The Mesoscale Structure of the 1998 Ice Storm and Probability of Occurrence of Similar Ice Storms

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***Abstract*—The January 1998 Ice Storm over southern Québec and surrounding regions was one of the most devastating winter events in Canadian history. Data from the McGill radar (as well as surface information) was used to illustrate the complex precipitation and kinematic fields of the storm. Precipitation bands were normally present; they were sometimes associated with strong low level jets and produced all types and combinations of surface precipitation (freezing rain, ice pellets and/or snow); and they were often aligned with the surrounding topography. Lightning data from the Canadian Lightning Detection Network showed that both positive and negative strikes occurred and that the polarity was somewhat linked to the type of surface precipitation. Based on a statistical climatology from 50 years of hourly observations, the likelihood of such a severe winter event is simulated and a severe ice storm is expected approximately once every 100 years.**

I. INTRODUCTION

Winter storms commonly occur over Canada and the United States. Such storms bring precipitation in the form of snow, rain, freezing rain and ice pellets and they often cause major problems for society. There continues to be a substantial amount of research conducted on these storms but it is far less than the reseach focused on severe summer weather. There is a growing recognition that winter storm issues need to be studied in more detail [1]. For example, the United States is in the process of developing a winter storm research program [2]. This program has identified some of the key American priorities spanning scales from the storms' large scale environment to their small scale internal structure and precipitation. In Canada, there is an awareness of the impact of winter storms and the types of storms that occur [3] but there is not yet an organized program to examine these.

The importance of winter storms was certainly clear in the wake of the January 1998 Ice Storm that caused huge problems to Eastern Canada and the Northeastern United States. It brought particular hardship to the Québec City – Montréal – Ottawa area. The Ice Storm seriously affected the electricity supply to 3.5 million people, shut down transportation, restricted emergency services and damaged personal property. There were an estimated 28 deaths in Canada and 19 in the United States [4] and $4 billion of damage caused by the Ice Storm in Canada and the United States [5] with $1 billion of damage in New York and Maine [6]. For a more detailed description of the amount of damage caused by the Ice Storm in Canada and the Northeastern United States, please refer to [1] and [6] - [8]. A map of the Québec City – Montréal – Ottawa region can be seen in **Fig. 1**.

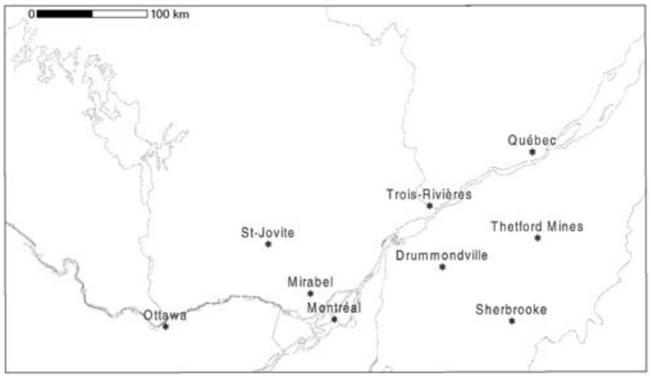

Fig. 1. Map of the Québec City – Montréal – Ottawa area.

Even though there have been many ice storms during the 20th century, none have caused the amount of damage inflicted by the 1998 event. It has been estimated that there have been 25 significant freezing rain events over Southern and Eastern Ontario since the 1880's and 22 in the Northern U.S. states bordering Southern and Eastern Ontario during the period 1909 – 2002 [4]. There is no one factor that determines the severity of an ice storm. Reference [9] noted that a December 1942 ice storm had a greater ice accumulation than an event in February 1961 but the later event was more severe due to the presence of high winds. As well, the determination of classifying severity can at times be subjective but it can be appreciated that major ice storms are a relatively common event occurring approximately every 5 years. In this context, it can therefore be easily seen how severe the 1998 Ice Storm was since freezing precipitation is so common in Eastern Canada and the Northeastern United States.

Despite the devastation of the Ice Storm, little research has been conducted on it. The few papers that have been published have focused on the planetary and synoptic scales with some discussion of topographic effects [7], [8] and climatology of ice storms including the 1998 event have been prepared [1]. None of these articles focused on the smaller scale features of the storm.

Given the importance of the Ice Storm and the lack of research on its smaller scale features, the main objective of this study is to document and better understand its internal structure, in particular the organization of its precipitation and associated thermodynamic and kinematic fields although considerable attention is also paid to its lightning generation. A secondary objective is to examine the probability of occurrence of such an event.

II. DESCRIPTION OF DATA SETS

There were a variety of data sets available for this study. The primary data set was 1 km x 1 km radar data from the McGill (Sainte-Anne-de-Bellevue) radar. This is an S-band radar and is the main radar system at the J.S. Marshall Radar Observatory. The radar was upgraded to make Doppler measurements in 1992 and dual-polarization measurements in 1999 (after the 1998 Ice Storm). With a 700 kW Klystron transmitter and a 9 m dish, the S-band radar is the largest weather radar in Canada. For more information on the McGill radar see [10].

Operational measurements were utilized in this study. Hourly surface weather observations were obtained for many operational sites but the primary sites used were Dorval International Airport in Montréal (now Pierre – Elliot Trudeau International Airport), Mirabel International Airport just outside Montréal, Jean Lesage International Airport in Québec City and MacDonald – Cartier International Airport in Ottawa. These sites were chosen as they were all major airports at the time and therefore had manual observers.

Lastly, lightning strikes collected from the Canadian Lightning Detection Network (CLDN). The CLDN is fully integrated with the United States National Lightning Detection Network [11] and CLDN has provided continuous lightning, over most of Canada and offshore to about 300 km.

Collectively, these large and diverse data sets allowed us to compile a detailed depiction of the 1998 Ice Storm.

III. LARGE SCALE AND MESOSCALE FEATURES OF THE 1998 ICE STORM

The 1998 Ice Storm struck the Québec City – Montréal – Ottawa region late in the evening on the 4th of January 1998 and continued until early on the 10th of January (local time). A series of low pressure systems had developed in the Southern United States and warm, moist air within these systems was advected from the Gulf of Mexico into Southern Ontario and Québec. A large, stationary Arctic high pressure system was centered over central Québec and persisted from the 5th of January to the 9th of January. This caused cold air to flow into the St. Lawrence and Ottawa River valley regions which the warm advected air could not dislodge.

This situation resulted in the precipitation mainly falling as freezing rain or ice pellets although rain and snow also occurred (distribution maps of the various forms of precipitation can be found in [12]). Some areas, especially those south of Montréal and along the south side of the St. Lawrence River, experienced in excess of 100 mm of freezing precipitation during the event and other areas experienced significant accumulations of ice pellets and snow (mainly the Québec City region).

Hourly observations illustrated a number of critical features. First, the precipitation did not occur continuously at any location over the duration of the event. The longest continuous occurrence of precipitation was in Montréal at 60 hours and Québec City experienced the longest duration of any single precipitation type: 40 hours of snow. Second, most of the precipitation fell as combinations rather than as a single type. Overall, mixed precipitation was observed 15% of the time for all stations, with Montréal being the site with the highest fraction of combinations (25%). Third, freezing rain and ice pellets was the most common combination. This combination was most common at Montréal (83% of the combinations), whereas snow and ice pellets together was most common at Québec City (88% of the combinations). Fourth, the transitions between types sometimes followed patterns similar to that predicted for a warm frontal passage with a 5-step process [13]. Such a pattern occurred at Montréal but not at Québec City. In fact, this pattern occurred twice at Mirabel and Ottawa. This implies there was a considerable systematic evolution of the melting layer at Mirabel, Montréal and Ottawa. Based on the work in [13], the observations at Québec City, mainly snow or snow and ice pellets, imply that the above melting layer did not substantially warm and when snow pellets and ice pellets occurred, there was a very tight relationship between the height and temperature of the melting layer. Finally, the time of occurrence of patterns of the different precipitation types was often similar between some sites but not between others.

For many areas, there was never a simple transition between rain and snow. At many sites, the first precipitation to occur was snow, followed by freezing drizzle and then ice pellets and freezing drizzle. There was no significant period and therefore quantity of rain. This also occurred at all the other hourly observation sites in the local area with the exception of Sherbrooke, which experienced significant amounts of rain. These observations indicate that when the precipitation structures passed through the Sherbrooke area, a warm layer of air was able to reach the ground or be sufficiently close to the ground that the precipitation fell as rain. It should be noted that when it rained in Sherbrooke, there was precipitation at the other sites from the same structure but the precipitation was in a different phase. Therefore, it can be seen that some areas preferentially had different forms of precipitation (Québec City for snow, Sherbrooke for rain) from the same precipitation structure, not from different precipitating structures.

IV. MESOSCALE FEATURES OF THE 1998 ICE STORM

Many precipitation bands and single cell structures evolved or passed through the range of the McGill radar. To examine the structures of the 1998 Ice Storm, the radar images from the entire event were examined and many high reflectivity mesoscale features were identified. Some were bands that were orientated relative to a frontal system that was passing, others formed relative to the topography, and others still had no discernible organized form.

From an analysis of radar images, four major mesoscale features were identified. These four features coincided with the start of the various forms of precipitation and also with perturbations in temperature and pressure at observation sites. It is therefore possible to associate these four peaks with the passing of frontal systems. The precipitation structures associated with these peaks also had the greatest areal coverage in the range of the McGill radar.

These peaks illustrated a number of features in terms of a relation to surface precipitation over the region. The following points were found:

- some structures produced different forms of precipitation simultaneously at different observation sites;
- several structures produced similar trends in the forms of precipitation; and
- different forms of precipitation were possible from the same region of a structure.

It was also found from hourly observations that within three of the four precipitating structures, solid forms of precipitation preferentially fell at Mirabel as opposed to Montréal. Therefore, it was possible to conclude that the local topography had an effect on the precipitation structures and, in turn, on the forms of precipitation.

V. LIGHTNING STRIKES DURING THE 1998 ICE STORM

During the 1998 Ice Storm, on the 9th of January, there were approximately 900 Cloud to Ground (CG) lightning strikes from 0958 UTC to 2245 UTC between the latitudes of 42 and 47 degrees and longitudes of 72 and 77 degrees, 30 seconds. The majority of these lightning strikes were negative but the overall average percentage of positive strikes was 21.8%. The average positive CG strike peak current at 39.34 kA was almost 5kA more than the average negative CG strike peak current at -34.50 kA) and in general the average positive CG strike peak current exceeded the negative CG strike peak current on an hourly basis. These results plus the timing of the lightning (the 9th of January, i.e. late into the Ice Storm), are similar to values or situations seen in the literature.

The clear majority of the positive and negative CG lightning strikes occurring in the range of the McGill radar were in the Appalachian Ranges to the south and east of Montréal. Clear "streaks" of negative strikes were observed and from radar images, these "streaks" originated from isolated cells. One such cell produced 15 negative strikes between 2005 and 2040 UTC and a further 16 negative strikes between 2055 to 2120 UTC. There were no positive strikes from this cell before or after these times in the range of the McGill Radar. A widespread cloud produced five positive and five negative strikes between 2015 and 2100 UTC. Prior to 2015 UTC, there had not been a strike since 1940 UTC. There were no lightning strikes from this section of cloud after 2100 UTC in the range of the McGill radar. The average positive strike from the mixed strike cloud was 50.0kA and the average negative strike from the mixed strike cloud was -60.7kA, which is larger than the positive average mainly due to a single -210.1kA strike.

Vertical cross sections were taken of the cloud which produced solely negative strikes and the cloud which produced mixed strikes. These cross sections show the height of the mixed strike cell is much lower compared to the negative cell, reaching up to only 5 km compared to the solely negative strike cell which reached up to 9 km. From a sounding taken at Ottawa close to the time that the mixed lightning strike occurred, it is possible to imply that there was a definite melting and refreezing layer to the mixed strike cloud. Therefore, the low cell height of the mixed strike cloud would also suggest that the average size of the lightning strike would be comparatively small, if charge transfer was based predominantly on collisions. However, this was not the case.

The mixed strike cloud passed over Montréal and the negative strike cloud passed over Burlington, Vermont. Surface observations were obtained and rain was recorded during the passing of the negative strike cloud and freezing rain during the passing of the mixed strike cloud. The topography would have affected near-surface temperatures at these two locations; these temperature variations in turn may have influenced the polarity of the lightning.

Therefore, it is possible that the melting and refreezing of the precipitation had an effect on both the size and polarity of the lightning strikes. Similar results were found in the literature [14], [15]. Reference [16] did note that the existence of a wind shear does facilitate the production of positive lightning strikes and based on soundings and an analysis of the Doppler radar scans from the McGill radar, there was both a large wind shear on the 9th of January during the 1998 Ice Storm and also a large number of positive lightning strikes.

VI. LIKELIHOOD OF OCCURRENCE BASED ON HOURLY OBSERVATIONS

During the 1998 Ice Storm, all forms of winter precipitation fell. However, there were varying amounts of the different types of precipitation recorded at the major cities in the affected region. Montréal and Ottawa experienced roughly equal durations of freezing rain and ice pellets but little snow whereas Québec City experienced mainly snow with sporadic ice pellets. It is clear the warm inversion layer did not reach as far as Québec City, or, if it did, the warm layer had cooled to below freezing levels. This is likely due to the region's valley system with large mountains (over 1000 m in height). When a warm layer did reach as far as Québec City, the cold air in the valley completely refroze the liquid precipitation.

Four quantities were calculated for Montréal based on over 50 years of hourly observations at Dorval International Airport. These four quantities were:

- number of days in a winter season (defined to be October 1st to April 30th) that an hourly observation of freezing rain occurred;
- number of hours in a winter season that an hourly observation of freezing rain occurred;
- average length of continuous hourly freezing rain; and
- average number of hours in a day when there was at least one hourly observation of freezing rain.

While it is clear the Ice Storm was a devastating event, based on the total number of days that experienced freezing rain and the average length of continuous freezing rain based on the hourly observations, it is not clear that the Ice Storm was unique. In both of these quantities, there were variations over time but nothing stood out.

However, it is clear from the total number of hours observed in a winter season and the average number of hours observed in a day, when freezing rain occurred, that the Ice Storm stands out. Based on historical data for Montréal, the average number of hours of freezing rain in a winter season was 27.2 h and the average number of hours in a day that experienced freezing rain was 3.4 h. The Ice Storm winter season experienced 74 h of freezing rain and the average number of freezing rain hours observed was 8.2 h. Therefore, the Ice Storm was devastating not just because of the high number of total hours of freezing rain but also the high number of hours of freezing hours in a day, compared to the last 50 years.

The definition of a severe icing event must therefore contain two features. It must produce many hours of freezing precipitation in a day and it must do so over a prolonged period, which leads to a seasonality signature. It has been noted in [5] that the intensity of freezing rain events tends to be light so it is usually the duration that defines the severity of an event. This fits with the definition outlined above.

Because there are over 50 years of hourly observations, a set of indices can be developed to produce probabilities of occurrence for the next hour's observation based on the current hour's observation. These probabilities lend themselves to the Markov Chain simulation technique. In a Markov chain simulation an initial state is established, a set of random numbers is generated, and, from the initial state and the indices, the next hour's observation. Furthermore, it is possible to estimate the probabilities on a monthly basis. More information on Markov chain simulations can be found in [17]-[19].

Two hundred years of winter seasons were simulated for Montreal and for simplicity only based on precipitation observations, not on any other quantities (i.e. wind speed, temperature, etc.). Based on the definition of a severe freezing rain event, initial results from the simulation would predict at least two severe events would have occurred over this period. The total number of hours of freezing rain observed in the two severe event seasons was 54 and 48 hours and the average number of hours of freezing rain in a day was 6.0 and 6.3 h respectively.

Based on historical hourly observations, it can therefore be assumed that a severe ice storm event of a similar scale to that of the 1998 Ice Storm is possible in the Montréal area in the next century. While simulations of this type have been conducted before for other forms of precipitation [17]-[19], it is not known to the authors if a similar type of simulation has been conducted specifically for the Ice Storm.

VII. CONCLUDING REMARKS

A study has been carried out of the structure of the 1998 Ice Storm that devastated parts of Eastern Canada and the North-Eastern United States. The focus was on the Montréal area which experienced some of the greatest impacts and for which a number of datasets were available, including hourly observations, lightning strike data and reflectivity and Doppler data.

From the observations and their interpretation, a number of conclusions were made:

- Mesoscale precipitation features occurred throughout the storm over the Montréal region.
- Mesoscale features were linked with the different forms of winter precipitation.
- Mesoscale features were linked with transitions between different forms or combinations of precipitation.
- Lightning was pronounced during the later period of the storm.
- Processes associated with the melting layer may have had an effect on the charge transfer between hydrometeors and therefore the polarity of lightning strikes.

It is also apparent that the surrounding topography had a large effect on the storm. Bands of precipitation, polarity of lightning strikes and the types of precipitation that fell at the various cities all were affected by topography.

A Markov Chain analysis was performed using the long-term hourly precipitation observations. Initial results suggest that a severe freezing rain event is possible in the next century.

In summary, a catastrophic event occurred in January 1998 in which freezing rain and associated forms of winter precipitation crippled the infrastructure of a region. This study has examined the internal structure of this storm.

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