From mm to cm...
Study of snow/liquid water ratios in Quebec

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Author: Ivan Dubé
Meteorologist
EWSO Rimouski

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Finally, thank you to all who have shown some interest in this project.

REMARKS

This document constitutes a comprehensive summary of the work performed by the author (up to March 2003) on the subject of snow density and, more specifically, on forecasting the snow/liquid water ratio, *i.e.* the conversion factor used to change a water equivalent amount into a snow accumulation. The terms “snow density” and “snow/water ratio” will be frequently used in this document. Although they both refer to the same snow characteristic, we will now define these terms to avoid any confusion:

- Snow density: $\frac{\text{snow mass}}{\text{occupied volume}}$ (g/cm3)
- Snow/water ratio: $\frac{\text{snow accumulation}}{\text{water equivalent}}$ (mm/mm)

Snow density and the snow/water ratio are inversely proportional. This means that the more the density increases (more mass for the same volume), the more the snow/water ratio diminishes (a lesser accumulation for the same water equivalent, *i.e.* compacted snowflakes). And the more the density diminishes (less mass for the same volume), the more the snow/water ratio increases (a higher snow accumulation for the same water equivalent, *i.e.* more air embedded within and/or between the crystals).

Snow density will be mentioned in a qualitative way only. However, the snow/water ratio, which will at times be identified as “ratio,” “mean ratio”, “average ratio,” or “conversion factor” (abbreviated by “R”), will be characterised both qualitatively and quantitatively. Since this is a ratio, its value will be annotated with the symbol “ **:l** ”. Here are some examples of the calculation of snow/water ratios and of water equivalent to snow conversions (water (mm) → snow (cm)).

Snow Accumulation	Water Equivalent	Snow/water ratio
10 cm	10 mm	10:1
12 cm	8 mm	15:1
2 cm	4 mm	5:1

Water Equivalent	Snow/water ratio	Snow accumulation
5 mm	20:1	10 cm
8 mm	12:1	9.6 cm
10 mm	7:1	7 cm

The most common or average value of the snow/water ratio is usually considered as 10:1. So, when talking about low density snow (or light snow), that will imply high snow/water ratios, *i.e.* higher than 10:1. Conversely, high density snow (heavy snow) will be associated with low snow/water ratios, *i.e.* lower than 10:1.

This document covers in a relatively detailed way many aspects related to snow/water ratio forecasting according to meteorological conditions as well as impacts on various fields of application. The size of this document might frighten many readers. Although a complete reading is suggested to properly understand the entire message, it is not absolutely necessary. Thus, we recommend reading at least the conclusions that correspond to each section of the document and that summarise the prominent points. Consulting the table of contents (in the following pages) can guide the reader to the sections that are of more interest to him or her.

In addition to the 10 main sections addressing the various subjects of interest, a series of Appendices is included at the very end of the document.These include , among other things, a list of acronyms and abbreviations used in the text and their meaning (Appendix I). For those of you who are not familiar with the MSC meteorological observation network in Québec, a table listing identification codes, complete names and various stations characteristics as well as a geographical map showing their location are presented (Appendix II).

Finally, questions and/or comments concerning the content of this document are welcomed. You can contact the author by mail, e-mail, fax or by telephone:

Ivan Dubé
EWSO - Rimouski
38 St-Germain Est
Rimouski, Quebec, Canada
G5L 1A2

Phone (418) 722-1482
Fax (418) 722-1485

e-mail: ivan.dube@ec.gc.ca

Good reading!

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1. INTRODUCTION

Snow density (or the snow/liquid water ratio) is a parameter to which very little importance has been attributed in operational meteorology. The systematic application of a conversion factor of “10 to 1”, to convert expected quantities of water equivalent into snow accumulations constitutes a flagrant proof of this. Moreover, we can wonder to what extent both snow accumulations and their water equivalent are taken into consideration during forecast verification and the performance evaluation of numerical models (QPF).

Yet, snow density is a very important parameter in many fields of activity. Just think about the impacts of snow (*i.e.* its density as well as itsquantity) on snow removal, transportation, construction, business, agriculture, exploitation of natural resources, tourism, avalanches, and hydrology (flood or water level forecasting, reservoir management, erosion, etc.). of . Therefore, we must now recognize the need to develop reliable and effective methods to diagnose and forecast snow density.

The main objectives of this study are to:

- develop awareness among meteorologists;
- identify and understand the various parameters and processes associated with snow density;
- develop appropriate and effective diagnosis/prognosis operational tools;
- improve the performance of snow accumulation forecasts;
- improve the level of service offered to various specialized clients (*e.g.*, hydrologists and publicsafety).

Reaching these objectives will help operational meteorologists better confront the many challenges, old and new, associated with precipitation forecasting, one of the MSC’s new priorities.

do this, a climatological study of snow/water ratios has been conducted in the Province of QuebecThe results are presented in Section 2. All the theoretical information associated with snow density was then collected to identify the physical processes that determine snow density. This aspect is covered in Section 3 of this document. Other climatological studies already published are presented in

Section 4. Section 5 marks a return to climatological results and their interpretation according to theory.

Various existing diagnosis/prognosis tools or techniques are evaluated in Section 6. The development of a complete snow/water ratio forecast algorithm that incorporates all parameters and processes affecting snow density is also described. Section 7 is dedicated to the verification of this The performance measurement based on a sample of 281 cases in Quebec is presented, as well as suggestions for improvement. The impact of snow density on various application fields such as snow accumulation, blowing snow, hydrology, and avalanche forecasting is examined in Section 8. Operational strategies are also suggested.

Future activities related to this study, many of which are to be performed in collaboration with different partners, are listed in SThey involve, among other things, the continuation of the verification process and climatological study, a more detailed study of conditions favourable for blowing snow and the integration of an additional field to numerical models.

2. CLIMATOLOGY OF SNOW/WATER RATIOS IN QUEBEC

Before undertaking the problem of forecasting the snow/water ratio, it seemed appropriate to conduct a climatological study on our Province to better identify the taskat hand. In fact, we normally seek to predict meteorological parameters inside the observed values. Such a study can also help us identify the various parameters and processes that influence snow density. Note that this climatological study is limited to snowfalls where the atmospheric temperature remained below the freezing point. Thus, it does not include cases of melting snow or mixtures with other types of precipitation like rain or drizzle, (freezing or not), or ice pellets. We wanted to specifically evaluate the range of snow/water ratios in snowfall situations where a factor of 10:1 traditionally applies.

a) Data:

The climatological study contains data observed within 3 winter seasons (from November 1st, 1999 to April 30th, 2002). Selected observation sites are: Val D'Or (YVO), Mirabel (YMX), Sherbrooke (YSC), Quebec (YQB), Mont-Ste-Anne (MSA - at its summit), Gaspé (YGP), Baie-Comeau (YBC), and Fermont (YWK). A map showing the locations is included in Appendix II. We wanted a good representation of the different climates observed in Quebec: the rather cold and continental climate of the North-West and North-Centre of the province (YVO/YWK), the milder climate that is slightly influenced by maritime air masses of South-West (YMX/YSC/YQB), the climate that is more strongly influenced by maritime air masses of the Eastern (YGP/YBC) and the mountain climate (summit of MSA). However, the arctic climate in the far-Northern regions is missing because of insufficient snow measurements. We do not exclude the possibility of widening the climatological study to these sectors if the necessary data eventually becomes available.

Following are the studied meteorological parameters: snow accumulation, water equivalent (that allows calculating the average snow/water ratio for each occurrence) and, for some of the most significant cases, surface wind and temperature. The data mainly come from the snow observation network and regular hourly observations (SA/METAR). Some selection criteria have been applied to limit the sample to significant and representative snow accumulation higher than 2.5 cm (or 1 inch), a temperature profile that remainsbelow the freezing point and no mixture with other types of precipitation. No restriction has been applied to surface wind observations.

Errors can be relatively frequent in these types of measurements, particularly in the presence of strong winds that cause blowing snow. The sites were selected in such a way as to obtain the most reliable data possible, with the possibility of validation with surrounding observations (for example, data from Dorval could have been used to validate data from Mirabel, Charlesbourg for Quebec city, Charlevoix for Mont-Ste-Anne, Noranda for Val D'Or, etc.). Following this type of counter-verification, only a few cases were eliminated (mainly at Mont-Ste-Anne). We hope the use of a high number of cases has helped to minimize potential errors.

b) Results:

According to the established selection criteria, a total of 490 cases were collected, including 78 cases of "abundant snow" (15 cm or more). The distribution of cases per observation site is shown in Table 1. Of course, the northernmost sites (such as Fermont) show a bigger proportion of cases, the winter season being significantly longer in comparison to the outhern parts of the province.

Station	# Cases	% Cases
YVO	56	11
YMX	49	10
YSC	71	14
YQB	70	14
MSA	57	12
YGP	49	10
YBC	56	11
YWK	82	18

Table 1: *Number and proportion of cases per observation site.*

Table 2 shows the distribution of snowfalls according to various accumulation intervals (from 2.5 to 50+ cm). Note that snowfalls lower than 15 cm represent the great majority of cases (84%), which still leaves a significant sample of cases of abundant snow. Also, a relatively high proportion of these (close to 25%), including many of the more "extreme" cases of 30 cm or more, come from Gaspé airport (YGP).

Accumulation (cm)	2.5-5	5-10	10-15	15-20	20-30	30-40	40-50	50+
# cases	166	155	91	44	25	7	1	1

Table 2: *Number of casesfor various intervals of snow accumulation.*

The "mean" snow/water ratio for each occurrence varies from 7:1 to 26:1 among the 490 cases, for an average of 13:1. By targeting only the 78 cases of abundant snow, we observe a gap of 8:1 to 22:1 and an average of 12:1. Evidently, the well-known "factor 10" does not constitute the one and only solution!

From the sample, the variation of the snow/water ratio has been evaluated on the basis of the various parameters. These parameters are: the winter season (or from one year to the next), the site, the month of the year, the snow accumulation, and the surface wind/temperature. Table 3 does not show any annual variation (significant variation would have been surprising), which heightens confidence in the validity of collected data.

Winter Season	99-00	00-01	01-02	TOTAL
Average snow/water ratio	13	13	13	13

Table 3: *Annual variation of the average snow/water ratio.*

The snow/water ratio varies significantly according to the observation site (Table 4). It seems that the milder the site's climate and/or the stronger the maritime influence, the lower the average ratio (thus, snow of higher density). Conversely, the colder and more continental the climatethe higher the ratios are (low density snow). Only Sherbrooke seems to depart from this rule. This particular case will be addressed later in the present document.

Station	YMX	YGP	YBC	YQB	MSA	YVO	YSC	YWK
Ratio	11	11	12	13	13	13	14	16

Table 4: *Variation in the average snow/water ratio for the different observation sites.*

The collected data also show a significant variation in the snow/water ratio depending on the month of the year (Table 5). The ratios are lower during the milder months, *i.e.*: beginning/end of winter season (November and April), and higher in mid-winter (December to March).

Month	NOV	DEC	JAN	FEB	MAR	APR
Ratio	11	14	14	13	12	11

Table 5: *Monthly variation in the average snow/water ratio.*

The variation in the snow/water ratio in accordance with the total snow accumulation for each event has also been examined (Table 6). We see little change other than a slight reduction of the average ratio (from 13 to 12) for cases of abundant snow (> 15 cm). However, this reduction could be attributed to a great proportion of these cases emerging from the YGP station (Gaspé) which, as mentioned above, shows a relatively low average snow/water ratio (*i.e.*: 11:1, the lowest among all studied sites).

Accumulation (cm)	2.5-5	5-10	10-15	15-20	20-30	30+
Snow/water ratio	13	13	13	12	12	12

Table 6: *Variation in the average snow/water ratio depending on total snow accumulation.*

According to statistics derived from 95 cases among the more significant (cases of abundant snow and some others), the snow/water ratio also varies with the observed mean surface wind and temperature. Summarized results in Table 7 suggest a reduction of average ratios with an increase in winds, for each identified range of temperatures. There also seems to be a "peak" in the average snow/water ratio between -10 and –20 ^{o}C. The ratios are in fact lower when the average surface temperature (during each occurrence) is higher than–10 or lower than –20 ^{o}C. In fact, this "signature" appears in each of the 3 wind intervals.

Wind → / **Temperature ↓**	**< 10kt**	**10-20kt**	**20-30kt**	**All winds**
0 to –5 ^{o}C	11	10	10	10
-5 to -10 ^{o}C	14	12	10	12
-10 to -15 ^{o}C	17	15	11	15
-15 to -20 ^{o}C	17	15	14	16
-20 to -25 ^{o}C	15	13	12	13
All temperatures	15	13	11	**Based on 95 cases**

Table 7: *Variation of the average snow/water ratio according to surface wind and temperature.*

c) Conclusions:

Following are the first conclusions that could be drawn up from this climatological study which as we recall, is limited to cases where snow is the only type of precipitation present and the profile of atmospheric temperature remains below the freezing point:

- the snow/water ratio (or snow density) varies considerably from one occurrence to another and is not limited to a single value (10:1),
- the snow/water ratio also varies according to many parameters, such as the geographical site, the month of the year, wind, and temperature,
- the influence of total snow accumulation by event on the snow/water ratio is not significant.

We will review the climatological results in more detail after examining the theory on snow density and other available climatological studies.

3. THEORY ON SNOW DENSITY

Snow density is directly related to its crystalline structure. This structure depends on many physical processes that occur within the cloud, under the cloud, and at ground level. All these processes will be described using the "top-down" approach, as if we followed snow crystals from their birth at the top of the clouds to their accumulation on the ground. We will end this section by listing the different meteorological parameters that affect snow density and that will need to be considered in the development of diagnosis/prognosis tools or techniques. But first, we will start with a quick review of cloud and precipitation microphysics.

a) Cloud and precipitation microphysics:

Since this subject is very well covered in many publications, we will only briefly review it here. For more details, you can consult one or several of the references mentioned in the bibliography at the end of this document.

To generate snow, ice-crystals must first be observed in the cloud. The formation of the first ice-crystals is facilitated by "ice nuclei". Clay particles in suspension in the atmosphere constitute the principle source of this type of nuclei (70%). Other significant sources are volcanic ashes and sand particles. These nuclei can initiate the freezing of supercooled droplets at much higher temperatures than for pure water (-40 ^{o}C). Table 8 lists different natural ice nuclei and the temperature at which they become active. As the temperature decreases, more and more nuclei become active. It is estimated that at -10 ^{o}C, 60% of clouds contain ice. At -15 ^{o}C, the proportion reaches 90%, and at -20 ^{o}C, it reaches 100%. The suggested "operational" threshold for the presence of ice in clouds is -10 ^{o}C. However, we must remember that a grey zone exists between -9 and-15 ^{o}C; that is, at temperatures higher than -9 ^{o}C, it is unlikely that ice will be found (supercooled water predominates). At temperatures lower than -15 ^{o}C, the presence of ice is almost assured (supercooled water is absent). Between these threshold values, ice and water can coexist.

Ice nuclei	Activation Temperature (°C)
Magnesite	-8
Kaolinite	-9
Hematite	-10
Brucine	-11
Volcanic ash	-13
Biotite	-14
Vermiculite	-15

Table 8: *Different types of natural ice nuclei and the temperature at which they become active. At -15°C, all the nuclei listed above are active.*

Following the activation of the ice nuclei, the Bergeron effect allows the growth of ice-crystals by deposition of water vapour of supercooled water. Through different processes more or less understood, ice-crystals are fragmented, causing a multiplication of ice-crystals and therefore accelerating their growth. The bigger crystals start to fall under the effect of gravity and collide with each other. This is described as growth by aggregation. In an environment of supercooled droplets, further crystal growth can occur through the process of accretion, *i.e.* collection of droplets by the snow crystals. This process, similar to riming, will be described in more detail in the next section.

Thus, crystals grow by:

- activation
- deposition (sublimation)
- fragmentation
- aggregation
- accretion

All these processes are strongly dependent on temperature and humidity conditions in the atmosphere. Let us now look at what specifically determines snow density.

b) In-cloud Processes:

The density of snow crystals depends on two main factors: shape and size.

i) Crystal Shapes

The various physical processes governing ice-crystal growth were listed in the preceding section. All these processes are strongly dependant on in-cloud temperature and humidity conditions. Many classifications of snow crystals have been established (*e.g.* Nakaya's in 1954), identifying different crystal shapes (also referred to as "types" or "habit"). The main ones are listed in Table 9 below, along with the range of temperatures at which they form.

Crystal shapes	Temperature (^{o}C)
Plates	0 to -3, -9 to -12, -18 to -22
Needles	-3 to -5
Columns	-5 to -9, < -22
Stars	-12 to -18

Table 9: *Main crystal shapes and ranges of temperature at which they form. These temperatures represent an average of the values published in various studies.*

The diagram shown on Figure 1—among many other similar diagrams previously published—shows the more complex relationship that exists between the temperature, the level of supersaturation, and the crystal type.

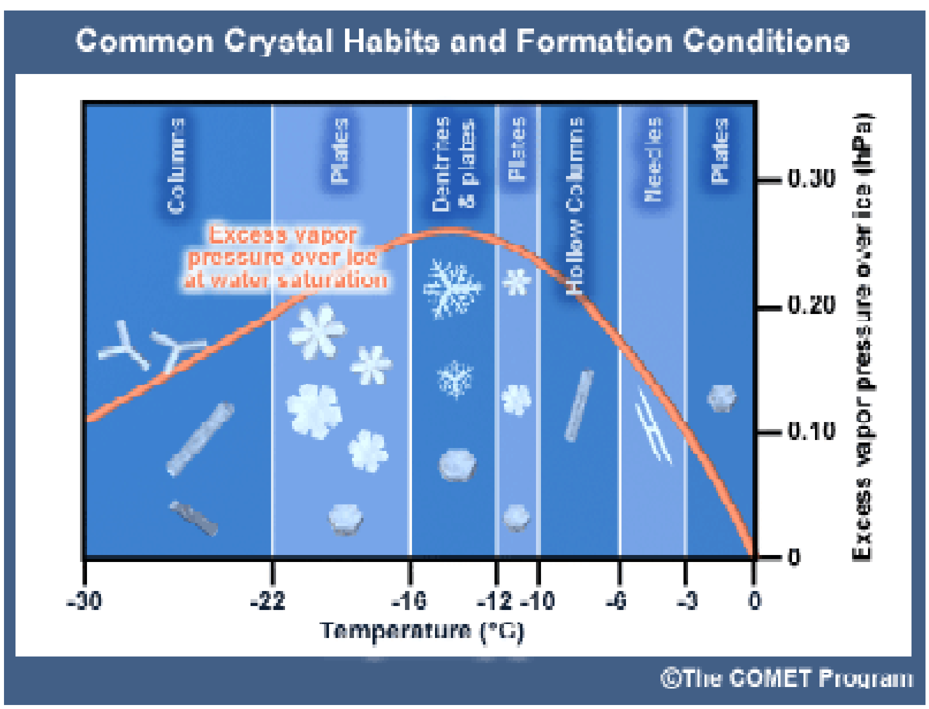

Figure 1: *Diagram showing favoured crystal habits according to temperature and the level of supersaturation. Source: COMET.*

In addition to these “pure” or “basic” crystal shapes, many “mixed” types exist. In fact, snow is not usually homogenous because as they fall, crystals generally pass through varying conditions of temperature and humidity, which leads to a superposition of different crystal types. The final shape of snowflakes often relates to a combination of pure forms. However, in favourable conditions (*e.g.* isothermal atmospheric profile), “perfect” crystals can be observed. In addition to these diverse crystal types, there are other forms of solid precipitation, such as ice pellets and hail, whose principles of formation differ (*e.g.* related to melting and freezing in the case of ice pellets).

As mentioned at the beginning of this section, the growth of snow crystals can occur by accretion in an environment of supercooled droplets. This process, which is usually observed at temperatures between 0 and -10 ^{o}C (ice being predominant at temperatures lower than -10 ^{o}C), significantly affects snow density. It favours high densities (densification by riming) since supercooled water droplets collected by snow do not produce an organized structure (*i.e.* by favouring ramifications). They are rather collected in a random way. In this manner, droplets will tend to fill in “empty” spaces (occupied by air) in snow-crystals and increase the density. Accretion will be more effective with certain types of crystals than with others. Figure 2 shows several examples of rimed crystals (subjected to accretion). Note that on these photographs, accretion seems more effective on crystals with a bigger surface (*i.e.* star/plate versus needle), which is explained by their greater capacity to collect droplets during their fall.

Accretion, which, as mentioned above, is produced in the presence of supercooled liquid water, will be favoured by a great number of condensation nuclei said to be “hygroscopic”. Since sea salts constitute excellent hygroscopic nuclei, we can therefore assume that accretion is much more frequent in a coastal environment or in air masses of maritime type than in continental regions/air masses. Case in point: the high frequency of drizzle/fog in coastal regions in comparison to continental regions. Orographic lift conditions also favour the accretion phenomenon, by facilitating water vapour condensation in the low levels and thus the formation of droplets. Briefly, all favourable conditions to the formation of freezing drizzle (FZDZ) will increase the potential of accretion or riming of the snow and will increase its density.

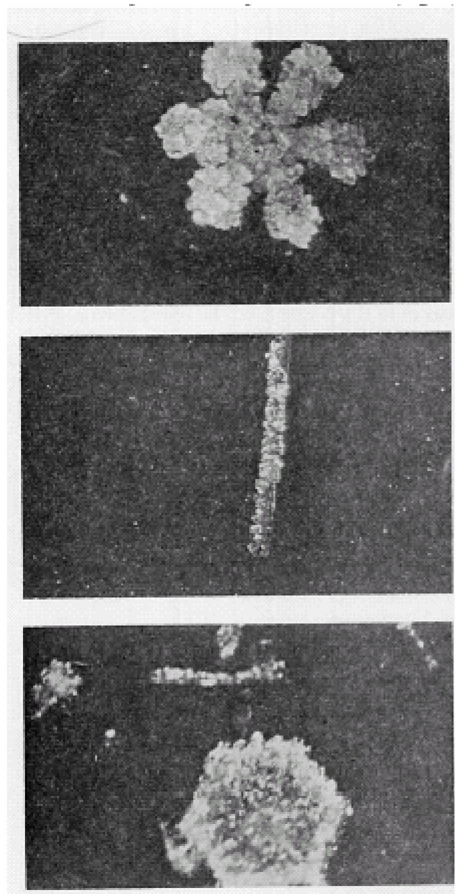

Figure 2: *Different pure crystal types subjected to accretion. From top to bottom: star, needle, plate. Source: Power et al (1963).*

Another factor affecting crystal growth to a lesser extent has been identified in laboratory. It pertains to the electrical field that would favour dendritic growth (*i.e.* many ramifications) by making branching appear at the extremities of crystals. This phenomenon seems related to the fact that water molecules are polarizable. However, it will not be addressed here any further since its impact carries relatively little significance and we are unable to measure/predict the electrical field (or variations of it) present in the atmosphere in an operational meteorology context.

ii) Crystal Size

Generally, the more voluminous snow-crystals are, the lesser their density since they occupy more "empty space". Conversely, the smaller crystals have a greater ability to compact in a denser assemblage. The size of crystals depends on many factors:

- residence time in the cloud
- temperature
- atmospheric pressure
- level of supersaturation with respect to ice

Figure 3 shows how snow crystal growth varies according to the first two factors listed above. You can see that optimal growth happens at temperatures close to -15 °C, which corresponds to the growth of stellar crystals, as mentioned above. Moreover, it is mentioned in many publications that the intersection of temperatures ~ -15 °C, the maximum of the ascending vertical motion and a high relative humidity (>80%) constitutes a good predictor for abundant or intense snowfalls. It would also correspond to thermodynamic conditions favourable to low density snow.

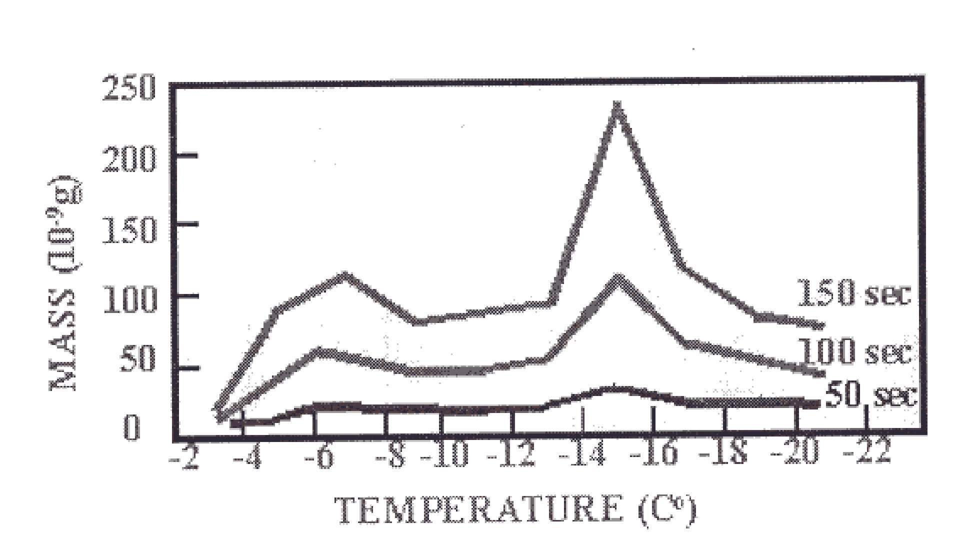

Figure 3: *Variation of snow-crystal mass according to temperature for different in-cloud residence times. Source: NCEP research Internet Site.*

Studies on the maximum dimension of snowflakes, completed with samples collected at various surface temperatures, allowed the identification of 2 ranges of optimal temperatures: a first one between 0 and -2 °C, which could be associated with the aggregation process (see sub-section 'iv'), and a second one between -12 and -15 ^{o}C, which could correspond to nearly isothermal profiles favourable to the growth of stellar crystals (temperature between -12 and -18 ^{o}C).

c) Sub-cloud Processes:

Between the base of the cloud and the surface of the ground, snow density can be affected by:

i) sublimation
ii) melting
iii) freezing
iv) aggregation
v) fragmentation of crystals.

i) Sublimation

Under the base of the cloud, the atmosphere's relative humidity will determine if snow leaving the cloud will reach the ground and, if so, how its density will be affected. In fact, a very dry layer of air sufficiently thick under the cloud will cause sublimation (or evaporation) of precipitation, thus the virga phenomenon. Conversely, if the air is very humid or close to saturation, snow-crystals will not be subjected to modifications related to sublimation. In the intermediate case of a layer just humid enough to allow precipitation to reach the ground, partial sublimation of snow will affect its density, in a more or less marked way according to the type of crystal. Types that are not very dense (*e.g.* stars), will sublime more rapidly and will quickly gain density under such conditions. However, denser types (*e.g.* ice pellets) will be subjected to a less important densification since their more compact form will not be modified as much as the one of ramified crystals, even if in both cases, there is sublimation and therefore reduction of the crystals' dimension.

ii) Melting

Melting of crystals in the atmosphere will happen when the air temperature rises above the freezing point. Such a layer can extend down to the surface (the level where T=0 ^{o}C corresponding to the freezing level), or else can be located aloft (commonly called "nose of warm air"). Melting can be partial or complete according to the thickness and average temperature of this layer (we could also talk about the snow's "residence time" in the warm air layer, related to the thickness of the layer and the fall velocity of snowflakes). Complete melting (snow changing to rain) will evidently eliminate any concept of snow density (snow/water ratio dropping to 0:1, *i.e.* no snow accumulation regardless of the measured water equivalent). Partial melting, causing wet or melting snow, or a mix of rain/snow, will significantly affect the density of snow accumulating on the ground. We can expect relatively heavy snow, thus snow/water ratios lower than 10:1, whatever the type of crystals (thus independent of the snow density before melting). The crystal type concept becomes practically useless for diagnosing the density after melting (partial or complete) of snow crystals. The predominance of rain or snow, related to characteristics of the warm air layer (thickness, average temperature, etc.), will be the determining factor in this case.

Note: The melting process has been described in this section (sub-cloud processes) by personal choice but it could very well happen inside the cloud. Melting of the snow irreversibly alters its density, whether it happens inside or under the cloud. The same logic applies to the freezing phenomenon, which follows.

iii) Freezing

Freezing of precipitation, after partial or complete melting of snow in a warm air layer aloft, will happen once temperatures return under the 0 ^{o}C threshold. As for the melting case, the degree of freezing (*i.e.* partial or complete) will depend on the thickness and average temperature of the cold air layer. The impact of this process on the density will be related to the type of precipitation reaching the ground. Different combinations of more or less pronounced warm air layers and more or less important cold air layers will result in various types of precipitation: ice pellets, mix of snow/freezing rain, snow mixed with a little rain, mix of snow/ice pellets, snow pellets, etc. These produce accumulations in accordance with a specific snow/water ratio. However, a thermal profile favourable to precipitation in the form of rain, freezing rain, rain mixed with either a little melting snow or ice pellets will not result in an accumulation of snow on the ground.

The melting process can reoccur after freezing when a second warm air layer is present. In this case, the same rules apply: the type or mixture of precipitation associated with the thermal profile will determine the density of accumulated snow.

iv) Aggregation

Aggregation, one of the crystal growth processes, corresponds to the unification of ice-crystals after collisions between them. Aggregation is principally active close to the freezing point, *i.e.* between 0 and -4 ^oC, with slightly "wet" snowflakes joining together more easily. Aggregation can also happen at lower temperatures in the case of stellar crystals (-12 to -18^oC), whereas the entanglement of ramified branches of this type of crystal replaces the greater adhering ability of wet snow crystals. There is a certain dilemma concerning the impact of aggregation on snow density. The formation of snowflakes of great dimension and comprising many ramifications following the aggregation of crystals favour in fact a reduction of density. However, as temperatures get closer to the freezing point, even partial melting of snowflakes will tend to favour densification. Furthermore, the latter will prevail in the majority of cases (this problem does not occur with stellar crystals that aggregate at temperatures far below the freezing point). The impact of aggregation on density also depends on the type of crystals present. For example, aggregation of ramified crystals (like stars) or needles will result in much lighter snowflakes than aggregation of more solid crystals such as columns or ice pellets. Figure 4 shows aggregated ice needles. Note the relatively low-density structure in view of the many built-in "empty spaces".

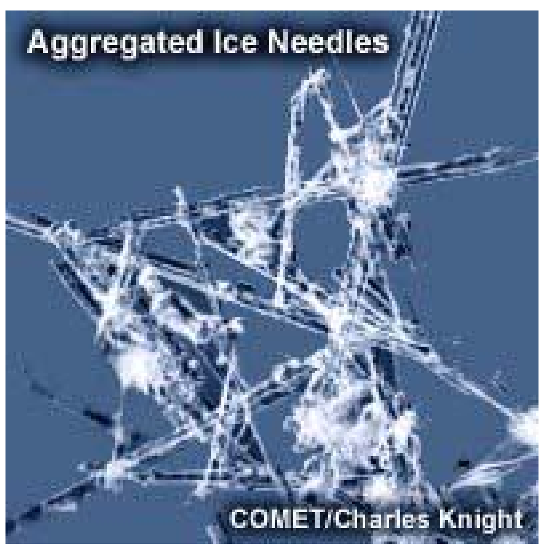

Figure 4: *Aggregated ice needles. Source: COMET.*

Therefore, aggregation can play a deciding role in obtaining low-density snow but only in some specific cases (*e.g.* aggregated needles or spatial dendrites at a temperature nearing -1 to -4 ^oC within a layer of significant thickness).

v) Fragmentation

The process of fragmentation is the result of strong winds causing collisions among crystals. These collisions tend to break crystals into many small fragments that will eventually compact into a denser assembly once accumulated on the ground. The level of fragmentation will greatly influence snow density, especially in the case of low-density crystals such as stars, which are also very fragile, and thus sensitive to collisions. Denser crystal types prove to be more resistant to collisions, thus less affected (or not affected) by the process of fragmentation. Moreover, the relatively high density of crystal types that compact more efficiently can not be significantly modified by the fragmentation process, as intense as it may be. In other words, there is a limit to the possible densification by fragmentation. A good example involves ice pellets: even in the absence of strong winds, they give rise to high densities because of their compact form (not ramified). In strong or severe wind conditions, collisions between ice pellets have little impact on their density because these particles are able to compact efficiently *a priori.*

d) Ground-level Processes:

Various processes can influence snow density upon initial contact with the ground:

i) fragmentation and compaction by wind (blowing snow)
ii) melting
iii) compaction under the weight of new snow
iv) ageing

i) Fragmentation and Compaction by Wind

Strong surface winds (usually 20 knots or more) cause wind transportation of snowflakes, *i.e.* blowing snow. As in the case of "atmospheric" fragmentation, snow crystals are then subjected to collisions. These collisions involve other crystals but also the ground (snow, ice, pavement, land, rock, etc.), breaking the snow crystals, which subsequently compact in a denser assemblage. Once more, this process will cause a more pronounced densification among ramified and fragile (low-density) crystals as opposed to solid dense ones (*e.g.* ice pellets).

ii) Melting

Ground-level melting (partial or complete) is very likely when the surface air temperature is higher than the freezing point. But even when air temperature is below 0^{o}C, melting of snow on the ground can take place if the ground is relatively warm and not frozen, usually in September or October. Heat emitted from the ground can cause partial or complete melting of freshly fallen snow and modify its density almost instantly. The presence of snow on the ground evidently has to be taken into consideration since a significant layer (2 or 3 cm) is sufficient to "insulate" the new accumulation, *i.e.* to prevent the heat transfer from the ground to the freshly fallen snow. Once again, the effect will be slightly different depending on the type of crystals involved. Low-density crystals will have a tendency to warm up more efficiently on contact with the ground than high-density crystals. You need only compare the melting period of a big stellar snowflake and a hailstone to be convinced.

iii) Compaction under the Weight of New Snow

Under the weight of subsequent snowfalls, it is highly probable that snow density on the ground will eventually be affected. However, this process is not instantaneous, which leads us to believe that it is possible to distinguish (and thus forecast) different layers of snow of distinct densities during an entire event (*e.g.* a period of 12 to 24 hrs). Moreover, many climatological studies—including the one conducted in the Quebec region and presented in this report (see Section **2 b**)—show that this process is negligible, which means that important snowfalls (*i.e.* 20, 30 or even 50 cm) do not possess a significantly higher density than the lower accumulations of snow (5 to 10 cm). In other words, it would be possible to observe 50 cm of light powder snow (*e.g.* snow/water ratio of 20:1) without the lower layer being significantly compacted by the upper layer. A period of rain following such a snowfall would however have a very visible effect on its density (snow would become significantly heavier). It would however be preferable in such a case to describe the event as "a light snowfall followed by rain" rather than "a heavy snowfall". Density modification caused by processes that follow the snow accumulation is discussed in the next paragraph.

iv) Ageing

The time snow lasts on the ground (*i.e.* its ageing) influences its density. In fact, after many hours or days, physical processes (*e.g.* melting, sublimation, liquid precipitation, etc.), mechanical processes (*e.g.* compaction) as well as thermodynamic processes (such as different types of crystal metamorphism) can considerably modify the density of the snowpack. Yet, this aspect will not be considered within the scope of this study. Although crucial for avalanche forecasting, ageing of snow is of lesser interest to meteorologists. However, that does not prevent them from providing specialists in this field the meteorological parameters that are necessary in their line of work.

e) Meteorological Parameters:

Following are the main meteorological parameters that affect snow density:

- temperature profile
- humidity profile
- vertical motion profile
- low level winds
- ground temperature

By evaluating the minimum necessary data to be retrieved from numerical models' available fields we can try to establish a list of parameters to consider in order to make a "serious" diagnosis/prognosis of the density (or snow/water ratio). At least 16 parameters were identified. They are summarized in Table 10 below:

Level	Temperature	Vertical Motion	Relative Humidity	Winds
500mb	X	X	X	
700mb	X	X	X	
850mb	X	X	X	
925mb	X		X	X
surface	X		X	X
ground	X			

Table 10: *Overview of the minimal meteorological parameters to consider.*

f) Conclusions:

In summary, many physical processes influence the growth (shape and size) of snowflakes as well as their possible transformation before/during their accumulation on the ground. These processes strongly depend on several meteorological parameters such as temperature, humidity, wind, and vertical motion profiles. Moreover, the impacts of these processes on density depend greatly on the type of snown crystals present. All this gives rise to a great variety of crystal types, rimed or not, fragmented or not, aggregated or not, each having a specific density (thus a specific snow/water ratio). This is very well represented in the snow classification from Magono and Lee (1966), which comprises 80 different types of crystals.

Figure 5 below shows examples of ice-crystals. There are many publications and Internet sites which address this fascinating subject. The reader is invited to consult these for more details.

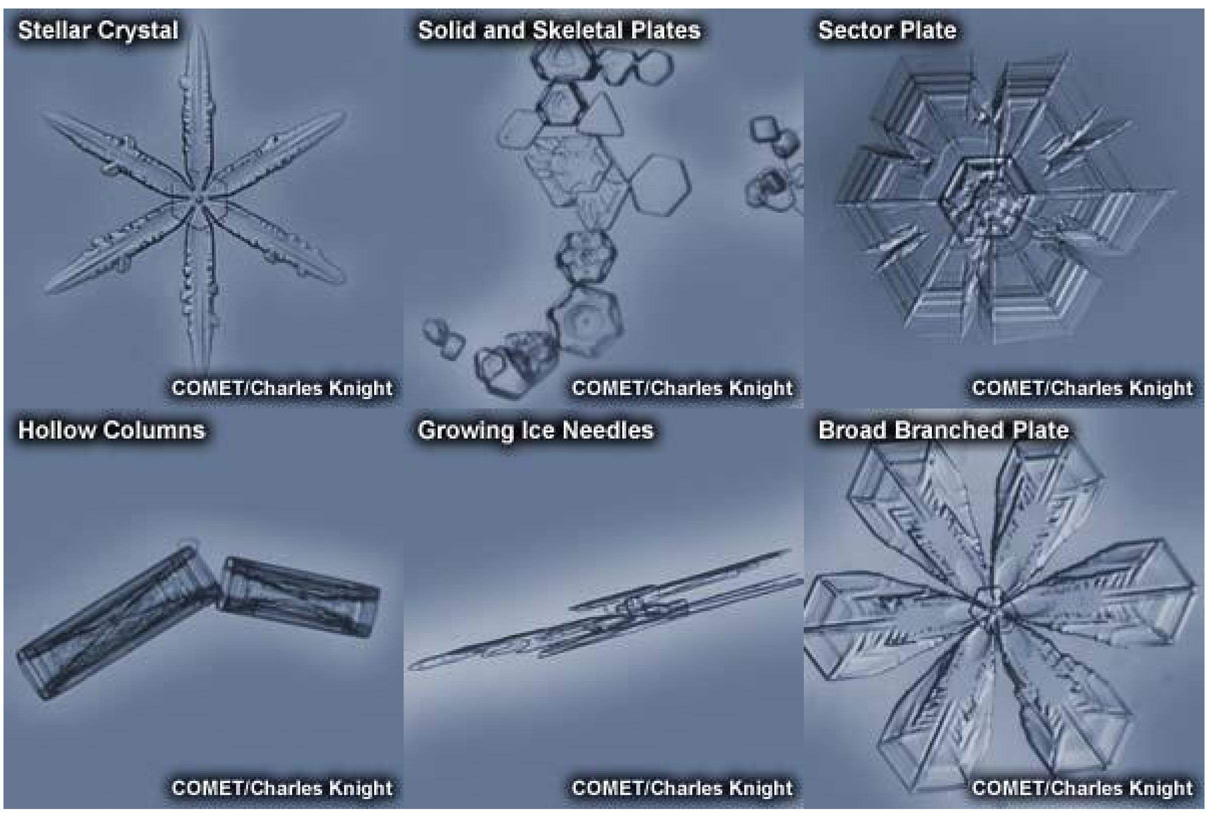

Figure 5: *Various ice-crystal habits. Source: COMET.*

4. OTHER CLIMATOLOGICAL STUDIES

To insure that the snow density problem would be well understood, it was deemed important to gather and consider as much information as possible. Several studies on snow density were found following intensive searches on the Internet and in the most accessible scientific publications. Most of this information, coming from various sources or fields such as hydrology or avalanches, will be summarized in this section. However, emphasis will be put on 2 studies originating from the meteorological community.

a) Summary of Several American Studies:

Many similarities emerged from studies published between 1950 and 2002: the lack of observations, the very limited interest shown by the meteorological community, and the inadequate use of the "ten-to-one" rule. A substantial variability in the density of freshly-fallen snow or in the snow/water ratio (*i.e.*, from 3 to 100:1) was observed. This variability was linked to geography, temperature and humidity. There are also references to the influence of winds (fragmentation) and the accretion process. Some of those studies are included in the bibliography at the end of the document. Others are referenced indirectly in publications also listed in the bibliography.

b) Canadian Study (Power *et al*, 1963):

This study was published in 1963 under the title "Snow Crystal Forms and Riming Effects as Related to Snowfall Density and General Storm Conditions". It is based on observed data collected during the winters of 1960-61 and 1961-62. Its main goal was to diagnose the snow/liquid water ratio, by establishing a link between snow density and the dominant crystal type, in order to convert measured snow accumulations (occasionally the only measurements available) into the appropriate water equivalent. This study also examined the influence of accretion (riming of the different snow crystals) and aggregation on snow density.

Data (depth of snowfall and water equivalent, as well as snow crystal samples for each event) were collected in downtown Montreal on a rooftop about 10 metres above ground. The samples were obtained from the clever device shown in Figure 6.

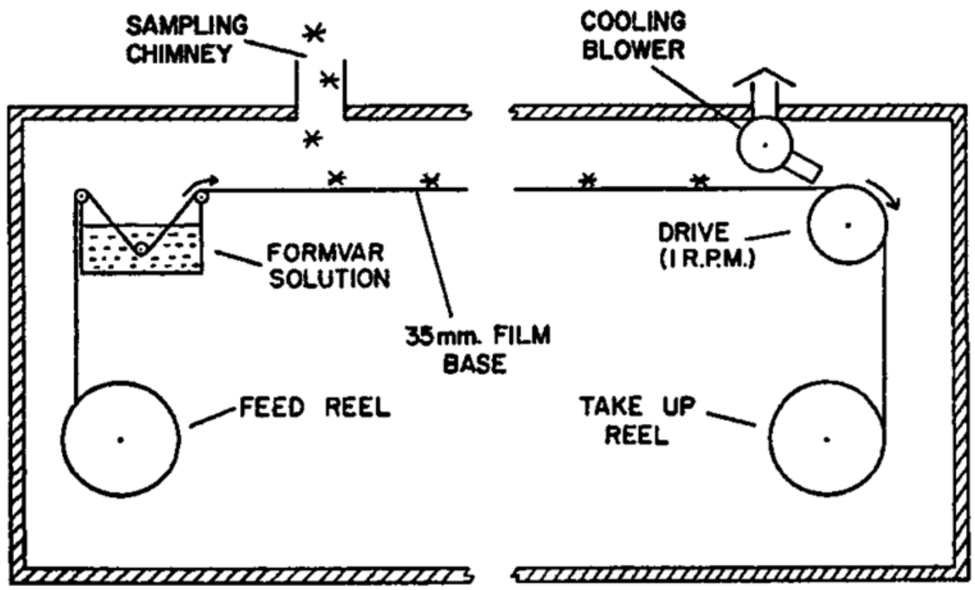

Figure 6: *Snow crystals collecting device. Source: Power et al.*

The device, a refrigerated metallic box, contained (just like a movie projector) a motor and film spools. First, the film ran through a formvar solution then collected the snow crystals as they fell into the box. A ventilator then rapidly dried the solution, thereby fixing the crystals' print on the film. These samples were examined and photographed using an electronic microscope (the complete process is described in the original study). For a little more than 25 snowfalls of 2 cm or more without the occurrence of rain or blowing snow (to insure validity of measurements), density values (snow/water ratios) could be associated to the observed crystal shapes (or combinations of various crystal types). The presence of accretion or aggregation could also be determined. The measured snow/water ratio varied from 4:1 to 33:1, averaging 11.8:1. Table 11 shows the different crystal types observed for different ranges of the snow/water ratio.

Measured Snow/water ratio	Crystal types observed
23- + :1	Stellar crystals
18-22:1	Stellar crystals
13-17:1	Stars, needles, mixed (*i.e.*, stars+plates)
9-12:1	Slightly rimed stars, plates, columns, mixed
6-8:1	Densly rimed stars, rimed plates
3-5:1	Ice pellets

Table 11: *Crystal shapes observed for different ranges of the snow/water ratio.*

The number of cases was sufficient to average the density, thus to calculate a mean snow/water ratio for different crystal types, rimed or unrimed (Tables 12 and 13).

Unrimed crystals	Mean snow/water ratio
Stars	20:1
Needles (aggregated)	16:1
Plates	12:1
Spatial dendrites*	11:1
Columns + plates	10:1

Table 12: *Mean snow/water ratios for different unrimed crystals (no accretion).*
** Spatial dendrites were defined by Nakaya (1954) as dendritic overgrowth on a crystal nucleus consisting of an assemblage of plates and/or columns.*

Rimed crystals	Mean snow/water ratio
Needles	10:1
Stars	9:1
Stars + plates	7:1
Plates	7:1
Ice pellets	4:1

Table 13: *Mean snow/water ratios for different rimed crystal types (significant accretion).*

In summary, the study found that stellar crystals possess the lowest density. Needles, generated at temperatures that favour aggregation (–3 to –5^{o}C), tend to form larger snowflakes (aggregates) rather than simple crystals, giving them a relatively low density. Plates, columns and ice pellets follow in an increasing order of density. The study also showed that accretion may greatly influence snow density; increases of 30 to 100% have been observed depending on the crystal type. Needles were less affected (densification of 30%) but stars were much more affected (just over 100%, the snow/water ratio changing from 20 to 9:1 following severe accretion). This concurs with the theory that accretion is more effective on larger crystals because of their greater capacity to collect droplets (see Section **3 b) i)**). The authors regarded these results as a good approximation and they insisted on the importance of significantly increasing the sample's size in order to achieve a higher confidence level. They suggested a number of ways to reach an adequate number of events. Unfortunately, this has not been realized as of yet; if it has, published results could not be found.

c) Study by P. Roebber *et al* (2003):

This climatological study is part of a very detailed analysis on snow density which is entitled "Improving Snowfall Forecasting by Diagnosing Snow Density". This study also covers the snow/water ratio diagnosis and its impact on snow accumulation forecasting, which will be reviewed later. The climatological section of this study is quite meaningful, particularly as it shows similarities with the Quebec study presented in Section 2.

The selection criteria are: a minimum of 5 cm of snow/2.8 mm water equivalent and surface winds less than 20 knots (to eliminate data corruption caused by blowing snow). Also, each event had to occur close to 00 or 12Z (Universal Time) and close enough to a radiosonde station to enable a possible correlation of density measurements with other meteorological parameters such as temperature and humidity profiles and surface winds. The resulting sample includes 1650 snowfalls over a period of 22 years (1973-94) at 28 radiosonde stations (see Figure 7).

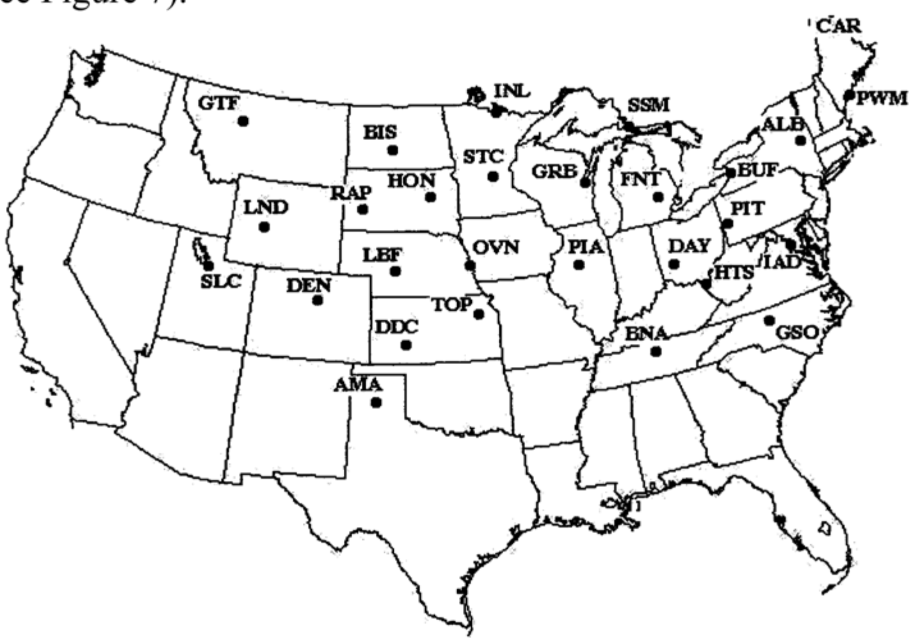

Figure 7: *Radiosonde network used in the Study. Source: Roebber et al (2003).*

The measured snow/water ratios range from 2:1 to 47:1, with a mean ratio of 15:1. Figure 8 shows the number of cases observed in accordance with the snow/water ratios. Many valuable statistics were calculated using the climatological data; in particular, the observed ratios nearing 10:1 (*i.e.* 9, 10 and 11:1) represent only 14% of all events; once again, we observe the inaccuracy of the ten-to-one rule.

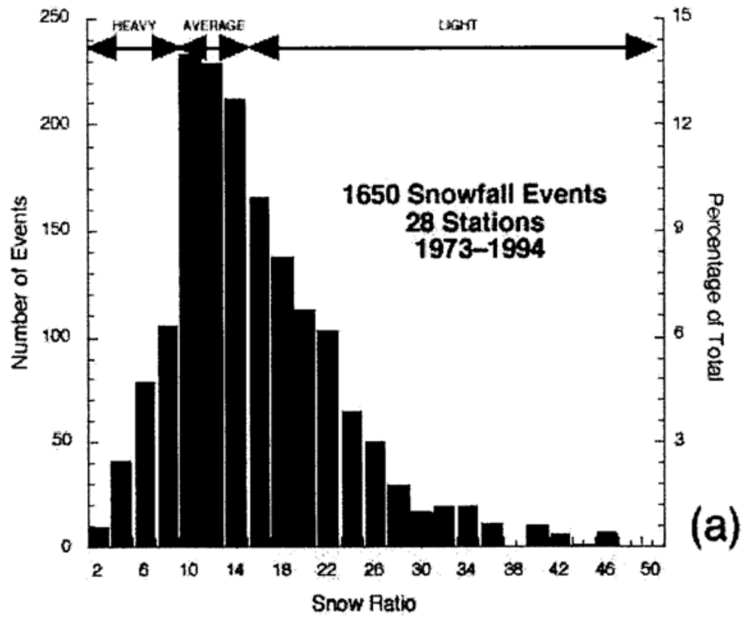

Figure 8: *Distribution of observed snow/water ratios from 1650 cases. Source: Roebber et al (2003).*

Figure 8 shows the 3 snow categories that were defined within this study: heavy, average and light snow. Table 14 presents the range of the snow/water ratios and the percentage of cases associated with each category.

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Snow category	Snow/water ratio	Proportion of cases
Heavy	< 9:1	14%
Average	9-15:1	41%
Light	> 15:1	45%

Table 14: *Snow categories and their corresponding snow/water ratios. The third column shows the occurrence of each category (as defined in the study by Roebber et al, 2003).*

d) Conclusions:

The different climatological studies that were reviewed confirm the significant variability of the snow/water ratio and, therefore, the inaccuracy of the systematic use of the ten-to-one rule. An undisputed relationship between snow density and the observed crystal type(s) has been established. The potentially significant role of accretion and aggregation on snow density was also demonstrated. The following section reviews in more detail the climatological results presented in Section 2.

5. INTERPRETATION OF CLIMATOLOGICAL RESULTS

An improved knowledge of the physical processes associated with snow density, gained through theory and various climatological studies, allows us to return to the Quebec study and further explore its results. The following section will not be limited to a more detailed description of the snow/water ratio climatology. It will also verify the theory's validity by determining if the snow/water ratio's "expected behaviour" is reflected in the climatological results. However, an adequate classification of snow will be the starting point.

a) Snow Classification:

The goal here is to define different snow types on the basis of their density using snow categories. As well as finding a distinct water-to-snow conversion factor for each category, which will help to quantify snow accumulations, this categorization will help in detemining its density. This process could be useful for passing detailed information to certain clients (*e.g.* snow removal) and also when associating snow with properties other than density (*e.g.* potential for compaction or wind transport (blowing snow)). We will review some of those properties later.

An optimal number of categories is required. A compromise had to be found between a number large enough to correctly determine several observed snow types and densities, and a reasonably limited number to allow for a realistic predictability level. This classification depended greatly on the climatological results obtained from the Quebec study and on the density measurements related to the various crystal types (see Sections **2** and **4b,** respectively).

Six categories are proposed:

1. **very heavy snow**: corresponds to ice pellets, snow mixed with rain, or melting snow;
2. **heavy snow**: associated to mixtures of snow and ice pellets, wet snow or significant accretion cases;
3. **average snow**: represents the most frequent cases, where a 10:1 ratio is appropriate;
4. **light snow**: its density is somewhat lower than average snow; it requires its own category based on the significant impact on snow accumulations and on its greater blowing snow potential;
5. **very light snow**: its density is even lower and the above mentioned characteristics are even more pronounced;
6. **ultra light snow**: the least dense snow with an associated snow/water ratio close to the maximum values observed.

These different categories and their associated range of snow/water ratios are shown in Table 15. A mean ratio, the most representative value of the snow/water ratio corresponding to each category, is also suggested.

Snow category	Snow/water ratio	Mean ratio
Very heavy	≤ 5.5:1	4:1
Heavy	5.6-8.5:1	7:1
Average	8.6-12.5:1	10:1
Light	12.6-17.5:1	15:1
Very light	17.6-22.5:1	20:1
Ultra light	≥ 22.6:1	25:1

Table 15: *Proposed snow categories with their associated snow/water ratio values. The third column shows the mean ratio suggested for each category.*

This classification will be useful in the further analysis of the climatological data and in the development of new techniques for the diagnosis/prognosis of snow/water ratios (Section 6).

b) Re-examination of Climatological Results [Quebec (1999-2002)]:

First, consider the distribution of snow categories for the 490 cases (Table 16):

Snow category	**Heavy**	**Average**	**Light**	**Very light**	**Ultra light**
Snow/water ratio	**5.6-8.5:1**	**8.6-12.5:1**	**12.6-17.5:1**	**17.6-22.5:1**	**≥ 22.6:1**
Early/late in season (NOV/MAR-APR)	**3%**	**70%**	**20%**	**6%**	**1%**
Mid-winter (DEC-JAN-FEB)	**1%**	**48%**	**37%**	**11%**	**3%**

Table 16: *Distribution of snow categories for the 490 cases included in the climatological study. Data is split between 2 periods over the winter season.*

It must be remembered that these cases were selected based on certain criteria: precipitation type limited to snow (no mixtures with other types of precipitation such as rain or drizzle, freezing or not, or ice pellets) and no melting snow (surface temperature below the freezing point). The goal was to evaluate the snow/water ratio variability when a ratio of 10:1 was systematically used. Not surprisingly, we note very few cases of heavy snow, which are probably associated to significant accretion or warm ground (*e.g.* early November). Note that in Table 16, average snow (~ 10:1) is predominant (70% of cases) in the early/late stage of the season (the mildest months). In mid-winter, lighter snow occurs as often as average snow (~50-50). This situation is due to cold air masses being more frequent at this time of the year, and which are generally more conducive to the formation of stellar crystals (-12 to –18^{o}C). Even though the occurrence of ultra light snow (>25:1) seems pretty rare, we should not question its relevance or predictability; it is observed under very specific and less frequent circumstances in Quebec but generally occurs more often in other climates such as in mountainous regions.

We will now examine the distribution of snow categories in relation to the different observation sites (see Table 17). As mentioned above, according to the established criteria, the occurrence of significant accretion resulting in heavy snow is mostly observed at Mirabel (YMX) and Gaspé (YGP), which constitute the milder sites and/or the ones more frequently influenced by maritime air masses. The occurrence of heavy snow observed at Mont-Sainte-Anne (MSA) is questionable due to the site being very exposed, and thus more subject to blowing snow, and to its observing schedule (once every 24 hours while the other sites observe every 6 or 12 hours). Sites YMX and YGP, as well as Baie-Comeau (YBC) which is also influenced by maritime air masses, observe a relatively low percentage of light or very light snow events and no occurrence of ultra light snow. Conversely, the colder and more continental the climate at the observation site is (from Québec City (YQB) to Val-D'Or (YVO) to Fermont (YWK)), the more often the occurrence of light snow (>12:1) is observed. This is due to generally colder temperatures during significant snowfalls, therefore favouring the growth of stellar crystals and, at the same time, reducing the potential for accretion. Table 17 shows quite a contrast between the first and last sites, YMX and YWK. Light snow (ratio >12:1) was observed only in 12% of the cases at Mirabel but in 81% of them in Fermont. Such an example demonstrates that the systematical use of a conversion factor of 10:1 at Fermont, or at other sites with similar climatic conditions, is not a very good option since it will often lead to an underestimation of snow accumulations.

Snow category	**Heavy**	**Average**	**Light**	**Very light**	**Ultra light**
Snow/water ratio	**6-8:1**	**9-12:1**	**13-17:1**	**18-22:1**	**23+:1**
YMX	**6%**	**82%**	**12%**	**0**	**0**
YGP	**6%**	**67%**	**27%**	**0**	**0**
YBC	**0**	**79%**	**14%**	**7%**	**0**
YQB	**1%**	**60%**	**26%**	**10%**	**3%**
MSA	**5%**	**53%**	**27%**	**10%**	**5%**
YVO	**0**	**50%**	**43%**	**5%**	**2%**
YSC	**0**	**45%**	**38%**	**13%**	**4%**
YWK	**0**	**19%**	**56%**	**21%**	**4%**

Table 17: *Distribution of snow categories for the 8 observation sites used in the climatological study (based on the 490 cases observed between November1999 and April 2002).*

Sherbrooke (YSC) constitutes a particular case. We would expect to find it higher in the above list *i.e.*, ahead of Val D'Or or even Québec City. We will analyse this a bit later… Let us examine Table 7 again (copied below as Table 18).

Wind → **Temperature ↓**	**< 10 kt**	**10-20 kt**	**20-30 kt**	**All winds**
0 to -5 ^{o}C	11	10	10	10
-5 to -10 ^{o}C	14	12	10	12
-10 to -15 ^{o}C	17	15	11	15
-15 to -20 ^{o}C	17	15	14	16
-20 to -25 ^{o}C	15	13	12	13
All temperatures	15	13	11	**Based on 95 cases**

Table 18: *Variation of the average snow/water ratio according to surface wind and temperature (same as Table 7).*

In Section **2 b)** we stated that an increase in surface wind speed generates a decrease in the average snow/water ratio. Not only was this observed in all cases (95) but also within each of the 5 temperature intervals. This confirms the impact of the fragmentation process on snow density, as described in Section **3 c) v).** Also, the snow/water ratio values seem to converge towards 10:1. When the average temperature is between 0 and –5^{o}C, the average snow/water ratio, with light winds, is already near 10 and shows little change when the winds are moderate or strong. At temperatures between –10 and –15^{o}C, however, the average ratio significantly decreases (from 17 to 11). This confirms the earlier statement from section **3 c) v)** about the efficiency of fragmentation with respect to crystal types and the limits of snow densification by fragmentation.

Let us now re-examine the fact that maximum values of the average ratio occur at surface temperatures between –10 and –20^{o}C (see Section **3 c) v)**). This tendency is observed in each of the 3 wind intervals (see Table 18). It suggests favourable conditions for low-density snow at surface temperatures near -15^{o}C and denser snow, on average, at temperatures lower than –20^{o}C or higher than –10^{o}C. Although we deal with surface temperatures and not in-cloud temperatures (where crystals actually grow), it can be stated that the results are in good agreement with the crystal type theory and their associated mean density (see Sections **3 b) i)** and 4 **b)**). The explanation is linked to the fact that the majority of the cases emerging from the sample are abundant snowfall events (>15 cm) and in great majority associated with synoptic situations promoting stable and nearly isothermal temperature profiles (*i.e.* ahead of warm fronts).

Some people, upon reviewing these results (Table 18), have disputed the validity of measurements taken when strong winds occur, suggesting that observers systematically report snow/water ratios of 10:1 under these circumstances. It is quite possible that this situation arises at times, but we do not believe this to be a routine application, the reason being that the data sample with winds of 20 to 30 knots shows only 30% of cases with a mean ratio of 10:1. Furthermore, the stellar crystals "signature" (*i.e.* peak of snow/water ratios near $-15\ ^{o}C$) is quite apparent in the strong wind interval as well as in 2 others which, in our opinion, validates the measurements. If the data were tainted, this phenomenon would not be observed so evidently.

Table 19 shows the monthly variation of the mean snow/water ratio for each observation site. It adds little additional information to the remarks expressed about Tables 16 and 17 but is included anyway as a reference.

	NOV	DEC	JAN	FEB	MAR	APR
YMX	11	13	12	11	10	9
YGP	11	11	11	11	10	10
YBC	10	12	14	12	10	10
YQB	10	15	15	11	11	-
MSA	9	16	13	12	15	10
YVO	11	14	15	12	11	11
YSC	11	16	15	15	12	11
YWK	13	16	17	15	17	14

Table 19: *Monthly variation of the average snow/water ratio for each observation site.*

As in the other tables, the sites are arranged in a more or less increasing order of snow/water ratio. Earlier, we questioned Sherbrooke's position in the list with its quite high snow/water ratios as opposed to sites in surrounding areas or further North. Following is an attempt at understanding this particular case using the knowledge acquired from theory and climatology up to this point.

c) Analysis of a Particular Case (YSC):

In order to explain the differences between the climatology of snow/water ratios in Sherbrooke and the one in Québec City and Mirabel, 4 main factors will be examined:

- the fragmentation potential
- the accretion potential
- elevation (with respect to Mean Sea Level)
- synoptic patterns responsible for significant snowfalls.

Significant snowfalls (more likely to be included in the data bank used in this climatological study) often occur ahead of a low-pressure system and/or a warm front; they are therefore associated with low level circulations from the East quadrant (NE, E or SE). In this kind of weather pattern, YSC is much less windy than YQB or YMX because the last two are located in the St. Lawrence Valley, where the winds are channelled in a northeast circulation, a well-known phenomenon. Figure 9 shows the wind rose for the 3 sites. Note the significant difference in the mean wind speed in the East quadrant: at YSC the winds very rarely reach or exceed 10 knots (5% of cases) whereas they do, more or less, in 25% of the cases at YMX and about 50% at YQB. The lighter winds observed at YSC decrease the potential for fragmentation of snow crystals and promotes higher snow/water ratios.

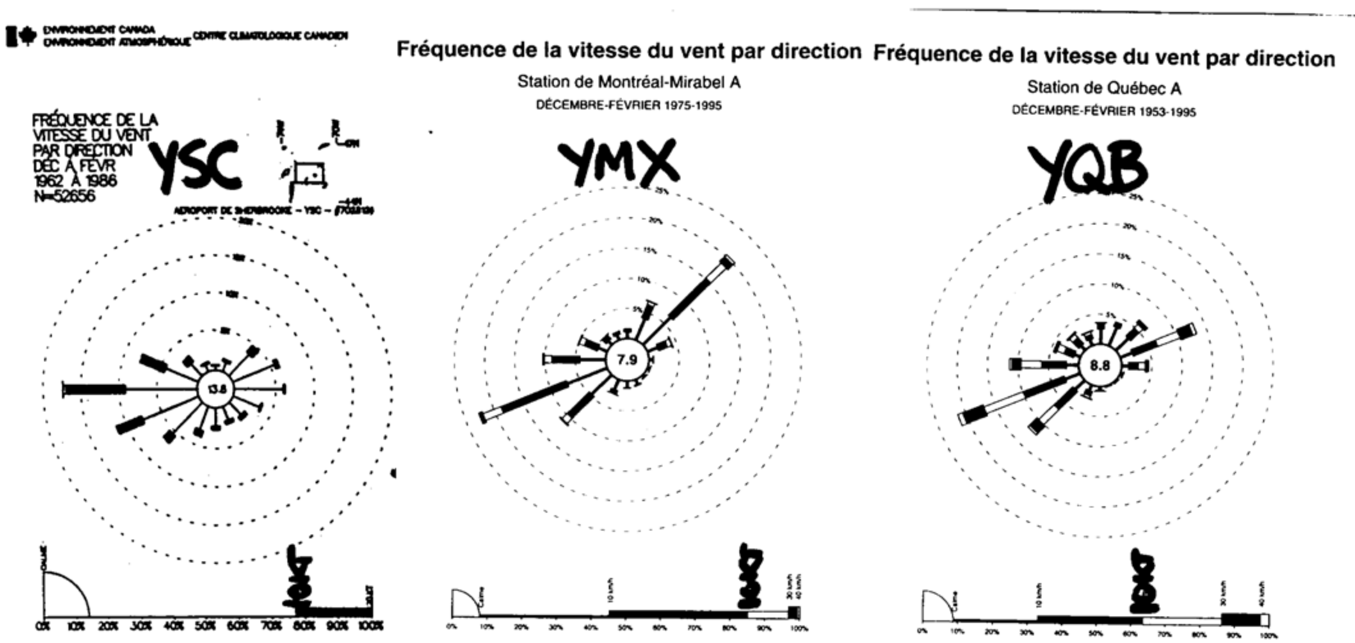


Figure 9: Wind roses for Sherbrooke (YSC), Mirabel (YMX) and Québec City (YQB) airports. Source: MSC.

Since YSC is located just west of the Appalachians, an easterly circulation is associated with light subsidence in the lower levels. This subsidence can postpone the formation of stratus clouds and inhibit the accretion process over the region. This is not necessarily the case at YQB and YMX where northeast circulations promote humidity and hygroscopic condensation nuclei advections from the St. Lawrence estuary. The potential for accretion would consequently be less at YSC, once more justifying higher snow/water ratios.

MSL elevations at YSC (791 ft), YMX (269 ft) and YQB (243 ft) show that YSC is significantly higher (by over 500 ft). Sherbrooke is therefore generally closer to the cloud base of a synoptic weather system over these regions (assuming a uniform cloud base height with respect to sea level). This means that the residence time of snow crystals in the low-levels, where accretion and fragmentation can affect their density, is shorter at YSC. This constitutes another factor which decreases the potential for densification and promotes higher ratios.

Finally, in addition to warm fronts, there is another synoptic pattern which often produces significant snowfalls in the Eastern townships (YSC): West or Northwest circulations behind low pressure systems or cold fronts. These relatively cold circulations, usually accompanied by instability and orographic lift, are also conducive to high snow/water ratios due to their associated thermal profiles (more likely to generate stellar crystals) and weak accretion potential. Moreover, such conditions will not generate much snow at YQB or YMX due to the low-level subsidence associated to northwesterly circulations (mountainous terrain to the northwest). The occurrence of this type of cases is therefore much higher at Sherbrooke, which again favours higher snow/water ratios.

d) Discussion on Snow/Water Ratios in Mountainous Regions:

As mentioned earlier (Section **5 c)**), snow/water ratios tend to be somewhat higher at greater elevations due to the absence of or to the lesser intensity/duration of the processes that affect snow density between the ground and the base of clouds where snow crystals were generated. These processes (see Section **3 c)**), except for aggregation, produce a densification of snow. The level or degree of densification will depend on their intensity as well as the crystal type(s) present. Sites at higher elevation, hence closer to the clouds (such as mountain tops), are generally much less affected by the densification processes in the lower levels (*e.g.*, fragmentation, sublimation, melting, etc.) than sites located in valleys or low-lying areas. A number of climatological studies refer to this situation in the Rockies. The variability of the snow/water ratio (or snow density) can be quite impressive over short distances in mountainous regions, evidently because of the rapid changes in elevation, but also because of the variability of the implicated meteorological parameters in the lower levels, according to valley orientations, thermal or orographic effects (gravity waves, subsidence, etc.). This has been observed in the Province of Québec, primarily in the greater Québec City area, where observing stations (*i.e.*, Québec City Airport, Charlesbourg, Mont-Ste-Anne, MRC Charlevoix, etc.) are located at different elevations and, in some cases, report very different snow/water ratio values during the same event (*i.e.*, 20:1 at mountain top, 10:1 at YQB and 15:1 at mid-elevations).

e) Conclusions:

The theory on snow density and the climatological results seem to show consistency. Some theory-driven characteristics can truly be observed in the climatological results. As well, some features of the theory can be used to explain some climatological results which initially looked inconsistent. This greatly enhances the confidence level in the concepts established so far. These concepts, based on theory as well as climatology, helped us to summarize the favourable conditions for low and high snow densities (shown in Table 20), and will be the basis for developing forecast tools and strategies.

Favourable conditions for low densities (High snow/water ratios)	**Favourable conditions for high densities (Low snow/water ratios)**
Growth temperature mainly between -12 et –18 °C (stars)	Growth temperature far from optimal range *i.e.* < -20 or > -10 °C
Temperature profile remaining below 0 °C (no melting)	Temperature ≥ 0 °C, near surface or aloft (producing RA/FZRA/PL/SP)
Temperature profile < -10 °C, continental air mass and/or light low-level subsidence (no accretion)	High liquid water content, maritime air mass and/or orographic lift (accretion)
High relative humidity (no sublimation)	Low relative humidity in the low-levels (rapid sublimation)
Temperature between -1 and -4 °C within a significant layer (aggregation of crystals)	Temperature < -5 °C in lower levels (no aggregation)
Light low-level winds (< 15 kt) (very little/no fragmentation)	Strong low-level winds (> 25 kt) (significant fragmentation)
Ground temperature < 0 °C (frozen or snow covered ground → no melting)	Ground temperature > 0 °C (warm ground → melting)

Table 20: *Summary of favourable conditions for low/high snow densities.*

6. DIAGNOSIS/PROGNOSIS OF THE SNOW/ WATER RATIO

Table 20 constitutes a simplified snow/water ratio diagnosis /prognosis tool. We will further study this topic in an attempt to develop one or more tools that will help meteorologists to efficiently diagnose and forecast snow density, thus the appropriate snow category, according to the classification established in Section **5 a)** (Table 15). First, let us examine some of the existing tools *i.e.* tools that have been used until now to convert water equivalents (mm) into snow accumulations (cm) and that have been identified by the author.

a) Existing Tools:

i) Ten-to-one rule (10:1)

Despite the fact that this rule constitutes the operational tool most frequently used by meteorologists, there is not much more to be said about it. Several climatological studies clearly demonstrated its inaccuracy in about 50% of all cases. However, it must be mentioned that under certain heavy snow conditions (ice pellets, melting snow or rain-snow mixtures), forecasters do not use this rule systematically. An approximate adjustment towards lower ratios is generally applied in these cases.

ii) Conversion Tables

Conversion tables based solely on surface temperature seem to be routinely used by meteorological observers to estimate snow measurements (when the water equivalent has been correctly measured but snow has been blown around by the wind), or water equivalent measurements (from the snow depth when snow did not enter the collector). The conversion table used by the NWS is shown below.

Surface temperature	Snow/water ratio
28-34 ^{o}F	10:1
20-27 ^{o}F	15:1
15-19 ^{o}F	20:1
10-14 ^{o}F	30:1
0-9 ^{o}F F	40:1
-20 to -1 ^{o}F	50:1
-40 to -21 ^{o}F	100:1

Table 21: *Conversion table used by the NWS showing the relationship between surface temperatures and snow/water ratios. Source: DOC/NOAA/NWS (1996).*

The fact that the operational use of these tables has been approved until now does not mean that they are adequate for diagnosing or forecasting snow/water ratios. It has been mentioned earlier that snow density is related to much more than one parameter. This type of correlation may work occasionally. However, such a diagnosis is far from a sure thing in view of the many factors potentially affecting snow density (*e.g.* accretion or fragmentation by strong winds). The surface temperature alone does not allow a diagnosis of the crystal type. It is possible to have milder or much colder temperatures aloft (where crystals grow) than at the surface, which will greatly affect the crystal type in occurrence and consequently, snow density. The consistent decrease of density with decreasing temperatures represents another weakness of this method. In practice, as well as in theory, it has been clearly shown that there is an optimal range of temperatures (around –15°C) where lower densities are observed. At lower temperatures (*e.g.*, –20 or –25 °C), a return to higher density crystals occurs. This peak does not appear in Table 21. As a result, this kind of conversion table will tend to overestimate snow/water ratios at low temperatures, and therefore to overestimate snow accumulations.

iii) B. Murphy Technique

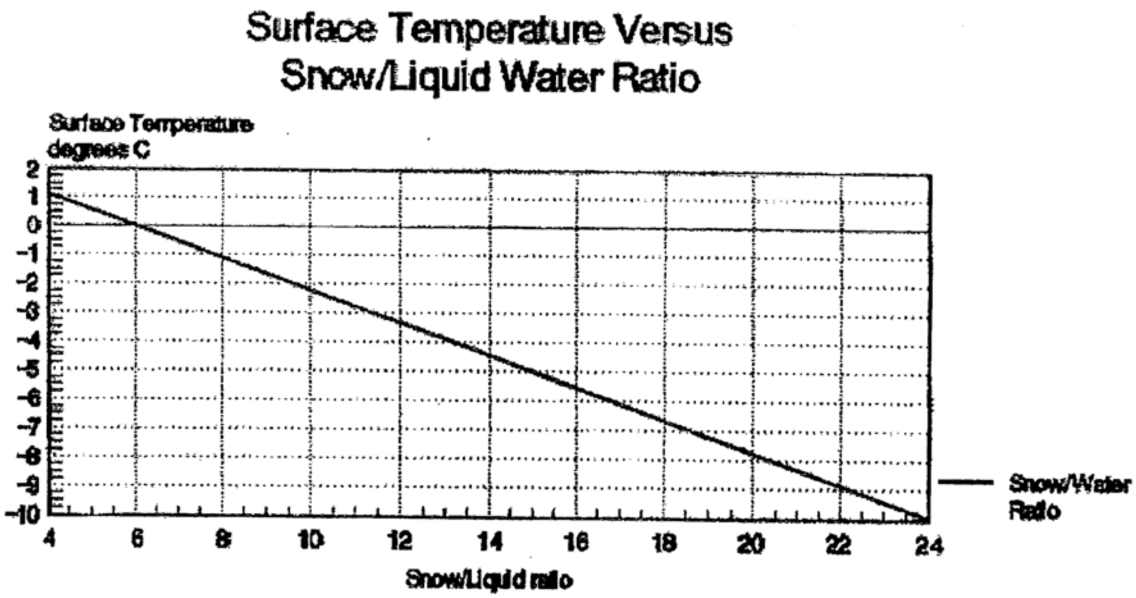
This technique based on the 1000-700 mb thickness (representative of the lower atmosphere's mean temperature) was developed in MSC's Ontario Region. It is available in Quebec using the visualization tool called "MAX".

Because the technique considers the mean temperature of the lower atmosphere rather than the surface temperature, it represents an improvement on conversion table values. However, a given partial thickness may correspond to many distinct temperature profiles (e.g. stable, unstable, inversion, etc.) and, therefore, to distinct snow/water ratios.

As with the conversion tables, a steady decrease of density with lower thicknesses (colder temperatures) constitutes a weakness of this method. The B. Murphy technique will also tend to overestimate snow/water ratios, as well as snow accumulations, at low temperatures. Furthermore, such an approach will not take into account the various processes affecting snow density (fragmentation, accretion, melting on the ground, etc.) and does not allow crystal type determination.

iv) Scofield/Spayd Diagrams

The first diagram is based on the surface temperature while the second is based on the 1000-500 mb thickness. Both diagrams are quite similar to the two previously mentioned tools and exhibit the same weaknesses.



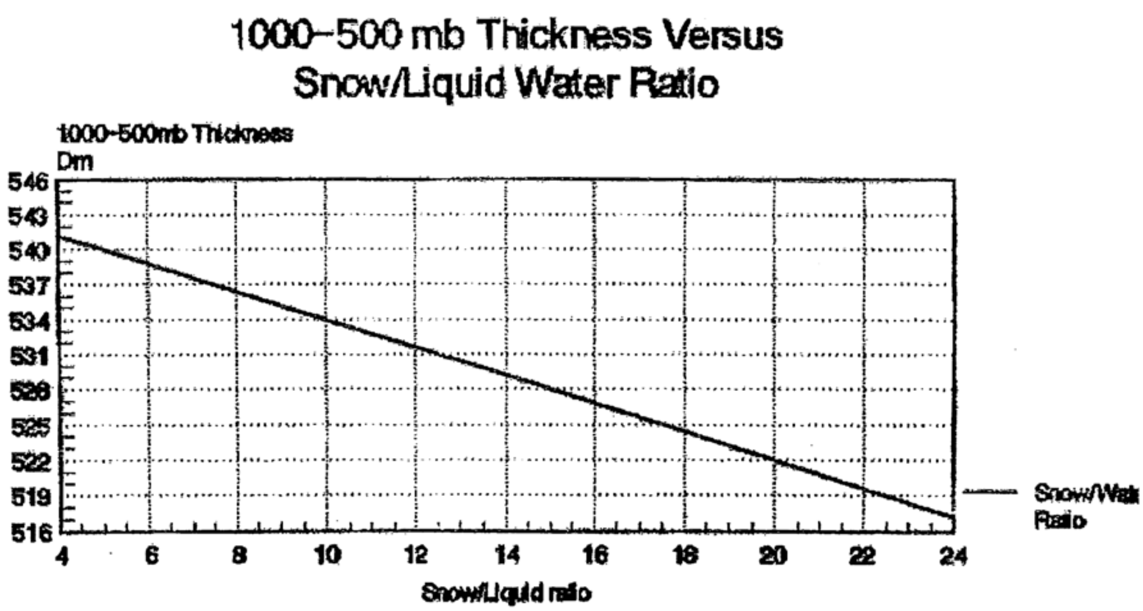


Figure 10: *Diagrams showing the relationship between the snow/water ratio and the surface temperature as well as the 1000-500 mb thickness. Source: Scofield and Spayd (1984).*

v) Trajectory Method

This method is based on the climatology of snow/water ratios according to low-pressure system trajectories (see Figure 11). Note the influence of maritime air masses compared with continental ones, and the temperature regimes associated to different storm tracks in the American Midwest.

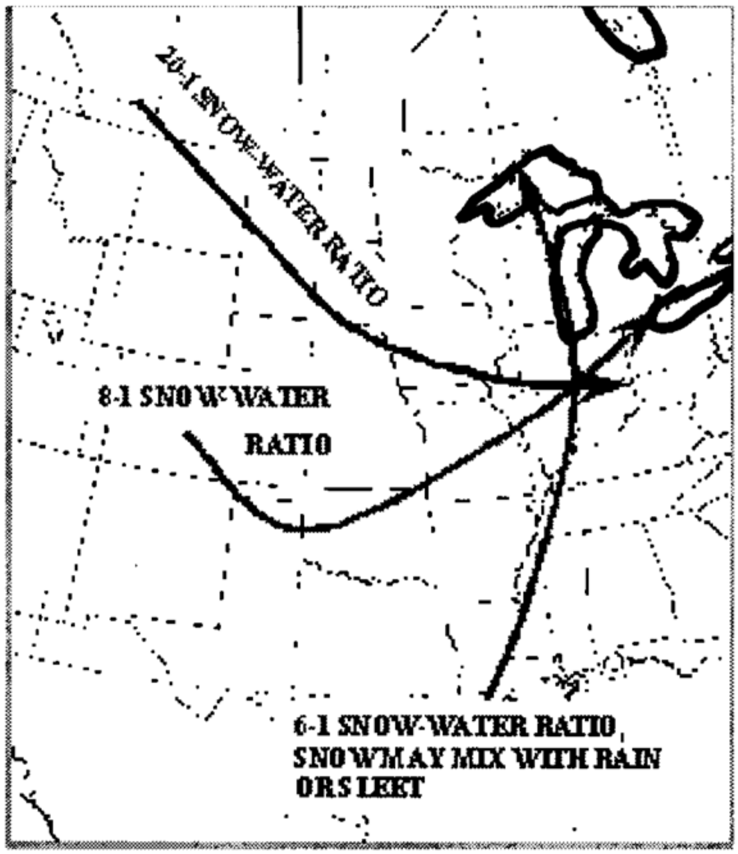


Figure 11: *Mean snow/water ratios for different trajectories of low-pressure systems crossing the American Midwest. Source: NCEP Research Internet Site.*

Although quite valid, this approach would not be really useful in Quebec for diagnosing/forecasting the most probable snow/water ratio, especially on a case-by-case basis. Even if we spent the necessary time and energy to develop this type of climatology for Quebec, it would not really lead to an accurate prognosis for any given case. Storms crossing the province give rise to quite a variety of scenarios (snow, ice pellets, rain, freezing rain, etc.) associated with one specific trajectory. Essential parameters such as the storm's intensity, the orientation of low-level jets, the time of year and even the intensity of the downstream high pressure system, can greatly influence the precipitation types and thus, snow density.

vi) Roebber *et al* Method

As we have seen earlier, the method developed by Paul Roebber and his associates is based on 3 snow categories: heavy < 9:1; average 9-15:1; and light >15:1. Snow/water ratio diagnoses are performed using correlations with 7 main factors: mean temperatures at low/mid-levels (1) and at mid/high-levels (2); relative humidity at low/mid/high levels (3-4-5); a ground compaction factor taking surface winds and the weight of snowfalls into account (6); and finally, a month index accounting for solar radiation (7). Compared to the previously reviewed approaches, this method presents a significant improvement with respect to the number and relevance of the parameters considered in the snow/water ratio diagnosis.

Published results show that this method predicts the correct snow category in 60% of the verified cases compared to 41% with climatology, 51% with the NWS conversion table (see Section **6 a) ii)**), and 25% with the ten-to-one rule. A contingency table summarizing the diagnostic performance over 333 independent cases follows (Table 22).

Forecast → **Observed ↓**	**heavy snow**	**average snow**	**light snow**
heavy snow	20	12	1
average snow	23	86	41
light snow	6	49	95

Table 22: *Contingency table of the snow/water ratio diagnosis for 333 cases using the Roebber et al method (2003).*

This performance seems somewhat disappointing, considering the low number of snow categories (3), whereas, as suggested in Section **5 a)**, a minimum of 6 categories is required. To demonstrate this, let us consider a diagnosis of "average snow": the Roebber *et al* method would indicate a snow/water ratio between 9 and 15:1. However, the distinction between events of "10:1" and "15:1" constitutes one of the main challenges facing operational meteorologists in Quebec. This method offers little help to forecasters since it combines two important thresholds within a single snow category.

Many factors could explain some of the wrong or "missed" diagnoses resulting from this approach. The main one could be linked to the fact that vertical motion is not taken into consideration. It is imperative to determine the main or primary crystal growth level in order to find the growth temperature and thus diagnose the crystal type and the appropriate snow category. We will return later to the importance of vertical motion in the snow density diagnosis. Since the fragmentation of crystals does not only occur at the surface but also between the surface and cloud base, we can include the absence of low-level winds within this technique's considered parameters as a second weakness. Another potential factor is the indirect contribution of ground temperature (use of a monthly index representative of solar radiation). Finally, another aspect relating to the efficiency of this approach involves the lack of events with strong surface winds (>20kt) within the data sample used to perform the correlations. We can only summise about the diagnostic performance in windy situations, which is often the case during significant snowstorms.

Nevertheless, the Roebber *et al* method represents a major improvement on previous techniques. Readers are invited to consult the complete publication to get more information about this technique.

b) Proposed tools:

We have seen that all identified existing tools have some shortcomings. Here, we have tried to develop comprehensive tools, *i.e. those* that consider all parameters and processes involved. The principal tool is a forecast algorithm which meets this requirement. The other tools consist of products or applications that support the algorithm or facilitate its use.

i) Forecast Algorithm

Many objectives were identified prior to the development of this algorithm. Using the top-down approach, the purpose was to build an algorithm which would:

- take into account all parameters and processes that determine snow density, as well as their impact according to each crystal type;
- respect the boundaries dictated by climatology;
- eventually be used operationally;
- be validated and adjusted through an ongoing verification program;
- be the basis for creating a water equivalent → snow conversion field that could be integrated into numerical models.

Before discussing the details surrounding the algorithm, let us presume of the presence of two essential factors:

- atmospheric conditions are favourable to the formation of clouds and precipitation that reaches the ground (hence, no sublimation resulting in virga);
- in-cloud atmospheric conditions (temperature, presence of ice nuclei, etc.) are conducive to the growth of ice crystals, as discussed in Section **3 a)**.

Operationally speaking, we will rely on current methods (*e.g.* numerical model outputs, short term forecasting techniques, radar data, etc.) to determine the occurrence of precipitation. Subsequently, the application of the algorithm, which also relies on the use of model outputs and traditional methods, will enable the diagnosis/prognosis of the appropriate snow category (among those defined in Table 15) and, therefore, the proper snow/water ratio: 0, 4, 7, 10, 15, 20 or 25. The "zero" value is needed for cases where no snow accumulation is forecast, a water equivalent or ice accumulation being sufficient (*e.g.* occurrences of rain, melting snow or freezing rain).

The snow/water ratio forecast algorithm is divided into two main sections:

- One for cases where the atmospheric temperature profile (from cloud top to the surface) remains below the freezing point (Tatm < 0 ^{o}C);
- Another one for cases where the atmospheric temperature rises above the freezing point (Tatm > 0 ^{o}C).

A) Tatm < 0 ^{o}C

In these types of cases, two major steps are needed to obtain the snow/water ratio:

1. Determine the crystal type;
2. Check the presence and determine the impact of various physical processes that can significantly affect snow density, according to the crystal type(s) present.

The following table summarizes the proposed approach to determine the most likely crystal type under various atmospheric conditions:

TPRIMARY → **TSECONDARY↓**	**0 to -3°C**	**-3 to-5°C**	**-5 to -12°C**	**-12 to -18°C**	**< -18°C**
0 to -3°C	mixed (10:1)	mixed (10:1)	mixed (10:1)	---	---
-3 to -5°C	mixed (10:1)	needles (10:1)	mixed (10:1)	---	---
-5 to -12°C	mixed (10:1)	mixed (10:1)	mixed (10:1)	mixed with stellar nucleus (15:1)	---
-12 to -18°C	---	---	spatial dendrites (10:1)	stellar crystals (25:1)	spatial dendrites (10:1)
< -18°C	---	---	---	mixed with stellar nucleus (15:1)	mixed (10:1)

Table 23: *Determination of crystal types based on primary and secondary growth temperatures. The primary temperature corresponds to the main crystal growth level, that is, at the intersection of* ω_{max} *and RH > 80%. The secondary temperature corresponds to a level below the main level where* $\omega < 0$, $T < 0C$ *and RH > 80%. The mean snow/water ratio suggested for each crystal type* <u>*before any modification*</u> *by one or several of the previously identified physical processes is also specified.*

The primary temperature is defined as the temperature at the main growth level of ice-crystals *i.e.* at the intersection of the maximum ascending vertical motion (ω_{max}) and relative humidity greater than 80%. The secondary temperature corresponds to the secondary growth level, *i.e.* a level <u>below</u> the main one where: there is ascending vertical motion ($\omega < 0$), the temperature remains below zero and the relative humidity is greater than 80%. In other words, the main growth level, through its corresponding temperature, dictates the dominant crystal type or the one constituting the snow crystals' nucleus. Also, by way of its temperature, the secondary level will determine if growth of the same crystal type will persist or if there will be a combination or layering of different crystal types before snowflakes are released from the clouds.

Table 23 shows 5 main crystal types; they will be used as a basis for determining the density:

1. mixed crystals
2. needles
3. spatial dendrites
4. mixed crystals with stellar nucleus
5. stars (or stellar crystals)

The snow/water ratio associated with each of these crystal types is also specified in the Table. It is representative of the density before any possible modification of crystals by one or more physical processes previously identified (see Sections **3 b), c)** and **d)**). We will now evaluate the the relative significance of atmospheric processes on density for each of these 5 types. The ground-level melting process will always be significant, as it promotes a rapid densification of snow. More information about its impact on density will be given later in this section.

1. Mixed crystals:

Crystals identified as "mixed" include the following types: pure columns, pure plates, any combination of columns and plates, with or without needles. Before considering any process affecting their density, we will assume that these crystals produce "average" snow (R=10:1). Mixed crystals, either growing at mild or at very low temperatures (*i.e.* below –18 ^{o}C) should, according to theory and climatological results, lead to the same snow category.

Among the different atmospheric processes affecting density, only accretion is deemed potentially significant when dealing with mixed crystals. When accretion is sufficiently intense, it increases the density, resulting in "heavy" snow (R=7:1), as seen in Section **4 b)** (see also Table 13). Since mixed crystals initially form a relatively compact structure, the presence of partial or even extensive sublimation or fragmentation will not increase density to the extent that a change in snow category would be required. Furthermore, the occurrence of aggregation does not promote a significant decrease of density for this type of crystals with very few ramifications (see Section **3 c) iv)**).

2. Pure needles

As stated in Section **3 b) i)** (see Table 9 and Figure 1), needles are generated under very specific conditions, *i.e.* in a relatively narrow temperature range (-3 to –5°C). They occur under a virtually isothermal profile, very close to -4°C. "Seeding" of this isothermal cloud layer by small ice-crystals from a colder layer above is also required because ice nuclei are activated at temperatures generally lower that –8 °C, as previously discussed. Therefore, it is not possible to produce needles or any other crystal type at temperatures above –8°C, without the contribution of other crystals. Considering these limitations, pure needles should be much less frequent than other crystal types. Needles are generally observed in combination with other shapes, and thus among the "mixed crystals" type.

Table 23 shows that in their single form, pure needles produce a relatively dense crystal structure and are therefore associated to a snow/water ratio of 10:1. Since these crystals grow at temperatures conducive to aggregation, (see Section 3 **c) iv)**), they are generally observed in aggregates (see Table 12, Section **4 b)**). These aggregates will tend to generate "light" snowfalls (R=15:1). Because needles have a small cross-section area resulting in a poor droplet collection capacity, accretion does not play a significant role with respect to their density (see Section **3 b) i)**, **4 b)**). When low-level winds are greater than 25 knots, the fragmentation of aggregates will tend to bring needles back to their simple form and thus to "average" snowfalls (R=10:1).

3. Spatial dendrites:

This crystal type, as defined by Nakaya (1954), corresponds to dendritic overgrowth (*i.e.* ramified stellar branches) on a crystal nucleus consisting of an assemblage of plates and/or columns. Spatial dendrites, as seen in Table 12, are in fact a relatively dense combination (R=10:1) of several crystal types which could have been included in the "mixed crystals" category. However, for now, it seems reasonable to keep this crystal type in a distinct category. This will allow for maintaining a separate verification of the associated snow/water ratio diagnosis, and help identify some of its characteristics. Spatial dendrites, due to their ramified extremities, could easily form aggregates of lighter density, and thus, produce "light" snowfalls (R=15:1). This situation could possibly occur in very unstable conditions (*e.g.* deep convective clouds developing in cold air masses moving over open water during the fall season or early winter), where the thermal profile promotes the growth and aggregation of this type of crystals (that is, $T_{primary}$ < -18°C, $T_{secondary}$ between -12 and -18 °C, and a surface temperature nearing -1 or -2 °C). However, the presence of strong winds in the low-levels (*i.e.*

greater than 25 knots, which is often the case during such weather events) would result in significant fragmentation and a return of the snow/water ratio to its initial value (10:1). Spatial dendrites are subject to densification by accretion (although quite rare at this crystal growth temperature) that will produce "heavy" snow (R=7:1) in significant cases.

4. Mixed crystals with stellar nucleus:

As in the case of spatial dendrites, these crystals are the product of a combination of stellar crystals with other types. However, stars are the dominant initial structure while other crystals grow on the periphery. Their nucleus having a relatively low-density, they generally produce "light" snowfalls (R=15:1). Significant accretion of this type of crystals increases their density so that "average" snow is most likely observed. Due to the relatively denser character of their shell (few ramifications), these crystals do not tend to form aggregates which have a significantly different density than their original structure. Also, significant fragmentation of crystals (maximum low-level winds > 25 kt) will result in a lower snow/water ratio *i.e.* associated with average snow (R=10: 1). Partial sublimation (*i.e.* not sufficient to totally evaporate precipitation) resulting from the presence of dry air under the clouds can also produce an equivalent densification (R=10:1).

5. Stellar crystals or stars:

The results shown in Sections 3 and 4 indicate that stars represent the crystal type having the lowest density. Tables 11 and 12, as well as the climatological results, allow the association of stars to a wide range of snow/water ratio values (10 to 30:1, or even higher). The snow/water ratio nominal value associated to unaltered stars should definitely belong to the ultra light snow category (R=25:1). If not, how could we observe the latter? Sublimation of ramified crystals occurs very quickly in a sufficiently dry atmospheric layer and the impact on density will be much more significant than for denser crystals (see Section **3 c) i)**). Partial sublimation of stars will cause some densification, hence a decrease of the snow/water ratio (R=15:1).

Logically, the low density of stars is associated with a greater fragility compared to other crystal types; for this reason, the fragmentation level will have a significant impact on the density of stellar crystals. Several fragmentation levels have been defined, and their associated threshold values are summarized in the following table.

Fragmentation level	Maximum low-level winds	Snow category	Suggested ratio
No fragmentation	0-5 kt	ultra light	25:1
Very slight fragmentation	5-15 kt	very light	20:1
Slighth fragmentation	15-25 kt	light	15:1
Extensive fragmentation	> 25 kt	average	10:1

Table 24: *Stellar crystals fragmentation levels and associated maximum wind threshold values (between the surface and cloud base), with the corresponding snow categories and proposed snow/water ratios.*

The accretion process significantly affects stellar crystals (see Section **4 b)**. For these types of crystals, the increase in density can reach 100%. A diagnosis or forecast of significant accretion will imply a drastic change in snow category (*i.e.* a transition towards average snow (R=10:1). The aggregation of stellar crystals and its impact on snow density are somewhat complex. First, we note that aggregation of "wet" crystals by adhesion, occurring at temperatures above –5 ^{o}C, is not very common with pure stars. Even under unstable conditions, it is quite difficult to get a sufficiently deep mild air layer in the lower levels to observe efficient aggregation when in-cloud temperatures are favourable to the growth of stellar crystals. However, regardless of temperature, entanglement of the crystals' ramified branches enables the formation of aggregates either in the atmosphere or as they accumulate on the ground, which significantly limits their compaction. But this process is, in some way, already accounted for in the suggested density or snow/water ratio. In other words, the aggregation of stars under light winds will not produce an assemblage more or less dense than if individual crystals become entangled as they accumulate on the ground.

To summarize the preceding paragraphs, Table 25 shows the various crystal types affected by each process, the favourable conditions for those processes to occur and the proposed thresholds to evaluate their intensity. Bear in mind that the melting process associated with warm ground will be analysed later.

Process	Accretion	Sublimation	Aggregation	Fragmentation
Crystal type(s) significantly affected	mixed, spatial dendrites, mixed with stellar nucleus, stars	mixed with stellar nucleus, stars	needles	aggregated needles, mixed with stellar nucleus, stars
Favourable conditions	supercooled droplets 0 < Tatm<-10 ^{o}C and RH > 95% in a significantly deep layer onshore/upslope flow	dry air layer sufficiently deep under cloud base (*e.g.* 1000 ft) where RH < 80% or T-Td > 3 ^{o}C (Layer not too dry or too deep or else virga will occur)	Tatm between 0 and -4 ^{o}C in a sufficiently deep layer (*e.g.* > 1000 ft)	none: V ≤ 5 kt very slight: 5 < V ≤ 15 kt slight: 15 < V ≤ 25 kt extensive: V > 25 kt where V represents the maximum wind speed between cloud base and the surface

Table 25: *Crystal types affected by various physical processes. Conditions favourable to the occurrence of these processes are also summarized.*

The potential for aggregation and fragmentation are relatively easy to evaluate since they are associated to parameters easily retrievable from surface and upper air observations or numerical model outputs. But for sublimation, the diagnosis is not as trivial. However, this is no great concern since this process is rarely observed during significant precipitation events (large snow accumulations are usually associated with near saturation in the low-levels), except perhaps at the onset of precipitation. Accretion is definitely the process most difficult to deal with since its diagnosis/prognosis is as challenging as the one for freezing drizzle or clear icing. If determining the occurrence of accretion (hence supercooled droplets) in clouds is a challenging task, estimating its intensity and duration is certainly not easier. A positive diagnosis of its occurrence needs to be followed by the determination of its impact on density *i.e.* whether the accretion is severe enough to justify a change in snow category. But this is easier said than done!

Table 26 lists all the possible crystal combinations previously described (17 of them) as well as the suggested snow/water ratios. These values are valid for frozen or snow covered ground (snow pack deep enough to insulate freshly fallen snow from ground heat).

Diagnosis #	Crystal types and alterations by various atmospheric processes	Suggested ratio
1	rimed mixed crystals	7
2	unrimed mixed crystals	10
3	needles, extensively fragmented	10
4	aggregated needles, slightly/not fragmented	15
5	rimed spatial dendrites	7
6	unrimed spatial dendrites	10
7	rimed mixed crystals with stellar nucleus	10
8	partially sublimated mixed crystals with stellar nucleus	10
9	mixed crystals with stellar nucleus, extensively fragmented	10
10	mixed crystals with stellar nucleus, slightly/not fragmented	15
11	rimed stars	10
12	partially sublimated stars, slightly/extensively fragmented	10
13	partially sublimated stars, very slightly/not fragmented	15
14	extensively fragmented stars	10
15	slightly fragmented stars	15
16	very slightly fragmented stars	20
17	unaltered stars	25

Table 26: *List of the 17 possible snow/water ratio diagnoses according to different crystal types and the presence and/or intensity of various atmospheric processes (accretion, sublimation, aggregation and fragmentation). Note: the ground is hereby considered frozen or snow covered by at least 2.5 cm.*

One final parameter needs to be evaluated: the ground temperature. Early in the fall (September and October), it plays a significant role in determining snow density. As seen in Section **3 d) ii),** when the ground is frozen or insulated by a 2 or 3 cm layer of snow, the density of snow accumulations is directly related to the crystal type and to several atmospheric processes. However, a relatively warm ground will transmit heat to freshly fallen snow, significantly increasing its density. Partial or complete melting of the snow will occur more or less quickly depending on: ground temperature, surface air temperature, precipitation intensity, crystal type, and on the type of soil (road, dirt, rock, vegetation, etc.). Table 27 shows the most likely impact of ground temperature on density. A mean snow/water ratio is suggested for each of the two categories defined to qualify unfrozen ground according to its temperature:

- slightly above zero (*e.g.* between 0 and 5 ^{o}C) → Tground > 0,
- well above zero (*e.g.* greater than 5 ^{o}C) → Tground >> 0.

Ground temperature	Forecast snow category	Suggested snow/water ratio
> 0 °C	Heavy	7
>> 0 °C	very heavy	4

Table 27: *Suggested snow categories and snow/water ratios with respect to ground temperature*.

The more noticeable impact of ground-level melting on low density crystals implies that the crystal type loses all its relevance when the ground is warm. Heavy and/or very heavy snow are likely early in the fall season even when the atmospheric temperature profile remains below 0°C. It is therefore not necessary to diagnose the crystal type in these cases. It could be tempting to use climatological data in order to determine specific periods (dates) when these ground temperature categories occur. However, the climate varies greatly from year to year and from one region to another (especially over mountainous terrain). We must therefore identify one or more reliable sources to determine the ground temperature (*e.g.* road weather data or numerical models).

It is important to remember that the ground temperature is a dynamic parameter and can vary considerably over a short period of time (*i.e.* a few hours). For example, let us consider a relatively warm ground without snow cover and the occurrence of solid precipitation in a cold air mass with a surface air temperature nearing –2 °C. Despite the cold air, the first snowflakes will likely melt on contact with the ground, which will then cool gradually after providing the necessary latent heat of fusion to melt the snow. If precipitation persists or intensifies, snow will start accumulating (despite partial melting) with a ratio of 4:1. Following a 1 or 2 cm snow accumulation, the ground will become somewhat insulated, enableing additional accumulations of a lesser density (R=7:1). When the accumulation reaches 3 cm, ground heat is almost totally insulated and average or lighter snow (R=10, 15 or even 20:1) can be observed. The ground will therefore be covered by several snow layers with distinct densities.

We have examined and summarized the characteristics of the five principal crystal types as well as the methods used to determine their density in accordance with various physical processes. In addition, we have described the impact of ground temperature on snow density, pointing out the uselessness of diagnosing the crystal type when the ground is relatively warm (>0°C) as well as the parameter's "dynamic" character.

Since the original algorithm cannot be presented in full in this document, it has been divided into several diagrams found in Appendix III. The second component of the algorithm, which follows, deals with cases where the air temperature profile exceeds 0 ^{o}C.

<u>B) Tatm > 0 ^{o}C</u>

In these types of cases, two principal steps are necessary to obtain the snow/water ratio:

1. determine the precipitation phase and/or type(s) occurring ;
2. adjust the snow/water ratio according to ground temperature

The crystal type is of no importance here in determining the snow category and the associated snow/water ratio, just as in the case of snow melting on contact with the ground.

The five precipitation types or mixtures that will be used to establish appropriate relationships between these precipitation types and their associated snow density are:

1. ice pellets
2. rain/snow mixture
3. snow/ice pellets mixture
4. wet snow
5. snow pellets

Let us now examine in more detail the characteristics of these types of precipitation as well as the conditions that are favourable to their occurrence.

1. Ice pellets:

Ice pellets (or sleet) are frozen rain drops. They are relatively small and very compact. The accumulation of ice pellets generally enters the "very heavy" snow category (see Section **4 b**), Table 13). This type of precipitation occurs in the presence of a significant warm air layer aloft, deep enough (≥ 2000 ft) or warm enough (> 3^{o}C) to insure complete melting of snow crystals and thus, their transformation into rain drops, followed by a cold air layer that leads to freezing of these drops (*e.g.* depth > 1000 ft and/or T < -5 ^{o}C). Snow grains (frozen water droplets or "frozen drizzle") also fit well in this category.

2. Rain/snow:

This type of mixed precipitation includes various combinations of snow with rain or freezing rain occurring simultaneously. They produce “very heavy” snow accumulations when snow is the dominant phase. If rain becomes dominant (rain mixed with a little snow), there is little chance of observing any snow accumulation on the ground. Rain/snow mixtures are usually associated to freezing levels between 1000 and 2000 ft.

3. Snow/ice pellets:

For combinations of snow and ice pellets to occur, a fraction of the snow must melt in a shallow warm air layer aloft (1000 to 2000 ft deep) and, subsequently, the resulting rain drops must freeze in a deep enough cold layer (>1000 ft). Such combinations will logically lead to an intermediate density compared to those respectively associated with snow (mixed crystals ⇒ average) and ice pellets (very heavy). Thus, mixtures of snow and ice pellets will very likely lead to “heavy” snow accumulations.

4. Wet snow:

The term “wet snow” refers to snow which is beginning to melt in an environment where temperature is above the freezing point. This partial melting occurs when the temperature and/or the residence time in the warm layer are not high/long enough to allow for snow to change to rain. The small droplets on the surface of the snowflakes promote a relatively dense snowfall. Wet snow occurs when the freezing level is near the surface (< 1000 ft) and/or temperature is slightly above zero ($0 < T < 1\,^{o}C$) in the warm layer.

5. Snow pellets:

Wet snow (as described above) will freeze after falling through a cold air layer ($T < 0^{o}C$). The resulting snowflakes resemble rimed crystals (subjected to accretion) and will have a similar density (heavy snow). The atmospheric conditions favourable to this type of precipitation are similar to those for ice pellets or freezing rain (warm layer aloft and cold layer underneath). But the warm air layer tends to be relatively shallow (< 1000 ft) or associated with temperatures just above the freezing point ($0 < T < 1\,^{o}C$). Wet snow pellets may also be observed in cases where crystals fall through a second warm layer near the surface. This will occur mainly in unstable conditions, often with surface temperatures significantly above the freezing point *i.e.* 2-6 ^{o}C.

Keep in mind that precipitation such as rain, freezing rain or other mixtures where rain is dominant (*e.g.* rain mixed with small amounts of snow or ice pellets) will result in no snow accumulation (R=0).

Table 28 summarizes the suggested snow/water ratios according to the different precipitation types or combinations. Since this table illustrates a logical follow-up to Table 26, we have opted to carry on with the numbering of diagnoses. The addition of the 9 new diagnoses listed below bring the total to 26 possible snow/water ratio diagnoses (assuming Tground ≤ 0, of course).

Diagnosis #	Precipitation type(s)	Snow category	Suggested ratio
18	Ice pellets	Very heavy	4
19	Snow mixed with small amounts of rain	Very heavy	4
20	Snow mixed with freezing rain	Very heavy	4
21	Snow mixed with rain and ice pellets	Very heavy	4
22	Snow mixed with ice pellets	Heavy	7
23	Wet snow	Heavy	7
24	Wet snow pellets	Very heavy	4
25	Snow pellets	Heavy	7
26	Rain, freezing rain, rain mixed with small amounts of snow or with ice pellets	N/A (no snow accumulation)	0

Table 28: *The 9 possible snow/water ratio diagnoses according to the precipitation type(s) in occurrence. Note: the ground is considered frozen or snow covered ($\geq$ 2.5cm).*

The verification presented in Section **7 c)** demonstrates a high correlation between proposed and observed values of the snow/water ratio for most of these diagnoses. The success of this forecasting method will greatly depend on the ability to accurately forecast precipitation type(s). To do so, the following methods can be used:

- The Bourgouin method;
- The freezing levels method;
- The partial thicknesses method;
- Various short-term forecasting methods (thickness correlation, extrapolation, etc.)

A detailed examination of these methods seems beyond the scope of this study. However, it should be noted that the Bourgouin method, part of Canadian numerical models, has proven to be quite reliable since its implementation. Meteorologists use the 3 other methods as a complement in certain conditions (*e.g.* freezing precipitation, mesoscale forecasting over mountainous terrain, etc.). Table 29 and Figures 12 and 13 provide some examples of the first 3 methods (since several regional versions may exist).

Precipitation type	**Positive energy (PE) (J/kg)**	**Negative energy (NE) (J/kg)**
Snow	0 < 5.6 (surface) < 2.0 (aloft)	N/A N/A N/A
Ice pellets	> 2.0 (aloft)	> 56 + 0.66 PE (surface)
Freezing rain	> 2.0 (aloft)	≤ 56 + 0.66 PE (surface)
Rain/snow	5.6-13.2 (surface) <2 (aloft) & 5.6-13.2(sfc)	N/A N/A
Rain	> 13.2 (surface)	N/A

Table 29: *Precipitation types (5) according to positive (T>0* ^{o}C*) and negative (T<0* ^{o}C*) energies (Bourgouin method). Source: CMC Reference Handbook.*

Case type	850-700mb thickness (dam)	1000-850mb thickness (dam)	Precipitation type for strong/weak vertical motion
No overlap	< 154 < 154 < 154	< 129 129-131 > 131	SN/SN (psbl FZDZ) SN/RASN (except RA/RA in warm sector) RA/RA
Overlap	< 154 < 154 < 154	< 129 129-131 > 131	SN (PL nr 154)/SN(PL/ZR nr 154) SNPL(ZR nr 154)/PLSN (except RA/RA in warm sector) RA/RA
	> 154 > 154 > 154	< 129 129-131 > 131	PL(SN nr 154)/FZRA PL FZRA (PL nr 154)/FZRA (RA) RA/RA

Figure 12: *Precipitaton types according to 850-700 mb and 1000-850 mb partial thicknesses. Source: MSC.*

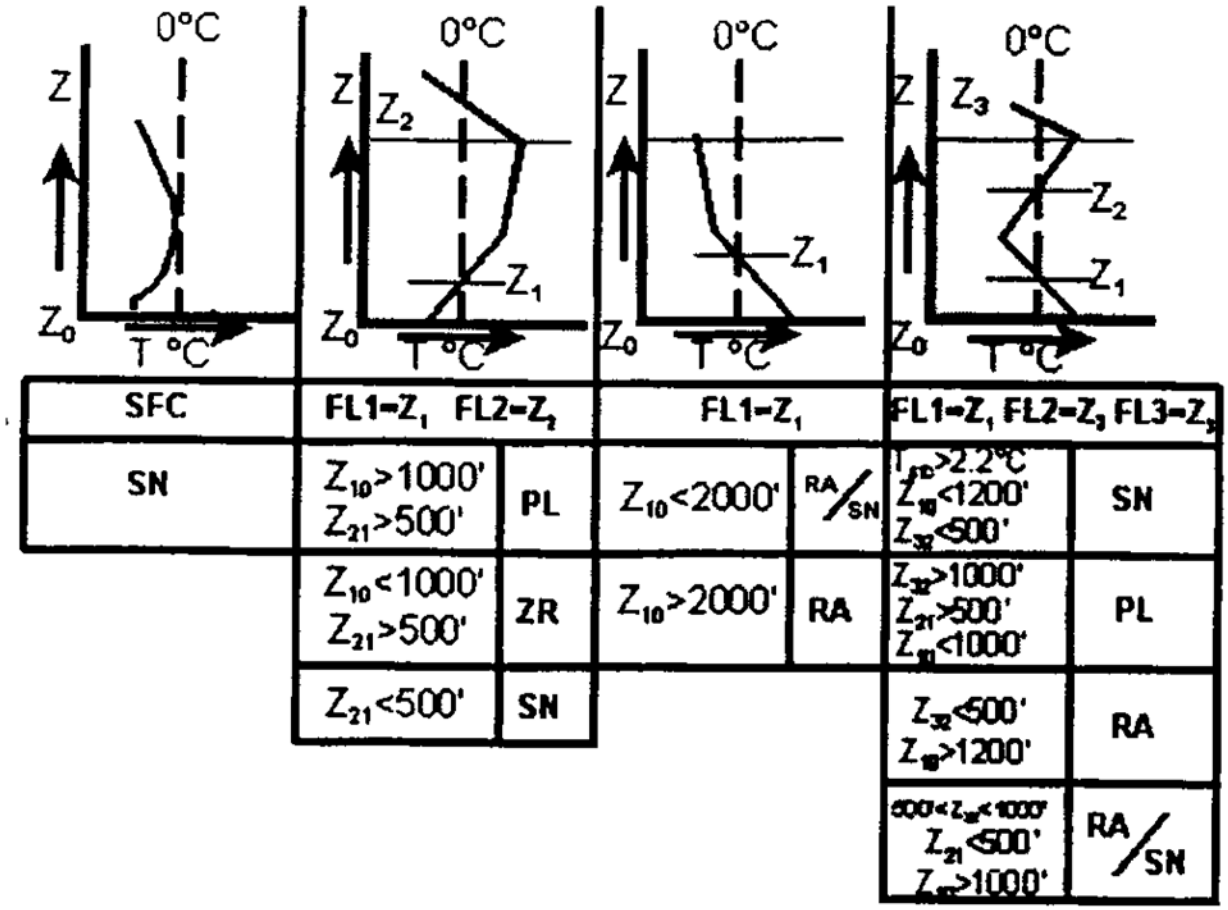


__Figure 13:__ Precipitation types according to freezing level(s). Source : Derouin (1973).

Another aspect left to be examined is the impact of a relatively warm ground on the density for each case in Table 28. Contrary to cases where the atmospheric temperature profile remains below the freezing point, the suggested snow/water ratios in relation to the two categories for unfrozen ground (Tground > 0 and Tground >> 0) will not be exactly the same for all diagnoses (see Table 27). In Table 28, the cases are initially associated with relatively dense snow. The exact nature of the precipitation determines its melting potential. For example, if we compare 2 cases of heavy snow, a snow/ice pellets combination should melt less rapidly when falling on warm ground than would wet snowflakes. As another example, involving very heavy snow, we can compare ice pellets with a rain/snow combination; logically, ice pellets should last a little longer. Table 30 summarizes the most likely impact of ground temperature on diagnoses #18 to 25.

Diagnosis #	Precipitation type(s)	Ground temperature (^{o}C)	Snow category	Suggested ratio
18	Ice pellets	≤ 0 > 0 >> 0	very heavy very heavy N/A	4 4 0
19	Snow mixed with a little rain	≤ 0 > 0 >> 0	very heavy N/A N/A	4 0 0
20	Snow mixed with freezing rain	≤ 0 > 0 >> 0	very heavy N/A N/A	4 0 0
21	Snow mixed with rain/ice pellets	≤ 0 > 0 >> 0	very heavy N/A N/A	4 0 0
22	Snow mixed with ice pellets	≤ 0 > 0 >> 0	heavy heavy very heavy	7 7 4
23	Wet snow	≤ 0 > 0 >> 0	heavy very heavy N/A	7 4 0
24	Wet snow pellets	≤ 0 > 0 >> 0	very heavy N/A N/A	4 0 0
25	Snow pellets	≤ 0 > 0 >> 0	heavy heavy very heavy	7 7 4

Table 30: *Proposed snow categories and snow/water ratios according to ground temperature for each diagnosis in Table 28. Tground ≤ 0 implies frozen ground or a significant snow cover (> 2.5 cm). Tground > 0 refers to temperatures between 0 and 5 ^{o}C and Tground >> 0 to temperatures above 5 ^{o}C.*

We have identified different cases of snow accumulations which can occur when the air temperature rises above the freezing point. An adequate snow/water ratio has been suggested for each one, according to the precipitation type(s) occurring and to the ground temperature. A diagram summarizing these diagnoses, along with those for cases where the thermal profile remains below 0 ^{o}C, can be consulted in Appendix III.

It would be beneficial to mention another type of snow crystals, which has not been addressed yet: ice crystals (IC). Ice crystals are formed when droplets freeze (or water vapour sublimates) at very low temperatures *e.g.* below –30 ^{o}C. They are often associated to high-pressure systems producing clear skies and light winds in very cold air masses near humidity or combustion sources (river, chimney, aircraft engine, etc.).

According to several publications, ice crystals have a very low density. It has been reported that their associated snow/water ratios can reach up to 100:1 ! In the present study, ice crystals will be attributed a snow/water ratio of 25:1, the same as ultra light snow. We have not introduced this diagnosis before on the grounds that, contrary to other diagnoses seen up to now, it is very difficult, or perhaps even irrelevant, to forecast a water equivalent amount (QPF) when ice crystals occur. They fall sporadically and generally cause small accumulations (very rarely exceeding 2 cm). From an operational perspective, ice crystals accumulations are not forecast as such, but their occurrence is usually covered in weather forecasts using expressions such as “a few snowflakes” or “isolated flurries”.

Table 31, which complements Table 28, shows the density characteristics of ice crystals. However, since no accumulation is usually forecast, the diagnosis will not be part of the complete algorithm. Since it will be considered an “unofficial” diagnosis, it was labelled #0 instead of #27.

Diagnosis #	Precipitation type	Snow category	Suggested ratio
0	Ice crystals	Ultra light	25

Table 31: *Additional diagnosis for ice crystals.*

Table 32 gathers the 26 possible diagnoses (as well as the one for ice crystals). They are grouped together according to their associated snow category (or their suggested snow/water ratio). Please note that a frozen or snow-covered ground was presumed (Tground ≤ 0 ^{o}C). To determine the change in density for each of these cases when the ground is relatively warm (mainly in early fall), please consult Tables 27 and 30.

R	Cases where Tatm > 0° C (warm layer at the surface or aloft)	R	Cases where Tatm < 0 °C (from cloud tops to surface)
		25:1	0. Ice crystals 17. unaltered stars (Vmax ≤ 5 kt)
7:1	22. snow mixed with ice pellets 23. wet snow 25. snow pellets	20:1	16. very slightly fragmented stars (5 < Vmax ≤ 15 kt)
4:1	18. ice pellets 19. snow mixed with a little rain 20. snow mixed with freezing rain 21. snow mixed with rain and ice pellets 24. wet snow pellets	15:1	15. slightly fragmented stars (15 < Vmax ≤ 25 kt) 13. partially sublimated stars, very slightly/not fragmented (Vmax ≤ 15 kt) 10. mixed crystals with stellar nucleus, slightly/not fragmented (Vmax ≤ 25 kt) 4. aggregated needles slightly/not fragmented (Vmax ≤ 25 kt)
0:1	26. rain, freezing rain, rain mixed with a little snow or wit ice pellets	10:1	ANY OTHER COMBINATION Among others, all mixed cases without accretion, stars with significant accretion, and all cases without accretion but with extensive fragmentation (Vmax > 25 kt)
		7:1	1. rimed mixed crystals 5. rimed spatial dendrites

Table 32: *Grouping of the various diagnoses based on crystal or precipitation types, according to their associated mean snow/water ratio. Tground≤ 0 is presumed, which is generally the case in Quebec. Tground ≤ 0 implies that the ground is frozen or covered by at least 2.5 cm of snow.*

There are not many ways to get ultra light or very light snow (R=25 or 20:1) and the conditions associated with their occurrence are easy to identify. In the case of light snow (R=15:1), Table 32 proposes 4 possibilities. However, diagnoses 4 and 13 are relatively rare due to limitations surrounding the conditions needed for their occurrence (see Section **6 b) I)**). By comparison, diagnoses 10 and 15 (mixed crystals with stellar nucleus and slightly fragmented stars) occur much more often. When air and ground temperatures remain below the freezing point, significant accretion of relatively dense crystals (mixed crystals and spatial dendrites) is required to produce heavy snow (diagnoses 1 and 5).

Before we move on to the next sub-section, the reader is reminded that diagrams detailing the forecast algorithm are provided in Appendix III. Figure 14 summarizes its major steps:

From the temperature profile (cloud top to surface), determine if :

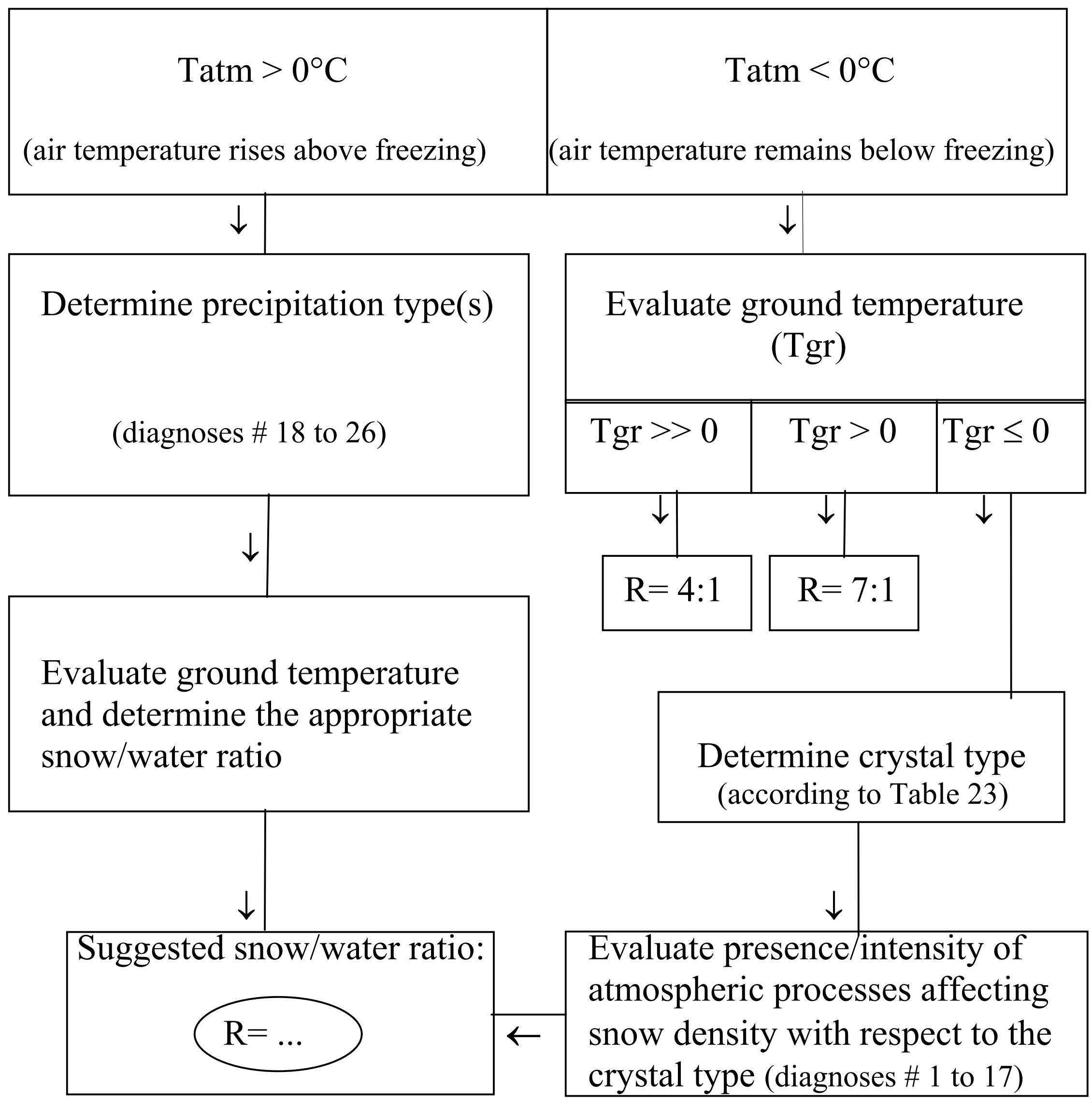


Figure 14: *Major steps of the snow/water ratio forecast algorithm.*

Having described the forecast algorithm, let us now examine some of the tools that can facilitate its operational use.

ii) Tephigrams/hodographs

From an operational perspective, the use of forecast tephigrams and hodographs allows for a quick viewing of temperature, humidity and wind profiles as predicted by numerical models at a given point and time. However, one significant parameter is missing: the vertical motion profile, which is essential when the temperature remains below 0 ^{o}C. This parameter will have to come from another source. With this information, we can begin the snow/water ratio forecast process by determining the crystal or the precipitation type(s), as the case may be, and subsequently evaluate the accretion, sublimation, aggregation and fragmentation potentials. Examples of tephigram and hodograph use are shown in Appendix IV, where cases studies are presented.

iii) Cross-sections (MAX)

The vertical cross-sections available on the MAX - or other display systems allow a quick 2-dimensional visualization of the temperature, humidity and vertical motion fields. These are useful in diagnosing the type of crystal growth as well as the accretion, sublimation and aggregation potentials within a given meteorological system. Since the model's wind field can not be displayed on these cross-sections, other sources, such as forecast hodographs, horizontal wind fields or alphanumerical products, must be consulted to extract maximum low level winds in order to determine the level of fragmentation, and therefore complete the snow/water ratio diagnosis/forecast process.

MSC's Quebec Region has produced a "macro" that facilitates and accelerates the downloading and display of required fields. As for the previous tool, examples of cross-sections can be found in Appendix IV.

iv) Climatology-based tools

As seen in Section **6 a) v)** (trajectory method), this type of tool has limited operational value and does not constitute a very useful method on a case-by-case basis. Moreover, the development of such tools would necessitate a large amount of data and time. Contrary to initial plans, it seems more efficient, for the time being, to improve on the proposed algorithm (see Sections 7 and 9) rather than spend time and energy on climatology-based tools.

v) Others

Other products can potentially assist in the application of the algorithm, or in some of its associated tests. For example, the potential for accretion (or occurrence of supercooled water droplets) is already addressed on CMC charts from the GEM model's "AVIATION" package, as shown on Figure 15 below.

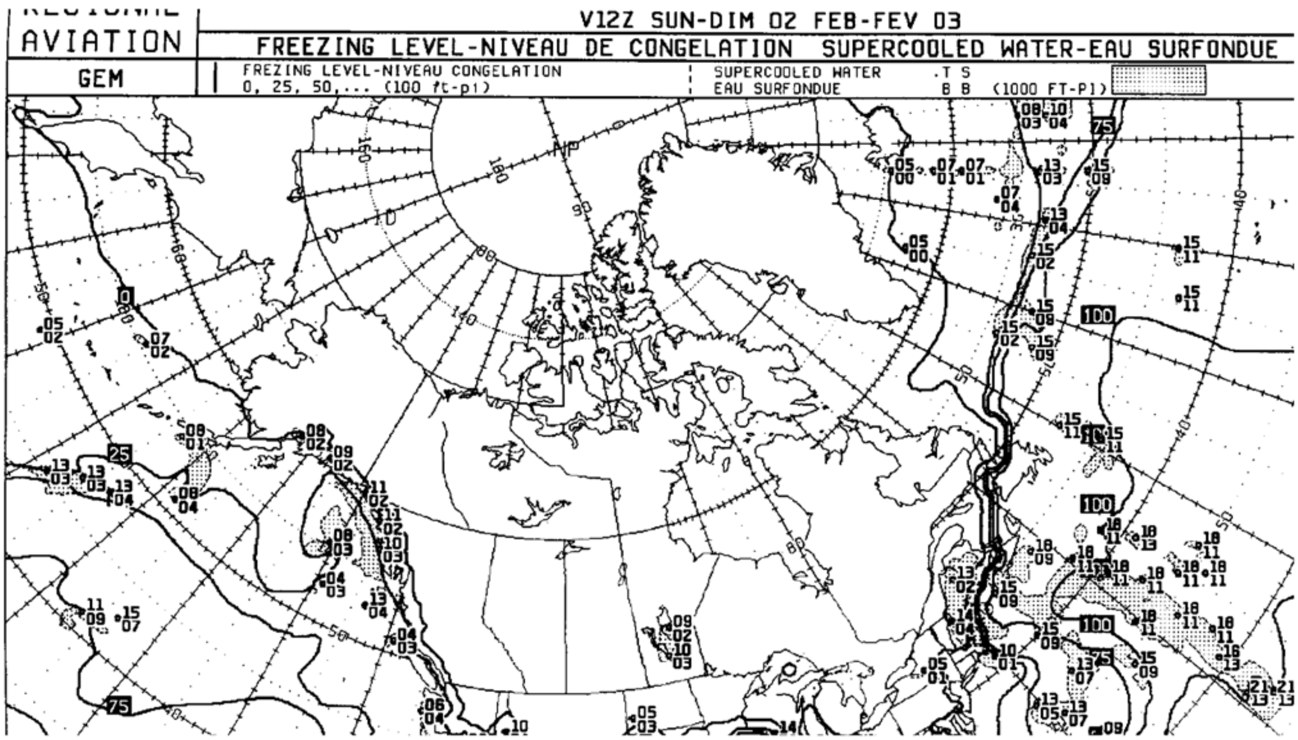


Figure 15: *CMC chart showing forecast areas of supercooled water droplets. Source: MSC.*

The fact that the accretion process is already parameterized in some way might eventually facilitate the integration of the snow/water ratio forecast algorithm within numerical models.

Another example (Figure 16) involves CMC experimental back trajectory charts. These charts can also facilitate the evaluation of accretion potentials as they provide a way of determining the origin of an air mass in the low-levels, hence some of its characteristics (*i.e.* continental or maritime, presence of hygroscopic nuclei, orographic lift or subsidence, etc.). Figure 16 compares back trajectories in two adjoining regions: Beauce (top) and Mauricie (bottom). The air mass affecting the Beauce region originates from the South-South-East (Gulf of Maine) and possesses maritime characteristics, whereas the one affecting the Mauricie region comes from the North-West and has continental properties.

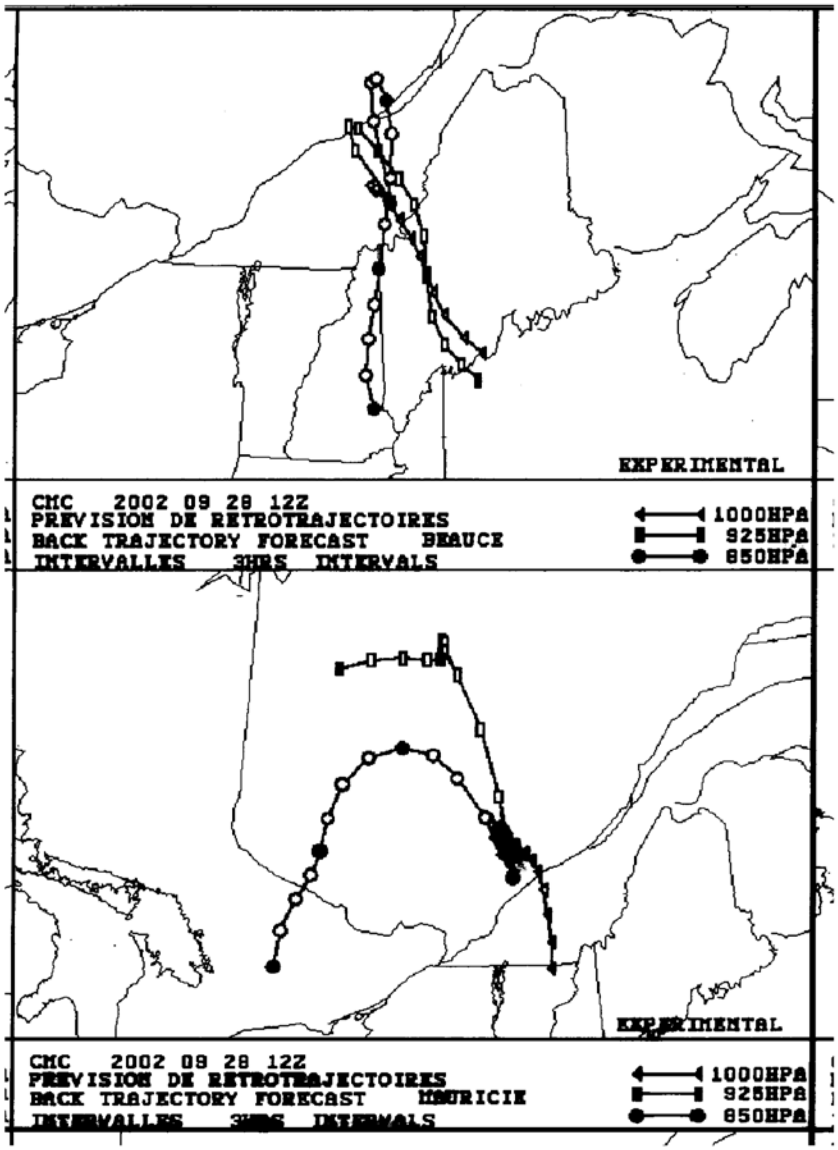


Figure 16: *CMC Experimental chart showing low-level back trajectories for 2 different regions (top, Beauce; bottom, Mauricie). Source: MSC.*

There are certainly other available products or existing techniques that could facilitate the application of the algorithm. But describing all of them is not one of the present study's main objectives. We will now conclude this section before addressing the forecast algorithm's verification.

c) Conclusions:

Several snow/water ratio forecasting techniques were examined and found inadequate. A new method was proposed, in the form of a forecast algorithm which takes into account all parameters and processes affecting snow density.

This relatively complex algorithm is based on physical principles and measurements rather than statistical correlations. It is divided into 2 main sections: The first applies to cases where snow melts (partially or fully) somewhere in the atmosphere; the second applies to cases where the air temperature remains below the freezing point. Following this first step, the snow/water ratio diagnosis continues by determining either the precipitation or crystal type(s) occurring, respectively. The presence and intensity of various physical processes (accretion, sublimation, aggregation, fragmentation, melting on the ground) are then evaluated to complete the diagnosis.

The algorithm generates 26 main diagnoses after all atmospheric processes have been considered (*i.e.* before evaluating ground-level melting). Following this final test, the total number of possibilities increases to 44, namely: 11 diagnoses of 0:1, 10 of 4:1, 8 of 7:1, 9 of 10:1, 4 of 15:1, 1 of 20:1, and 1 of 25:1. (Note: The number of diagnoses associated with each snow category is not linked in any way to their frequency of occurrence, which will be examined in the next section.

Meteorological conditions that produce light to ultra light snow (R= 15, 20 or 25:1) are very limited. It seems very unlikely that the current tendency to underestimate snow/water ratios, thus snow accumulations (through a systematic use of the 10:1 rule), can be turned around. In a way, the proposed algorithm could be described as “cautious”, *i.e.* it should not generate high values of the snow/water ratio (or very low densities) too easily. This is a desirable characteristic at this stage of development to insure a reasonable credibility of this method. It is considered preferable to forecast a value of 15:1 when values of 20 or even 25:1 are observed (which represents an improvement over the traditional ratio of 10:1), rather than to forecast 15 or 20:1 ratios when average snow (10:1) is observed. We will re-examine this topic in Section 7.

The ability to accurately forecast precipitation or crystal types will greatly influence the algorithm’s performance. In addition, the difficulty in forecasting the presence and/or the intensity of accretion and to accurately evaluate ground temperatures in early fall will be determining factors in some cases. More detail regarding the sources of potential errors associated with the use of the algorithm will be examined in the next Section.

In addition to the forecast algorithm, a few "secondary" tools were presented. Details about these tools and their practical application are found in Appendix IV. Among others things, the importance of the vertical motion field in determining the crystal type, hence the snow/water ratio, is demonstrated.

Initially, operational use of this algorithm may seem unrealistic. The high number of diagnoses to perform over many locations, every 3 hours over periods of 12, 24 or 48 hours, can quickly exceed a reasonable value. However, we must take into consideration that many of these diagnoses can be performed very rapidly. For example, the occurrence of strong low-level winds around an intense low pressure system implies substantial fragmentation and virtually eliminates any possibility of observing light snow ($R \geq 15:1$). Once familiar with the technique, forecasters will be able to quickly detect situations where ratios other than the traditional 10:1 would be appropriate. For that matter, the algorithm could have been developed in this context, *i.e.* initially assuming a 10:1 snow/water ratio and searching for meteorological conditions favourable to different values (*e.g.* accretion and melting for lower values, stellar crystal growth with light winds and no accretion for higher values, etc.)

At this point, it seems highly desirable to seriously consider the integration of the algorithm into the operational numerical model, either directly or in post-processing of its outputs. The snow/water ratio could be computed at every grid point, every 3 hours (*i.e.* 00, 03, 06, …, 45, 48H). This new field, displayed on a chart or through a visualization tool such as MAX, or integrated in a graphical forecast production tool such as SCRIBE, would greatly assist operational meteorologists in efficiently and appropriately converting forecast water equivalents into snow accumulations. Sections 8 and 9 will briefly review this topic.

7. VERIFICATION OF THE ALGORITHM

The algorithm proposed in Section 6 and Appendix III was verified between November 1, 2002 and February 24, 2003. The results are presented in the following pages.

a) Methodology:

The first step in the verification process was to establish the events' selection criteria:

- access to snow and water equivalent measurements;
- accumulations greater than 1 cm or 1 mm;
- periods of 3 to 12 hours representative of only one diagnosis (in order to compare actual observations to a single forecast diagnosis – not an average of two different diagnoses);
- access to radiosonde observations and/or to GEM model data for the same period.

Contrary to the climatological study (Section 2), no restrictions were imposed regarding temperature or occurrence of any type of precipitation. In accordance with these criteria, 281 cases were selected over the 3-½ months period. Cases covered 11 main regions of Quebec. These regions as well as the 33 observation sites used are listed in Table 33.

Region	Observation sites
Abitibi/Chibougamau	YVO, Noranda, YMT
Maniwaki	WMW, WMJ
Montréal	YUL, YMX, YHU, Ormstown
Trois-Rivières	YRQ, Acqueduc de Trois-Rivières, Bécancour
Estrie/Beauce	YSC, Granby, WHV, St-Ferdinand
Québec City	YQB,Charlesbourg,CampMercier,Forêt Montmorency
Charlevoix	WIS, Mont-Ste-Anne
Bas-Saint-Laurent	St-Antonin, Rimouski, WYQ, YYY, St-Arsène
Gaspésie	YGP, Bonaventure
Côte-Nord	YBC, YZV, Rivière-au-Tonnerre
Fermont	YWK

Table 33: *Regions included in the verification process and their respective observation sites. Station names in full, their locations and elevations are provided in the table and on the map shown in Appendix II.*

Near half of the observation sites belong to Environment Canada's official observing network. The others are part of the climatological snow observing network. Many other weather stations also belong to these two networks but, unfortunately, they could not be used for verification purposes. In many cases, only one of the two required measurements (snow or water equivalent) is reported while other stations systematically observe the same snow (in cm) and water (in mm) measurements (*i.e.* R=10:1). Most of the selected stations also report the precipitation type(s), present or past (last 6 or 12 hours), which facilitates the verification process when temperatures exceed zero Celcius. As seen in Section 6, the precipitation type(s) occurring constitute(s) the main factor in determining the snow/water ratio in this type of case.

Data required to apply the algorithm were retrieved for each of these cases (temperature, humidity and vertical motion profiles, wind, etc.). An elaborate diagnosis was performed considering all possibilities (see Tables 26 and 28, Section 6, or the detailed algorithm in Appendix III). Please note that since the verification period started on November 1st and ended on February 24th, all cases are associated with a frozen ground (Tground ≤ 0 ^{o}C). This means the proposed snow/water ratio modifications in Table 27 and 30 were not tested within the current verification process. In a similar fashion, diagnosis #26 (from Table 28), which corresponds to cases of rain or mixed precipitation producing no snow accumulations (R=0), was not a part of the verification process. Therefore, a total of 25 diagnoses were tested.

It must be emphasized that the algorithm was verified in a diagnostic mode rather than a prognostic one. In other words, all available data following each event were used in the verification; For cases where air temperature remained below zero (most of the 281 cases), this has little influence on the results as data forecast by the operational numerical model was almost exclusively used. These diagnoses would have been the same had they been completed before the event (prognostic mode), except perhaps in cases where significant accretion was suspected. In such cases, the occurrence of freezing drizzle at the surface or aloft greatly affected the diagnosis. For cases where air temperature exceeds the freezing point and where precipitation types are determinant, we can expect the performance measured in diagnostic mode to be superior to the one in forecast mode. Nevertheless, it was considered highly preferable to proceed this way since the main goal is to to test the accuracy of snow/water ratios suggested by the algorithm for each type or combination of precipitation, rather than our ability to accurately forecast the precipitation type(s). The latter, however, remains a significant component of the snow/water ratio forecast process.

The verification process allowed us to compile cases from different regions over the same time period; conversely, we were also able to compile several subsequent verification cases while evaluating the algorithm performance for one single region, **as long as distinct diagnoses were generated** according to the varying weather conditions. We were especially cautious to avoid too many similar cases in the same region over a given period. Hence, when neighbouring sites in the same region (*e.g.* YUL/YHU or YQB/Charlesbourg) provided similar data and meteorological conditions leading to the same diagnosis, only one of these cases was retained *i.e.* the one designated as the "main station" for this region (usually the first one listed in Table 33). Unused data were still noted in the verification database for validation purposes.

b) Climatology:

In the following pages, the observed data collected during the verification process will be examined from a climatological perspective. First, the climatology of observations will be adressed. Then, the distribution of the different diagnoses generated by the algorithm will be discussed.

Climatology of observations

The sample of 281 cases could be used to produce a new snow/water ratio climatological study. We could in fact re-calculate the statistics from Section 2, but this would add very little to the existing knowledge. We will therefore limit ourselves to the following statistics:

- regional distribution of cases;
- snowfall distribution;
- observed extremes;
- mean;
- median;
- snow category distribution.

Table 34 shows the regional distribution of the 281 verified cases. At first glance, the results look very satisfactory. The breakdown seems to result in a good compromise between population, level of economic activity, geographic area and frequency of snowfalls in each region.

Region	# Cases
Abitibi/Chibougamau	31
Maniwaki	7
Montréal	46
Trois-Rivières	16
Estrie/Beauce	27
Québec City	37
Charlevoix	24
Bas-Saint-Laurent	33
Gaspésie	21
Côte-Nord	16
Fermont	23

Table 34: *Regional distribution of the 281 verification cases.*

Let us now examine the distribution of cases according to snowfall amounts (Table 35). Compared to the climatological study (see Table 2), we note a greater proportion of cases with less than 5 cm (68% versus 38%) and much fewer abundant snow cases (3% versus 16%). We can suggest many reasons for this situation. First, because of the lack of a limit on positive temperatures and on the presence of other precipitation types, the verification sample contains many more cases of heavy snow. These cases, corresponding to relatively low snow-water ratios, tend to be associated with smaller snow accumulations. Shorter periods (3 to 12 hrs) can also account for the observed differences. The climatological study considered the "mean" snow/water ratios for each event, whereas the verification process imposed that longer events be divided into several short each associated to a specific diagnosis.

Accumulation (cm)	0-2,5	2,5-5	5-10	10-15	15-+
# cases	108	82	63	19	9

Table 35: *Number of cases for various snowfall intervals.*

We calculated the snow/water ratio corresponding to each of the 281 cases using the observed snowfall amounts and water equivalents. The ratio varies between 1.9:1 and 40:1, its mean value is 12.6:1 and its median value is 11.5:1. The resulting values are a little lower than in the climatological study (Section **2 b)**), which again, may be related to the higher number of cases of heavy snow associated with mild temperatures (> 0 ^{o}C) or mixed precipitation cases.

The following table illustrates the distribution of verified cases according to observed snow categories.

Snow Category	Very heavy	Heavy	Average	Light	Very light	Ultra light
Snow/water ratio	≤ 5,5:1	5,6-8,5:1	8,6-12,5:1	12,6-17,5:1	17,6-22,5:1	≥ 22,6:1
# Cases	14	29	130	72	21	15
% Cases	5%	10%	46%	26%	7.5%	5.5%

Table 36: *Number and percentage of cases for each snow category (total of 281 cases).*

As with the analysis of the climatological results (Table 16), we note that the average snow category, although the most frequently observed, does not overshadow the other types of snow. Results from Table 36 imply, after grouping the heavy and light categories, the more general distribution that follows:

- heavy snow ($R \leq 8.5$): 15%
- average snow ($8.5 < R \leq 12.5$): 46%
- light snow ($R > 12.5$): 39%

It would have been preferable to have the verification period covering an entire winter season, *i.e.* extending until May, in order to produce a more representative distribution. Thus, these statistics should be revised later. In the meantime, considering the fact that late winter as well as early fall tend to favour the occurrence of heavy snow, these preliminary results can be extrapolated to produce a rough estimate of the true annual distribution:

- heavy snow ($R \leq 8.5$): 25%
- average snow ($8.5 < R \leq 12.5$): 50%
- light snow ($R > 12.5$): 25%

This means that, on an annual basis, the 10:1 rule is accurate in barely 50% of the cases. It must be noted that this rule is not systematically used by meteorologists in many cases likely to produce heavy snow (*i.e.* Tsfc > 0 ^{o}C, rain and mixed snow, ice pellets, etc.). In those cases, meteorologists do not rely on specific tools but rather on their experience to approximately convert water equivalents into snow. For now, let us roughly estimate the current performance in cases of heavy snow at approximately 70%. By combining this performance with the one resulting from the 10:1 rule, we get the following global performance :

- heavy snow: 25% of cases with a 70% success rate → 17.5%
- average snow: 50% of cases with a 100% success rate → 50%
- light snow: 25% of cases with a 0% success rate → 0%

Global performance: → 67.5%

This result, partially hypothetical, is only an approximate measurement of the current operational performance. Still, it will be interesting to compare it with the one resulting from the algorithm's verification.

Climatology of diagnoses

Application of the algorithm on the 281 cases led to an equal number of diagnoses. Their distribution in accordance with the established reference numbers in Section 6 is shown in Tables 37 and 38.

Diagnosis #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
# cases	7	60	1	0	0	18	11	2	30	47	0	0	1	8	33	19	8

Table 37: *Number of verification cases for each diagnosis where Tatm remains below zero Celcius (total of 245 cases).*

Diagnosis #	18	19	20	21	22	23	24	25
# cases	1	4	8	1	8	14	0	0

Table 38: *Number of verification cases for each diagnosis where Tatm exceeds zero Celcius (total of 36 cases).*

Note that some diagnoses are much more common than others. Within the sample, no cases were observed for 6 of the 25 diagnostics. There are relatively few cases where the air temperature exceeds 0°C (Table 38), which could be a reflection of the relatively cold 2002-2003 winter season (at least until February 24th). Partial sublimation (#8, 12 and 13) as well as accretion cases (#1, 5, 7 and 11) also seem to be relatively rare. Although this probably reflects reality, we must admit that the difficulty to accurately diagnose these processes could also be a factor.

We can calculate the percentage of each crystal type, as determined by the algorithm, using the results of diagnoses 1 to 17 (Table 37). This was done following an appropriate grouping of the diagnoses. Results are shown in Table 39.

Diagnosis #	Crystal type	% of cases
1-2	Mixed	27%
3-4	Needles	1%
5-6	spatial dendrites	7%
7-10	Mixed with stellar nucleus	37%
11-17	Stars	28%

Table 39: *Distribution of the diagnosed crystal types (based on 245 cases).*

These results are not surprising. As stated in Sections **3 b) i)** and **6 b) i)**, the growth of pure needles requires atmospheric conditions that are very specific. It is quite normal (and desirable) for this type of relatively rare crystals to rarely be diagnosed by the algorithm. We could also have anticipated the low percentage of spatial dendrites occurences; Table 23 indicates that the formation of these crystals requires either a strong in-cloud temperature inversion or a very cold main growth temperature. Although quite possible, these conditions are much less frequent than those producing the 3 main crystal types (mixed, mixed with stellar nucleus and stars).

c) Performance measurements:

It is now time to introduce the contingency table resulting from the comparison of the observed snow/water ratios and those suggested by the algorithm for the 281 cases. Table 40 is divided according to the different snow categories, as defined in Section 5. The number of cases corresponding to each combination of "observed versus forecast" snow categories is entered in the appropriate space. The bold numbers in the diagonal represent the successful diagnoses (or hits); the numbers below the diagonal, an underestimation of the snow/water ratio; and the numbers above, an over-estimation.

It is interesting to note that no diagnosis generated by the algorithm deviates from the observation by 2 or more categories. All diagnoses are successful or belong to an adjacent category.

Forecast by Algorithm → Observed ↓	Very heavy snow (4:1)	Heavy snow (7:1)	Average snow (10:1)	Light snow (15:1)	Very light snow (20:1)	Ultra light snow (25:1)
Very heavy snow (3-5)	**13**	1				
Heavy snow (6-8)	1	**25**	3			
Average snow (9-12)		3	**116**	11		
Light snow (13-17)			11	**60**	1	
Very light snow (18-22)				10	**11**	
Ultra light snow (23+)					7	**8**

Table 40: *Snow category contingency table (forecast by the algorithm versus observed) for the 281 verification cases. The bold numbers in the diagonal represent hits or successful diagnoses. Numbers below the diagonal correspond to an underestimation of the snow/water ratio, and the numbers above, to an over-estimation.*

Using the contingency table we can now establish the credibility of each type of diagnosis (*i.e.* for each snow category), as well as the overall credibility. We define credibility as:

(# of hits / # of diagnoses)

Therefore, the credibility measures the proportion of diagnoses that correspond to the observed value. Table 41 presents the derived results.

Forecast snow category	#hits / # diagnoses	Credibility
Very heavy	13/14	93%
Heavy	25/29	86%
Average	116/130	89%
Light	60/81	74%
Very light	11/19	58%
Ultra light	8/8	100%
All categories	233/281	82.9%

Table 41: *Diagnosis credibility for each snow category (and all events combined).*

At first glance, credibility of the diagnoses seems excellent, except for the light and very light categories (R=15 and 20:1). We will examine the possible sources of errors later on to help us better understand these results. However, we could at this point introduce a slight alteration to the credibility calculations. It would indeed be "fair" to assume that the diagnoses which underestimate the snow/water ratio in cases of observed very light or ultra light snow do not necessarily represent "misses" or "failures". Such is the case with the 10 diagnoses of light snow (R=15:1) where very light snow (R~20:1) occurred, as well as with the 7 diagnoses indicating very light snow when ultra light snow (R~25:1) occurred. We could well assume that these diagnoses are "successful" since they show a significant improvement with respect to the 10:1 rule. This would imply that in a case where we expect a 10 mm water equivalent for example, a diagnosis of 15 cm would not necessarily constitute a "bad" forecast if 20 cm are in fact observed. The expected 15 cm snow accumulation is definitely better than the 10 cm traditionally forecast. If we accept this hypothesis, we can calculate new (modified) credibility values (see Table 42). As a result, each type of diagnosis indicates an excellent performance.

Forecast snow category	Credibility
very heavy	93%
heavy	86%
average	89%
light	86%*
Very light	95%*
Ultra light	100%
All categories	89%*

Table 42: *Modified diagnosis credibility for each snow category and global credibility. *Considering diagnoses underestimating the snow/liquid ratio by one category in cases of observed very light and ultra light snow as hits, because of the definite improvement they represent compared to the 10:1 rule.*

We will now examine the probabilities of detection for each snow category, defined as:

(# of hits / # of observed cases)

The resulting values are shown in Table 43. Performance is generally very good except for very light and ultra light snow cases.

Observed snow category	# hits / # observed	Probability of detection
Very heavy	13/14	93%
Heavy	25/29	86%
Average	116/130	89%
Light	60/72	83%
Very light	11/21	52%
Ultra light	8/15	53%

Table 43: *Probability of detection for each snow category, according to the 281 cases.*

This decrease in performance with respect to the higher snow/water ratio values (non-detection) reflects a certain cautiousness within the structure of the forecast algorithm. The latter, in addition to offering a global performance that is quite satisfactory, also presents the advantage of limiting the very and ultra light snow diagnoses (those that depart the most from the traditional 10:1 ratio) to conditions truly conducive to their occurrence. As seen in Section 6, this characteristic of the algorithm is highly desirable, especially at the preliminary stage of operational use. It is definitely preferable to sacrifice the detection of some "extreme" events for the benefit of maintaining a higher credibitility. In other words, we would not want the algorithm to overestimate too easily the snow/water ratios in very and ultra light snow occurrences. For example, cases predicted with a ratio of 25:1, when observed values are closer to 10 or 15:1, would produce significant overestimates of snow accumulations, and consequently a decrease in credibility of the algorithm.

As was done with the credibility, it would be fair to regard the light/very light snow diagnoses as successful when very light/ultra light snow is observed. New probability of detection values, *i.e.* that take this assumption into account, are shown in Table 44.

Observed snow category	Probability of detection
Very heavy	93%
Heavy	86%
Average	89%
Light	83%
Very light	100%*
Ultra light	100%*

Table 44: *Modified probability of detection for each snow category according to the 281 cases verified.* Considering diagnoses underestimating the snow/liquid ratio by one category in cases of observed very light and ultra light snow as hits, because of the definite improvement they represent compared to the 10:1 rule.*

It would be relevant to evaluate the algorithm's global performance in prognostic mode before further detailing the verification results. It was mentioned in Section **7 a)** that the verification process occurred in diagnostic mode, and that this had minimal effects on most of the results. However, cases where atmospheric temperatures exceeding the freezing point were diagnosed, which represent almost all the observed cases of heavy or very heavy snow (36/40), indicate a superior performance to the one expected in prognostic mode. The ability to accurately forecast the precipitation type(s) in occurrence would certainly have affected the results.

Going back to the global performance calculation done in Section **7 b),** the 10:1 rule was attributed a result of 67.5%. In applying the same methodology, we can attempt to estimate the algorithm's <u>minimal</u> performance. For heavy snow (R ≤ 8.5), which represents ~25% of all cases, we previously estimated the performance at 70%. But, the excellent performance of the algorithm in diagnostic mode with heavy snow occurences (Tables 40, 41 and 43) shows the accuracy of the proposed links between precipitation types and snow/water ratios (Table 28). It seems logical to assume that the performance in prognostic mode will be improved; we therefore estimate a performance of at least 75% for heavy snow cases. For occurrences of average snow (50% of annual cases), where the rule of 10:1 produced a perfect score (100%), the proposed performance of 89% (Table 41) will be used for the algorithm. For the enlarged light snow category (R>12,5), Tables 40 and 41 propose a minimal performance of 74%, which represents a substantial improvement compared to 0% resulting from the 10:1 rule.

Combining the 3 expanded categories, we obtain the following minimal global performance:

- heavy snow: 25% of cases with a 75% success rate → 19%
- average snow: 50% of cases with an 89% success rate → 45%
- <u>light snow: 25% of cases with a 74% success rate → 18.5%</u>

Global performance → 82.5%

The potential gain associated to the use of the algorithm is therefore estimated at near 15%.

The verification process, in addition to evaluating the algorithm's performance, can also be used to improve it by fragmenting the verification to evaluate each diagnosis separately. For now, only the diagnoses with a sufficient number of cases will be examined. Tables 37 and 38 show that no such cases occurred for 6 of the 25 diagnoses; the threshold has been set at 7 cases. Thus, a total of 13 diagnoses (# 1, 2, 6, 7, 9, 10, 14, 15, 16, 17, 20, 22 and 23) will be individually analysed. Their performances are presented in Tables 45 to 50, according to the forecast snow category.

Forecast ratio = 4:1	**Diagnosis # 20**
Robs=4	**7**
Robs=7	1
Robs=10	
Robs=15	
Robs=20	
Robs=25	
Credibility →	**88%**

Table 45: *Performance of diagnosis 20 (very heavy snow).*

Forecast ratio = 7:1	**Diagnosis # 1**	**Diagnosis # 22**	**Diagnosis # 23**
Robs=4			
Robs=7	**6**	**7**	**12**
Robs=10	1	1	2
Robs=15			
Robs=20			
Robs=25			
Credibility →	**86%**	**88%**	**86%**

Table 46: *Performance of diagnoses 1, 22 and 23 (heavy snow).*

Forecast ratio =10:1	**# 2**	**# 6**	**# 7**	**# 9**	**# 14**
Robs=4					
Robs=7			3		
Robs=10	**57**	**15**	**8**	**27**	**6**
Robs=15	3	3		3	2
Robs=20					
Robs=25					
Credibility→	**95%**	**83%**	**73%**	**90%**	**75%**

Table 47: *Performance of diagnoses 2, 6, 7, 9 and 14 (average snow).*

Note: Robs → observed snow/water ratio

Forecast ratio = 15:1	Diagnosis # 10	Diagnosis # 15
Robs=4		
Robs=7		
Robs=10	10	1
Robs=15	**34**	**25**
Robs=20	**3***	**7***
Robs=25		
Credibility →	**72% (79)****	**76% (97)****

Table 48: *Performance of diagnoses 10 and 15 (light snow).*
**: Cases where very light snow was observed; however, while missed in theory, it shows a clear improvement compared to the traditional 10:1 factor, and can in a way be considered successful.*
***: Modified credibility (in braquets) derived from the above assumption.*

Forecast ratio= 20:1	Diagnostic # 16
Robs=4	
Robs=7	
Robs=10	
Robs=15	1
Robs=20	**11**
Robs=25	**7***
Credibility →	**58% (95)****

Table 49: *Performance of diagnosis 16 (very light snow).*
**: Cases where ultra light snow was observed; however, while missed in theory, it shows a clear improvement compared to the traditional 10:1 factor, and can in a way be considered successful.*
***: Modified credibility (in braquets) derived from the above assumption.*

Forecast ratio = 25:1	Diagnostic # 17
Robs=4	
Robs=7	
Robs=10	
Robs=15	
Robs=20	
Robs=25	**8**
Credibility →	**100%**

Table 50: *Performance of diagnosis 17 (ultra light snow).*

These results confirm the validity of several diagnoses. The following ones show an excellent performance (≥ 90%) and a sufficient number of cases substantiate their value:

- # 2 : mixed crystals (95%)
- # 9 : mixed crystals with stellar nucleus, fragmented (90%)
- # 17: unaltered stellar crystals (100%)

The number of cases for diagnosis 17 is rather low (8). Although open to debate, it is validated, as were diagnoses 2 and 9, on the basis of its very restrictive character (see Section 7 and Appendix III) and its perfect credibility.

The following diagnoses demonstrate a good performance (80-90%) but are not numerous enough (less than 20) to definitely prove their validity:

- # 1 : rimed mixed crystals (86%)
- # 6 : spatial dendrites (83%)
- # 20 : snow mixed with freezing rain (88%)
- # 22 : snow mixed with ice pellets (88%)
- # 23 : wet snow (86%)

The following diagnoses show a moderate performance (< 80%) but few verification cases:

- # 7 : mixed crystals with stellar nucleus, rimed (73%)
- # 14 : extensively fragmented stellar crystals (75%)
- # 16 : very slightly fragmented stars (58%)
  (or 95%, depending on the chosen assumption)

The two light snow diagnoses of Table 48 (10 and 15) are based on a relatively high number of cases (47 and 33, respectively). Their performance is moderate (or excellent, depending on the chosen credibility for #15). However these 2 diagnoses do not share the same weakness. Diagnosis #10, corresponding to cases of mixed crystals with stellar nucleus with slight/no fragmentation, tends to overestimate the snow/water ratio. For diagnosis #15, corresponding to cases of slightly fragmented stars, the opposite is true. This kind of information could prove to be be useful in the future to adjust the threshold values currently established in the algorithm (*e.g.* fragmentation thresholds).

However, it is too early to significantly modify the proposed algorithm. The actual performance is considered, for now, quite satisfactory since most of the missed cases (near 70% of them) correspond to an underestimation of the snow/water ratio. As previously discussed, this is preferable to a tendency to overestimate ratios (generating false alarms), as it preserves a good credibility while outperforming current operational methods. It is also important to remember that the verification process is still young and that there are not enough cases to rigorously evaluate the performance of several diagnoses. We should also keep in mind that missed diagnoses are not all associated with weaknesses or imperfections of the algorithm. Many others sources of errors exist and are described below. A list of possible improvements to the algorithm will follow.

d) Sources of errors:

Aside from errors induced by the algorithm, many factors can contribute to an erroneous snow/water ratio diagnosis or, at least, to a disparity between the snow category forecast by the algorithm and the one observed at a given site. The sources of errors identified within this verification process are as follows:

- measurement errors;
- occurrence or intensity of accretion;
- use of model data;
- ground temperature estimation.

<u>Measurement errors</u>

Errors in the measurement of snow accumulations and their water equivalent are unavoidable, particularly under windy conditions. Blowing snow affects the amounts deposited on snow boards as well as the amounts entering snow collectors used to measure the water equivalent. We should not dread this type of error; although virtually omnipresent, it will not necessarily have a sufficiently strong impact to cause a category change with respect to the real observed category. This is what mainly motivated the use of snow categories (hence, snow/water ratio intervals) over more discrete values (*i.e.* 8, 9, 10, 11, 12, etc.). Thus we are hoping for minor errors to go unnoticed. For example, let us consider a 13 cm snowfall with a water equivalent of 7.9 mm (R=16.5) where the observer estimates the following amounts: 11 cm and 7.6 mm, giving a snow/water ratio of 14.5. This result departs slightly from reality but it still corresponds to the same snow category, namely light snow (R=13 to 17). However, even a very small error can produce a category change. Consider now another example where 12.3 cm and 10 mm fall on the ground (R=12.3 $\rightarrow$ average snow). The observation then calls for 12.7 cm and 10 mm (R=12.7 $\rightarrow$ light snow).

This 4 mm difference is enough to warrant a category change and therefore produces an erroneous diagnosis. This type of situation really occurred during the verification process. Table 48 shows a total of 11 observed cases of average snow which correspond to missed light snow diagnoses (#10 and #15). However, 5 of these 11 cases presented a calculated snow/water ratio equal to 12.5, the exact limit between average and light snow categories. These 5 diagnoses were therefore "missed" by a very slight margin.

Data from surrounding stations can possibly offer a certain validation of the observations, a reassuring element to consider in evaluating measurement errors For example, the Montreal and Québec City areas include many observation sites. The few measurements that were deemed doubtful over these regions were validated or rejected based on the agrrement with measurements from nearby sites.

Accretion

The accretion process, which can significantly affect the density of almost all crystal types, occurs under specific conditions that are fairly difficult to forecast. We should not hope to forecast the presence of significant accretion much more successfully than in the case of freezing drizzle, which is not very encouraging for operational meteorologists. Moreover, the challenge is not limited to the occurrence of this process but also to its intensity, which will determine if there will be enough densification of snow by riming to justify a change in snow category. However, our knowledge of the favourable condtions for supercooled droplet formation as well as the coexistence of snow crystals with the liquid phase is somewhat limited. That is why the proposed criteria to diagnose significant accretion (Table 25 and diagrams of Appendix III) are fairly primitive. A more comprehensive algorithm is needed to minimize the errors associated with the accretion process, and thus improve the snow/water ratio forecasting performance.

Numerical models

Diagnostic errors can also arise from the use of numerical model data. Temperature, humidity and vertical motion profiles used when applying the algorithm were extracted from the operational model outputs, except for very few cases in Maniwaki and Sept-Iles where radiosonde data (temperature and humidity) are available. The crystal growth levels and their associated temperatures were therefore always estimated, which had a direct impact on all diagnoses dependant of the crystal type (#1 to 17). Even a small error in one or more of the abovementioned meteorological fields can potentially lead to an erroneous determination of the crystal type and hence, to a wrong diagnosis.

The same reasoning applies when evaluating levels (or intensity) of accretion or fragmentation. In the latter case, low-level wind data extracted from the model constituted the main source of information for applying the algorithm and thus, diagnosing the snow/water ratio. Any disparity between the numerical model's wind field and reality which involved the crossing of one fragmentation threshold produced an erroneous diagnosis.

As seen in Sections **6 b) I)** and **7 a)**, the success of diagnoses in cases where the air temperature exceeds the freezing point (#18 to 26) is directly related to the ability to accurately forecast the precipitation type(s). This capability is strongly dependent on the model's performance (storm track, temperature and humidity profiles, precipitation intensity, wind and thermal advections, orography, etc.). This implies that the performance of every diagnosis produced by the algorithm is, in one way or another, dependent on the accuracy of the numerical model output.

We might expect that limiting the algorithm verification to cases where radiosonde data are available (resulting in a very small sample over Quebec….) can eliminate the inherent errors associated to numerical models. However, a major problem would remain: the absence of vertical motion measurements. This parameter is essential in the majority of diagnoses and has to be extracted from the corresponding model field. The sole use of radiosonde data would also make it impossible to produce a diagnosis every 3 to 6 hours, since data is only collected twice a day (synoptic hours: 00 and 12 UTC). If we limited the verification of diagnoses to these two daily periods, we would downsize the verification sample even more.

<u>Ground temperature</u>

There is at least another factor which could potentially diminish the algorithm's performance: the estimation of ground temperature. The current verification process could not verify this factor but, hopefully, this will be done in the near future. However, we can expect that some errors will likely be introduced when using ground temperature estimates as this type of measurement is too sparse, or even unavailable in most circumstances.

e) Possible improvements:

Some aspects addressing potential improvements of the proposed forecasting algorithm have been covered in previous paragraphs. They are summarized below, along with other ideas for possible improvements:

- To carry on with the specific verification of each diagnosis, in an effort to increase the sample mainly for diagnoses where little or no occurrences were observed (*e.g.* cases involving needles, significant accretion, partial sublimation, ice pellets or rain/snow mixtures);

- To develop an efficient method or algorithm able to accurately forecast significant accretion events;

- To test the impact of a relatively warm ground (Tground > 0, >> 0) on snow density from actual early fall cases (September and October);

- To verify the relationships between temperature/relative humidity profiles and the crystalline types as well as the relationships between the crystal types and snow density using experimental measurements (*e.g.* AIRS data);

- To test the algorithm in other regions (*e.g.* Western Canada);

- To develop a "fragmentation coefficient" that would take into account, in addition to the maximum low-level wind speed, the depth of the layer where these strong winds occur, the stability and orography (*i.e.* representative of the collision potential caused by mechanical turbulence in the low-levels).

f) Conclusions:

Verification of the snow/water ratio forecast algorithm over 11 regions in Quebec during the 2002-2003 winter is based on 281 cases. The performance level achieved by the algorithm is very encouraging considering it is in its first stages of development. The results show an estimated overall performance in prognostic mode at a little over 80%.

The verification process highlighted one desirable characteristic of the algorithm: the tendancy to sacrifice the detection of some extreme events (very high ratios) for the benefit of a higher credibitility.

The verification specific to each diagnosis reflected the need to significantly increase the verification sample before considering any major modification to the algorithm. Potential improvements were still identified and many of these will be subjected to further study (see Section 9).

Finally, the algorithm undoubtedly demonstrated a clearly superior performance to that of the 10:1 rule. Consequently, it has an excellent potential for operational use.

8. APPLICATIONS

In this section, we will examine the impact of snow density on various applications: snow accumulation and blowing snow forecasting, hydrology and avalanches. Some operational forecasting strategies will also be discussed.

a) Snow Accumulations:

It is rather obvious that using an appropriate water equivalent → snow conversion factor will significantly improve snow accumulation forecasts. According to climatology (Sections **2** and **7 b)**), the traditional 10:1 ratio is adequate in about 50% of cases, whereas verification of the algorithm clearly shows a superior performance (see Section **7 c)**).

Examples of the significant impact of snow density on snow accumulations, thus on activities such as snow removal, are shown in Tables 51 and 52 below.

Observation Site	Accumulation (cm)	Observed Water Equivalent (mm)	QPF from GEM (mm)	Measured Ratio
Quebec	4.2	1.4	0.8	30:1
Charlesbourg	3.2	1.0	1.0	32:1
Forêt Montmorency	3.1	1.0	1.4	31:1
Charlevoix	3.8	1.4	0.5	27:1
Mont-Ste-Anne (base)	2.6	0.8	1.0	32:1
Mont-Ste-Anne (sum.)	3.0	1.0	1.0	30:1

Table 51: *Case of January 6th, 2003 in the Quebec City area and surrounding localities.*

Observation Site	Accumulation (cm)	Observed Water Equivalent (mm)	Measured Ratio
Charlesbourg	18	6.6	27:1
Camp Mercier	21	9.4	22:1
Forêt Montmorency	20.4	7.9	26:1

Table 52: *Abundant snow case from January 25-26th, 2003 over sectors just north of Quebec City. The QPF from the GEM regional model for the same period varied between 6 and 7 mm.*

In the case of January 6th, the reported snow accumulations turned out to be much greater than predicted, *i.e.* between 3 and 5 cm, which was confirmed by snow removal operators. As discussed at the beginning of this document, we could have believed initially that this under-estimation of snow accumulations was caused by a poor performance from the operational model. However, it really was not the case here. As shown in Table 51, the observed water equivalents (from 0.8 to 1.4 mm) are very similar to those forecast by the model (from 0.5 to 1.4 mm). This negative bias can be explained by the fact that “ultra light” snow occured, as demonstrated by snow/water ratios nearing 30:1. The application of the algorithm, in this case, would have led to a conversion of 25:1, thus to a forecast of 2 to 4 cm. Although not perfectly accurate, such a forecast would have represented a favourable alternative to the ten-to-one rule.

The second case (Table 52) involves more impressive accumulations, that is, close to 20 cm. Once again, precipitation amounts forecast by the GEM model (6-7 mm) might seem disappointing. However, these values approach the observed 6 to 9 mm. High snow/water ratios (near 25:1) explain the rather surprising snow accumulations, as well as the non-detection of this abundant snowfall (≥ 15 cm).

It is important to recognize the specific needs of various meteorological forecast users. With respect to snow removal (road maintenance) and ski resort management, for example, the specification of the snow type (category), in addition to snow accumulation forecasts, would certainly be useful and appreciated. For the general public, this sort of detail is obviously not as relevant, but could still prove to be somewhat useful. By “specification”, we refer to the qualitative and/or quantitative description of snow density. To that end, we have many options:

- qualitatively describe snow accumulations according to one of 6 categories (very heavy, heavy, average, light, very light, ultra light),

- quantify the type of snow by specifying the snow/water ratio, density and/or water equivalent associated with the snow accumulation.

If needed, each specialized forecast product could be adapted to satisfy the needs and preferences of the client to whom it is directed to.

Beyond the diagnosis of an appropriate snow/water ratio, a judicious use of snow accumulation intervals within weather forecasts could also help in improving their accuracy. Intervals (*e.g.* “10 to 15 cm”, “20 to 30 cm”, etc.) are often used in public forecasts (or other products) to represent the uncertainty or variation in QPF over some sectors. They could also be used to cover the uncertainty or the range of possible values of the snow/water ratio. Some examples are shown in Table 53.

QPF	Forecast Ratio	Forecast Snow Accumulation	Snow Accumulation using 10:1 Rule
10 mm	10 or 15:1	10 to 15 cm	10 cm
8 mm	15 or 20:1	10 to 15 cm	From 5 to 10 cm
2 mm	20 or 25:1	Near 5 cm	2 cm

Table 53: *Examples of the use of snow accumulation intervals in public forecasts for different values of QPF and snow/water ratios.*

Using appropriate snow/water ratios and intervals can help to significantly improve the accuracy of snow accumulation forecasts, by comparison with the performance obtained with a systematic conversion of 10:1. The choice of intervals will usually be influenced by the level of confidence in the snow/water ratio forecast and/or the QPF. The latter will most certainly remain the most determining and challenging element of snow accumulation forecasting. If the use of a more representative snow/water ratio would contribute positively to the forecast process, it would not compensate for errors in precipitation amounts as forecast by numerical models.

One last aspect will be discussed before moving on to the next subject: the diagnosis of snow accumulations *a posteriori*. The snow/water ratio is not only useful in improving snow accumulation forecasts, but also in estimating accumulations in a given location, following a precipitation event, from a water equivalent measurement.

For example, let us consider a water equivalent measurement of 12.4 mm reported by an autostation after a low-pressure system moved through the area. A conversion made with a 10:1 ratio and suggesting a snow accumulation of exactly 12.4 cm is not very likely, regardless of weather conditions present during the event. At the very least, a little uncertainty should be demonstrated (*e.g*. from 10 to 15 cm). However, a serious diagnosis of the snow/water ratio, based on observed data and/or numerical model outputs, offers the possibility to evaluate more rigorously the most probable snow accumulation in that area. Thus, in this case, we could associate a diagnosis of heavy snow (R=7:1) to an accumulation of 8 to 10 cm, a diagnosis of light snow (R=15:1) to an accumulation of 15 to 20 cm, a diagnosis of very light snow (R=20:1) to an accumulation of 20 to 25 cm, etc.

Obviously, whenever possible, this type of diagnosis should be validated with snow/water ratio observations from surrounding stations, *i.e.* where meteorological parameters and physical processes determining snow density were similar enough to get the same diagnosis. Estimation of snow accumulations *a* *posteriori* by the suggested method could also turn out to be useful in preparation of significant weather or storm summaries (*e.g.* AWCN bulletins). In these situations, meteorologists should demonstrate some common-sense and mention the approximate nature of the accumulation and/or use intervals judiciously. Although this practice does not replace an official measurement, it unquestionably constitutes an excellent alternative to the systematic use of the 10:1 conversion factor. It is in fact deplorable that this latter method should be used for this purpose.

b) Blowing Snow:

Blowing snow is observed when the force exerted by the wind is greater than the resistance of snow particles. Therefore, blowing snow mainly depends on wind speed and cohesion of the snowpack, which is itself dependent on several parameters such as: density, age, temperature, ground type, orography, etc. It is logical to think that in the presence of strong winds (> 20kt), the lighter the snow (low-density), the greater the potential for blowing snow. In this case, it is clear that an accurate snow/water ratio forecast will greatly help to detect significant blowing snow events, whether blowing snow occurs during or after a snowfall.

Over most regions of Eastern Quebec, blowing snow occurs regularly in winter, causing the closure of a several main (20/132/138) and secondary roads. These closures are problematic in terms of public safety because they interfere with transportation and the delivery of essential services (ambulance, police, fire-fighting, etc.).

Table 54 shows wind (direction, average speed, and gusts), snow accumulation and mean snow/water ratio values observed during several major blowing snow events (*i.e.* causing multiple road closures) which occurred over three different regions of Eastern Quebec.

Region	Road #	Wind (kt)	Accumulation (cm)	Mean Ratio	Observed Weather
Bas-St-Laurent	132	W 20G30	10-15	15:1	BS
Bas-St-Laurent	132	NW 20G30	5-10	15:1	BS
Gaspésie	132	N 25G40	45	12:1	S/BS
Bas-St-Laurent	132	NE 25G40	10-20	12:1	S/BS
Bas-St-Laurent	132	NW 25G35	10-15	10:1	BS
Bas-St-Laurent	20	NE 25G35	20-30	11:1	S/BS
BSL/Gaspésie	20/132	NE 25G35	15-30	12:1	S/BS
Bas-St-Laurent	132/232	W 20G30	10-15	15:1	BS
Gaspésie/Côte-Nord	132/138	W 30G45	10-20	10:1	BS

Table 54: *Cases of widespread blowing snow causing road closures over Eastern Quebec. The mean snow/water ratios have been calculated from the measured precipitation occurring before (BS cases) or during (S/BS cases) blowing snow events.*
BS: blowing snow only, S/BS: simultaneous snow and blowing snow.

From these cases and other similar ones, the wind threshold required to observe widespread blowing snow (justifying the issue of a weather warning) increases with snow density. Table 55 constitutes an outline of the relationship between snow density (or snow category) and surface winds for significant blowing snow and simultaneous snow/blowing snow events.

Snow Category	Snow/water ratio	Wind threshold (kt) BS	Wind threshold (kt) S/BS
Very heavy	4:1	No blowing snow	No blowing snow
Heavy	7:1	30G40	25G35
Average	10:1	25G35	20G30
Light	15:1	20G30	15G25
Very light	20:1	15G25	n/a
Ultra light	25:1	10G20	n/a

Table 55: *Minimal values of surface winds required to generate widespread blowing snow according to the different snow categories established in this study.*
n/a: not applicable since very light or ultra light snow can only be observed with light winds.
BS: blowing snow only, S/BS: simultaneous snow and blowing snow.

For example, following an ultra light snowfall (R=25:1), the presence of winds gusting to 20 knots (about 40 km/h) is enough to cause near zero visibilities. Significant blowing snow will not occur simultaneously with very light or ultra light snowfalls, simply because these snow categories can only be observed with light winds (≤ 5 or 15kt). The more or less intense fragmentation that occurs when winds exceed 15 knots will diminish the snow/water ratio to a value of 10 or 15:1.

The last Table, considered for now as a preliminary guide, can certainly help to better target blowing snow events, *i.e.* to efficiently detect major occurrences and to limit false alarms. However, it does not take into consideration all the implicated parameters (*e.g.* temperature, ground type or orography, fresh snow amount, etc.). Pursuing this kind of work is part of future developments related to this study (see Section 9).

Strategically, it seems preferable to rely on cases of low-density snow (high snow/water ratios) to forecast widespread blowing snow. It is also recommended to soft-pedal on blowing snow warnings when heavy snow is expected, unless, of course, winds are strong enough and respect the proposed criteria (see Table 55).

The following two cases, which occurred at the end of the 2002 winter, illustrate quite well some of the preceding statements, as well as the importance of snow density in forecasting blowing snow. Figure 17 below summarizes the storm that affected Eastern Quebec on March 22nd and 23rd, 2002.

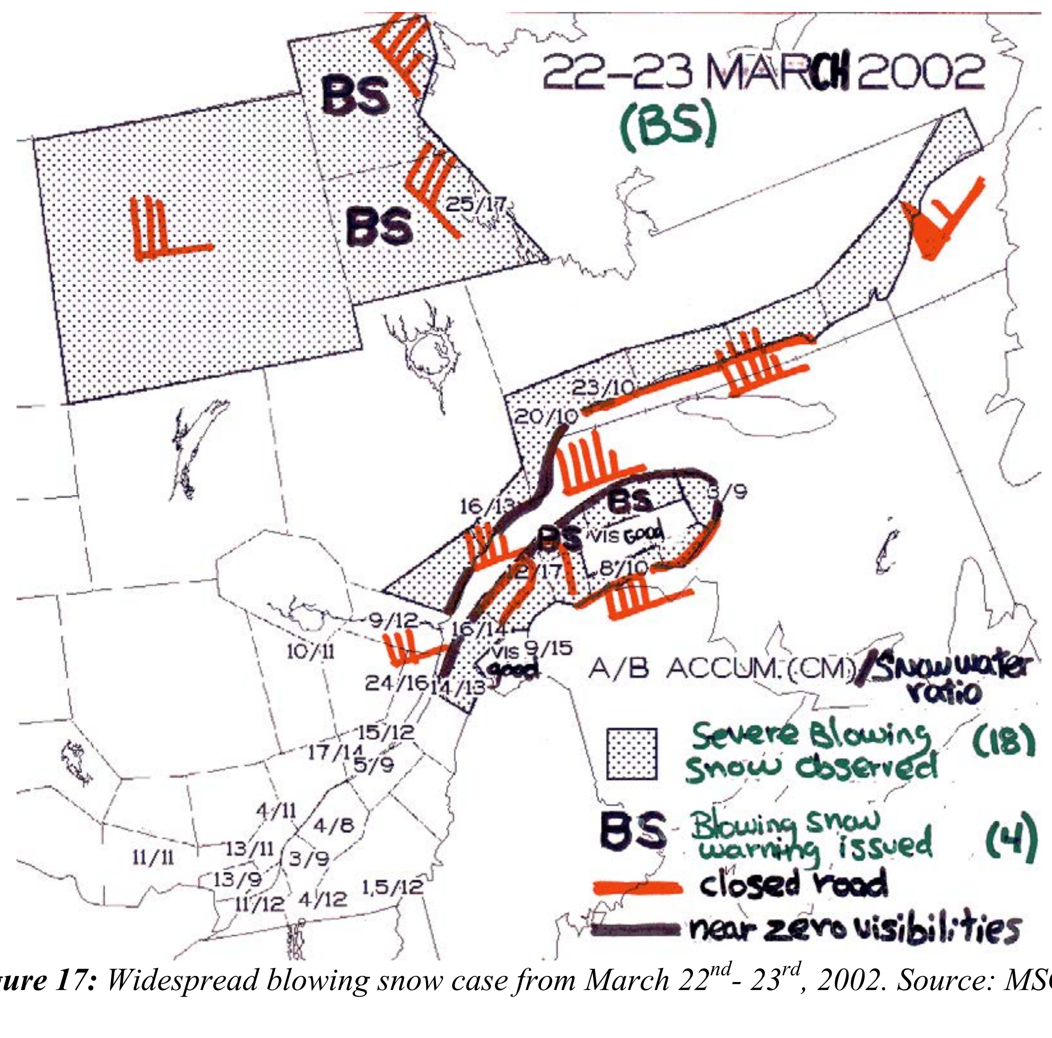


Figure 17: *Widespread blowing snow case from March 22nd- 23rd, 2002. Source: MSC.*

Subsequent to snowfalls varying from 8 to 25 cm, strong westerly winds (from 25 to 55 knots) developed, reducing visibilities to near zero in blowing snow and causing multiple road closures in several regions. The observed snow/water ratios varied between 9 and 17, depending on the region. In total, 18 public regions (shaded) experienced weather conditions sufficiently severe to warrant the issue of a blowing snow warning. However, the warning issued prior to the event only applied to 4 regions (identified: BS). Figure 17 shows that for the most affected regions, the previously established wind thresholds have been respected quite well. For example, in the Gaspésie and Basse-Côte-Nord regions, where snow/water ratios only reached 9 or 10:1, wind gusts up to 45 or 55 knots were sufficient to compensate for the relatively dense snow. In the Bas-St-Laurent and Fermont regions, winds at 20 knots gusting at 30 knots were strong enough to deteriorate road conditions considerably. Low-density snow (ratios of 13 to 17:1) observed in these sectors definitely played an important role in this case.

Let us now examine a second case that occurred only a few days later, on March 26th and 27th (Fig. 18).

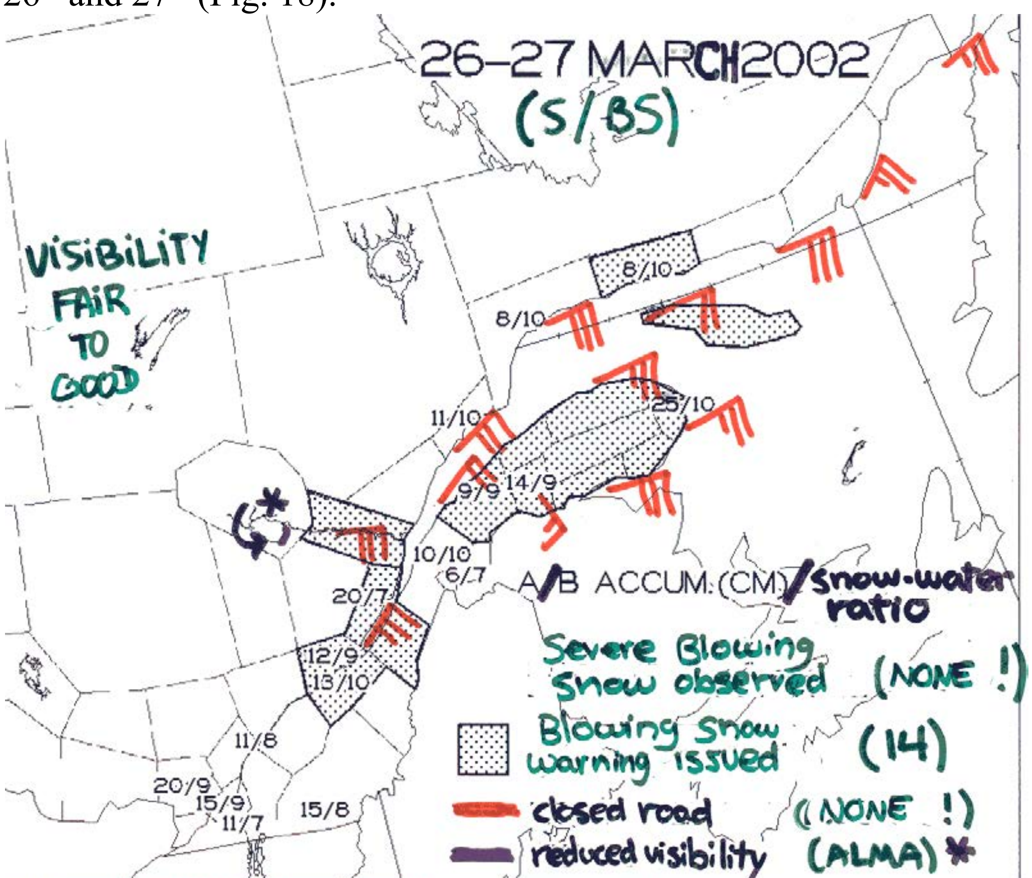


Figure 18: *Blowing snow false alarm cases from March 26th and 27th, 2002. Source: MSC.*

This case is quite different from the previous one. Snow mixed with some ice pellets and strong northeast winds were expected in Eastern and Central

Quebec ahead of a low-pressure system. Precipitation (from 8 to 25 cm) as well as winds up to 25 or 30 knots did in fact occur. However, none of the 14 blowing snow warnings issued before the event (shaded areas) did verify. Not a single road was closed. Poor visibilities were only reported briefly over one road section near Alma (Lac-St-Jean region). Relatively heavy snow (snow/water ratios measured between 7 and 10:1) was associated to the snow/ice pellets mixture. These observations are in accordance with the proposed relationships in Table 55. Therefore, use of the latter could have prevented several false alarms in this case.

Before moving on to the next application, let us mention that the impact of blowing snow is not limited to visibility restrictions and road closures. This phenomenon also causes snow drifts which require continuous plowing (or road clearance), even after precipitation has ended. The presence of blowing snow is generally accompanied by a great spatial variability of snow accumulations, according to wind exposure. For example, following a light snowfall of 20 cm, the development of strong winds causing blowing snow can bring accumulations of 40 to 50 cm in some areas while snow depth can be reduced to almost nothing over exposed sites. In mountainous regions, the wind transport of snow also influences the risk of avalanches. This field will be addressed in Section **8 d)**.

An accurate snow density forecast as well as the use of solid relationships between snow categories, wind, and blowing snow could potentially help: to improve the performance with the issuing of blowing snow warnings, to give more accurate weather forecasts to snow removal clients, and to better serve the people responsible for avalanche forecasting.

c) Hydrology:

As mentioned in Section **8 a)**, using an appropriate conversion factor will bring about an improvement of snow accumulation forecasts. However, it will not automatically be the case for forecasts of a hydrological nature (*e.g.* specialized forecasts issued by the MSC - Quebec to support flood or water level management). In these types of products, the water equivalent constitutes a very important parameter. With the operational tool currently used (SCRIBE), only one type of accumulation can be specified: snow, ice pellets, ice or water equivalent. Given a case of very heavy snow (*e.g.*, wet snow) with an associated snow/water ratio of 4:1, we currently cannot indicate that a snow accumulation of 10 cm is expected in a given area and that this snowfall corresponds to a 25 mm water equivalent. Under these circumstances, which occur regularly in the spring, we cannot completely fulfil our mandate, *i.e.* inform snow removal operators that they will have to clear the roads, and warn dam managers and public security officials that a significant amount of water is expected. To adequately accomplish this task, forecast production tools such as SCRIBE would have to be modified so that it becomes possible to differentiate snow and water accumulations. With these 2 distinct concepts as well as a new snow/water ratio field integrated to their work tool, forecasters would be able to provide better service to clients concerned with both solid and liquid precipitation amounts. Such a request is part of a series of recommendations recently submitted to CMC's SCRIBE team by a national committee.

d) Avalanches:

In North America, avalanche forecast services are generally provided by field specialists. In Canada, a specialized centre operates in Western Canada: the Canadian Avalanche Centre (CAC), located in Revelstoke, British Colombia. In Quebec, a new office, the "Centre d'avalanche de la Haute-Gaspésie", has recently been inaugurated (January 2003). Details relating to this type of forecast go beyond the scope of this study. We will therefore restrict ourselves to the following facts:

- Both the snow amount and its density constitute important or even essential parameters in the avalanche forecasting process;
- Wind transportation of snow, which, as described previously, is a phenomenon directly related to snow density, is also an important factor to consider when evaluating the potential for avalanches.

MSC's involvement in this field (collaboration with avalanche centres) could very well grow in the coming years. The ability to forecast snow density in the short-term will potentially allow meteorologists to offer this partner a broader ensemble of meteorological parameters useful to their operations. More detail on avalanche forecasting is available in some of the reference documentation listed in the bibliography as well as in many other publications.

e) Conclusions:

The use of an appropriate snow/water ratio will potentially bring many benefits to various standard and specialized weather forecast users. Whether by way of more precise snow or water accumulation forecasts, an adequate qualitative or quantitative description of snow density, more accurate blowing snow warnings, or a more complete support to avalanche forecast centres, snow/water ratio forecasting can only improve the quality of weather products and services provided by meteorologists with respect to precipitation or public safety. However, this points out the need to integrate this new meteorological parameter into the available fields and to adapt our work tools accordingly.

9. FUTURE DEVELOPMENTS

Many projects related to the present snow/water ratio study will continue to progress over the months/years to come. The following list briefly describes the activities in progress as well as potential future work:

- To complete the climatological study by extending its coverage to extreme northern regions of Quebec and, if possible, to other regions of Canada;
- To carry through the verification process initiated in Quebec, and eventually extend it to the rest of Canada and parts of North America;
- To futher collaborate with COMET staff in order to develop a possible "training module" covering the various aspects of snow density.
- To participate in the AIRS II (2004) project, by verifying the veracity of the proposed links between the identified meteorological parameters and physical processes, observed crystal types and measured snow densities. *[AIRS (Alliance Icing Research Study) is a research project on aircraft icing including many organzations (MSC, NRC, NCAR, NASA, FAA, Météo France, UKMet and several universities). Data collected while flying through various weather systems (i.e. temperature and humidity profiles, crystal types, presence of supercooled water, etc.), will greatly assist in achieving the task described above];*
- To adjust/improve the forecast algorithm in accordance with results obtained from the activities described above;
- To integrate a snow/water ratio field into numerical models;
- To adapt SCRIBE or other forecast production tools as well as bulletin formats in order to better serve specialized clients who need detailed precipitation forecasts (*e.g.* hydrologists, snow removal operators, etc.);
- To go deeper into the study of conditions favourable for blowing snow in accordance with various parameters, *e.g.* snow density;
- To develop new products to adequately support avalanche forecast centres.

Obviously, all of the above-mentioned activities will not be carried out by the author alone. The collaboration of other individuals or staff from various organizations (*e.g.*, COMET, CMC, SCRIBE development team, AIRS, etc.) has been or will be solicited.

10. CONCLUSION

Most of the objectives established at the beginning of this project have been accomplished. Knowledge of the various factors that determine snow density has been acquired through a climatological study of snow/water ratios in the Quebec region, other climatological studies that were already published, and through a detailed study of theoretical aspects.

Evaluation of existing snow/water ratio forecasting methods has led to the conclusion that they are incomplete and inadequate. A forecast algorithm that considers all the implicated parameters and processes has been developed. This algorithm is divided into 2 main sections: one for cases where the atmospheric temperature rises above the 0 °C threshold somewhere between cloud top and the surface, the other for cases where the temperature remains below the freezing point. In the first case, the diagnosis is mainly based on the precipitation type(s) occurring. In the second case, it is the type of snow crystals present that generally determines the appropriate snow/water ratio. The diagnosis must however be completed by evaluating the impact of various processes that can affect snow density: accretion, sublimation, aggregation, fragmentation and melting of crystals on the ground.

The algorithm generates 25 main diagnoses which correspond to a "mean" or "suggested" value for the snow/water ratio, associated with 6 snow categories: very heavy snow (R= 4:1), heavy snow (R= 7:1), ordinary snow (R= 10:1), light snow (R= 15:1), very light snow (R= 20:1), and ultra light snow (R= 25:1). A 26th main diagnosis is added to cover cases of snow completely melting in the atmosphere, therefore not generating any snow accumulation (R=0).

The level of performance achieved by the algorithm in diagnostic mode after verification of 281 cases, about 83%, is very encouraging. Although a slightly weaker performance is expected in forecasting mode (approximately 80%), this represents a substantial improvement compared to the currently used methods. The algorithm, as suggested, seems efficient enough to consider using it operationally.

The operational application of the algorithm could potentially bring many benefits to various forecast users. Be it through more accurate snow or water accumulation forecasts, an adequate qualitative or quantitative description of snow density, an improved performance with blowing snow warnings or a better support to avalanche forecast centres, the use of an appropriate snow/water ratio can only enhance the quality of products and services offered by meteorologists to users concerned with public safety and/or needing detailed precipitation data. The integration of a snow/water ratio field in numerical models as well as an adaptation of forecasting tools will be essential to insure an efficient use of these concepts in an operational setting.

Improvement of the algorithm as well as the elaboration of many applications related to snow density will continue through future activities, many of them in collaboration with various partners.

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«Forme des cristaux de neige et origine des avalanches»:
www.di.ens.fr/~granboul/enseignement/formes/cristauxneige/

Research Site NCEP (NOAA):
www.hpc.ncep.noaa.gov/research/snow2a

«All about snow»:
nsidc.org/snow/faq.html et facts.html

«Snow crystals»:
www.its.caltech.edu/~atomic/snowcrystals.net

«Wintertime cloud microphysics review»:
www.crh.noaa.gov/arx/micrope.html

«The importance of snow microphysics for large snowfalls»:
www.erh.noaa.gov/er/hq/ssd/snowmicro/index.html

Site du Centre d'avalanche de la Haute-Gaspésie : www.centreavalanche.qc.ca

APPENDICES

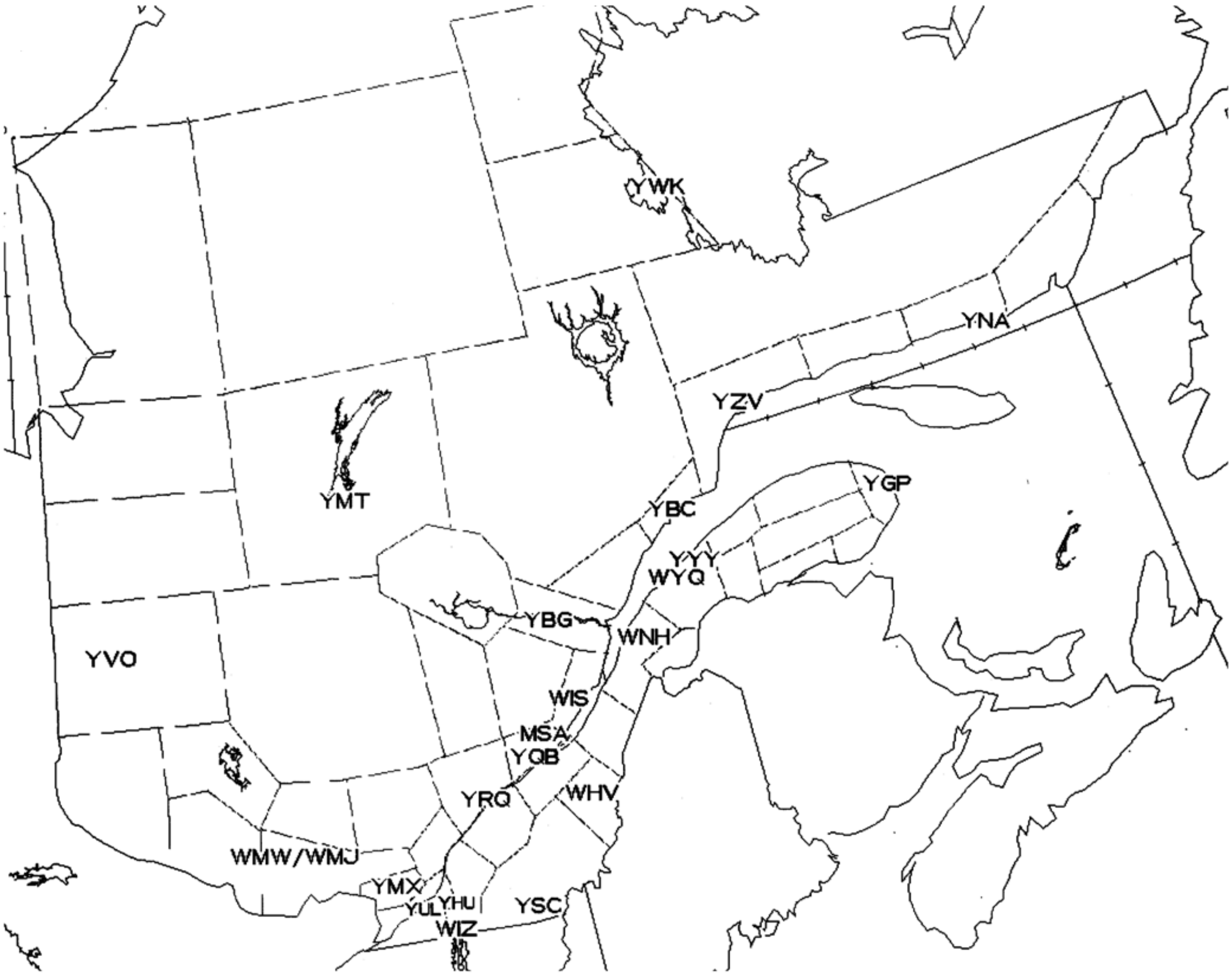
APPENDIX I: ACRONYMS AND ABBREVIATIONS

AIRS	Alliance Icing Research Study
BSL	Bas-St-Laurent
BS	blowing snow
C	degrees Celsius
CAC	Canadian Avalanche Centre
cm	centimetre
CMC	Canadian Meteorological Centre
dam	decameter
DZ	drizzle
E	east
e.g.	for example
NE	negative energy
PE	positive energy
et al	and others
EWSO	Environmental and Weather Services Office
FAA	U.S. Federal Aviation Administration
F	degrees Fahrenheit
FL	freezing level
fig.	figure
frag.	fragmented
FZDZ	freezing drizzle
FZRA	freezing rain
GEM	Global environmental multiscale (Canadian operational model)
IC	ice crystals
i.e.	that is
IP	ice pellets
kt	knot(s)
MAX	graphical display system used at MSC
mb	millibar
METAR	encoding format of meteorological observations
mm	millimetre
MRC	County Regional Municipality
MSC	Meteorological Services of Canada
MSL	mean sea level
n/a	not applicable
NASA	U.S. National Aviation and Space Administration
NCAR	U.S. National Centre for Atmospheric Research
NE	North-East
NRC	National Research Council

PIREP	aircraft pilot report
PL	ice pellets
QPF	quantitative precipitation forecast
R	rain or Snow/water ratio
RA	rain
RAPL	mixture of rain and ice pellets
RASN	mixture of rain and snow
RH	relative humidity
S	snow
SA	encoding format of meteorological observations
S/BS	simultaneous snow and blowing snow
SCRIBE	graphical forecast production tool
SE	South-East
sfc	surface
SLD	supercooled large droplets
s.n.	stellar nucleus
SN	snow
SNPL	mixture of snow and ice pellets
SNRA	mixture of snow and rain
SNRAPL	mixture of snow, rain, and ice pellets
SP	snow pellets
T	temperature
Tair	air temperature
Tatm	atmospheric temperature
Td	dewpoint
Tgr/Tground	ground temperature
Tsfc	surface air temperature
UKMet	Meteorological services of the United Kingdom
V	wind
Vmax	maximum low-level wind
ω	vertical motion
ωmax	maximum vertical motion
ZL	freezing drizzle
ZR	freezing rain

APPENDIX II: DETAILS ON OBSERVATION SITES

STATION	NAME	LATITUDE (N)	LONGITUDE (W)	ELEVATION (m)
MSA-b	Mont-Ste-Anne (base)	~ 47’04	~ 70’55	~ 800
MSA-s	Mont-Ste-Anne (summit)	~ 47’04	~ 70’55	~ 175
WHV	Beauceville	46'12	70'47	229
WIS	Charlevoix	47'17	70'38	719
WIZ	L’Acadie	48’20	73’21	44
WMJ/WMW	Maniwaki	46'17	76'00	201
WNH	Rivière-du-Loup	47'48	69'33	146
WYQ	Pointe-au-Père	48'31	68'28	5
YBC	Baie-Comeau	49'08	68'12	22
YBG	Bagotville	48’20	71’00	159
YGP	Gaspé	48'47	64'29	33
YHU	St-Hubert	45'31	73'25	25
YQB	Québec	46'48	71'24	74
YMT	Chibougamau	49'46	74'32	387
YMX	Mirabel	45'41	74'02	82
YNA	Natashquan	50'11	61'49	11
YRQ	Trois-Rivières	46'21	72'41	60
YSC	Sherbrooke	45'26	71'41	241
YUL	Dorval	45'28	73'45	36
YVO	Val D'Or	48'03	77'47	337
YWK	Wabush Lake (Fermont)	52'56	66'52	551
YYY	Mont-Joli	48'37	68'13	52
YZV	Sept-Iles	50'13	66'15	53


YWK
YNA
YZV
YMT
YBC
YGP
YYY
WYQ
YBG
WNH
YVO
WIS
MSA
YQB
YRQ
WHV
WMW/WMJ
YMX
YUL
YHU
YSC
WIZ

APPENDIX III: SNOW/WATER RATIO FORECAST ALGORITHM

The principal steps of the snow/water ratio forecast algorithm are summarized in Figure 14 (Section 6). A little more detailed version is presented in the following pages. The entire algorithm is divided into 7 diagrams (identified from **A** to **G**). The very first step of Diagram **A** consists in determining if the atmospheric temperature rises above or remains below the freezing point. In the first case, the snow/water ratio diagnosis carries through on Diagram **A**, according to the precipitation type(s) present and the ground temperature. The Table at the bottom of this page (borrowed from Section 6 – Table 28), serves as a reminder of the different possible diagnoses in this type of cases (#18-26). If the atmospheric temperature remains below zero, the diagnosis continues on Diagram **B**, where the ground temperature (Tgr) is evaluated. If the ground temperature is above zero (ground not frozen or not covered by a significant layer of snow), the snow/water ratio is determined according to the value of Tgr. If the ground is frozen or covered by at least 2.5cm of snow, the next step is to determine the most probable crystal type (using the Table following Diagram **B)**. Diagrams **C**, **D**, **E**, **F**, or **G** will be used to complete the diagnosis according to the identified crystal type (mixed crystals, needles, spatial dendrites, mixed crystals with stellar nucleus, and stars, respectively). Each of these 5 diagrams tests the impact of one or more physical processes on density (depending on the crystal type), and specifies favourable conditions for their occurence and/or different thresholds to determine their intensity. The various results correspond to diagnoses #1-17, as listed in Table 26 of Section 6. Ideally, for a given site, we should diagnose the snow/water ratio for all periods of 3 hours when precipitation is forecast (QPF>0), since it corresponds to the time step of the operational model.

Diagnosis #	Precipitation type(s)
18	Ice pellets
19	Snow mixed with a little rain
20	Snow mixed with freezing rain
21	Snow mixed with rain and ice pellets
22	Snow mixed with ice pellets
23	Wet snow
24	Wet snow pellets
25	Snow pellets
26	Rain, freezing rain, rain mixed with a little snow or ice pellets

FORECAST ALGORITHM (A)

From the temperature profile (from cloud top to the surface), determine if:

Tatm > 0°C	Tatm < 0°C
(atmospheric temperature rises above the freezing point)	(atmospheric temperature remains below the freezing point)
↓	↓ See Sections: B, C, D, E, F, G.

Determine the type(s) of precipitation present:
(diagnosis #)

18	19	20	21	22	23	24	25	26
PL	SNRA	SN FZRA	SNRAPL	SNPL	SN(Tsfc>0)	SP(Tsfc>0)	SP(Tsfc<0)	RA, FZRA, RASN, RAPL

↓ (26) R= 0

↓

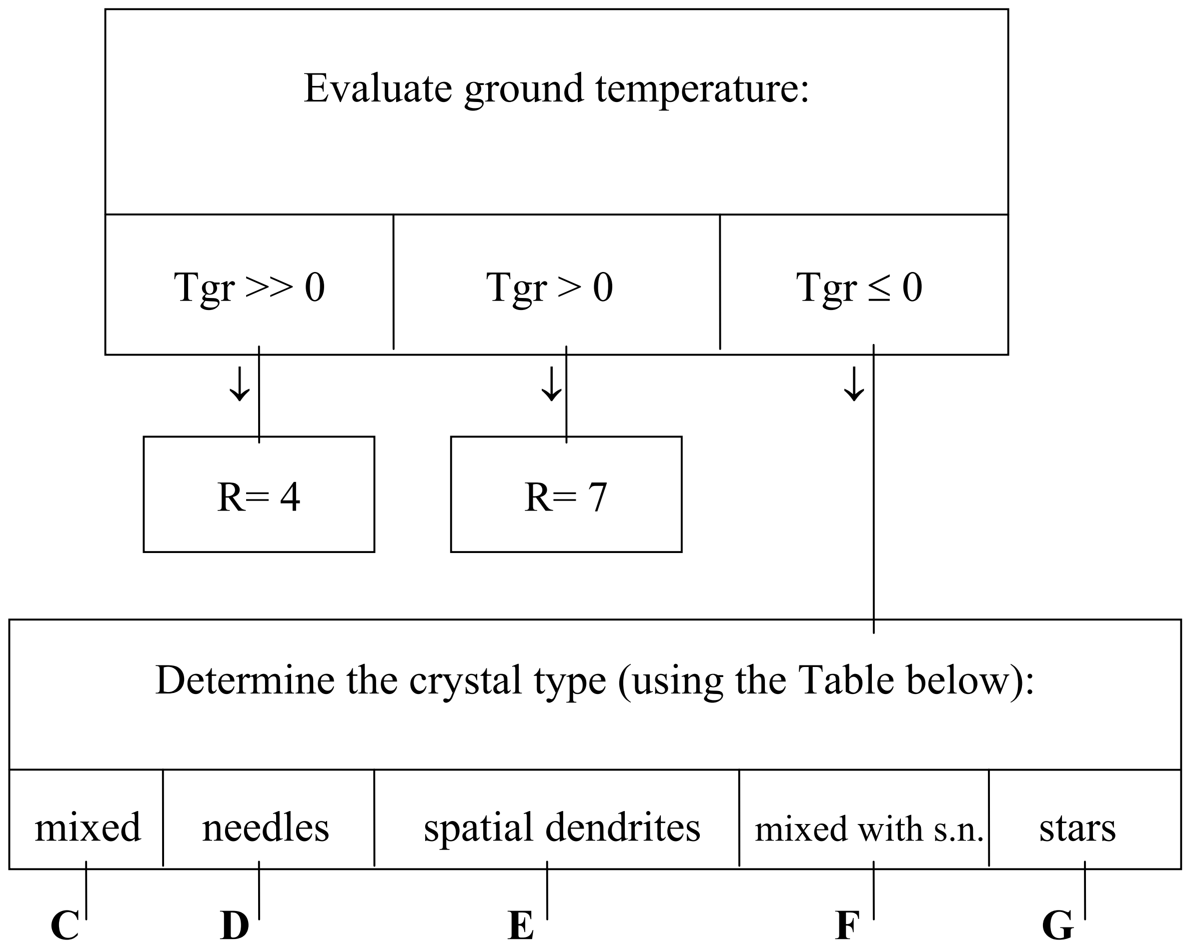
Evaluate ground temperature

Tgr: >> 0 (or ≥ 5C), > 0 (or from 0 to 5C), ≤ 0 (or snow/ice covered)

↓

#18	#19	#20	#21	#22	#23	#24	#25	Tgr
0	0	0	0	4	0	0	4	**>> 0**
4	0	0	0	7	4	0	7	**> 0**
4	4	4	4	7	7	4	7	**≤ 0**

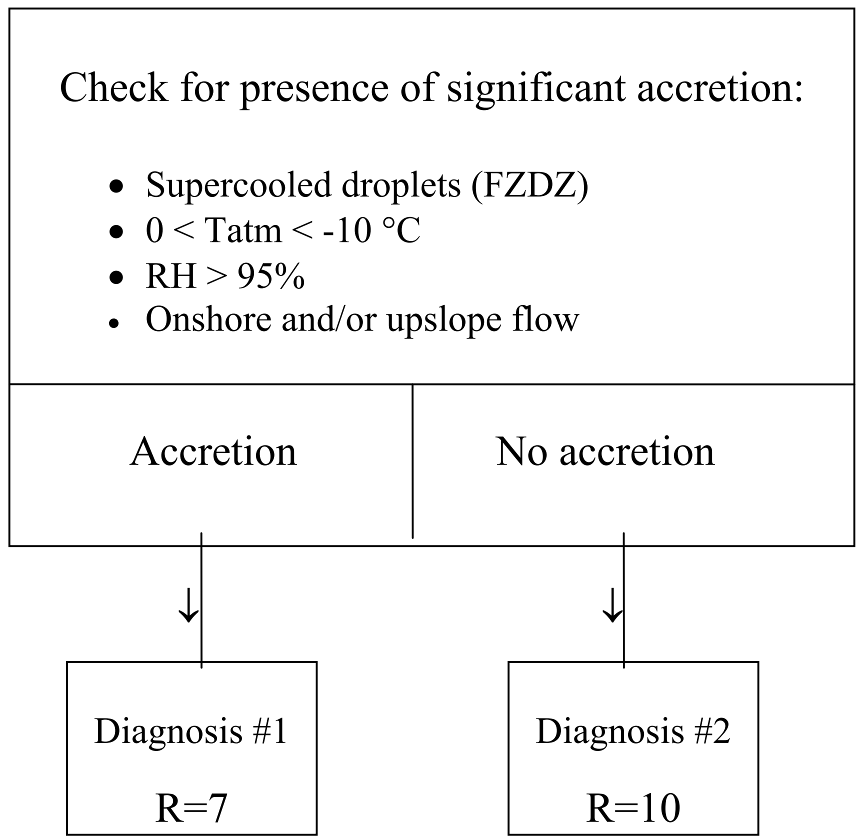
FORECAST ALGORITHM (B) ***(cases where Tatm < 0)***



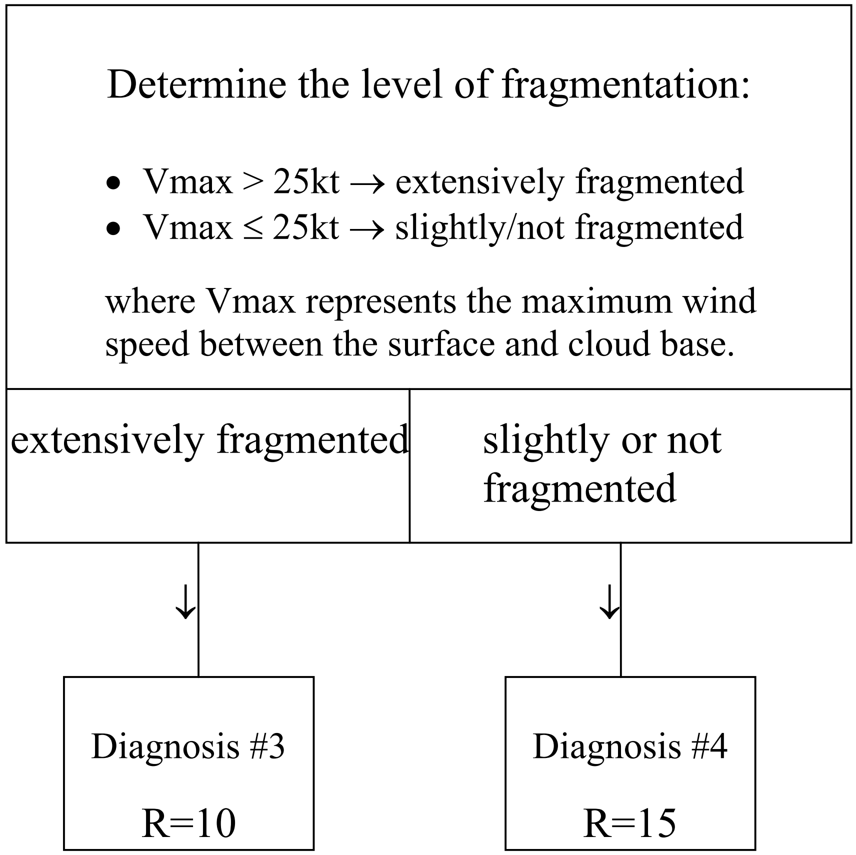
Primary T → **SecondaryT↓**	**0 to -3°C**	**-3 to -5°C**	**-5 to -12°C**	**-12 to -18°C**	**< -18°C**
0 to -3°C	Mixed	Mixed	Mixed	---	---
-3 to -5°C	Mixed	Aggregated Needles	Mixed	---	---
-5 to -12°C	Mixed	Mixed	Mixed	Mixed with stellar nucleus	---
-12 to -18°C	---	---	Spatial dendrites	Stars	Spatial dendrites
< -18°C	---	---	---	Mixed with stellar nucleus	Mixed

The primary temperature corresponds to the main crystal growth level, that is, at the intersection of ω_{max} *and RH > 80%. The secondary temperature corresponds to a level below the main level where* $\omega < 0$*, T < 0C and RH > 80%.*

FORECAST ALGORITHM (C) ***(mixed crystals)***



FORECAST ALGORITHM (D) ***(aggregated needles)***



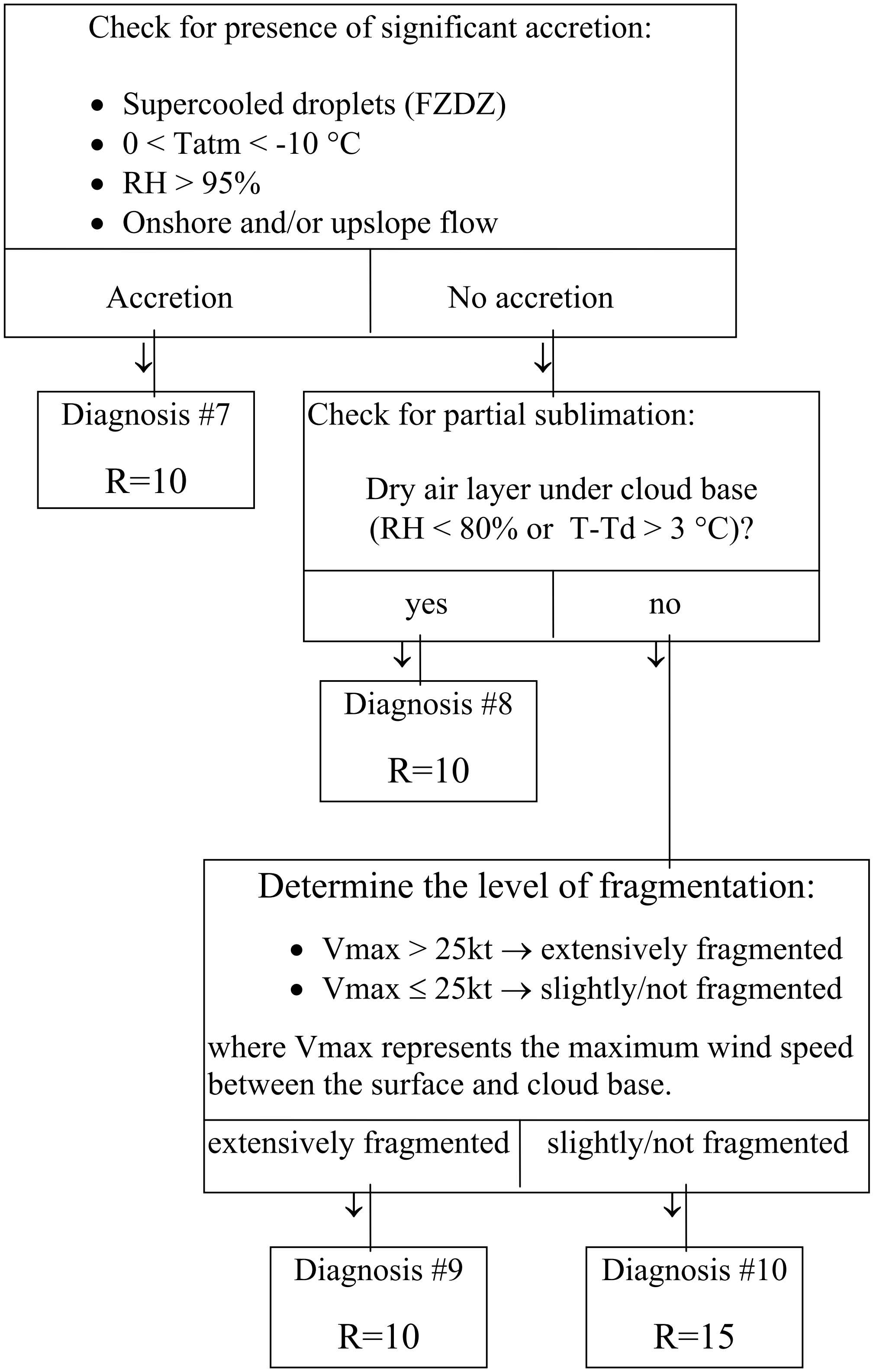
FORECAST ALGORITHM (E) *(spatial dendrites)*

Check the presence of significant accretion:

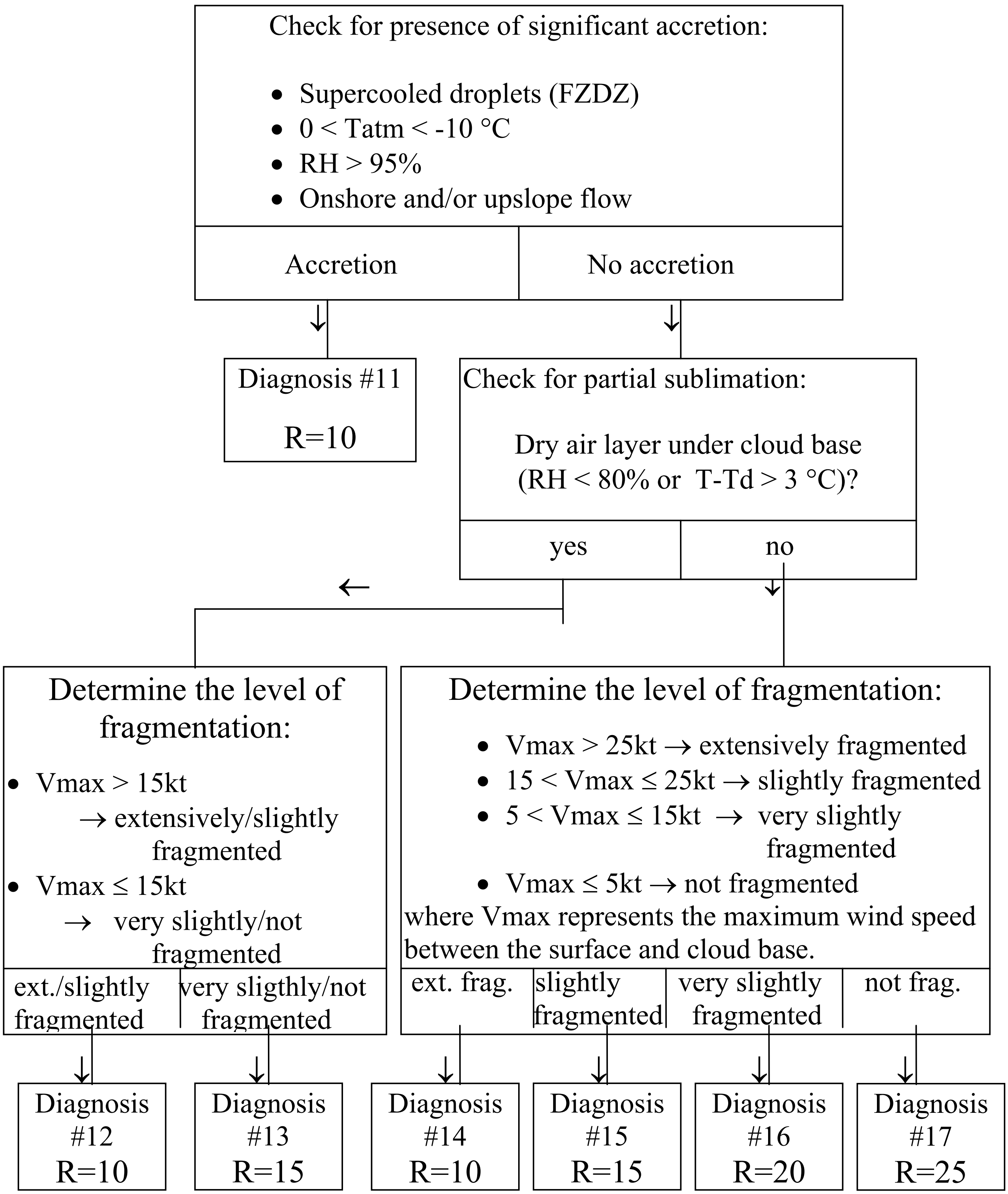
- Supercooled droplets (FZDZ)
- 0 < Tatm < -10 °C
- RH > 95%
- Onshore and/or upslope flow

Accretion	No accretion
↓	↓
Diagnosis #5 R=7	Diagnosis #6 R=10

FORECAST ALGORITHM (F) *(mixed crystals with stellar nucleus)*



FORECAST ALGORITHM (G) *(stars)*



APPENDIX IV: EXAMPLES AND CASE STUDIES

Some interesting cases compiled over two winter seasons (2000-2001 and 2001-2002) are presented in the following pages. The first 4 cases demonstrate the use of tephigrams and hodographs. Unfortunately, the vertical motion field was not available for these cases. The last 2 cases cover the use of cross-sections to visualize in two dimensions several meteorological fields needed for the diagnoses; they demontratre very well the importance of vertical motion in determining the appropriate crystal type and snow/water ratio.

These cases were selected according to the following criteria:

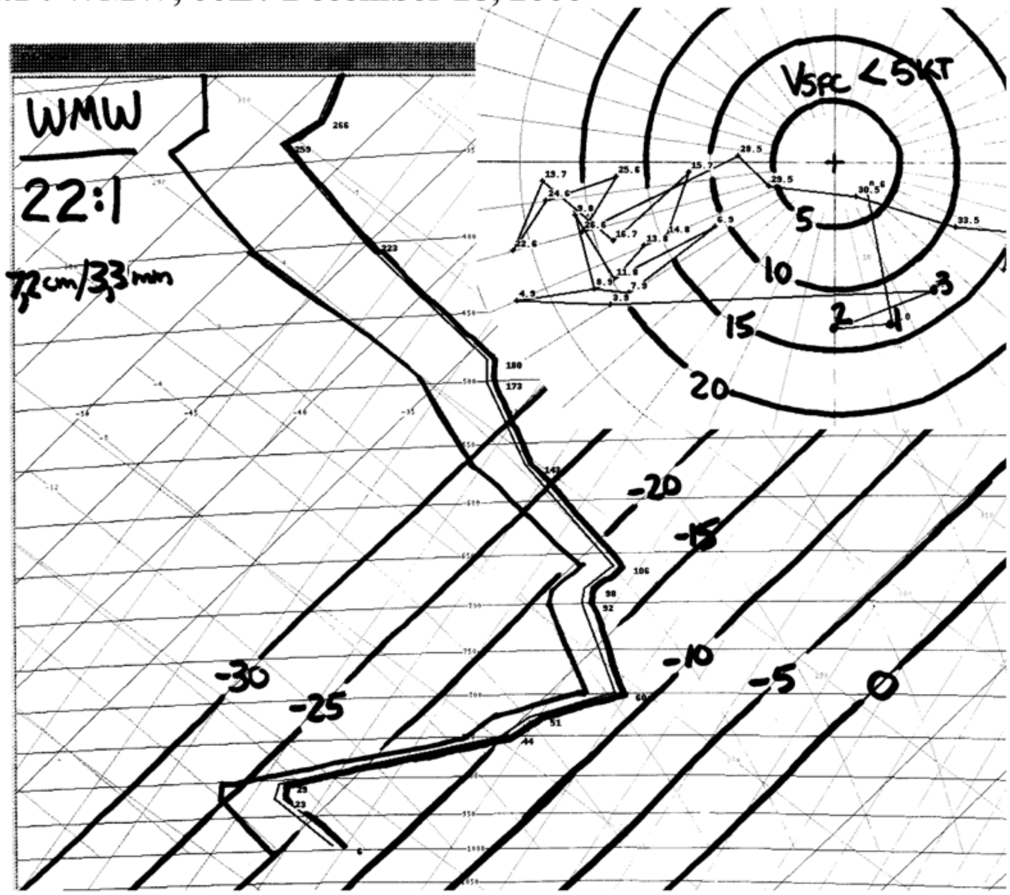
- significant snowfalls (> 5 cm);
- events centered around time of radiosonde observations (00 or 12Z for the tephigram cases);
- meteorological conditions during the events leading to only one algorithm diagnosis (*e.g.* no data collected over 6 hours when the first 3 hours would be associated with a certain diagnosis and the last 3 hours with a different diagnosis).

As for the verification process, we do not want to compare an observed ratio with the average of 2 different ratios corresponding to 2 distinct diagnoses resulting from the algorithm.

The case studies show how to extract the required data for the application of the forecast algorithm. Different diagnoses are made, using the diagrams from Appendix III, and compared to the observed values.

1. Use of tephigrams / hodographs:

Case #1.1 : WMW, 00Z / December 28, 2000



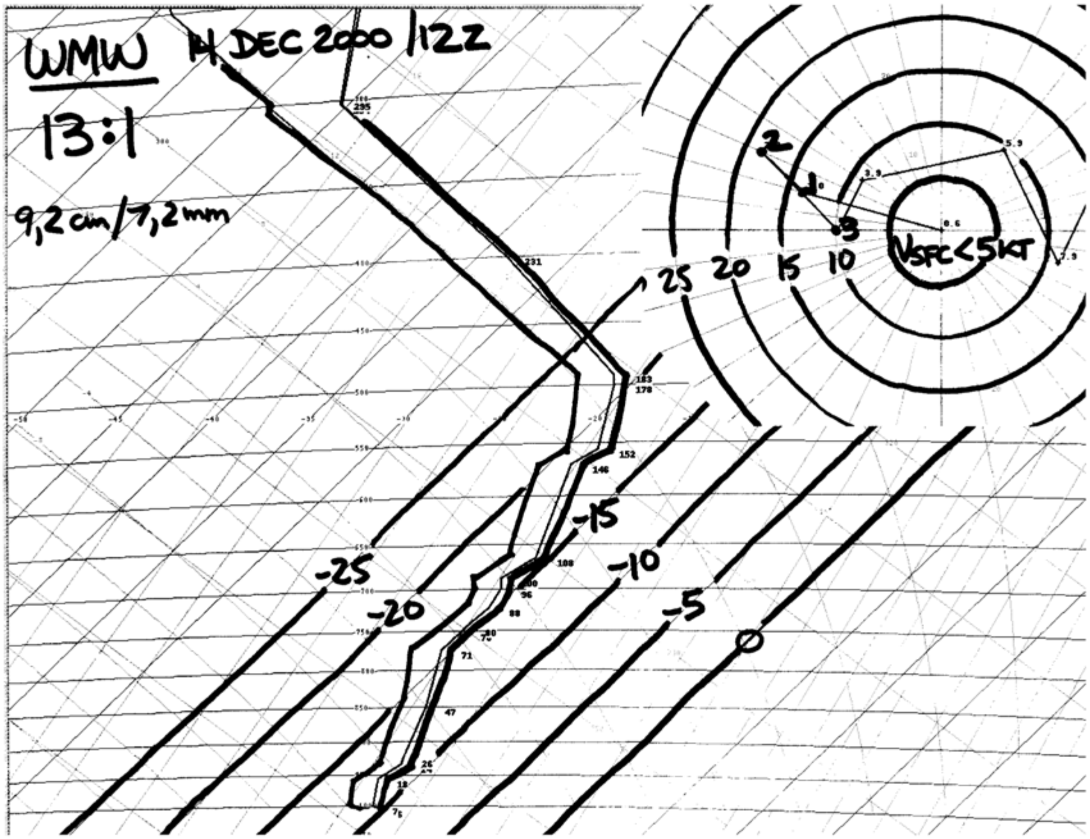
Despite the absence of information about vertical motion, we can reasonably say that the above tephigram shows a thermal profile favourable to the growth of stellar crystals (**stars**). The air temperature remains under the freezing point, generally in the range of –12 to –18 °C inside the cloud (base ~2500 ft and top ~10,000 ft). Applying the algorithm (diagram G) leads to the following diagnosis:

- Tground < 0 °C (end of December);
- No significant accretion (too cold);
- No significant sublimation (T-Td ~ 3 °C under cloud base)
- Very slight fragmentation (5 < Vmax ≤ 15 kt, according to hodograph)

⇒ **Diagnosis #16 : R=20**

This corresponds quite well to the observed ratio: **7.2 cm / 3.3 mm → R=22**

Case #1.2 : WMW, 12Z / December 14, 2000



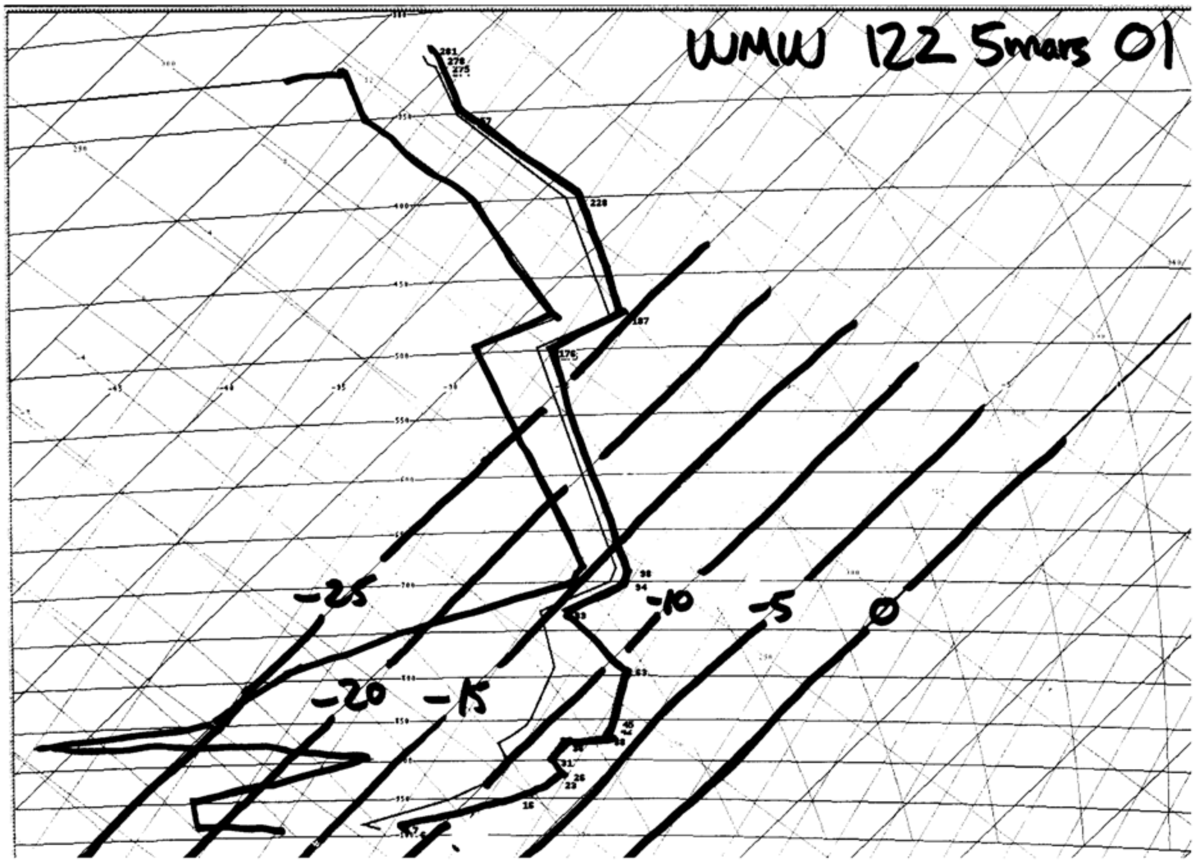
This is a similar case, *i.e.* the temperature profile is again favourable to the formation of stars (–12 to –18 °C). Using the appropriate section of the algorithm (diagram G) leads to the following diagnosis:

- Tground < 0 °C (mid-December)
- No significant accretion (too cold)
- No significant sublimation (T-Td < 3 °C)
- Slight fragmentation (15 < Vmax ≤ 25 kt, according to hodograph)

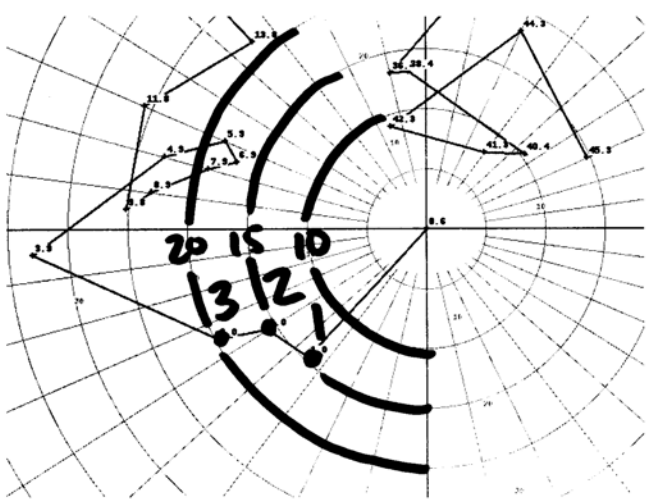
⇒ **Diagnostic #15 : R=15**

Which comes close to the observed value: **9,2 cm / 7.2 mm → R=13**

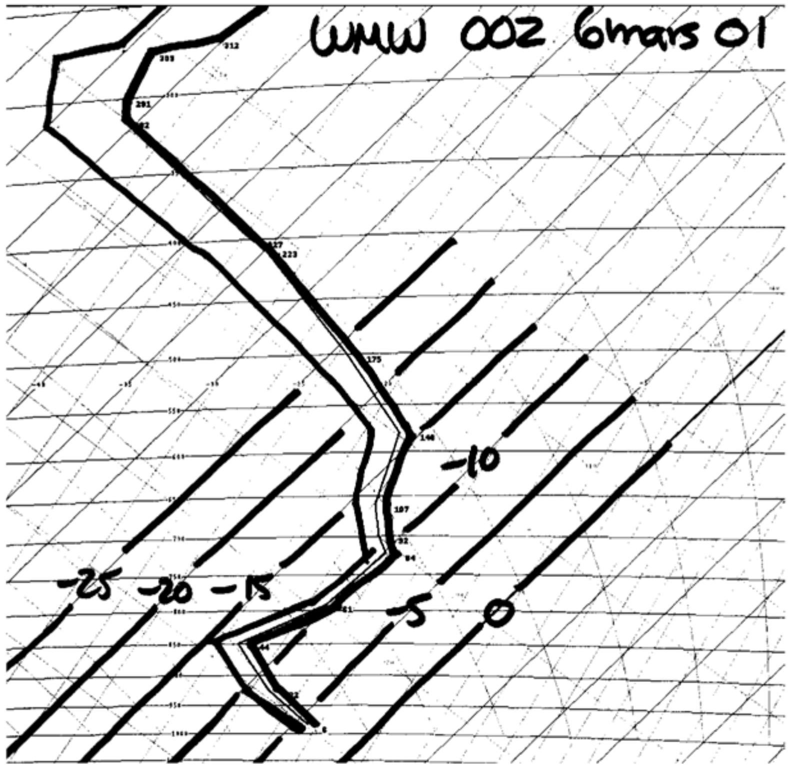
Case #1.3 : WMW, March 5, 2001



The radiosonde data from March 5th at 12Z (above), which was collected prior to the snowfall of interest, indicates the presence of very dry air in the lower levels. The hodograph below (March 6th at 00Z), representative of the conditions on March 5th, shows warm air advection over Maniwaki (northeasterly surface wind gradually veering to southerly aloft).



Following is the tephigram for March 6th at 00Z (12 hours later):



It shows a significant moistening of the air mass in the lower levels. Since northeasterly surface winds generally tend to drain dry air over this area, it can be inferred that air saturation was produced by evaporation or sublimation of precipitation falling from mid-level clouds. This situation is really not favourable to the accretion process. Also, the T and Td profiles indicate supersaturation with respect to ice but not necessarily with respect to water, hence the dominant occurrence of snow (little or no supercooled water). The 00Z thermal profile indicates temperatures of –12 to -18 ^{o}C at mid-levels (10,000 to 16,000 ft) and somewhat higher temperatures (-9 to –12 ^{o}C) in the lower atmosphere. Using the crystal type diagnostic table, **mixed crystals with stellar nucleus** are determined the most probable. Given frozen ground (which is still snow-covered at the beginning of March), we proceed with the snow/water ratio diagnosis using diagram F:

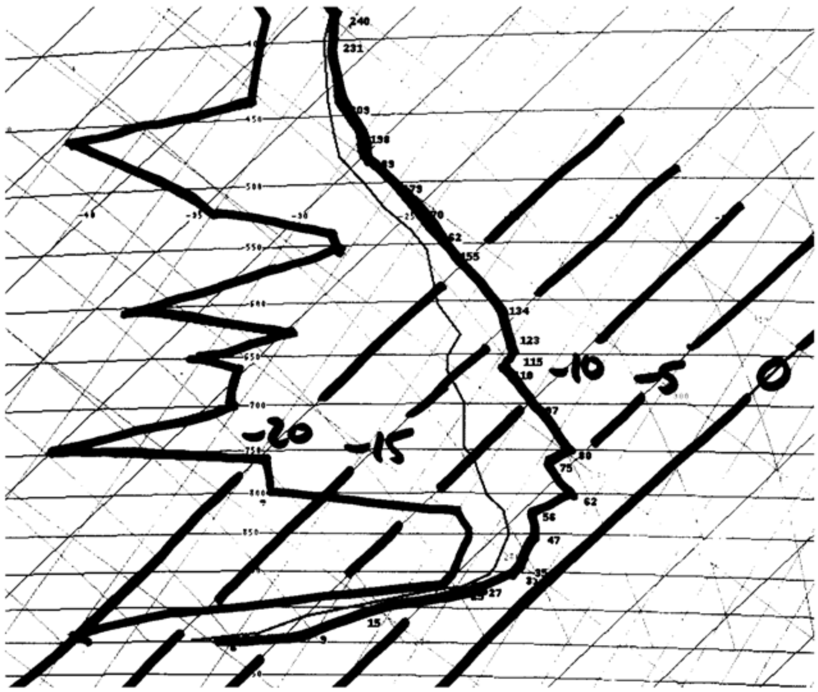
- No significant accretion (too cold)
- No significant sublimation (T-Td < 3 ^{o}C)
- Slight fragmentation (Vmax ≤ 25 kt, according to hodograph)

⇒ **Diagnosis #10 : R=15**

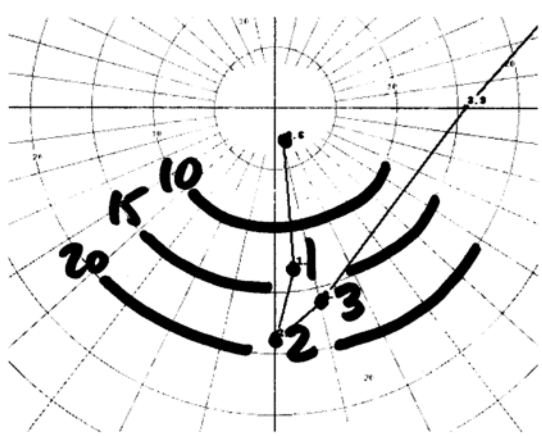
This matches quite well the observed ratio: **10 cm / 6.8 mm → R=14.7**

Case #1.4 : WMW, February 10, 2002

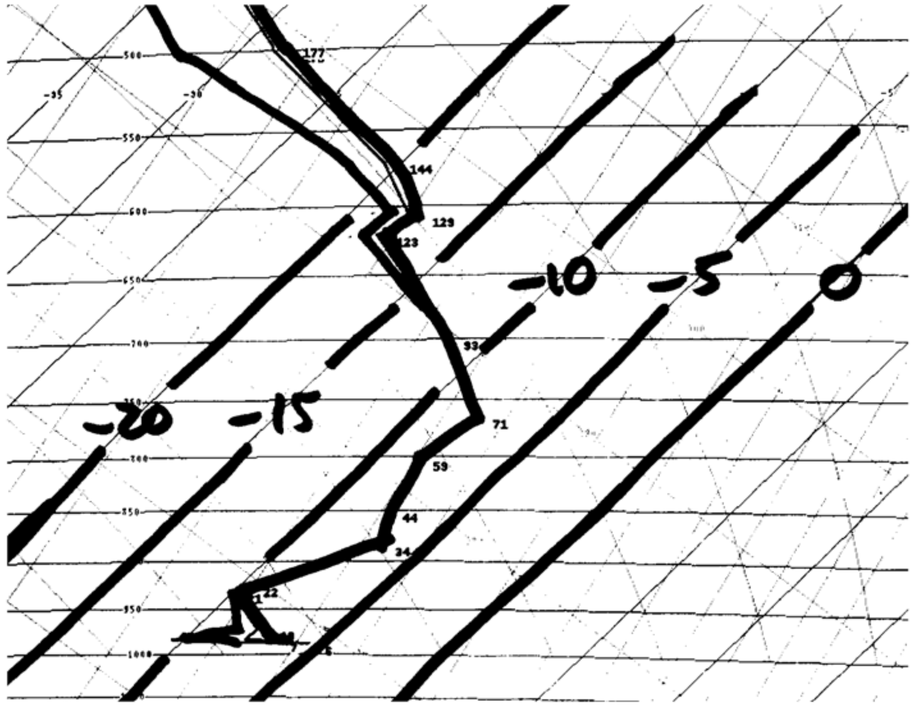
This case is similar to the previous one: same site, corresponding hours of the day, time of year and QPF. Also, the same type of crystals is present. First, let us look at the radiosonde data for February 10th at 12Z i.e., close to 12 hours before the event:



The observed humidity profile suggests the presence of low-level and high-level clouds. Marginally favourable to snow, this looks more like a freezing drizzle pattern: saturated layer between –3 and –7 °C and moderate northerly winds in the low levels (see following hodograph) producing a light orographic lift in the area.



The following tephigram shows the conditions on February 11th at 00Z:



Note that, as opposed to case #13, the air is entirely saturated with respect to water in a significant layer (2000 to 9000 ft), where temperatures vary approximately between –7 to –10 °C. Contrary to the preceeding case, saturation of the air mass is not the sole product of evaporation/sublimation of precipitation but rather, of humidity advection. This meets the significant accretion criteria previously established. This option will therefore be selected in the snow/water ratio diagnosis. Again, the thermal profile seems to favour the growth of **mixed crystals with stellar nucleus** (-12 to –18°C in the upper part of the clouds, followed by milder temperatures –7 to -12 °C underneath). Diagram F will therefore be used:

- Significant accretion

⇒ **Diagnostic #7 : R=10**

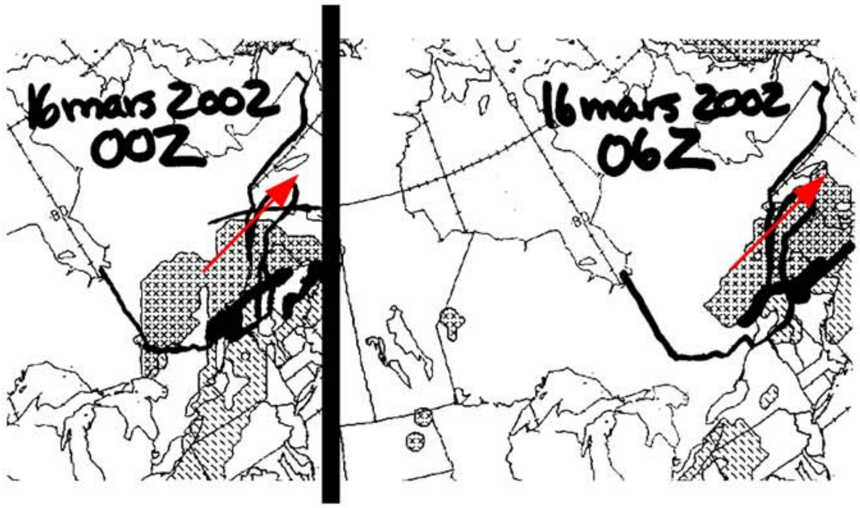
This agrees with reality: **8 cm / 8.6 mm → R=9.3**

Note: Freezing drizzle was in fact observed. Moderate clear icing was reported (PIREP) in the Maniwaki area during the event.

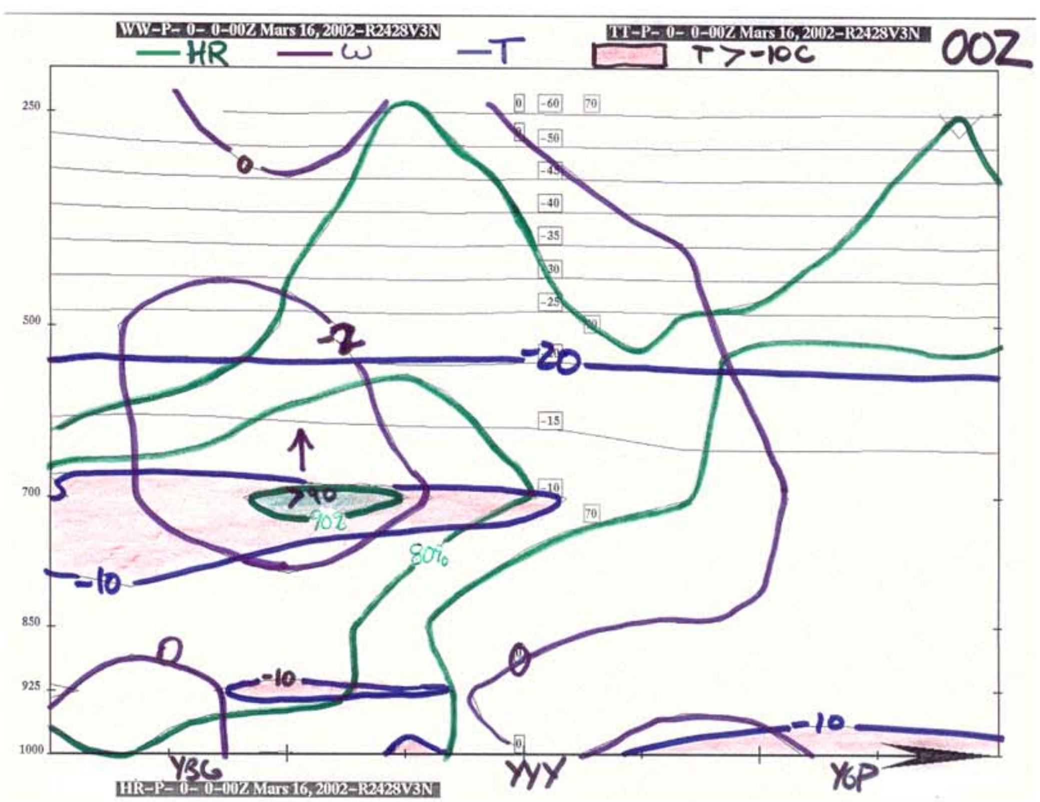
2. Use of cross-sections (MAX):

Case #2.1 : March 16, 2002

Let us examine a low-pressure system that affected the central and eastern parts of Quebec on March 16, 2002. The following figures show the precipitation patterns, as forecast by the regional GEM model shortly before the event.



The following East-West vertical cross-sections cover the snow area, from the Saguenay region (YBG) through the Lower St. Lawrence region and the Gaspe Peninsula (YGP), as identified by the arrows on the above figures.



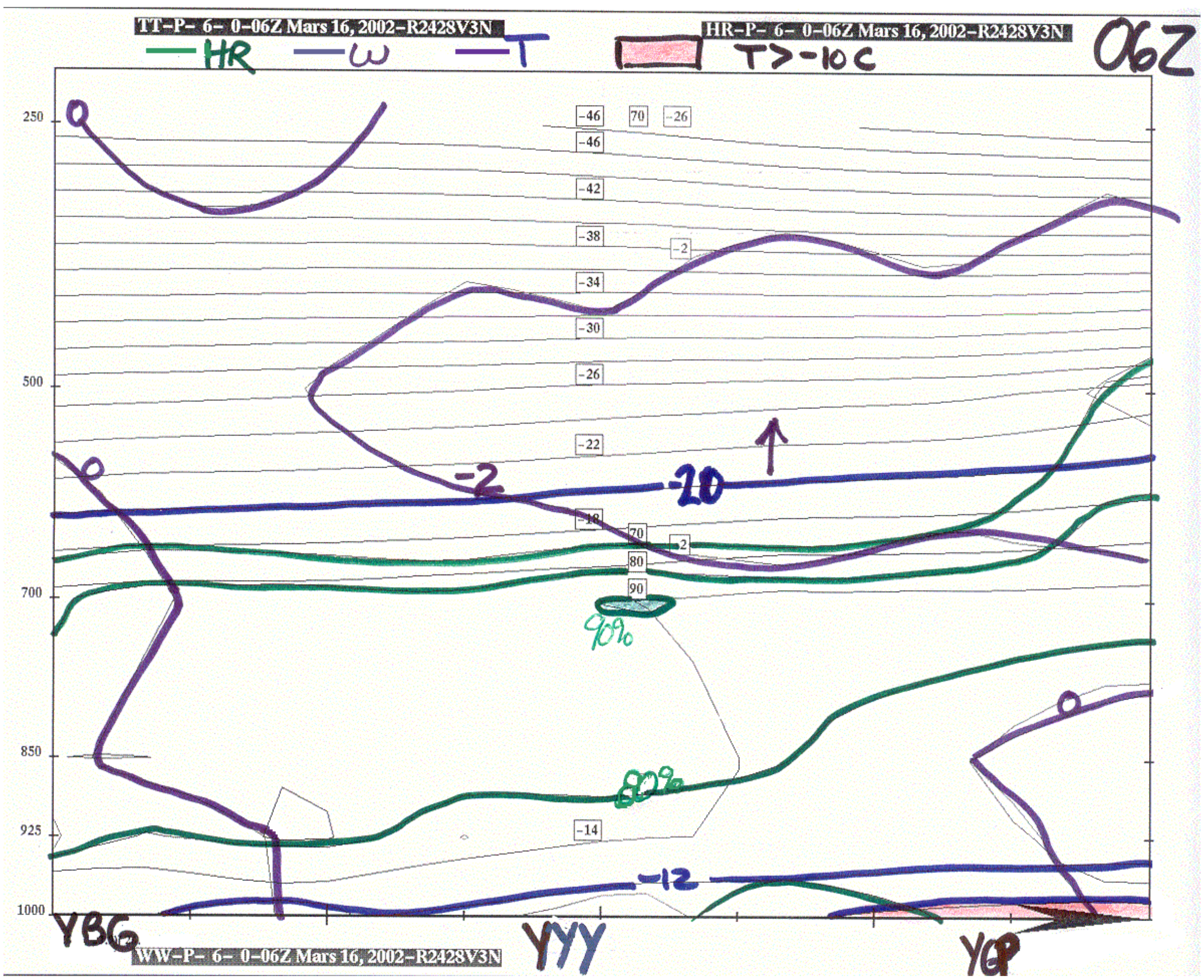
The first cross-section, at the bottom of the previous page, valid for March 16th at 00Z, shows the temperature, relative humidity and vertical motion profiles. At the time, snow was observed at YBG but not at YYY or YGP. In the left portion (West), milder air (>10 °C) is present between 800 and 700 mb. The intersection of upward vertical motion and the maximum relative humidity implies a main crystal growth temperature near -10 °C (-8 to -13 °C) over YBG. The temperature remains very close to –10 °C between the main growth level (700 mb) and the surface. The most likely crystal type over the Saguenay area should therefore be of the **mixed** kind, *i.e.* combination of plates and columns, possibly mixed with a few stellar crystals.

Using diagram C, from Appendix III, the diagnosis for YBG is:

- No significant accretion (although a little is possible),

⇒ **Diagnosis #2: R=10**

As the precipitation area moved eastward, snow eventually reached YYY and YGP. This shows up on the second cross-section (below), valid at 06Z:



The 06Z cross-section shows (as does the 03Z one, not shown here) that milder air (>10^{o}C) aloft has retreated South. The intersection relative humidity exceeding 80% and the upward vertical motion implies primary and secondary growth temperatures ranging from –12 to –18 ^{o}C, hence, the generation of **stars**. The snow/water ratio diagnosis for YYY can be produced using diagram G:

- No accretion (too cold)
- No significant sublimation
- Very slight fragmentation (Vmax~15 kt according to model outputs)

⇒ **Diagnosis #16 : R=20**

The situation is slighty different at YGP. The 06Z cross-section shows a layer of milder air (-8 to –10 ^{o}C) near the surface on the easternmost sectors, *i.e.* Baie-des-Chaleurs and Gaspé. This low-level warming is associated with an easterly circulation from the Gulf of St- Lawrence generated in front of the low-pressure system. This onshore circulation advects relatively milder maritime (moist and saline) air over these sectors, and also produces orographic lift at the base of the Gaspé mountains. These factors significantly increase the potential for accretion. Snow should therefore be denser than at YYY. Diagram G indicates:

- Significant accretion

⇒ **Diagnosis #11 : R=10**

The following Table compares the 3 diagnoses with the corresponding observations collected during this event:

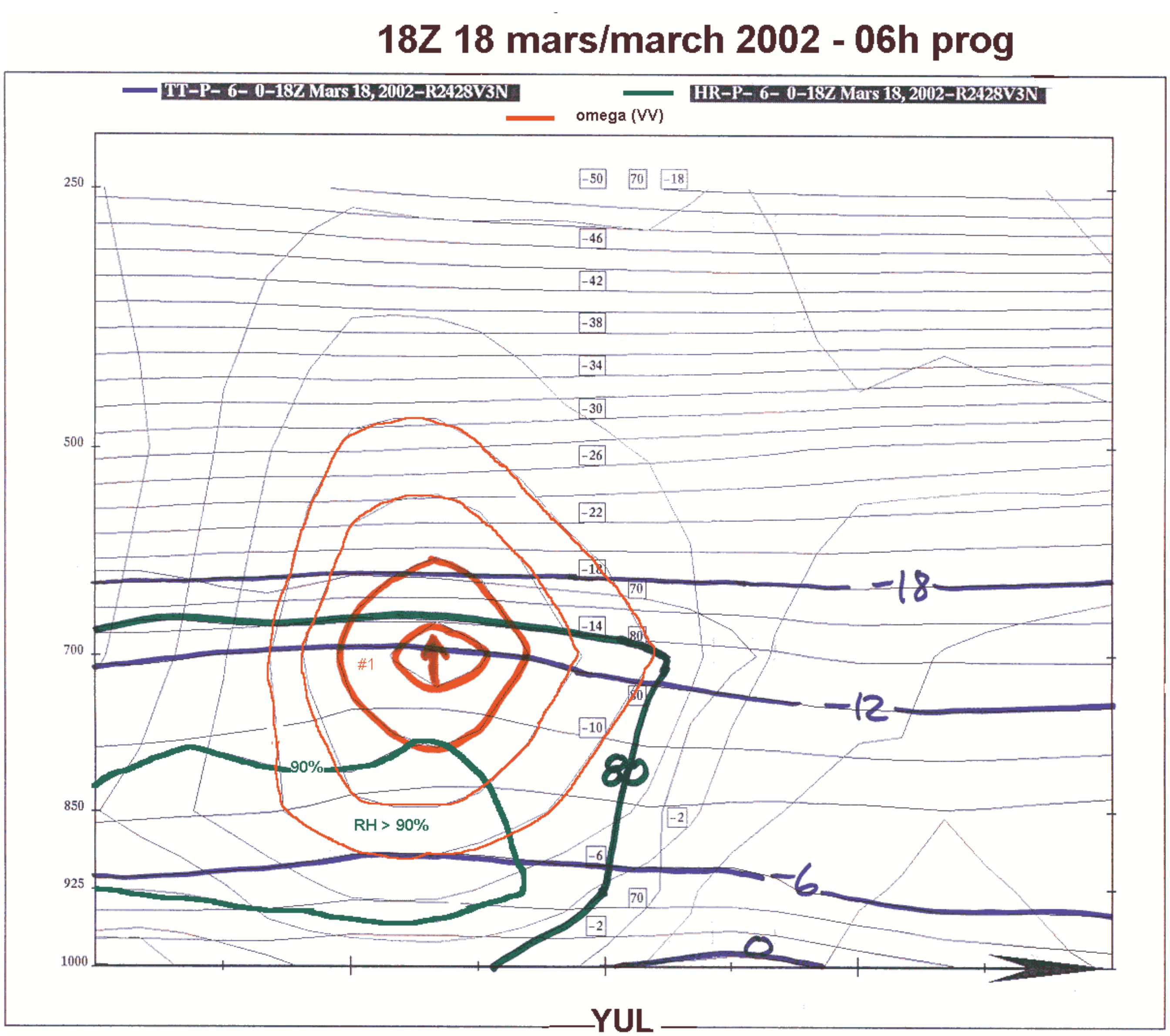
Region	Station	Snowfall (cm)	Water equivalent (mm)	Observed ratio	Forecast ratio
Saguenay	Bagotville Lac Bouchette	8 15	8 13.4	10 11.2	10
Lower St-Lawrence	Rimouski	13	6.8	19	20
Gaspé Peninsula	Gaspé Bonaventure	5.4 11	5.2 9	10.4 12.2	10

The results are highly satisfactory as they once again demonstrate the ability of the proposed algorithm to accurately forecast the snow/water ratio, and therefore the appropriate snow category.

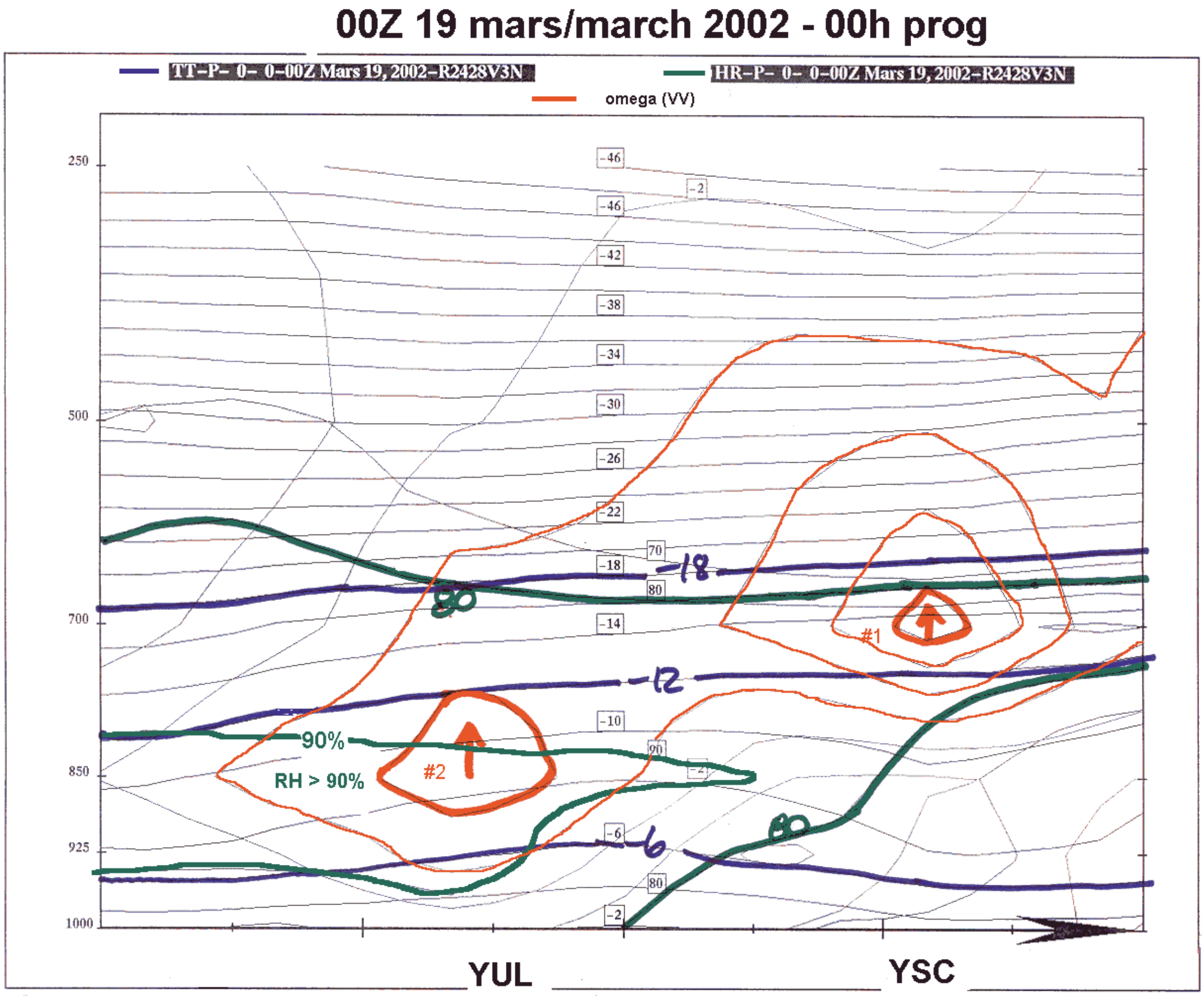
Case #2.2 : March 18-19, 2002

This second case involving vertical cross-sections will demonstrate the crucial importance of considering the vertical motion when diagnosing or forecasting crystal types, and thus, snow/water ratios.

A significant snowfall hit the Greater Montreal region (YUL) on March 18, 2002. Accumulations of 15 to 25 cm were observed between March 18th at 18Z (1PM local) and the 19th at 06Z (1AM local). The following cross-section is valid for March 18th at 18Z and shows the atmospheric conditions at the onset of the event:



The second cross-section (below) is valid for March 19 at 00Z (7PM local) and shows the atmospheric conditions at mid-point in the event.



Note the presence of 2 distinct centres (or maximums) of ascending vertical motion (highlighted by arrows and identified as #1 and #2). The first centre, just upstream from Montreal (YUL) at 18/18Z, moved over the Estrie region (YSC) at 19/00Z. It is associated with snowfalls that occured between 18/18Z and 19/00Z over the Montreal area. The second centre is associated with the additional snowfalls that occurred after 19/00Z (between 00 and 06Z). The first centre is higher aloft (~700mb). The temperatures at this level (-12 to –16 °C, interpolating over YUL using the 2 figures) indicate the presence of stellar crystals in the upper portions of the clouds. Somewhat lower, milder temperatures (-8 to –12°C) suggest a change to other crystal types (plates and columns). We can therefore expect that snow crystals falling over Montreal before 19/00Z will be of the **“mixed with stellar nucleus”** kind. The second vertical motion maximum, much lower than the first (850 mb), suggests milder growth temperatures (-5 to –12°C) and the formation of a different type of snow crystals, namely **"mixed crystals"**.

Despite high relative humidity and mild temperatures in the low-level clouds, conditions are not favourable enough to cause significant accretion. Relatively dry conditions before the event show that the air mass probably moistened by the sublimation of snow crystals rather than by humidity advection. This somewhat decreases the possibility of observing supercooled liquid water in the clouds, hence significant accretion of snow crystals, at least for the first portion of the event (from 18/18Z to 19/00Z). The occurrence of accretion over YUL is far more likely after 19/00Z. However, the relatively unstable thermal profile leads us to believe that sustained accretion over a significantly deep layer is doubtful. An isothermal profile would have been a better indicator of significant accretion.

Although possible in the Estrie region (YSC) given the low-level subsidence, the sublimation of crystals was not a significant factor in the Montreal region (YUL). Except for the first few minutes at the onset of precipitation, relative humidity in the lower levels was greater than 80% throughout the event.

Based on the forecast hodograph for Montreal (below), the maximum forecast winds in the lower levels did not exceed 25 kt during the event; we can therefore conclude that there was little fragmentation in occurrence.

Montreal, March 19, 00Z

It is important to mention that the surface temperature remained near –1 or –2°C during the entire event. We need not be concerned about possible melting of the snow aloft or on the ground (Tground < 0 in mid-March). The snow/water ratio diagnosis for the Montreal region before and after 19/00Z can be produced using diagrams F and C respectively:

Before 00Z (18/18Z to 19/00Z)

- No significant accretion
- No significant sublimation
- Slight fragmentation (Vmax ≤ 25 kt, from hodograph)

⇒ **Diagnosis #10 : R=15**

After 00Z (19/00Z to 19/06Z)

- No significant accretion

⇒ **Diagnosis #2 : R=10**

The following table summarizes snowfall and water equivalent measurements taken at 3 sites in the Montreal area: Mirabel (YMX), Dorval (YUL) and L'Acadie (WIZ). Snow/water ratios resulting from these measurements are compared with ratios forecast by the algorithm.

Site	Period	Snow (cm)	Water (mm)	Observed ratio	Forecast ratio
YMX	before 00Z	19.9	13.8	14.4	15
	after 00Z	5.9	4.6	12.8	10
YUL	before 00Z	12.8	8.8	14.5	15
	after 00Z	5.6	4.6	12.1	10
WIZ	before 00Z	7.0	4.5	15.5	15
	after 00Z	8.0	6.8	11.7	10

As expected, we observe a significant decrease in the snow/water ratios after 00Z, justifying a change from light snow to average snow.