A Method to Determine Precipitation Types

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ABSTRACT

A method to diagnose surface precipitation types is suggested. Most cases of freezing rain and ice pellets occur with a layer warmer than 0°C extending above a surface-based layer of air colder than 0°C. The procedure uses predictors proportional to the product of the mean temperature of a layer and its depth. These predictors can be seen as areas on aerological diagrams. A positive area is associated with a layer warmer than 0°C, conversely a negative area is associated with a layer colder than 0°C. The same predictor is used to discriminate snow from rain. A statistical analysis was applied using the North American aerological stations network to determine a set of criteria for discriminating freezing rain, ice pellets, snow, and rain. Once the criteria are known, the precipitation type can be easily diagnosed using temperature profiles from upper-air observations or from numerical weather prediction models. The method has been in operational use at the Canadian Meteorological Centre since 1995.

1. Introduction

Forecasts of winter precipitation types have long been a concern for weather forecasters (Brooks 1920) because they may have important consequences for human activities. Inconveniences associated with freezing rain, snow, or ice pellets can range from disturbing local ground transportation or aircraft operations to paralyzing a large region. For example, the great ice storm of January 1998 dramatically affected eastern Canada from 4 to 10 January 1998. The accumulation of freezing rain and ice pellets exceeded 100 mm in many areas of southwestern Quebec and eastern Ontario during that period. As a result, thousands of trees were downed, hydro wires and pylons were destroyed, and transportation was greatly affected. At least 25 people died in the storm and nearly one million people were left without heat or electricity for more than a week (Reagan 1998). This was rather an extreme case, but it illustrates the need of issuing accurate forecasts of precipitation types.

The observed precipitation type depends on specific atmospheric conditions that include thermal and moisture distributions, vertical motion, cloud, and ice nuclei distributions. However, it has long been recognized that the vertical temperature profile is of prime importance (see, e.g., Wagner 1957; Koolwine 1975; Bocchieri 1980; Czys et al. 1996). In some situations, a temperature variation of only 1°C is sufficient to induce a transition between different phases, for example between freezing rain and rain or between snow and rain. This implies that an accurate vertical temperature profile forecast is needed if one hopes to correctly determine precipitation types. Although temperature is most important, ideally any diagnostic for precipitation type will take account of all related atmospheric parameters.

One way to include all the physics associated with precipitation type is to develop a sophisticated explicit microphysics model. However, these models are expensive in computer time, limiting their operational applications. Furthermore, a knowledge of initial hydrometeor phases or distributions, cloud condensation, and ice nuclei distributions is needed but not routinely observed. Some optimized microphysics models will likely become available in the future, but in the meantime other alternatives must be used to routinely forecast precipitation types. The most common approach is to derive statistical relationships between some predictors and different precipitation types. Relationships are simple to derive using an adequate database of easily available parameters, generally related to temperature and moisture. Once, developed, this approach requires very little computer time to produce forecasts. Other techniques, such as that of Czyz et al. (1996), are physically based and remain to be evaluated.

This paper describes the development and testing of a new method for diagnosing precipitation type, called the area method. A general description of the problem of precipitation type diagnosis is given in section 2, along with a discussion of some existing objective di-

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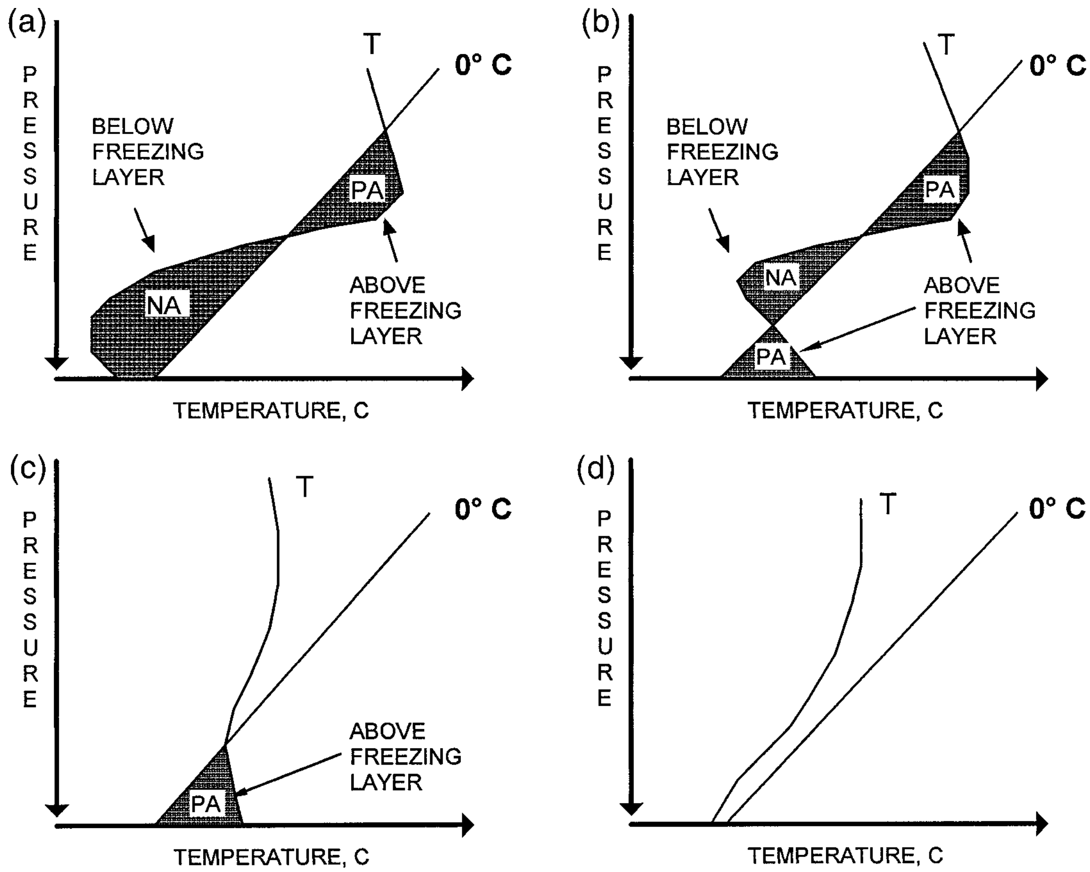

FIG. 1. Schematic diagram showing typical vertical temperature profiles leading to (a) freezing rain or ice pellets, (b) ice pellets or rain, (c) snow or rain, and (d) snow. Positive (PA) and negative (NA) areas are indicated (see text for details).

agnosis techniques. The area method is presented in section 3. Section 4 includes results of tests of the new method and results of comparison tests with some of the techniques described in section 2. This paper concludes with a discussion.

2. Diagnosis of precipitation type

As stated previously, it is the vertical temperature profile that is the main determinant of precipitation type. If the profile crosses the 0°C isotherm one or more times, then rain, freezing rain, ice pellets, snow, or mixtures of these hydrometeors can occur. In this section, typical temperature profiles associated with different precipitation types are described.

Freezing rain or ice pellets are possible whenever precipitation falls through a layer warmer than 0°C and through a subfreezing layer underneath (Fig. 1a). This occurs when warm air advection, generally associated with extratropical cyclones, is stronger aloft than near the surface. Conditions favorable to freezing rain or ice pellets will persist longer if low-level cold air advection is present, which is frequently associated with topographically induced cold air drainage, or with cold air remaining trapped in valleys. However, if the layer warmer than 0°C aloft in Fig. 1a is too small, precipitation will be snow, but not ice pellets or freezing rain.

If there is a warming sufficient to bring surface temperatures above 0°C and little temperature change aloft, a vertical profile as given by Fig. 1a will become as given in Fig. 1b. Just above the surface-based warm layer, precipitation may be in the form of freezing rain or ice pellets (if the above freezing layer aloft is large enough) as discussed above. If freezing rain is present, water drops may remain supercooled, especially large and rapidly falling ones, as they reach the surface.

Freezing rain is reported by observers when drops freeze on impact with an ice accretion indicator, the ground, or other objects at or near the earth's surface according to reporting standards. Freezing rain may be reported with surface temperatures above 0°C. However, it is a rare occurrence, because ice accretion indicators or other objects rapidly adjust their temperature to the ambient temperature. For that reason, we decided to exclude freezing rain from possible precipitation type associated with a sounding similar to Fig. 1b and will not be considered further. If freezing rain is present just above the surface-based warm layer, we expect rain to be reported at the surface. If ice pellets rather than freezing rain are present, they may melt and be reported as rain at the surface or they may survive the fall and be reported as ice pellets, possibly mixed with rain. Again, if the above freezing layer aloft is too small, snow will be present above the surface-based warm layer. In that case, rain or snow may be reported depending on conditions. As a result, a profile as in Fig. 1b may produce rain, ice pellets, mixed rain and ice pellets, or snow.

While an above freezing layer aloft is required for freezing rain and ice pellets situations, diagnosis of precipitation type also requires discrimination between rain and snow. This may be difficult when temperatures in the low levels are slightly above 0°C (Fig. 1c). With soundings as in Fig. 1c, snow, rain, or mixed snow and rain are possible. If there is no above freezing layer (Fig. 1d), snow is generally expected, but it is also possible to get freezing drizzle (Bluestein 1993; Huffman and Norman 1988). This phenomenon is due to the fact that droplets of drizzle are very small and hence more likely to remain in liquid form than larger droplets at the same below freezing temperatures. This situation will not be considered further.

Many operational techniques have been developed to associate specific atmospheric conditions to different precipitation types. When the method proposed in this paper was developed, the Derouin (1973) method was used operationally at the Canadian Meteorological Centre (CMC) and the Cantin and Bachand (1993) method was applied in some Canadian regional centers. Later on, the method proposed here was tested against two recently available techniques, the Ramer (1993) and Baldwin and Contorno (1993) methods. For those reasons, we will now briefly review those four methods.

a. Derouin (1973) method

This method uses only the heights of up to three freezing levels as predictors to determine the precipitation type. If there is more than one freezing level, height differences between adjacent freezing levels are also used as predictors. As an example, rain will be predicted in the case of a single freezing level higher than 2000 ft (about 610 m), otherwise it will be mixed rain and snow. This example reveals a problem with this method: the same diagnostic is obtained regardless of the value of the mean temperature in the layer from the surface to 2000 ft. Only the heights of the freezing levels are considered, not the vertical temperature distribution.

b. Cantin and Bachand (1993) method

This method utilizes the thicknesses of the 1000–850- and 850–700-hPa layers as predictors (Koolwine 1975) for precipitation types. These thicknesses are directly related to the mean temperature of the considered layer. A thickness larger than 154 dam in the upper layer (850–700 hPa) generally indicates a layer with temperatures warmer than 0°C. On the other hand, a thickness lower than 131 dam in the lower layer (1000–850 hPa) suggests temperatures under 0°C at or near the surface. For example, conditions leading to freezing rain are a 850–700-hPa thickness larger than 154 dam combined with a 1000–850-hPa thickness between 129 and 131 dam. The same upper-layer thickness combined with a lower-layer thickness less than 129 dam would yield ice pellets, while a value above 131 dam would result in rain. An advantage of this technique is that a synoptic map of the location of precipitation types can be produced. It should be noted that the criteria associated with this method are not fixed in operational forecasting. They are modified by forecasters in each situation based on subjective evaluations of different parameters such as the intensity of vertical motion or the cold air advection or typical synoptic patterns. Also, the technique was developed for eastern Canada and is not directly applicable to other geographical areas, especially over mountainous areas.

c. Ramer (1993) method

The technique proposed by Ramer uses temperature (T), relative humidity (RH), and wet-bulb temperature (T_W) on different pressure levels to diagnose precipitation types. This procedure performs two checks before doing a full calculation. First, if the surface wet-bulb temperature is greater than 2°C, liquid precipitation is diagnosed. Second, if T_W remains below a specified value at all levels, solid precipitation is expected. A full calculation will be needed if neither condition is satisfied. The basic parameters (T, RH, T_w) are used to determine layers where precipitation is likely to be generated and also to determine the ice fraction. A generating layer exists if relative humidity exceeds a specified threshold value over a sufficiently thick layer. The generating level is defined as the top of the highest generating layer. The ice fraction is the basic quantity calculated for diagnosing the precipitation type. Precipitation at the generating level is assumed to be entirely liquid if the wet-bulb temperature is above a specified value. Otherwise, it is considered fully frozen. If frozen precipitation is diagnosed at the generating level and if the wet-bulb temperature is below freezing for the entire sounding below the generating layer, solid precipitation is assumed. As precipitation falls, the ice fraction value changes according to the wet-bulb temperature and to the relative humidity vertical distribution. The precipitation type is given by the values of the ice fraction and the wet-bulb temperature at the surface. If the ice fraction is greater that a specified threshold (e.g., 0.85), solid precipitation will be diagnosed. If the ice fraction is lower than another threshold (0.04), liquid precipitation is expected. Mixed precipitation is diagnosed for an ice fraction between these two values.

d. Baldwin and Contorno (1993) method

This last method was adapted from a technique used by the Japanese Meteorological Agency (Sato 1992, personal communication). The basis for this method is to decide whether or not ice crystals can form and, if so, determine their subsequent phase changes as they fall through the atmosphere. Ice crystals are expected to form if there is a layer with a dewpoint depression of less than 2 K and a dry-bulb temperature of less than 269 K. Those ice crystals will go through different phase changes based on the wet bulb temperature profile and on the dry-bulb temperature in the layer near the ground. If no ice crystals are initially diagnosed, liquid precipitation is expected to reach the ground. In that case, freezing rain is anticipated if the lowest layer is cold enough.

The Ramer (1993) and Baldwin and Contorno (1993) methods were developed using NWP-derived fields. Therefore, they are model dependant and may yield somewhat less accurate results when used with a different model.

3. Development of the area method

In this section, a new predictor that can be associated with an area on an aerological diagram is described. That predictor is used to establish different statistical relationships to diagnose different precipitation types from a vertical temperature profile.

a. Definition of a new predictor for precipitation type

The temperature variation of a falling hydrometeor and its resulting phase changes are largely driven by the temperature of the environment (Pruppacher and Klett 1980). A hydrometeor falling in a layer with above freezing temperatures will become liquid if the residence time (time to fall through a given layer) is great enough. Conversely, a hydrometeor moving through a below freezing layer will eventually become solid. This suggests two important parameters to diagnose precipitation type: the mean temperature of a layer ($\overline{T}_l$) and the resident time. The temperature $\overline{T}_l$ is readily available from an observed or forecast vertical temperature profile. This is not the case for the resident time, which depends on the height (H) of the considered layer; on the terminal velocity of hydrometeors; and on the mean vertical motion (Pruppacher and Klett 1980; Czys et al. 1996). Assuming a constant vertical motion and a constant terminal fall speed, the resident time depends only on H, which is simple to extract from a vertical temperature profile.

It is possible to combine $\overline{T}_l$ and H by multiplying them together. That new predictor can be regarded as proportional to an area on a standard tephigram (Iribarne and Godson 1981) or on other thermodynamic diagrams:

$$\overline{T}_l H \propto \text{Area}. \quad (1)$$

The area can be computed for layers with temperatures above or below 0°C. We define a positive (negative) area on a tephigram as the area between the 0°C isotherm and the environment temperature in the above (below) freezing layer (Fig. 1a). With these definitions, clearly a positive area (PA) will warm a solid hydrometeor, possibly inducing a transition from solid to liquid, while a negative area (NA) may cool water droplets sufficiently to produce ice pellets. The positive and negative areas can be used as predictors in statistical relationships with precipitation type, as will be shown below.

Even if the method is initially developed using a tephigram, it is not necessary to use this diagram. According to Iribarne and Godson (1981), the areas can be computed using

$$c_p|\text{Area}| = c_p \oint T\, d\ln\theta = c_p \overline{T}_l \ln\left(\frac{\theta_{\text{top}}}{\theta_{\text{bottom}}}\right), \quad (2)$$

where c_p is the specific heat capacity at constant pressure, T the absolute temperature, θ the potential temperature, θ_{top} the potential temperature at the top of the layer, θ_{bottom} the potential temperature at the bottom of the layer, and $\overline{T}_l$ the average temperature in the layer extending from θ_{top} to θ_{bottom}. Equation (2) provides an easy way to evaluate the negative or positive area size.

b. Dependent data

To determine the criteria to be used to discriminate among precipitation types, a database of cases of collocated surface precipitation observations and upper air soundings was established. The upper air soundings provided the observed vertical temperature profile needed to establish the different criteria. The precipitation had to be reported within 1 h of the time that the sounding was taken and at the same location; hence, the number of cases per season is relatively limited. The data were taken from the 1989–90 and 1990–91 cold seasons over North America.

The database consisted of 54 cases used to discriminate between freezing rain and ice pellets, 119 cases for rain and snow, and 3–5 cases of ice pellets and rain. These last cases present a degree of uncertainty because there are no observations of the hydrometeors' state (freezing rain or ice pellets) aloft as they begin to fall through the surface-based above freezing layer (Fig. 1c). The hydrometeors' state has to be diagnosed aloft. If freezing rain is diagnosed aloft, we assume that droplets' temperature will rise rapidly and rain will be observed at the surface. On the other hand, if ice pellets are diagnosed aloft, the warm layer may or not induce a phase change from ice pellets to rain.

To discriminate between freezing rain and ice pellets, the parameters considered were positive area, negative area, ratio of positive to negative area, mean 1000–850- and 1000–700-hPa temperatures, surface temperature, and dewpoint. For rain–snow discrimination, they were the freezing level, positive area for the surface-based warm layer, mean 1000–850- and 1000–700-hPa temperatures, saturation height (cloud base), surface temperature, and dewpoint.

The criteria used to discriminate among the different precipitation types were determined using the previously described database as the training sample. Then, the 1991–92 cold season was used as an independent sample to test the criteria. The independent sample consisted of 29 cases used to discriminate between freezing rain and ice pellets, 42 cases for rain and snow, and 9 cases of ice pellets changing to rain or not.

c. *Determination of criteria*

A particular precipitation area may consist of regions where a single type occurs, with a transition region in between. In the transition region, more than one type of precipitation occurs simultaneously. Any set of criteria for diagnosing precipitation types must take account of situations where one precipitation type may occur simultaneously with one or more others in a transition zone.

It is important to note that the method proposed here uses a perfect-prog approach (Klein et al. 1959), and it is based directly on observations and not on NWP-derived fields. That means that the method can be applied to any NWP model and the accuracy of the results will be related to the quality of the forecast vertical temperature profile. Furthermore, the method was developed using soundings from all across North America, so it is not region specific.

As mentioned above, several parameters to discriminate among different precipitation types were tested. Predictors and precipitation types were plotted to allow a graphic screening of the different types.

1) CRITERION TO DISCRIMINATE BETWEEN FREEZING RAIN AND ICE PELLETS

The most promising predictors were the positive and negative areas. Figure 2 shows a plot of all reports of freezing rain, ice pellets, or a mix of the two as a function of those two parameters. This figure indicates a fairly clear separation between freezing rain and ice pellets cases.

Figure 2 also reveals that even a small PA (at least 2 J kg^{-1}, based on the rain/snow transition sample) will lead to freezing rain as long as the NA is relatively small (less than about 50 J kg^{-1}). It is to be noted that with a small PA (slightly more than 2 J kg^{-1}), it is possible to get some snow mixed with either freezing rain or ice pellets. However, we did not attempt to discriminate cases of freezing rain or ice pellets mixed or not with snow.

If the NA becomes larger than about 200 J kg^{-1}, then freezing rain is no longer expected, but rather ice pellets.

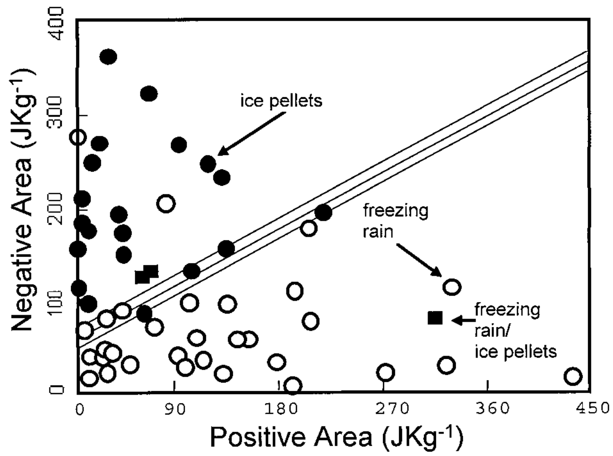

FIG. 2. Plot of freezing rain, ice pellets, and mixed freezing rain and ice pellets as a function of positive and negative areas. Solid lines represent criteria to discriminate between freezing rain and ice pellets as given by Eq. (4). These cases correspond to Fig. 1a.

Furthermore, inspection of Fig. 2 suggests an easy way to establish the criteria. It is merely a matter of drawing a straight line, which allows the maximum separation between the different types. The equation of that line was determined using the least squares method and is

$$\mathrm{NA} = 56 + 0.66\mathrm{PA}, \tag{3}$$

where NA represents the negative area (J kg^{-1}) and PA the positive area (J kg^{-1}).

Equation (3) prescribes the relation between PA and NA for cases where freezing rain and ice pellets are equally likely. From the previous discussion and from Fig. 2, it should be obvious that a larger measured NA than the one given by Eq. (3) for a specific PA will lead to ice pellets. Conversely, a smaller value of PA will lead to freezing rain.

Figure 2 also indicates that the chosen parameters do not allow a perfect separation between the two considered precipitation types. There are conditions for which both types can be observed. Simultaneous occurrences are indeed observed in nature. For that reason we introduce a transition zone, in which both types are possible, by adding or subtracting 10 J kg^{-1} to Eq. (3). Therefore, if a given temperature profile shows an above freezing layer above a surface-based below freezing layer, the most probable precipitation type will be

$$\begin{aligned}&\text{ice pellets,} \quad \text{if NA} > 66 + 0.66\text{PA};\\ &\text{freezing rain, if NA} < 46 + 0.66\text{PA}; \quad \text{and}\\ &\text{freezing rain and/or ice pellets,}\\ &\qquad \text{if } 46 + 0.66\text{PA} \le \text{NA} \le 66 + 0.66\text{PA}.\end{aligned} \tag{4}$$

Figure 2 shows a case where freezing rain was reported with a positive area close to zero and a large negative area. This could be a case of freezing drizzle reported as freezing rain.

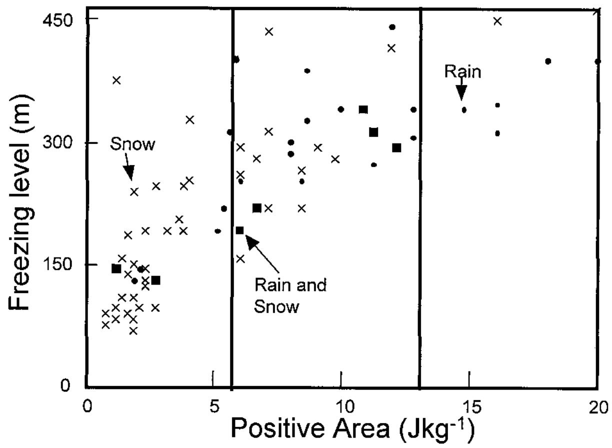

FIG. 3. Plot of rain, snow, and mixed rain and snow as a function of positive area and freezing level for cases with a small positive area (less than 20 J kg^{-1}). These cases correspond to Fig. 1c. Solid vertical lines represent criteria to discriminate between rain and snow as given by Eq. (5).

2) Criterion to discriminate between rain and snow

The most obvious situation for snow to occur is when there are no above freezing temperatures in the vertical temperature profile at a particular site, that is, there are no positive areas, either aloft or based at the surface. In the situation where a surface-based warm layer exists but not aloft (Fig. 1c), the possible precipitation types are rain, snow, or a mix of the two. Using the positive area associated with that warm layer as a predictor, we find that the most probable precipitation type will be

$$\begin{aligned} &\text{snow,} && \text{if} && \text{PA} < 5.6\ \text{J kg}^{-1}; \\ &\text{snow and/or rain,} && \text{if } 5.6\ \text{J kg}^{-1} \leq && \text{PA} \leq 13.2\ \text{J kg}^{-1}; \\ &\text{and} && && \\ &\text{rain,} && \text{if} && \text{PA} > 13.2\ \text{J kg}^{-1}, \end{aligned} \tag{5}$$

where PA represents the warm layer area at the surface (Fig. 1c).

Figure 3 shows the distribution of rain and snow as a function of the freezing level and of the positive area for a subset of cases with small positive areas (PA between zero and 20 J kg^{-1}). Small positive areas are generally associated with surface temperatures not much above the freezing point. In our sample, they represent 71 cases (23 cases of rain, 41 cases of snow, 7 cases of rain and snow) of the total sample (119 cases). We chose not to include the cases with large positive areas (greater than 20 J kg^{-1}) associated with temperatures well above freezing. Figure 3 also shows that the freezing layer by itself does not allow for discrimination between rain and snow.

TABLE 1. Criteria for discriminating between freezing rain and ice pellets: number of cases correctly forecast over the total number observed using the development sample (cold seasons of 1989–90 and 1990–91) by three methods (area, Derouin, Cantin and Bachand).

	Diagnosed by category			
Method	Ice pellets (IP)	Freezing rain (ZR)	Mixed IP/ZR (IPZR)	Total by category
Area	16/20	28/31	0/3	44/54 (81%)
Derouin	19/20	1/31	—	20/51 (39%)
Cantin and Bachand	10/20	24/31	—	34/51 (67%)

Our database shows that a PA aloft of at least 2.0 J kg^{-1} is required to induce a transition from solid to liquid precipitation. This mean that a PA of less than that value will not lead to significant melting of solid hydrometeors. In such a case, the criteria for rain/snow transition will be applied. For instance, a temperature profile as shown by Fig. 1a, with a positive area of less than 2 J kg^{-1}, would lead to snow, but not to freezing rain or ice pellets. On the other hand, a surface PA of 5.6 J kg^{-1} or more is necessary to melt snow, at least partially. There seems to be somewhat of a discrepancy here, which can probably be explained by microphysics of clouds and precipitation considerations. First, ice crystals grow rapidly in a water saturated environment (Pruppacher and Klett 1980). Second, smaller ice crystals are easier to melt than larger ones. Therefore, ice crystals will be smaller and easier to melt in the warm air aloft than in a water-saturated environment in a surface-based layer. Since we are mainly interested in continuous, synoptic precipitation, we assume that the environment has reached saturation.

3) Criteria to discriminate among ice pellets, freezing rain, and rain

The area method follows a hydrometeor as it falls through layers at different temperatures from aloft to the surface. Figure 1b shows a vertical temperature profile with a negative area and two positive areas, one aloft and one at the surface. What will be the hydrometeor state as it reaches the surface for such a temperature profile? To answer that question, we estimate the different changes in the hydrometeor states as it falls. The hydrometeor goes through an above freezing layer

TABLE 2. As in Table 1 but for criteria for discriminating between rain and snow.

	Diagnosed by category			
Method	Snow (S)	Rain (R)	Mixed R/S	Total by category
Area	36/53	33/51	11/15	80/119 (68%)
Derouin	0/53	12/51	14/15	26/119 (22%)
Cantin and Bachand	23/53	3/51	10/15	36/119 (30%)

TABLE 3. As in Table 1 but for criteria for discriminating between ice pellets and rain.

Method	Diagnosed by category IP	Diagnosed by category R	Total by category	Diagnosed as mixed	Total by category and mixed
Area	2/3	0/2	2/5 (40%)	1	3/5 (60%)
Derouin	2/3	0/2	2/5 (40%)	1	3/5 (60%)
Cantin and Bachand	3/3	0/2	3/5 (60%)	0	3/5 (60%)

TABLE 5. As in Table 2 but for the independent sample (cold season of 1991–92).

Method	Diagnosed by category S	R	R/S	Total by category
Area	22/25	10/10	5/7	37/42 (88%)
Derouin	0/25	10/10	6/7	16/42 (38%)

aloft and then through a below freezing layer. If the positive area aloft is larger than 2 J kg^{-1}, we can use criteria given by Eq. (4) to estimate the hydrometeor state, whether freezing rain or ice pellets, as it begins to fall through the surface based above freezing layer. If we conclude that upper air conditions are suited to formation of freezing rain aloft, as the hydrometeor begins to move through the surface-based above freezing layer, we change the precipitation-type diagnostic from freezing rain to rain.

On the other hand, if we conclude that conditions are favorable to formation of ice pellets as the hydrometeor starts to move through the surface-based above freezing layer, we have to determine if ice pellets will melt or not. The sample of reports, showing ice pellets with a positive surface temperature, is very small. The problem is more daunting when it comes to cases where ice pellets might have melted, since it is also necessary to diagnose the possible presence of ice pellets aloft. Despite the limited data available, it is assumed that the same criteria used to melt snow [Eq. (5)] apply to melting ice pellets.

4) CASES OF MIXED SNOW AND FREEZING RAIN OR SNOW AND ICE PELLETS

Our database does not contain cases of mixed snow and freezing rain or snow and ice pellets. The area method cannot diagnose a mixture of these precipitation types. As mentioned previously, a PA aloft of at least 2.0 J kg^{-1} is required to induce a transition from solid to liquid precipitation. Therefore, if the PA aloft is less than that threshold, rain and snow criteria [Eq. (5)] should be applied, otherwise criteria associated with the presence of a warm layer aloft [Eq. (4)] should be used. Further work is needed to determine a transition zone, based on the PA aloft, in which snow and freezing rain or snow and ice pellets are simultaneously present.

4. Verification and comparison with different methods

In this section, we evaluate the performance of the new method and compare it to results obtained from other techniques. Section 4a describes results obtained with the area, the Derouin, and the Cantin and Bachand methods using the development sample.

a. Comparison of different methods using the development sample

Tables 1, 2, and 3 show the results obtained by three methods (area, Derouin, Cantin and Bachand) using the development sample (cold seasons of 1989–90 and 1990–91). From the database, a precipitation type is determined for each case, using each of the three methods. The totals represent the number of cases correctly forecast over the total number of cases observed. A second total is shown for certain cases and includes cases in the transition zone other than reports of mixed precipitation, for example, where the method in question cannot discriminate between two precipitation types.

In Table 1, Derouin's method shows little skill in discriminating between freezing rain and ice pellets, and forecasts far too many cases of ice pellets. The Cantin and Bachand method performs better than the Derouin method, but tends to diagnose too much freezing rain. However, it should be kept in mind that this technique requires some subjective adjustments as mentioned in section 2. The area method shows little bias and provides the best results, that is, a correct diagnosis by category in 81% of cases. Table 2 shows all three methods have difficulty in discriminating between rain and snow, since the sample was made up of the most marginal cases. However, the area method is the most ac-

TABLE 4. As in Table 1 but for the independent sample (cold season of 1991–92).

Method	Diagnosed by category IP	ZR	IPZR	Total by category
Area	7/7	16/18	1/4	24/29 (83%)
Derouin	7/7	0/18	0/4	7/29 (24%)

TABLE 6. As in Table 3 but for the independent sample (cold season of 1991–92).

Method	Diagnosed by category IP	R	R/IP	S	Total by category and mixed
Area	0/0	5/5	2/2	0/2	7/9 (78%)
Derouin	0/0	0/5	0/2	1/2	1/9 (11%)

TABLE 7. Contingency table using the Baldwin–Contorno method and temperature profiles from the Canadian operational Regional Finite Element model to forecast precipitation types at three Canadian reporting stations, Toronto (Ontario), Montréal (Québec), and Fredericton (New Brunswick) for the period from 12 to 22 Jan 1995. Percentage correct: 87%.

Forecast	ZR	IP	R/S	S	R	Total
Obs						
ZR	10	—	—	1	1	12
IP	—	1	—	2	—	3
R/S	—	—	2	1	—	3
S	—	1	—	12	—	13
R	—	—	—		15	15
Total	10	2	3	15	16	46

curate, while the other two give less accurate results. Table 3 shows equivalent results for the three methods' yields; however, the sample size is very small.

A note of clarification is in order; these results from the area method are based on the dependent sample, but it is an independent sample for the other two methods. As a result, the area method may be favored; results shown in the next section were obtained from independent samples for all methods.

b. *Verification of the different methods using the independent sample*

This section describes verification results of the precipitation-type diagnosis based on the 1991–92 independent sample. Note that the Cantin and Bachand method was not included due to lack of data.

Tables 4, 5, and 6 show that the area method produces a much better diagnostic than the Derouin method. This is related to the difficulty of the Derouin method in forecasting freezing rain and to its tendency to forecast mixed rain and snow instead of just snow for cases with a small positive area.

There were two cases where ice pellets were diagnosed with the area method but snow was observed. These happened when the observed negative area was very large (605 and 618 J kg^{-1}). The development sample did not contain any cases with negative areas as large as this. To detect such cases, a new criterion should be added to diagnose snow even in the presence of an above freezing layer aloft larger than 2 J kg^{-1}. As a tentative criterion, we propose that for negative areas larger than 600 J kg^{-1}, snow be diagnosed rather than ice pellets.

In general, verification with the independent sample gives results similar to those obtained from the development sample. This suggests either that the two samples are statistically similar, or that the method is robust with respect to application to different samples, or both.

c. *Performance comparison using NWP model temperature profiles*

Methods to determine precipitation types may become powerful when coupled to a numerical weather prediction model. The area method was tested during a period that was characterized by the occurrence of a variety of precipitation types from 12 to 22 January 1995. The 6- and 12-h forecast temperature profiles from the Canadian operational Regional Finite Element model (Mailhot et al. 1989) were used to forecast the precipitation types. Three Canadian reporting stations were considered, Toronto (Ontario), Montréal (Québec), and Fredericton (New Brunswick). Three other techniques were tested at the same time, the Derouin (1973) method, the Baldwin and Contorno method (1993), and the Ramer (1993) method. Contingency tables were prepared for the four different methods, considering freezing rain, ice pellets, mixed rain and snow, snow, and rain.

The results from this last verification are shown in Tables 7–10. All methods, including Derouin, performed well on that small sample, even though the area method was slightly better than the others. It also shows that the method performs well using input from a NWP model.

TABLE 9. As in Table 7 but using the Derouin method. Percentage correct: 85%.

Forecast	ZR	IP	R/S	S	R	Total
Obs						
ZR	7	4	—	—	1	12
IP	—	2	—	1		3
R/S	—	—	3	—	—	3
S	—	1	3	9	—	13
R	—	—	—		15	15
Total	7	7	6	10	16	46

TABLE 8. As in Table 7 but using the area method. Percentage correct: 93%.

Forecast	ZR	IP	R/S	S	R	Total
Obs						
ZR	11	—	—	—	1	12
IP	—	2	—	1		3
R/S	—	—	3	—	—	3
S	1	—	—	12	—	13
R	—	—	—		15	15
Total	12	2	3	13	16	46

TABLE 10. As in Table 7 but using the Ramer method. Percentage correct: 83%.

Forecast	ZR	IP	R/S	S	R	Total
Obs						
ZR	9	1	—	1	1	12
IP	1	1	—	1		3
R/S	—	—	3	—	—	3
S	1	—	—	10	2	13
R	—	—	—		15	15
Total	11	2	3	12	18	46

5. Discussion and conclusions

Different parameters were evaluated to develop a statistical method to diagnose precipitation types. The most promising predictive parameters were the positive and negative areas associated with an above or below freezing layer. The size of an area is proportional to the mean temperature and depth of a layer. Criteria to differentiate among the different types were developed using a sample of cases from the 1989–90 and 1990–91 cold seasons. The area method discussed in this paper comprises that set of criteria.

The area method was evaluated and compared to other techniques (Baldwin and Contorno 1993; Ramer 1993; Derouin 1973; Cantin and Bachand 1993) using dependent and independent samples (note that no independent sample was available for the Cantin and Bachand method). The area method yielded better results than the other techniques on the different samples used in this work. It is worth noting that the Cantin and Bachand technique was designed to be subjectively modified by forecasters. An objective application of its criteria will likely degrade its performance. The Baldwin–Contorno and Ramer techniques gave results only marginally less accurate than the area method.

The area method is based on observations from all over North America, which makes it general since it is not NWP model dependent or region dependent. Results show the area method's ability to discriminate among the different precipitation types. However, the method also has some shortfalls. A more complete method would use a hydrometeor size distribution with associated temperature, falling velocity, and a combination of states (liquid, solid). Such a method would also consider important ambient parameters such as the moisture profile, vertical motion, condensation nuclei, etc. Neglecting those factors is equivalent to reducing the hydrometeor radius distribution to a single value, to consider only one phase at any given time and therefore to have a single falling velocity and one hydrometeor temperature. This means that a given temperature profile will result in the same heat transfer to a hydrometeor whether it is a slowly falling snowflake or a large water drop falling much more rapidly. These simplifications will have an impact on the diagnosed precipitation type. Also, the area method does not attempt to diagnose freezing drizzle and to discriminate cases of freezing rain or ice pellets mixed or not with snow. Little additional work would be needed to correct that last shortfall. The method was developed using stations from the North American aerological network. It is possible that a modified version of the method based on site-specific criteria would yield better results. Finally, the method may be improved by adding new cases to the initial development sample or by using different statistical techniques; for example, multiple discriminant analysis (Miller 1962) is probably well suited to that type of problem.

Following testing conducted in January 1995, the area method became operational at CMC in the spring of 1995. A new NWP model, the Global Environmental Multiscale (GEM) model, was introduced (Côté et al. 1998a,b) at CMC in 1997. As expected, the area method continued to provide good results with that new NWP model. In fact, the precipitation type forecast is expected to improve as NWP models make better forecasts of the vertical thermal structure. CMC has begun to evaluate the potential use of the area method to diagnose the different precipitation types in the vertical. That information would be useful to assess icing. Also, the area method could be applied to quantitative precipitation forecast (QPF) output of GEM to give QPFs for each precipitation type.

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