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On the simulation of winter precipitation types

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[1] Winter storms produce major problems for society, and the key responsible factor is often the varying types of precipitation. The objective of this study is to better understand the formation of different types of winter precipitation (freezing rain, ice pellets, snow, slush, wet snow and refrozen wet snow) within the varying and interacting environmental conditions in many winter storms. To address this issue, a one-dimensional cloud model utilizing a double-moment bulk microphysics scheme has been developed. Temperature and moisture profiles favorable for the formation of different winter precipitation types were varied in a systematic manner in an environment where snow is falling continuously through a temperature inversion. The ensuing precipitation evolved as a result of the variations in atmospheric temperature and moisture arising from phase changes such as melting and freezing. This study underlines the often complex manner through which different precipitation types form. It also demonstrates that the formation of semimelted particles can have a profound effect on the evolution of precipitation types aloft and at the surface. Furthermore, some types of precipitation only form within a narrow range of environmental conditions.

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1. Introduction

[2] Winter storms cause major disruptions to society in various regions of the world. Their effects are often associated with the production of various precipitation types as well as with related hazardous surface conditions. Such storms are commonly observed during winter over Canada [*Stewart et al.*, 1995] and the northern United States [*Cortinas et al.*, 2004].

[3] The varying precipitation types at the surface occur in the transition region of storms where the precipitation changes from rain to snow or vice versa. The different types of precipitation are often observed along a warm front (Figure 1). The precipitation can exist in different states: solid, liquid and solid-liquid combinations. The definitions of many winter precipitation types are given by *Glickman* [2000] and they are summarized in Table 1. It should be noted that there is no definition for mixed phase precipitation which is almost completely liquid but contains some ice. In these instances, the original snowflakes are no longer discernible. In the absence of any definition, we define these precipitation particles as ‘‘slush’’ (Table 1).

[4] It is also possible to observe a mixture of winter precipitation types at the surface. For example a mixture of ice pellets, snow, freezing rain and/or rain is sometimes found [*Stewart and King*, 1987; *Stewart and Crawford*, 1995; *Zerr*, 1997]. This arises because there is a spectrum of sizes occurring in the atmosphere and different sizes can evolve differently. For example, smaller particles are more likely to completely melt within the melting layer than larger ones [*Stewart et al.*, 1990a; *Zerr*, 1997].

[5] The production of the precipitation also has a major impact on the atmosphere and the ensuing form of precipitation [*Wexler et al.*, 1954; *Kain et al.*, 2000; *Lackmann et al.*, 2002]. For example, in a saturated environment where the temperature is warmer than 0°C, heat is extracted from the atmosphere because of melting. This process occurs until the temperature reaches 0°C. At that temperature, thermal equilibrium is established and the ice particles cease to melt, thus an isothermal layer of 0°C is formed [*Findeisen*, 1940]. Isothermal layers a few hundreds of meters deep commonly occur in stratiform rain situations which can extend to a depth of 1 km in the vicinity of transition regions. Latent heating associated with refreezing can also influence significantly the temperature field.

[6] Despite the increasing understanding of winter precipitation and its associated weather, accurate prediction of precipitation types is still difficult. It has been long known that the most important factor influencing the precipitation types at the ground is the temperature profile [*Wagner*, 1957; *Bocchieri*, 1980; *Czys et al.*, 1996] and statistical techniques have been developed to help in their prediction. For example, *Bourgouin* [2000] recently developed a method to predict precipitation types at the surface on the basis of the temperature and moisture profile. The types of precipitation depend both on the area of the melting layer (i.e., area above 0°C on the tephigram) as well as the area of the subfreezing layer near the surface.

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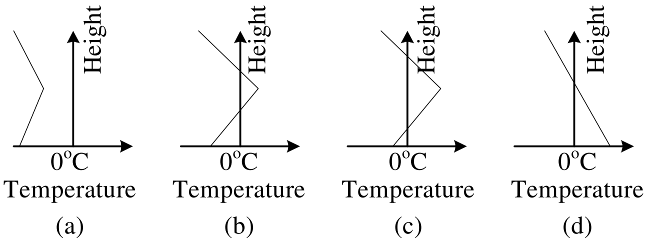

Figure 1. A typical time evolution of a temperature profile and precipitation types at the surface during the passage of a warm front and the associated evolution of precipitation type: (a) snow, (b) ice pellets, (c) freezing rain, and (d) rain. See Table 1 for symbol definitions that are used in the diagram.

[7] The challenge of predicting winter precipitation is starting to affect the focus of national research programs. For example, the United States is developing a winter storms research program [*Ralph et al.*, 2005]. In their plans for modeling hazardous winter conditions, they point out that [*Ralph et al.*, 2005, p. 1626] "The most important problem to be addressed is forecasting precipitation type. This is primarily a problem in physics rather than dynamics."

[8] Given the importance of winter precipitation types and our gaps in its understanding, it is important to carry out a detailed study of their formation within the atmosphere. The objective of this paper is to better understand the basic physics of the formation of winter precipitation and its interaction with the environment. Detailed evolution of precipitation types and environmental conditions through a column is examined using typical temperature profiles and various other atmospheric conditions.

[9] The paper is organized as follow: Section 2 describes the one-dimensional (1-D) cloud model and the microphysics scheme used in this study. Section 3 explains the experimental design. Section 4 shows a comparison between precipitation formed with and without the inclusion of the semimelted categories using a typical temperature profile. Section 5 focuses on the average temperature profile associated with various precipitation types and other combinations. Concluding remarks are given in section 6.

2. Model Description

[10] A systematic study of winter precipitation formation has been performed using a one-dimensional kinematic cloud model coupled to the double-moment version of the multimoment bulk microphysics scheme described by *Milbrandt and Yau* [2005a, 2005b]. Several modifications appropriate for this study have been made to the scheme and we focus in this section on the new particle categories added. A number of other similar schemes have been reported in the literature, including *Murakami* [1990], *Lin et al.* [1983], *Kong and Yau* [1997], and *Reisner et al.* [1998].

[11] The one-dimensional kinematic cloud model is initialized with vertical profiles of pressure (p), height (z), temperature (T) and dew point temperature (T_d). There are 100 vertical levels evenly spaced. We only considered sedimentation and microphysics growth and decay processes (double-moment bulk microphysics scheme) while turbulence and advection are neglected.

[12] In the microphysics scheme the size distribution of each hydrometeor category is represented by an analytic function. Two moments of the size distribution are predicted for each category. The zeroth moment gives the total number concentration and the third moment is proportional to the mass mixing ratio. Microphysical growth rates are formulated following *Milbrandt and Yau* [2005a, 2005b].

[13] In the original scheme, six hydrometeor categories representing the total hydrometeor spectrum are included. They are divided into two different main types, liquid and completely frozen particles. Cloud droplets and rain compose the liquid categories and ice, snow, graupel and hail are the frozen categories. Since the "hail" category includes tiny frozen drops and this study involves only winter cases, we shall henceforth refer to precipitation in this category as ice pellets.

[14] Winter storms are often associated with particles composed of a mixture of water and ice. Therefore two semimelted categories have been added in the model: slush and wet snow. We also define freezing rain as rain that exists at temperatures below 0°C and assume that wet snow

Table 1. Definition of Various Winter Precipitation Types

Precipitation Types	Symbols	Definition
Rain[a]	R	Precipitation in the form of liquid water drops that have diameters greater than 0.5 mm, or, if widely scattered, the drops may be smaller.
Freezing rain[a]	ZR	Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground on exposed objects.
Snow[a]	S	Precipitation composed of white or translucent ice crystals, chiefly in complex branch hexagonal form often agglomerated into snowflakes.
Ice pellets[a]	IP	A type of precipitation consisting of transparent or translucent pellets of ice, 5 mm or less in diameter.
Graupel[a]	G	Heavily rimed snow particles, often called snow pellets. Sometimes distinguished by shape into conical, hexagonal, and lump (irregular) graupel.
Wet snow[a]	WS	Deposited snow that contains a great deal of liquid water. If free water entirely fills the air space in the snow it is classified as "very wet" snow.
Refrozen wet snow	RWS	Refrozen wet snowflake.
Slush	SL	Precipitation composed of a mixture of liquid and ice in which the original snowflake's shape is not discernable.

[a]From *Glickman* [2000].

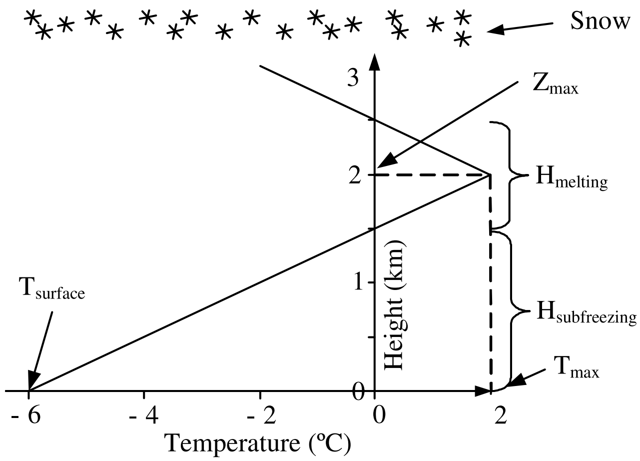

Figure 2. Description of the sounding parameters: surface temperature ($T_{surface}$), maximum temperature and its height (T_{max} and Z_{max}), depth of the melting layer ($H_{melting}$), and depth of the subfreezing layer ($H_{subfreezing}$). The typical sounding studied assumes saturated conditions.

freezes at temperatures colder than 0°C to form refrozen wet snow.

[15] *Stewart et al.* [1990b] identified four mechanisms for forming semimelted particles. However, in this study, we only consider his first mechanism which is partial melting. Given that the current scheme does not account for semimelted particles, initial steps have therefore been taken to address this limitation.

[16] Melting usually occurs at temperatures above 0°C. In our calculations, we assume that semimelted particles are formed when snow melts at a wet bulb temperature between 0°C and 1°C. Within that temperature range, the amount of melted snow is divided into three equal categories: rain, slush and wet snow; depending whether the particles have melted completely, considerably, or little. However, no constraint on the particle's diameter has been assumed. If little melting has occurred the particle still appears like snow but with droplets occurring on the lattice structure. If more melting has occurred the particles will collapse into a drop with a similar shape but still containing some ice.

[17] Given the lack of measurements on the actual breakdown between these types, it has been assumed that wet snow is mainly composed of ice and the slush category is mainly composed of water. In the microphysics scheme, the size distribution and fall velocity parameters of wet snow are similar to those of snowflakes while those of slush are similar to the rain category. Also, we assume that wet snow melts equally at temperatures above 1°C into two categories: rain and slush. Slush completely changes into rain at temperatures warmer than 1.5°C. The thresholds for categories have been chosen to be consistent with the limited available observations of *Matsuo et al.* [1981].

[18] Slush is considered similar to rain in that it can evaporate but since it also contains ice, it will freeze at temperatures colder than 0°C. In this case, the freezing will produce ice pellets. It has been recognized that ice pellets mainly form from refreezing of semimelted snowflakes having a high liquid fraction [*Stewart and King*, 1987].

[19] The rate of refreezing of the semimelted snowflakes depends on the amount of water in the particles and the environmental temperature. Because no measurements have been made to determine the amount of water within a slush particle, a linear relation between freezing and temperature is assumed. A temperature at which slush will be all refrozen is assumed to be −3°C, based upon surface observations of ice pellets reported by *Hanesiak and Stewart* [1995]. Thus complete refreezing of the particle occurs at that temperature. Slush has a higher probability of freezing than supercooled drops because the small amount of ice within it initiates the freezing process. The rate of change in mixing ratio for temperature between −3°C and 0°C is linearly related to the temperature. At $T \leq -3$°C, all the slush particles are changed into ice pellets and at $T \geq$ 0°C no ice pellets are formed. The total number concentration varies similarly. The latent heating due to the refreezing of semimelted particles is calculated from the mixing ratio of slush converted into ice pellets. Note that latent heating is released because the particle is almost entirely composed of liquid and we assume a negligible amount of ice within it. It is recognized that further research is needed to quantify these thresholds between the forms of precipitation but this is beyond the scope of this present work.

3. Experimental Design

[20] The formation of many types of winter precipitation is due to the presence of a melting layer aloft and a subfreezing layer below. The melting layer allows frozen precipitation to melt or partially melt and the subfreezing layer allows their complete or partial refreezing. This section describes the experimental procedures employed.

[21] We defined a typical temperature profile favorable for the formation of various winter precipitation types (Figure 2). This temperature profile is extends up to 3 km above the surface where the temperature is −6°C. The maximum temperature inversion is 2°C. The depth of the melting layer is 1 km and the depth of the subfreezing layer is 1.5 km. Similar soundings have been observed during winter storms [*Hanesiak and Stewart*, 1995; *Zerr*, 1997]. However, most soundings observed have a minimum temperature above the surface instead of being at the surface, often due in part to latent heating releases from the freezing of freezing rain at the surface [*Lackmann et al.*, 2002] which we neglect.

[22] In our experimental setup representing a typical situation for mixed phase winter precipitation, snow falls continuously at a water-equivalent precipitation rate of 5 mm/h from 3 km above the surface into the typical temperature profile (Figure 2). The snow falls into the melting layer and phase changes may occur, depending on the atmospheric conditions, thus forming various types of particles.

[23] A detailed study of the typical temperature profile has been carried out. The impacts of variations from the typical temperature profile were investigated. Systematic variations were made to the surface temperature, the depth of the subfreezing and melting layers, and the maximum temperature of the inversion. These parameters directly influence the amount and type of precipitation formed [*Zerr*, 1997]. For instance, we varied the maximum temperature of

the melting layer by keeping all the other parameters constant. The stability of the atmosphere has been varied in order to obtain a maximum temperature of 2°C, 4°C and 6°C in the middle of the melting layer. The same procedure has been carried out for the three other parameters (surface temperature, depth of the melting and subfreezing layer) described in Figure 2. The surface temperatures studied were −0.5°C, −1°C, −2°C, −4°C, −6°C. The depths of the melting layer studied were 1000 m, 1500 m and 2000 m and the depths of the subfreezing layer studied were 1500 m, 1000 m and 500 m.

4. Winter Precipitation Types Evolution

[24] A detailed examination of winter precipitation type formation has been carried out. The following results show the evolution of the winter precipitation types at the surface and aloft as well as their interaction with the environment when snow falls into a melting layer followed by a subfreezing layer below.

4.1. Comparison of the Precipitation Formed Considering Formation of Semimelted Particles

[25] The following sections discuss the formation of the various precipitation types including the semimelted particle categories and the impact on the environmental conditions. The amount of each precipitation type is described by its mass content which is its mixing ratio multiplied by the air density. This investigation has been carried out using a typical temperature profile showed in Figure 2.

4.1.1. Vertical Evolution With No Semimelted Particles

[26] The model has been run with the original scheme (i.e., without the semimelted category) initialized by the sounding in Figure 2. Figures 3a and 3b show an illustrative example of the temperature and moisture profile with the associated precipitation types after 60 min. This time was chosen because it represented the point when almost half of the temperature inversion had disappeared and many precipitation types had been formed within the atmosphere. Snow initially falls from an elevation of 3 km. When it reaches the melting layer it melts and cools the atmosphere generating an isothermal layer of 0°C. The cooling generated by this melting leads to supersaturation and the formation of cloud droplets by condensation which acted to warm the environmental air and therefore to reduce somewhat the effect of cooling due to melting.

[27] A subsaturated layer is generated just above the surface. Temperatures in this layer are warmed by collisional freezing of freezing rain and frozen particles which generates a subsaturated layer. Hence frozen particles sublimate and liquid drops evaporate in the layer and these processes act to slightly cool the environment and add moisture into the layer. The actual temperature and degree of subsaturation in this layer are then functions of competing factors.

[28] The results show a mass content of rain significantly smaller than that of snow. For a single particle, the mixing ratio has a monotonic relation with the terminal velocity of particles. However, in a double-moment bulk scheme, in which the mass mixing ratio and the total number concentration of each hydrometeor category are predicted, the mass-weighted bulk terminal velocity is not monotonically related to the mixing ratio. For example, a population of hydrometeors with a given mixing ratio can have a relatively low number concentration, and thus have a large mean particle size and correspondingly large mass-weighted terminal velocity. On the other hand, another population with the same mixing ratio can have a high number concentration and thus have a small mean particle size and low bulk terminal velocity. In the scheme used here, the melting leads to a decrease in snow concentration and mixing ratio associated with an increase of the rain concentration and mixing ratio. For both categories, the mean diameters increase with melting but at a different rate. Also, it has been shown that sedimentation in a double-moment bulk scheme compares much closer to sedimentation from an analytic bin model calculation than sedimentation from a single-moment scheme, where the terminal velocity depends only on the mixing ratio. See *Milbrandt and Yau* [2005a] for a detailed discussion of sedimentation in bulk schemes.

4.1.2. Vertical Evolution With Semimelted Particles

[29] The model was run using the modified scheme which allows the formation of semimelted particles. Figures 3c and 3d show the temperature, moisture and the precipitation type profiles after 60 min. Snow starts to melt in the melting layer and forms rain, wet snow and slush but the semimelted particles are only formed when the temperature is between 0°C and 1°C and wet snow is allowed to melt into rain and slush at temperatures between 1°C and 1.5°C. The melting of snow decreases the temperature and generates an isothermal layer at 0°C. Again, the cooling by melting causes supersaturation to trigger the formation of cloud droplets. That process acts to reduce the impact of cooling by melting.

[30] When the rain falls into the subfreezing layer, it is referred to as freezing rain. Slush, which formed from melting snow, freezes into ice pellets when it reaches the subfreezing layer. This warms the layer just below the inversion. Also, collisions of ice pellets and freezing rain increase the amount of ice pellets and decrease the amount of freezing rain. The atmosphere warms as a result of freezing, and a subsaturated layer forms below the inversion. Snow, refrozen wet snow and ice pellets sublimate, and slush and freezing rain evaporate in this layer. Also, the warming near the surface is caused by the formation of ice pellets and graupel from the collision of frozen particles and freezing raindrops near the ground at an earlier time.

4.2. Temperature, Moisture, and Precipitation Types Profiles Comparison

[31] Many more precipitation types are formed within the atmosphere when semimelted particle formation is included in the model than when they are not allowed to form. Without semimelted particles, cloud, rain, graupel and freezing rain only are allowed. In contrast, with semimelted particles, cloud, rain, freezing rain, graupel, wet snow, refrozen wet snow, slush, and ice pellets are formed.

[32] It should also be noted that the temperature and moisture profiles are somewhat different. For example, subsaturation occurs near the surface when semimelted particles are not included and it occurs just below the

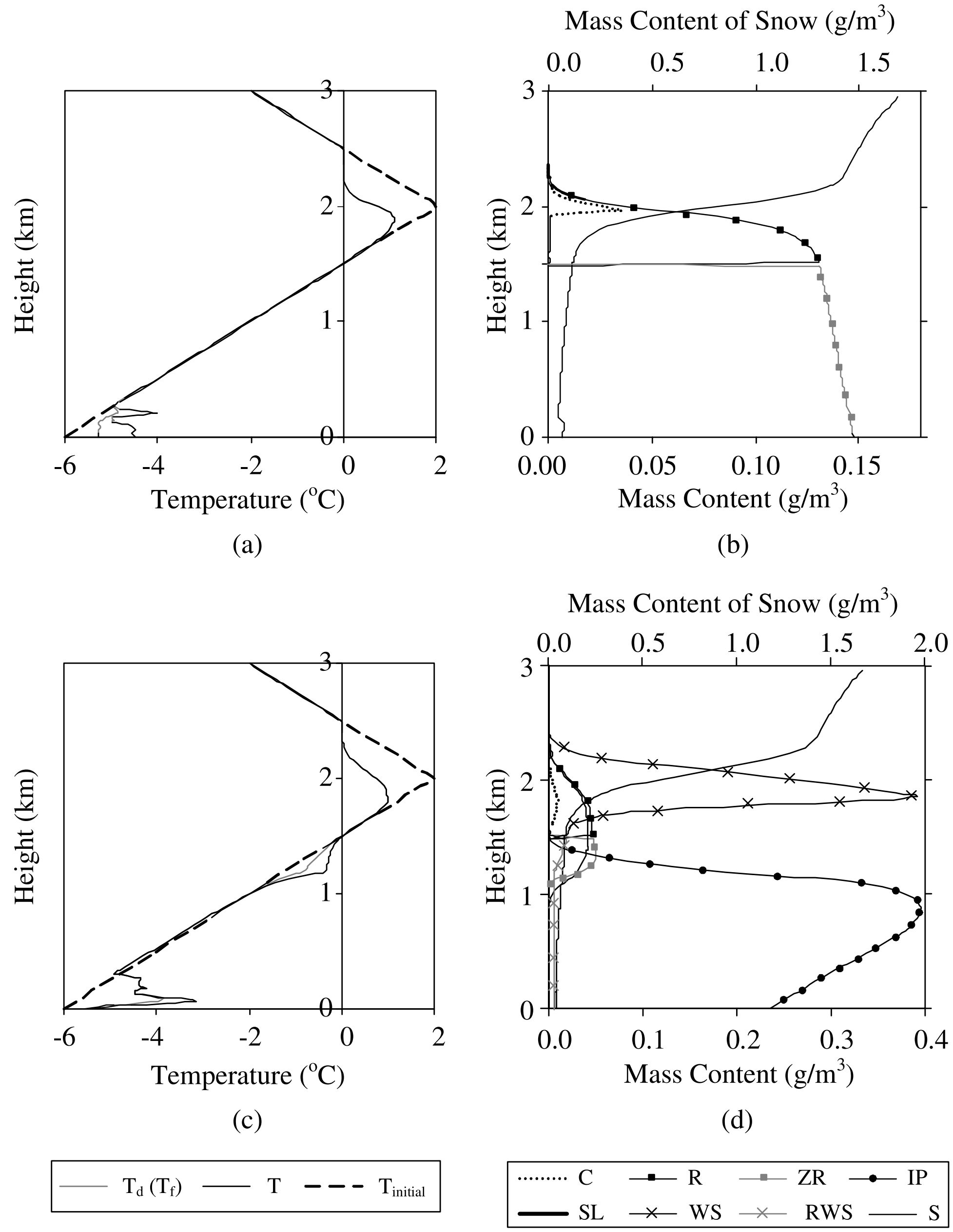

Figure 3. Temperature, moisture and precipitation type profiles initialized by the typical sounding after 60 min. T_d (T_f) is the dew (frost) point when the moisture profile is ≥0°C (≤0°C). The top axis of the right column shows the mass content of snow, and the bottom axis shows the mass content of the other precipitation types. (a and b) Associated with no semimelted particles and (c and d) associated with the formation of semimelted particles. See Table 1 for symbol definitions that are used in the diagram.

melting layer when these particles are allowed. There is also a greater warming near the surface.

4.3. Surface Precipitation Comparison

[33] The comparison of the evolution of surface precipitation types is shown in Figure 4. Figure 4a shows the surface precipitation types associated with the conditions in which the formation of semimelted particles is not allowed. In the first hour, graupel, ice pellets and freezing rain are reaching the surface. Then, ice pellets followed by snow are falling at the surface. However, with semimelted particles included (Figure 4b), the precipitation types reaching the surface first are ice pellets and graupel with essentially no freezing rain. During the second hour, a mixture of ice pellets, refrozen wet snow and snow is falling at the surface. The first peak in ice pellets is formed by the collection of freezing rains and frozen particles as well as refrozen slush produces by semimelted snowflakes and wet snowflakes. However, the second peak in ice pellets is produced by frozen slush formed by the semimelting of snow.

[34] The drop in the total precipitation rate in the case associated with no semimelted particles is linked to two main factors. First, evaporation and sublimation above the surface act to reduce the overall precipitation rate until

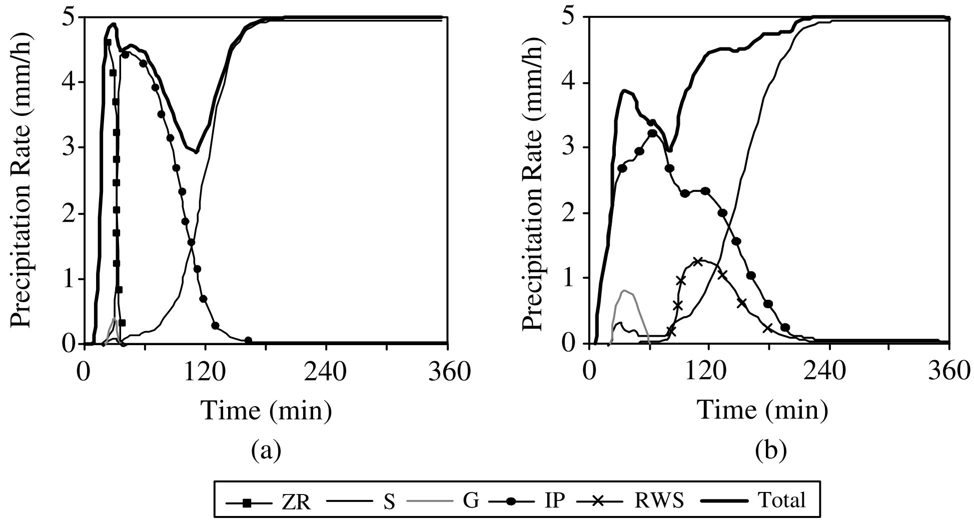

Figure 4. Comparison of surface precipitation evolution associated the typical temperature profile shown in Figure 2. (a) Surface precipitation excluding the semimelted categories and (b) surface precipitation including the semimelted categories. See Table 1 for symbol definitions that are used in the diagram.

steady state conditions of complete saturation are obtained. Second, in the case of no semimelted particles, the drop in total precipitation rate is associated with the transition of freezing rain into snow and it is correlated with the complete disappearance of the temperature inversion. Additional time is required for the snow to reach the surface after the freezing rain because of differences in the fall velocities. When semimelted particles are included, the drop in total precipitation is associated with the processes forming fast falling ice pellets. The drop in the total precipitation rate is caused by the beginning of the wet snow, which produces less slush to refreeze into ice pellets.

[35] The formation of semimelted particles within the melting layer enhances the amount of ice pellets and eliminates the amount of freezing rain near the surface. This arises because the formation of semimelted particles triggers additional means of producing ice pellets (such as slush freezing) and these triggers in general also lead to a reduction in supercooled liquid (i.e., freezing rain) due to, for example, collisions with ice particles (collisional freezing). The inclusion of semimelted particles gives a better reproduction of the different types of winter precipitation and has implications for the formation of other precipitation types.

5. Average Temperature Profile

5.1. Relation Between Sounding Parameters and Precipitation Types

[36] The previous section shows that the melting layer and its maximum temperature as well as the subfreezing layer and its minimum temperature directly affect the precipitation types and their amounts. To quantify the contribution of these factors, a melting and refreezing parameter has been used on the basis of the work of *Zerr* [1997] who analyzed soundings associated with surface precipitation types. Five precipitation types and/or combinations have been studied because they were the most common ones occurring in our calculations. On the basis of the surface precipitation rate, we studied the evolution of precipitation types in time at the ground. Then, we investigated the temperature profiles leading to the highest surface precipitation rate of these five selected precipitation types and combinations. The five combinations are freezing rain (ZR), ice pellets (IP), freezing rain and ice pellets (ZR-IP), ice pellets, refrozen wet snow and snow (IP-RWS-S), freezing rain, ice pellets, slush, refrozen wet snow and snow (ZR-IP-SL-RWS-S). In the case of ZR-IP, we choose the temperature profile associated with the highest precipitation rate of both precipitation types. For IP-RWS-S, the cases correspond to the temperature profile associated with the highest precipitation rate of wet snow. Finally, for ZR-IP-SL-RWS-S, we choose the case with the highest precipitation rate of slush at the surface.

[37] Following *Zerr* [1997], the refreezing and the melting parameters are calculated to examine the influence of the melting and subfreezing layer on the surface precipitation using the data given by *Theriault* [2004]. The refreezing parameter developed by *Zerr* [1997] is

$$\beta_F = T_{min} H_{subfreezing} \tag{1}$$

where (T_{min}) is the minimum temperature within the subfreezing layer and ($H_{subfreezing}$) is the depth of the subfreezing layer. The melting parameter is

$$\beta_M = T_{max} H_{melting} \tag{2}$$

where (T_{max}) is the maximum temperature within the melting layer and ($H_{melting}$) is the depth of the melting layer. A large positive value of the melting parameter is associated with favorable conditions for complete melting of frozen particles. On the other hand, a low negative value of the refreezing parameter indicates conditions favorable for refreezing.

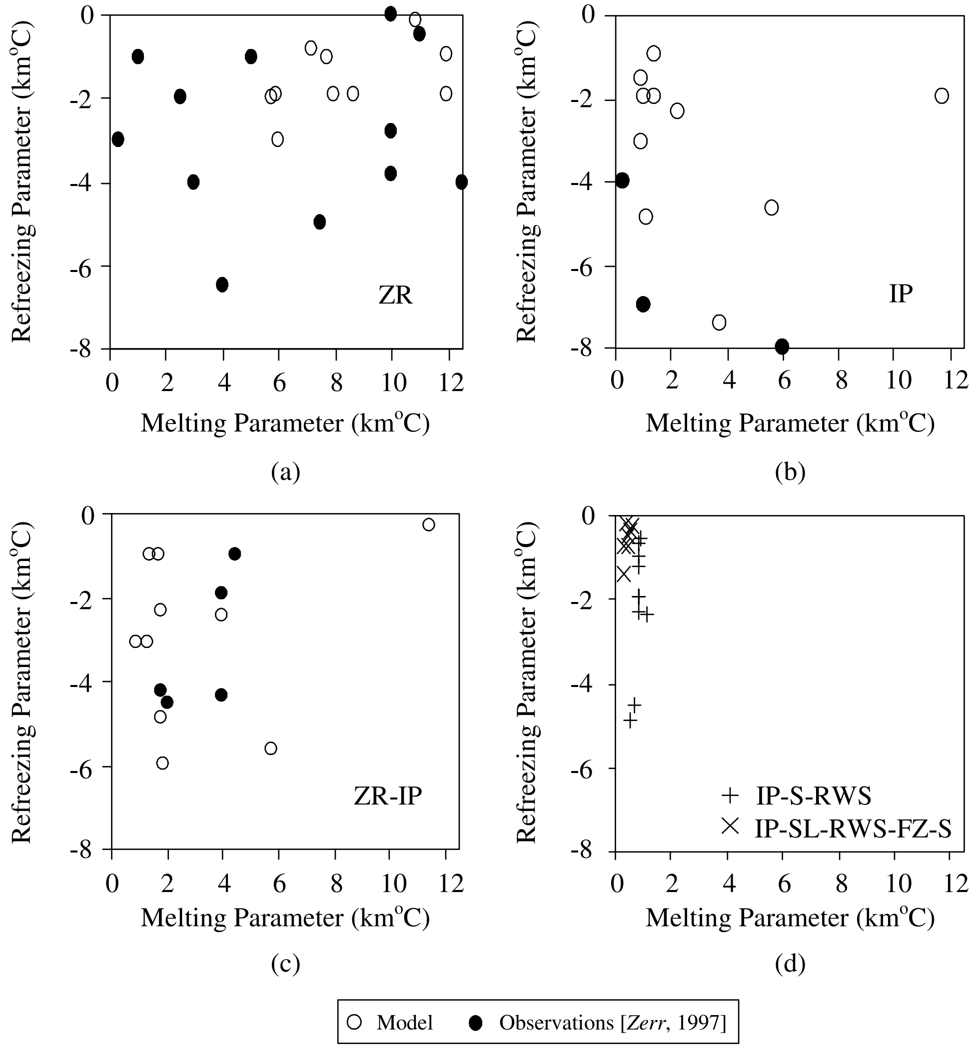

Figure 5. Relation between the refreezing and melting parameter obtained with the bulk microphysics scheme and a comparison with observations [*Zerr*, 1997]. See Table 1 for symbol definitions that are used in the diagram.

[38] These parameters from our calculations as well as from observations [*Zerr*, 1997] are plotted in Figure 5. Freezing rain events are associated with a high refreezing parameter and a high melting parameter (Figure 5a) because freezing rain is more likely to melt completely and not to refreeze. Also, most cases of ice pellets are associated with low refreezing and melting parameters (Figure 5b), indicating that ice pellets are favorable for refreezing without being completely melted reasonable agreement with *Zerr* [1997]. Finally, the ZR-IP events are also associated with similar melting parameters as those for IP events but the refreezing parameter differs (Figure 5c). Some of the refreezing parameters are situated between the ZR and IP events.

[39] It should be noted that some of our ZR, IP and ZR-IP results differed considerably from those of *Zerr* [1997]. This was expected for at least two reasons. First, there is often some degree of uncertainty in the observation of surface precipitation types during winter storms. Reported freezing rain instances can, for example, also include particles having some ice within them. Second, the observed melting parameters calculated by *Zerr* [1997] extend up to 30 km°C. Only the parameters within our range (up to 10 km°C) could be compared with his work. The melting parameter in this study is lower than in the study by *Zerr* [1997] because the maximum temperature of the melting layer used was 6°C but in the atmosphere it is possible to observe freezing rain at a much higher inversion temperature (up to 10°C). This furthermore implies that the lapse rates of the observed temperature profiles will vary considerably more than what was allowed in our calculations.

[40] There are no operational observations of precipitation types associated with partial melting. In principal, *Zerr* [1997] could not include these types in his calculations but model-based calculations of melting and refreezing parameters were nonetheless computed. The IP-RWS-S events are associated with low negative and positive values of the refreezing and melting parameters (Figure 5d). This means that they are not favorable for complete melting but favorable for complete refreezing. Such an evolution is linked with two of the three precipitation types (IP, RWS) [*Stewart*

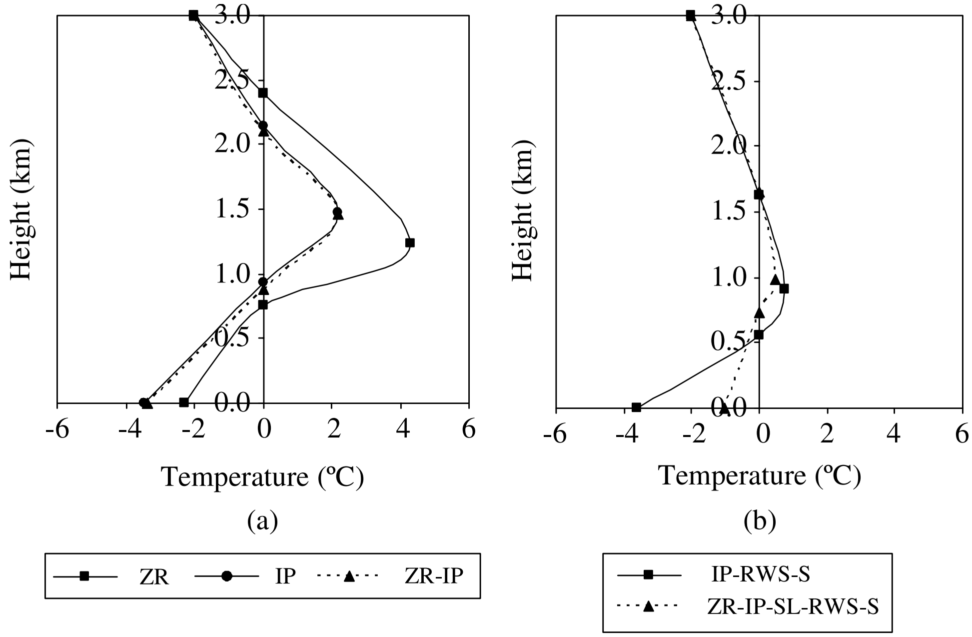

Figure 6. Typical sounding associated with (a) ZR, IP, and ZR-IP and (b) IP-RWS-S and ZR-IP-SL-RWS-S. See Table 1 for symbol definitions that are used in the diagram.

and King, 1987; *Stewart et al.*, 1990a]. A mixture of ZR-IP-SL-RWS-S is associated with a low negative refreezing parameter and low positive values of the melting parameter (Figure 5d). This implies that some of the particles are not susceptible to complete melt or refreeze (SL, RWS). It should be noted that those two combinations are occurring at the end of the evolution, when the temperature inversion is almost eliminated. Thus a small amount of snow can be present.

5.2. Average Soundings for Single Precipitation Types and Their Combinations

[41] An average sounding associated with the surface precipitation studied in section 5.1 is determined by averaging the depth of the melting layer, the maximum temperature, the depth of the subfreezing layer and the minimum temperature for the cases shown in Figure 5a.

[42] The average temperature profiles associated with ZR, IP and ZR-IP are shown in Figure 6a. A warmer temperature and a deeper melting layer are associated with ZR when compared to IP and ZR-IP. This arises because snow will most likely melt completely before reaching the surface. However, ZR-IP is associated with a slightly warmer and deeper melting layer temperature relative to IP but the shallowest subfreezing layer is associated with freezing rain because the rain will not have time to refreeze in the subfreezing layer before reaching the surface. The surface temperature also has an impact on the surface precipitation types: the coldest surface temperatures are associated with ice pellets and the warmest surface temperatures with freezing rain.

[43] The simulations also produced many cases in which a mixture of precipitation types reached the surface at the same time. The average soundings associated with a mixture of ice pellets, refrozen wet snow and snow (IP-RWS-S) as well as a mixture of freezing rain, ice pellets, slush, refrozen wet snow and snow (ZR-IP-SL-RWS-S) are shown in Figure 6b.

[44] The combination of frozen particles (IP-RWS-S) is associated with a deeper and warmer melting layer than ZR-IP-SL-RWS-S. However, both temperatures are near 1°C, where the semimelted particles can form. The greater depth of the melting layer allows more melting of snow. The important features are the temperature and depth of the subfreezing layer. A warmer and shallower subfreezing layer is associated with a mixture of liquid, semimelted and frozen particles (ZR-IP-SL-RWS-S) in comparison with a mixture of frozen particles (IP-RWS-S). This implies less freezing of slush into ice pellets allowing semimelted particles as well as frozen and liquid particles to reach the surface. However, the conditions for IP-RWS-S imply a complete freezing of every particle before reaching the surface.

5.3. Comparison of the Sounding Parameters

[45] The depth and temperature of the melting and subfreezing layer for each precipitation type or combinations of types are shown in Figure 7a. For ZR and ZR-IP, the characteristics of the average depth of the melting and subfreezing layer are comparable to *Zerr* [1997]. For IP events, the melting layer is deeper than the subfreezing layer in the model but the opposite is true in the observations. In general, the comparison illustrates that the patterns of the melting and freezing layer are consistent. The model results show an increase of subfreezing layer depth from ZR to ZR-IP and IP and the opposite for the melting layer depth. However, as mentioned previously in section 5.1, the results are not expected to be completely comparable to observations because of, for example, uncertainties in observed surface precipitation types, and variations in temperature

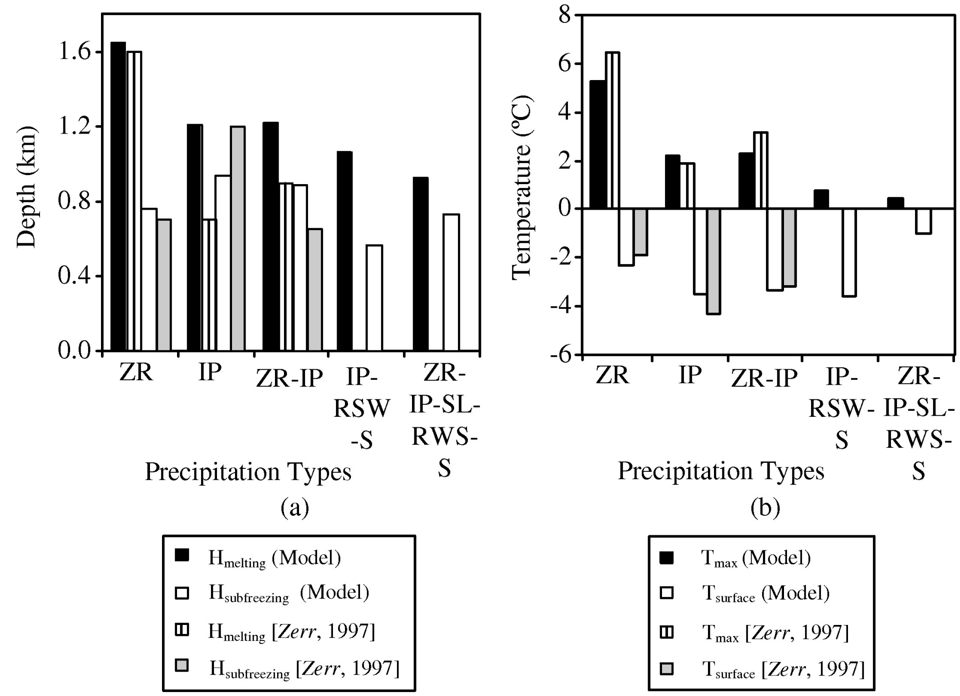

Figure 7. A comparison of the model results and observations [*Zerr*, 1997]. (a) Average depth of the melting and subfreezing layers and (b) average maximum and surface temperatures. See Table 1 for symbol definitions that are used in the diagram.

and moisture profiles between the observations and model experiments.

[46] The maximum and surface temperatures for ZR, IP and ZR-IP have also been compared to the observations analyzed by *Zerr* [1997]. The results obtained with the model compare well with the observations (Figure 7b). However, the maximum temperature associated with ZR is slightly less than the observations. The main reason is due to the range of maximum temperature used in this study. Freezing rain is associated with inversion temperatures up to 10°C [*Zerr*, 1997]. Also, the ice pellet quantity is enhanced by collisional freezing with freezing rain, which is one possible reason that the maximum temperature is almost the same for ZR, IP and ZR-IP. On the other hand, surface temperatures obtained with the model are comparable to the surface temperatures observed by *Zerr* [1997]. However, we did not expect exact agreement because the minimum temperature in his work does not necessarily correspond to the surface temperature. The minimum temperature is often observed above the surface [*Zerr*, 1997], whereas our minimum temperature was always at the surface. Such differences in the subfreezing layer temperature profile were discussed earlier in the paper, when the profile bounds were established (section 3).

[47] Furthermore, because of the fact that semimelted particles are not officially recorded by meteorological instruments [*Environment Canada*, 1992], the comparison between the model-generated precipitation type combinations and observations is impossible. However, IP-RWS-S is associated with the deepest and warmest depth of the melting layer as well as the shallowest and coldest subfreezing layer (Figures 7a and 7b). Thus the large amount of semimelted particles formed in the melting layer will be more likely to refreeze before reaching the surface and a combination of frozen precipitation will occur at the surface. On the other hand, the depths of the melting and subfreezing layers associated with ZR-IP-SL-RWS-S are similar as well as the temperatures of the refreezing and melting layer (near 0°C). That particle type combination is associated with the warmest surface temperature. Thus the conditions are favorable for a combination of liquid, liquid-solid and solid particles to reach the surface.

5.4. Ranges of Temperature and Depth

[48] Many atmospheric conditions can be associated with ZR, IP, ZR-IP, IP-RWS-S and ZR-IP-SL-RWS-S. This section shows that the threshold values of the relevant parameters lead to various precipitation type combinations at the surface.

[49] Figure 8 shows the ranges of melting and subfreezing layer depths as well as the maximum and surface temperature associated with the various single precipitation types and combinations. It is evident that there are classes of winter precipitation in terms of their range of maximum temperature (Figure 8a). IP and ZR-IP are produced within a wide range of temperatures (1–6°C); ZR is produced within a medium range (4–6°C); ZR-IP-SL-RWS-S and IP-RWS-S are only produced within a narrow range (≥1°C). However, all these categories are produced within a wide range of minimum temperature (Figure 8b) except for the combination of liquid, semimelted and frozen particles where the temperature varies from −1°C to −3°C. These three classes arise because of differences in the production processes. A variety of situations can all lead to ZR, IP and ZR-IP.

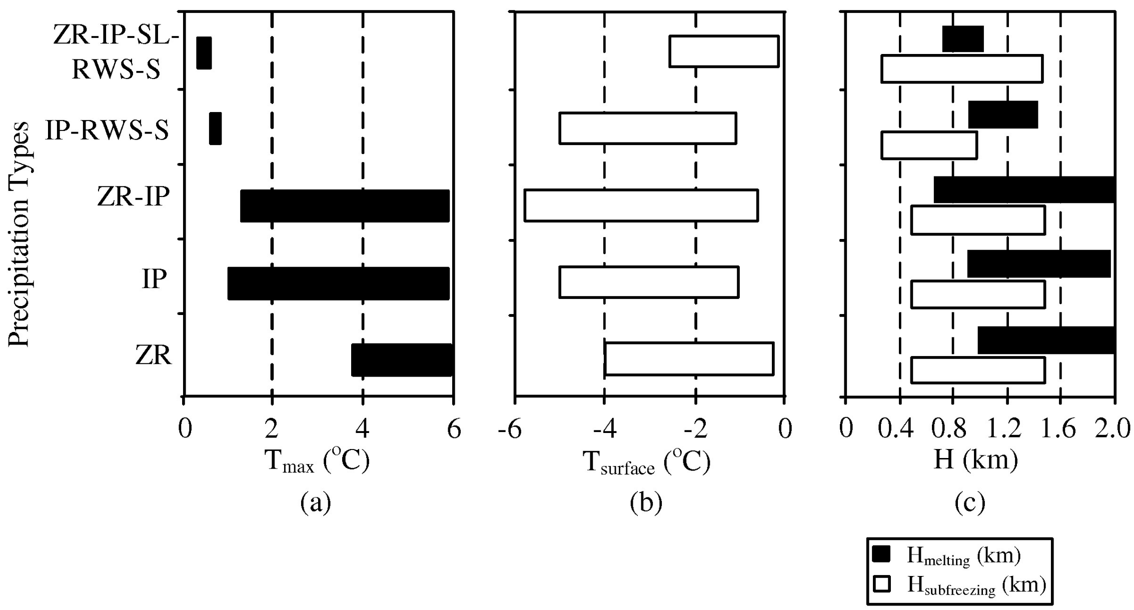

Figure 8. Ranges of (a) maximum and (b) surface temperatures as well as (c) depth of the melting and subfreezing layers associated with ZR, IP, ZR-IP, IP-RWS-S, and ZR-IP-SL-RWS-S. See Table 1 for symbol definitions that are used in the diagram.

However, for the other two combinations, the required precise production mechanisms result in the narrow ranges.

[50] In terms of the depth of the melting and subfreezing layers (Figure 8c), we should point out that ZR-IP-SL-RWS-S is associated with the narrowest range of melting layer depth and the widest range of refreezing layer depth. Also, ZR, IP and ZR-IP have a wide range of melting layer and subfreezing layer depths. However, ZR-IP events have the widest range (up to 1 km) in both the depths of the melting and subfreezing layers in comparison to any other precipitation type or combination.

6. Concluding Remarks

[51] A study of the formation of winter precipitation and its evolution within various environmental conditions has been conducted. The investigation has been carried out using a one-dimensional cloud model coupled with a double-moment microphysics scheme. Various improvements to the scheme, involving the incorporation of semimelted particles, have been made for the purposes of this study. The evolution of various precipitation types formed in a vertical column from snow falling continuously from above a temperature inversion down to the surface has been examined.

[52] The incorporation of semimelted hydrometeor categories had a major impact on the simulation of the various precipitation types within the atmosphere and eventually at the surface. First, wet snow and slush are allowed to form. These are important types of precipitation in many storms. Second, the formation of these forms of precipitation allowed new mechanisms for forming other forms of precipitation. A good example is that the freezing of slush was often the main factor leading to ice pellets. Third, the phase changes associated with partial melting and freezing as well as the formation of other types of particles led to major changes in atmospheric temperature and moisture. This in turn resulted in altered forms of precipitation.

[53] This study provides insight into the pattern of vertical profiles leading to precipitation types and their combinations. Increasing surface temperature, depth and temperature of the melting layer, as well as decreasing depth of the subfreezing layer, enhance the amount of accumulated freezing rain and diminish the amount of ice pellets. In contrast, combinations of particles involving semimelted particles are more likely to be produced from a temperature profile near 0°C.

[54] The occurrence of a particular precipitation type or combinations of types can be associated with a range of atmospheric profiles. A profile is characterized by the depth and temperature of its melting layer as well as by the depth and minimum temperature of its subfreezing layer. First, the profiles leading to each precipitation type and combination of type were quantified through the use of melting and refreezing parameters [e.g., *Zerr*, 1997]. These two parameters exhibited variations for the same precipitation types and their combinations. This illustrates that precipitation types and their combinations are not produced within a single unique profile; some variation is allowed. Secondly, the range of conditions varies greatly with precipitation type or combination of precipitation type. For example, instances of IP and ZR-IP are associated with the widest ranges of conditions whereas instances of ZR-IP-SL-RWS-S are linked with the narrowest ranges. This illustrates that the profiles must be very precise to simulate some combinations, in particular those involving semimelted particles.

[55] This study has highlighted various modeling and observational requirements. First, a critical issue that needs to be addressed in more detail in the future is the evolution and interactions between particles very close to 0°C, both

above and below that value. Particles rapidly change their morphology, phase and terminal velocity in this region. There is often a wide variety of particle types present simultaneously, interacting through collisions resulting from different fall velocities and turbulence. Second, there is a critical need for appropriate observations. Operationally, semimelted particles are not reported at all. There is also a need for detailed experiments that will define the vertical temperature and moisture profile as well as that of the precipitation. Such information would be of enormous help in improving models such as ours.

[56] In conclusion, understanding the physics of the formation mechanisms of winter precipitation types is an important issue for the forecasting of many winter storms. This article has begun to address this crucial issue by examining a number of critical processes affecting the formation of winter precipitation.

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