ON THE CHARACTERISTICS OF AND PROCESSES PRODUCING WINTER PRECIPITATION TYPES NEAR 0°C

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Particle characteristics, formation mechanisms, and wind field impacts on distributions of winter precipitation types, such as freezing rain and ice pellets, are discussed.

Most of us are quite familiar with winter precipitation. The typical image one has is of snow. But, a wide variety of precipitation types occurs at temperatures near 0°C including freezing rain, freezing drizzle, ice pellets, snow pellets, and wet snow that can occur alone or in combinations.

Such precipitation leads to major impacts (Fig. 1). In Canada, examples include the 1998 Ice Storm, which was the most costly natural disaster in the country's history (Risk Management Solutions 2008) until a 2013 flooding event in Alberta. It was recognized as early as the 1950s that ice storms are the most striking hazard for many Canadian communities (Hewitt and Burton 1957). Audrey et al. (2005) conducted a study involving collisions on roads during precipitation in 27 cities across Canada and found that freezing precipitation and rain mixed with snow were the types of precipitation most likely associated with collisions leading to major injuries. In the United States, Changnon (2003) pointed out that 87 freezing rainstorms over the period 1949–2000 caused property damage in excess of $1 million. Houston and Changnon (2007) also showed that freezing rain has the potential for a more severe societal impact than snowfall or rainfall for the same mass of precipitation. In Germany, Frick and Wernli (2012) pointed out the many consequences on infrastructure and transportation of a devastating 2005 wet snow event. The aviation industry is especially susceptible to impacts from winter precipitation types, not just aloft from supercooled rain, freezing drizzle, or wet snow (see, e.g., Cober et al. 2001) but also at the surface with hazardous icing from these precipitation types as well as from combinations such as ice pellets with freezing rain (Rasmussen et al. 2001; Federal Aviation Administration 2005).

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Fig. 1. An illustration of ice accumulation from freezing rain. This event occurred on 20 March 2008 in Moncton, NB, Canada. [Photograph courtesy of M. Grandmaison.]

Winter precipitation types can have immense impacts on ecosystems and wildlife. Irland (2000), Millward and Kraft (2004), and Zhou et al. (2011) pointed out that freezing rainstorms lead to major direct impacts on forests and these in turn may lead to secondary consequences such as soil erosion and landslides. Rain falling on snow leads to an ice crust and, in regions where food is only available for animals in winter by pawing through the snow, this can lead to devastating consequences (Putkonen et al. 2009; Hansen et al. 2013).

Several studies have examined the climatology of this precipitation. Carriere et al. (2000) developed a freezing precipitation (freezing rain, ice pellets, and freezing drizzle) climatology over western and central Europe and found that it is not uncommon, with a frequency on the order of 0.5%–1% of all reports. Cortinas et al. (2004) found that these precipitation types occur most frequently over the central and eastern United States and Canada and that Newfoundland has the highest values of approximately 50, 30, and 80 h annually of freezing rain, ice pellets, and freezing drizzle, respectively. Cortinas et al. (2004) also pointed out the importance of topographical features, water source proximity, and extratropical cyclone tracks on the occurrence of this precipitation.

A number of studies have examined the large- and mesoscale weather patterns associated with winter precipitation types. For example, Rauber et al. (2001b) found that seven types of weather systems lead to freezing rain in the eastern part of the United States, and Ressler et al. (2012) pointed out the varying synoptic conditions leading to freezing rain in the St. Lawrence valley. Many in-depth case studies have also been carried out, especially for freezing precipitation (see, e.g., Martner et al. 1992; Rauber et al. 1994; Roebber and Gyakum 2003). Collectively, there has been substantial progress made in understanding the flow patterns associated with many of the precipitation types, especially over North America.

Attention has also been paid to trends in the occurrence of winter precipitation types. Studies such as Mekis and Vincent (2011) over Canada and Nayak et al. (2010) over portions of the Rocky Mountains illustrate a general shift toward more rain and less snow over the last few decades. Hanesiak and Wang (2005) inferred an increase in freezing rain occurrence in some areas of the Canadian Arctic. Furthermore, Cheng et al. (2011) and Lambert and Hansen (2011) inferred future freezing rain occurrence using climate scenario information over North America. Both studies predicted a substantial northward shift of the belt of freezing rain. However, Lubchenco and Karl (2012) pointed out that freezing rain is one of the most poorly understood types of extreme events over the United States and so one needs to be cautious in interpreting its trends.

Although there have been a number of studies of synoptic and mesoscale weather patterns, climatology, and trends associated with winter precipitation types, there continues to be a need to examine them from a precipitation physics perspective. It has been 20 years since the last review of the formation mechanisms, characteristics, and organization of winter precipitation types (Stewart 1992) and significant progress has been made.

We feel that it is important to have a firm grasp of the detailed nature of the precipitation near 0°C. Although many factors need to be considered in its full understanding and prediction, these need to rest on a strong foundation of understanding the precipitation itself. Perhaps there is a sense that this foundation is already in place, but we feel that there are still considerable uncertainties. This article seeks to raise awareness of this precipitation by summarizing and synthesizing our understanding of the physics of its formation, identifying some of the associated science gaps, and commenting on prediction implications.

This article therefore examines a subset of the overall needs identified in Ralph et al. (2005) in the report on a workshop addressing improvements in short-term cool season quantitative precipitation forecasting (QPF). All four workshop working groups reporting in Ralph et al. (2005) identified issues and challenges associated with precipitation type among their key findings, with the data assimilation and modeling working group stating that "the most serious problem associated with wintertime QPF is the accurate determination of precipitation type when the surface temperature is near freezing."

TYPES AND THEIR CHARACTERISTICS.

There are many types of winter precipitation. They can be liquid, solid, or a combination. The particle density, size, shape, and terminal velocity can vary as well. The typical precipitation types referred to in the community are summarized in Table 1.

Recent findings on ice pellets characteristics lead to the need for clarification of their definition. Ice pellets can fall as aggregates; that is, a particle can fall that is a combination of more than one ice pellet (Crawford and Stewart 1995; Gibson and Stewart 2007; Gibson et al. 2009). This type of particle is probably the same as that mentioned by Brooks (1920) as "agglomerations." Aggregates made up of several tens of components have been reported, although 2–3 components is most common. These components may be relatively distinct or they can be fused together into one mass.

Even the term "wet snow" does not do justice to the wide variations in liquid water fraction that occur within this precipitation type. For a snowflake largely composed of dendritic crystals, Mitra et al. (1990) found a sharp increase in the melting particle's terminal velocity at a liquid fraction of approximately

Table 1. Official and unofficial definitions of terms for winter precipitation types discussed in this article. Official definitions refer to those found in the online version of the *Glossary of Meteorology* (Glickman 2000).

Name	Definition
Ice particles	
Ice crystal[a]	Pristine ice crystal
Ice pellet[a]	Type of precipitation consisting of transparent or translucent pellets of ice, 5 mm or less in diameter
Ice pellet aggregate[d]	Individual ice particles linked or fused together
Refrozen wet snow[b]	Partially melted snow that refroze
Sleet[a]	In the United states, this term refers to ice pellets
Snow[a]	Precipitation composed of white or translucent ice crystals, chiefly in complex branch hexagonal form and often agglomerated into snowflakes
Snow pellet[a]	Precipitation consisting of white, opaque, approximately round (sometimes conical) ice particles having a snowlike structure, and about 2–5 mm in diameter
Liquid particles	
Drizzle[a]	Very small, numerous, and uniformly distributed water drops; by convention, drizzle drops are less than 0.5 mm in diameter
Freezing drizzle[a]	Drizzle that falls in liquid form but freezes upon impact to form a coating of glaze
Freezing rain[a]	Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground and on exposed objects
Rain[a]	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
Supercooled rain[a]	Liquid precipitation at temperatures below freezing
Mixed-phase particles	
Almost melted particle[b,d]	Precipitation mainly composed of liquid water, but with some ice, and the original ice particle's shape is not discernible
Liquid core pellet[c]	Partially refrozen particle with an ice shell and liquid water within it
Semimelted snow pellet[d]	Snow pellet that has undergone some melting
Wet snow[a]	Snow that contains a great deal of liquid water

[a] Glickman (2000).

[b] Thériault et al. (2006).

[c] Thériault and Stewart (2007).

[d] Terminology used in this article.

70%, suggesting that this may be a threshold for wet snowflakes to collapse into another form. It is not known how this threshold varies between snowflakes composed of different crystals. As well, Stewart et al. (1995) measured wet snow fractions of 20%–40% in a storm occurring over Newfoundland. No other quantitative measurement of the liquid fraction of snowflakes has been found in the literature. The fraction of liquid in wet snow therefore varies from minimal values to a maximum on the order of 70%.

Some types of winter precipitation do not have an official definition and these are also included in Table 1. For example, a term has not been officially developed for the partially melted precipitation that has collapsed from its original snowflake shape. As discussed in several articles (Knight 1979; Matsuo and Sasyo 1981a,b,c; Fujiyoshi 1986; Mitra et al. 1990), liquid droplets first appear at the tips of a snowflake during melting and then within the crystal lattice, but the snowflake does not collapse. This is wet snow. Only later, after more melting has occurred, does the snowflake collapse into a semispherical particle composed of both liquid and solid. We will refer to this as an almost melted particle in the rest of this article. The ice eventually fully melts to form a drop.

It was also not until recently that the phrase "liquid core pellets" was referred to in the literature (Thériault and Stewart 2007). However, Kimura and Kajikawa (1984) must have observed these particles since they noted that some "outer shells of ice spheres partially filled with water" had fallen along with ice pellets in a Japanese storm.

Even if all these types of precipitation, or the subtleties of officially defined precipitation, are not referred to commonly, it is important to recognize their existence. As discussed in other parts of this article, they can be essential to the formation of other precipitation types and their presence can affect, for example, remote sensing interpretations.

FORMATION OF PRECIPITATION TYPES.

Melting and refreezing processes. Ice-phase processes such as melting and freezing are often linked with the formation of the various types of winter precipitation (Figs. 2 and 3). There are many pathways for precipitation in various forms to reach the surface and such forms can furthermore occur simultaneously. These pathways will be discussed in more detail below in this and in other parts of the article.

Depending on temperature and moisture conditions, different types of ice crystals are formed aloft (as summarized by, e.g., Libbrecht 2005). These often collide to form snowflakes, which melt at least partially as they fall toward the surface in a layer with wet-bulb temperatures above 0°C. They may reach the surface in this environment or they may fall into a lower, subfreezing layer where they at least begin to refreeze. For particles undergoing refreezing with an

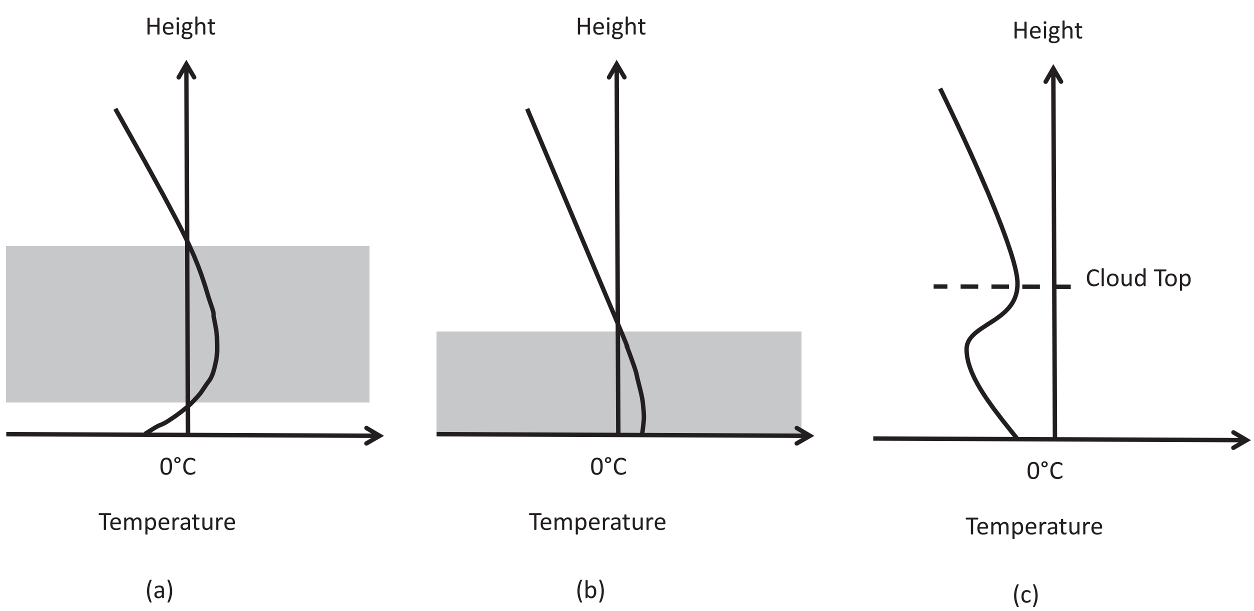

Fig. 2. Schematic temperature profiles associated with (a) ice-phase-related production of freezing precipitation; (b) wet snow, almost melted particles, and rain; and (c) freezing drizzle. [Panels (a),(b) are adapted from Frick and Wernli (2012) and (c) is adapted from Bernstein (2000).] Shading indicates the melting layer, a lower subfreezing layer is shown in (a), and the inclusion of cloud top in (c) was made to indicate its relatively low height in association with freezing drizzle.

ice shell, internal pressures can deform or fracture the original particle or produce spicules; such processes can increase particle concentrations (see, e.g., Gibson and Stewart 2007; Stewart and Crawford 1995).

Collisions aloft may involve cloud droplets as well. Collisions of supercooled droplets with ice crystals can lead to snow pellets and collisions with larger snowflakes can lead to accreted snowflakes. Although speculative, the subsequent melting and at least partial freezing of these accreted particles may follow somewhat different paths in terms of precipitation types. A semimelted snow pellet is already somewhat compact; its freezing would result in a particle that would probably be referred to as an ice pellet. If the snow pellet melts enough, however, it would collapse down to an even smaller size (an almost

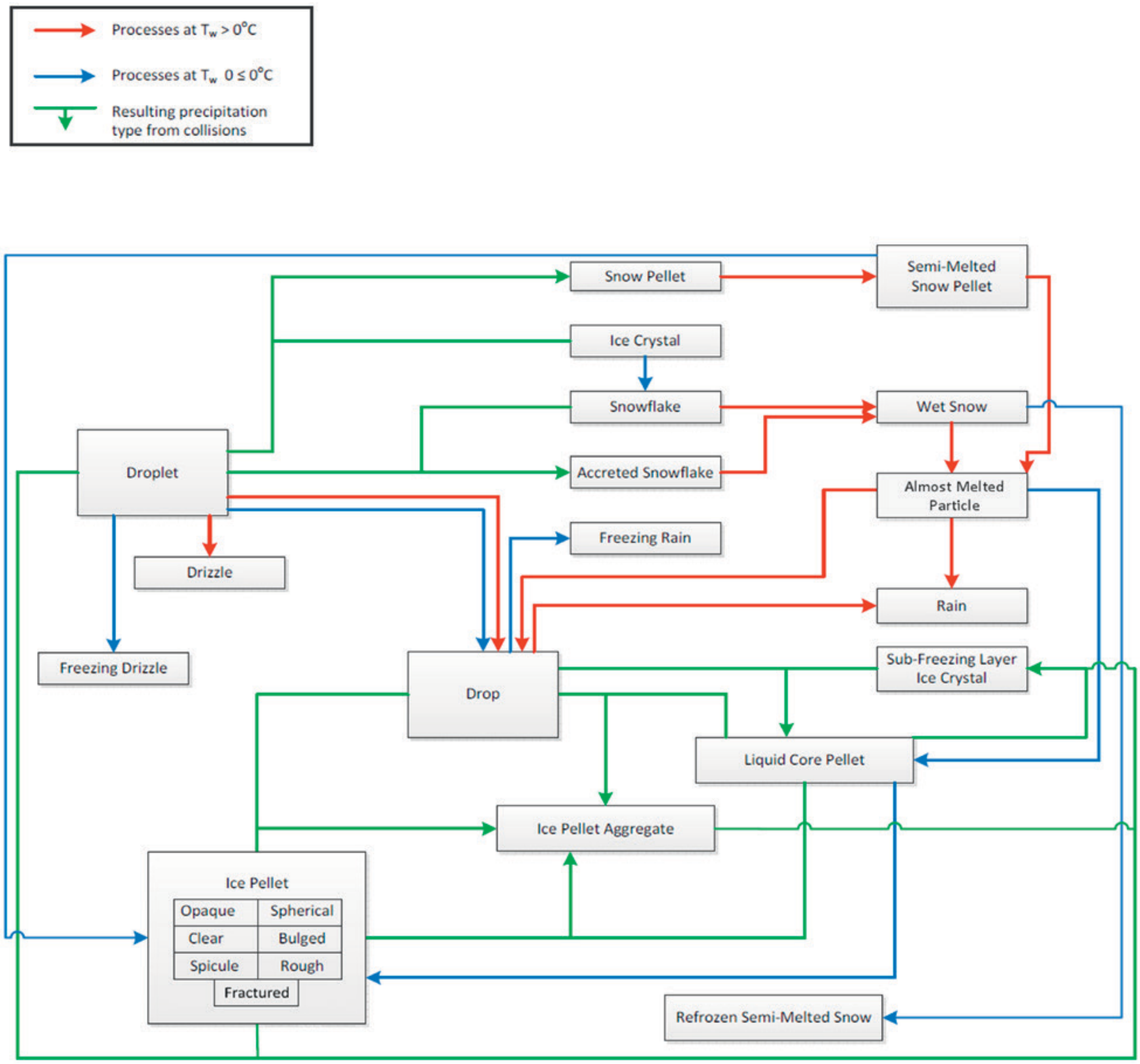

Fig. 3. Schematic diagram illustrating some of the possible pathways through which winter precipitation types are produced near 0°C. Wet-bulb temperature is shown by T_w (although particle temperature can be different) and some of the pathways can occur simultaneously. Processes besides melting, freezing, and collisions (e.g., condensation and deposition) are sometimes associated with the production of the precipitation types but are not shown. It is assumed that nucleation led to the initial production of (cloud) droplets and ice crystals; nucleation can also initiate the freezing of drops that are further assumed to evolve into liquid core pellets; and almost melted particles begin to freeze as liquid core pellets. Special attention is paid to ice crystals that may be formed in the subfreezing layer below an inversion through collisions between (cloud) droplets and ice pellets, liquid core pellets, or ice pellet aggregates. Partial melting if temperatures exceed 0°C just above or at the surface is not included in this schematic.

melted particle), which, on freezing, would still be referred to as an ice pellet. Visually, the former path would probably lead to an opaque ice pellet whereas the latter, with little ice within, may be almost clear, although embedded air bubbles also affect its opacity. In contrast, a large accreted snowflake would need to melt substantially before it collapsed so that its subsequent freezing would lead to an ice pellet. It is not known whether the approximate 70% threshold for the collapse of snowflakes, as referred to earlier, would apply to accreted snowflakes.

As discussed in the preceding paragraphs, the formation of many types of winter precipitation near 0°C involves at least partial phase changes, although melting and freezing processes at such temperatures are difficult to quantify due to their complexity (see, e.g., Knight 1979). The governing heat and mass transfer equations have been described by, for example, Pruppacher and Klett (1997) and updated recently by Thériault and Stewart (2010). In the case of the winter precipitation types discussed in this article, temperatures are not far from 0°C and so times and distances to melt in and above the freezing layer are long. As well, there is always a spectrum of ice particle sizes aloft and the largest particles in terms of radius typically melt the slowest. So, the smallest particles at temperatures above 0°C (in a saturated environment) tend to be liquid and the largest ones tend to be the least melted.

An important issue is whether and, if so, how the freezing process is initiated in the subfreezing layer below an inversion. Particles falling into this layer with some ice will immediately start to freeze but supercooled raindrops will not necessarily freeze. If cold enough, there is a chance that these supercooled raindrops will be nucleated and begin to freeze toward ice pellets as inferred in previous studies, including that by Zerr (1997). It may be that liquid core pellets are always produced during this freezing but this has not been shown. Thériault et al. (2010) suggested that this factor decreased the amount of freezing rain in the 1998 Ice Storm affecting Montreal, Quebec, Canada.

Few studies have examined the drop size distribution of freezing rain but substantial variations have nonetheless been noted. In particular, Chen et al. (2011) found a relatively large number of small drops, whereas Iwai (1970) found a dearth of small drops and an abundance of large drops when compared with the expected Marshall–Palmer distribution. Given the relatively low precipitation rates typically associated with freezing rain, often substantially less than 10 mm h^{-1}, and the relatively shallow distances over which the spectra can evolve, such widely different results likely reflect substantial differences in the initial particles aloft. As well, if large drops are observed in freezing rain events, there must be a sufficiently warm and/or deep melting layer for those to occur; otherwise, a kernel of ice will remain within the hydrometeor by the time it reaches the subfreezing layer and it would freeze into an ice pellet or a liquid core pellet. The two studies, Iwai (1970) and Chen et al. (2011), examined events with only freezing rain; a later part of this article discusses size spectral features when combinations of precipitation types, including freezing rain, occur.

One additional consideration is that the melting and/or subfreezing layer may be subsaturated, in which case the ensuing evaporation would preferentially eliminate the small drops. This may have been a factor in producing the drop size spectra observed by Iwai (1970).

Liquid-phase processes. Liquid-phase processes are associated with the formation of freezing drizzle as well as some freezing rain (see, e.g., Huffman and Norman 1988). These processes operate when water vapor condenses and the precipitation particles are formed as supercooled droplets. If the droplets do not travel through an environment cold enough to initiate freezing through ice nucleation as they fall, they will remain supercooled and reach the surface as freezing drizzle or freezing rain. Such instances generally produce lower precipitation rates than from ice-phase processes; cloud tops are generally lower with less likelihood of large drops being formed.

Bernstein (2000) illustrated typical temperature and moisture vertical profiles favorable for freezing drizzle across North America (Fig. 2c). Freezing drizzle can reach the surface at temperatures at least as low as −14°C and as warm as 0°C; drizzle in turn can occur over a wide temperature range above 0°C. Associated cloud-top heights tend to be low, sometimes below 2 km, but can reach almost 4 km above sea level. Freezing drizzle profiles commonly illustrate a low-level inversion and temperatures within it can exceed 0°C but, with warm cloud-top temperatures, ice formation would not occur anyway. Despite a general sense of freezing drizzle formation, there are still considerable uncertainties. One of the most critical is ice nucleation (Rasmussen et al. 2002). If it does not occur, all liquid processes operate as described above but, if it does occur, the more complicated situation involving ice-phase processes will. In addition, many freezing drizzle drops are small and they can evaporate in the subcloud region before reaching the surface.

Several studies have pointed out that both paths for producing freezing rain and freezing drizzle are important but their relative contributions vary. Huffman and Norman (1988) and Rauber et al. (2000) showed that all-liquid formation processes are more common than those formed at least in part through ice-phase processes. In contrast, Carriere et al. (2000) studied vertical temperature profiles during freezing rain events over Europe and found that 70% and 30% were accounted for by ice-phase and all-liquid mechanisms, respectively.

COLLISIONS INVOLVING PRECIPITATION TYPES. Precipitation particles typically fall at different speeds and because of this they can interact through collisions in the melting or subfreezing layers (see, e.g., Zhang et al. 2011). There can even be large variability in fall speeds for nonspherical particles even if their overall sizes are similar; this again contributes to collisions. For example, Yuter et al. (2006) showed that the fall speed of wet snow varied from 0.5 to 3.5 m s^{-1}, depending on the degree of wetness. Such variations contribute to aggregation and the ensuing more massive particles require higher temperatures or, somewhat equivalently, higher energies for complete melting.

The environment near 0°C is especially suitable for the production of large snowflakes through such collisions. As summarized by Stewart (1992), there were reports in the literature about a century ago of very large snowflakes, sometimes exceeding 20 cm in diameter, at the surface; Lawson et al. (1998) carried out a detailed study of such precipitation. When mentioned, surface temperatures were always close to 0°C. If such temperatures existed aloft, melting would have been slow and the particles would have been sticky over a considerable depth. Collisions would preferentially have led to such large sizes.

Another type of collision involves semimelted and liquid particles in a melting layer aloft or near the surface. Any such collision leading to a single combined particle would reduce the number of liquid particles and enhance the mass of semimelted ones. In the melting layer aloft such interactions would be expected to increase the temperature needed for precipitation to be completely liquid since the larger ensuing semimelted particles would melt slower. In situations with no subfreezing layer below, this would lead to semimelted particles occurring at higher temperatures at the surface. In situations with a subfreezing layer below, more semimelted particles would fall into this layer and begin to freeze. This is a means of increasing the likelihood of ice pellets at the surface.

In the subfreezing layer below an inversion, supercooled raindrops can also collide with particles with an ice shell (liquid core pellets) or are completely frozen (ice pellets). The collisions would result in the liquid particles fusing with the other particles, beginning to freeze, and therefore forming ice pellet aggregates (Fig. 4). Such aggregates have often been found in winter storms (Gibson et al. 2009). This process furthermore reduces the number of supercooled raindrops that can reach the surface as freezing rain. In a theoretical study, Carmichael et al. (2011) calculated that, with a precipitation rate of 5 mm h^{-1} over a 1200-m-deep subfreezing layer, such collisions would reduce the flux of freezing rain by close to 20% if particles with diameters above 1 mm were ice pellets and those below were supercooled raindrops. The degree of reduction through such aggregation depends directly on the precipitation rate and subfreezing layer depth and inversely on the maximum size of the supercooled raindrops. However, there has not been an observationally based study to confirm these assertions.

Ice pellets may also collide with liquid core pellets in the subfreezing layer (Gibson and Stewart 2007). If the collision fractured the latter particle's ice shell, the combined particle would also be evident as an ice pellet aggregate. But, again, there has been no observationally based study to confirm this possibility.

Collisions between cloud droplets and ice pellets (or liquid core pellets or ice pellet aggregates) can also occur in the subfreezing layer. Given that the temperature in this layer is often of order −5°C, the ingredients for an ice multiplication process such as Hallett–Mossop (Hallett and Mossop 1974) can be present. This process is one explanation for the simultaneous occurrence at the surface of ice pellets and needles that are either single crystals or combined into aggregates (Stewart and Crawford 1995).

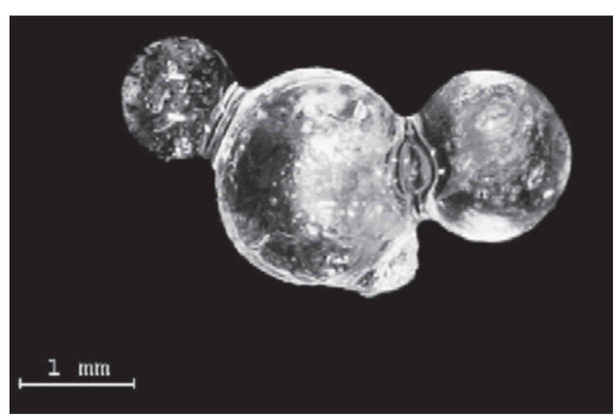

Fig. 4. Photograph of an ice pellet aggregate on 4 Nov 2003 at Montreal–Mirabel International Airport, near Montreal. [Adapted from Gibson and Stewart (2007).]

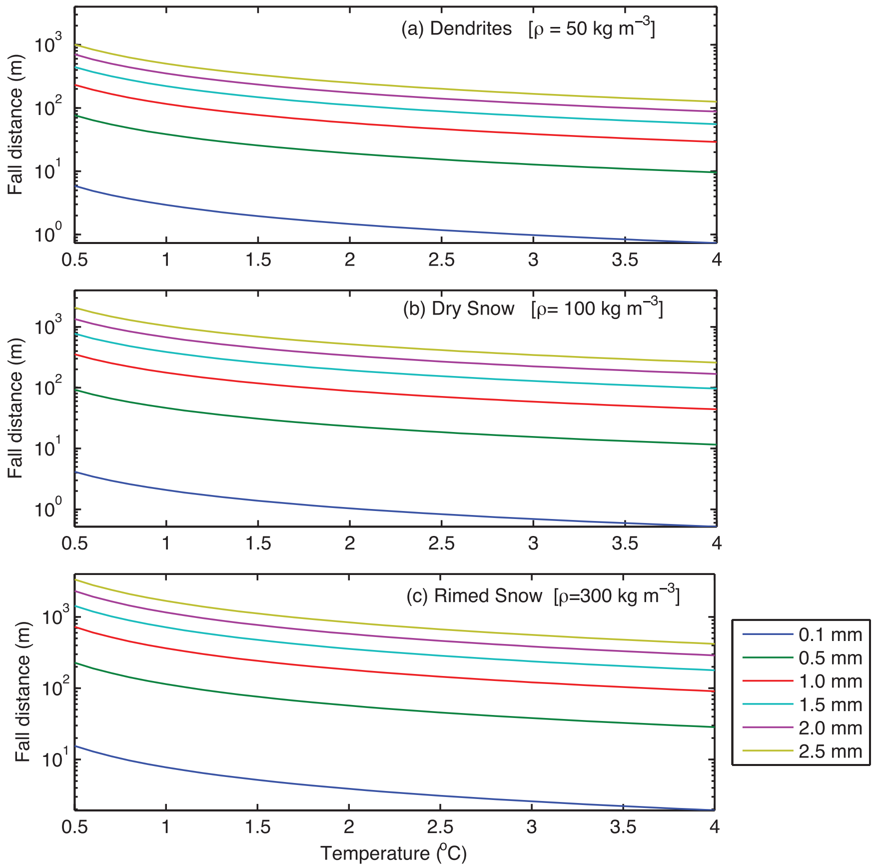

Fig. 5. The distance needed to completely melt different densities and sizes of snow particles: (a) dendrites, (b) dry snow, and (c) rimed snow. The melting parameterization is based on Szyrmer and Zawadzki (1999). The mass–diameter relationship and terminal velocity of dendrites follow Woods et al. (2007) and Rasmussen et al. (1999), respectively; dry snow follows Field et al. (2005), and Ferrier (1994), respectively; and rimed snow Milbrandt and Yau (2005). The diameters are liquid water equivalent.

In that study, many of the ice pellets discussed were very "rough," being completely covered with frozen droplets. Interestingly, the official weather observer reported that a mixture of ice pellets and snow was occurring. However, the reported snow (needles) is believed to have been produced just above the surface in the subfreezing layer rather than having fallen from a much higher elevation through an inversion. This snow (needles) could also consequently collide with supercooled raindrops (if present). Then, freezing to form more ice pellets or liquid core pellets would be initiated and hence also reduce the likelihood of freezing rain at the surface.

MELTING- AND FREEZING-LAYER CHARACTERISTICS.

Quantification of the degree of particle melting aloft is especially difficult because there is a wide range in particle characteristics. Chen et al. (2011), for example, inferred that particles aloft in a freezing rain event were rimed and the common presence of radar bright bands aloft in other freezing rain events indicates stratiform conditions aloft. A field of rimed particles requires a substantially greater depth to melt than a field of snowflakes or pristine crystals (Fig. 5). In conditions associated with an inversion layer aloft, particles containing ice are more likely to reach the subfreezing layer if they were originally rimed or underwent riming; such particles would begin to freeze into, for example, ice pellets. The approximate 1360-m depth and 4.9°C maximum temperature of the melting layer separating ice pellets (thinner, cooler layers) and freezing rain (thicker, warmer layers), as determined from sounding observations in Zerr (1997), should correspond to general thresholds for the complete melting of either rimed or pristine particles.

Regardless of the mechanism that initiates freezing, the likelihood of complete refreezing is also critical. According to Zerr (1997), the average depth of the subfreezing layer for all mixed-phase observations is 770 m, ranging up to a maximum 1760 m. For ice pellets or snow mixed with ice pellets, the average sub-freezing-layer depth is 1220 m, ranging up to a maximum of 1760 m.

How do the observed depths compare with those calculated from first principles for freezing? The governing equations for freezing (Pruppacher and Klett 1997), as well as those accounting for terminal velocity, have been used to determine depths required for freezing as a function of sub-freezing-layer temperature (Fig. 6). The required depth increases rapidly with increasing air temperature and drop size. For example, at temperatures < −2°C, drops of diameter < 2.5 mm will freeze within 1000 m if it is assumed that little or no ice was initially present in the particle. A key point is that, for the subfreezing temperatures often associated with transition regions, the depths needed to completely freeze drops are of the same order as the available depths. Therefore, detailed microphysical calculations are typically required to infer whether particles are all ice at the surface.

PRECIPITATION-TYPE TRANSITION REGIONS.

The region between snow on one side and rain on the other spans distances from a few kilometers to a few hundred kilometers and is referred to by several names including precipitation-type transition region (used here), transition region, rain–snow boundary, and transition zone. We will now discuss some of this region's features.

Precipitation-type organization. The transition between rain and snow can occur with or without freezing rain. In the latter case, the actual temperature evolution does not (generally) contain an inversion aloft. All initial snow will begin to melt as temperatures exceed 0°C under saturated conditions and, under simple idealized conditions of systematically increasing temperatures, this will lead to an organized evolution of precipitation types.

Consider an atmospheric column with a constant lapse rate, initially below 0°C everywhere but with a continuous size spectrum of snowflakes falling to the surface. Now assume steadily increasing temperatures throughout the column, such as may be associated with a warm front. There will be four steps between the initial occurrence of snow and the final occurrence of rain. Once near-surface temperatures exceed 0°C, only modest melting will occur on any snowflake and so only wet snow occurs (step 1); at slightly warmer temperatures, smaller particles melt enough to collapse so wet snow and almost melted particles fall (step 2); at warmer temperatures, some of the particles melt completely so a combination of rain plus the other two categories occurs (step 3); as temperatures warm further, all particles have either melted completely or collapsed (step 4); finally all particles have melted completely. When occurring simultaneously, sizes should generally increase as the liquid fraction and particle density decreases. The thresholds separating these steps vary with lapse rate, initial particle characteristics, and humidity, as discussed by Stewart and King (1987).

Now consider a warming situation with an inversion aloft and a lower subfreezing layer and further assume that any particle containing ice at the top of the subfreezing layer refreezes before reaching the surface. There will be five steps between snow and rain. Once inversion temperatures exceed 0°C, the evolution described above starts to occur but now the particles refreeze to form ice pellets or refrozen wet snow along with freezing rain and one step is a combination of all three. The fifth step is freezing rain alone before surface temperatures rise above 0°C and rain occurs. This evolution was discussed by Stewart and King (1987) and observed by, for example, Henson et al. (2007). However, this evolution also assumes that no liquid core pellets reach the surface and that supercooled raindrops are not frozen through ice nucleation. Accounting for such complexities would add additional combinations.

Subsaturated environmental conditions. Conditions are not always near saturation in precipitation-type transition regions and this affects the thresholds between rain and snow. Studies by, for example, Yuter et al. (2006) mentioned that conditions were essentially saturated and that the majority of large snowflakes had melted by 0.5°C. Matsuo and Sasyo (1981a,b) found that only rain was reported above approximately 1.5° and 5°C for a relative humidity near saturation and at 60%, respectively. Fuchs et al. (2001) and Harder and Pomeroy (2013) also illustrated

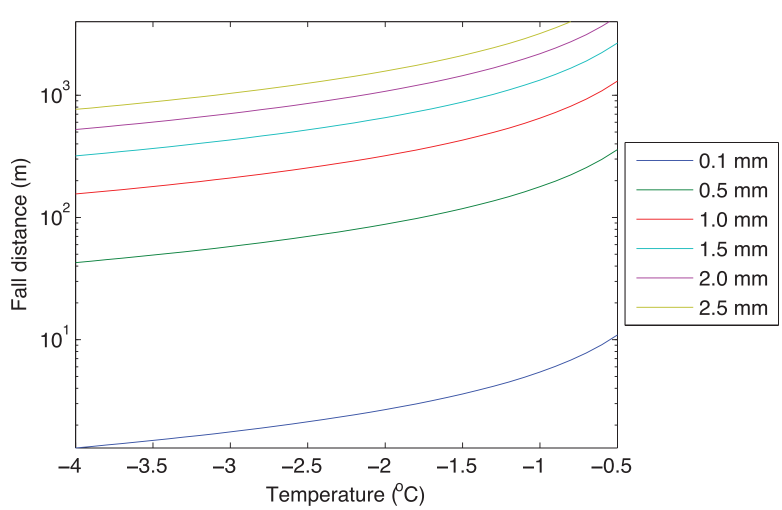

FIG. 6. The distance required to completely freeze drops of various sizes within varying air temperatures. The time to freeze the drop is based on Johnson and Hallett (1968) and the terminal velocity of raindrops is based on Szyrmer and Zawadzki (1999). The diameters are liquid water equivalent.

the critical importance of subsaturation. Temperature alone is not enough to develop overall criteria for the edges of the nonfreezing rain transition region and low moisture content drives the warmer edge to higher temperatures. However, if one considers the wet-bulb temperatures in Matsuo and Sasyo, the comparable threshold values only range from approximately 1.5° to 2.2°C at 100% and 60% relative humidity, respectively.

Overall, variations in relative humidity affect the temperature threshold for and rate of melting as well as the likelihood of cloud droplets that could be captured by falling precipitation particles. Quantifying the evolution of precipitation within precipitation-type transition regions must account for such varying environmental conditions, not only at the surface but aloft as well. For example, saturated cases would tend to occur within ascending air and be more likely to be linked with rimed particles whereas subsaturated cases would tend to occur within descending air with nonrimed particles.

Precipitation phase at the surface. Several studies have examined the probability of occurrence of rain, snow, and their mixture across transition regions (e.g., Auer 1974; Kienzle 2008; Dai 2008). Collectively, these studies illustrated that there is naturally a systematic increase in the probability of liquid as temperatures increase. For example, one study found an almost linear increase in the probability of rain from temperatures near 0°C to approximately 4°C (U.S. Army Corps of Engineers 1956).

Although there is a qualitative sense as to how precipitation types vary across a transition region, no quantitative measurements appear to have been made. To illustrate this issue, a one-dimensional cloud model coupled with a bulk microphysics scheme (Thériault and Stewart 2010) was used in a systematic manner. This bulk microphysics scheme was used because it accounts for many of the precipitation types discussed in this article. The model was initialized with a snow falling continuously from aloft at a liquid equivalent rate of 2 mm h^{-1} and with idealized vertical temperature and moisture profiles. We assumed that the vertical temperature lapse rate follows a standard atmosphere (6.5°C km^{-1}) and that the atmosphere was saturated with respect to liquid water. A series of numerical simulations were conducted by varying the surface temperature from –2° to +6°C, which impacts the depth of the melting layer near the surface. When considering the total amount of liquid, the simulations illustrate that its fraction does not necessarily increase in a linear manner with surface temperature, at least under these idealized conditions (Fig. 7).

Trajectories. Within environments with background horizontal and vertical air motions, there can be important consequences on the precipitation reaching the surface. Furthermore, sounding information may be somewhat misleading. Sondes move upward and downwind; particles fall downward and downwind. The air being sampled by the sonde is therefore not the same as that experienced by the particles. With temperatures near 0°C, this can mean, for example, that an inversion aloft is not detected by a sonde but is experienced by a particle. It can also mean

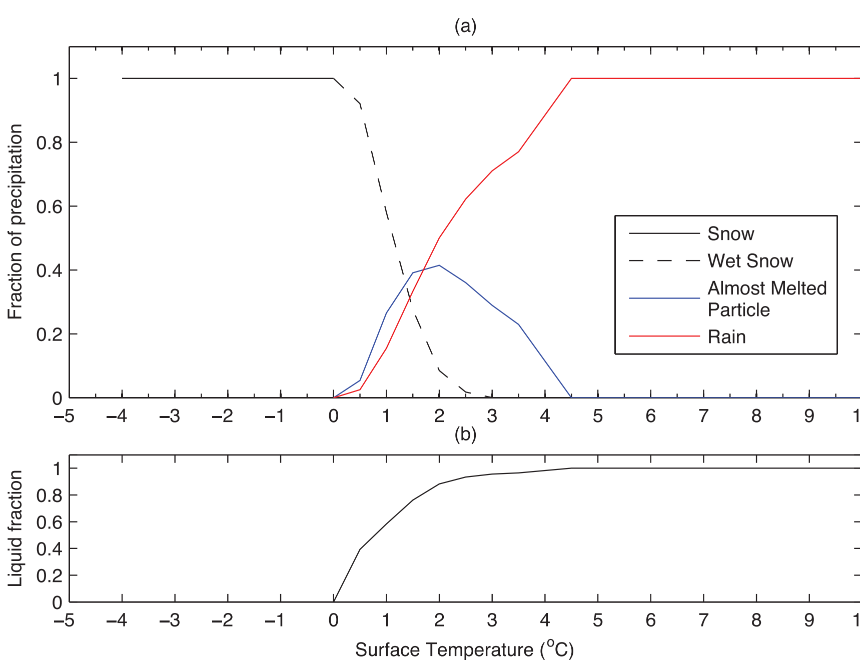

Fig. 7. Cloud model simulations of the variations in precipitation type and liquid mass fraction across 0°C at the surface. The initial snow characteristics are the same as in Fig. 5 and the lapse rate under saturated conditions is 6.5°C km^{-1}. (a) The fraction of precipitation types at the surface and (b) the liquid mass fraction associated with these precipitation types. The initial precipitation is 2 mm h^{-1} and the snow density is assumed to decrease with increasing size in a manner similar to Mitchell et al. (1990).

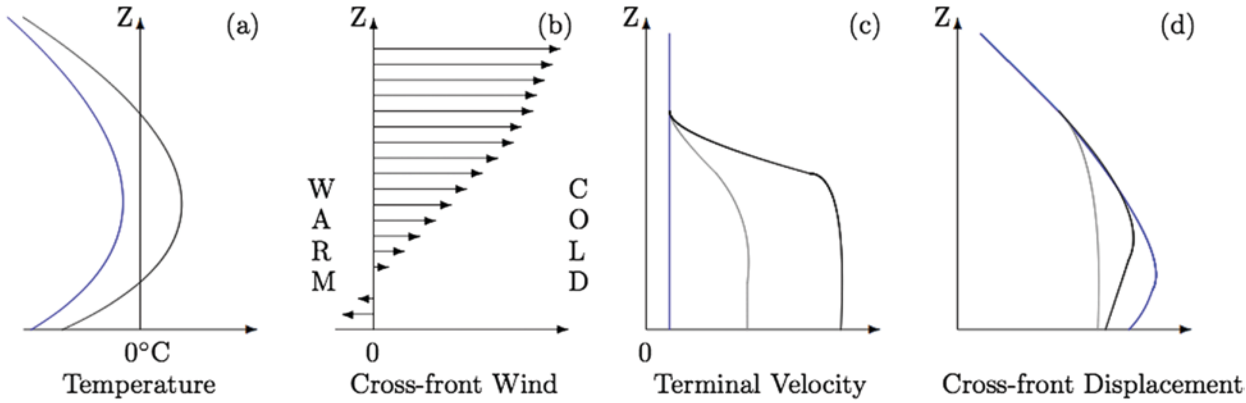

Fig. 8. A schematic of the trajectories of particles in close proximity to a transition region: (a) a typical vertical temperature profile associated with melting of snow (black) and no melting (blue); (b) a typical vertical cross-front wind profile with warm-air advection aloft and cold-air advection at lower levels; (c) a schematic of the varying terminal velocity profile of snow (blue line), snow gradually changing to rain aloft (solid black line), and snow rapidly melting aloft (boldface solid black line); and (d) the trajectory of the precipitation particles with the terminal velocities in (c). [Adapted from Thériault et al. (2012a).]

that, even if there is no inversion in a vertical column, the particle may experience one so that freezing rain produced through ice-phase processes can occur at the surface (Donaldson and Stewart 1993).

Trajectories also affect the distribution of the precipitation amount at the surface. If the particles are all the same type and are evenly distributed aloft, there is no impact at the surface. If the particles are the same type but the mass–size distribution aloft is variable, the varying trajectories of particles with different fall speeds alter the distribution at the surface. Finally, if different portions of the falling particle spectra undergo changes in type as they fall, this accentuates the differences experienced at the surface (Fig. 8). For example, Thériault et al. (2012b) examined how a peaked mass distribution of snow aloft would evolve as it fell to the surface in a relatively weak storm with an inversion and subfreezing layer. Two numerical experiments were carried out: one assuming instantaneous melting and the other with gradual melting computed with detailed calculations. The gradual melting case led to a spread-out distribution with maximum precipitation rates of about 50% of those calculated with instantaneous melting.

Effects of orography. Transition regions do not just occur over flat terrain; they also occur along sloped terrain. Snow at higher elevations and rain at lower ones is an inherent aspect of many winter storms (see Stoelinga et al. 2012 for a recent discussion). This region spans along-slope distances of order a few 10s to a few 100s of meters and is referred to by several names such as the rain–snow line and the snow level (warmer side). Minder et al. (2011), for example, defined the snow line as the elevation at which the precipitation was 50% rain and 50% snow.

It is also well recognized that the locations of transitions with freezing precipitation can be strongly affected by topography. Such regions influence the occurrence and persistence of warm and cold air through processes such as cold-air damming and cold-air trapping (see, e.g., Forbes et al. 1987; Keeter et al. 1995; Rauber et al. 2001b; Roebber and Gyakum 2003; Cortinas et al. 2004).

At least in the case of transitions between rain and snow in association with orography, they, as in the case of flat terrain, can be characterized by saturated (Lumb 1983a,b) or subsaturated (Thériault et al. 2012a) conditions. This implies that the temperatures on their warm (lower) sides can vary substantially even if conditions aloft are similar. What degree of saturation occurs in association with a sloped transition region, along with the attendant kinematic conditions, is critical.

FORECASTING PRECIPITATION TYPES.

Empirical techniques. Empirical thermodynamically based techniques have long been used to infer the presence of precipitation types employing the associated environmental conditions as a guide. Such techniques utilize surface temperature, while some also consider humidity, to deduce the presence of rain and snow (see, e.g., Auer 1974; Matsuo et al. 1981a,b; Dai 2008; Kienzle 2008). To infer freezing precipitation, several studies have utilized temperature and humidity profiles (see, e.g., Baldwin et al. 1994; Czys et al. 1996; Rauber et al. 2001a; Matsushita and Nishio 2008) and Bourgouin (2000) used positive and negative thermal energy concepts in the melting and subfreezing layers.

In many instances, thermodynamic conditions and thresholds are combined into "top-down decision systems" that consider the likelihood of ice formation and the various steps in subsequent evolution cycles. The work of Baumgardt (2014a,b) that was also referred to by Lackmann (2011) is an example of this approach. These top-down systems have contributed substantially to improvements in operational predictions of winter precipitation but they have limitations. These arise because there are wide variations in the precise conditions leading to precipitation types (e.g., inversions aloft are not always saturated); these techniques do not currently consider the effects of varying precipitation rates (which can affect maximum particle size); they do not currently cover the full range of precipitation types and combinations that actually occur (e.g., ice pellet aggregates and liquid core pellets); and they do not consider the effects of particle trajectories within background wind fields.

To build on these thermodynamic-related approaches, radar information is increasingly being utilized. Reflectivity and its profiles, shear layer heights, and polarimetric information all provide insights into precipitation aloft and near the surface. Studies such as Zhang et al. (2011) illustrate some of the improved capabilities of such information.

Physically based parameterization. Numerical weather prediction models now utilize sophisticated cloud and precipitation parameterization to account for the formation of winter precipitation types. The general concept behind these microphysics schemes is a bulk approach, which assumes an analytic size distribution of each hydrometeor category (i.e., Milbrandt and Yau 2005; Thompson et al. 2008; Morrison et al. 2005). The hydrometeor categories generally include ice, liquid, and vapor phases.

Even though these microphysics schemes are very sophisticated and account for most of the processes forming clouds and precipitation, some processes leading to winter precipitation are missing. For example, we are aware of only one bulk microphysics scheme tracking the liquid fraction in ice categories falling through the melting and subfreezing layers (Frick et al. 2013) even though this fraction is needed for predicting wet snow or freezing rain rather than ice pellets. However, this scheme is not yet used in a forecast model.

CONCLUDING REMARKS. Winter precipitation types near 0°C are important from fundamental scientific as well as from societal and ecological perspectives. Our changing climate is expected to trigger significant alterations in the occurrence of this precipitation.

There are many types of winter precipitation near 0°C. Not all have even been officially named and some of the official definitions need to be revised. These can be all liquid, all solid, or combinations of phases. Their density, size, and terminal velocity all vary and many of the types occur simultaneously.

There has been considerable progress in understanding the physics of the precipitation formation but there are still challenges. Understanding the implications of accretion for precipitation-type evolution, quantifying rates and consequences of phase changes (both melting and freezing) of the highly variable precipitation in saturated and subsaturated environments, and understanding collisional interactions between the precipitation types (and their aftermaths) remain challenges. The conditions leading to pronounced ice pellet aggregation are not even clear; their occurrence varies widely under seemingly similar conditions (Crawford and Stewart 1995). The importance of ice nucleation at temperatures near 0°C needs attention since it strongly affects the likelihood of freezing drizzle formation and it can trigger ice formation in the subfreezing region and reduce the likelihood of freezing rain. Models must be able to account for mixed-phase particles that may well interact with liquid or solid ones.

Although the focus of this article has been on the precipitation itself, a better understanding is needed of the factors governing its directly associated and interacting thermodynamic, dynamic, and moisture environment over flat and sloped terrain. Ralph et al. (2005) had identified a number of these factors, including boundary layer and land surface conditions, as impediments to better prediction. There is even a need to understand the rare conditions under which not one but at least two inversions occur (e.g., Carlson 1980; Martner et al. 2007).

New opportunities to address winter precipitation types are coming. Continuing improvements in ground-based measurements are leading to the better determination of the mass, type, shape, phase, and fall velocities of this precipitation (see, e.g., Rasmussen et al. 1999). Expansion of polarimetric radar coverage over, for example, North America has the potential for major improvements in inferring their occurrence and evolution aloft (see, e.g., Kumjian et al. 2013). Computational capabilities of research and operational models are steadily increasing so progress in accounting for winter precipitation-type evolution is ongoing. The efficient exploitation of such opportunities rests on a solid foundation of knowledge, including the precipitation physics perspective discussed in this article.

We encourage in-depth examination of other issues associated with precipitation near 0°C. Given this article's focus on precipitation characterization and formation, it is an opportune time to examine observational capabilities and requirements for monitoring the precipitation, synoptic/mesoscale, and surface environments, including sloped terrain, diabatic interactions between the environment and the precipitation, simulation and forecasting progress and requirements, and occurrence in our future climate. Collectively, such activities, perhaps in part through synthesis articles, would lead to a comprehensive assessment of this precipitation, its associated environment, and its prediction.

In summary, winter precipitation types near 0°C are associated with many impacts on society and ecosystems and they are formed through numerous, often simultaneous and interacting, ice- and liquid-phase processes that are typically restricted to relatively shallow depths and narrow horizontal regions but not all of these are well understood. To contribute to the reduction of their impact, sophisticated observational techniques and microphysical modeling schemes are required and progress is being made.

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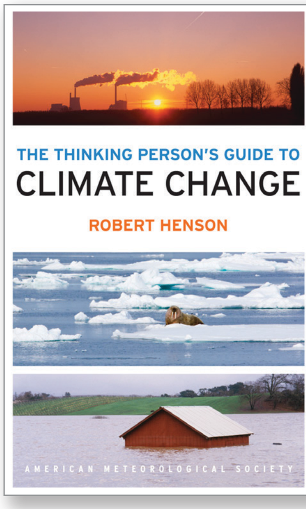

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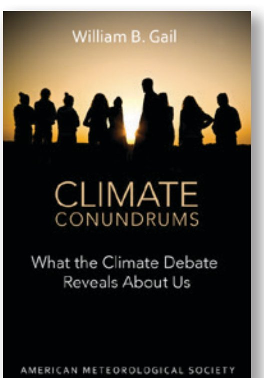

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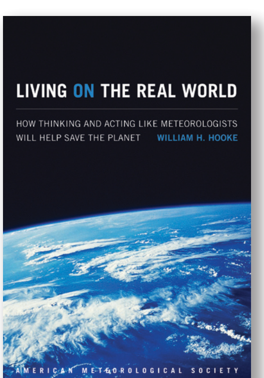

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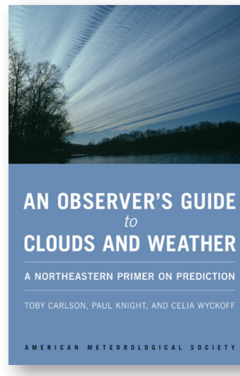

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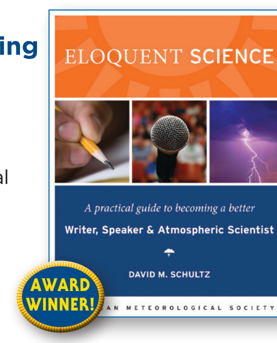

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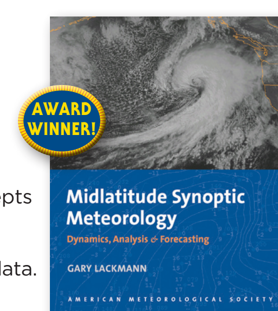

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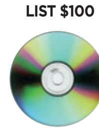

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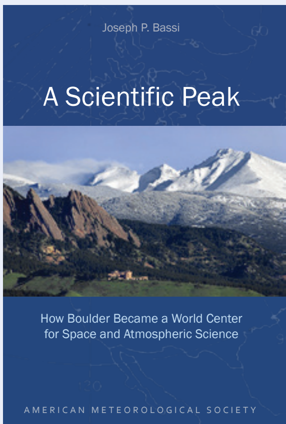

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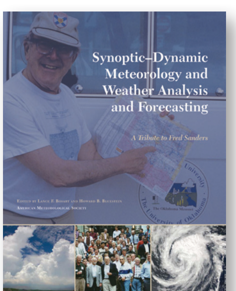

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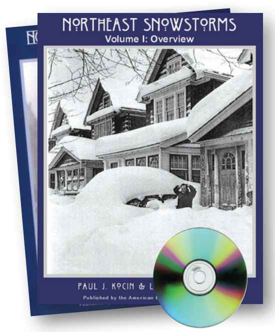

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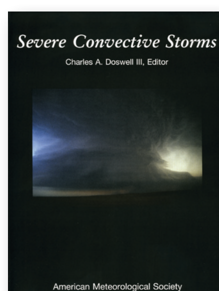

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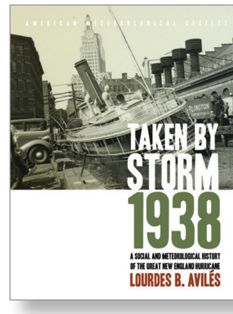

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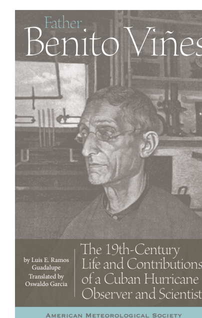

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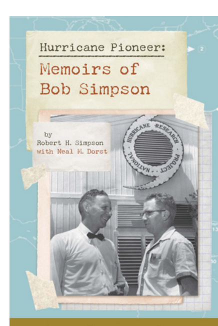

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