On the Dependence of Winter Precipitation Types on Temperature, Precipitation Rate, and Associated Features

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(Manuscript received 10 June 2009, in final form 31 December 2009)

ABSTRACT

The phase of precipitation formed within the atmosphere is highly dependent on the vertical temperature profile through which it falls. In particular, several precipitation types can form in an environment with a melting layer aloft and a refreezing layer below. These precipitation types include freezing rain, ice pellets, wet snow, and slush. To examine the formation of such precipitation, a bulk microphysics scheme was used to compare the characteristics of the hydrometeors produced by the model and observed by a research aircraft flight during the 1998 ice storm near Montreal, Canada. The model reproduced several of the observed key precipitation characteristics. Sensitivity tests on the precipitation types formed during the ice storm were also performed. These tests utilized temperature profiles produced by the North American Regional Reanalysis. The results show that small variations (±0.5°C) in the temperature profiles as well as in the precipitation rate can have major impacts on the types of precipitation formed at the surface. These results impose strong requirements on the accuracy needed by prediction models.

1. Introduction

Precipitation produced within winter storms can be in the form of snow (s), ice pellets (ip), and freezing rain (zr) as well as particles composed of both liquid and ice such as wet snow (ws). This precipitation can lead to hazardous surface conditions. For instance, precipitation consisting of liquid water falling through subfreezing temperatures can lead to icing on structures possibly with severe consequences. The 1998 ice storm in Montreal, Canada, is one such example and was one of the most catastrophic weather events in Canadian history (Henson et al. 2007).

The various types of winter precipitation are commonly observed along a warm front where a temperature inversion is often formed. They are summarized in Table 1. This environment consists of a melting layer aloft (T > 0°C) and a refreezing layer (T < 0°C) below. When snow falls through the melting layer, it begins to melt and eventually reaches the lower refreezing layer as either wet snow, slush (sl), or rain (r). Slush refers to snow that has almost completely melted and has collapsed down to a smaller size but still contains some ice (Thériault et al. 2006). In contrast, wet snow has melted somewhat but has not collapsed. The precise type of precipitation reaching the bottom of the melting layer (defined here as the critical level) has a major impact on the type of precipitation formed within the refreezing layer. For instance, if slush reaches the critical level it will refreeze partially into a particle composed of an ice shell and liquid core, also called a liquid core pellet (lcp; Thériault and Stewart 2010), and depending on the temperature profile, it may refreeze completely into ice pellets before reaching the surface.

Interactions among particle types can also affect the precipitation types occurring at the surface. For instance, the collection of ice crystals (i) by a supercooled drop at subfreezing temperatures will initiate the freezing of the drop, and act to form an ice pellet as suggested by Hogan (1985).

Despite the increasing understanding of winter precipitation, accurate prediction is still difficult. This difficulty

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DOI: 10.1175/2010JAMC2321.1

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arises, in part, because of the strong dependence on environmental conditions: temperature, moisture, and vertical and horizontal motion, as well as cloud condensation and ice nuclei distribution. Statistical techniques have been developed to predict various types of winter precipitation (e.g., Derouin 1973; Cantin and Bachand 1993; Bourgouin 2000). However, these methods omit important factors such as particle size distribution and background wind fields. They also do not allow for mixed phase precipitation alone or in combination with other types. In contrast, a mixture of precipitation types is often reported. For example, it is very common to observe a mixture of ice pellets and freezing rain. Sometimes these precipitation types are observed with ice crystals (Crawford and Stewart 1995).

Given the importance of determining the precise type of precipitation formed within the atmosphere and reaching the surface during winter storms, the goal of this paper is to study the formation of precipitation types within various temperature profiles and assess their sensitivity to changes in these profiles and the precipitation rate.

To accomplish this, a bulk microphysics scheme developed to study winter precipitation (Thériault and Stewart 2010) coupled with a one-dimensional kinematic cloud model will be utilized. This scheme includes partial melting of snowflakes and the refreezing of mixed phase particles. The precipitation type characteristics will be studied using in-flight measurements during the 1998 ice storm (Cober et al. 2001). Furthermore, the scheme will be used as a tool to investigate the sensitivity of the precipitation types to the temperature profile and the precipitation rate during this event.

Note that the goal of this study is not to simulate the storm’s features but to study the microphysical details of the formation of winter precipitation types, including their sensitivity to the temperature and other fields.

This paper is organized as follows: section 2 describes the experimental design. An investigation of the characteristics of the precipitation types formed during the 1998 ice storm over Mirabel, an airport north of Montreal, is carried out and compared with in-flight measurements in section 3. Section 4 discusses the results of the sensitivity experiments of precipitation types to the temperature profile and precipitation rate. Concluding remarks are presented in section 5.

2. Experimental design

The various precipitation types formed within winter storms are studied using a bulk microphysics scheme (Thériault and Stewart 2010). Many precipitation categories have been added to the parameterizations used by Milbrandt and Yau (2005b). The bulk microphysics scheme includes five ice hydrometeor categories—ice crystals, snow, refrozen wet snow (rws), and two ice pellet categories (ipA and ipB); two liquid hydrometeor categories—rain and cloud droplets (c); and one semimelted category—slush. In addition, the scheme description also includes more precipitation categories that change depending on whether the temperature is above or below 0°C. For instance, supercooled rain (sr) and liquid core pellets are, respectively, rain and slush at temperatures below 0°C and wet snow is snow when the wet-bulb temperature is above 0°C. Freezing rain will be used to

<table>
<thead>
<tr>
<th>Hydrometeor</th>
<th>Symbol</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain</td>
<td>r</td>
<td>Precipitation in the form of liquid water drops that have diameters &gt;0.5 mm, or, if widely scattered, the drops may be smaller</td>
</tr>
<tr>
<td>Freezing rain</td>
<td>zr</td>
<td>Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground and on exposed objects</td>
</tr>
<tr>
<td>Supercooled rain</td>
<td>sr</td>
<td>Liquid precipitation at temperatures below freezing</td>
</tr>
<tr>
<td>Snow</td>
<td>s</td>
<td>Precipitation composed of white or translucent ice crystals, chiefly in complex branch hexagonal form and often agglomerated into snowflakes</td>
</tr>
<tr>
<td>Ice pellets</td>
<td>ipA and ipB</td>
<td>A type of precipitation consisting of transparent or translucent pellets of ice, ≤5 mm in diameter</td>
</tr>
<tr>
<td>Wet snow</td>
<td>ws</td>
<td>Snow that contains a great deal of liquid water</td>
</tr>
<tr>
<td>Refrozen wet snow</td>
<td>rws</td>
<td>Refrozen wet snowflake</td>
</tr>
<tr>
<td>Slush</td>
<td>sl</td>
<td>Precipitation composed of a mixture of liquid and ice in which the original snowflake’s shape is not discernable</td>
</tr>
<tr>
<td>Ice crystals</td>
<td>i</td>
<td>Pristine ice crystals</td>
</tr>
<tr>
<td>Cloud droplets</td>
<td>c</td>
<td>Small nonsedimenting water droplets</td>
</tr>
<tr>
<td>Liquid core pellets</td>
<td>lcp</td>
<td>Liquid core pellets: partially refrozen drop with an ice shell and liquid water within it</td>
</tr>
</tbody>
</table>

Note that the goal of this study is not to simulate the storm’s features but to study the microphysical details of the formation of winter precipitation types, including their sensitivity to the temperature and other fields.

This paper is organized as follows: section 2 describes the experimental design. An investigation of the characteristics of the precipitation types formed during the 1998 ice storm over Mirabel, an airport north of Montreal, is carried out and compared with in-flight measurements in section 3. Section 4 discusses the results of the sensitivity experiments of precipitation types to the temperature profile and precipitation rate. Concluding remarks are presented in section 5.
refer to supercooled rain reaching the surface at sub-freezing temperatures.

The evolution of the precipitation categories falling through a melting layer and a lower refreezing layer is summarized in Fig. 1. When snow reaches the melting layer it is called wet snow even if it is the same prognostic variable. It is assumed that the smallest snowflakes melt completely before the largest ones. Based on that assumption, wet snow melts partially into slush and slush melts completely into rain when falling through the melting layer.

The type of precipitation reaching the surface largely depends on the liquid fraction of the melting precipitation at the critical height (Fig. 1). For instance, if wet snow reaches the critical height, it will begin to refreeze into refrozen wet snow. On the other hand, if slush reaches the critical height, it is transformed into liquid core pellets. Depending on the temperature and depth of the refreezing layer, the liquid core pellets will refreeze partially or completely into ice pellets (ipA) before reaching the surface.

Finally, when falling in the refreezing layer, rain becomes supercooled rain. If ice crystals are locally produced in the refreezing layer, they may interact with supercooled rain to form ice pellets (called ipB). The difference between the two categories of ice pellets is their formation mechanism. One is formed by refreezing semi-melted particles (ipA) and the other one is formed by contact between supercooled rain and pristine ice crystals or ice nucleation (ipB).

The microphysics scheme is coupled to a one-dimensional kinematic cloud model that has been described in Thériault and Stewart (2007). It has also been used in Milbrandt and Yau (2005a) and Thériault et al. (2006). The model is initialized with vertical profiles of temperature ($T$) and dewpoint temperature ($T_d$). There are 151 vertical levels evenly spaced (with respect to height) over an air column 3.5 km deep, and hydrostatic balance is assumed.

3. Winter precipitation-type characteristics

Precipitation characteristics and their formation mechanisms are investigated and compared with in-flight data collected during the 1998 ice storm. Many flights were made during this storm (Cober et al. 2001). However, only one was made through a melting and a refreezing layer within 25 km of Mirabel Airport where surface observations are available (www.climate.weatheroffice.ec.gc.ca).

a. In-flight data and method

Data from flight 008 of the third Canadian Freezing Drizzle Experiment (CFDE III) are used for this study (Cober et al. 2001). A mixture of ice pellets and freezing
rain was observed at Mirabel during the flight (Henson et al. 2007). The aircraft used was the National Research Council Convair 580 (Cober et al. 1995; Isaac et al. 2001) and the data collected include liquid water measurements, aerosol, precipitation, and cloud droplet spectra as well as the rate of icing.

Images of the particles were obtained with three different probes. These probes are the 2D-C, 2D-P, and 2D-G, each measuring different ranges of particle sizes. Figure 2 shows an example of the images obtained with the 2D-C probe (Cober et al. 2001) at four different levels. The width of each strip is 0.8 mm.

The particles are classified by their shape as being either circular (CI) or irregular (IR). In general, the circular particles are assumed to be liquid drops or ice pellets, and the irregular particles to be ice crystals or snow. The four strips of particle images shown in Fig. 2 were obtained at four different times during the flight corresponding to various heights of interest. For example, Fig. 2a shows particles present above the melting layer and they are mainly irregular particles (ice crystals and snowflakes), whereas Fig. 2c shows particles at the critical level and they are mainly spherical. Based on such images, the concentration of particles is computed at each level. The computation considers all the particles entirely recorded and those extrapolated from partial recordings.

The model is initialized using the observed temperature profile (Fig. 3). The atmosphere is saturated with respect to water; therefore, the dewpoint temperature is the same as the temperature. The melting layer is approximately 1.6 km deep and has a maximum temperature of 3.4°C. The refreezing layer has a minimum temperature of −7°C, a surface temperature of −5°C, and a depth of 1.6 km. The observed size distribution intercept \( N_0 = 3 \times 10^6 \) m\(^{-3}\) and the mass mixing ratio of precipitation \( Q = 1.7 \times 10^{-4} \frac{\text{kg}_{\text{snow}} \text{kg}_{\text{air}}^{-1}}{\text{kg}_{\text{air}}} \) measured above the melting layer were used to initialize the model. It is assumed that snow continuously falls from above the melting layer (3.5 km).

In the following section, the mass content, size distribution, and total number concentration of the precipitation produced by the model are compared with observations. Also, an investigation of the microphysical processes associated with the precipitation types formed is carried out.

### b. Precipitation types simulated

The results of the model can be seen in Fig. 4. Figure 4a shows the mass content profiles of the precipitation types formed falling through the observed temperature profile. When snow reaches temperatures \( >0^\circ \text{C} \), it melts into slush and potentially interacts with raindrops. Because
of the very warm and deep melting layer, all the slush and wet snow completely melt within 800 m of the top of the melting layer. Thus, only liquid precipitation reaches the refreezing layer, resulting in no ice pellets being produced by the refreezing of semimelted particles within the refreezing layer.

At 500 m above the ground (Fig. 4a), the temperature is favorable for the formation of ice crystals formed by deposition nucleation. Since the atmosphere is saturated with respect to water, it is supersaturated with respect to ice. Hence, at temperatures $<-5^\circ C$, the environmental conditions are favorable for the formation of ice crystals by deposition nucleation (Milbrandt and Yau 2005b). Those ice crystals interact with the supercooled drops to form ice pellets (ipB). The mass content of ice pellets (ipB) is then enhanced by colliding with supercooled rain before reaching the surface. A mixture of freezing rain, small ice pellets, and a trace of ice crystals reaches the surface. This corresponds to the many precipitation types recorded simultaneously at Mirabel (Henson et al. 2007).

Figure 4b shows the number concentration fraction of irregular and circular particles observed during the flight and produced by the model. It is assumed that the irregular particles produced by the model are snow, wet snow, and slush. The other precipitation categories have a spherical shape. The particles are mainly irregular in shape above the melting layer. The amount of irregular particles decreases when particles fall into the melting layer and the fraction increases again 500 m above the surface. The model results are comparable with observations with respect to the shape, however, not in the quantity of particles. For example, the number of irregular particles is predicted by the model to be mainly zero within the melting layer whereas a small fraction of particles was considered to be irregular from the observations.

FIG. 3. The vertical temperature profile associated with flight 008 during the 1998 ice storm on 8 Jan 1998. The time period is 2020:00–2046:30 UTC.

FIG. 4. (a) The mass content profiles of rain (r), supercooled rain (sr), ice crystals (i**), snow (s*), wet snow (ws*), slush (sl), and ice pellets (ipB*) formed within the temperature profile shown in Fig. 3. The precipitation types marked with * are scaled by a factor of 0.1 and with ** by a factor of 100. (b) The number fraction of CI and IR particles measured by the instruments during the flight (dashed lines) and produced by the model (solid lines). Subscript $m$ is for the model results and subscript $o$ for the observations. The gray shading indicates vertical levels where $T > 0^\circ C$. 

![Graph of temperature profile](image-url)
The melting layer is too deep and warm to allow particles to survive without melting completely.

The model results may also be compared with the particle images shown in Fig. 2. Above the melting layer, at 3.3 km, snow is mainly produced by the model and it agrees with the irregular particles shown in Fig. 4b. Just below the top of the melting layer (3.0 km), a mixture of wet snow, rain, and slush is produced by the model, and a mixture of both circular and irregular particles is observed. At the critical height (1.6 km)—the bottom of the melting layer—mainly circular particles are observed and this is comparable with the model results in Fig. 4a.

Finally, at 0.3 km above the surface, a mixture of both irregular and circular particles is evident in the image. The observed irregular particles could be the pristine ice crystals produced locally by deposition nucleation. Also, the circular particles could be supercooled drops or ice pellets produced by the collision of supercooled drops and ice crystals. The model results produced a mixture of ice crystals, supercooled drops, and ice pellets (ipB) near the surface.

c. Precipitation size distribution

The size distribution of the precipitation types produced within the observed temperature profile is compared with observations. Figure 5 shows the size distribution.
of irregular and circular particles compared with each type of precipitation formed. The four levels shown are the same as those in Fig. 2.

Figure 5a shows the size distribution of snowflakes initialized above the melting layer. It is comparable with the total observed spectrum of particles. The observed circular particles measured could possibly be small ice crystals.

Below the top of the melting layer (3.0 km), a mixture of slush, rain, and wet snow is produced by the model and their size distributions are shown in Fig. 5b. The size spectrum of rain is mainly comparable to the observed smaller size spectra diameters. Next, the slush size distribution is between the rain size spectra and the wet snow size spectra. It matches the irregular and circular particles observed and the wet snowflakes match the larger irregular particles concentration.

Many irregular particles smaller than slush are observed but not produced by the model. This is a model limitation because a truncated inverse exponential size distribution is assumed in the microphysics parameterization. Those irregular particles could be the result of large slush particles and/or wet snow that have broken while melting.

Furthermore, there is a gap between the slush and wet snow size distribution in Fig. 5b. This gap is explained by the instantaneous change of density when wet snowflakes collapse into slush because the real diameters are shown as opposed to the liquid water equivalent diameter. The parameterization of melting snow assumes that when wet snow melts into slush its density will vary significantly. Thus, the observed irregular particles with diameters (or the dimension of the major axis) within the gap could either be slush with a density lower than assumed in the scheme or wet snow with a density higher than assumed in the scheme. It should also be noted that no gap would exist between slush and wet snow threshold diameters if liquid water equivalent diameters would be shown instead of the actual physical diameters.

Figure 5c compares the size distribution obtained by the model and the size distribution of circular and irregular particles at the critical height. Because of the warm and deep melting layer, only rain should reach the critical height. The slope simulated by the model is comparable with the observations; however, the intercept of the size distribution is underpredicted. Some large irregular particles are observed and are not reproduced by the model. It is possible that the larger irregular particles are large rain drops distorted from spheres by friction as they fall. The particle analysis software may not recognize the distorted spheres as drops.

At 0.3 km (Fig. 5d), the size distribution produced by the model is also underpredicted by less than one order of magnitude. However, the slopes of the freezing rain and ice crystal distributions match the measured values. Theoretically, circular particles are supercooled rain and small ice pellets whereas irregular particles are ice crystals.

d. Summary

Overall, key aspects of the precipitation type evolution within a vertical profile in the Mirabel area during the 1998 ice storm have been accounted for. Many of the precipitation characteristics observed during the flight have been reproduced by the model. The observational limitations, as well as the model assumptions, act to limit detailed comparisons between numerical results and observations at both large and small sizes.

In terms of observational limitations, the analysis of particle images taken during the flight is at times very difficult. For instance, very small irregular particles could look circular on an image and be, in reality, ice crystals. Also, there are some limitations with measuring the size of very large snowflakes. For example, they can break up upon contact with the measuring probes.

In terms of model limitations, there are at least two issues. First, no cloud droplets are produced in these simulations and this has an impact on the lack of small particles at the bottom of the refreezing layer. This could also have an impact on the formation of other precipitation types within the refreezing layer. No vertical motion was utilized and so there was no ongoing means of producing droplets by this mechanism. From the observations, high concentrations of cloud droplets are present near the surface (~205 cm$^{-3}$ at 400 m) and the presence of cloud droplets could lead to more accretion between ice crystals and an increase of ice pellets (ipB).

Furthermore, it could also trigger another formation mechanism of ice pellets by the Hallett–Mossop secondary ice multiplication (Hallett and Mossop 1974). The interaction of ice pellets by contact nucleation and cloud droplets could lead to the formation of ice crystals and thus, a larger amount of small ice pellets. Second, the assumption that the exponential form of the size distribution is truncated by threshold diameters as for slush and wet snow is also a limitation. This produces a gap between the size of, for instance, wet snow and slush. Also, it can lead to limitations when modeling smaller and larger particle sizes of an evolving distribution of precipitation types.

4. Sensitivity study

The sensitivity of the precipitation types with respect to the vertical temperature profile is now examined. The experiments are conducted using the data observed during the 1998 ice storm in the Montreal area. Milton and Bourque (1999) divided the event into two critical icing periods. The first is between 2300 UTC 5 January and
1300 UTC 6 January 1998 and the second is between 2300 UTC 7 January and 2300 UTC 9 January 1998. This study will focus on the second icing period, as several types of precipitation as well as combinations of types were observed in Montreal.

North American Regional Reanalysis (NARR) products are used as a guide to analyze the sensitivity of the precipitation types formed during the second icing period to the background environmental conditions. NARR is an assimilated operational dataset archived every 3 h with a 32-km grid spacing. The data are archived from 1978 to present. Further information is given in Mesinger et al. (2006). The surface observations were obtained from the National Climate Data and Information Archive. The hourly surface precipitation types observed at the Pierre Elliott Trudeau Airport (Montreal) during the second icing period were freezing rain only, a mixture of freezing rain and ice pellets, or ice pellets only.

The temperature profiles between 0000 and 1500 UTC 8 January 1998 were interpolated over Montreal using the NARR data. The NARR temperature fields for this aforementioned time period are shown in Fig. 6a. The temperature fields show a melting layer aloft and a re-freezing layer below. These are typical temperature structures associated with freezing rain and/or ice pellets. During that time period, the temperature and depth of the melting layer varied significantly with respect to time. For example, the height of the upper 0°C isotherm increases from 2.1 km at 0000 UTC to 2.6 km at 1500 UTC with a dip at 1200 UTC. The temperature of the melting layer reaches a minimum of 0.5°C at 1200 UTC and is warmer both before and after this time.

The surface precipitation types observed at the Pierre Elliott Trudeau Airport are also shown in Fig. 6b. At 0000 UTC, only freezing rain is reported. Freezing rain mixed with ice pellets started at 0100 UTC and ended at 0800 UTC. This was followed by 4 h of only ice pellets. Freezing rain mixed with ice pellets was again observed from 1200 to 1500 UTC.

To simulate the precipitation types formed, the microphysical parameterization developed (Thériault and Stewart 2010) is used with a one-dimensional cloud model. Six temperature profiles between 0000 and 1500 UTC, inclusively, are studied. The atmosphere is assumed to be saturated with respect to liquid water. Snow is assumed to continuously fall at a rate of 1 mm h$^{-1}$ from above the melting layer and the model is run until steady-state conditions are reached. This precipitation rate is a close approximation to that inferred from surface accumulations during the time period.

The sensitivity of precipitation types to small temperature changes was investigated. Specifically, between 0000 and 1500 UTC 8 January 1998, each entire vertical temperature profile was varied systematically ($\Delta T = \pm 0.1^\circ, \pm 0.2^\circ, \pm 0.3^\circ, \pm 0.4^\circ, \text{and } \pm 0.5^\circ$). The characteristics of the precipitation types formed such as slush, liquid core pellets, and ice pellets are examined and a temperature field reproducing many of the precipitation types observed will be shown and referred to as the adjusted temperature field.

a. Sensitivity of surface precipitation types to the temperature

Sensitivity tests of the precipitation types to the temperature profile have been carried out. Figure 7 shows the surface precipitation types using the temperature profiles from NARR data and with variations of up to $\pm 0.5^\circ$C with increments of 0.1°C. The NARR temperature field has been used as a guideline.

At 0000 UTC, mostly freezing rain is produced by the temperature profiles studied. However, the coldest temperature profile ($\Delta T = -0.5^\circ$C) is associated with ice...
pellets (ipB) produced by collisional freezing through the interaction of supercooled drops and pristine ice crystals (Fig. 7a). This temperature profile is associated with a minimum temperature in the refreezing layer favorable for the formation of ice crystals. The observed surface precipitation types are produced with the unchanged NARR temperature profile.

The precipitation types at 0300 UTC are shown in Fig. 7b. The surface precipitation types observed are reproduced without varying the NARR temperature profile. A mixture of freezing rain, ice pellets, and refrozen wet snow is produced at colder temperatures. As the temperature increases, the amount of ice pellets and refrozen wet snow decreases and the amount of freezing rain increases almost linearly. This is associated with an increase of the depth of the refreezing layer leading to the formation of partial frozen particles such as liquid core pellets at the surface (ΔT = 0.4°C). The warmest temperature profile is associated with only freezing rain.

At 0600 UTC, the coldest temperature profile produced a mixture of ice pellets and freezing rain at the surface. As the temperature increases, the amount of ice pellets decreases and this correlates with an increase in the amount of freezing rain up to ΔT = 0°C. After that point, only freezing rain reaches the surface. The surface precipitation types observed are reproduced at a temperature variation of −0.2°C.

The precipitation types formed at 0900 UTC (Fig. 7d) are similar to those at 0600 UTC. The mixture of ice pellets and freezing rain is produced at a temperature of −0.5°C and only freezing rain is produced at +0.1°C. However, the main difference is the occurrence of liquid core pellets. They are formed over a wider range of conditions than at 0300 and 0600 UTC. Furthermore, the
The observed precipitation type is not exactly reproduced within the variations of the temperature profile. The results show that a decrease of 0.5°C produced the maximum amount of ice pellets. However, this is assuming an initial precipitation rate of only 1 mm h\(^{-1}\). A sensitivity test varying the initial precipitation rate is conducted in section 4b.

Several precipitation types are associated with the temperature variation at 1200 UTC (Fig. 7e). They vary from snow for a colder temperature profile to refrozen wet snow at \(D_T = 0.8\)°C. As the temperature increases, refrozen wet snow is mixed with ice pellets and at \(D_T = 0.5\)°C freezing rain is mixed with refrozen wet snow and ice pellets. The temperature variation of 0.2°C produced exactly the same combination of freezing rain and ice pellets. The temperature variation of 0.1°C produced exactly the same combination of freezing rain and ice pellets observed assuming that refrozen wet snow is observed as ice pellets.

Finally, at 1500 UTC (Fig. 7f), three different types of precipitation are formed within the various temperature profiles. A mixture of freezing rain and ice pellets (ipA and ipB) is produced within the coldest temperature profile. As the temperature increases, the precipitation types change into freezing rain only at \(D_T = 0.8\)°C. The surface precipitation types observed are reproduced by a temperature variation of 0.1°C.

The majority of the surface precipitation types reported during the second icing period of the 1998 ice storm was reproduced by using the NARR temperature profiles as a guide, with a variation of ±0.5°C (Table 2). Based on those results, a vertical temperature profile time series that reproduced most of the precipitation types observed between 0000 and 1500 UTC 8 January 1998 in the Montreal area is shown in Fig. 8.

The adjusted temperature field is shown and compared to the NARR temperature field in Fig. 8. The 0°C isotherms are very similar at 0000, 0300, and 1500 UTC. There is a small difference at 0600 and 0900 UTC. However, the greatest difference is at 1200 UTC where the depth of the melting layer is deeper than the NARR data. The associated precipitation types produced by the adjusted temperature are summarized in Table 2.

Therefore, many of the surface precipitation types observed during the time series were replicated by the model with a temperature variation of ±0.5°C. A description of the precipitation types formed aloft is given in the following section.

### b. Sensitivity of precipitation types to the precipitation rate

An important issue is the impact of a varying precipitation rate on the precipitation types reaching the surface. A precipitation rate of 1 mm h\(^{-1}\) has been used as the base value to study the sensitivity of the precipitation types to the temperature profile. This assumption is based on the total accumulation of precipitation and the hours of precipitation during the second icing period of the 1998 ice storm in Montreal. However, radar observations shown in Henson et al. (2007) indicate that the precipitation rate was not constant during that period; it fluctuated substantially. For example, radar information implies an increase of precipitation rate of >5 mm h\(^{-1}\) over the Montreal area at 0800 UTC. Thus, sensitivity tests of the precipitation types relative to the initial snowfall

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**Table 2. Comparison of the surface precipitation types observed (Fig. 6b) with the model results obtained with the NARR temperature field (Fig. 6a) and the adjusted NARR temperature field (Fig. 8). Here, the symbol ip refers to observed ice pellets.**

<table>
<thead>
<tr>
<th>Time (UTC)</th>
<th>0000</th>
<th>0300</th>
<th>0600</th>
<th>0900</th>
<th>1200</th>
<th>1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface obs</td>
<td>zr</td>
<td>zr–ip</td>
<td>zr–ip</td>
<td>ip</td>
<td>zr–ip</td>
<td>zr–ip</td>
</tr>
<tr>
<td>NARR*</td>
<td>zr</td>
<td>zr–ipA</td>
<td>zr</td>
<td>zr–lcp</td>
<td>rws</td>
<td>zr</td>
</tr>
</tbody>
</table>

* Model results.

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**Fig. 8.** The adjusted temperature field (°C) producing many of the precipitation types observed at the surface (Fig. 6b) during the 1998 ice storm. The gray lines indicate the temperature field and the thin black lines are the 0°C isotherms. The thick black lines are the 0°C isotherms of the unadjusted NARR temperature field (Fig. 6).
rate are carried out here using the temperature profile at 0900 UTC (Fig. 6).

The precipitation types formed from the initial snowfall rate depend also on the snow size distribution. The snow size distribution is assumed to follow an inverse exponential function defined as

$$N_s(D_s) = N_{0s} \exp(-\lambda_s D_s),$$

where $N_{0s}$ is the intercept, $\lambda_s$ is the slope parameter of the size distribution, and $D_s$ is the dimension of the snowflake’s major axis. Some studies (Sekhon and Srivastava 1970; Brandes et al. 2007) have investigated the variation of the intercept parameter with both temperature and precipitation rate. In this initial study, it is assumed that the intercept of the size distribution, $N_{0s}$, depends only on the temperature and does not vary with the precipitation rate as in Cox (1988). An increase of the mass of snow initialized aloft, keeping the intercept constant, decreases the slope and produces larger snowflakes. Four initial snowfall rates, 1, 2, 5, and 10 mm h$^{-1}$, have been studied. Only three temperature profiles have been studied in this section and they are $\Delta T = 0.08$ C and $\Delta T = 0.58$ C.

For the warmer temperature profiles, $\Delta T = 0$ C and $\Delta T = 0.5$ C, no significant changes in the precipitation types reaching the surface are observed. However, the precipitation types formed by the temperature profile 0.5 C colder than NARR vary significantly with the initial snowfall rate (Fig. 9). For example, assuming an initial precipitation rate of 1 mm h$^{-1}$, 70% of the total amount of precipitation is freezing rain but this fraction drops to 22% if the precipitation rate is increased to 10 mm h$^{-1}$.

Since the amount of freezing rain formed with a precipitation rate of 10 mm h$^{-1}$ is small, it is possible that it was not reported by the observers. The refrozen wet snow could also have been confused with ice pellets since this category of precipitation is not officially reported by the observer. Therefore, an increase in the precipitation rate decreases the amount of freezing rain and a sufficiently high precipitation rate could lead to its elimination.

Overall, the results of this analysis show that the initial precipitation rate affects the precipitation types at the surface by producing larger snowflakes. Larger snowflakes will likely melt partially to produce slush and refreeze into ice pellets within the refreezing layer compared to low precipitation rates associated with smaller snowflake sizes. These snowflakes will more likely melt completely when falling within the same atmospheric conditions and produce freezing rain.

c. Occurrence of liquid core pellets and ice pellets

The precipitation types formed aloft within the adjusted temperature fields are investigated. The goal of this investigation is to determine the vertical levels at which slush completely melts into rain and liquid core pellets completely freeze into ice pellets. This is critical, for example, because if liquid core pellets reach the surface they may break upon impact with a subfreezing surface and this would lead to surface icing.

Figure 10 shows temperature and threshold levels at which melting and freezing are complete and it shows also the corresponding melting and refreezing parameters. For a given temperature and depth of the refreezing layer, larger slush particles will refreeze completely into ice pellets deeper into the refreezing layer compared to smaller slush particles.

The temperature profile parameters such as the depth and temperature of the melting layer and the refreezing layer are used to describe the melting and the freezing parameters defined by Zerr (1997). The melting parameter is defined as

$$\beta_m = H_m T_{\text{max}},$$

where $H_m$ is the depth of the melting layer and $T_{\text{max}}$ is the maximum temperature of the melting layer. The refreezing parameter is defined as

$$\beta_f = H_f T_{\text{min}},$$

where $H_f$ is the depth of the refreezing layer and $T_{\text{min}}$ is the minimum temperature of the refreezing layer.
At 0000 UTC, the threshold height is above the lower 0°C isotherm meaning that no slush reaches the refreezing layer to form liquid core pellets. The highest melting parameter also occurs at this time. However, at all other times, the threshold line is below the lower 0°C isotherm. Therefore, liquid core pellets and ice pellets were produced in the refreezing layer from 0300 to 1500 UTC. It should be noted that, for most of the time, slush is mixed with rain and wet snow within the melting layer and liquid core pellets are often mixed within freezing rain and refrozen wet snow within the refreezing layer.

At later times, both melting and freezing parameters decrease to reach a minimum at 1200 UTC. This minimum also corresponds to the highest level at which liquid core pellets completely refreeze. Because smaller particles have been formed in the shallow melting layer, they refreeze at higher levels within the deep refreezing layer. The value of the melting parameters at 0600 and 1500 UTC is comparable but the freezing parameters differ. At 1500 UTC, the refreezing parameter is lower than at 0300 UTC, allowing the particle to refreeze completely at higher levels above the surface. For instance, between 0200 and 0900 UTC, liquid core pellets completely refreeze into ice pellets at heights near the surface (≈250 m). They are associated with a high melting parameter and a low refreezing parameter. For colder temperature profiles (1200 UTC), they are formed at approximately 750 m above the surface. These results suggest that liquid core pellets could have reached the surface between 0300 and 0900 UTC, affecting the severity of icing at the surface during the storm.

5. Concluding remarks

In summary, an investigation of the precipitation characteristics during the 1998 ice storm in the Montreal area and a sensitivity study of the precipitation types to the temperature profile and to the precipitation rate have been carried out. These studies were conducted using a bulk microphysics scheme (Thériault and Stewart 2010) coupled with a one-dimensional kinematic cloud model. The vertical evolution of the precipitation was examined with the model in conjunction with aircraft measurements made during the 1998 ice storm. Many of the
precipitation type characteristics observed during the flight were reproduced by the model with some limitations. This analysis shows that the microphysical processes forming the various precipitation types are complex. For example, melting of wet snow and slush occurred within the melting layer. In contrast, ice nucleation and collisional freezing of supercooled drops with ice crystals occurred within the refreezing layer.

The model also has limitations. For instance, the model did not include cloud droplet formation through the vertical ascent of air. If this factor had been considered, the initial formation of ice pellets may have led to more ice crystals being formed through the Hallett–Mossop process (Hallett and Mossop 1974). These ice crystals in turn would have collided with supercooled drops and accelerated the formation of ice pellets. It should be noted that microphysical feedbacks have not been considered in this study as the aim was to examine the precipitation types formed within prescribed observed vertical temperature and humidity profiles.

The sensitivity of surface precipitation types to the vertical profile of temperature was addressed with the model using the North American Regional Reanalysis data as a guide for the temperature fields. The selected time period for the study was during one of the major icing periods within the 1998 ice storm. It was shown that, assuming a precipitation rate of 1 mm h$^{-1}$, a temperature difference in the profile of only 0.5°C would have an important impact on the precipitation types formed during this catastrophic event. For instance, at 0300 UTC 8 January 1998 a mixture of freezing rain and liquid core pellets was produced at the surface. If the temperature of this profile were increased by only 0.5°C, only freezing rain would have reached the surface. On the other hand, a decrease of temperature by 0.5°C changes the precipitation types to a mixture of freezing rain and ice pellets. Thus, this major event may have been much less catastrophic if the temperature was only 0.5°C colder.

This sensitivity study also considered the effects of the initial snowfall rate on surface precipitation types. It was demonstrated that, within the same temperature profile, different precipitation rates lead to different types of precipitation. For instance, in one temperature profile studied, the total amount of freezing rain is decreased by a factor of 3 assuming a precipitation rate of 10 mm h$^{-1}$ rather than a precipitation rate of 1 mm h$^{-1}$. In these calculations, it is assumed that the increase in precipitation rate is associated with an increase in the concentration of large snowflakes, which do not melt as easily in the melting layer and are more likely to freeze before reaching the surface. Furthermore, an increase of the snowflake concentration could cool the temperature profile until an isothermal layer is formed through the latent heating of cooling.

Collectively, this analysis illustrates the challenge of correctly predicting surface precipitation types. Numerous processes can influence the phase and features of precipitation, including ice multiplication. Such processes depend critically on, for instance, temperature, relative humidity, and precipitation size distribution. As well, small changes in temperature and significant precipitation rate can lead to major variations in the types of precipitation at the surface.

The sensitivity studies further suggest that liquid core pellets may have reached the surface during the 1998 ice storm. These have not been reported by observers but, if so, this may also have affected the ensuing icing at the surface. If the shell of such particles cracks, the liquid would have frozen onto structures. With their attached ice shell, the nature of the icing would probably be different (rougher) than that caused by freezing rain alone.

The occurrence of liquid core pellets was examined in relation to the energy available in the melting and refreezing layers as indicated by the melting and refreezing parameters. The results show that a high melting parameter is associated with liquid core pellets refreezing lower in the refreezing layer than those associated with a low melting parameter. On the other hand, the refreezing parameter gives an indication of the level at which the liquid core pellets completely refreeze into ice pellets. For instance, larger liquid core pellets, associated with a higher melting parameter, refreeze at a lower level of the atmosphere than smaller liquid core pellets for the same refreezing parameter. These parameters give an indication of the phase and size of precipitation particles reaching the surface.

Overall, this study has illustrated that, when the temperature is near 0°C, forecasting precipitation types requires high precision in the prediction of the temperature profile and, at times, the precipitation rate. Furthermore, some microphysical processes can occur in the subfreezing region if key thresholds are reached and these may also affect the types of precipitation reaching the surface. Such conditions imply that accurately predicting precipitation types is a major challenge for operational models.

Acknowledgments. We thank the Natural Sciences and Engineering Research Council of Canada (NSERC), Environment Canada, and the Institute for Catastrophic Loss Reduction (ICLR) for the financial support needed to accomplish this work. We also thank Georges Isaac for providing us in-flight data collected during the third Canadian Freezing Drizzle Experiment. One author (JMT)
also thanks NSERC, Environment Canada, and McGill University for postgraduate scholarships.

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