The Snow/Snow Water Equivalent Ratio and its Predictability across Canada

by

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ABSTRACT

The current practice of snowfall forecasting in Canada is to determine the snow water equivalent (SWE) expected to precipitate using a numerical weather predication model and then multiplying this amount by a snow/SWE ratio to determine the forecast snow depth. The 10:1 "rule of thumb" is still widely used operationally as this ratio, even though it is well-known to introduce error in the forecasts because the density of snow is highly variable. In 2003 Ivan Dubé developed a decision tree type algorithm to find the snow/SWE ratio which has subsequently been automated in 2004 by the Meteorological Service of Canada (MSC). The objectives of this study are to explore the behaviour of snow/SWE ratio by developing a Canada-wide climatology of this quantity and examining performance of the MSC algorithm over the winter 2004-2005 using several verification techniques. We found that the mean annual snow/SWE ratio across Canada is 13:1 with large variations temporally and spatially and that the MSC algorithm performed with equal or better skill than the 10:1 algorithm in 84% of the events.

RÉSUMÉ

À l'heure actuelle, les prévisions de chutes de neige au Canada sont déterminées en terme de quantité d'eau à l'aide d'un modèle numérique. La valeur obtenue est par la suite multipliée par un rapport de conversion neige/eau en vue d'obtenir l'accumulation de neige au sol. En pratique, un rapport empirique de 10 :1 est la plupart du temps utilisé bien qu'il puisse fausser la prévision du fait de la variabilité de la densité de la neige. En 2003, Ivan Dubé a développé un algorithme d'arbre de décision pour déterminer ce rapport. Celui-ci fut automatisé par le Service Météorologique du Canada en 2004. Le but de ce travail est d'étudier le comportement du rapport de conversion neige/eau. Pour ce faire, une étude climatologique du Canada de ce rapport a été accomplie. De plus, le rendement de l'algorithme développé par le Service Météorologique du Canada a été comparé à des observations obtenues durant l'hiver 2004-2005. Il a été démontré que le rapport de conversion de neige à eau possède une moyenne annuelle de 13 :1 et peut varier fortement dans le temps et dans l'espace. Il a aussi été prouvé que dans 84% des cas, l'algorithme du Service Météorologique du Canada génère des résultats équivalents ou supérieurs à la règle 10 :1.

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Chapter 1

Introduction

Snow commonly occurs in the winter over Canada and many other mid- to high- latitude regions. This snow causes enormous problems to society in the form of costly snow removal operations, slowed transportation networks and damaging avalanches. In other ways it is beneficial. The winter snow pack especially that deposited in the mountains is a source of water for cities and farmland irrigation during the summer months and winter sports are a source of income and recreation. Planning and organization of activities in all these areas require accurate snowfall forecasting.

Snowfall depth forecasting in Canada uses a two-pronged approach. First, the mass of liquid precipitation, called the snow water equivalent (SWE), is determined from a numerical weather prediction model and then, using a snow to SWE ratio, the forecast snowfall depth is found. The ratio most commonly used for this process is the ubiquitous 10:1 rule of thumb which gives a value of 1 cm snow on the ground for 1 mm of liquid precipitation (Potter 1965). In practice, the density of snow varies dramatically (from 3:1 to 100:1) so it is quite possible that the total mass of snow is predicted well but its depth on the ground will not be.

Cold season quantitative precipitation forecasting (QPF) is sometimes regarded as being "easier" than warm season QPF due to the relative rarity of convection during the winter months. In support of this, the performance of the Canadian Global Environmental Multiscale (GEM) regional model as measured by several skill scores (calculated monthly by the CMC and available on their internal website) does show improvement in the winter season over the summer season.

Nevertheless, there is still room for improvement in cold season QPF, which has its own unique problems. The current method of snowfall forecasting, as outlined in the Meteorological Service of Canada's forecaster's manual, is to use the liquid water output (in millimetres) from the GEM 15km resolution regional model, then determine the precipitation type using the Bourgouin method (Bourgouin 2000) and finally, if the precipitation type is determined to be snow, multiplying by 10 (except in a few special cases of $T_{ground} > 0°C$) to get the forecast snowfall depth.

Therefore, performing a winter season precipitation verification of a forecast model against observations using snowfall depth amounts would hide a significant error that is not due to the forecast model but rather, due to the use of the 10:1 approximation. As an example, Table 1-1 shows a case on January 6th, 2003 in the Quebec City region where the QPF from GEM was accurate but the forecast accumulation clearly was not.

Table 1-1: Case of January 6th, 2003 in Quebec City and surrounding localities (Dubé 2003).

Observation Site	Observed Accumulation (cm)	Observed SWE (mm)	Snow/SWE Ratio	Forecast Accumulation (cm)	QPF from GEM (mm)	Forecast Error
Quebec	4.2	1.4	30:1	0.8	0.8	80.95%
Charlesbourg	3.2	1.0	32:1	1.0	1.0	68.75%
Fôret Montmornecy	3.1	1.0	31:1	1.4	1.4	54.84%
Charlevoix	3.8	1.4	27:1	0.5	0.5	86.84%
Mont-Ste-Anne	3.0	1.0	30:1	1.0	1.0	66.67%

In 2003 Ivan Dubé at the MSC Quebec (Dubé 2003) developed a decision tree type algorithm to predict the snow/SWE ratio based on the vertical temperature and humidity profiles, vertical wind velocity and surface wind speeds. With these input fields, the algorithm predicts a crystal type and then makes assumptions about the density of different crystal types to output a snow/SWE ratio.

The motivation behind and development of this algorithm is outlined in the report "From mm to cm… Study of snow/liquid water ratios in Quebec." The Dubé algorithm was developed and verified using only Quebec region data and climatology. In Section 9: Future Developments of his report, Dubé mentions among other points: the need to extend the coverage of the climatological study to all of Canada, and the need to extend the verification process to all of Canada.

As a contribution to an Environment Canada initiative to improve cold season precipitation forecasting through the use of this algorithm in a slightly modified form, the objective of this thesis is to answer the first two needs that were listed: to carry out a Canadian-wide climatology of snow/SWE ratio and verification of the Dubé algorithm.

This thesis is organized as follows: Chapter 2 describes the physical causes of snow density variation. Chapter 3 details previous attempts at snow/SWE ratio forecasting and explains the algorithm being verified in this thesis. Chapter 4 will describe the quality control procedures we performed on our observational data set. In Chapter 5 we will construct a climatology of snow/SWE ratio across Canada using our quality controlled observational data set. In Chapter 6 we will perform a verification of the new algorithm. Finally, Chapter 7 will summarize and conclude the thesis.

Chapter 2

Physical Causes of Variation in Snow Density

The unique and special beauty of snow crystals has motivated both scientists and laypeople to study them throughout history. The earliest known detailed account of snow crystals is from René Descartes in his study *Les Météores*. Also of note is the stunning book of more than 2000 snow crystal photographs taken by Wilson Bentley and published in his 1931 book, *Snow Crystals*. The adage that "no two snowflakes are identical" is considered common knowledge in popular culture.

However, snowflakes' complicated shape is reflective of the complicated conditions in which they were formed, and for that reason the scientific study of snow crystal types, their mass to diameter relationships, and their density has only been undertaken fairly recently. This chapter aims to explore the physics behind the snow/SWE ratio; more specifically, what temperature and humidity profiles lead to different crystal types, how crystal type affects snow/SWE ratio and then the various physical processes (sublimation, melting, freezing, aggregation, accretion, fragmentation, compaction and ageing) that also influence this ratio. The exploration will be carried out through a review of the scientific literature available on this subject.

2.1 Definitions

Because snow/SWE ratio and snow density are so intimately related, the two terms are often used inter-changeably. Their magnitude is inversely proportional so that a high snow/SWE ratio is equivalent to a low density of snow and vice versa. Snow Water Equivalent (SWE) is the depth of melted liquid water contained in a volume of snow so the snow/SWE ratio is a measure of how many times greater a volume of a given mass of snow occupies than the volume the same mass of water would occupy.

Equation 2-1 and equation 2-2 are the snow density and snow/SWE ratio equations respectively. Equation 2-3 is the relationship between snow/SWE ratio and density. Since water has a density of 1000 kg m^{-3} the 10:1 approximation assumes a density of snow of 100 kg m^{-3}. However, the density of snow varies considerably. In the United States it has been measured to vary between 10 to 350 kg m^{-3} as summarized by Judson and Doesken (2000). This range of densities corresponds to a range of snow/SWE ratios of 3:1 to 100:1. Similar studies have been carried out in Canada (Goodison and Metcalf 1981).

$$\text{Snow density} = \text{snow mass (g)} / \text{occupied volume (cm}^3\text{)} \quad (2\text{-}1)$$

$$\text{Snow/SWE ratio} = [\text{snow accumulation (mm)} / \text{water equivalent (mm)}]:1 \quad (2\text{-}2)$$

$$\text{Snow/SWE ratio} = [1000/\text{density of the snow (kg/m}^3\text{)}]:1 \quad (2\text{-}3)$$

2.2 Individual Ice Crystal Habits

What are the physical causes of the variation in snow density? Snow is always less dense than water due to interstitial spaces of air trapped in the packing of snow as it accumulates. The amount of air space is directly related to crystal habit (shape) with the ferny dendrites being the least dense basic shape and ice pellets or graupel being the densest. We will now describe the formation and density of different crystal habits.

A snowflake begins with the creation of an ice crystal in a cloud with a temperature below 0°C either through the freezing of a liquid droplet or direct deposition of ice from the vapour phase. Both processes are more commonly a heterogeneous nucleation, in which case there are ice nuclei present in the cloud (Rogers and Yau 1989).

Whichever process, homogeneous or heterogeneous, creates the ice crystal a fundamental change in its shape takes place. A water molecule is made up of two positively charged hydrogen atoms and one more massive, negatively charged oxygen atom. The hydrogen atoms are bonded to the oxygen atom at angles of 105° each. In the gaseous and liquid phases, these molecules are rather loosely organized but in the solid phase they are tightly bound in a hexagonal crystal lattice with two basal facets and six prism facets. It is the growth rate of the basal facets compared to the prism facets that determine whether the crystal will be, for example, a thin plate or a long column (Libbrecht 2003).

The pioneering Japanese scientist Ukichiro Nakaya was the first researcher to grow snow crystals in the laboratory (1954). Because he was able to carefully control the temperature and supersaturation conditions under which the crystals grew, he was able to produce a table of crystal morphology based on these parameters. He was also the first scientist to produce a classification scheme of snow crystals based on appearance.

Although Nakaya's research was performed in the laboratory it was assumed his results would extend to natural snowflakes. Magono and Lee (1966) confirmed his results by taking similar measurements in the field during snowstorms. They also extended the results to low temperatures and produced a snowflake classification scheme, based on appearance, which is still widely used.

The physics of snowflake growth is a rich field and many studies deepening our understanding of this subject have been performed and are still ongoing. Of note are Kobayashi (1961), Ryan et al. (1976), Fukuta and Takahashi (1999), Bailey and Hallett (2002) and Bailey and Hallett (2004).

Figure 2-1 is a crystal morphology based on temperature and supersaturation (Libbrecht

2003). It can be seen from the figure that the cloud temperature at which the crystals are produced is the primary controller of crystal habit. Between 0°C and –5°C plates are formed, between –5°C and –10°C columns, prism and needles are formed, between –10°C and approximately –23°C plates and dendrites are formed, and at temperatures lower than –25°C plates and columns are formed. The supersaturation with respect to ice in the cloud controls the growth rate of the crystal but does not affect crystal habit. So, in the case of columns, which are formed by the preferential growth of the basal facet, increasing the saturation increases this growth rate, causing needles to be formed. In the case of plates, which are formed by the preferential growth of the prism facet, increasing the saturation causes sectored plates and dendrites to be formed. The exception is at temperatures below approximately –25°C when increasing supersaturation causes the crystal habit to change from plate to column. In all cases increased residence time in a cloud leads to increased crystal size.

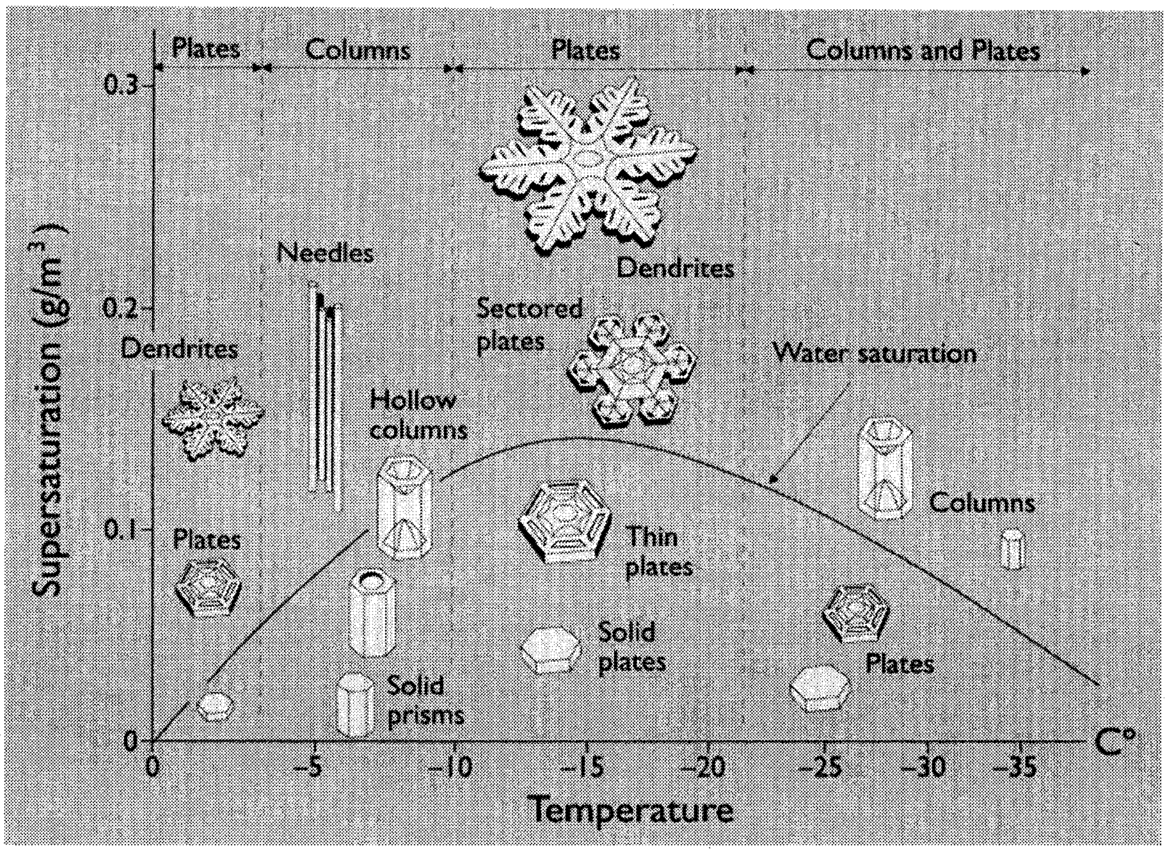


Figure 2-1: Crystal morphology as a function of in-cloud temperature and supersaturation with respect to ice (Libbrecht 2003).

We have seen that crystal habit depends on two parameters of the cloud in which the crystals are formed: temperature and supersaturation with respect to ice. The density of individual ice crystals has been studied by Ryan et al. (1976) and Fukuta and Takahashi (1999). Fukuta and Takahashi performed measurements of ice crystal growth under free fall in a supercooled cloud tunnel. They calculated a quantity they called apparent density, defined as the mass divided by the volume that circumscribes the crystal, of individual crystals formed under various temperatures. Figure 2-2 is a graph of apparent density as a function of temperature from their paper. They do not mention crystal habit specifically but if we compare Figure 2-1 and Figure 2-2 we can infer that plates and dendrites have lower densities and columns and needles have higher densities. This figure, and their paper, neglects the effect of supersaturation on density. Work has been done which links individual crystal density to crystal habit and is summarized in Rasmussen et al. (1999); reproduced in small part in Table 2-1.

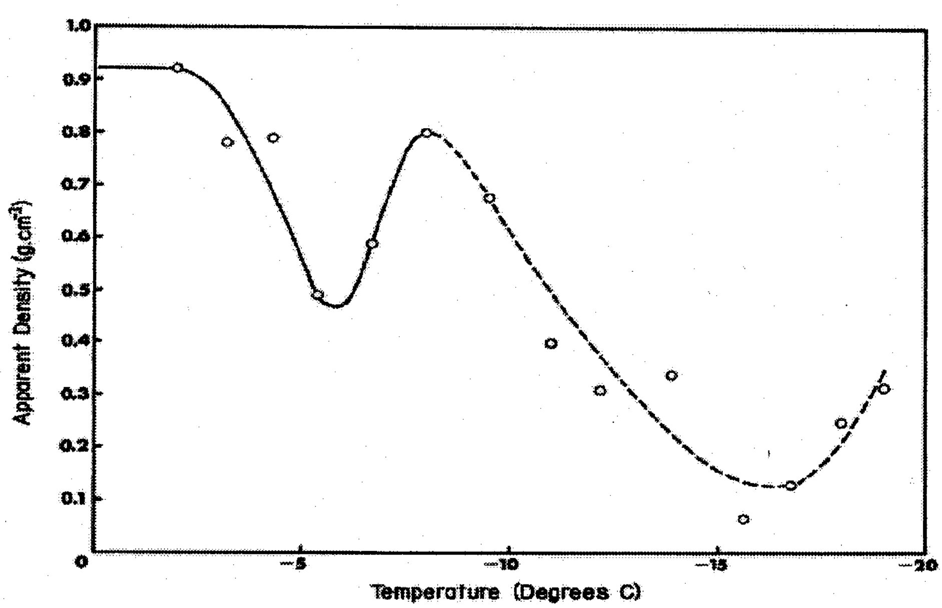


Figure 2-2: Apparent crystal density as a function of temperature for a single ice crystal (Fukuta and Takahashi 1999).

Table 2-1 Densities of several individual crystal types (Rasmussen et al. 1999)

Habit Description	Density (kg m^{-3})
Thick Plate	930
Dendrite	500
Short Columns	700
Elementary Needles	800

2.3 Atmospheric Processes

We have now described individual crystal habits and their densities. If individual crystal habit were the sole determinate of snow density, we would only need to know the temperature and relative humidity in a cloud to know the density of freshly fallen snow from that cloud. However, a snowflake is made of many packed ice crystals. Conway and Sloane (1993) have shown if the ice crystals in a snowflake are packed as tightly as possible, the density of the snowflake will be 0.75 of the density of the individual crystals that the snowflake is composed of. Furthermore, there are other physical processes which act on the snowfall: sublimation, melting, freezing, aggregation, accretion, fragmentation, compaction and ageing. In the remainder of this section we will discuss the impact of these physical processes on the density of snow.

Sublimation is the direct vaporization of ice without passing through the liquid phase. If there is a sufficiently thick dry layer beneath the cloud which snowflakes fall through, they will be subjected to sublimation. Sublimation (or evaporation) is the cause of virga. It affects most strongly the light density crystal types (*e.g.* dendrites) but not the forms that are already compact (*e.g.* ice pellets) (Dubé 2003).

Melting occurs when the snowflakes pass through a layer where the temperature is above 0°C and the snowflakes change from the solid phase to the liquid phase. Depending on the depth of the layer and the residence time of the snowflake inside it, the snow can partial or completely melt. In every case, melting leads to an increase in density and therefore a decrease in snow/SWE ratio (Dubé 2003).

Freezing can occur if the snow has partially or completely melted and then falls through a layer with a temperature less than 0° C. Depending on specifics, a profile of this type can produce: ice pellets, mix of snow/freezing rain, snow mixed with a little rain, mix of snow/ice pellets or snow pellets, all of which have an associated high density (Dubé 2003).

Aggregation is the growth of snowflakes by ice crystals sticking together or becoming entangled after a collision. The adhesion efficiency between ice crystals stuck together is primarily dependent on temperature. Warmer temperatures increase adhesion efficiency with a maximum at 0°C. Measurements have shown that maximum snowflake size occurs around this temperature (Rogers 1974). Dendrites can become entangled mechanically even at very cold temperatures. (Schemenauer 1981) Aggregation in all cases acts to decease density by increasing interstitial spaces although in the case when it is occurring near 0°C the effect can be overshadowed by partial melting of the crystals (Dubé 2003).

Accretion, also known as riming, occurs inside a cloud where there is the presence of supercooled water droplets as well as ice, which freeze on collision to ice crystals. It always acts to increase density by filling in interstitial spaces but is more effective on crystals with larger surface area, since those crystal types have larger collision efficiencies (Dubé 2003).

Fragmentation is the break-up of crystals by the wind by subjecting snowflakes to collisions. It can happen at any layer in the atmosphere but it is most pronounced on the ground. It always leads to denser snow but has a stronger effect on fragile low density crystal types than to more compact ones (Dubé 2003).

Compaction is an increase in the density of a layer of snow through the pressure of the weight of snow above it. It acts to increase the density of snow in all cases but the time scale on which it acts is still under debate. Dubé (2003), through his climatological studies, believes compaction is not a factor on daily time scale. However in a study by Doesken and McKee (2000), it was found that the sum of 4, 6 hourly measurements of snow depth during a snow event could increase the measured depth by 19% over one daily measurement. Although ageing is one of the causes for increased density over time, compaction and settling is certainly playing a role. Other studies have seen increased snow/SWE ratio in larger accumulation events and speculated that compaction may be the cause (Ware *et al.* 2004). In Chapter 7 we will also show that we have found increased snow/SWE ratio with increased accumulation although we consider other causes in addition to compaction.

Ageing, also called metamorphism, stems from the tendency of thermodynamic processes to reduce surface free energy. A minimum in surface free energy corresponds to a minimum in the ratio of surface area to volume: a sphere. Metamorphism acts to transform the ice crystal shape into a rounded ice particle over time. It acts on the time scales of several days or weeks and acts more swiftly at warmer temperatures (LaChapelle 1969).

2.4 Snow on the Ground

Much work has been done analyzing the density of individual crystals even though there are complications involving estimating the volume a crystal occupies, but surprisingly little work have been done measuring the density of a layer of fresh snowfall. We will discuss the findings of three sources on this subject, Power *et al.* (1964), LaChapelle (1969) and Rasmussen (1999).

It is the study by Power *et al.* upon which Dubé bases his values of snow/SWE ratio for the different snow types. They took measurements from a Montréal rooftop during the winter with an ingenious snowflake recording device. It was a 5" deep, cold box with a moving film strip on a reel inside. Snowflakes fell through an aperture at the top of the box and were recorded on the film strip to be analyzed later. The team took measurements of snow depth from a snowboard and weighed the snow to find its mass and therefore could calculate the density. They found that the lightest snowflakes were made of dendrites with a density 30–50 kg m^{-3} (33:1–20:1). In the density range of 51–75 kg m^{-3} (20:1–13:1) were pure needles, mixed falls of rimed dendrites and needles, and some assemblages of columns and plates. In the density range of 76–100 kg m^{-3} (13:1–10:1) were combinations of columns and plates, pure plates, and spatial dendrites. Snowfalls greater than 100 kg m^{-3} were found to be almost entirely rimed crystals. Furthermore, they estimated riming increased the density of needles by 30%, plates 65% and dendrites 100%.

LaChapelle is primarily an avalanche scientist who has done considerable work in the field of fresh snowfall density because it has important applications for avalanche prediction. He took observations of crystal type and snow density, as well as produced corresponding photographs, in 1952 on the Juneau Ice Field in Southeastern Alaska and in 1953 on the Greenland Ice Cap. In his book, *Field Guide to Snow Crystals*, he gives the fallowing densities based on his observations, highly aged snow: 500 kg m^{-3} (2:1), rime-free stellar crystals with no surface wind: 60 kg m^{-3} (17:1), clusters of plates and irregular particles falling between –9°C and –12°C: 100–120 kg m^{-3} (10:1–8:1), stubby columns falling at a surface temperature of –21°C: 150 kg m^{-3} (7:1), and lightly to heavily rimed sheaths and needles: 170–330 kg m^{-3} (6:1–3:1). In general, LaChapelle found higher values of snow density than Power *et al.*

The last paper we will discuss is Rasmussen *et al.* (1999). This paper contains a very detailed summary of subject of snowflake density, citing Magono and Nakamura's (1965) range of measured snowflake densities of 5–200 kg m^{-3} (200:1–5:1). We have already reproduced part of their summary in Table 2-1 for individual crystals, but they also discuss the density of snowflakes of different types, included rimed particles.

In summary, we have explored the physics underlying ice crystal formation, the density of individual ice crystals, considered the other physical processes acting to control the density of a snowflake and surveyed some of the studies measuring density of freshly fallen snow. We have seen that snow/SWE ratio of freshly fallen snow is a complicated topic without a long history of study. However, the subject is enjoying something of a revival recently, with interest being generated in improved forecasting of this quantity.

Chapter 3

Snow/SWE Ratio Forecasting Tools

The first attempt at snow/SWE ratio forecasting was the 10:1 approximation. The murky origins of this approximation reach back to Canada before the turn of the 20^{th} century. Potter (1965) quotes from an instruction manual to Canadian observers printed in 1878 that "A long series of experiments conducted by General Sir H. Lefroy, formerly Director of the Toronto Observatory, led to the conclusion that this relation (one to ten) is true on the average." The instructions go on to say "It is not affirmed that it holds true in every case, as snow varies in density." So for a long time it was known that the 10:1 approximation had its faults. The rest of this chapter will describe the state of snow/SWE ratio forecasting now, at the turn of the 21^{st} century.

3.1 Previous Forecasting Tools

3.1.1 National Weather Service Look-Up Table

One popular, if largely unjustified, technique is to use some type of look-up table, usually based on temperature. There is one such table in use at the United State's National Weather Service (Kyle and Wesley 1997) reproduced in part here in Table 3-1.

The original intention for this table was to give a more accurate way of estimating SWE at stations equipped only with a snow ruler, in place of using the 10:1 approximation but it is also sometimes being used as a forecast tool.

Table 3-1: Part of a National Weather Service look-up table predicting snow/SWE ratio based on surface temperature (Kyle and Wesley 1997).

Melt Water Equivalent (Inches)	New Snowfall (Inches)						
	Temperature (F)						
	34 to 28	27 to 20	19 to 15	14 to 10	9 to 0	-1 to -20	-21 to -40
trace	trace	0.1	0.2	0.3	0.4	0.5	1.0
0.01	0.1	0.2	0.2	0.3	0.4	0.5	1.0
0.02	0.2	0.3	0.4	0.6	0.8	1.0	2.0
0.03	0.3	0.5	0.6	0.9	1.2	1.5	3.0
0.04	0.4	0.6	0.8	1.2	1.6	2.0	4.0
0.05	0.5	0.8	1.0	1.5	2.0	2.5	5.0
0.06	0.6	0.9	1.2	1.8	2.4	3.0	6.0
0.07	0.7	1.1	1.4	2.1	2.8	3.5	7.0
0.08	0.8	1.2	1.6	2.4	3.2	4.0	8.0
0.09	0.9	1.4	1.8	2.7	3.6	4.5	9.0
0.10	1.0	1.5	2.0	3.0	4.0	5.0	10.0
0.11	1.1	1.7	2.2	3.3	4.4	5.5	11.0
0.12	1.2	1.8	2.4	3.6	4.8	6.0	12.0
0.13	1.3	2.0	2.6	3.9	5.2	6.5	13.0
0.14	1.4	2.1	2.8	4.2	5.6	7.0	14.0
0.15	1.5	2.3	3.0	4.5	6.0	7.5	15.0
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

This look-up table has a number of problems. The only meteorological parameters used are surface temperature and accumulation. We have seen that it is the temperature in the cloud where the ice crystals form that controls their habit. Even if we accept surface temperature as a proxy for upper-air temperatures, the table totally neglects the effect of humidity on snow/SWE ratio. In addition, Table 3-1 shows decreasing snow density with decreasing temperatures in a monatomic fashion with the very high value of snow/SWE ratio of 50:1 given for temperatures between –30°C and –40°C, when we have seen that density has a minimum at around –15°C, after which it increases. For these reasons, it is obvious that this table is inadequate as a forecasting tool.

3.1.2 Scofield/Spayd Diagrams

Another type of look-up type table in use operationally is the Scofield and Spayd (1984) diagram which uses 1000–500 mb thickness to forecast snow/SWE ratio. This is somewhat of an improvement over the previous method since by using the 1000–500 mb thickness, a measure of the mean temperature throughout this layer of the atmosphere; it is attempting to estimate the cloud temperature instead of just surface temperature. This technique suffers from the same flaws as the NWS look-up table: lack of consideration of atmospheric humidity and monatomically decreasing values of snow/SWE ratio for decreasing temperature. These flaws make the Scofield/Spayd technique inadequate as a forecasting tool.

3.1.3 Trajectory Method

In North America there are well-known, frequently occurring storm tracks. Storms with certain trajectories are known to have certain temperature and humidity characteristics that they take from the terrain they pass over. For instance, nor' easterners are known to be warm and extremely humid, producing heavy snowfalls with low snow/SWE ratios. Storms originating in the Canadian arctic can also have low ratios because their air masses consist of air with temperatures less than –25˚C. Lake-effect snow has some of the highest ratios in the country, because those type of storms are moderately cold and humid, perfect conditions for dendritic growth. This knowledge is the basis for a trajectory technique informally outlined in a National Oceanic and Atmospheric Association (NOAA) webpage (www.hpc.ncep.noaa.gov/research/snow2a). However, the technique is time consuming and not always accurate as there are many modifying factors that can change the snow/SWE ratio in a storm, regardless of its trajectory.

3.1.4 Roebber *et al.* Method

An important forecasting technique has been developed by Roebber *et al.* (2003). They used a 10-member ensemble of artificial neural networks to develop a technique using 7 input parameters: mean temperatures at low to mid levels, mean temperatures at mid to high levels, relative humidity at low, mid and high levels, a ground compaction factor (taking into account surface wind speed and compaction under the weight of snow), and a monthly solar radiation factor. The output snow/SWE ratios are divided into three classes: heavy (1:1–9:1), average (9:1–15:1) and light (> 15:1). Forecasts using this technique are publicly available online at: http://sanders.math.uwm.edu/cgi-bin-snowratio/sr_intro.pl.

Roebber *et al.* published a study showing that 60.4% of events in their validation data set were correctly forecast; a large improvement over the 45% correct they found using the 10:1 approximation and 51% found using the NWS look-up table. As Dubé points out, 60.4% correct is a somewhat low result considering there are only 3 categories of forecasts possible. Dubé goes on to speculate that one source of possible error in their method is that although the temperature throughout the atmosphere is taken into account, the actual cloud level where the crystals are being formed is not considered. Nevertheless, the Roebber *et al.* method is a significant improvement over the other methods mentioned in this chapter.

We have now surveyed several of the most popular forecasting techniques for snow/SWE ratio. Due to the complexity of causes of snow/SWE ratio, not many methods for forecasting this quantity have been created. We have also shown that the methods currently available, besides being limited, are flawed. The next section will address this lack, by outlining a technique developed by the MSC Quebec to forecast snow/SWE ratio in Canada.

3.2 MSC Algorithm

3.2.1 Dubé Algorithm

The original form of the MSC algorithm was developed by Ivan Dubé at the MSC Quebec in 2003 and is outlined in his report "From mm to cm… Study of snow/liquid water ratios in Quebec". Quoting from this report, the objectives in creating this algorithm were to

> 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; [and] be the basis for creating a water equivalent → snow conversion field that could be integrated into numerical models.

The form of the algorithm is a decision tree, using as input the meteorological parameters that control snow density (vertical temperature profile, vertical humidity profile, vertical and surface winds and the ground temperature) to determine the crystal habit and the extent to which other processes are affecting the crystal (sublimation, melting, freezing, aggregation and fragmentation). The algorithm has 26 categories (called diagnoses) of snow type when all these processes are taken into account. Each category has a snow/SWE ratio associated with it, one of 5 possible values: 4:1, 7:1, 10:1, 15:1 or 25:1. These are mean values that have been determined empirically and are primarily from the study by Powers *et al.* (1964). An important distinction between this algorithm and some other techniques used to forecast snow/SWE ratio is that this method is based on physical principles principals rather than on statistically determined values.

Having discussed the broad outline of the algorithm we will now turn to describing in detail the individual steps in the decision tree. A schematic diagram of the algorithm in full is given in Appendix A. The first step in this algorithm is to determine if at any point in the atmosphere from cloud top to the ground the temperature is above 0°C. We will now consider the case where $T_{atm} < 0$.

If $T_{atm} < 0°C$ then the first step is to determine crystal habit and the second is to check for the presence of other physical processes. Table 3-2 shows the technique through which the algorithm determines crystal habit based on a primary temperature (the temperature at the main growth level of the crystals) and secondary temperature (the temperature of a layer below the main one where there is ascending vertical motion and a relative humidity greater than 80%). The table also lists the snow/SWE ratio associated with the different crystal habits before any modification by other atmospheric processes.

Table 3-2: Crystal habit determination based on primary and secondary growth temperature. The snow/SWE ratio associated with each crystal habit in this table is unmodified by physical processes (Dubé 2003).

	Primary Temperature (deg C)				
Secondary Temperature	0 to -3	-3 to -5	-5 to -12	-12 to -18	< -18
0 to -3	mixed (10:1)	mixed (10:1)	Mixed (10:1)	—	—
-3 to -5	mixed (10:1)	needles (10:1)	Mixed (10:1)	—	—
-5 to -12	mixed (10:1)	mixed (10:1)	Mixed (10:1)	mixed with stellar nucleus (15:1)	—
-12 to -18	—	—	spatial Dendrites (10:1)	stellar crystals (25:1)	spatial dendrites (10:1)
< -18	—	—	—	mixed with stellar nucleus (15:1)	mixed (10:1)

Crystal habit classification has already been discussed in Chapter 2 but we will now define the crystal habit terms listed in Table 3-2 in the context of the Dubé algorithm. A mixed crystal refers to any combination of pure columns, pure plates, columns and plates, all either with or without needles. They are assumed to have the same snow/SWE ratio regardless of their formation temperature. Mixed crystals have a compact structure and so sublimation and fragmentation does not affect this crystal type; only accretion can.

Needles on their own in a snowfall are relatively rare. Although they can commonly be found in combination with other crystal types, resulting in the mixed category, the atmospheric conditions creating pure needles are very specific. Individual needles have a relatively low snow/SWE ratio but since they occur in mild temperatures, aggregates, leading to a high ratio, are easily produced. Accretion is not a significant factor because needles have a small cross-section, but fragmentation of aggregates can be significant.

The category of spatial dendrites comes from the classification by Nakaya (1954) as a crystal with a nucleus of an assemblage of plates and/or columns with stellar branches. Because of these extremities, this crystal type can form low density aggregates if they pass through an atmospheric layer warm enough. This can occur when conditions in the atmosphere are considered thermodynamically unstable. Spatial dendrites are affected by fragmentation and accretion.

Mixed crystals with stellar nuclei is a mixed crystal type classification with dendrites as the predominant crystal type in combination with other crystals. This classification has a light density. They can be significantly affected by accretion, fragmentation and evaporation but not aggregation.

The final crystal type is called stars, corresponding to what is commonly referred to as dendrites. It is the crystal type having the lowest density and can have snow/SWE ratios from 10:1 to 25:1 and even higher. This crystal type is strongly affected by all the atmospheric processes: evaporation, fragmentation, aggregation (even at low temperatures since their branches become entangled) and accretion.

Table 3-3 lists the algorithm's 17 possible diagnoses for a situation in which the atmosphere is everywhere below 0°C. The possible diagnoses in Table 3-3 are fairly detailed. This table is only valid in the situation in which the ground is frozen. If the ground temperature is between 0°C and 5°C the snow/SWE is considered to be 7:1 regardless of crystal classification and if the ground temperature is greater than 5°C then the snow/SWE ratio is considered to be 4:1.

Table 3-3: The 17 possible diagnoses in the case where T_{ground} and $T_{atmosphere} < 0°C$.

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

Having thoroughly discussed the case where $T_{atm} < 0°C$, we will now explain the case in which there is an atmospheric layer with $T_{atm} > 0°C$. In this instance it is necessary to determine the precipitation type instead of the crystal type. Since the crystals will melt, their original habit is irrelevant. The 5 different precipitation types are: ice pellets, a rain/snow mixture, a snow/ice pellet mixture, wet snow and snow pellets. The definitions of these crystal types do not differ in the algorithm from the standard definitions so we will not expand on the meaning of these precipitation types. Table 3-4 is a summary of the classification categories possible if $T_{atm} > 0°$ C and the associated snow/SWE ratio. Finally, the consequences of a ground temperature above 0° C are somewhat complicated and are left to be iterated in Appendix A.

In this section, we have discussed the algorithm developed by Ivan Dubé. The algorithm in this form was verified in the Quebec region between November 1, 2002 and February 24, 2003 using radiosonde and GEM model data to determine the vertical temperature, humidity and wind profile. The results of this verification will be discussed in Chapter 6 in the context of comparison with the verification performed as part of this thesis.

Table 3-4: The 9 possible diagnoses in the case where Tatmosphere < 0°C but T_{ground} > 0°C.

Diagnosis #	Crystal types and alterations by various atmospheric processes	Suggested ratio
18	Ice pellets	4:1
19	Snow mixed with small amounts of rain	4:1
20	Snow mixed with freezing rain	4:1
21	Snow mixed with rain and ice pellets	4:1
22	Snow mixed with ice pellets	7:1
23	Wet snow	7:1
24	Wet snow pellets	4:1
25	Snow pellets	7:1
26	Rain, freezing rain, rain mixed with small amounts of snow or with ice pellets	1:1

3.2.2 Automation

Since one major motivation in creating a snow/SWE ratio forecasting algorithm was to aid operational forecasters in improving their wintertime precipitation forecasts, it was necessary to automate the algorithm. The automation was carried out in 2004 by Viateur Turcotte at the MSC Quebec region and in the process several changes in the algorithm were made. For the remainder of the chapter we will discuss these changes.

First, it has been established that it is the humidity and temperature at the cloud level which affects crystal habit but we have not yet discussed how the algorithm determines the cloud height. In Dubé's original algorithm, which relied on visually examining sounding data, an estimate of cloud height was relatively straightforward. However, although there was a rule for finding the cloud height in the original algorithm (the level where ω is maximum and RH > 80%), in practice this rule was too simplistic to be accurate. The automated version of the algorithm incorporates a module called Stratus, a Transport Canada program that was originally developed to forecast cloud ceiling at airports. According to MSC Quebec, incorporating this program into the algorithm increased its performance.

Second, it's obvious that in order to use the algorithm in a forecast mode, the input meteorological parameters must be forecasts also. In the MSC algorithm the input parameters (vertical temperature profile, vertical humidity profile, vertical and surface winds, and ground temperature) are predicted from the GEM regional 15 km resolution model. Using a forecast model introduces an error of its own since the input parameters to the algorithm will not perfectly reflect the true state of the atmosphere. It is important that the QPF from GEM is not an input parameter. The algorithm calculates a snow/SWE ratio which is afterwards multiplied by the QPF to attain a snowfall forecast. Because of this, error in GEM's QPF forecast will not translate into error in the forecasted ratio (although it will be a source of error for the final snowfall forecast).

Third, the automated algorithm is run only at GEM forecast times. GEM is initialized at 00 UTC and 12 UTC daily and at each initialization it creates a forecast for every subsequent 3 h up to 48 h into the future. The algorithm is run for each of these forecast times for each initialization and therefore several forecasts will overlap at a given observation time. In fact, at every 3 h starting at 00 UTC, there are four GEM forecasts valid at that time. At each forecast time a snow/SWE ratio for the previous 6, 12 and 24 h leading up to that time is calculated by averaging 3 hourly periods. Because of this averaging, the range of values: [4:1, 5:1, …25:1] are possible whereas in the original algorithm only 4:1, 10:1, 15:1, 20:1 and 25:1 (named heavy snow, average snow, light snow, very light snow and ultra light snow) were possible. We will return to the issue of forecast times in Chapter 6, the verification.

Lastly, the automated algorithm was found to be computationally expensive. If it is to be used operationally it needs to complete a run in a reasonable amount of time. In order to save time, the automated algorithm only calculates a snow/SWE ratio at a grid point where GEM is forecasting precipitation. Consequently there will be snowfall events that go unforecast and forecast events that do not occur.

The MSC algorithm in its original and post-automation form has now been outlined and discussed. The basic form of the algorithm is a decision tree structure that uses several meteorological parameters to determine the crystal habit formed and the magnitude of its alteration by various physical processes. This result of this determination leads to a diagnosis within one of 26 possibilities, each with an associated snow/SWE ratio. Figure 3-1 is a schematic of the steps in the snowfall forecast process using the algorithm. In order to view the forecast, the automated algorithm is available publicly online at http://www.wul.qc.ec.gc.ca/meteo/Prev_maritime/animateur_e.html

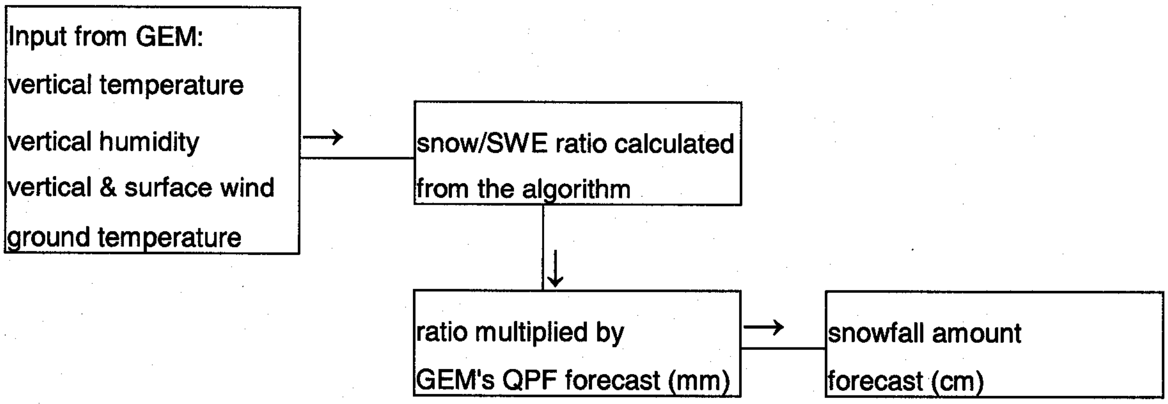


Figure 3-1: Schematic of the snowfall depth forecast process using the MSC algorithm.

Chapter 4

The Observational Data Set

The two measurements needed to calculate snow/SWE ratio are daily snowfall and daily precipitation. Daily snowfall is a measurement of the depth of freshly fallen snow in a 24 h period whereas daily precipitation is a measurement of the melted liquid equivalent of any precipitation type, including snow, in a 24 h period. The best practices for measuring daily snowfall and daily precipitation come from the World Meteorological Organization (WMO) gauge intercomparison project (Goodison et al. 1998). That is, daily snowfall depth is measured with a metric snow ruler (with a resolution of ±0.1 cm) on a snowboard. Daily precipitation depth is measured in a Nipher shielded snow gauge (with a resolution of 0.1 mm). The purpose of the Nipher shield is to reduce aerodynamic wind loss of precipitation, an error which increases with increasing wind speed.

Any forecast verification; however it is performed, is fundamentally a comparison of observations against predictions. Since errors arise in taking measurement as well in forecasting it is important to consider the quality of the observational data set to be used in the verification. This consideration is particularly crucial in this thesis because of the way that the 10:1 approximation is entrenched in the minds and practices of meteorologists and weather observers.

4.1 Station Selection

At the start of this study, a comprehensive list of 848 stations across Canada that were reporting daily snowfall and daily precipitation from October 2004 to February 2005 was identified by querying Environment Canada's National Climate Data and Information Archive. Figure 4-1, a histogram of the frequency of snowfall events by snow/SWE ratio in this data set is dominated by a spike at the ratio of 10:1.This is a bias caused by the 10:1 approximation being used not just in forecasting, but in place of actual measurements. To eliminate this bias we have performed extensive quality control procedures on the observations which will be outlined in this chapter.

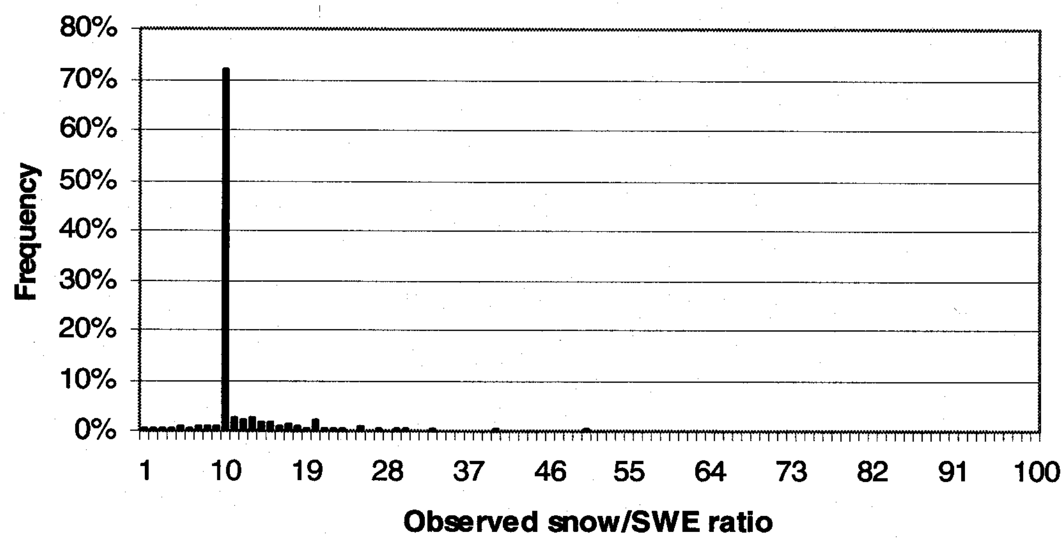


Figure 4-1: Frequency of snow/SWE ratios in the National Climate Data and Information Archive.

The first step in quality controlling the observation data set was to determine which of these 848 stations were to be used in the verification and which eliminated. It was known in advance that many of these stations were completely automated and did not have the capacity to directly measure daily snowfall. These stations measure SWE using a Belfort precipitation gauge. Then, this value of SWE is multiplied by 10 and the estimation is reported as the daily snowfall amount in the archive. In contrast, there are many manned stations that measure daily snowfall with a ruler and snowboard but are not equipped with a Nipher snow gauge. They make the opposite estimation of the automated stations and divide their daily snowfall amount by 10, then report that value as the SWE. These stations were eliminated by identifying every station that systematically reported a value of 10:1 on every occasion throughout the winter. After this filtering, the new list contained 253 stations, a significant decrease.

It still remained to identify which of these stations were reliable, that is, following the WMO standard for snowfall and SWE measurement consistently. A number of the stations, including some volunteer stations, did not have a Nipher snow gauge. However, sometimes on a day when the temperature would rise above zero, any snow that was caught in the observer's rain gauge would melt. This value of SWE would be recorded and transmitted. With the assistance of Monique Lapalme at the MSC Prairie, NWT and Nunavut region, stations that had no Nipher gauge but who were still occasionally reporting a snow/SWE ratio different than 10:1 were also identified and eliminated.

There is another way that erroneous or misleading measurements are reported. Some automated stations are equipped with an SR50-L: Ultrasonic Distance Sensor which is manufactured by Campbell Scientific Canada. It measures the elapsed time between the emission and return of an ultrasonic pulse and in this way claims to be able to measure the height of snow on the ground. Taking the difference between daily measurements is considered the daily snowfall amount and in combination with the Belfort rain gauge a snow/SWE ratio can be calculated. However, the readings from the SR50 are plagued with problems. The snow/SWE ratios it reports are highly variable and even sometimes nonsensical, particularly during the fall and spring months when the ground is not entirely covered in snow. The SR50 is sensitive to blowing snow, snow drifts and uneven melting because it is stationary. A human observer is able to take measurements in an area which is representative of the conditions on the ground and the SR50 cannot. Despite these problems, the daily snowfall accumulations measured are entered into the National Climate Data and Information Archive.

As an example, Table 4-1 shows the data available for Fôret Montmorency, a station using the SR50 instrument, for part of the month of December 2004. The shaded boxes drawing attention to the total snowfall and snow on the ground totals for the 9th, 10th, and 12th of December are just a sample of the measurement problems in this table alone. On the 9th, there was 28 cm of snow measured on the ground, on the 10th the SR50 measured 7 cm falling over the day but a snow on the ground at the end of the day of still 28 cm. On the 12th the instrument measured 1 more cm of snowfall, but a snow on the ground of 42 cm, that is, 8 cm more than the day before. Also, the column where snow/SWE ratio is calculated shows how unreliable this instrument is for this type of measurement. In one month alone it is showing a range of ratios between 2:1 and 64:1.

Table 4-1: An example of daily observations from Fôret Montmorency, a station measuring snow depth with an SR50 type instrument.

Fôret Montmorency -- December 2004							
	Max Temp	Min Temp	Total Rain	Total Snow	SWE	Snow on Grnd	snow/SWE ratio
	°C	**°C**	**Mm**	**cm**	**mm**	**Cm**	
Day							
1	-1.3	-7.5	0	7	15	10	5
2	-4.5	-16.9	M	M	0.4	17	
3	-12	-22.6	0	2	3.5	16	6
4	-5.4	-21	0	4	0.7	18	57
5	-3.4	-18.7	M	M	2.8	22	
6	-12.7	-26.9	M	M	0.4	19	
7	-10	-26.3	0	9	16.3	19	6
8	-5	-11.4	0	1	5.6	29	2
9	-3.4	-16.6	M	M	0	28	
10	-2.4	-16.5	M	7	1.1	28	64
11	-4.9	-7.6	0	5	21	34	2
12	-6	-11	M	1	1.4	42	7
13	-4.8	-11.6	0	2	3.6	42	6
14	-11.5	-18.4	M	M	0	43	
15	-7.7	-24.2	M	1	0	41	
16	-5.6	-13.4	0	4	3.4	42	12
17	-4	-26.1	0	1	6.2	47	2
18	-9.2	-28.3	M	M	0	44	
19	-4.5	-9.4	0	5	2.4	43	21
20	-6.3	-22.7	0	1	2.6	48	4
21	-14.2	-26.2	M	M	0	47	
22	-2.6	-19.5	0	7	7.9	47	9
23	6.5	-4.9	M	M	61.6	54	
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.

After assistance from Monique Lapalme in identifying which stations were using the SR50 instrument, these stations were eliminated from our study. The situation is particularly bad in the Quebec region where 10 out of 26 stations were eliminated in this way. There are also several stations which are full 24 hour manned synoptic stations, like Regina and Saskatoon in Manitoba, but their precipitation measurements are determined with the SR50 and Belfort rain gauge. After stations that were taking measurements using this combination of instruments were eliminated, the list of stations to include in this study was decreased to 152.

There were a few stations in the data set, like Fort Good Hope in the Northwest Territories, whose snow/SWE ratio were 10:1 in not every case, but in the vast majority, and other days had suspicious values, such as 4:1 even in the absence of solid precipitation. These stations were excluded from the study as having unreliable data and the number of stations was reduced to 141.

Figure 4-2 shows the geographical distribution of stations across Canada. It can be seen in this figure that even after so many stations were eliminated there is still good coverage of all the climatic regions in Canada, even in the Arctic. Noticeably, it is regions of Quebec that have the least coverage. This is in part because of Quebec's dependence on the SR50 type of instrument.

Finally, four of the remaining 141 stations: Edmonton City Centre Airport Alberta, Dryden Airport Ontario, Earlton Airport Ontario, and Muskoka Airport Ontario, were converted from manned to fully automated stations after January 19th 2005. The data from these stations can only be used for this study on the days before this date. A complete list of the stations used in this study is given in Appendix B.

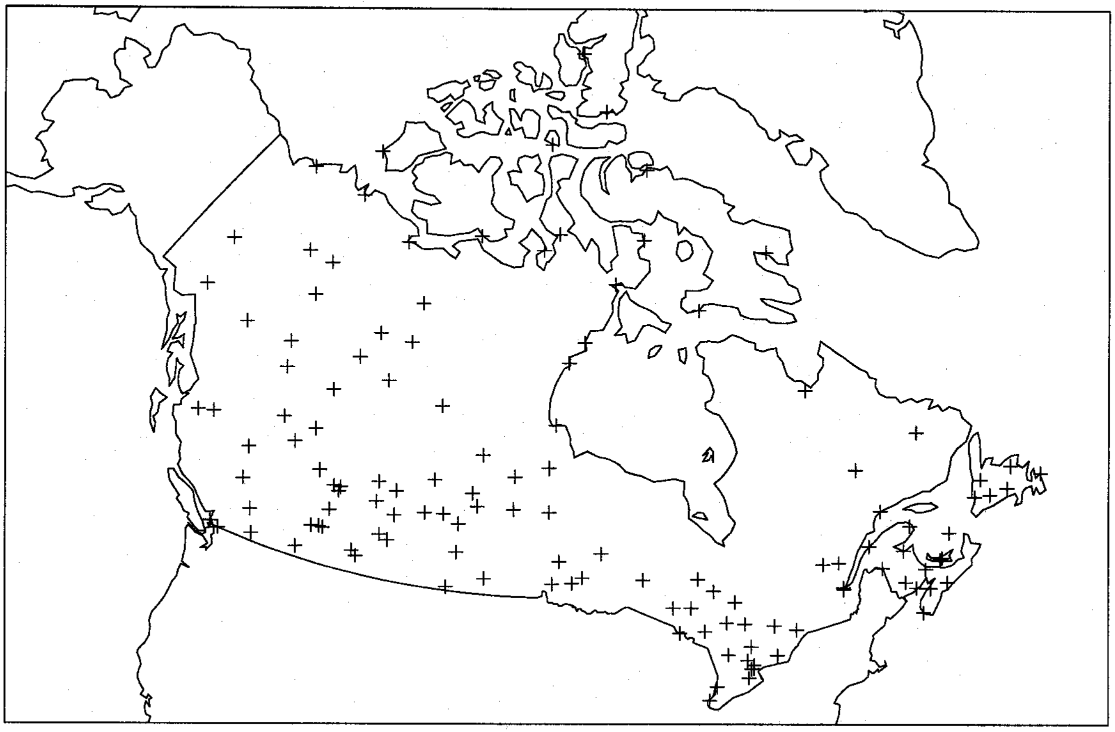


Figure 4-2: The geographic distribution of stations used in this study. Darker crosses occur when closely spaced stations overlap.

4.2 Measurement Frequency

Environment Canada operates two classes of stations: synoptic stations and climatic stations. Synoptic stations are manned 24 hour stations with a day measured from 06 UTC–06 UTC. At these stations, six hourly snowfall and SWE are measured and submitted on a station's handwritten reports that are given to the regional MSC office at the end of every month but these values are never transmitted or archived electronically. Instead, only the total daily value, the sum of 4, 6 hourly measurements, is archived in the National Climate Data and Information Archive. Finding the daily total by adding 4, 6 hourly measurements instead of taking one daily measurement reduces the impact of ground-level compaction and snow pack metamorphism, both of which lower the snow/SWE ratio and increase the density. It has been shown that the more frequently snow depth is sampled in a given interval; the more depth is measured (Doesken and

McKee 2000).

The stations belonging to the climatological snow observing network follow an 8 am to 8 am local time day, although the stringency with which these hours are applied varies. There are a few climatological stations in the Prairie region, such as Nipawan Airport in Saskatchewan, that follow a 12 UTC–12 UTC day for recordkeeping purposes but that opens at 8 am. Their procedure for calculating daily snowfall is to estimate from the snow on the ground when they open in the morning, what percentage fell overnight (before 6 am) to add to the total from the day before, and what percentage fell after 6 am to add to the total of that day. Knowing the start and end times for what a particular station calls a day will become important during the verification of the snow/SWE ratio algorithm when we will match forecast and observation time intervals.

4.3 Quality Control

Observations are available from the National Climate Data and Information Archive usually within two days after the measurement is taken. At this time, the data undergo only the most preliminary quality control, such as the elimination of extreme values and obvious transcription errors. Over the next months, the data are then subjected to more rigorous quality control procedures at the regional MSC offices. These processes involve each individual measured quantity being compared graphically to the value obtained by neighboring stations. The quality control is carried out by a human expert.

However, one important source of error for our study is not eliminated through this quality control procedure. It is well known the Nipher type snow gauge is subject to an error due to the under-catching of snow in high wind conditions resulting in a low value of SWE (Goodison, 1978). An under-catch will produce high values of snow/SWE ratio. Table 4-2 shows how the snow/SWE ratio is affected by under-catch in the Nipher. In the archive, SWE is not wind corrected. During strongly windy conditions the under-catch may make measurements extremely unreliable and it is up to the discretion of the observer how to correct the data in events where it is obvious there is an error.

Frequently, when the Nipher is obviously not giving correct results, the observer reports a snow/SWE ratio of 10:1as a default value instead of the inflated ratio measured.

Table 4-2: The effect of Nipher gauge under-catch on the snow/SWE ratio.

snowfall measured on a snowboard (cm)	SWE measured in a Nipher (mm)	snow/SWE ratio
1	1	10:1
1	0.8	13:1
1	0.6	17:1
1	0.4	25:1
1	0.2	50:1

Goodison (1978) calculates that the surface wind speed at which the error exceeds 10% is 5.5 m/s. Therefore, all observations taken when the maximum hourly surface wind speed exceeds 5.5 m/s were removed from the data set.

Because of the uncertainty in the instruments used to make measurements (±0.1 cm in the case of the snow ruler and ±0.1 mm in the case of the Nipher precipitation gauge) smaller accumulations can have greater measurement errors. Figure 4-4 is a scatter-plot snow/SWE ratio as a function of SWE accumulation. There may be unrealistically inflated ratios in low accumulation events. In order to remove this error, a somewhat arbitrary condition of a minimum SWE accumulation of 1 mm was required to keep the observation in the data set.

Finally, two last criteria were applied to the data set. The first was to eliminate all daily snow events when rain was reported coincidentally with snow except for a trace amount. The second was to eliminate all instances when snow was measured on the ground but only a trace amount of SWE was found. This happens quite frequently, especially in Northern Canada, but these cases are rejected as being unquantifiable.

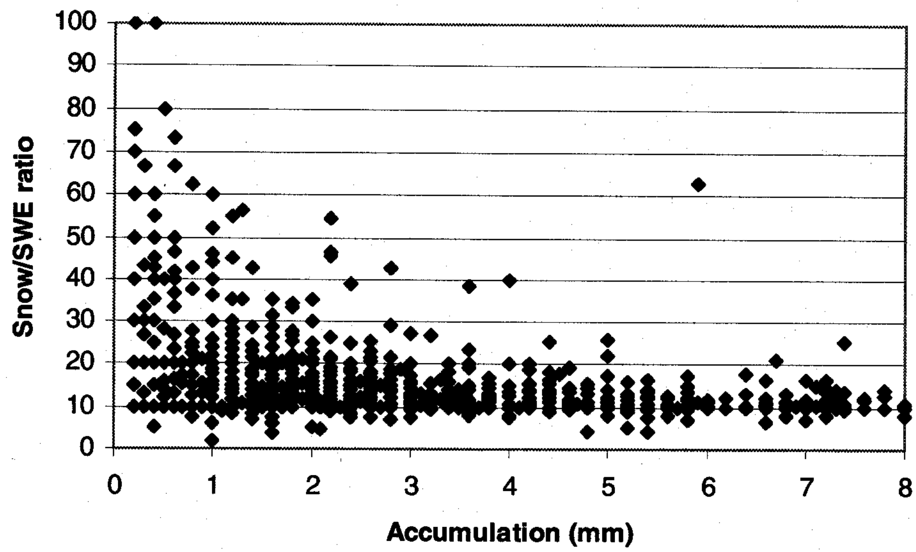


Figure 4-3: Snow/SWE ratio as a function of accumulation.

Even after these cases are removed, the data set still contains a preponderance of 10:1 snow/SWE ratios in all years for which we have data. This can be clearly seen in Figure 4-3 which is a histogram of the frequency of snow/SWE ratios in October 2004–April 2005. It is certain that some of these events were simply recorded as having a 10:1 ratio with only one of the measurements, daily snowfall, or daily SWE actually having been taken. This value is simply used as a default in many cases and the same histogram as Figure 4-3 plotted for individual stations show this same effect to greater or lesser degree. However, it is also certain that many of the events really did have a 10:1 snow/SWE ratio as it is a commonly occurring ratio. All events have been left in the data set for the purposes of verification of the MSC algorithm because, besides the eliminations we have described above, no scientific justification could be found for adjusting the remaining data artificially through something like a weighting scheme, without reference to independent studies of climatology without this flaw, or to other data sets.

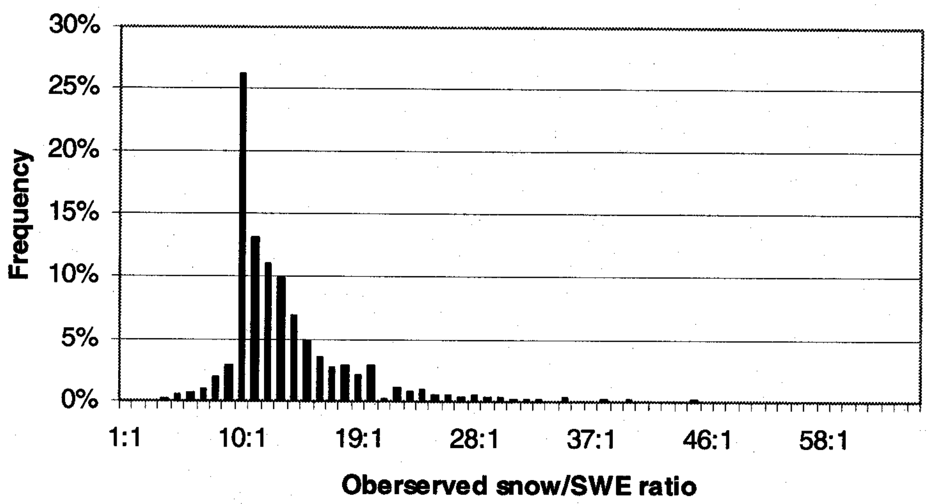


Figure 4-4: Frequency of snow/SWE ratios in the quality controlled observational data set.

In summary, due to the importance of high quality, accurate measurements when verifying any forecast model or algorithm, great care was taken to quality control the observations used in this study. The methods used have been outlined in detail in this chapter. However, even after a stringent elimination of suspicious data points through the methods described in this chapter, some bias remains as an excess of 10:1 snow/SWE observations.

Chapter 5

Climatology of Snow/SWE Ratio

Because depth and liquid equivalent of the snow pack are so important to mid- and high latitude regions, many studies of their climatology by region and by season have been made (Doesken and Judson 1997, McKay et al. 1981, Brown et al. 2003). An excellent online source for Canadian snow cover and snow pack liquid equivalent climatology is the Canadian Snow Atlas maintained by the Canadian Cryospheric Information Network at http://www.socc.ca/snow/atlas/index.cfm. This web site also provides a rough climatology of snow density in Canada based on bi-weekly snow course measurements taken by the MSC. However, climatology studies of the snow/SWE ratio of freshly fallen snow have rarely been undertaken, probably due greatly to difficulties in compiling accurate measurements of this quantity as outlined in Chapter 4.

5.1 Previous Studies

The report by Potter (1965), Water Content of Freshly Fallen Snow, was previously discussed as giving the source of the 10:1 approximation. But this report also discusses the results of the first accurate measurements of SWE after the implementation of the Nipher gauge throughout Canada. He finds a range of snow/SWE ratio of 3.6:1 to 50:1

and even produced a rough, undetailed contour map of the climatology of this ratio, with lowest mean values of 10:1 on the ocean coasts and highest mean values of 12:1 in the prairies

One of the first studies in the United States was made by LaChapelle (1962). We have discussed his book *The Field Guide to Snow Crystals*, from 1969, in Chapter 2 in the context of giving his findings on the density of different snow crystal types. Previous to writing this book, he performed a climatology of the density of freshly fallen snow at several avalanche stations in the Rocky Mountains. His motivation for performing the study was that certain snow densities were more likely to cause avalanches, mainly a snowfall with a density very different from mean density at that station. He found mean values of snow/SWE ratio ranging from 10:1 to 14:1. This study is still widely cited in the literature on this topic despite its age.

The problem of snow density forecasting for fresh snowfall was neglected after the 1960s but has been getting more attention recently from several groups and as part of this endeavor studies comparing mean snow/SWE ratio for several stations have been made. Also, some contour maps have been made of the climatology of this factor in the United States and Canada. We will now discuss a sampling of these studies.

Goodison and Metcalfe (1981) performed an experiment designed to test the efficacy of a new instrument for measuring snow density as compared to the more traditional snow ruler and Nipher gauge combination. As part of this comparison they give a table of the ratio found by dividing the Nipher measurements by the MSC ruler measurements for 19 stations across Canada (excluding the Arctic) for the years 1979–1981. The inverse of their ratio is the snow/SWE ratio used throughout this paper. They found the average ratio for Canada was 12:1. Table 5-1 gives the mean ratio from this study by region although for Ontario region there was only one station used, Monticello, and for the Prairie and Western regions only two stations were used.

Table 5-1: Mean snow/SWE ratio by region in Canada (Goodison et al. 1981).

Atlantic Region	10:1
Quebec Region	10:1
Ontario Region	14:1
Prairie Region	10:1
Western Region	14:1
Pacific Region	13:1

In a widely cited paper Judson and Doesken (2000) examines the density of freshly fallen snow at 6 avalanche stations in the mountains of Colorado and Wyoming from 1994–1998. The measurements were taken once daily in the morning. New snow depth was measured on white snow boards and SWE was calculated from cores extracted from the boards. This study, as in the previous, finds an average snow/SWE ratio higher than 10:1. In this case the average is found to be 13:1. Table 6.2 gives the highest, lowest and mean snow/SWE ratio as calculated from their paper. This table contains one of the highest ever observed ratios of 100:1, in Dry Lake.

Table 5-2: Highest, lowest and mean snow/SWE ratio at several Rocky Mountain Stations (Judson and Doesken 2000).

Station Name	Lat.	Long.	Elev.	highest snow/SWE ratio	lowest snow/SWE ratio	mean snow/SWE ratio
Steamboat Springs	40° 28'	106° 49'	2120	67:1	6:1	14:1
Dry Lake	40° 32'	106° 47'	2560	100:1	6:1	13:1
Teton Pass	43° 40'	110° 57'	2440	37:1	5:1	12:1
Eisenhower Tunnel West Portal	39° 41'	105° 55'	3360	33:1	8:1	13:1
Red Mountain Pass	37° 54'	107° 43'	3400	50:1	6:1	13:1
Wolf Creek Pass	37° 29'	106° 47'	3244	50:1	4:1	10:1

One figure from this paper is a distribution of density by number of events for each of their stations, reproduced here as Figure 5-1. The snow/SWE ratio is inversely proportional to the density so in this figure decreasing density means an increasing ratio. A density of 100 kg m^{-3} corresponds to a ratio of 10:1. It can be seen that each station has a characteristic distribution but all show a wide range of possible ratios.

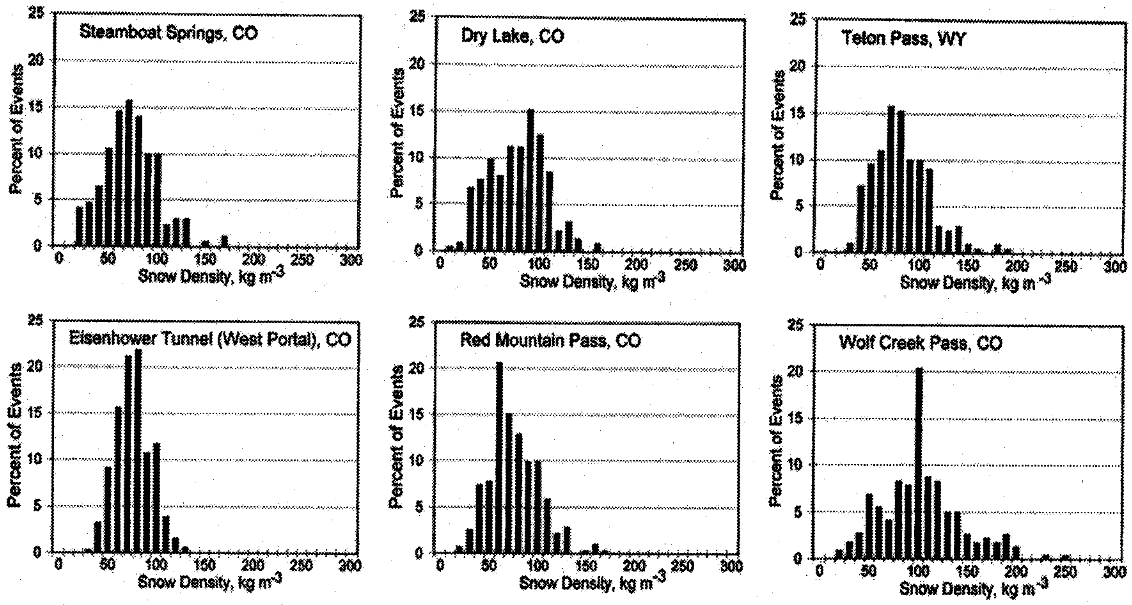


Figure 5-1: Frequency of snow densities at several Rocky Mountain stations (Judson and Doesken 2000).

We have already called attention to the work being done by Roebber *et al.* (2003) in the field of forecasting snow density. In their paper devoted to creating a new forecast model for snow density they briefly discuss the mean (15.6:1), median (14.1:1) and distribution of the snow/SWE ratios in their dataset which consists of observations in the United States between the years 1973–1994, encompassing 1650 events. Figure 5-2 is a the histogram of the frequency of snow/SWE ratio in their study. It can be seen in this figure the skewness toward higher values of ratio in the dataset. This fact is confirmed by the calculated mean of the data set being larger than the median.

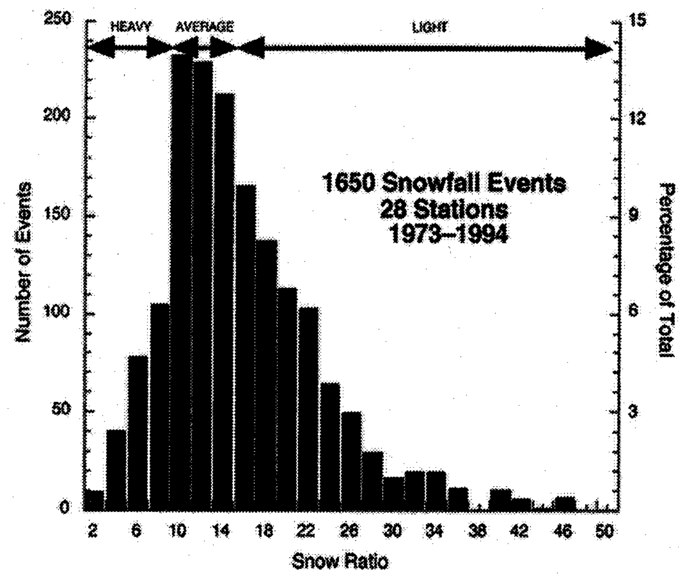


Figure 5-2: Frequency of snow/SWE ratios for several U.S. stations (Roebber *et al.* 2003).

In a Canadian study, Whiteley (2004) examined the mean densities for 34 Ontario locations. The dataset used for this climatology was the Canadian Climate Normals for 1971–2000 which include monthly mean snowfall and SWE measurements. Whitely makes special mention of the difference between "inland" stations and "lake-effect" stations because lake-effect stations typically have much lower mean densities. In fact, we will see later in the chapter that lake-effect snow is some of the least dense in North America. Whiteley found that no station in the study had a monthly mean density of less than 100 kg m^{-3}. Table 5-3 is a summation of some of the results from this paper.

Table 5-3: Mean monthly snow/SWE ratio for inland and lake-effect influenced stations in Ontario. (Whiteley 2004).

	Northern Ontario	Southern Ontario
inland stations	11:1	11:1
lake-effect stations	12:1	13:1

We will now explore the results from studies aimed at producing climatological maps of the snow/SWE ratio of freshly fallen snow in both the United States and Canada. This type of map is useful for quickly showing trends in the snow/SWE ratio by latitude and geographical location. However, these maps can have errors due to interpolation, especially in regions with sparse station coverage.

A very comprehensive climatology of snow/SWE ratio in the contiguous United States has been carried out by Baxter *et al.* (2004) at Saint Louis University. An interactive map of this climatology, showing contours of snow/SWE ratio and a histogram of the ratio versus number of cases for each state's major population center is available online at http://www.eas.slu.edu/CIPS/Research/slr/slrmap.htm. This map shows a trend towards higher ratios in the mountains, in the colder, continental interior and in lake-effect regions. Lower ratios are found in the warmer south and on the Atlantic and Pacific coasts, although there is great range in the distribution of ratios from station to station. Baxter *et al.* also calculate the mean, 12.6:1 and median, 11.4:1 of the dataset showing a skew toward positive values in their dataset. Figure 5.3 is a contour map taken from their website.

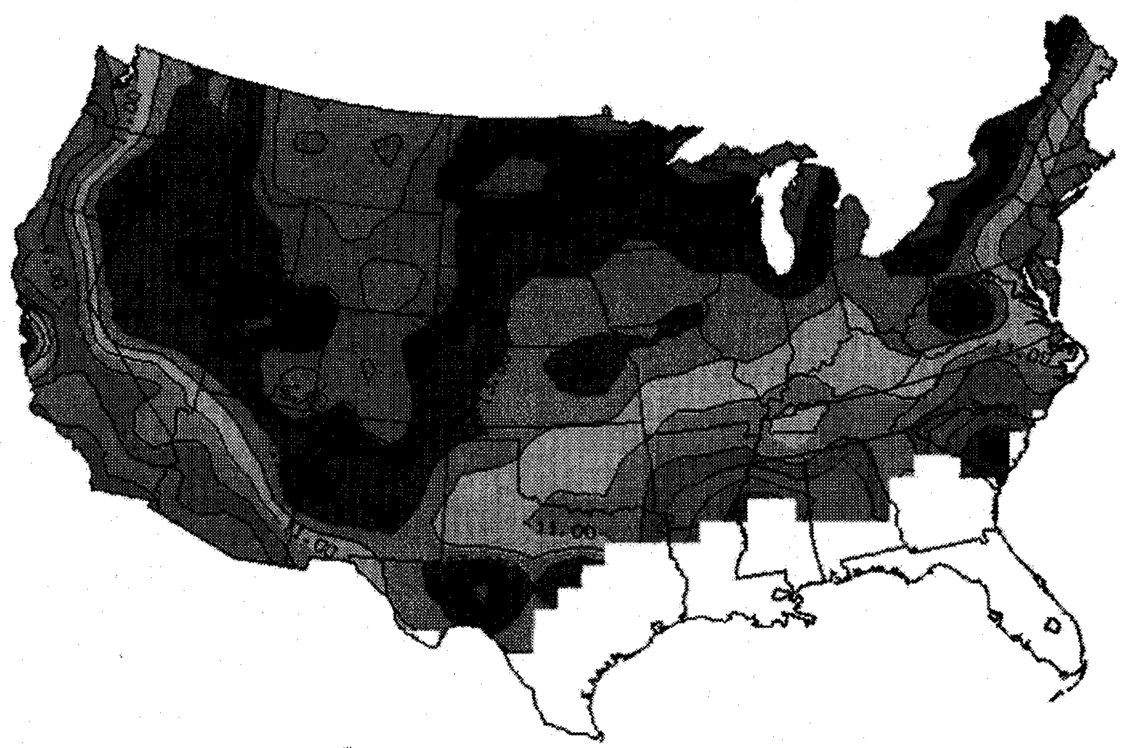


Figure 5-3: Climatology of snow/SWE ratio in the United States (Baxter *et al.* 2004).

In Canada, Mekis and Hopkinson (2004), recognizing the inadequacy of the 10:1 approximation, tried to find an alternative for more accurately estimating the SWE at a station that is only equipped with a snow ruler and built a climatology of a factor called the Snow Water Equivalent Adjustment Factor (SWEAF). To find this factor, they used 321 stations for the period 1960–2001 with a snow ruler and Nipher and they carefully corrected for wind caused error using the exposure codes for each of the 321 stations. Figure 5-4 is their final contour map. In this map we can see similar trends as shown in other studies such as higher values in the continental interior and in the lake-effect regions.

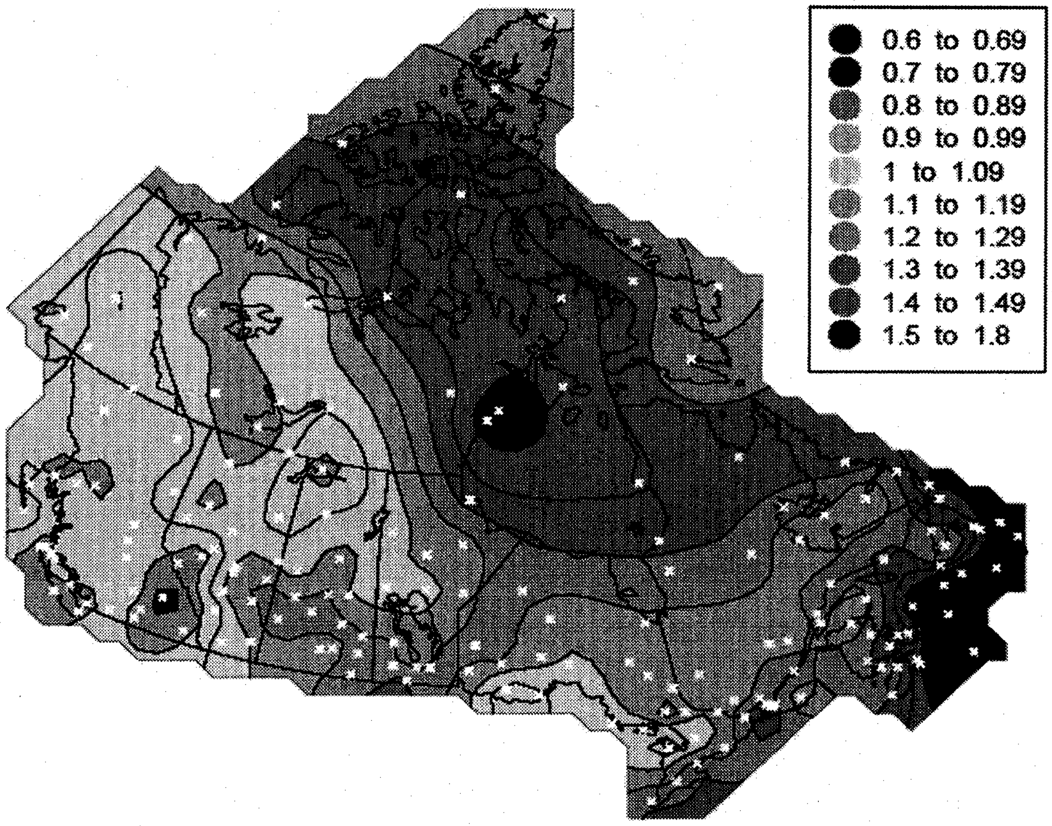


Figure 5-4: Canadian climatology of SWEAF. White crosses represent stations used in the study (Mekis and Hopkinson 2004).

Dubé performed a climatology using data from November–April, 1999–2002 using 8 stations in southern Quebec. He found the snow/SWE ratio for each event varied from 7:1 to 26:1 with an average of 13:1. He also found that the ratio varied by station, with higher ratios at the colder more continental stations and lower ratios where the maritime influence was greater. The ratio also varied by season, being lowest in November and April, and highest in December through February. Table 5-4 shows the frequency at which different snow/SWE ratios were observed in the study.

Table 5-4: Frequency of observed snow/SWE ratio by season in Quebec (Dubé 2003).

Snow category snow/SWE ratio	Heavy ≤ 8.5:1	Average 8.6:1 - 12.5:1	Light 12.6:1 - 17.5:1	Very Light 17.6:1 – 22.5:1	Ultra Light ≥ 22.6:1
Early/Late (NOV/MAR - APR)	3%	70%	20%	6%	1%
Mid-winter (DEC - JAN - FEB)	1%	48%	37%	11%	3%

We have now made a survey of the literature available on the climatology of snow/SWE ratios in Canada and the United States. It has been seen that this ratio varies considerably spatially and in agreement with the physics of snow/SWE ratio as discussed in Chapter 2. That is, in general we expect moderately cold (between –10°C and –25°C) and humid climates to have low density snow, whereas both warmer (above –10°C) and extremely cold (below –30°C) regions have snow with higher density.

5.2 Climatology

The first step in our verification was to make a climatology of our own using the National Climate Data and Information Archive for the stations which we had already isolated for use in our study through the quality control procedures detailed in Chapter 4. On the advice of staff at Environment Canada we chose to use as a time period October–April, 1989–1995 because after 1995 observations at stations were no longer maintained by Environment Canada and it was felt that pre-1995 data would be the most reliable. Nevertheless, as Figure 5-5 illustrates, there is still a bias toward 10:1 as was discussed previously. Baxter *et al.* (2002) discuss similar (although of significantly lesser magnitude) findings in their data set so this bias is known to be a common problem, albeit one that is very difficult to isolate and correct. We have no way of knowing when the measurements were taken correctly and when they were just estimated as having a 10:1 ratio, furthermore, since each station has different observers, each station has a totally independent percentage of bias. For these reasons, no correction has been applied except for repeating the same quality control procedures as outlined in Chapter 4.

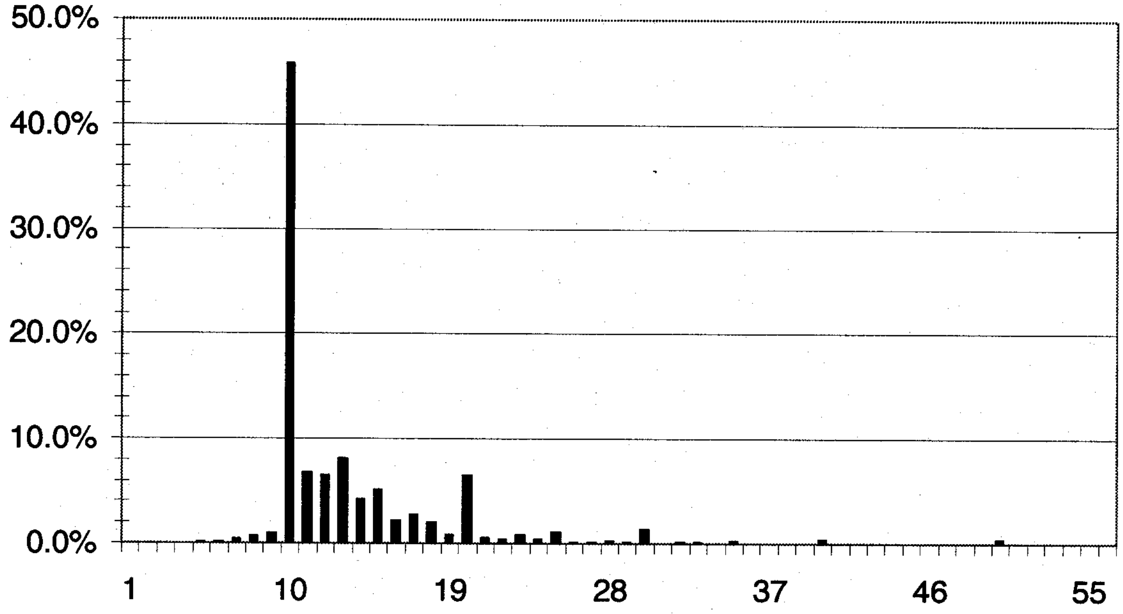


Figure 5-5: Frequency of snow/SWE ratios in Canada during November–April, 1989–1995.

In this data set the mean snow/SWE ratio is 13.3:1 and the median is 10.8:3 showing the same skew toward higher ratios as has been found in other studies (Baxter *et al.*, 2002; Roebber *et al.*, 2003 and Dubé 2003). However, this data set does not have as large a difference between the distribution of snow/SWE ratio in the early/late part of the winter season and the mid-season as Dubé found. One possible reason is that there are large variations in the length of winter season across Canada so that in the Arctic regions November, March and April are still very cold and capable of producing low density snow. Table 5-5 is the snow category of snow/SWE ratio in our data set by part of the season, in the same format as Dubé.

Table 5-5: Frequency of observed snow/SWE ratio by part of season in Canada.

Snow category snow/SWE ratio	Heavy ≤ 8.5:1	Average 8.6:1 - 12.5:1	Light 12.6:1 - 17.5:1	Very Light 17.6:1 – 22.5:1	Ultra Light ≥ 22.6:1
Early/Late (NOV/MAR – APR)	2%	64%	20%	9%	5%
Mid-winter (DEC - JAN - FEB)	1%	61%	22%	10%	6%

We have been discussing the variation of snow/SWE ratio by climatic region in Canada. Figure 5-6 is a map of the stations used in this study with their corresponding mean snow/SWE ratio, indicated by color. Because of the bias toward 10:1 that we have discussed at length, the ratio values may be somewhat depressed. Nevertheless, some familiar geographic trends can be seen.

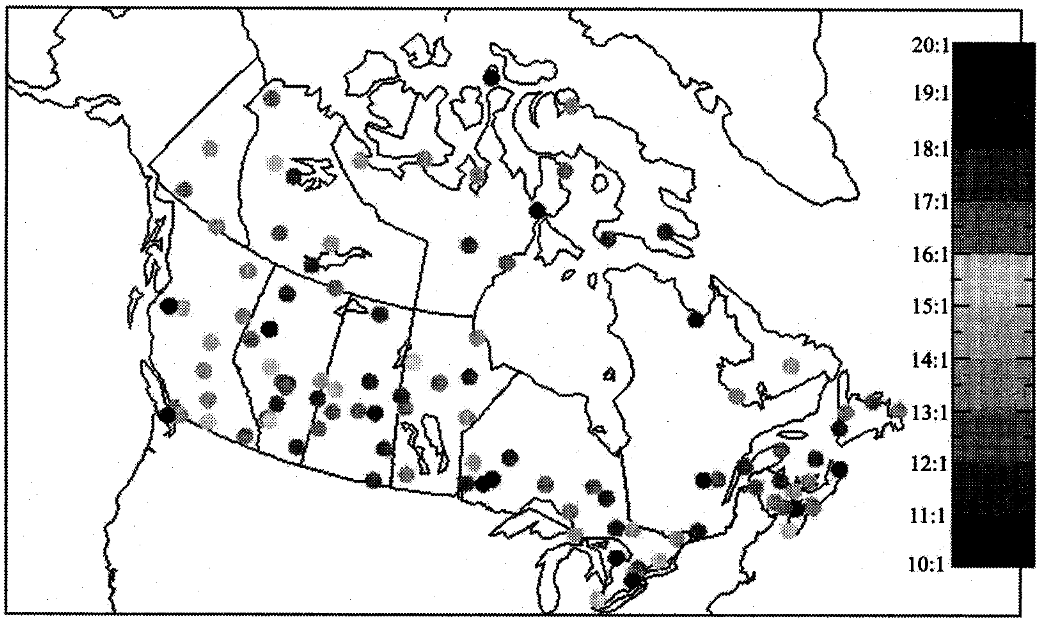


Figure 5-6: Observed mean snow/SWE ratio at several stations for the period of October–April, 1989–1995.

The highest ratios are in the moderately cold Prairies and also in the lake-effect influenced regions east of the Great Lakes and the Bay of Fundy. Low ratios are found in the coastal regions and also in the extremely cold Arctic. There are large bodies of water in this region but for October–April, these bodies of water are frozen. The cause of these high densities is average temperatures below –25°C (for example, the mean February surface temperature of Pond Inlet, Nunavut is –34°C). Rae (1951), claimed to frequently measure a ratio of 5:1 in the Arctic. In addition to this however, harsh climatic conditions combined with frequent blowing snow events make measurement difficult in this region so there is likely to be more bias toward 10:1 in this region than in the others, which would depress the means. Table 5-6 presents the mean annual snow/SWE ratio by region.

Table 5-6: Mean observed snow/SWE ratio by region for the period October–April, 1989–1995.

	Mean Forecast snow/SWE ratio
British Columbia	13:1
Prairies	14:1
Nunavut	12:1
Yukon & NWT	14:1
Ontario & Quebec	12:1
Atlantic	13:1

By making a survey of the literature and creating our own climatology of snow/SWE ratio we have seen several trends. In general, ratios are lowest in warmer regions like on the coasts and also in the extremely cold regions like the Arctic. Ratios are highest in the mountains, in the moderately cold continental interior, and in lake-effect regions. However snow/SWE ratios are highly variable both spatially and temporarily. An understanding of climatology will help us understand the results of our verification, which will be discussed in the next chapter.

Chapter 6

Verification of the Algorithm

Having quality controlled our observational data; the final step in the verification process is to compare the observed snow/SWE ratios to those predicted by the MSC algorithm. In order to do this we must resolve grid point and forecast time differences in the observational and forecast data sets. We will assess the performance of the algorithm using several evaluation methods, and examine the relationship of the algorithm's performance to several important variables: accumulation, surface temperature, surface wind speed, climatic region and month of the year. This chapter will also address how the results of this verification compare with the original Quebec verification performed by Dubé (2003).

6.1 Forecast — Observation Couplets

In order to perform a verification, the beginning and end times of both the forecast and observation in a couplet must be the same. Environment Canada's National Climate Data and Information Archive reports snow depth and SWE daily. This coarseness of measurement is unfortunate for our verification since, depending on changing weather conditions, snow density during an event can change hourly or less. As discussed in Chapter 4, there are two types of stations in Canada: synoptic stations and climatic stations. The distinction is important since the two types of stations have different start and end times for their daily values. Synoptic stations run from 06 UTC–06 UTC but climatic stations run from 8 am–8 am local time with a few exceptions in the Prairies, which run from 12 UTC–12 UTC.

The MSC algorithm creates forecasts at many different times. Its input is from the GEM model, initialized at 00 UTC and at 12 UTC each day. At each initialization time, GEM creates a 48 h forecast in 3 h intervals. Therefore, at any given time, there are 4 overlapping valid forecasts. To illustrate this point we present Table 6-1, which has entries for every forecast made by GEM over a 3 day period. As an example, the shaded boxes represent all the valid overlapping forecast times at 00 UTC on Day 3. In this case the overlapping forecast times are a 12, 24, 36 and 48 h forecast.

Table 6-1: A summary of all GEM forecasts in a 3 day period.

Day	UTC	Forecast time (hours after initialization)																		
1	00	3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48			
1	12					3	6	9	12	15	18	21	24	27	30	33	36	39	42	45
2	00									3	6	9	12	15	18	21	24	27	30	33
2	12													3	6	9	12	15	18	21
3	00																	3	6	9
3	12																			

The MSC algorithm calculates a snow/SWE ratio at every GEM forecast time for the 6, 12 and 24 hours previously, if there is enough data to do so. For instance, if the algorithm uses a 9 h GEM forecast, not enough time in the model run has elapsed to calculate a ratio for the 12 hours previous. Since the forecast time scheme is complicated, Table 6-2 is an example of the algorithm output from November 5th, 2005 for station YWK.

Table 6-2: An example of the different forecasts times from the MSC algorithm. This example is valid for station YWK (Wabush Lake, Nfld).

Station	Date	Observation Time (UTC)	GEM forecast used (h)	snow/SWE ratio for period 6 hours in advance of observation time	snow/SWE ratio for period 12 hours in advance of observation time	snow/SWE ratio for period 24 hours in advance of observation time
YWK	2004/11/05	0000	12	0	10:1	Not possible
YWK	2004/11/05	0000	24	10:1	10:1	10:1
YWK	2004/11/05	0000	36	10:1	10:1	10:1
YWK	2004/11/05	0000	48	10:1	10:1	10:1
YWK	2004/11/05	0300	3	Not possible	Not possible	Not possible
YWK	2004/11/05	0300	15	0	10:1	Not possible
YWK	2004/11/05	0300	27	0	11:1	10:1
YWK	2004/11/05	0300	39	0	10:1	10:1
YWK	2004/11/05	0600	6	14:1	Not possible	Not possible
YWK	2004/11/05	0600	18	10:1	10:1	Not possible
YWK	2004/11/05	0600	30	14:1	13:1	13:1
YWK	2004/11/05	0600	42	0	10:1	10:1
YWK	2004/11/05	0900	9	12:1	Not possible	Not possible
YWK	2004/11/05	0900	21	11:1	11:1	11:1
YWK	2004/11/05	0900	33	13:1	13:1	13:1
YWK	2004/11/05	0900	45	11:1	11:1	11:1
YWK	2004/11/05	1200	12	12:1	12:1	Not possible
YWK	2004/11/05	1200	24	13:1	12:1	12:1
YWK	2004/11/05	1200	36	12:1	13:1	13:1
YWK	2004/11/05	1200	48	13:1	13:1	12:1
YWK	2004/11/05	1500	3	11:1	Not possible	Not possible
YWK	2004/11/05	1500	15	13:1	13:1	Not possible
YWK	2004/11/05	1500	27	12:1	12:1	12:1
YWK	2004/11/05	1500	39	10:1	12:1	12:1
YWK	2004/11/05	1800	6	12:1	Not possible	Not possible
YWK	2004/11/05	1800	18	14:1	13:1	Not possible
YWK	2004/11/05	1800	30	11:1	11:1	11:1
YWK	2004/11/05	1800	42	11:1	12:1	12:1
YWK	2004/11/05	2100	9	13:1	12:1	Not possible
YWK	2004/11/05	2100	21	15:1	14:1	13:1
YWK	2004/11/05	2100	33	11:1	12:1	12:1
YWK	2004/11/05	2100	45	12:1	12:1	12:1

Clearly there are several different combinations of forecast time interval that will overlap the observational time interval. In order to make the best possible decision for which combination to use, some exploration of the snow/SWE ratio forecast data set is necessary. Table 6-3 compares the mean 6, 12 and 24 hourly snow/SWE ratios from our forecast data set and also compares the mean snow/SWE ratio for all the GEM input forecast times. In this table the variance of the different intervals of forecast snow/SWE ratio (either the 6, 12 or 24 h interval) is small, with a value of 0.02. The variance for the different GEM input forecasts times is also small, with a value 0.01. These results are encouraging as they indicate that the algorithm is producing similar results regardless of which GEM forecast input time or snow/SWE ratio interval is being used to make a forecast.

Table 6-3:Comparison of the mean snow/SWE ratio for all possible forecasts of the algorithm for all sites.

GEM Forecast time used (hrs)	6 hour ratio	12 hour ratio	24 hour ratio	Mean
3				
6	11.2:1			11.2:1
9	11.3:1	11.2:1		11.2:1
12	11.2:1	11.1:1		11.2:1
15	11.4:1	11.2:1		11.3:1
18	11.4:1	11.3:1		11.3:1
21	11.4:1	11.3:1	11.1	11.3:1
24	11.2:1	11.0:1	10.9	11.0:1
27	11.3:1	11.2:1	11.0	11.1:1
30	11.2:1	11.2:1	11.0	11.1:1
33	11.3:1	11.2:1	11.0	11.2:1
36	11.1:1	11.0:1	10.8	11.0:1
39	11.2:1	11.1:1	10.9	11.1:1
42	11.3:1	11.2:1	10.9	11.1:1
45	11.1:1	11.1:1	10.9	11.1:1
48	11.0:1	11.0:1	10.8	11.0:1
Mean	11.2:1	11.1:1	10.9	

It is well known that GEM model predicts precipitation more accurately in the 24–48 h forecasts than the shorter range ones because it needs time to "spin-up" systems. Although the MSC algorithm does not use the quantitative precipitation forecast from GEM as an input parameter, in order to save on computation time, the algorithm is only run when GEM is forecasting precipitation at a grid point. Therefore, it will create the most forecast–observation couplets when the 24–48 h GEM forecast times are used as input.

Taking all this into consideration, the forecast times used for this verification are as follows: snow/SWE ratio forecasts for the 24 hours previous to 06 UTC, using the 42 h GEM forecast as input for synoptic stations, snow/SWE ratio forecasts for the 24 hours previous to 15 UTC, using the 39 h GEM forecast as input for climatic stations and snow/SWE ratio forecasts for the 24 hours previous to 12 UTC, using the 26 h GEM forecast for stations on 12 UTC-12 UTC day. To clarify, the boxes corresponding to these selected times are shown shaded in blue in Table 6-2. In the case of climatic stations, using this forecast time matches exactly their observation day only in the stations operating on Mountain Standard Time. Unfortunately, it is not possible to match up more closely the observational and forecast time periods for the climatic stations, since the algorithm is run only every 3 hours.

Besides having the same start and end times, a forecast and observation must be at the same point in space in order to perform a verification. In our observational data set, the stations are irregularly spaced with latitudes and longitudes given in the station list of Appendix B. The algorithm is run on the same 15 km resolution grid as the GEM model. Therefore, in the forecast data set, a bicubic interpolation (de Boor, 1962) has been performed to calculate its values at the same points as the stations being used in this study.

6.2 Algorithm Evaluation

6.2.1 Evaluation of the Algorithm Using Contingency Tables

A common tool used in forecast verification is a contingency table. A contingency table is a method of comparing two categorical variables, in this case the forecast ratios and observed ratios, in order to examine relationships between them. This section will be devoted to exploring the algorithm performance using this tool.

In order to build a contingency table, the range of possible values in the two variables must be identical and in a manageable number of categories. The range of snow/SWE ratio in our observational data set is from 4.4:1 to 55.0:1 in increments of 0.1. However, the range of the MSC algorithm is from 4:1 to 25:1 in whole number increments. In order to make these two ranges compatible we have followed the same classification as Dubé in his original development and verification. That is, snow/SWE ratio will be broken into 6 categories, each category with a range of values associated with it. Any forecast or observation within the range of a category will be given one associated value for that category. Table 6-4 is the 6 categories, their ranges, and assigned values.

Table 6-4: Categories used in the contingency tables as well as their range and assigned value.

	very heavy snow	heavy snow	average snow	light snow	very light snow	ultra light snow
range	3:1 - 5:1	6:1 - 8:1	9:1 - 12:1	13:1 - 17:1	18:1 - 22:1	23:1 +
assigned value	4:1	7:1	10:1	15:1	20:1	25:1

A contingency table can be built with our results, matching forecast and observational couplets (Table 6-5). Each box in the table corresponds to a certain forecast and observation. The percentage inside each box corresponds to the frequency with which that couplet appears. The grey shaded center diagonal boxes represent correct forecasts. The number above the diagonal represents under-forecasts (predicted values that were lower than observed) and the numbers below the diagonal represent over-forecasts (predicted values that were higher than observed).

Table 6-5: Contingency table of the MSC algorithm in comparison with the observational data set.

	Observed					
Forecast	very heavy snow	heavy snow	Average snow	light snow	very light snow	ultra light snow
very heavy snow		0.4%	0.9%	0.2%	0.1%	
heavy snow	0.2%	0.5%	4.3%	0.8%	0.5%	0.1%
average snow	0.1%	1.6%	38.6%	18.1%	7.3%	3.6%
light snow	0.1%	0.3%	7.5%	7.1%	2.0%	1.4%
very light snow		0.2%	0.9%	1.3%	1.0%	0.9%
ultra light snow				0.1%		

We can now make several points about these results. One important comparison of the algorithm is to the 10:1 approximation. Table 6-6 is the contingency table which results when this approximation is used. Another important comparison is against a set of randomly generated "forecast" values in the same range (4:1—25:1) and compared against observation. Table 6-7 is a table of this random "forecast" type of comparison.

Table 6-6: Contingency table for the 10:1 approximation.

	Observed					
Forecast	very heavy snow	heavy snow	average snow	light snow	very light snow	ultra light snow
very heavy snow						
heavy snow						
average snow	0.3%	3.0%	52.2%	27.6%	10.8%	6.0%
light snow						
very light snow						
ultra light snow						

Table 6-7: Contingency table for the randomly generated "forecasts".

	Observed					
Forecast	very heavy snow	heavy snow	average snow	light snow	very light snow	ultra light snow
very heavy snow		0.1%	4.0%	1.7%	0.9%	0.4%
heavy snow		0.5%	8.1%	4.1%	1.7%	1.2%
average snow	0.1%	0.9%	9.1%	4.6%	2.0%	1.0%
light snow	0.2%	0.8%	12.4%	7.0%	2.7%	1.2%
very light snow	0.1%	0.5%	11.4%	7.7%	2.3%	1.3%
ultra light snow	0.2%	0.1%	7.1%	2.6%	1.2%	0.9%

Using these contingency tables, we can calculate the percentage of correct forecasts in each case by adding the percentages in the grey shaded boxes. The percentage correct for the MSC algorithm is 47.3%, for the 10:1 approximation it is 52.2%, and for the randomly generated "forecasts" it is 19.7%. In comparison, the Roebber *et al.* method had 60.4% correct forecasts although they had 3 categories in their verification instead of 6.

In the percentage correct calculation, the 10:1 approximation is out-performing the algorithm by 5%. This is a simplistic way to compare the two methods and it does not reflect the fact that, for many events, the algorithm may not be correct within the limits of the observed category but it is still an improvement over the 10:1 approximation. For example, it is an improvement when the algorithm forecasts light snow and ultra light snow is observed. The percentage of events wherein the algorithm performs with equal or greater skill than the 10 :1 approximation is 84.1%, a significant result. Also, the algorithm is clearly outperforming the randomly generated set of snow/SWE ratios and so demonstrates skill at mimicking the actual physics of the atmosphere.

6.2.2 Evaluation of the Bias

Another type of verification score is the bias. In this context, bias refers to the tendency for the algorithm to under- or over-forecast. Table 6-8 is the bias in these contingency tables. As expected, the random "forecasts" show an almost equal percentage of over- and under-forecasts whereas the 10:1 approximation and the algorithm both show a tendency to under-forecast the snow/SWE ratio.

Table 6-8: The bias of several different snow/SWE ratio forecast schemes.

Bias	
Under-forecasting	Over-forecasting
MSC algorithm	
40.6%	12.2%
10:1 approximation	
44.4%	3.3%
random "forecasts"	
35.0%	45.2%

6.2.3 Evaluation of the Algorithm Using Mean Absolute Error

A strength of the MSC algorithm is that its range of forecast values closely reflects the observed range of snow/SWE ratio. We will now perform the verification using a skill score which does not compress this range into categories, the Mean Absolute Error (MAE). We will compare the MAE of the algorithm to that of several other methods.

Equation 7-1 is the equation of the MAE. In this equation F is the forecast value of snow/SWE ratio and O is the observed value. One useful attribute of this skill score is that the absolute error gives the between the forecast snow/SWE ratio and the observed ratio. For example, an observation of 10:1 and a forecast of 12:1 would have an absolute error of 2. Table 6-9 is the results from calculating the MAE for the algorithm, the 10:1 approximation, and set of random forecasts. Also in this table is the MAE that results from replacing 10:1 (a low value) with 13:1 (the average value in Canada) in the 10:1 approximation.

$$MAE = \frac{1}{n}\sum^{n}|F - O| \quad (7\text{-}1)$$

Table 6-9: MAE for several forecast schemes. The best score is underlined.

Mean Absolute Error			
MSC algorithm	10:1	Random forecasts	13:1
3.8	3.9	6.4	<u>**3.4**</u>

Using this skill score, the algorithm is slightly out-performing the 10:1 approximation. The algorithm has an MAE of 3.8 and the 10:1 approximation has an MAE of 3.9. The randomly generated forecasts show considerably less skill, with an MAE of 6.4 and the last column of Table 6-9 is the technique with the lowest MAE, the (newly invented) 13:1 approximation.

As an indication of the average difference between forecast and observation, the MAE scores in Table 6-9 are slightly inflated due to the mismatch between the ranges of possible ratios in the forecast data set and the observational data set. For example, for events with an observed 55:1 snow/SWE ratio, the algorithm can at best forecast 25:1, since this is the opposed upper limit of the algorithm. Table 6-10 is the MAE calculated for the same 4 forecast tools with snow/SWE ratios above 25:1 removed from the data sets. As expected, an improvement is evident in all 4 techniques, although more so for the 10:1 approximation instead of the algorithm because, for light density events, the algorithm is outperforming the approximation.

Table 6-10: MAE for several types of snow/SWE ratio. Events with an observed snow/SWE ratio greater than 25:1 have been removed. The best score is underlined.

Mean Absolute Error			
MSC algorithm	10:1	Random forecasts	13:1
3.2	3.3	6.0	<u>**2.8**</u>

It is useful to examine the MAE for our previously established categories of snow/SWE ratio. Table 6-11 contains the results from calculating the MAE for the ranges of ratio corresponding to very heavy snow (3:1–5:1), heavy snow (6:1–8:1), average snow (9:1–12:1), light snow (13:1–17:1), very light snow (18:1–22:1) and ultra light snow (23:1+). The percentage of observations that fell into these categories is shown in this table.

Table 6-11: MAE by category of snow/SWE ratio for the algorithm and the 10:1 approximation. The best score in a given category is underlined.

	MSC algorithm	10:1	% of events in this category
very heavy snow	<u>**4.8**</u>	5.3	0%
heavy snow	3.7	<u>**2.5**</u>	3%
average snow	1.7	<u>**0.7**</u>	51%
light snow	<u>**3.5**</u>	4.4	28%
very light snow	<u>**7.8**</u>	9.5	11%
ultra light snow	<u>**16.7**</u>	19.4	6%

In this table's results, the algorithm is out-performing the 10:1 approximation in categories representing 54% of the events in our data set. Although in the average snow category (51% of the events) the algorithm performs very well, the 10:1 approximation has a large advantage. We have discussed in Chapter 4 that there is still a bias remaining in the observational data set towards an excess of 10:1 reports and in the case of observations with a ratio of 10:1, the MAE of the approximation is 0. Also in this table we can see that although the very light and ultra light snow represents 17% of events, both forecast techniques perform very poorly in this observed snow/SWE range.

6.3 Algorithm Performance and its Relationship to Several Parameters

6.3.1 Accumulation

In the observational data set used in this verification, daily SWE accumulation ranges from 1 mm to 40.4 mm. In terms of human impact, events with an approximately greater accumulation than 5 mm become important; therefore operational forecasters are especially concerned with correctly forecasting these events. This section will explore the relationship between the performance of the MSC algorithm and accumulation.

We will discuss accumulation in terms of SWE. Since SWE is a measure of water mass, it is a more consistent measure to use than snowfall depth. Depending on the snow/SWE ratio, a given snowfall depth could be equivalent to many values of water equivalent mass. For example, dendritic, lake-effect snow events are known to have large accumulations in terms of snow depth. However, they also have high snow/SWE ratios. A 10 cm snowfall of such an event with a snow/SWE ratio of 25:1 would produce only 4 mm on SWE, a small amount of liquid water.

Figure 6-1 is a scatter-plot of the snow/SWE ratio in the observational data set as a function of SWE accumulation. The values begin at 1 mm because smaller accumulation events were not included in the observational data set. A strong trend can be seen in this figure of snow/SWE ratio decreasing with increasing SWE accumulation; a result which has been found in other studies (Ware *et al.* 2004).

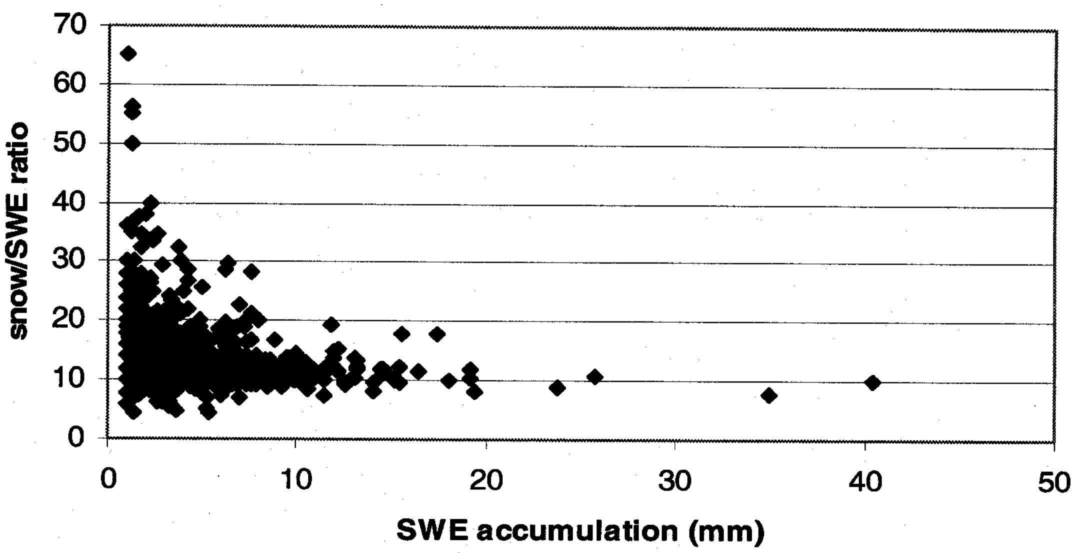


Figure 6-1: Snow/SWE ratio as a function of SWE accumulation in the observational data set.

To illustrate the distinction between measuring accumulation in SWE and measuring snow depth we present Figure 6-2, the snow/SWE ratio in our observations as a function of snow depth. In Figure 6-2, the trend of decreasing ratio with increasing depth still exists but is less pronounced. High snow/SWE ratios (>20:1) continue to be present in events producing up to 21 cm whereas in Figure 6-1 high snow/SWE ratios (> 20:1) are present only up to 7 mm SWE events. The data set is the same for both figures. This shows that the relationship between snow/SWE and SWE accumulation, a measure of mass, is stronger than that between snow/SWE ratio and snow depth.

The cause of decreasing snow/SWE ratio with increasing accumulation is not certain. There are at least 3 possible causes, all of which may be acting in concert. First, the physics causing large accumulation events may also be causing low snow/SWE ratio. For example, the amount of moisture an air mass can hold depends on temperature. Warmer air masses can contain more precipitatable water, leading to larger accumulation events, and we have seen in Chapter 2 that warmer temperatures are responsible for lower snow/SWE ratios. Stewart (1992) found large accumulations in the transition region (air temperatures near 0°C) of snow events and such cases are normally of low ratio.

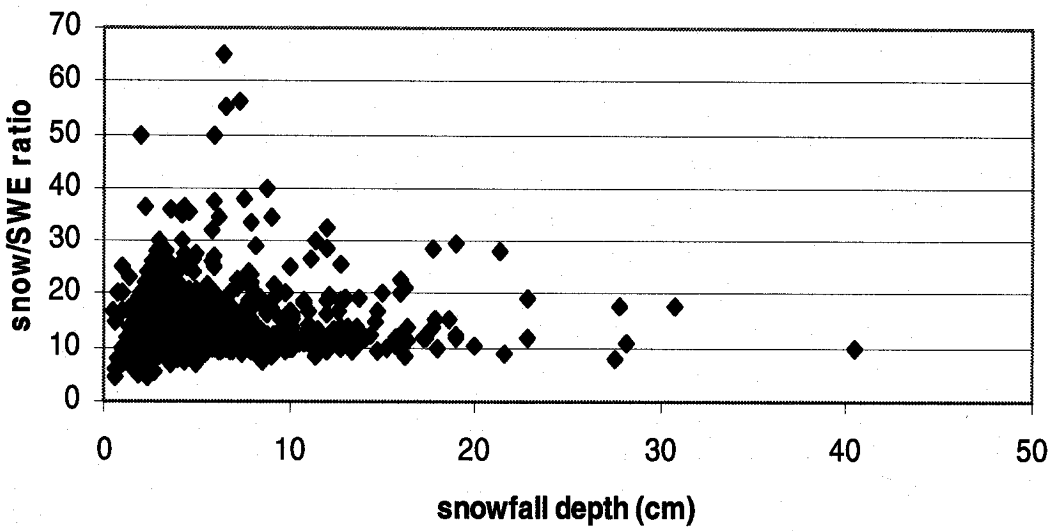


Figure 6-2: Snow/SWE ratio as a function of snowfall depth in the observational data set.

Second, as we discussed in Chapter 4, due to the measurement uncertainty inherent in the instruments used to make observations (±0.1 cm with a ruler and snowboard and ±0.1 mm with a Nipher SWE gauge) smaller accumulation events are prone to larger measurement error. For example, making a measurement error of 0.1 mm in a 1 mm event causes a 10% error in snow/SWE ratio whereas the same measurement error on a 10 mm event will only give a 1% error in the value of snow/SWE ratio. A 10% error can cause a large change in ratio whereas a 1% error will not change the measured ratio. As a consequence of this, we should see decreasing variance with increasing accumulation. Figure 6-1 does show decreasing variance with increasing accumulation. However, if this were the sole cause of the trend, the ratios should converge on the mean value, but in this figure they converge to slightly below the mean value.

A third explanation for this trend is compaction. The weight of a layer of freshly fallen snow compresses the layers underneath, increasing the density and decreasing the measured snow/SWE ratio. Doesken and McKee (2000), found that the sum of 4, 6 hourly measurements of snow depth during a snow event could increase the measured depth by 19% over one daily measurement. Therefore, even the synoptic stations in our study would be subject to the effect since they calculate their daily values as a sum of 4, 6 hourly measurements. In contrast, Dubé (2003) did not find that compaction was acting on his observations; however, he used 3 hourly measurements in his study.

To determine if the MSC algorithm increases its performance in high accumulation events, which would make it useful to operational forecasters, we will calculate the MAE for several categories of accumulation. Table 6-13 is the results of this calculation. The MSC algorithm performs significantly better (35%–50%) in the important events of SWE accumulation greater than 5 mm.

Table 6-12: MAE of the MSC algorithm and 10:1 approximation for several categories of SWE accumulation.

Daily SWE (mm)	MAE
1–5	4.0
5–10	2.6
10–15	2.0
15 +	2.6

6.3.2 Surface Temperature

As we have discussed in Chapter 2, it is not the surface temperature which controls crystal habit, but rather the temperature inside the cloud where crystal formation takes place. The few exceptions are where the surface temperature is above 0°C and ice pellets, freezing rain or melting occur. Therefore, we do not expect to see a significant correlation between surface temperature and absolute error in the algorithm. Nevertheless, it is important to test this assumption and examine the relationship between surface temperature and algorithm performance.

Figure 6-3 is a scatter-plot of snow/SWE ratio as a function of mean daily surface temperature in the observational data set. As expected, no relationship between surface temperature and snow/SWE ratio (except in events with a surface temperature above 0°C) can be seen in this figure.

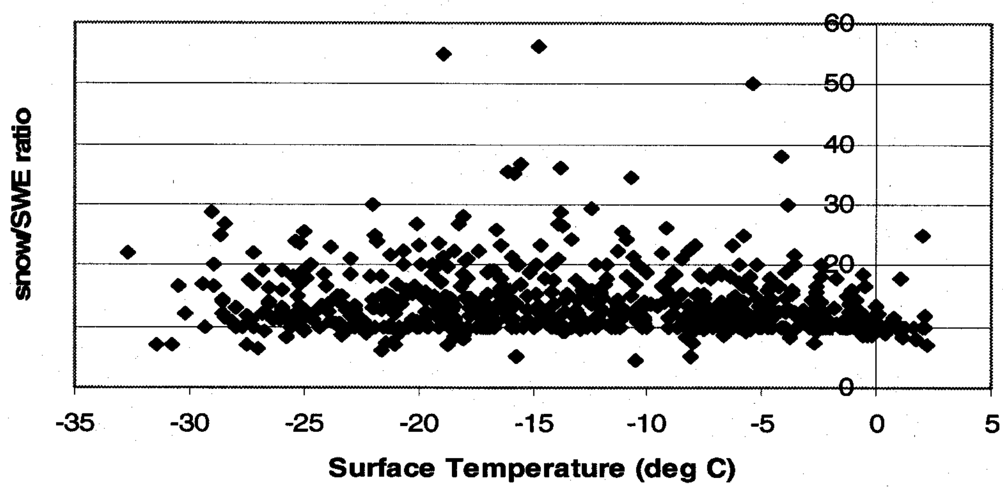


Figure 6-3: Snow/SWE ratio as a function of mean daily surface temperature in the observational data set.

Figure 6-4 is the scatter-plot of snow/SWE ratio as a function of mean daily surface temperature in the forecast data set. The range of possible values are more compressed in this data set, since only 4:1–25:1 are permitted values in the MSC algorithm. In Figure 6-4, there is a slight relationship between the two variables. Snow/SWE ratios greater than 20:1 are only seen in the temperature range of –5°C to approximately –20°C. The snow/SWE ratios decrease above –5°C and below –20°C. As in the observational data set, events with a surface temperature above 0°C have a low snow/SWE ratio.

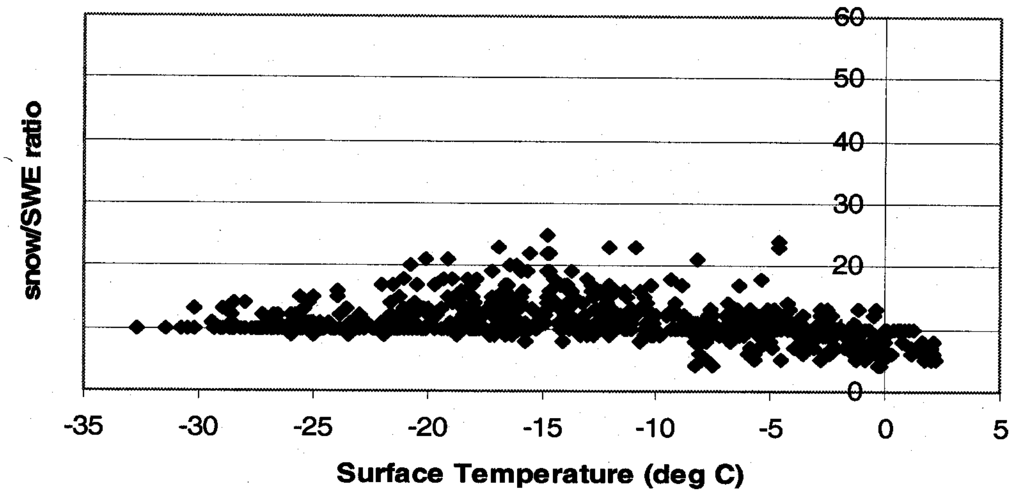


Figure 6-4: Snow/SWE ratio as a function of mean daily surface temperature in the forecast data set.

We can now build a table exploring the MAE for several categorical ranges of mean daily surface temperature to determine if the slight differences in relationship to surface temperature between the observations and forecasts have an effect on the MAE of the MSC algorithm. In Table 6-14 there is no strong correlation between mean daily surface temperature and the MAE.

Table 6-13: MAE of the MSC algorithm for several categories of mean daily surface temperature.

Mean daily surface temperature °C	MAE
≥ 0	3.6
-5 – 0	3.8
-10 – -6	3.4
-15 – -11	4.1
-20 – -16	3.7
≤ -21	4.1

6.3.3 Surface Wind Speed

In Chapter 2 we have seen that surface wind speed does have some effect on the snow/SWE ratio because it can lead to the fragmentation of the snowflakes and individual snow crystals into smaller shards, which can then be packed more densely. Increasing surface winds increase the snow density and lower the snow/SWE ratio.

We have also seen in Chapter 2 that different crystal types are affected differently. For instance, needles are already densely packed (in the absence of significant aggregation) and so greater fragmentation hardly affects them. On the other hand, a ferny dendrite crystal is strongly affected by wind speed as they can shatter. In Figure 6-5, a scatter-plot of snow/SWE ratio as a function of surface wind speed, there is no relationship between these two variables because of the way that different crystal types are affected by wind speed,

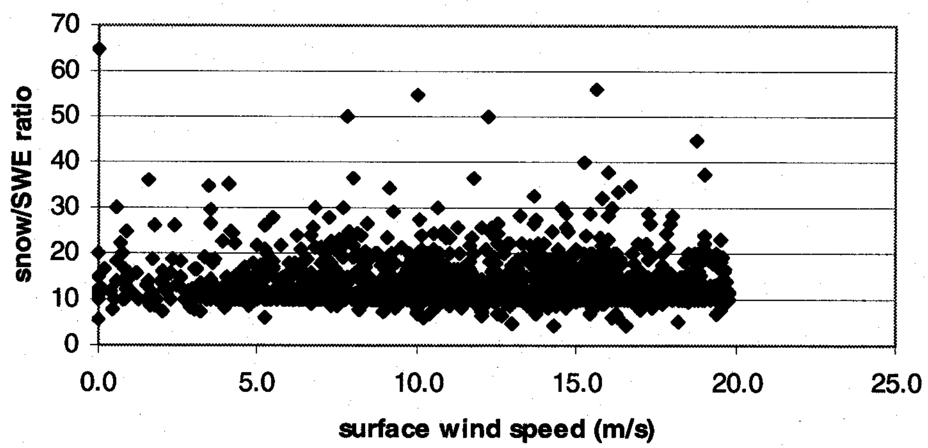


Figure 6-5: Snow/SWE ratio as a function of surface wind speed

Table 6-15 is the MAE of the MSC algorithm for several categories of wind speed. For unknown reasons the algorithm's performance increases slightly with increasing wind speed.

Table 6-14: MAE of the MSC algorithm for several categories of surface wind speed.

Surface wind speed (km/h)	MAE
0 – 5	4.5
6 – 10	4.2
11 –15	3.7
16 – 19.8	3.1

6.3.4 Climatic Region

In our examination of the climatology of snow/SWE ratio in Chapter 5 we discussed at length the different climatic regions in Canada. These different regions have different annual values of temperature, humidity, and wind speed, all factors that control snow/SWE ratio. The MSC algorithm was originally developed and verified only in Quebec and an objective of this thesis is to extend the verification to the different climatic regions in Canada. This section is devoted to performing this objective.

For this verification we will consider the following regions: Atlantic Canada, British Columbia, Nunavut, Ontario and Quebec, the Prairies, and the Yukon and Northwest Territories. In Table 6-16 is the mean observed snow/SWE ratio in the regions we have defined. The trends in observed ratio in this table are similar to the trends in the climatology of Chapter 6. That is, higher ratios are found in the cold interior and lower ratios in Atlantic Canada. The high value of 14.3:1 found in British Columbia is reflective of the interior, mountain stations that contribute to the mean value of snow/SWE ratio in that province.

Table 6-15: Mean observed and forecast snow/SWE ratio for different regions in Canada.

	Mean Observed snow/SWE ratio	Mean Forecast snow/SWE ratio	Mean Observed ratio (w/o > 25:1)
Atlantic	13.2:1	10.6:1	12.4:1
British Columbia	14.3:1	11.2:1	13.3:1
Nunavut	13.1:1	11.3:1	12.3:1
Ontario & Quebec	13.0:1	10.7:1	12.5:1
Prairies	13.4:1	11.5:1	12.9:1
Yukon & NWT	15.5:1	12.2:1	14.5:1

Table 6-16 also contains the mean forecast snow/SWE ratio by region. It can be seen from this table that in all regions the forecast is closer to the observations than the 10:1

approximation. However, the algorithm is forecasting lower than observed mean ratios. One reason for this under-forecasting is due to the difference in range of possible values in the two data sets. For this reason, the mean observed ratio for each region, with events having a ratio greater than 25:1 removed, is also given in Table 6-16. The performance of the algorithm improves in this comparison.

Next, we will calculate the MAE of the MSC algorithm and of the 10:1 approximation, to examine their performance by region. In Table 6-17, the algorithm out-performs the 10:1 approximation in British Columbia, the Prairies, and the Yukon and Northwest Territories. The two techniques perform with equal skill in Nunavut and in the Atlantic whereas the 10:1 approximation out-performs the algorithm in Ontario and Quebec. Nevertheless, in no region is there a large difference in MAE between the two techniques.

Table 6-16: MAE of the MSC algorithm and 10:1 approximation for regions of Canada. The best score in each region is underlined.

	MAE of MSC algorithm	MAE of 10:1 approximation
British Columbia	**4.1**	4.4
Prairies	**3.6**	3.7
Nunavut	3.6	3.6
Yukon & NWT	**5.2**	6.0
Ontario & Quebec	3.4	**3.1**
Atlantic	3.4	3.4

In the Yukon and Northwest Territories, an area with many observed ratios greater than 25:1, the algorithm performs slightly worse than in the other regions. We recalculated the MAE of the algorithm in the Yukon and Northwest Territories with the greater than 25:1 events removed, and found an improved value of 4.4. The similarity in MAE of the MSC algorithm in all regions of Canada is a significant result. Although the algorithm was developed and originally verified only in Quebec, it successfully captures the behavior of snow/SWE ratio in other, different climatic regions.

6.3.5 Month

In our examination of the climatology of snow/SWE ratio in Chapter 5, we found that snow/SWE ratio has large variations not just regionally, but seasonally as well. This is to be expected. The early and late parts of the winter season are warmer and more humid than the cold and dry mid-winter. This section will explore the relationship between the performance of the MSC algorithm and month.

The relationship between mean snow/SWE ratio and month is controlled by three factors. First, we expect the snow/SWE ratio to increase with decreasing temperatures from early to mid-winter and then decrease with increasing temperature from mid- to late winter in regions were the mean monthly temperature does not fall below approximately –25°C at cloud level. Second, decreasing temperatures cause increasing ratio only until approximately –25°C, at which point continuing to decrease the temperature causes a decrease in snow/SWE ratio. In Northern Canada, the monthly mean temperature is well below –25°C in the mid-winter. Third, decreasing the excess vapor density over ice decreases the ratio and the colder an air mass is, the less moisture it can contain. Therefore, decreasing temperatures and decreasing humidity can counteract each other. Figure 6-5 is the mean snow/SWE ratio by month in Canada and broadly follows the expected trend. As we found in the climatology of Chapter 5, the mid-season (December, January and February) snow/SWE ratios are slightly higher than the early/late (November and March) season ratios.

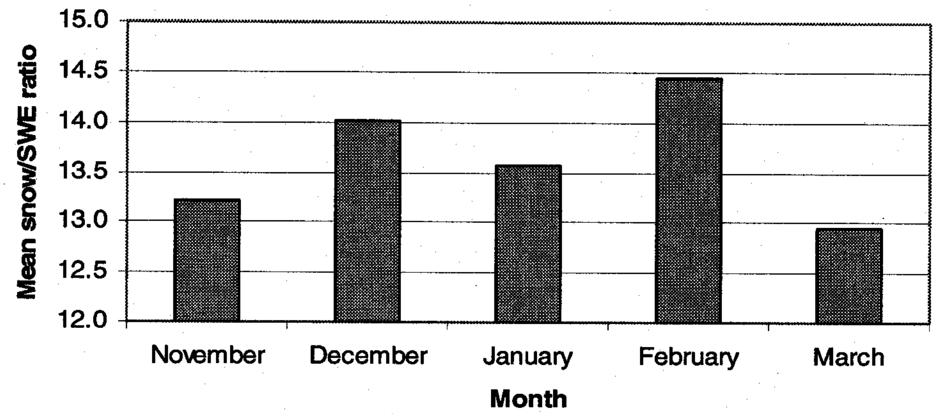


Figure 6-6: Snow/SWE ratio by month in Canada.

Table 6-18 is the MAE of the MSC algorithm by month. The algorithm performs slightly better in January but for most parts of the winter there is no significant change in MAE.

Table 6-17: MAE of the MSC algorithm by month.

Month	MAE
November	3.9
December	3.7
January	3.6
February	3.9
March	4.0

6.3.6 Frequency of Snow/SWE Ratio

One insightful way to examine the data is to construct a histogram of the frequency at which various snow/SWE ratios are observed and forecasted. We have seen from our calculation of the bias, presented in Table 6-8, that both the 10:1 approximation and the MSC algorithm tend to under-forecast ratios, but the details of this need to be examined.

In Figure 6-6, the distribution of snow/SWE ratios for both the forecast and observational data set are presented. The x-axis of this figure is truncated at a ratio of 28:1 but ratios as high as 65:1 exist in the observational data set. The frequency distribution of forecast snow/SWE ratio matches the observational distribution much more closely than the 10:1 approximation. The 10:1 approximation forecasts a 10:1 ratio with 100% frequency. In this respect the MSC algorithm shows significant improvement.

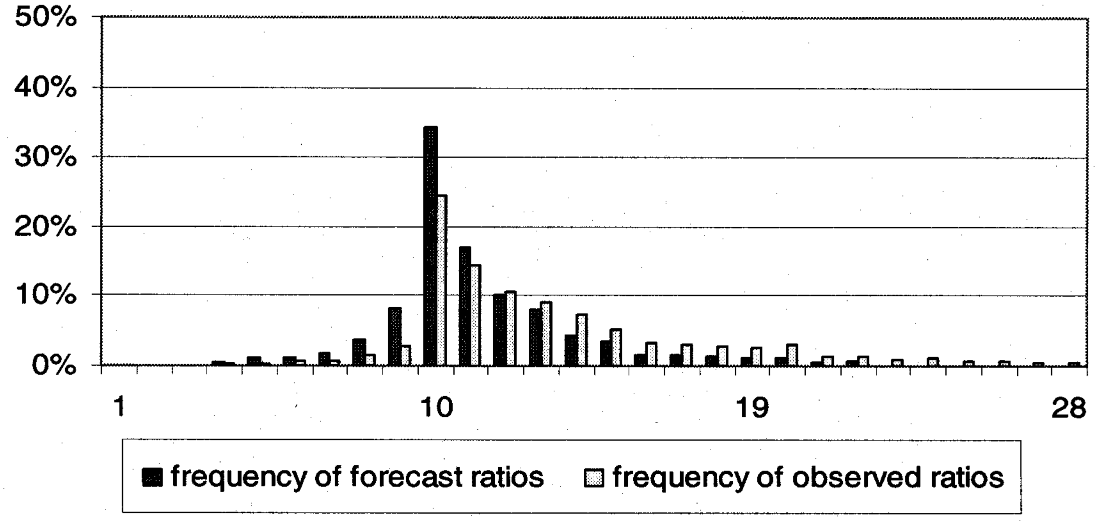


Figure 6-7: Frequency of snow/SWE ratios in the MSC algorithm forecast and the observational data sets.

Nevertheless, there are some differences between the two frequency distributions. In Figure 6-6 the tendency of the algorithm to over-forecast low ratios (< 11:1) and to under-forecast high ratios (>11:1) can be seen. The curves of the two frequency distributions are very similar in shape, but are offset.

In Chapter 3 we outlined the decision tree structure of the MSC algorithm. Depending on atmospheric conditions provided to the algorithm by GEM forecast input, the algorithm will output 1 of a possible 26 diagnoses. Each of these diagnoses has an assigned snow/SWE ratio but the ratio assigned to a diagnosis is not necessarily unique. For, example 5 different diagnoses (rimed spatial dendrites, rimed mixed crystals, snow mixed with ice pellets, wet snow and snow pellets) are assigned a snow/SWE ratio of 7:1.

We calculated a distribution frequency of snow/SWE ratio intrinsic in the algorithm itself. This was done in the following way. The number of diagnoses with a given snow/SWE ratio (*e.g.* 5 diagnoses with a ratio of 7:1) was divided by 26, the total number of diagnoses. Figure 6-7 is the result of this calculation. This is a simplistic evaluation of the frequency distribution intrinsic in the algorithm because not all diagnoses are equally probable to occur, but it can be seen in Figure 6-7 that there is a skewness toward low ratios in the set of possible diagnoses.

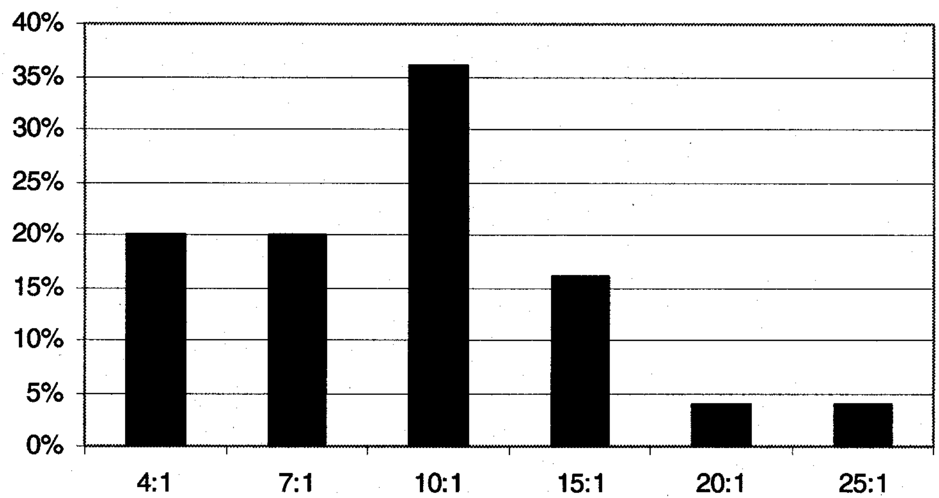


Figure 6-8: Frequency of assigned snow/SWE ratio in the set of 26 possible diagnoses.

6.4 Comparison with the Original Quebec Validation

After the development of the original algorithm, what we have termed the Dubé algorithm in Chapter 3, Dubé performed a verification of the technique. For the verification he used the same stations as in the development of the algorithm but for a different winter season (November–April, 1999–2002 for the development and November–April, 2002–2003). This section will examine the results of the original Quebec validation.

Table 6-18 is a reproduction from Dubé's report "From mm to cm.... Study of snow/liquid water ratios in Quebec". This contingency table is in the same format as given for our verification in Table 6-5. Whereas the current verification finds a percentage correct (by adding the shaded boxes in the center diagonal) of 47.3%, the original, Quebec-only verification had a percentage correct of 82.9%. This is a large difference that must be explained.

Table 6-18: Contingency table of the Dubé algorithm in the original Quebec verification (Dubé 2003).

	Observed					
Forecast	very heavy snow	heavy snow	Average snow	light snow	very light snow	ultra light snow
very heavy snow	4.6%	0.4%				
heavy snow	0.4%	8.9%	1.1%			
average snow		1.1%	41.3%	3.9%		
light snow			3.9%	21.4%	0.4%	
very light snow				3.6%	3.9%	
ultra light snow					2.5%	2.8%

The exact cause of the difference is not certain because there are several differences between the methodologies of the original verification and the current one. They are listed in Table 6-19. Some of these differences are more important than others. For example, we have shown that the MAE of the algorithm is very similar regardless of region or month. This means the algorithm performs equally well in each region and month. Therefore differences between the two verifications in these parameters are unimportant. In contrast, an important difference is that Dubé used higher-resolution 3 hourly data instead of mean daily information for the verification.

Table 6-19 : A list of the differences between the original verification and the current verification.

Original Verification 2002-2003	This verification 2004-2005
Observations every 3 hours	Daily observations
Verification ran from Oct. – April	Verification ran from Nov. – March
Quebec stations only	Canada-wide station coverage
Stations with SR50 included	Stations with SR50 excluded
Dubé algorithm	MSC algorithm
Algorithm output values found by human	Algorithm output totally automated
Input: soundings & analysis , Diagnostic mode	Input: GEM forecast model, Prognostic mode

However, the fundamental difference is that Dubé's verification was performed in diagnostic mode whereas the current one is performed in prognostic mode. To run an algorithm in diagnostic mode means all available data (including soundings, ground observations and analysis) following each event were used as input. The original verification was performed in this way with the knowledge that the algorithm would perform better in diagnostic mode rather than prognostic mode. The purpose of the original verification was to test the algorithm alone, using the best possible knowledge of the state of the atmosphere.

In contrast, the current verification is performed in purely prognostic mode. The MSC algorithm has been modified from the Dubé algorithm in order to make it useful as an operational forecasting tool. Therefore, it uses as input GEM forecast fields and any error in the input field propagates through the technique itself, leading to decreased performance.

Chapter 7

Summary and Concluding Remarks

7.1 Summary

The depth of a layer of freshly fallen snow is an important forecast product but it requires knowledge of two parameters, the mass of precipitation that has fallen and the density of the snow. Knowing the amount of liquid precipitation from a weather prediction model, we would like to forecast snow depth by using a snow/snow water equivalent (SWE) ratio. This ratio is a comparison of the density of the snowfall (10–350 kg m^{-3}) to the density of water (1000 kg m^{-3}). The most commonly used approximation of the snow/SWE ratio is 10:1 but it has long been known to be an oversimplification (Potter 1965).

This thesis has presented a detailed analysis of the snow/SWE ratio in Canada by discussing factors governing snow density variation, detailing previous attempts at snow/SWE ratio forecasting, constructing a climatology of snow/SWE ratio in Canada, and performing a verification of a new algorithm developed by MSC Quebec for predicting this quantity.

In describing the physical causes of snow density variation, we identified two major factors. One is the individual crystal habit, dependent on the temperature and humidity inside the cloud where it is formed. The density of an individual crystal decreases as the temperature is lowered until approximately -15°C after which density begins to increase. Increasing humidity acts to decrease density. The other factor is the action of various atmospheric processes on the crystals: sublimation, melting, freezing, aggregation, accretion, fragmentation, compaction and ageing. All these processes except aggregation act to increase the density of snow, although the magnitude of their impact depends on the individual ice crystal type present initially.

In detailing previous attempts at snow/SWE forecasting we discussed the 10:1 approximation, various look-up table type techniques, and a neural network based algorithm. The 10:1 approximation was shown to be flawed because it is a constant value whereas the snow/SWE ratio is highly variable. The two look-up tables discussed, the National Weather Service table and the Scofield and Spayd (1984) diagrams, were shown to be inadequate because they used only surface temperature or atmospheric thickness as an indicator of snow/SWE ratio and neglected entirely the effect of humidity. The neural network approach of Roebber et al. (2003) was shown to be a considerable improvement over previous methods; forecasting correct snow/SWE ratio in 60% of events. Nevertheless, it is obvious that a great deal of progress must be made in addressing this issue.

To begin to address the issue we constructed a climatology of snow/SWE ratio for Canada and this led to several important findings. First, we found that 10:1 is not the average value of snow/SWE ratio in Canada. In our data set, 10:1 was a lower limit for the annual average ratio at a given station, whereas the mean across Canada was 13:1 and the maximum was 19:1.

Second, we found large variations in this quantity regionally. That is, warmer climatic regions (coastal and southern regions) tended to have lower ratios, moderately colder regions (the continental interior) tended to have higher ratios and the very coldest regions (the Arctic) had lower ratios. Regions with high humidity and moderately cold temperatures (the lake-effect regions downwind of the Great Lakes and the Bay of Fundy) had the some of the highest values of snow/SWE ratio in Canada. Such results are consistent with the physical processes of snow density that depend on temperature and humidity, as previously discussed.

Third, snow/SWE ratio varies by month. In general it is highest in mid-winter and lower in the early and late winter; this tendency is quite consistent with the change in temperature that occurs over the season. In any given month however, both high and low ratio events are possible. In all the findings from our climatology study, we are in agreement with other studies performed on this topic in United States and with the Quebec climatology from Dubé (2003).

We performed a verification of a new algorithm developed at the MSC Quebec for forecasting snow/SWE ratio across Canada. This algorithm was originally developed by Ivan Dubé 2003 and later automated with some modifications by Viateur Turcotte in 2004. The algorithm uses the Canadian Global Environmental Multiscale (GEM), 15 km resolution forecast fields of vertical temperature profile, vertical humidity profile, vertical and surface winds, and ground temperature as input. The algorithm has a decision tree structure which uses the GEM input fields to determine one crystal type diagnosis out of possible 26. Each diagnosis has an associated snow/SWE ratio. In this verification we compared the snow/SWE ratio output from the algorithm to observed snow/SWE ratio archived in the National Climate Data and Information Archive of Environment Canada. Because of this procedure, the GEM quantitative precipitation forecast (QPF) is not used in this verification.

Three techniques were used to assess the performance of the algorithm. First, by grouping the range of forecast and observed ratios into discrete categories we compared the forecast/observation couplets in a contingency table. Using this technique we found the algorithm was correct in 47.3% of the events, whereas the 10:1 approximation was correct in 52.2% of the events. However, there were many events where the approximation performed equally as well, or was an improvement over, the 10:1 approximation. Using this evaluation, in 84.1% of the events the algorithm performs with equal or greater skill than the 10:1 approximation.

Second, the bias of the algorithm and the 10:1 approximation were calculated. The algorithm under-forecast the snow/SWE ratio in 40.6% of the cases and over-forecast in 12.2% of the cases. The 10:1 approximation under-forecast in 44.4% of the cases and over-forecast in 3.3% of the forecasts. Both the algorithm and the 10:1 approximation showed a strong tendency to under-forecast the snow/SWE ratio although the algorithm under-forecast in 4% less events than the 10:1 approximation.

Third, the Mean Absolute Error (MAE) of the algorithm and the 10:1 approximation were also calculated because this skill score does not require the range of forecast and observed variables be simplified into discrete categories. Using this technique we found the algorithm had a MAE of 3.8 and the 10:1 approximation had a MAE of 3.9. By all measures we calculated in this verification the new algorithm is performing at least equally to the 10:1 approximation and in several ways is an improvement. The algorithm more accurately reflects the range of values of snow/SWE ratio we have found observed across Canada.

7.2 Concluding Remarks

In Section 9: Future developments of his report "From mm to cm.... Study of snow/liquid water ratios in Quebec" (2003), Ivan Dubé identifies as important future work the need to "complete the climatological study by extending its coverage to…other regions of Canada" and "to carry through the verification process initiated in Quebec, and…extend it to other parts of Canada". This thesis has addressed both these points in an attempt to further our understanding of the characteristics and predictability of snow density and snow/SWE ratio.

In the same section of his report, Dubé also lists as future work "to adjust/improve the forecast algorithm in accordance with results obtained from the [climatology and verification]". Using only the results of this thesis it is difficult to identify how to improve the performance of the algorithm for several reasons. Since the algorithm's input parameters are from the GEM forecast model, errors from GEM can cause errors in the algorithm output. As well, several of the 26 crystal type diagnoses in the algorithm have the same snow/SWE ratio (*e.g.* 10:1 or 15:1) assigned to them and in those cases it is impossible to determine, if an error is present, whether it is from an incorrect diagnoses or from an incorrect ratio. However, one suggested improvement to the algorithm is that a diagnosis be created with a higher snow/SWE ratio than 25:1. In our observational data set we found 4% of the snowfall events had ratios greater than 25:1 and that these ratios can occur even in high impact, large accumulation events of 5 cm or greater but such values are not allowed in the algorithm.

One future area of research is studying the relationship between a layer of freshly fallen snow and its constituent crystal type. In Chapter 2 of this thesis it was noted that, whereas many studies on the density of individual snow crystals has been performed, very few on the density of freshly fallen snow have been. Additionally, in the winter of 2005 the MSC began archiving the diagnosis number (and therefore crystal type) forecast by their algorithm. By making observations of crystal type in freshly fallen snow, this data could be compared to the algorithm's predictions. This would refine the verification process by differentiating between an error in diagnosis and an error in the snow/SWE ratio assigned to that diagnosis.

In conclusion, the physics behind the variation in snow/SWE ratio are very complex. For this reason, studies attempting to explaining or forecast this quantity have had limited success. This thesis describes important beginning steps in addressing this crucial topic.

Appendix A

Schematic of the Dubé Algorithm

FORECAST ALGORITHM (A)

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

$T_{atm} > 0°$ C (atmospheric temperature rises above the freezing point)	$T_{atm} < 0°$ C (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
PL	SNRA	SN FZRA	SNRA PL	SNPL	SN ($T_{sfc}>0°$ C)	SP ($T_{sfc}>0°$ C)	RA, FZRA, RASN, RAPL

25 ↓ Ratio = 1:1

↓

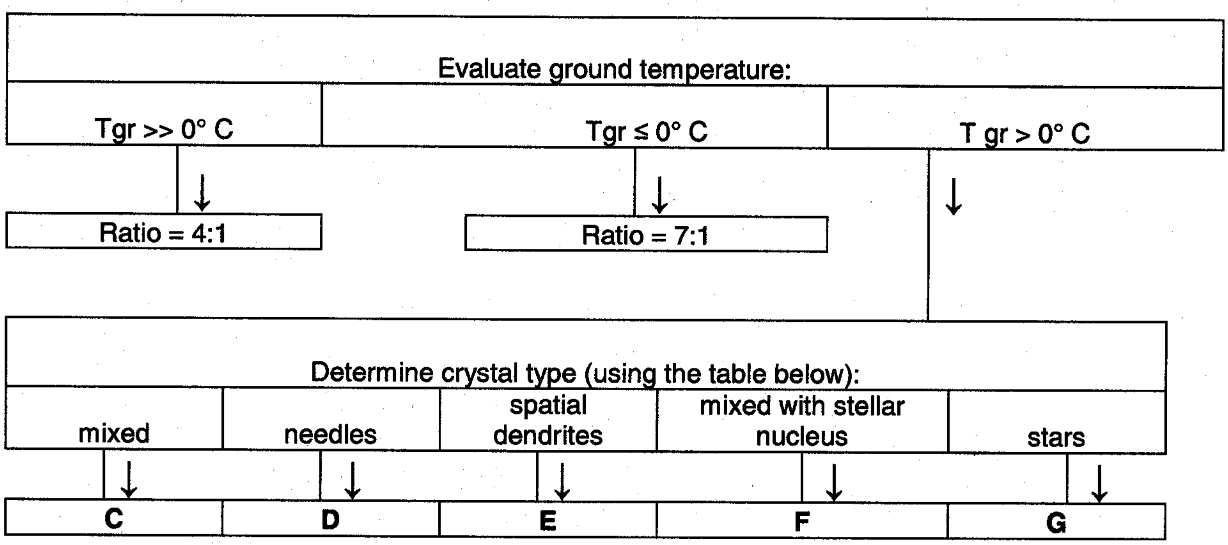
Evaluate ground temperature

T_{gr}: >> 0° (or ≥ 5° C), > 0° (or from 0 to 5° C), ≤ 0° (or snow/ice covered)

↓

18	19	20	21	22	23	24	25
1	1	1	1	4	1	1	4
4	1	1	1	7	4	1	7
4	4	4	4	7	7	4	7

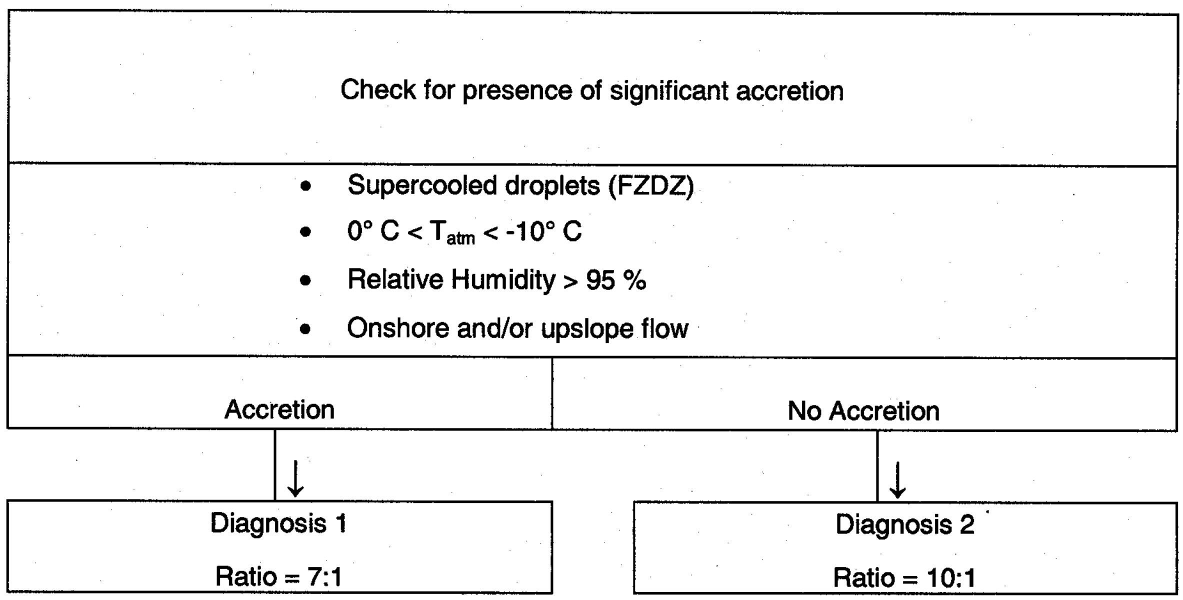
FORECAST ALGORITHM (B) (cases where $T_{atm} < 0° C$)



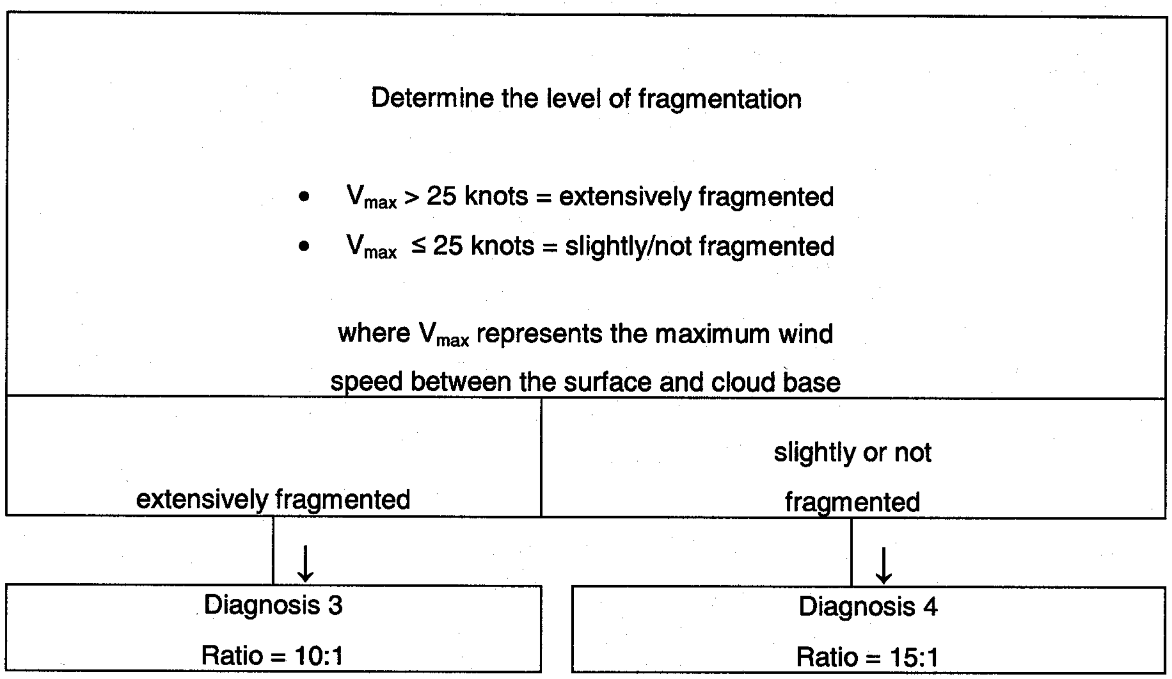
Secondary Temperature	Primary Temperature (deg C) 0 to -3	-3 to -5	-5 to -12	-12 to -18	< -18
0 to -3	mixed (10:1)	mixed (10:1)	Mixed (10:1)	—	—
-3 to -5	mixed (10:1)	needles (10:1)	Mixed (10:1)	—	—
-5 to -12	mixed (10:1)	mixed (10:1)	Mixed (10:1)	mixed with stellar nucleus (151)	—
-12 to -18	—	—	spatial Dendrites (10:1)	stellar crystals (25:1)	spatial dendrites (10:1)
< -18	—	—	—	mixed with stellar nucleus (151)	mixed (10:1)

The primary temperature is the level of main crystal growth (ω is maximum and RH > 80%) and the secondary temperature is the level underneath the main one where ω <0, T<0 and RH> 80%.

FORECAST ALGORITHM (C) (mixed crystals)



FORECAST ALGORITHM (D) (aggregated needles)



APPENDIX A

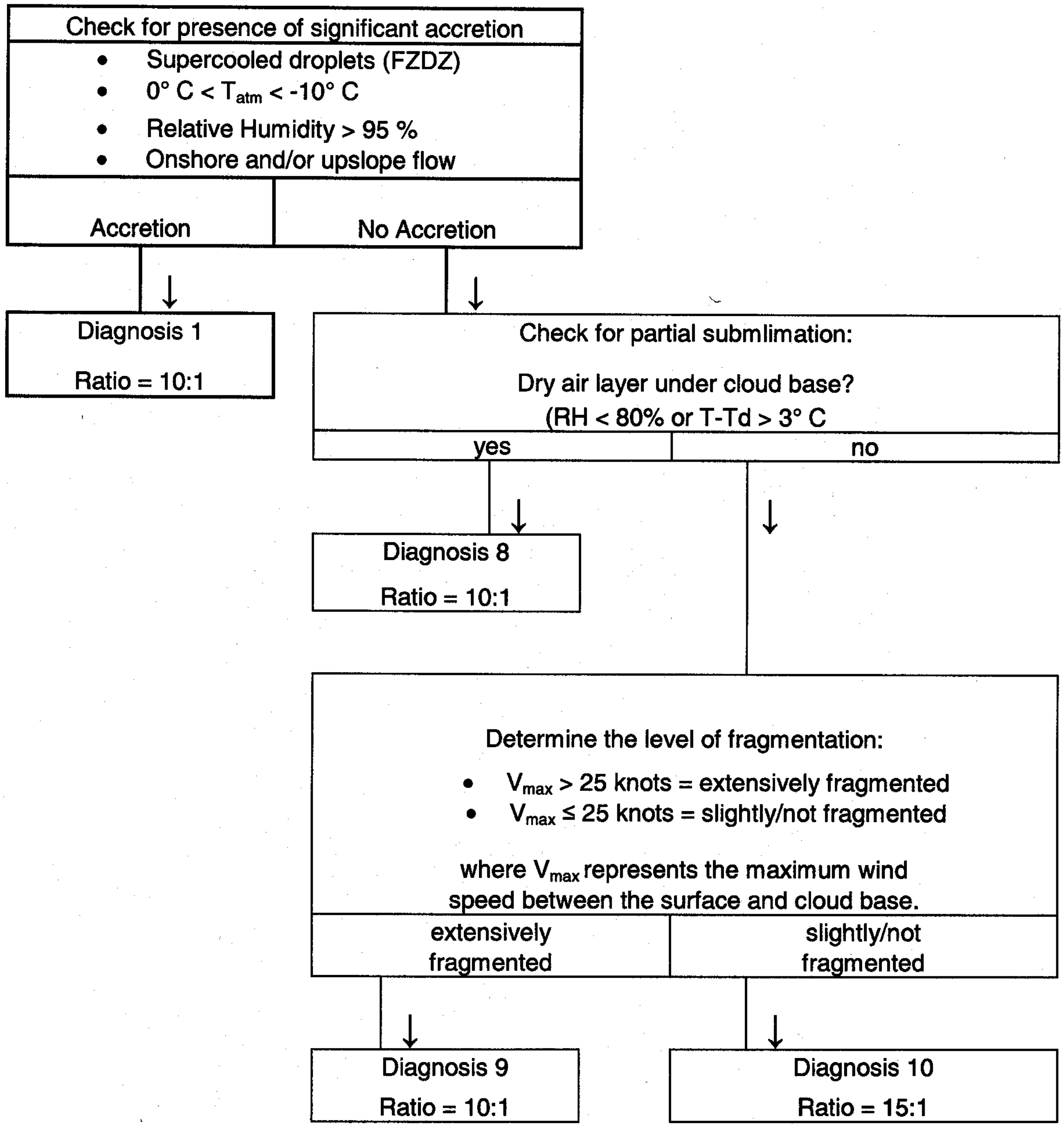
FORECAST ALGORITHM (E) (spatial dendrites)

Check for presence of significant accretion

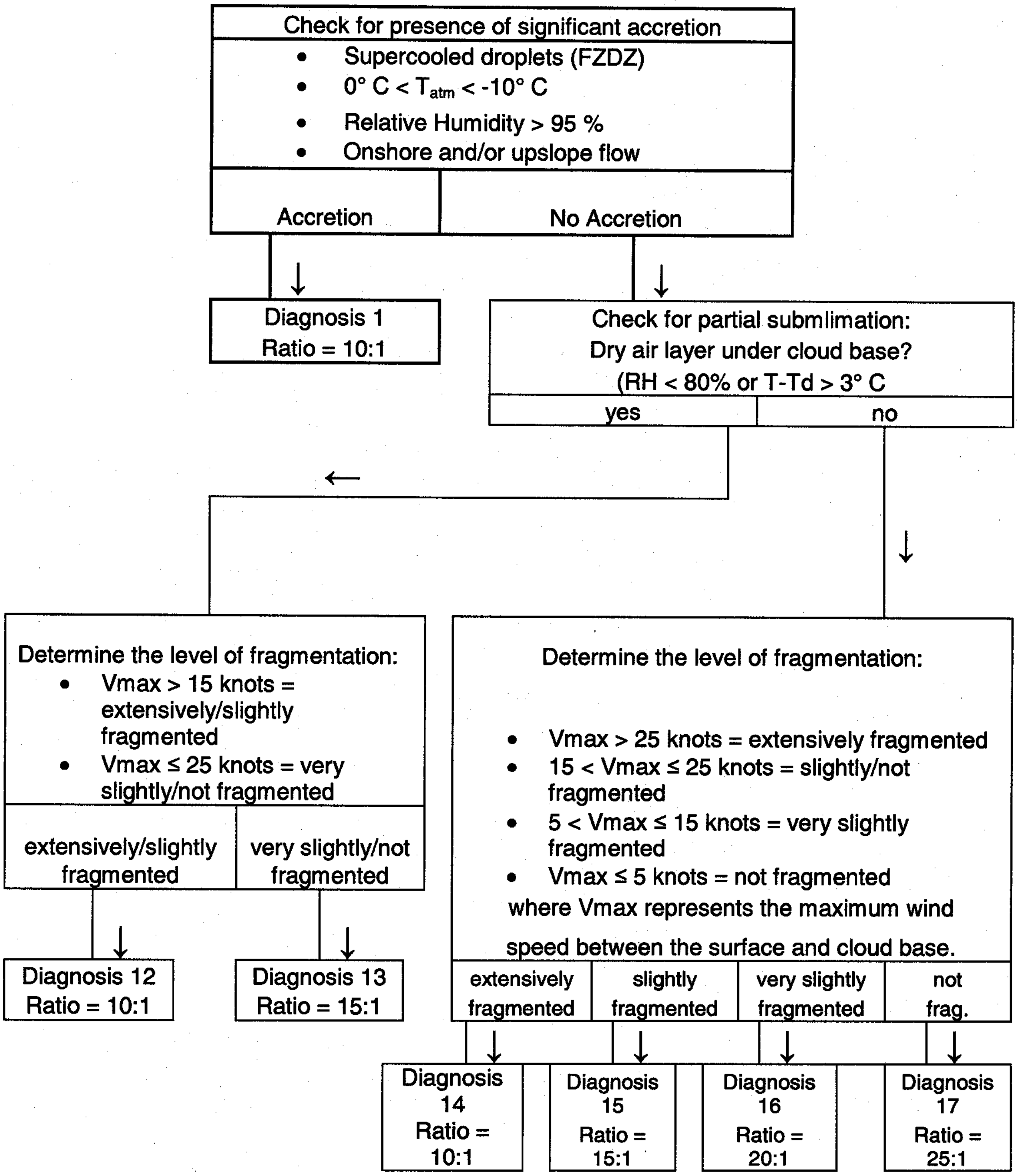
- Supercooled droplets (FZDZ)
- 0° C < T_{atm} < -10° C
- Relative Humidity > 95 %
- Onshore and/or upslope flow

Accretion	No Accretion
↓	↓
Diagnosis 1 Ratio = 7:1	Diagnosis 2 Ratio = 10:1

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



FORECAST ALGORITHM (G) (stars)



Appendix B

List of Stations Used in the Verification

Climate ID	WMO ID	Name	Province	Latitude	Longitude	Altitude
1018620	YYJ	Victoria Int'l Airport	BC	48.6	-123.4	19.2
1068130	YXT	Terrace Airport	BC	54.5	-128.6	217.3
1077500	YYD	Smithers Airport	BC	54.8	-127.2	521.8
1096450	YXS	Prince George Airport	BC	53.9	-122.7	691.3
1098940	YWL	Williams Lake Airport	BC	52.2	-122.1	940.3
1100030	YXX	Abbotsford Airport	BC	49.0	-122.3	57.9
1108447	YVR	Vancouver Int'l Airport	BC	49.2	-123.2	4.3
1126150	YYF	Penticton Airport	BC	49.5	-119.6	344.1
1152102	YXC	Cranbrook Airport	BC	49.6	-115.8	939.4
1163780	YKA	Kamloops Airport	BC	50.7	-120.4	345.3
1183000	YXJ	Fort St John Airport	BC	56.2	-120.7	694.9
1192940	YYE	Fort Nelson Airport	BC	58.8	-122.6	381.9
2100700	YMA	Mayo Airport	YT	63.6	-135.9	503.8
2101200	YQH	Watson Lake Airport	YT	60.1	-128.8	687.3
2101300	YXY	Whitehorse Airport	YT	60.7	-135.1	706.2
2201575	YJF	Fort Liard Airport	NT	60.2	-123.5	215.2
2202000	YFR	Fort Resolution Airport	NT	61.2	-113.7	160.3
2202101	YFS	Fort Simpson Airport	NT	61.8	-121.2	169.2
2202200	YSM	Fort Smith Airport	NT	60.0	-112.0	205.1
2202400	YHY	Hay River Airport	NT	60.8	-115.8	165.5
2202582		Inuvik UA	NU	68.3	-133.5	103.2
2202800	YSM	Norman Wells Airport	NT	65.3	-126.8	73.5
2203058	ZPK	Paulatuk	NT	69.3	-124.1	6.3
2203912	YUB	Tuktoyaktuk Airport	NT	69.4	-133.0	4.6
2204000	YWY	Wrigley Airport	NT	63.2	-123.4	150.3

2204100	YZF	Yellowknife Airport	NT	62.5	-114.4	205.7
2300707	YCS	Chesterfield Inlet Airport	NU	63.4	-90.7	9.8
2300902	YCO	Kugluktuk Airport	NU	67.8	-115.1	22.6
2302335	YHK	Gjoa Haven Airport	NU	68.6	-95.8	46.2
2303986	YXN	Whale Cove Airport	NU	62.2	-92.6	12.2
2400600	YCB	Cambridge Bay Airport	NU	69.1	-105.1	27.4
2400635	YTE	Cape Dorset Airport	NU	64.2	-76.5	50.0
2401200	WEU	Eureka	NU	80.0	-85.9	10.4
2402346	WGZ	Grise Fiord	NU	76.4	-82.9	44.5
2402350	YUX	Hall Beach Airport	NU	68.8	-81.2	8.2
2402594	YFB	Iqualuit UA	NU	63.8	-68.5	21.9
2403053	YXP	Pangnirtung Airport	NU	66.1	-65.7	22.6
2403201	YIO	Pond Inlet Airport	NU	72.7	-78.0	55.2
2403490	YUT	Repulse Bay Airport	NU	66.5	-86.2	24.4
2403500	YRB	Resolute Cars	NU	74.7	-95.0	67.4
2403854	YYH	Taloyoak Airport	NU	69.5	-93.6	28.0
2503648	WSY	Sachs Harbour Climate	NT	72.0	-125.3	87.5
3012205	YEG	Edmonton Int'l Airport	AB	53.3	-113.6	723.3
3012208	YXD	Edmonton City Centre Airport	AB	53.6	-113.5	670.6
3013961	YLL	Lloydminster Airport	AB	53.3	-110.1	668.7
3025480	YQF	Red Deer Airport	AB	52.2	-113.9	904.6
3031093	YYC	Calgary Int'l Airport	AB	51.1	-114.0	1084.1
3034480	YXH	Medicine Hat Airport	AB	50.0	-110.7	716.9
3036240	YSD	Suffield Airport	AB	50.3	-111.2	769.6
3053600		Kananaskis	AB	51.0	-115.0	1391.10m
3067372	YZU	Whitecourt Airport	AB	54.1	-115.8	782.4
3072920	YQU	Grande Prairie Airport	AB	55.2	-118.9	669.0
3073146	YOJ	High Level Airport	AB	58.6	-117.2	338.3
3075040	YPE	Peace River Airport	AB	56.2	-117.4	570.9
3081680	YOD	Cold Lake Airport	AB	54.4	-110.3	541.0
4012400	YEN	Estevan Airport	SK	49.2	-103.0	580.6
4019080	YQV	Yorktown Airport	SK	51.3	-102.5	498.3
4040587		Bickleigh	SK	51.3	-108.4	670.5
4043900	YKY	Kindersley Airport	SK	51.5	-109.2	694.0
4045600	YQW	North Battleford Airport	SK	52.8	-108.3	548.3
4056240	YPA	Prince Albert Airport	SK	53.2	-105.7	428.2
4064150	YVC	La Ronge Airport	SK	55.1	-105.3	378.6
4065058	YLJ	Meadow Lake Airport	SK	54.1	-108.5	480.4
4075518	YBU	Nipawin Airport	SK	53.3	-104.0	371.9
4083323		Hudson Bay 13W	SK	52.9	-102.6	422.0
5010480	YBR	Brandon Airport	MB	49.9	-100.0	409.4
5050960	YFO	Flin Flon Airport	MB	54.7	-101.7	303.9
5052880	YQD	The Pas Airport	MB	54.0	-101.1	270.4
5060606		Churchill UA	MB	58.7	-94.1	28.5
5061001	YGX	Gillam Airport	MB	56.4	-94.7	145.1
5061376	YIV	Island Lake Airport	MB	53.9	-94.7	236.5
5061646	YYL	Lynn Lake Airport	MB	56.9	-101.1	356.6
5062922	YTH	Thompson Airport	MB	55.8	-97.9	222.2

6016527	YPL	Pickle Lake Airport	ON	51.5	-90.2	386.2
6016975	YRL	Red Lake Airport	ON	51.1	-93.8	385.6
6032119	YHD	Dryden Airport	ON	49.8	-92.8	412.7
6034075	YQK	Kenora Airport	ON	49.8	-94.4	406.1
6037775	YXL	Sioux Lookout Airport	ON	50.1	-91.9	390.1
6042716	YGQ	Geraldton Airport	ON	49.8	-86.9	348.7
6052259	YEL	Elliot Lake Airport	ON	46.4	-82.6	331.3
6057592	YAM	Sault Ste Marie Airport	ON	46.5	-84.5	192.0
6061361	YLD	Chapleau Airport	ON	47.8	-83.3	446.5
6068150	YSB	Sudbury Airport	ON	46.6	-80.8	347.5
6072225	YXR	Earlton Airport	ON	47.7	-79.8	243.2
6073975	YYU	Kapuskasing Airport	ON	49.4	-82.5	226.5
6078285	YTS	Timmins Airport	ON	48.6	-81.4	294.7
6085700	YYB	North Bay Airport	ON	46.4	-79.4	370.3
6106000	YOW	Ottawa Macdonald Cartier Intl Airport	ON	45.3	-75.7	114.0
6115525	YQA	Muskoka Airport	ON	45.0	-79.3	281.9
6119500	YVV	Wiarton Airport	ON	44.8	-81.1	222.2
6127514	YZR	Sarnia Airport	ON	43.0	-82.3	181.1
6139525	YQG	Windsor Airport	ON	42.3	-83.0	189.6
6153194	YHM	Hamilton Airport	ON	43.2	-79.9	237.7
6158350		Toronto	ON	43.7	-79.4	112.5
6158733	YYZ	Toronto Lester B Pearson Int'l Airport	ON	43.7	-79.6	173.4
6158875	YTR	Trenton Airport	ON	44.1	-77.5	86.3
7011309		Charlesbourg Parc Orlean	QC	46.9	-71.3	114.3
7025250	YUL	Montreal / Pierre Elliott Trudeau Intl Airport	QC	45.5	-73.8	35.7
7027039	WIT	Ste-Clothilde	QC	45.2	-73.7	53.0
7047912		Sept-Iles UA	QC	50.2	-66.3	53.1
7052605	YGP	Gaspe Airport	QC	48.8	-64.5	32.9
7054096	WST	La Pocatiere	QC	47.4	-70.0	31.0
7055120	YYY	Mont-Joli Airport	QC	48.6	-68.2	52.4
7060400	YBG	Bagotville Airport	QC	48.3	-71.0	159.1
7066685	YRJ	Roberval Airport	QC	48.5	-72.3	178.6
7113534	YVP	Kuujjuaq Airport	QC	58.1	-68.4	39.3
8100503	ZBF	Bathurst Airport	NB	47.6	-65.8	58.8
8101000	YCH	Miramichi Airport	NB	47.0	-65.5	32.9
8101500	YFC	Fredericton Airport	NB	45.9	-66.5	20.7
8103200	YQM	Moncton Airport	NB	46.1	-64.7	70.7
8104900	YSJ	Saint John Airport	NB	45.3	-65.9	108.8
8104928	YSL	St Leonard Airport	NB	47.1	-67.8	241.7
8202000	YZX	Greenwood Airport	NS	45.0	-64.9	28.0
8202250	YHZ	Halifax Int'l Airport	NS	44.9	-63.5	145.4
8206500	YQI	Yarmouth Airport	NS	43.8	-66.1	43.0
8300300	YYG	Charlottetown Airport	PE	46.3	-63.1	48.8
8300425		Elmwood	PE	46.3	-63.3	67.0
8400413		Bay D'espoir Gen Stn	NL	48.0	-55.8	22.9
8400812		Burnt Pond	NL	48.2	-57.3	298.7

		Newfoundland				
8401501	YDF	Deer Lake Airport	NL	49.2	-57.4	21.9
8401700	YQX	Gander Int'l Airport	NL	49.0	-54.6	151.2
8403506	YYT	St John's Airport	NL	47.6	-52.7	140.5
8403800	YJT	Stephenville Airport	NL	48.5	-58.5	25.6
8501900	YYR	Goose Airport	NL	53.3	-60.4	48.8
8502799	WFP	Nain	NL	56.5	-61.7	7.6
8504175	YWK	Wabush Lake Airport	NL	52.9	-66.9	550.5
22010KA	YWJ	Deline Airport	NT	65.2	-123.4	212.8
220L001	YLK	Lutselk'e Airport	NT	62.4	-110.7	178.9
220N001	YOA	Ekati Airport	NT	64.7	-110.6	469.4
301222F	WSE	Edmonton Stony Plain	AB	53.5	-114.1	766.3
303F0PP	YBW	Springbank Airport	AB	51.1	-114.4	1200.0
4067PR5	YSF	Stony Rapids Airport	SK	59.3	-105.8	245.4
506B047	YNE	Norway House Airport	MB	54.0	-97.8	223.7
6059D09	YXZ	Wawa Airport	ON	48.0	-84.8	287.1
610FC98		Petawawa Hoffman	ON	45.9	-77.3	153.0
611KBE0		Egbert Care	ON	44.2	-79.8	252.0
615HMAK	YKZ	Toronto Buttonville Airport	ON	43.9	-79.4	198.1
615S001		Toronto North York	ON	43.8	-79.5	187.0
701Q004	WJB	Ste-Foy (University of Laval)	QC	46.8	-71.3	91.4
701S001	WQB	Quebec / Jean Lesage Intl Airport	QC	46.8	-71.4	74.1
702FHL8	WVQ	St-Anne-de-Bellevue 1	QC	45.4	-73.9	39.0
705C2G9	YGR	Iles de la Madeleine Airport	QC	47.4	-61.8	10.7
707DBD4	WDQ	La Tuque Quebec	QC	47.4	-72.8	168.9
840C401	YAY	St Anthony Airport	NL	51.4	-56.1	28.0

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