7)	1019.5 (5.9)	-2.3 (2.2)	0.7 (1.5)	8.7 (2.5)	-7.0 (3.8)	-17.4 (7.5)	11.9 (4.7)	1.7 (6.3)
2	607 (8.40)	0.1 (4.4)	-2.7 (5.2)	1013.4 (8.7)	-4.0 (2.7)	-0.2 (1.8)	9.1 (2.2)	-6.1 (4.0)	-13.3 (7.4)	3.3 (7.3)	4.8 (6.2)
3	577 (7.99)	-4.0 (3.6)	-6.1 (4.1)	1011.9 (4.8)	1.8 (3.4)	-2.9 (2.7)	9.4 (1.6)	-11.0 (3.7)	-16.6 (5.4)	16.0 (5.5)	1.9 (6.1)
4	202 (2.80)	3.9 (5.8)	2.5 (6.2)	1002.1 (7.9)	-1.2 (5.6)	3.3 (2.9)	9.4 (1.7)	-5.5 (6.0)	-8.5 (6.9)	10.8 (5.6)	22.0 (6.9)
<i>Sioux Lookout</i>											
1	988 (12.59)	-3.6 (4.7)	-6.9 (4.5)	1019.0 (5.8)	-1.1 (1.6)	2.3 (1.7)	7.9 (3.0)	-8.4 (3.5)	-19.1 (8.2)	9.2 (4.3)	1.7 (6.4)
2	435 (5.54)	-2.2 (6.0)	-5.1 (6.3)	1013.3 (8.3)	-3.0 (1.9)	-0.7 (2.3)	9.2 (2.0)	-7.7 (4.3)	-14.7 (8.3)	-0.3 (7.7)	3.5 (6.2)
3	598 (7.62)	-4.4 (3.1)	-6.0 (2.9)	1010.0 (4.0)	1.3 (2.3)	-2.9 (3.0)	8.2 (3.3)	-10.4 (2.6)	-14.0 (3.3)	13.6 (8.5)	-1.2 (5.8)
4	155 (1.97)	-6.5 (4.3)	-8.4 (4.6)	1002.8 (9.5)	1.1 (2.7)	-4.0 (2.6)	9.8 (1.0)	-12.7 (4.0)	-15.6 (5.8)	1.8 (7.9)	-4.6 (7.2)
<i>Sudbury</i>											
1	1039 (13.22)	-3.0 (4.0)	-5.3 (4.4)	1020.1 (6.1)	-1.5 (2.3)	2.7 (2.6)	8.6 (2.6)	-7.3 (4.1)	-17.0 (7.9)	11.9 (4.8)	2.7 (5.9)
2	669 (8.51)	-2.8 (5.9)	-5.6 (6.6)	1013.7 (8.7)	-4.2 (2.6)	-3.1 (3.6)	9.0 (2.4)	-7.0 (4.2)	-14.2 (7.6)	2.5 (7.7)	3.6 (6.3)
3	645 (8.21)	-4.8 (4.0)	-6.9 (4.5)	1012.5 (5.7)	-0.1 (2.6)	-4.3 (3.0)	9.6 (1.4)	-10.4 (3.7)	-17.3 (5.4)	15.5 (6.0)	1.4 (5.7)
4	289 (3.68)	2.6 (4.2)	1.8 (4.4)	1002.3 (8.0)	-3.6 (4.1)	5.2 (4.1)	9.3 (1.8)	-4.2 (3.5)	-6.3 (3.0)	10.7 (6.7)	22.2 (5.9)
<i>Thunder Bay</i>											
1	840 (10.71)	-2.8 (4.2)	-5.1 (4.2)	1019.0 (5.9)	-0.5 (2.2)	0.4 (1.6)	8.2 (3.0)	-7.4 (3.6)	-17.6 (7.8)	10.5 (4.5)	1.9 (6.4)
2	649 (8.27)	-0.9 (4.6)	-3.5 (5.2)	1014.2 (8.2)	-3.0 (3.1)	-1.3 (2.3)	8.9 (2.3)	-6.9 (4.4)	-13.3 (6.9)	1.4 (7.3)	4.1 (6.5)
3	524 (6.68)	-4.3 (4.0)	-6.6 (4.3)	1012.4 (5.4)	0.7 (3.2)	-2.8 (2.5)	9.6 (1.4)	-9.3 (2.8)	-13.0 (3.8)	11.7 (3.9)	3.0 (5.2)
4	188 (2.40)	2.7 (1.9)	1.4 (3.7)	1003.1 (7.9)	-3.1 (5.0)	3.2 (5.0)	9.6 (1.3)	-3.3 (2.7)	-8.8 (7.7)	6.4 (5.7)	23.8 (4.6)
<i>Timmins</i>											
1	894 (11.46)	-3.3 (4.2)	-5.7 (4.5)	1019.8 (5.8)	-0.6 (1.5)	2.2 (1.9)	8.2 (3.0)	-7.8 (3.8)	-17.3 (7.2)	10.9 (4.8)	2.0 (6.0)
2	435 (5.58)	-3.1 (6.0)	-5.6 (6.5)	1012.5 (9.1)	-2.6 (2.1)	-1.0 (2.8)	9.1 (2.2)	-7.2 (4.4)	-14.0 (7.7)	1.0 (7.7)	4.9 (6.6)
3	615 (7.88)	-5.5 (4.0)	-7.4 (4.1)	1012.7 (6.3)	0.5 (1.6)	-3.7 (3.1)	9.8 (1.3)	-10.4 (4.1)	-15.6 (5.1)	12.5 (5.0)	2.2 (6.6)
4	235 (3.01)	-1.1 (4.7)	-3.0 (5.3)	1003.2 (8.4)	1.2 (2.7)	-4.5 (2.8)	9.7 (1.2)	-6.8 (4.2)	-10.0 (4.8)	1.2 (7.6)	-2.5 (7.3)

^a Air temperature

^b Dew point temperature

^c Positive value is for westerly wind

^d Positive value is for southerly wind

Table 14 (Continued)

Type	Days (% frequency)	Surface						700 hPa			
		Ta (°C) ^a	Td (°C) ^b	Pressure (hPa)	U-wind ^c (ms-1)	V-wind ^d (ms-1)	Cloud Cover (10 ^{ths})	Ta (°C) ^a	Td (°C) ^b	U-wind ^c (ms-1)	V-wind ^d (ms-1)
<i>Toronto</i>											
1	1164 (14.72)	-0.7 (3.4)	-2.8 (3.6)	1021.2 (5.5)	-0.7 (2.1)	0.4 (1.9)	8.4 (2.6)	-6.5 (3.9)	-16.8 (7.2)	12.9 (5.1)	1.6 (6.4)
2	627 (7.93)	1.2 (4.2)	-1.3 (4.6)	1014.8 (8.2)	-3.6 (3.3)	-1.5 (2.4)	9.2 (2.0)	-5.0 (3.7)	-12.6 (7.5)	4.4 (7.3)	4.2 (6.2)
3	522 (6.60)	-3.5 (3.4)	-5.6 (3.9)	1014.1 (5.8)	1.3 (2.0)	-4.4 (2.8)	9.5 (1.7)	-10.2 (3.4)	-13.9 (4.6)	17.9 (5.1)	4.7 (5.3)
4	190 (2.40)	3.6 (4.0)	2.4 (3.9)	1002.7 (7.8)	-0.8 (5.2)	4.3 (3.9)	9.2 (1.9)	-3.4 (4.1)	-6.0 (4.7)	15.3 (7.4)	21.3 (6.3)
<i>Trenton</i>											
1	1081 (13.67)	-1.5 (3.8)	-3.6 (3.9)	1021.5 (5.6)	-0.9 (2.1)	0.0 (1.9)	8.2 (2.7)	-6.6 (4.1)	-16.4 (7.1)	13.2 (5.3)	2.1 (6.4)
2	648 (8.19)	0.3 (5.0)	-2.2 (5.4)	1015.1 (8.4)	-3.2 (2.2)	-1.9 (2.2)	8.9 (2.4)	-5.5 (3.9)	-12.9 (7.5)	4.3 (7.6)	3.9 (6.5)
3	579 (7.32)	-3.8 (3.9)	-5.9 (4.5)	1013.1 (6.3)	-0.6 (2.6)	-3.5 (2.0)	9.8 (0.9)	-10.2 (3.0)	-14.1 (4.7)	17.9 (4.8)	5.1 (5.6)
4	173 (2.19)	4.3 (3.8)	3.0 (3.7)	1000.5 (7.8)	-2.2 (4.4)	4.3 (4.9)	9.5 (1.6)	-3.4 (3.8)	-5.5 (4.2)	13.6 (7.1)	21.4 (6.6)
<i>Wiaraton</i>											
1	1249 (15.95)	-1.5 (3.6)	-4.1 (3.9)	1020.7 (5.8)	-1.3 (2.1)	2.5 (2.7)	8.1 (3.0)	-7.3 (3.8)	-17.5 (7.7)	12.4 (4.9)	1.7 (6.1)
2	607 (7.75)	0.2 (4.2)	-2.5 (4.8)	1014.2 (8.5)	-3.9 (2.8)	-1.3 (2.7)	8.9 (2.4)	-5.7 (3.8)	-13.0 (8.1)	3.3 (7.3)	3.7 (6.2)
3	478 (6.10)	-4.7 (4.0)	-7.2 (4.4)	1014.7 (5.7)	0.0 (2.8)	-3.8 (2.6)	9.7 (1.2)	-11.7 (3.9)	-17.4 (5.5)	14.9 (6.3)	1.1 (6.3)
4	166 (2.12)	2.7 (4.7)	1.3 (4.5)	1002.4 (7.5)	-1.2 (5.9)	5.6 (4.6)	9.3 (1.9)	-5.0 (4.6)	-8.2 (5.9)	14.5 (8.3)	20.8 (5.9)
<i>Windsor</i>											
1	1075 (13.59)	-1.1 (3.4)	-3.4 (3.5)	1021.6 (5.6)	-0.5 (2.2)	1.5 (2.2)	8.0 (3.0)	-6.0 (3.7)	-17.0 (7.9)	12.4 (5.1)	1.7 (6.3)
2	715 (9.04)	1.0 (4.3)	-1.4 (4.7)	1016.4 (7.8)	-3.7 (2.9)	-2.4 (3.0)	9.0 (2.4)	-4.8 (3.8)	-12.8 (8.0)	4.8 (7.6)	3.1 (6.3)
3	362 (4.58)	-2.6 (3.0)	-4.9 (3.7)	1016.9 (5.1)	0.2 (2.4)	-5.9 (2.2)	9.7 (1.2)	-8.4 (3.9)	-14.0 (5.7)	17.4 (5.1)	3.3 (5.7)
4	157 (1.98)	4.4 (5.4)	2.9 (5.7)	1003.7 (9.0)	-1.2 (6.3)	6.1 (3.9)	9.4 (1.8)	-3.7 (3.7)	-8.9 (7.5)	13.7 (8.0)	19.9 (5.1)
<i>Binghamton</i>											
1	436 (8.86)	-2.8 (5.2)	-6.1 (5.7)	1020.5 (7.3)	0.9 (2.9)	0.4 (3.1)	8.3 (3.1)	-6.7 (3.7)	-17.7 (8.1)	17.2 (6.2)	0.8 (7.2)
2	477 (9.70)	1.5 (3.8)	-0.9 (4.5)	1015.8 (8.1)	-2.3 (2.9)	0.6 (3.4)	9.4 (2.0)	-3.7 (3.4)	-10.8 (7.1)	7.5 (8.7)	4.5 (7.4)
3	553 (11.24)	1.1 (4.7)	-2.4 (5.0)	1015.2 (7.3)	-0.3 (2.4)	2.8 (2.7)	8.9 (2.5)	-5.6 (4.7)	-13.2 (7.2)	14.6 (7.1)	5.0 (6.7)
4	208 (4.23)	5.6 (7.5)	3.0 (7.9)	1008.6 (10.3)	-0.2 (3.3)	2.6 (3.6)	9.1 (2.5)	-2.1 (4.1)	-8.0 (7.0)	14.9 (8.5)	11.2 (8.2)
<i>Buffalo</i>											
1	311 (6.29)	-1.5 (4.8)	-4.7 (5.4)	1021.3 (6.6)	0.9 (3.2)	0.7 (2.9)	8.6 (2.7)	-8.4 (3.6)	-18.7 (6.6)	17.2 (5.6)	0.0 (7.1)
2	533 (10.78)	2.6 (3.9)	-0.2 (4.3)	1016.2 (8.2)	-2.8 (2.5)	-0.5 (2.8)	9.4 (1.7)	-4.4 (3.3)	-12.4 (7.5)	6.7 (8.2)	3.7 (6.6)
3	552 (11.17)	2.5 (4.9)	-1.6 (4.9)	1014.5 (6.7)	0.7 (3.1)	2.9 (2.9)	9.2 (2.0)	-7.5 (4.6)	-14.7 (6.5)	13.8 (7.3)	4.6 (6.4)
4	201 (4.07)	5.7 (8.1)	2.6 (8.2)	1009.8 (11.3)	1.1 (4.4)	2.5 (4.0)	9.4 (1.8)	-4.0 (4.8)	-9.6 (7.2)	12.6 (8.5)	9.1 (7.7)

^a Air temperature

^b Dew point temperature

^c Positive value is for westerly wind

^d Positive value is for southerly wind

Table 14 (Continued)

Type	Days (% frequency)	Surface						700 hPa			
		Ta (°C)a	Td (°C)b	Pressure (hPa)	U-windc (ms-1)	V-windd (ms-1)	Cloud Cover (10 th)	Ta (°C)a	Td (°C)b	U-windc (ms-1)	V-windd (ms-1)
<i>Burlington</i>											
1	366 (7.35)	-3.5 (6.1)	-7.5 (6.2)	1021.5 (8.1)	-0.3 (2.2)	0.8 (3.3)	8.1 (3.2)	-9.0 (3.8)	-19.2 (7.7)	17.4 (6.1)	0.7 (7.6)
2	476 (9.55)	2.4 (4.0)	-0.4 (4.4)	1015.2 (8.0)	-0.8 (2.2)	-0.1 (2.9)	9.4 (1.8)	-4.7 (3.7)	-12.1 (7.5)	6.4 (9.4)	4.3 (7.7)
3	632 (12.69)	1.5 (5.2)	-2.6 (5.1)	1013.7 (7.9)	-0.8 (1.8)	3.3 (3.7)	9.1 (2.2)	-7.8 (5.1)	-14.8 (7.3)	14.0 (7.2)	4.8 (7.1)
4	191 (3.83)	4.8 (8.3)	1.7 (8.5)	1007.7 (10.5)	-0.8 (2.2)	2.9 (4.4)	9.4 (1.8)	-3.6 (4.2)	-8.3 (6.2)	14.3 (9.7)	11.7 (8.0)
<i>Chicago</i>											
1	294 (5.93)	-2.6 (5.2)	-5.6 (5.4)	1022.2 (6.9)	0.9 (2.5)	0.1 (3.1)	7.4 (3.6)	-7.6 (3.5)	-19.0 (7.4)	15.1 (4.8)	-1.6 (6.6)
2	701 (14.13)	3.1 (3.6)	0.3 (3.8)	1015.9 (7.4)	-2.9 (2.8)	-1.6 (3.4)	9.4 (1.7)	-3.8 (3.2)	-11.8 (7.0)	6.3 (7.7)	3.4 (6.5)
3	453 (9.13)	1.8 (4.7)	-1.3 (4.3)	1014.6 (6.5)	0.5 (2.5)	2.6 (3.3)	8.7 (2.5)	-5.7 (4.5)	-15.3 (6.6)	11.7 (6.5)	3.5 (7.1)
4	184 (3.71)	5.9 (7.4)	3.2 (7.9)	1011.1 (11.3)	-0.6 (4.1)	1.0 (4.3)	9.3 (2.0)	-3.8 (5.3)	-11.3 (7.6)	9.8 (7.6)	8.4 (7.5)
<i>Cleveland</i>											
1	329 (6.62)	-1.4 (4.9)	-4.6 (5.3)	1021.8 (6.7)	1.4 (2.4)	0.7 (3.2)	8.0 (3.4)	-7.4 (3.6)	-19.1 (7.6)	17.5 (5.9)	-1.5 (7.6)
2	575 (11.57)	3.2 (3.8)	0.4 (4.5)	1016.5 (7.6)	-2.1 (2.5)	-0.6 (3.3)	9.4 (1.8)	-3.9 (3.3)	-12.2 (7.7)	7.7 (8.2)	2.7 (7.0)
3	565 (11.37)	2.7 (4.5)	-1.3 (4.6)	1015.7 (6.6)	0.8 (2.3)	3.4 (3.1)	9.0 (2.4)	-6.3 (4.5)	-14.5 (6.8)	14.2 (6.4)	4.3 (6.4)
4	205 (4.12)	7.2 (7.4)	4.2 (8.0)	1010.2 (10.4)	0.5 (3.8)	2.5 (3.9)	9.0 (2.6)	-2.6 (4.3)	-8.6 (7.7)	13.1 (8.4)	9.1 (6.9)
<i>Dayton</i>											
1	334 (6.79)	-2.2 (5.0)	-5.2 (5.5)	1022.8 (6.9)	1.2 (2.9)	0.0 (2.9)	7.7 (3.7)	-6.0 (3.7)	-18.9 (8.1)	17.1 (5.5)	-1.0 (7.1)
2	577 (11.73)	2.5 (4.1)	-0.2 (4.7)	1018.1 (7.2)	-2.4 (2.5)	-1.1 (3.1)	9.2 (2.2)	-2.9 (3.1)	-10.9 (7.5)	8.4 (7.7)	3.5 (7.1)
3	510 (10.37)	3.0 (4.4)	-0.8 (4.5)	1016.8 (6.0)	0.4 (2.6)	3.0 (2.9)	8.7 (2.9)	-4.6 (4.0)	-13.3 (7.1)	14.1 (6.0)	4.5 (6.5)
4	232 (4.72)	9.2 (6.0)	6.7 (6.4)	1009.5 (8.5)	1.1 (3.4)	2.6 (3.4)	9.1 (2.3)	-1.3 (3.8)	-7.5 (6.2)	15.2 (7.3)	10.4 (6.6)
<i>Des Moines</i>											
1	311 (6.32)	-3.4 (5.3)	-6.5 (5.8)	1021.2 (7.6)	0.4 (2.9)	0.0 (3.3)	7.5 (3.6)	-6.2 (3.8)	-17.7 (7.2)	13.7 (4.9)	-1.9 (7.0)
2	715 (14.53)	2.6 (4.3)	-0.2 (4.5)	1016.0 (7.3)	-2.8 (2.9)	-1.0 (3.0)	9.3 (2.0)	-3.4 (3.4)	-11.6 (6.6)	5.3 (6.9)	3.3 (6.3)
3	351 (7.13)	0.9 (5.3)	-2.3 (5.2)	1014.3 (6.7)	-0.7 (2.6)	2.3 (3.3)	8.1 (3.4)	-4.1 (4.3)	-14.6 (6.1)	10.2 (6.0)	2.8 (7.6)
4	170 (3.45)	2.8 (9.6)	0.1 (10.2)	1011.1 (12.5)	-0.6 (3.6)	0.1 (4.5)	8.7 (2.8)	-3.3 (5.8)	-10.9 (6.1)	8.2 (6.4)	6.1 (7.3)
<i>Detroit</i>											
1	293 (5.97)	-2.4 (5.4)	-5.5 (5.3)	1021.1 (6.9)	1.7 (2.7)	-0.1 (3.1)	7.7 (3.6)	-7.4 (3.6)	-18.9 (7.3)	16.8 (5.6)	-1.6 (7.0)
2	665 (13.55)	2.2 (3.8)	-0.6 (4.0)	1016.6 (7.6)	-2.7 (2.7)	-1.5 (2.7)	9.1 (2.3)	-3.7 (3.3)	-11.7 (7.5)	7.8 (7.8)	3.8 (6.7)
3	518 (10.56)	1.2 (4.3)	-1.6 (4.2)	1014.7 (6.5)	0.3 (2.8)	2.3 (3.1)	8.9 (2.4)	-6.6 (4.5)	-14.7 (6.9)	13.7 (6.6)	4.1 (6.8)
4	176 (3.59)	5.5 (8.1)	2.9 (8.6)	1009.0 (11.4)	-0.2 (4.3)	1.3 (4.3)	9.1 (2.2)	-3.3 (4.9)	-9.3 (7.2)	11.4 (7.9)	9.7 (7.9)

^a Air temperature

^b Dew point temperature

^c Positive value is for westerly wind

^d Positive value is for southerly wind

Table 14 (Continued)

Type	Days (% frequency)	Surface						700 hPa			
		Ta (°C) ^a	Td (°C) ^b	Pressure (hPa)	U-wind ^c (ms ⁻¹)	V-wind ^d (ms ⁻¹)	Cloud Cover (10 ^{ths})	Ta (°C) ^a	Td (°C) ^b	U-wind ^c (ms ⁻¹)	V-wind ^d (ms ⁻¹)
<i>Indianapolis</i>											
1	334 (6.75)	-2.3 (5.0)	-4.8 (5.4)	1022.3 (6.6)	0.8 (2.9)	-0.4 (2.9)	7.7 (3.6)	-5.8 (3.5)	-18.2 (8.2)	16.2 (5.2)	-1.1 (7.1)
2	647 (13.07)	3.1 (4.0)	0.3 (4.5)	1017.4 (7.4)	-2.8 (2.9)	-1.3 (2.8)	9.3 (2.0)	-3.0 (3.0)	-11.3 (7.4)	8.1 (7.5)	3.5 (6.9)
3	475 (9.59)	3.1 (4.3)	-0.1 (4.3)	1016.2 (5.7)	-0.2 (2.8)	2.3 (2.7)	8.8 (2.7)	-4.1 (3.8)	-13.7 (7.1)	13.9 (6.3)	4.5 (7.0)
4	228 (4.61)	8.8 (6.7)	6.7 (7.1)	1009.5 (8.8)	0.5 (4.0)	1.4 (3.7)	9.0 (2.5)	-1.6 (3.8)	-8.4 (6.3)	14.2 (7.2)	9.1 (7.0)
<i>Minneapolis</i>											
1	262 (5.20)	-5.5 (5.8)	-8.8 (6.5)	1021.7 (7.3)	-0.3 (2.9)	1.0 (2.8)	7.9 (3.4)	-7.5 (3.9)	-18.8 (7.5)	12.9 (4.7)	-2.2 (6.3)
2	687 (13.64)	2.0 (4.2)	-1.3 (4.4)	1014.2 (7.8)	-3.0 (2.9)	-0.8 (3.4)	9.3 (2.0)	-4.1 (3.6)	-12.0 (6.7)	3.8 (7.2)	3.5 (6.4)
3	433 (8.60)	-1.3 (5.7)	-4.5 (5.4)	1013.3 (6.5)	-1.1 (2.5)	1.8 (3.3)	8.6 (2.9)	-6.3 (4.7)	-16.2 (6.5)	10.1 (7.0)	1.1 (7.3)
4	159 (3.16)	-1.0 (9.2)	-4.4 (9.8)	1014.8 (13.6)	-2.3 (3.4)	0.0 (4.5)	9.1 (2.4)	-6.2 (6.5)	-13.3 (6.7)	4.8 (6.8)	5.3 (7.2)
<i>Peoria</i>											
1	293 (6.03)	-2.6 (4.8)	-5.2 (5.3)	1022.3 (6.6)	0.2 (2.7)	0.2 (3.1)	7.9 (3.4)	-6.8 (3.7)	-18.2 (7.3)	15.3 (5.1)	-2.0 (6.9)
2	646 (13.30)	2.7 (3.8)	0.3 (4.1)	1016.7 (7.3)	-2.9 (2.9)	-1.5 (2.9)	9.3 (2.0)	-3.6 (3.1)	-11.9 (7.0)	6.6 (7.4)	3.3 (6.7)
3	402 (8.28)	2.1 (4.8)	-0.6 (4.6)	1014.8 (6.4)	-0.4 (2.2)	2.5 (3.0)	8.7 (2.8)	-4.6 (4.4)	-14.7 (6.8)	11.9 (6.2)	4.1 (7.3)
4	176 (3.62)	6.8 (7.1)	4.5 (7.9)	1009.7 (10.0)	0.1 (3.7)	1.2 (3.9)	9.2 (2.2)	-2.7 (4.4)	-10.2 (7.0)	10.5 (7.3)	8.7 (6.7)
<i>Pittsburgh</i>											
1	323 (6.45)	-1.8 (5.2)	-5.5 (5.5)	1020.3 (7.0)	1.4 (2.7)	-0.3 (2.4)	8.0 (3.3)	-7.0 (3.7)	-18.6 (8.1)	17.7 (5.5)	0.0 (7.4)
2	590 (11.78)	3.1 (4.0)	-0.3 (5.0)	1016.1 (7.2)	-1.8 (2.4)	-0.7 (2.1)	9.2 (2.2)	-3.4 (3.1)	-11.6 (7.8)	8.6 (8.1)	3.5 (6.9)
3	526 (10.51)	2.4 (4.7)	-2.1 (5.2)	1015.4 (6.5)	0.1 (2.4)	1.6 (2.1)	8.9 (2.4)	-5.7 (4.3)	-14.2 (6.9)	14.9 (6.5)	4.2 (6.9)
4	220 (4.39)	8.4 (6.4)	4.9 (7.1)	1007.9 (9.9)	0.2 (3.3)	1.9 (2.7)	9.4 (1.9)	-2.2 (3.6)	-7.4 (7.3)	13.5 (8.0)	9.5 (7.1)

^a Air temperature

^b Dew point temperature

^c Positive value is for westerly wind

^d Positive value is for southerly wind

Figure 17 Annual time series of the total number of winter seasonal (November to April) days with freezing rain-related weather types for 15 stations in Canada.

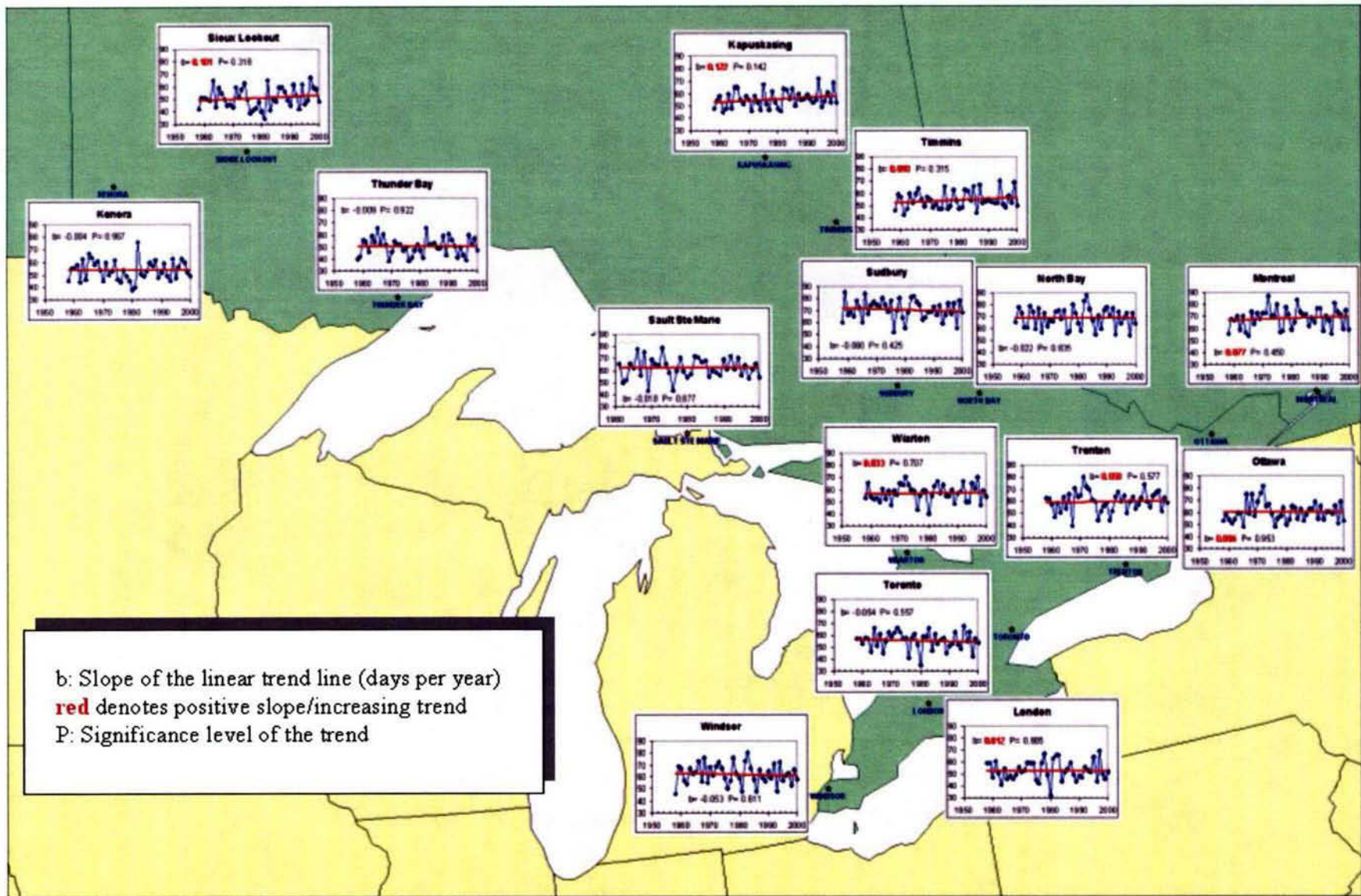


Figure 18 Annual time series of the total number of winter seasonal (Nov.–Apr.) days with freezing rain-related weather types for 12 stations in the U.S.

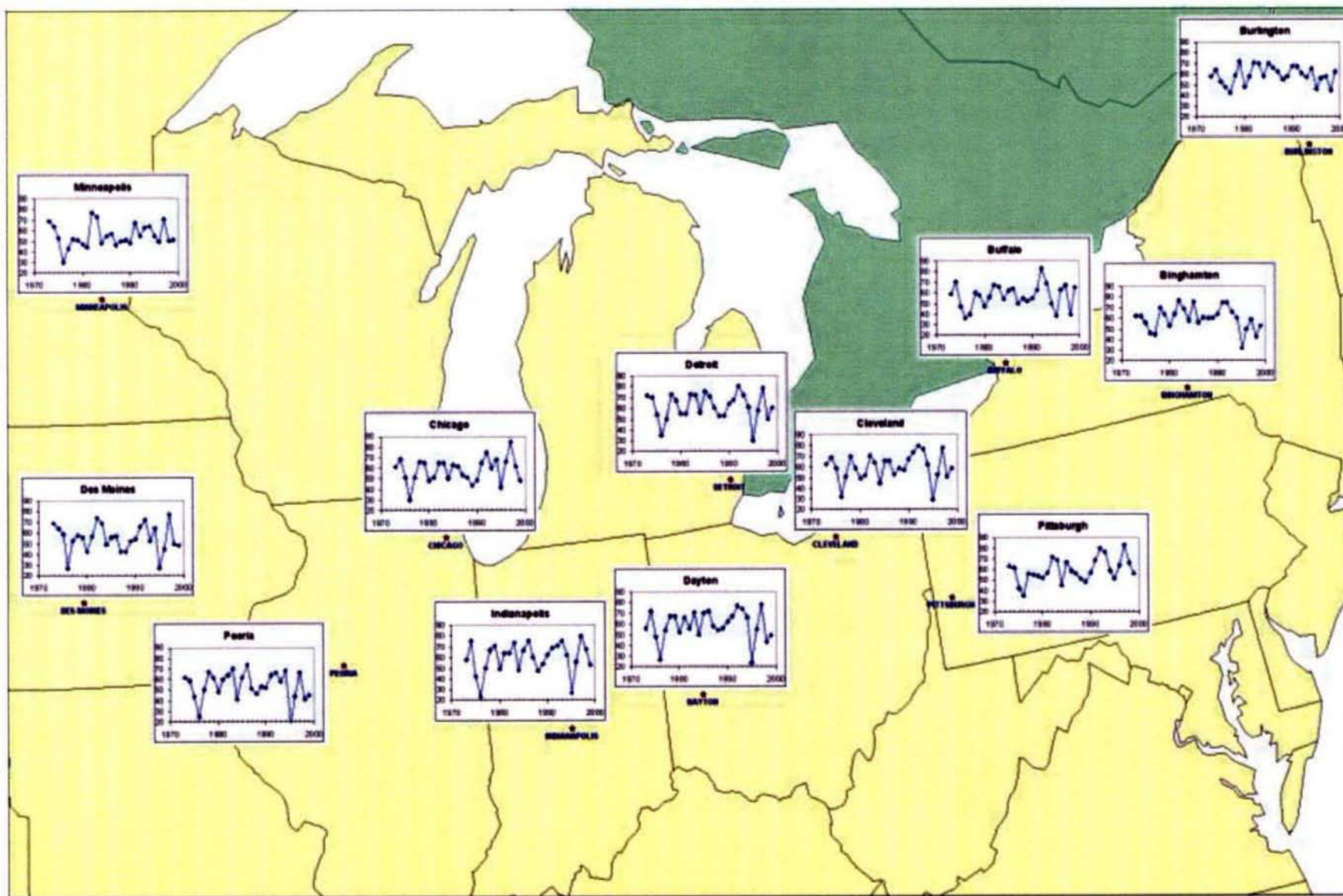


Figure 19 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of three groups based on 1/3 interval of the difference between the highest and lowest frequency of the freezing rain-related weather types in December. (The horizontal axis is monthly mean frequency (days) of the freezing rain-related weather types.)

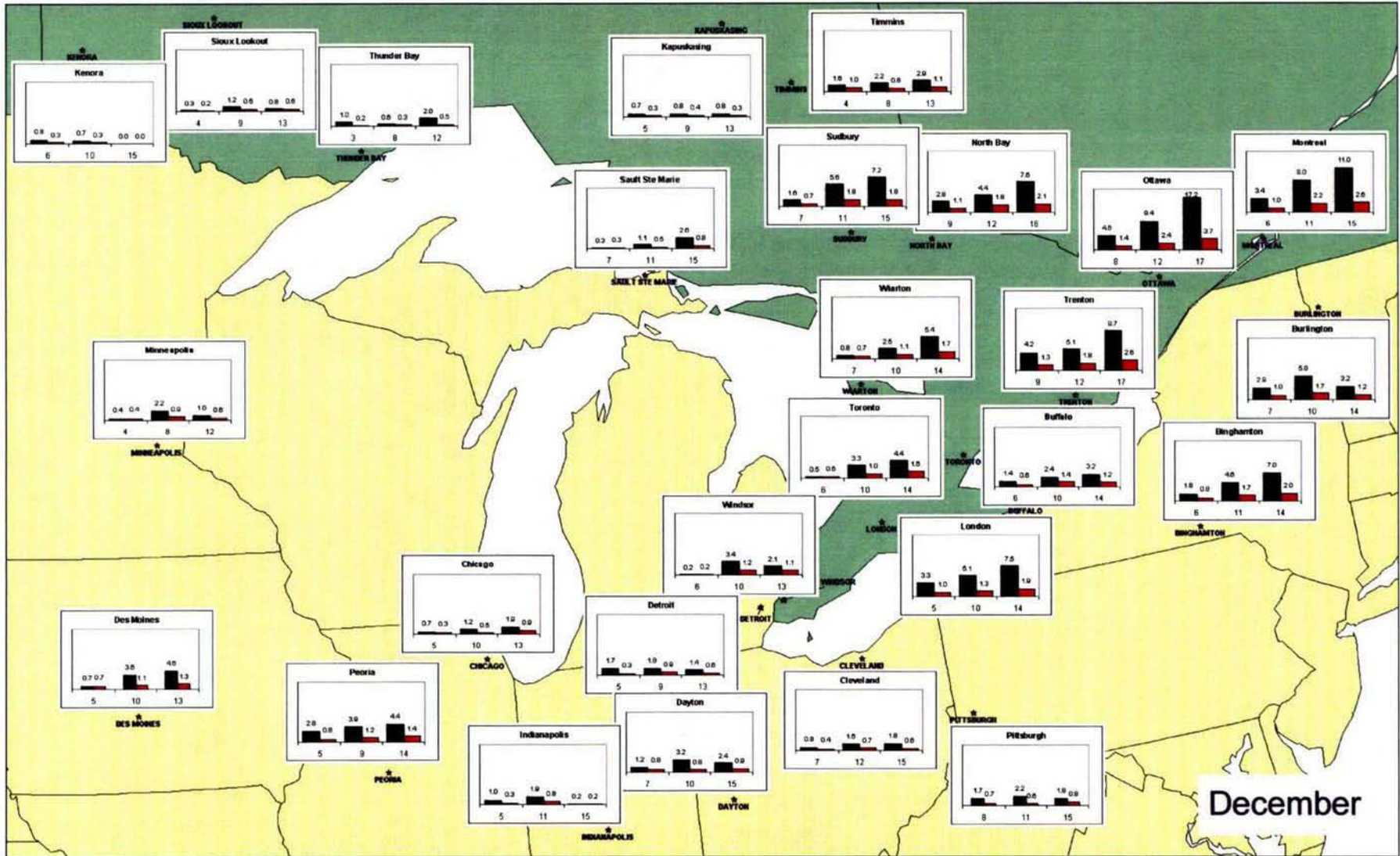


Figure 20 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of three groups based on 1/3 interval of the difference between the highest and lowest frequency of the freezing rain-related weather types in January. (The horizontal axis is monthly mean frequency (days) of the freezing rain-related weather types.)

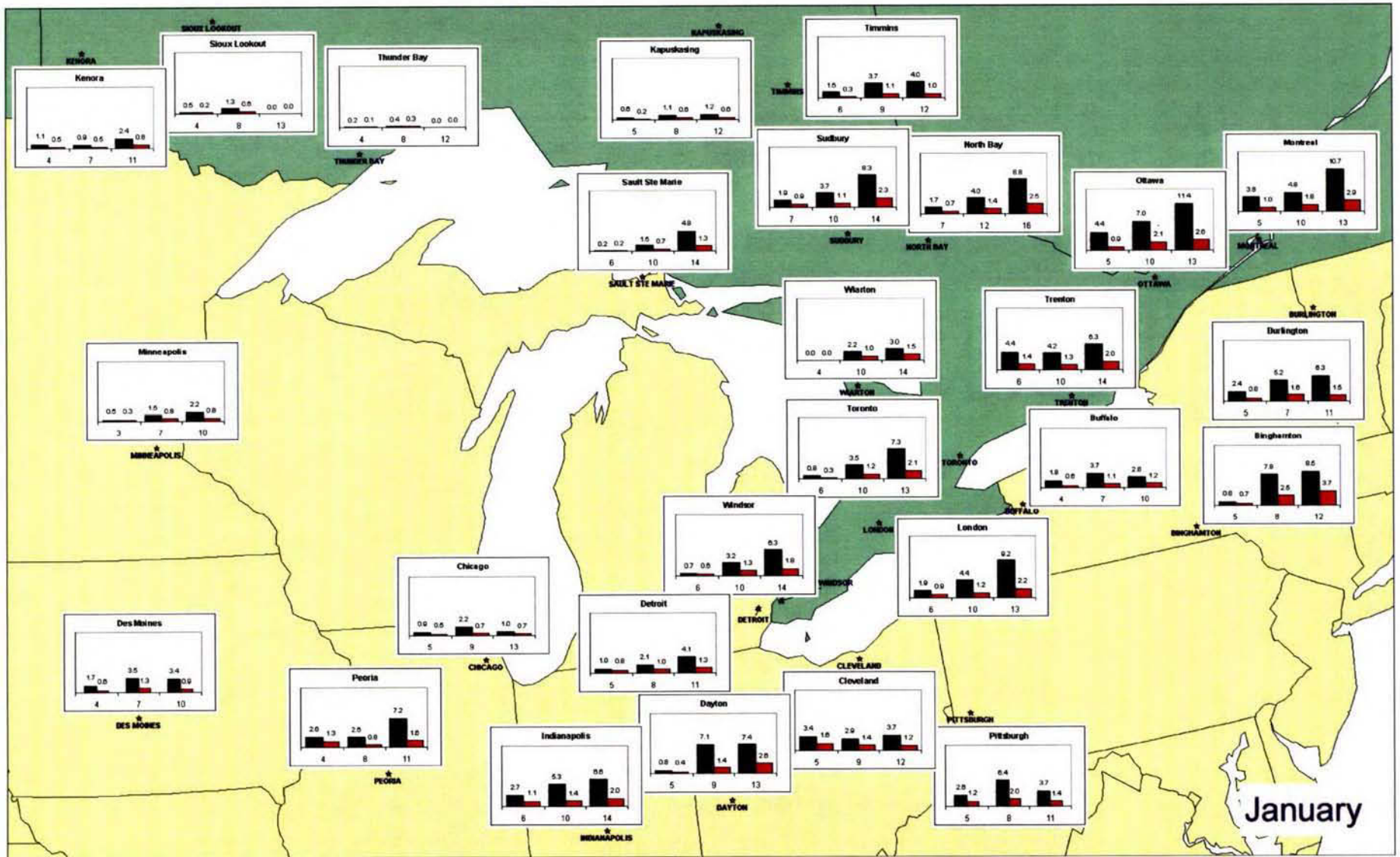
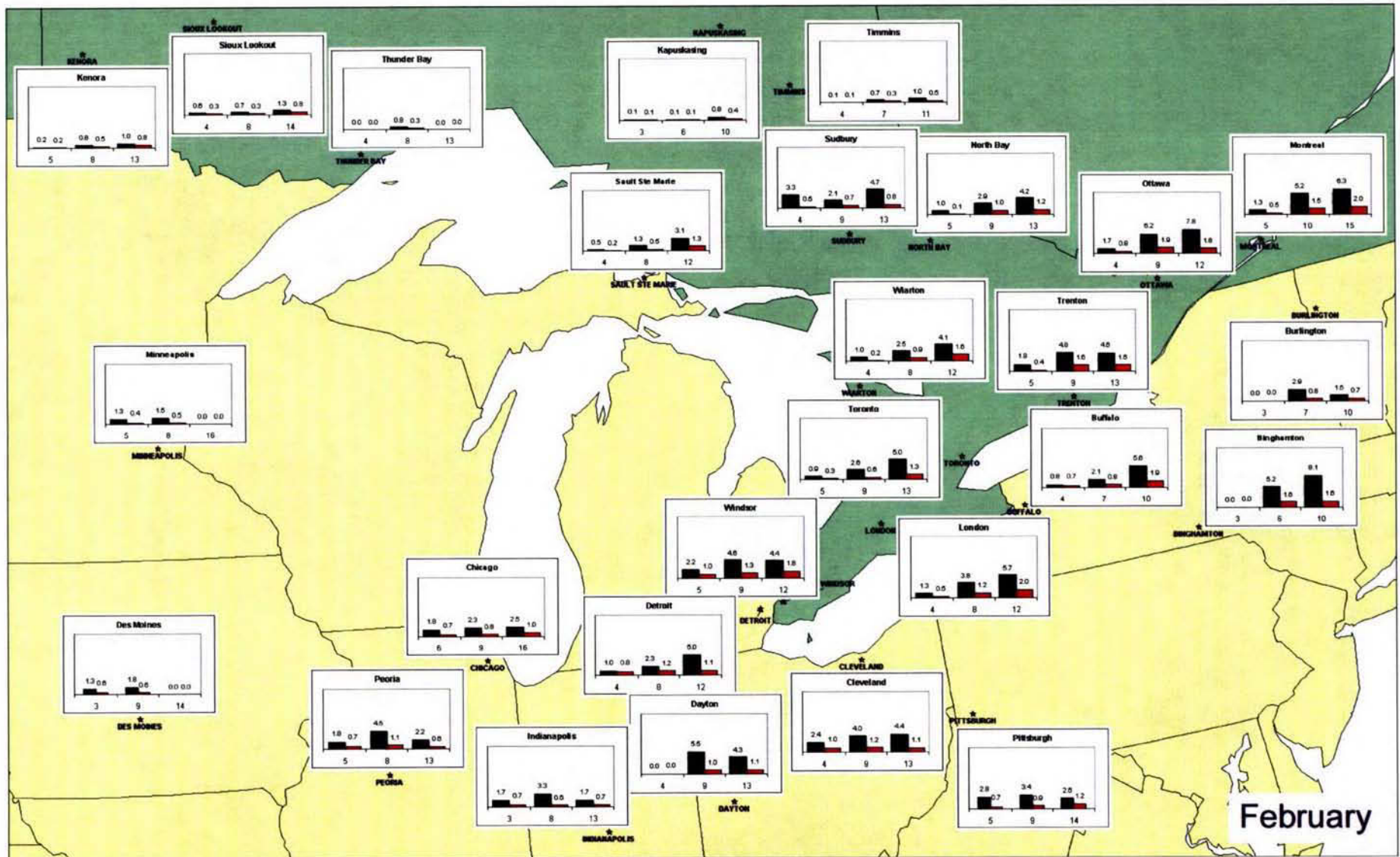


Figure 21 Monthly mean total hours (blue bar) and days (red bar) of freezing rain events within each of three groups based on 1/3 interval of the difference between the highest and lowest frequency of the freezing rain-related weather types in February. (The horizontal axis is monthly mean frequency (days) of the freezing rain-related weather types.)



8.0 Conclusions

Society's vulnerability to natural weather hazards such as ice storms is increasing (i.e. Changnon 1999, 2000). As population increases and society becomes more urbanized, both the size and number of targets impacted by storms increases. Today's society relies heavily on electronics while business operates on "just-in-time" delivery. We are thus extremely vulnerable when, for example, ice storms interrupt our supply of electricity, water supplies, and communications, as well as delay our ground and air-based transportation.

Ice Storm '98 provided us with a devastating reminder of just how vulnerable society is to severe freezing rain storms. In order to be better prepared for future severe ice storms, communities need to know the future risks from severe ice storms of magnitudes approaching those of Ice Storm '98. Better severe ice storm risk information will allow better emergency planning in regions or communities identified as more at risk from this hazard. It will also help communities to identify critical infrastructure and allow improved planning and design of this infrastructure to minimize future risks.

A variety of methodologies were used in this study to identify areas within southern and eastern Ontario that might be at risk from an increase in freezing rain, and in severe ice storms, in particular. An analysis of freezing rain hours and days of occurrence for the period 1953-2001 showed that the Ottawa Airport has an annual average of almost 37 hours of freezing rain and 10 days with some occurrence of freezing rain. These frequencies were much higher than the station averages at the remaining 13 Ontario locations, Montreal Airport, and 12 selected northern U.S. stations. In southern Ontario, London reported the highest annual average of hours (24) and days (7) with freezing rain. The lowest frequencies of freezing rain occurred over northwestern Ontario. An extreme value analysis of freezing rain return periods conducted by MacIver and Auld (2000) also identified the Dundalk Highlands area northwest of Toronto as having freezing rain risks comparable to those over the Ottawa River Valley.

It is also speculated that the Great Lakes may play a role in decreasing the frequency of freezing rain on the western and southern shores of Lake Ontario and northern shore of Lake Erie during the fall, early winter and early spring. Freezing rain storms may also decelerate as they cross the Great Lakes, which could prolong the duration of freezing rain in the central and eastern Great Lakes region.

The results of the freezing rain trend analysis would suggest that the risks of average freezing rain occurrence have remained relatively the same or have been decreasing in northwestern Ontario, southern Ontario or central Ontario during the period 1953-2001. The increasing trends in average conditions over northern Ontario, Ottawa and Montreal over the same period (sites away from the influence of the Great Lakes) are statistically non-significant and hence offer no conclusive evidence of an increased risk of freezing rain occurrence over the period. An investigation of the relationship between monthly mean temperature and freezing rain events revealed some interesting site-specific results. In particular, on average in January, the monthly total frequency of freezing rain events at

Ottawa, Montreal, Sudbury and North Bay increases from the lowest to highest temperature quintiles. Each of these sites is not directly influenced by flows and temperature inputs from the Great Lakes and has a high seasonal frequency of occurrence of freezing rain relative to the remaining study locations.

Communication towers are normally the last structures to fail in an ice storm. The CRREL icing-related communications tower collapse database helped in identifying severe ice storms that have occurred in Canada since 1958 and in the U.S. since 1929. A total of 251 collapses have occurred in Canada since 1958. In Ontario, only one communication tower collapse has been recorded over this period and this occurred during Ice Storm '98. The linkage between the most severe ice storms and the collapse of communication towers underscores the importance of maintaining high ice loading and wind design criteria for these towers.

An assessment of daily climatological data, hourly weather sequences and historical proxy data identified 25 ice storms (including Ice Storm '98) that have occurred in southern and eastern Ontario since the mid-1800s. The January 1998 Ice Storm was identified as the storm of greatest duration, areal extent, ice accumulation and impacts recorded for Ontario since at least the late 1800s. Five communication towers collapsed in Canada with this storm (13 tower failures were reported in the northeastern U.S.). Notwithstanding the occurrence of the 1998 event, major ice storms have occurred less frequently in Ontario in the past few decades than during the previous hundred years. Although the amount of freezing precipitation that may fall at any one time may have changed very little, the number of such incidents has certainly declined. It is not possible to say whether or not this tendency will continue.

During the period 1909–2002, 22 major ice storms were identified for the northern U.S. states bordering southern and eastern Ontario. Icing-related communication tower collapses occurred during several of these storms. Eight of these storms were also identified as having produced 20 mm or more of freezing rain in southern and/or eastern Ontario.

The storm track analysis for the significant Ontario and northern U.S. ice storms during the period from 1948–2002 identified at least three features common to these storms:

- 1) a warm, moist mid-upper level flow originating in the Gulf of Mexico, and in some cases, an additional moisture source from the Atlantic Ocean;
- 2) presence of a cold Arctic high pressure area to the north of these storms, generally centered over Quebec;
- 3) slow-moving storm systems.

A meteorological assessment of the synoptic and weather situations accompanying the selected ice storms determined that the ice storms that impacted on the northern U.S. had similar points of origin and followed similar tracks to other storms that impacted heavily on southern and eastern Ontario. However, it appears that in most cases, the northern

¹ Excluding the 1970 Essex, Ontario collapse which may have occurred on another date.

U.S. storm centres were located approximately 100–200 km further south at the time of freezing rain occurrence. This observation would lead one to speculate that if storm tracks were to shift north under climate change, the frequency of ice storms could possibly increase in southern and eastern Ontario in a future climate. However, climate change science cannot yet predict how storm tracks will change in a warming climate or if such changes could potentially lead to regional increases or decreases in ice storms.

A statistical map typing approach was also used to identify the weather patterns associated with freezing rain events in south-central Canada and in the northern U.S., with particular emphasis on the longer duration (i.e. ≥ 6 hour duration during a day). The weather typing methodology identified four to six synoptic types from a total of 18 major winter synoptic types as the primary freezing rain categories for the study area. However, no significant trends in the frequency of freezing rain related weather types were found at the 14 Ontario stations and Montreal location. The results of an additional analysis showed that, in general, the monthly total frequency of freezing rain dramatically increases from the lowest to highest frequencies of the weather types. An extension of the map typing approach to GCM output could provide a means of investigating whether the frequency of freezing rain related weather types, and possibly freezing rain occurrence, is projected by climate models to increase in the climate of the 21st century.

The subjective and statistical approaches to investigating ice storm risks in southern and eastern Ontario have produced information which should prove useful for municipalities and for Ontario Provincial Bill 148 that amends the provincial Emergency Preparedness Act. Bill 148 emphasizes the role of disaster prevention or adaptation, as well as traditional emergency preparedness. It requires that each municipality and ministry in Ontario undertake a risk assessment and critical infrastructure identification process and develop plans to prevent disasters and to better prepare for emergencies. As part of this risk assessment, municipalities need to identify their vulnerability to a variety of natural hazards including Ice Storms. The province has given municipalities until 2006 to develop disaster mitigation plans. Meanwhile, municipalities have only been given one year, 2003–2004, to identify the natural hazards which may pose a risk locally. Detailed and accurate high impact weather and climatological information will be required to meet needs at the community scale.

Future research to build on the results of this study could include work in the following areas:

- Extension of freezing rain and ice storm research to other Canadian regions, including Quebec and Atlantic Canada, through collaboration with other Environment Canada meteorological centres outside of Ontario;
- Collaborative research with U.S. scientists on U.S. average freezing rain and ice storm climatology;
- Resolving U.S. data concerns and extending U.S. data period of record prior to 1973;
- Resolving differences and patterns between average freezing rain climatology and severe ice storm climatology;

- Additional investigation into Canadian communication tower collapses, involving collaboration with CRREL.

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- The Montreal Gazette

Online versions of:

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- National Weather Service Forecast Office: Northern Indiana
<http://www.crh.noaa.gov/iwx/climate/cli/wxhisttdy/Feb9.shtml>
- <http://www.leaderherald.com/millennium/19001909/stroll.html>

2. 1953 U.S. ice storm:

- <http://www.erh.noaa.gov/er/bgm/news/jan02.txt>

3. 1964 U.S. ice storm
 - National Weather Service Forecast Office: Albany, New York. Miscellaneous – Past storms <http://www.erh.noaa.gov/er/aly/Past/WINTER.htm>

4. 1978 U.S. ice storm
 - National Weather Service Forecast Office: Central Illinois <http://www.crh.noaa.gov/ilx/trivia/martriv.htm>

5. U.S. ice storm
 - National Weather Service Forecast Office: Buffalo, New York
<http://www.erh.noaa.gov/buf/winter-pns5.htm>
<http://www.erh.noaa.gov/er/buf/rocice.htm>
<http://www.geocities.com/jfm292/IceStorm/ice1.htm>

6. 2002 U.S. ice storm
 - <http://www.noanews.noaa.gov/stories/s857.htm>

