Winter Precipitation Types and Icing at the Surface

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Abstract—**Winter storms produce major problems for society including icing on surface structures. The objective of this study is to better understand the formation of winter precipitation types, in particular liquid and semi-melted particles, within varying, and interacting, environmental conditions. A one dimensional cloud model utilizing a double-moment microphysics scheme has been improved to address this issue. Temperature and moisture profiles favorable for the formation of different winter precipitation types were varied in a systematic manner in an environment in which snow is falling continuously from above a temperature inversion. The study illustrated, for example, the often-complex manner through which different precipitation types formed including freezing rain and semi-melted particles can have a profound effect on the evolution of precipitation types as well as on icing structure.**

I. Nomenclature

C	Cloud Droplets	R	Rain
ZR	Freezing Rain	I	Ice Crystals
S	Snow	G	Graupel
IP	Ice Pellets	SL	Slush
WS	Wet Snow	RWS	Refrozen Wet Snow

II. Introduction

WINTER storms are often associated with the production of various precipitation types as well as icing on structures. Icing is fundamentally produced by the freezing of liquid and semi-melted particles on a subfreezing surface.

The varying precipitation types occur in the transition region of the storms where the precipitation changes from rain to snow or vice versa. It is often observed along a warm front. Fig. 1 shows the evolution of temperature profile when surface precipitation is changing from snow to rain. This precipitation can exist in different 'states': solid, liquid and solid-liquid combinations. The definitions of many winter precipitation types are found in [1] and they are given in Table 1. It should be noted that there is no definition for mixed phase precipitation which are almost completely liquid but have some ice. In these instances, the original snowflakes are no longer discernible. In the absence of any definition, we define these as 'slush' particles (Table 1).

Mixed phase particles are formed when the environmental temperature is close to 0^{o}C through partial melting or partial freezing. Reference [2] describes the four mechanisms associated with formation of semi-melted particles and these are partial melting, partial refreezing of a semi-melted snowflakes, collision of snowflakes with a raindrop and accretion raising the snowflakes temperature to 0^{o}C.

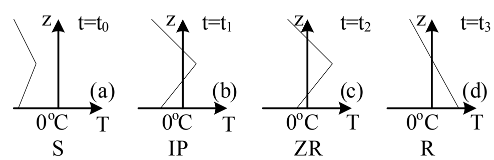

Fig. 1. A typical time evolution of temperature profile and precipitation types at the surface during the passage of a warm front.

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 [3]. In their plans for modeling hazardous winter conditions, they point out that "The most important problem to address is the forecast of *precipitation type*. This is primarily a problem in physics rather than dynamics."

TABLE 1
DEFINITION OF VARIOUS WINTER PRECIPITATION TYPES (GLIKMAN, 2000)

Precipitation Types	Definitions
Rain	Precipitation on 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	Rain that falls in liquid form but freezes upon impact to form coating surface of glaze upon the ground and on exposed object.
Snow	Precipitation composed of white or translucent ice crystals, chiefly in complex branch hexagonal form and often agglomerated into snowflakes.
Ice Pellets	A type of precipitation consisting of transparent or translucent pellets of ice, 5 mm or less in diameter.
Graupel	Heavily rimed snow particles, often called snow pellets. Sometimes distinguished by shape into conical , hexagonal, and lump (irregular) graupel.
Wet Snow	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
Slush	A mixture of liquid and solid in which the original snowflake's shape is not discernible.

Given the importance of winter precipitation types and our gaps in its understanding, the objective of this paper is to better understand the basic physics of liquid and semi-liquid particles formation and its interaction with the environment. A detailed evolution of precipitation types and environmental conditions through a column is examined using typical temperature profiles and by studying various other atmospheric conditions.

III. Model Description

A systematic study of winter precipitation formation has been performed with a 1-D cloud model calling a double-moment microphysics scheme. The double-moment microphysics scheme follows a bulk approach in which the size distributions of each hydrometeor category are represented by an analytic function. Many modifications have been made to the model [4] in order to carry out this study because it was developed by [5] to analyze a summer hailstorm over Alberta. The Section will focus on the new particle category added to the scheme.

To begin, the original double microphysics scheme predicts the total concentration and mixing of six hydrometeor categories which are divided into two different branches: frozen and liquid. Cloud droplets and rain are part of the liquid category and ice, snow, graupel and hail are in the frozen category. Hail will be called ice pellets in this study because winter soundings are used. Their characteristics are described in [5].

Two semi-melted categories have been added in the model: slush and wet snow. Furthermore, we define freezing rain as rain existing below 0^{o}C. We further assume that wet snow freezes at temperature below 0^{o}C to form refrozen wet snow.

Melting occurs at warm temperatures and in our calculations we assume that semi-melted particles are therefore formed when the wet bulb temperature between 0^{o}C and 1^{o}C. Within that temperature range, the amount of melted snow is divided into three *equal* categories: rain, slush and wet snow. This breakdown refers to whether the particles have melted completely, a great deal, or a little. However, no constraint on the particle's diameter has been assumed. If little melting has occurred the particle still appears to be like snow but droplets occur on the lattice structure. If more melting has occurred the particles will have collapsed down to a drop with a similar shape but it still contains some ice. 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 double-moment microphysics scheme, wet snow is described like a snowflake and slush like a raindrop (in terms of size distribution and sedimentation). Also, we assume that wet snow melts at temperatures > 1^{o}C into 2 equal categories: rain and slush, slush completely changes into rain at temperatures > 1.5^{o}C. The thresholds for categories have been chosen to be consistent with the limited available observations [6]. 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.

Slush is considered to be similar to a raindrop in that it can evaporate but it contains ice so it also freezes at temperature < 0^{o}C. In this case, the freezing will produce an ice pellet. It has been recognized that ice pellets mainly form by refreezing semi-melted snowflakes having a high percentage in liquid compared to ice [7].

The rate of refreezing of the semi-melted 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 into ice pellets is assumed to be -3^{o}C, based upon surface observations of ice pellets reported by [8]. Thus, complete refreezing of the particle occurs at that temperature. Slush has a higher probability of freezing than a supercooled drop because the small fraction of ice within it activates the freezing process. However, no slush will refreeze at temperature ≥ 0 ^{o}C. The latent heating due to the refreezing of semi-melted particles is calculated from the mixing ratio of slush converted into ice pellets [4]. 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.

The microphysical processes allowed for wet snow are sublimation and melting because it is similar to other frozen particles. Because only a small amount of water is assumed to be present on the surface of the wet snowflakes, freezing of wet snow generates refrozen wet snow (T < 0^{o}C) without releasing a significant amount of latent heating.

IV. Experimental Design

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 will describe the experimental procedures employed.

We defined a typical temperature profile favorable for their formation (Fig. 2). Similar soundings have been observed during winter storms [8], [9]. However, most soundings observed have a minimum temperature above the surface instead of being at the surface. That particular profile is often at least somewhat a consequence of latent heating releases from the freezing rain freezing at the surface [10] which we neglect in this study.

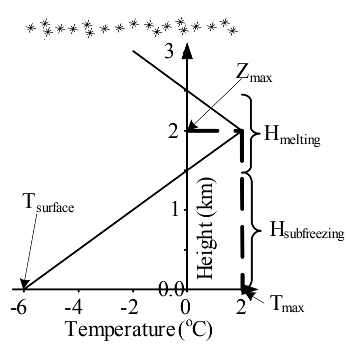

Fig. 2. Description of the sounding parameter: Surface temperature ($T_{surface}$), maximum temperature and its height (T_{max}, Z_{max}), depth of the melting layer ($H_{melting}$), depth of the subfreezing layer ($H_{subfreezing}$). The typical sounding studied is that temperature profile in saturated conditions.

In our typical situation, we drop snow continuously at 5 mm/h water equivalent from 3 km above the surface into our temperature and moisture defined environment. It is falling into the melting layer of the atmosphere and, depending on the atmospheric conditions, phase changes may occur, forming various types of particles.

A detailed study of the typical temperature profile has been carried out. Also, a systematic variation of the surface temperature, the depth of the subfreezing layer and the maximum temperature of the inversion were varied systematically have been defined. These parameters directly influence the amount and type of precipitation formed [9]. The temperature profiles studied are shown in [4].

V. WINTER PRECIPITATION TYPES EVOLUTION

A detailed study of winter precipitation type formation has been carried out with a double-moment microphysics scheme [5]. The following results show the evolution of the precipitation types at the surface and aloft as well as their interaction with the environment.

A. Temperature, Moisture and Precipitation Types Profiles Comparison

First, the model has been run with the original scheme (i.e. without the semi-melted category) initialized by the typical sounding (Fig. 2). It shows an illustrative example of the temperature and moisture profile with the associated precipitation types after 60 min (Fig. 3 a&b). This time was chosen because it represented when almost half of the temperature inversion had disappeared and many precipitation types have been formed within the atmosphere. Snow initially falls from 3 km, when it reaches the melting layer it melts and cools the atmosphere generating an isothermal layer of 0^{o}C. The cooling generated by this melting led to supersaturation and the formation of cloud droplets by condensation which acted to warm the environmental air and therefore to somewhat reduce the cooling-by-melting effect. The rain formed from melting of snow is changed into freezing rain within the subfreezing layer.

The model was next run using the modified scheme allowing the formation of semi-melted particles. Fig. 3c&d shows 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 semi-melted particles are only formed when the temperature is between 0^{o}C and 1^{o}C and wet snow is allowed to melt into rain and slush at temperatures between 1^{o}C and 1.5^{o}C. The melting of snow decreases the temperature and generates an isothermal layer at 0^{o}C. Again, the cooling by melting causes supersaturation triggering cloud droplet formation. That process acts to reduce the cooling impact of melting.

When the rain reaches the subfreezing layer, it changes into 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 drops increase the amount of ice pellets, decrease the amount of freezing rain, warm the atmosphere as a result of the freezing, and therefore a subsaturated layer is formed below the inversion.

Comparing Fig.s 3b&d, many more precipitation types are formed within the atmosphere when semi-melted particle formation is included in the model than when they are not allowed to form. Without semi-melted particles, cloud, rain, graupel and freezing rain only are formed. In contrast, with semi-melted particles, cloud, rain, freezing rain, graupel, wet snow, refrozen wet snow, slush, and ice pellets are formed.

Finally, it should also be noted that the temperature and moisture profiles are somewhat different (Fig. 3a&c). For example, subsaturation occurs near the surface when no semi-melted particles are allowed and it occurs just below the melting layer when these particles are allowed as well as a greater warming near the surface. The subsaturated layer near the surface is formed by collision between ice pellets and freezing rain drops in both cases. However, only the case considering semi-melted particles generates a subfreezing layer below the inversion due to the freezing of slush into ice pellets.

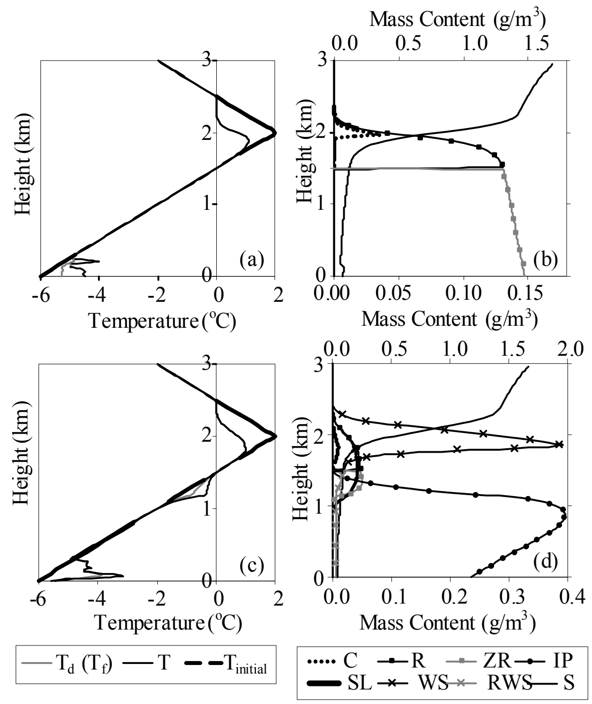

Fig. 3. The temperature (T), moisture and precipitation type profiles initialized by sounding (Fig. 2) after 60 min. T_d (T_f) is the dew (frost) point when the moisture profile is > 0^{o}C (< 0^{o}C). The upper axis of the right hand plot shows the mass content of snow and the lower axis shows the mass content of the other precipitation types. Upper plots are associated with no semi-melted particles formed and the lower ones are associated with formation of semi-melted particles.

B. Surface Precipitation Types Comparison

The comparison of the evolution of surface precipitation types is shown in Fig. 4. Fig. 4a shows the surface precipitation types associated with the conditions in which the formation of semi-melted particles is not allowed. In the first hour, graupel, ice pellets and freezing rain are reaching the surface. Then, freezing rain followed by snow is falling at the surface. However, with semi-melted particles allowed (Fig. 4b), the precipitation types reaching the surface first are ice pellets and a small amount of graupel with 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 rain drops and frozen particles as well as refrozen slush produces by semi-melted snowflakes and wet snowflakes. However, the second peak in ice pellets is produced by frozen slush formed by the semi-melting of snow.

The drop in the total precipitation rate in the case associated with no semi-melted particles is linked with at least two factors. First, evaporation and sublimation above the surface act to reduce the overall precipitation rate until steady state conditions of complete saturation are obtained. Second, in the case considering no semi-melted 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. There is a “gap” in time required for the snow to reach the surface after the freezing rain. In the case considering semi-melted particles, 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 end of the wet snow, which produces less slush to refreeze into ice pellets.

The formation of semi-melted particles within the melting layer enhances the amount of ice pellets and eliminates the amount of freezing rain near the surface which will reduce icing. However, icing can still occur aloft because of freezing rain and slush can not yet change into ice pellets. This arises because the formation of semi-melted 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 (freezing rain) due to, for example, collisions with ice particles (collisional freezing). The semi-melted inclusion gives a better reproduction of the different types of winter precipitation and has implications for the formation of other precipitation types.

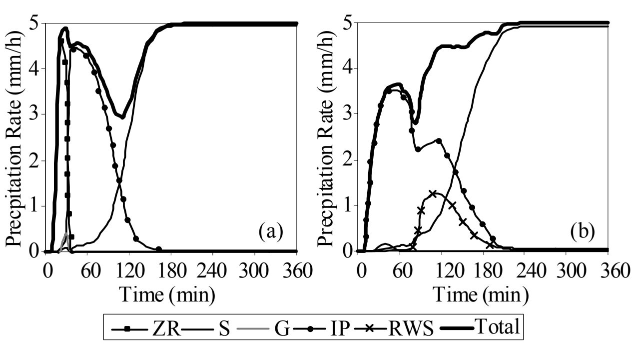

Fig. 4. Comparison of the surface precipitation evolution associated with sounding (Fig. 2). (a) Surface precipitation excluding the semi-melted categories, (b) Surface precipitation including the semi-melted categories

VI. AVERAGE TEMPERATURE PROFILE

A. Relation Between Sounding Parameter and Precipitation Types

To quantify the contribution of the melting layer and its maximum temperature as well as the subfreezing layer and its minimum temperature, a melting and refreezing parameter has been used. This is based on the work done in [9] who analyzed soundings associated with surface precipitation types. The initial soundings studied are described in [4].

Observed temperature profiles associated with single and various combination precipitation types at the surface have been chosen. Five combinations have been studied because they were the most common ones in our calculations. We choose the extremes situations.

- *Freezing rain (ZR)*: > 99% of the total precipitation was freezing rain
- *Ice pellets (IP)*: > 90% of the total precipitation was ice pellets
- *Freezing rain and ice pellets (ZR-IP)*: Approximately 50% of each precipitation type was present
- *Ice pellets, refrozen wet snow and snow (IP-RWS-S)*: > 3% of the total amount of precipitation was refrozen wet snow mixed with ice pellets and snow
- *Freezing rain, ice pellets, slush, refrozen wet snow and snow (ZR-IP-SL-RWS-S)* : > 1% of the total precipitation types was slush mixed with freezing rain, ice pellets, refrozen wet snow and snow

From now on, the symbols above describing the precipitation type combinations will be used for easier reading. The data used are described in [4]. However, we will focus on liquid and semi-liquid cases.

From [9], a calculation of the refreezing and the melting parameter is carried out to examine the influence of the melting and subfreezing layer on the surface precipitation. The melting parameter is the product of the depth of the melting layer and its maximum temperature and the refreezing parameter is the product of the depth of the subfreezing layer and the minimum temperature. A large positive value of the melting parameter is related to 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.

These parameters are plotted in Fig. 5a&b from our calculations as well as from observations [9]. Also, freezing rain events are associated with a low refreezing parameter and high melting parameter. This is partially due to the fact that freezing rain is more likely to completely melt and not refreeze. Many of these results are comparable to [9]. Finally, the ZR-IP events are also associated with similar melting parameters to those of IP events but the refreezing parameter differs. Some of the refreezing parameters are situated between the ZR and IP events.

It should be noted that some of our ZR, IP and ZR-IP results differed considerably from those in [9]. 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 [9] extend up to 30 km^{o}C. Only the parameters within our range (up to 10 km^{o}C) could be compared with his work. The melting parameter in this study is lower than [9] 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 allowed for in our calculations. Also, few ZR-IP events have been observed in our calculations.

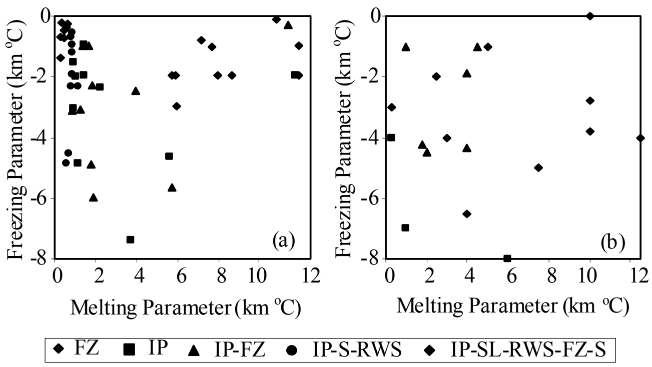

Fig. 5. Relation between the refreezing and melting parameter associated with various surface precipitation types. (a) is the present model and (b) is observed results [9].

There are no operational observations of precipitation types associated with partial melting and [9] could therefore not include these types in his calculations but model-based calculations of melting and refreezing parameters were nonetheless calculated. A mixture of ZR-IP-SL-RWS-S is associated with a low negative refreezing parameter and low positive values of the melting parameter. This implies that some of the particles are not susceptible to complete melting or refreezing (SL, RWS) [7]. 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.

B. Average Soundings for Single Precipitation Types and their Combinations

An average sounding associated with the surface precipitation studied in the previous Section 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.

The average temperature profiles associated with ZR, IP and ZR-IP are shown in Fig. 6a. A warmer temperature and a deeper melting layer are associated with ZR in comparison with IP and ZR-IP. This arises because snow will most likely completely melt before reaching the surface. However, ZR-IP is associated with a slightly warmer and deeper melting layer temperature compared to IP. However, 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 warmest surface temperatures are associated with freezing rain.

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 Fig. 6b.

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 formation of semi-melted particles is allowed. The greater depth of the melting layer allows more melting of snow. The important characteristic is the temperature and depth of the subfreezing layer. A warmer and shallower subfreezing layer is associated with a mixture of liquid, semi-melted 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 semi-melted particles to reach the surface as well as frozen and liquid particles. However, the conditions for IP-RWS-S imply a complete freezing of every particle before reaching the surface.

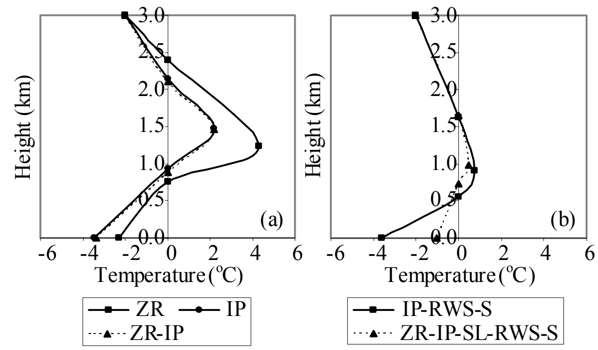

Fig. 6. Typical sounding associated with (a) ZR, IP and ZR-IP as well as (b) IP-RWS-S and ZR-IP-SL-RWS-S.

C. Ranges of Temperature and Depth

Many atmospheric conditions can be associated with ZR, IP, ZR-IP, IP-RWS-S and ZR-IP-SL-RWS-S. This section will show the threshold values of these parameters leading to various precipitation type combinations studied at the surface.

Fig. 7 shows the maximum and surface temperature ranges 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 temperature. 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 those categories are produced within a wide range of minimum temperature except for the combination of liquid, semi-melted and frozen particles where the temperature varies from -1°C to -3°C. These three classes arise because of differences in production processes. A variety of situations all lead to ZR, IP and ZR-IP. However, for the other two combinations, they require precise production mechanisms which lead to the narrow ranges.

In terms of the depth of the melting and subfreezing layer (Fig. 8), we should point out that ZR-IP-SL-RWS-S is associated with the narrowest range of melting layer depth and 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 depth of the melting and subfreezing layer in comparison to any other precipitation type or combination.

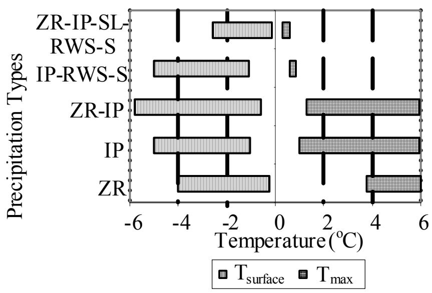

Fig. 7. Ranges of maximum and surface temperature associated with ZR, IP, ZR-IP, IP-RWS-S, ZR-IP-SL-RWS-S.

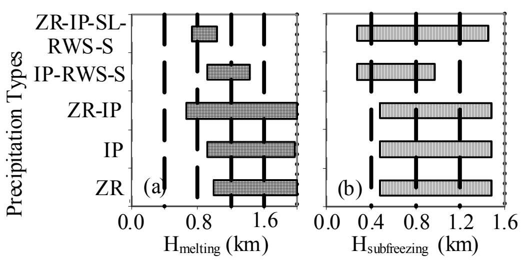

Fig. 8. Ranges of the depths of the melting and subfreezing layers associated with ZR, IP, ZR-IP, IP-RWS-S, ZR-IP-SL-RWS-S.

VII. Concluding Remarks

An improved understanding of winter precipitation formation, in particular the ones leading to icing (liquid and mixed phase particles) has been achieved in this study.

The incorporation of semi-melted hydrometeor categories had a major impact on the simulation of the various precipitation types within the atmosphere and eventually at the surface. First of all, this allowed for the formation of wet snow and slush. These are important types of precipitation in many storms. Second, the formation of these forms of precipitation allowed new mechanisms of 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 the atmospheric temperature and moisture. This in turn led to altered forms of precipitation.

The study also showed that the occurrence of a particular precipitation type or combinations of types can be associated with a range of atmospheric profiles. First, the melting and refreezing parameters (such as [9]) 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. Instances of, for example, 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 semi-melted particles. It should be noted that all the cases studied have a surface temperature below 0^{o}C, thus cases associated with liquid and semi-liquid particles would be associated with icing at the surface.

In conclusion, understanding the physics of the formation mechanisms of winter precipitation types is important for the forecasting of many winter storms and associated icing. Right now, empirical techniques are generally used to account for this varying form of precipitation. However, the development of a microphysics scheme able to predict liquid particles, solid particles and those with a mixture of solid and liquid will be a big improvement to the field. This research has begun to address this crucial issue of examining a number of critical processes affecting the formation of winter precipitation and its types leading to icing.

VIII. Acknowlegment

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