2A.2

A SIMPLE PHYSICALLY BASED SNOWFALL ALGORITHM

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1. INTRODUCTION

The era of highly detailed digital forecasts has raised client expectations and their demand for detailed and skillful *quantitative snowfall forecasts* (QSF). The challenge of accurate QSF, given improved numerical weather prediction (NWP) of quantitative precipitation forecasts (QPF), lies in the ability to accurately assess the snow ratio and its evolution throughout a winter storm.

A primary goal of this work is to improve upon forecasts of significant snowfall by proposing a more skillful alternative to the traditional assumption of a 10:1 snow ratio (e.g. 10 inches of snow would equate to one inch of water when melted). A simple snowfall algorithm has been created to accomplish this goal. The algorithm effectively captures the storm average snow ratio for each event which infers skill in forecasting the one-hour variability of snow ratio and in part further validates the connection between the distribution of vertical motion and snow ratio as proposed by Baumgardt (1999); Waldstreicher (2001) and Dubè (2003).

The algorithm uses an empirically based area or weighted average approach relating the vertical distribution of vertical motion in saturated regions to the vertical temperature profile to predict a snow ratio at regularly spaced time intervals over a given storm. The snow ratios are then multiplied by the QPFs for each interval and summed to yield a storm-total snowfall.

The algorithm also serves as a physically based conceptual model which provides an appreciation for the evolution of the snow ratio and snow crystal types throughout a given snowstorm. As a consequence of its physical basis it also provides a means for evaluation and adjustment by the operational forecaster.

The following sections will briefly review the snow microphysics used to construct the algorithm followed by a full description of the algorithm itself. Example applications of the algorithm to several snowstorms, which together sample the spectrum of observed snow ratio as defined in climatological investigations by Baxter et al. (2005) will then be presented. Finally, conclusions and future work will be discussed.

2. BACKGROUND

There are several recent studies that have looked at both climatological distributions and ranges of observed snow ratios (e.g., Baxter et al. 2005) and at ratios of observed snow crystal aggregates (Dubè 2003). Climatologies of observed snow ratios show a range with a lower limit 2:1 and an upper limit approaching 50:1 for significant snowfalls [e.g. greater than 2 inches as defined by (Roebber et al. 2003)]. An interesting feature of the climatologies (Fig 1.) of observed snow ratios is that the mean observed values are closer to 13:1 versus the traditionally assumed value of 10:1[1]. Roebber et al. (2003) found a similar distribution and mean in their climatological investigation of snow ratios as part of their work building a neural network based snow ratio prediction system.

In another study (Dubè 2003) investigated the variability of observed snow ratios given a predominately observed crystal type (Table 1). Not surprisingly, dendrites accounted for the highest ratios while rimed crystals of any type accounted for the lowest snow ratios.

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[1] The ubiquity of 10:1 ratios in the dataset are believed to be in part due to the incorrect application of the 10:1 ratio to snowfall rather than its actual measurement using correct methods.

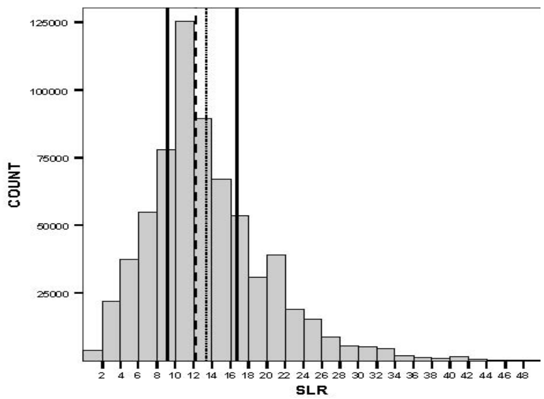

FIG 1. *Histogram of observed snow ratios. Solid lines represent 25th and 75th percentiles, long dashed line represents the median, and short dashed line represents the mean (from Baxter et al. 2005)*

Stellar Dendrites	> 25
Dendrites / Needles	18 - 25
Mixed Dendrites and Plates / Needles	12 - 18
Slightly Rimed Dendrites / Columns or Plates	9 - 12
Significantly Rimed Crystals	5 - 9
Ice Pellets / Snow Grains	3 - 5

TABLE 1. *Observed snow ratios associated with various crystal types and degrees of riming (adapted from Dubè, 2003).*

2.2 *Snow Density*

The snow ratio is inversely proportional to snow crystal density (e.g., high (low) density crystals yield low (high) snow ratios). Snow crystal density itself is primarily a function of temperature and humidity (Fig. 2). Highly spatial or low density crystals such as dendrites are favored at temperatures between -12° and -18° Celsius. Lower density crystals also form at high levels of relative humidity, or more specifically at greater degrees of supersaturation with respect to ice. Conversely, higher density crystals such as columns and smaller plates form at temperatures that are either warmer or colder than this range and also at marginal degrees of supersaturation.

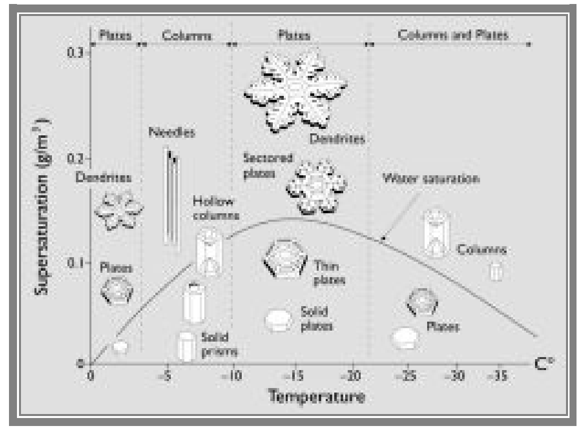

FIG 2*. Relationship of snow crystal type and relative density (inferred by size) to temperature and relative humidity (from Libbrecht, 1999).*

Another temperature range favorable to the formation of low density crystals occurs at temperatures around -5° Celsius. At these temperatures, long thin needle like crystals are favored. Some insight into the overall complexity of snow crystal density as a function of formation temperature can be seen in Fig. 3. In this experiment crystals were grown under controlled conditions for 10 min. Two distinct minimums in density can be seen in the figure, one for the growth of needles at -5° Celsius and a second slight greater peak for stellar dendrites at -15° Celsius.

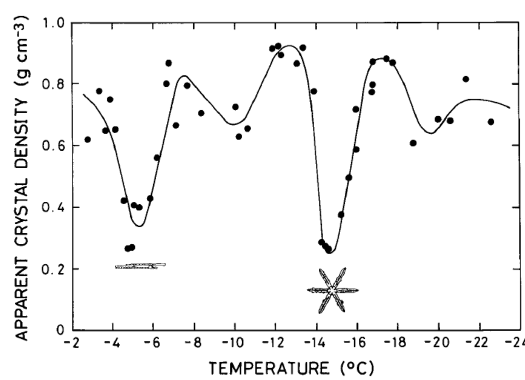

FIG 3. *Variation of apparent crystal density with temperature, under controlled conditions, at a growth time of 10 min (from Fakuta, 1999).*

2.3 *Ice Deposition Nuclei*

Ice crystals do not form spontaneously until temperatures drop to near -40° Celsius. At warmer temperatures, atmospheric aerosols are needed to act as a catalyst in the formation of incipient snow crystals. The activation temperatures of various ice deposition nuclei are shown below in Table 2.

There are two physical implications of Table 2. First, the formation of super-cooled cloud water droplets will generally be favored over ice crystals at cloud temperatures warmer than -10^{o} Celsius (Baumgardt 1999) which strongly infers a greater probability of riming at these temperatures. Second, one would expect a lower likelihood of seeing an abundance of crystal habits such as needles which form at warmer temperatures.

Silver Iodine	**-4**
Sea Salt	**-8**
Kaolinite	**-9**
Volcanic Ash	**-13**
Vermiculite	**-15**

TABLE 2. *Activation temperatures of various ice deposition nuclei (from Baumgardt, 1999).*

2.4 ***Snow Production Zone (SPZ)***

The SPZ is a region of favored snow production and growth, particularly via the Bergeron-Findeisen process. Several processes intersect in the SPZ, defined here as the range of temperatures between -12^{o} to -18^{o} Celsius inclusive, that result in especially efficient conditions for the production of low density snow. The first as mentioned previously is that highly spatial dendritic snow crystals are favored in this temperature range. Secondly, the SPZ is characterized by large crystal growth rates (Fig. 4). Lastly, numerous types of ice deposition nuclei are active in this zone favoring the formation of ice crystals rather than super-cooled water droplets.

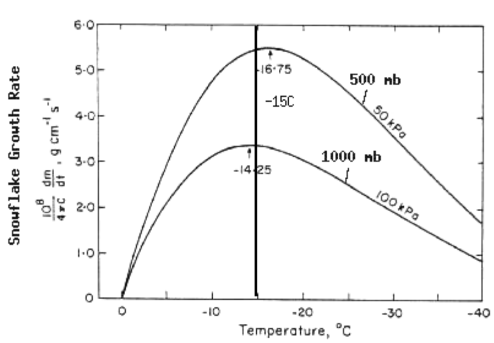

FIG 4*. Normalized snow crystal growth rates as a function of temperature (adapted from Byers 1965).*

2.5 ***Role of Vertical Motion***

Vertical motion influences the observed snow ratio in two critical ways. First, assuming saturated conditions, it is directly related to the rate of precipitation production. Secondly with respect to ice formation, it influences the persistence and the degree to which supersaturation can be maintained in the presence of growing ice crystals. The degree of supersaturation directly influences crystal density through the branching potential of growing ice crystals (Libbrecht 1999).

In terms of the Bergeron-Findeisen precipitation process, the SPZ represents a region of increased precipitation efficiency (relative to cold precipitation processes) in which low density crystals are likely to form. This infers that to a first approximation, a persistent vertical motion maxima collocated with the SPZ would be very conducive to producing both high snowfall rates and high ratio dendritic snowfalls. Such a correlation was noted and dubbed the "*Cross-Hair Approach*" in a study by Waldstriecher (2001). Other studies by Baumgardt et al. (1999) and Dubè et al. (2003) further support such an approach.

Vertical motion maxima below the SPZ would infer greater formation of super-cooled cloud droplets versus ice crystals leading to significant riming of snow crystals forming in the layer as well as those falling into the layer from above. In cases where cloud temperatures were no colder than -10^{o} Celsius, snow grains are common. Such crystals are heavily rimed having the consistency of sand and are dense with ratios ranging from 3:1 to 5:1. Going further, if cloud temperatures are no colder than -8^{o} Celsius one may not observe the formation of snow at all. Rather freezing drizzle would be observed in such an instance (Baumgardt 2001).

Vertical motion maxima that persist above the SPZ are likely to produce crystals such as plates and columns which have intermediate densities and ratios. Such crystals may, upon descending through the SPZ, grow branches reducing their density. Such crystals are called spatial dendrites and are commonly observed, possibly rimed, during synoptic scale storms where deep vertical motion produces clouds that span a large temperature range. In such situations, one could infer that the degree of branching will depend on the amount of lift present in the SPZ and the number of snow crystals falling into the layer from above. High numbers of crystals would require more lift to maintain sufficient supersaturation for the occurrence of significant branching. This process would occur such that an equilibrium for branching is established depending upon the ratio of vertical motion above the SPZ to the SPZ itself.

Overall the character of snowflakes reaching the ground represents a natural integration of all the temperature and humidity conditions each snowflake experiences from its formation to subsequent free fall through cloud, sub-cloud, and exposure to near surface conditions. A relatively cold atmosphere with a persistent vertical motion maxima contained within the bounds of the SPZ would be expected to produce the lowest density snows with the greatest potential to reach significant depth.

3. DESCRIPTION OF ALGORITHM

The snowfall algorithm in part serves as a logical extension of the Cross-Hair approach and the snow ratio flow-chart (Dubè 2003). It uses the distribution of vertical motion relative to cloud temperatures to calculate a snow ratio at several points during a potential storm using NWP datasets. The snow ratios for each period are then multiplied by corresponding QPF to yield the QSF for each period of time. Finally, the QSFs can be summed over a potential storm to obtain a forecast storm- total snowfall.

Calculating the snow ratio is the linchpin of the approach and involves four steps:

(1) Find the maximum upward vertical velocity (UVV) contained in a cloudy layer. Cloudy is defined as a NWP model layer with a relative humidity with respect to ice equal or greater than 90 percent.

(2) Calculate a weighting factor to be applied to the layer snow ratio found in step (3). This weighting factor is a function of the UVV, max UVV, and the thickness of the layer. Specifically, the function is calculated as follows:

$$Weighting\ Factor = \omega[\frac{\omega}{\omega_{\max}}]^2(\Phi_2 - \Phi_1)$$

Where (ω) is the layer average upward vertical motion and (Φ) is the geopotential height. Lastly, the weighting factors are summed over all layers to be used in step 4.

(3) Calculate a snow ratio for each model layer using a relationship that maps snow ratio as a function of temperature.

(4) Calculate the weighted contribution of the snow ratio for each layer using the formula below. Finally, the weighted layer snow ratios are summed to obtain the snow ratio.

$$Weighted\ \ Snow\ Ratio\ =$$

$$SR(T) \times \frac{layer\ Weighting\ \ Factor}{\sum layer\ Weighting\ \ Factors}$$

Figure 5 shows the temperature to snow ratio curve referred to in step 3 above. It was constructed using a set of cubic splines applied to data from Table 1 and the observational data from Fig.1 suggesting that 50:1 serves as an upper limit to the snow ratio for significant snowfall.

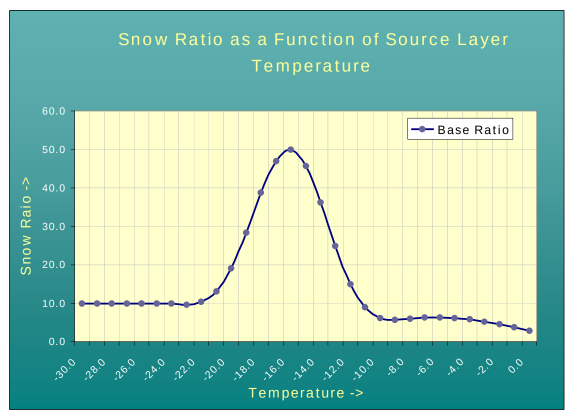

***FIG 5**. Function relating temperature to snow ratio. Data adapted from Baxter, 2005; Dube, 2003; and Ware, 2004.*

The weighting factor in step 2 is the result of trial and error using data from several key cases. In essence, the layer with the most vertical motion will contribute the most to the observed snow ratio. It was found that the addition of a weighting factor would enhance the degree to which the layer with the maximum UVV influences the snow ratio. Testing revealed that employing the weighting factor improved the ability of the algorithm to capture the extremes in observed snow ratios.

One of the interesting outcomes of this approach is that it does not require an arbitrary vertical motion threshold as could be implied by the Cross-Hair approach and the method used by Dubè (2003). The contribution of each layer is relative to the column total vertical motion no matter how small or large it is. This also eliminates any issues of vertical motion scaling that can be a function of the vertical or horizontal resolution of a given NWP system.

There are however, a couple of important assumptions. It is assumed that the NWP model produces relatively accurate profiles of vertical motion and temperature. As noted by Waldstreicher (2001), and based on personal experience, there is at least a moderate amount of confidence in this assumption based on experience gained using various conceptual models and diagnostic approaches, especially when NWP systems indicate a degree of run to run consistency, especially on the larger (synoptic and meso-alpha) scale. The second assumption is that the NWP QPF is accurate given an otherwise accurate NWP forecast. Indeed the whole of this work is leveraged on the validity of this assumption.

The last step would be to account for the sub-cloud and surface processes of melting and fragmentation which are not the focus of this paper, but are considered in the computer applications discussed in section 3.2.

3.1 *Example Calculation*

As an example, consider the simple cloud and data in Figure 6. Assume the thickness of each layer is 500m. Using this data, an example calculation of the snow ratio is illustrated below.

(1) The first step is to find the max UVV which in this case would be 12 cm/s occurring in the lowest layer of the cloud.

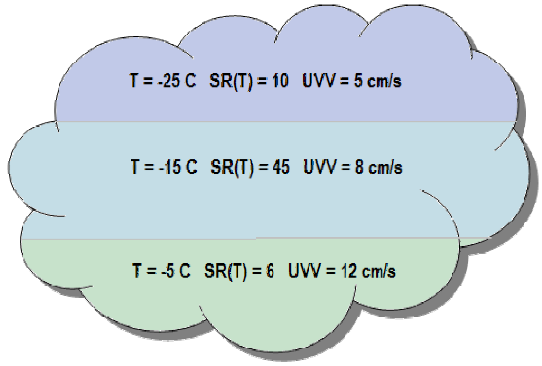

***FIG 6**. Theoretical 3-layer cloud with given temperatures (T), resulting snow ratio (SR) from Figure 4, and upward vertical velocities (UVV).*

(2) Next, calculate the weighting factor from the UVV, $UVV_{max,}$ and layer thickness for each layer and then sum them up.

From layer 1:

$$5 \times [\frac{5}{12}]^2 \times (500\ ) \cong 870$$

From layer 2:

$$8 \times [\frac{8}{12}]^2 \times (500\ ) \cong 1{,}778$$

From layer 3:

$$12 \times [\frac{12}{12}]^2 \times (500\ ) \cong 6000$$

Finally, the sum of the weighting factors from the three layers yields:

$$870 + 1778 + 6000 = 8648$$

(3) This step has been completed with the snow ratio data given by SR(T) in each cloud layer of Figure 6. For example, from Figure 5, for example that given a cloud layer temperature of -25^{o} Celsius the snow ratio would be 10:1.

(4) Finally, the snow ratio contribution is calculated for each layer by multiplying the layer snow ratio from step (3) by the results of step (2) divided by the sum of the weights (also found in step (2)):

From layer 1: $10 \times (\frac{870}{8648}) \cong 1$

From layer 2: $45 \times (\frac{1778}{8648}) \cong 9$

From layer 3: $6 \times (\frac{6000}{8648}) \cong 4$

Finally, the snow ratio contributions from each layer are summed to yield the snow ratio:

$1 + 9 + 4 = 14$ **or (14:1)**

3.2 *Computer Applications*

The objective nature of the algorithm allows it to be easily implemented on a computer. Two versions of the algorithm have been written for computational use. The first is a Perl based program that uses vertical model soundings from the NAM, GFS, or WorkStation version of the Eta that are processed for use in the Bufkit software (Mahoney and Niziol 1997). This version of the program also uses precipitation type logic to improve on its snow ratio and snowfall calculations. Bufkit sounding data are advantageous because they have the full native model vertical resolution, as well as very high temporal resolution (hourly for the NAM and Workstation Eta, 3-hourly for the GFS), yielding the best estimate of forecast snow ratio and potential snow accumulation at a given point. It also allows a forecaster to evaluate the snow ratio through visual inspection of the soundings using the Bufkit or equivalent software package.

The second program is based on Python and exclusively for use in the National Weather Service's Graphical Forecast Editor (GFE; Hansen et al. 2001). This GFE "Smart Tool" (LeFebvre et al. 2001) has the advantage of producing aerial distributions of snow ratio and snowfall. This version allows the forecaster to deliver more robust gridded forecasts of snowfall.

4. CASE EXAMPLES

Below are four cases which together span the climatological variability of observed snow ratios. The first event is an example of a high snow ratio event in which the maximum UVV was collocated with the SPZ. The second event occurred at Grand Rapids, MI, and is case where the maximum UVV is located above and at much colder temperatures than the SPZ. In the third example, a high density snowfall over northern Maine is examined. In this case, the maximum UVV is located below and warmer than the SPZ. Additionally, there is little cloud or UVV at temperatures colder than -12^{o} Celsius for the latter half of the event. The fourth and last example is of a large nor'easter where climatologically normal snow ratios were observed over northern Maine.

4.1 Presque Isle, Maine - *January 20, 2005*

The first example occurred over northern Maine on January 20, 2005. The system featured an inverted trough with a NW–SE axis across Aroostook County in, the largest county east of the Mississippi River. Several consecutive forecasts from the NAM indicated a narrow strip of around a half inch of QPF across northern Maine. These forecasts also indicated a fairly narrow large amplitude vertical motion maxima centered at -17^{o} Celsius. In fact, most of the vertical motion and cloud was below 16,000 feet above mean sea-level. The airmass was also cold with no riming layer present below the SPZ. The result was 16 inches of snow with a liquid equivalent of 0.54 inches. This equates to a storm snow ratio of about 29:1. Figure 7 depicts temperature and vertical motion profiles from the NAM for a time section through the event for Presque Isle, ME. Table 3 shows output from the Perl version of the algorithm which in this case predicted a storm average snow ratio of 26:1. Notice that the highest hourly snow ratios of 31:1 coincide with the highest precipitation rates and both of these occur simultaneously with the intersection of the UVV maxima with the SPZ. It can also be seen how the snow ratio decreases as the forecast axis of vertical motion rises above the SPZ.

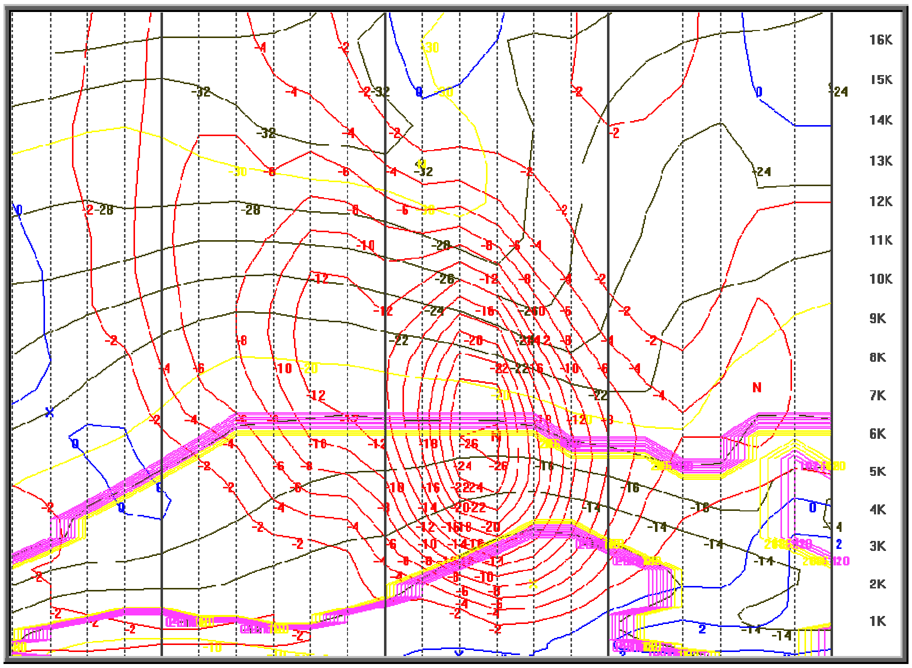

***FIG 7**. Time Section for KPQI from the 00Z 20 Jan 2005 NAM showing intersection of 30 μbs^{-1} vertical velocity maxima (red contours) with upper or colder part of SPZ (magenta and yellow contours). Green contours are temperatures in* ^{o} Celsius.

January20, 2005 NAM 00Z
Station ID: KPQI Presque Isle, Maine

FHR	Tsfc	QPF	SR	QSF	STS	STP
03	10	0.01	27:1	0.4	0.4	0.01
04	11	0.01	17:1	0.3	0.6	0.03
05	12	0.01	19:1	0.3	0.9	0.04
06	12	0.02	28:1	0.5	1.5	0.06
07	13	0.02	28:1	0.6	2.1	0.09
08	13	0.03	30:1	0.9	3.0	0.12
09	13	0.04	30:1	1.3	4.3	0.16
10	14	0.07	31:1	2.0	6.3	0.22
11	14	0.07	30:1	2.2	8.5	0.30
12	14	0.06	25:1	1.4	9.9	0.36
13	14	0.04	20:1	0.8	10.8	0.40
14	15	0.04	19:1	0.7	11.5	0.44
15	15	0.03	18:1	0.6	12.2	0.47

***Table 3.** Example output from Perl version of snowfall algorithm based on 00Z 2005Jan20 NAM input. Columns include: forecast hour (FHR), Surface temperature, quantitative precipitation forecast (QPF), snow ratio (SR), quantitative snow forecast (QSF), storm total snowfall (STS) and storm total precipitation (STP).*

4.2 Grand Rapids, MI - *January 22, 2005*

The second case illustrates intermediate snow ratios during an event at Grand Rapids, MI (Fig. 8). A very interesting aspect of this case is the 15,000 Ft deep SPZ present during the highest precipitation rates. The observed snow ratio for the event was 17:1 with mainly spatial dendrites noted by the Science Operations Officer at the Grand Rapids WFO during the event.

As discussed previously, the inference is that plates and columns formed at temperatures of -30^{o} Celsius in the region of max UVV and then grew branches as they fell through the deep SPZ. Apparently, the more modest UVV located in the SPZ was not enough to lead to larger branching and smaller snow densities that one might have expected with such a deep SPZ present.

The algorithm predicted a storm average snow ratio of 18:1. The hourly variations ranged from 12:1 to as high as 30:1 in the latter part of the event. Table 4 presents sample output from the Perl algorithm similar to Table 3. Table 5 presents a diagnostic of the algorithm at forecast hour 23, the forecast time when the maximum UVV is most pronounced above the SPZ. This illustrates how the algorithm was able to correctly emphasize the region of the cloud with the greater UVV in the snow ration calculation.

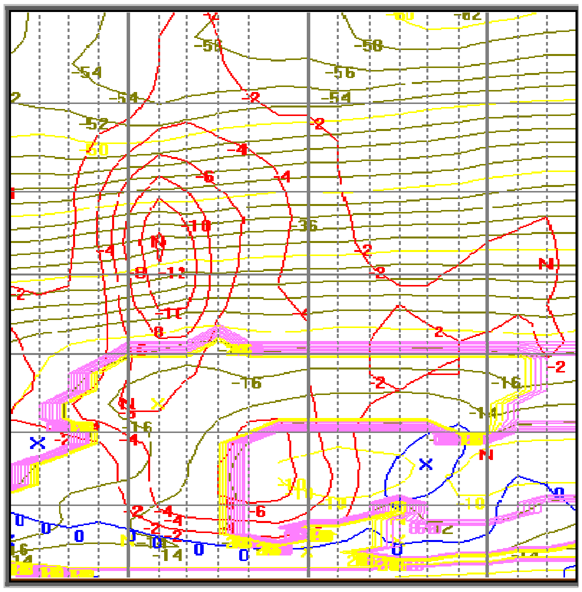

FIG 8. Time Section for KGRR from the 12 UTC 21 January 2005 NAM showing max 12 μbs^{-1} vertical velocity maxima (red contours) above 15,000 foot deep SPZ (magenta and yellow contours). Gray horizontal lines represent 5,000 Ft intervals.

January21, 2005 NAM 12Z
Station ID: KGRR Grand Rapids, Michigan

FHR	Tsfc	QPF	SR	QSF	STS	STP
12	15	0.00	0:1	0.0	0.0	0.00
13	15	0.00	0:1	0.0	0.0	0.00
14	15	0.00	0:1	0.0	0.0	0.00
15	14	0.00	0:1	0.0	0.0	0.00
16	13	0.00	0:1	0.0	0.0	0.00
17	13	0.01	13:1	0.2	0.2	0.01
18	13	0.03	17:1	0.4	0.6	0.04
19	13	0.04	18:1	0.7	1.3	0.08
20	13	0.05	16:1	0.7	2.1	0.13
21	13	0.05	18:1	0.9	3.0	0.18
22	13	0.05	15:1	0.7	3.7	0.22
23	13	0.04	15:1	0.6	4.3	0.27
24	13	0.06	19:1	1.1	5.4	0.32
25	13	0.05	26:1	1.3	6.7	0.37
26	13	0.03	30:1	0.8	7.5	0.40
27	15	0.01	17:1	0.3	7.8	0.41
28	16	0.01	12:1	0.1	7.9	0.43
29	17	0.00	0:1	0.0	7.9	0.43
30	19	0.00	0:1	0.0	7.9	0.43
31	20	0.00	0:1	0.0	7.9	0.43
32	20	0.00	0:1	0.0	7.9	0.43
33	19	0.00	0:1	0.0	7.9	0.43
34	17	0.00	0:1	0.0	7.9	0.43
35	13	0.00	0:1	0.0	7.9	0.43
36	8	0.00	0:1	0.0	7.9	0.43

Table 4: Example output from Perl version of snowfall algorithm based on 12Z 2005Jan21 NAM input. Columns same as Table 3.

Jan. 21, 2005 NAM 12Z – Fcst. Hour: 23
Station ID: KGRR Grand Rapids, Michigan

Pres	RH	UVV	Wtvv	Temp	SR
53Mb	2%	0.00	0.00%	-58.2	10:1
81Mb	2%	0.00	0.00%	-58.2	10:1
110Mb	2%	0.00	0.00%	-57.2	10:1
139Mb	2%	0.00	0.00%	-56.9	10:1
167Mb	8%	0.00	0.00%	-56.7	10:1
193Mb	15%	0.00	0.00%	-56.3	10:1
215Mb	16%	0.00	0.00%	-55.9	10:1
235Mb	28%	0.00	0.00%	-55.8	10:1
253Mb	38%	0.00	0.00%	-55.7	10:1
271Mb	58%	0.00	0.00%	-55.2	10:1
290Mb	82%	0.00	0.00%	-54.1	10:1
310Mb	93%	-0.04	0.46%	-51.7	10:1
331Mb	96%	-0.15	2.01%	-47.9	10:1
354Mb	95%	-0.47	6.30%	-43.5	10:1
378Mb	97%	-0.95	12.43%	-39.2	10:1
402Mb	98%	-1.35	17.12%	-35.2	10:1
427Mb	98%	-1.35	16.38%	-31.7	10:1
451Mb	98%	-1.07	12.51%	-28.6	10:1
475Mb	98%	-0.83	9.28%	-25.6	10:1
500Mb	98%	-0.55	5.85%	-22.7	10:1
524Mb	98%	-0.34	3.45%	-20.2	17:1
548Mb	98%	-0.28	2.74%	-18.1	38:1
571Mb	98%	-0.28	2.63%	-16.5	49:1
595Mb	98%	-0.23	2.06%	-15.3	47:1
618Mb	98%	-0.19	1.60%	-14.6	42:1
641Mb	98%	-0.15	1.22%	-14.6	42:1
664Mb	97%	-0.09	0.69%	-15.1	46:1
686Mb	97%	-0.07	0.49%	-15.5	49:1
707Mb	97%	-0.07	0.46%	-15.6	49:1
728Mb	97%	-0.07	0.43%	-15.6	49:1
748Mb	97%	-0.07	0.41%	-15.4	48:1
767Mb	97%	-0.07	0.39%	-15.1	46:1
786Mb	97%	-0.07	0.37%	-14.7	43:1
804Mb	97%	-0.07	0.35%	-14.2	39:1
822Mb	97%	-0.05	0.24%	-13.8	34:1
839Mb	97%	-0.02	0.11%	-13.5	31:1
855Mb	97%	-0.01	0.04%	-13.4	29:1
871Mb	96%	-0.00	0.01%	-13.5	31:1
887Mb	96%	0.00	0.00%	-13.9	35:1
901Mb	96%	0.00	0.00%	-14.1	37:1
914Mb	97%	0.00	0.00%	-13.7	32:1
927Mb	98%	0.00	0.00%	-13.0	25:1
937Mb	97%	0.00	0.00%	-12.7	22:1
946Mb	96%	0.00	0.00%	-12.6	20:1
953Mb	96%	0.00	0.00%	-12.3	18:1
960Mb	97%	0.00	0.00%	-12.0	15:1
966Mb	97%	0.00	0.00%	-11.7	13:1
971Mb	97%	0.00	0.00%	-11.4	11:1
975Mb	97%	0.00	0.00%	-11.1	10:1
980Mb	97%	0.00	0.00%	-10.8	9:1

Table 5: *Example diagnostic output from Perl version of snowfall algorithm for forecast hour 23 from the 12Z 2005Jan21 NAM input. The calculated snow ratio for this hour was 15:1. Columns include: pressure level (Pres); relative humidity with respect to ice (RH); upward vertical velocity (UVV), weighting factor (Wtvv) expressed as the percent of the sum of all layer weighting factors; temperature in Celsius (T); and layer snow ratio (SR).*

4.3 Caribou, Maine – December 11, 2004

In this case, a synoptic scale area of low pressure tracked across central Maine. As the low approached, a large dry slot advected ahead of the low and over northern Maine while relatively shallow but significant vertical motion associated with warm air advection continued below the dry slot.

While some sleet was observed during the event, mostly heavily rimed snowflakes or snow grains fell. Caribou recorded 4 inches of snow with a 5:1 ratio. The snow had the texture of sand which made for a deceivingly hard clean-up.

Unfortunately, both the NAM and GFS had forecast temperature errors of 1^{o} to 3^{o} Celsius too warm between 900 and 700 hPa for this event. The temperature errors were likely associated with an error in the forecast track of the low, which was too far north. The errors could be seen by comparing both 12Z and 00Z soundings at Caribou to the forecast vertical profiles at those times from the NAM and GFS (not shown). The NAM also overestimated the precipitation amounts at the beginning of the storm when the UVV maximum was located at colder temperatures.

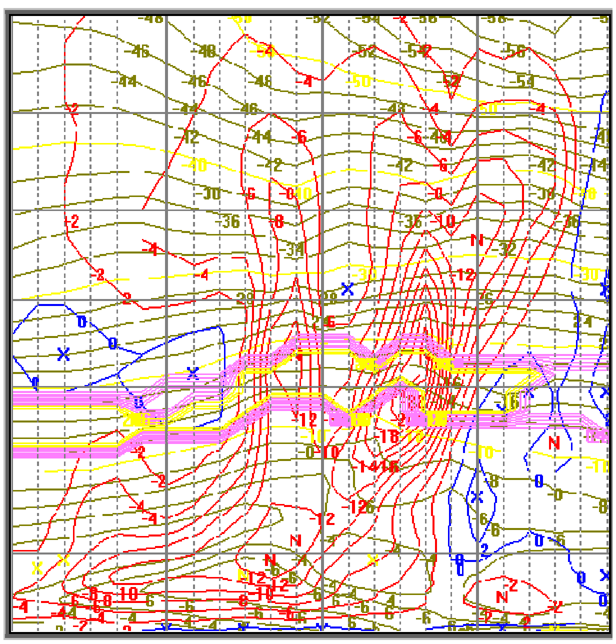

FIG 9. *Time Section for KFVE from the 12 UTC 10 December 2004 NAM showing area of UVV collocated with temperatures of -5^{o} Celsius during time of steadiest precipitation. Gray horizontal lines represent 5,000 Ft intervals.*

The vertical time sections and output shown in Fig. 9 and Table 6 are for nearby Frenchville, ME, which more closely resembled the verifying Caribou soundings. Looking at Table 6, snow ratios are initially greater than 15:1, but subsequently fall rapidly to 5:1 as the dry slot moves overhead and UVV maximum become centered at temperatures warmer than -10^{o} Celsius. The NAM also indicated precipitation rates of 0.10 inches per hour during the time of higher snow ratios but these rates and their duration were both over forecast. About one-inch of higher snow ratios was observed over the first two hours of the storm.

December 10, 2004 NAM 12Z
Station ID: KFVE – Frenchville, Maine

FHR	Tsfc	QPF	SR	QSF	STS	STP
18	16	0.00	0:1	0.0	0.0	0.00
19	18	0.00	0:1	0.0	0.0	0.00
20	20	0.06	25:1	1.5	1.5	0.06
21	21	0.13	18:1	2.4	3.9	0.19
22	22	0.11	11:1	1.2	5.0	0.30
23	24	0.08	10:1	0.8	5.8	0.37
24	25	0.07	8:1	0.5	6.3	0.44
25	25	0.08	16:1	1.2	7.5	0.52
26	26	0.10	14:1	1.4	8.9	0.62
27	27	0.10	6:1	0.6	9.5	0.72
28	28	0.07	5:1	0.4	9.8	0.79
29	29	0.07	5:1	0.4	10.2	0.86
30	31	0.03	5:1	0.2	10.4	0.89
31	31	0.03	5:1	0.1	10.5	0.92
32	31	0.04	5:1	0.2	10.7	0.96
33	30	0.07	5:1	0.4	11.1	1.03
34	30	0.05	5:1	0.3	11.4	1.08
35	30	0.04	5:1	0.2	11.5	1.12
36	31	0.01	5:1	0.1	11.6	1.13

Table 6*. Example output from Perl version of snowfall algorithm based on 12Z 2004Dec10 NAM input. Columns same as Table 3.*

4.4 Caribou, Maine – February 2, 2003

This final case is of a classic Nor'easter that struck northern Maine on February 2, 2003. The low developed off the coast of North Carolina and moved north-northeast across Nova Scotia and into the Gulf of St Lawrence. The storm brought widespread heavy snow and blizzard conditions to northern Maine. Just southeast of Presque Isle and across the border in New

Brunswick, Canada mainly sleet and freezing rain fell.

Caribou received 24 inches of snow with a storm snow ratio of 12:1. Snow accumulations were somewhat hard to measure due to significant blowing and drifting of the snow. The accumulation and ratio were taken at a nearby wind protected area just a mile from the airport. These readings also compare well to those in a wind protected area taken in Presque Isle, Maine 14 miles to the south of Caribou.

The algorithm produced storm snow ratios of 13:1. The maximum vertical motion was generally located below the SPZ but a significant percentage of the maximum velocities extended into and above the SPZ. From personal experience, this profile is typical of most Nor'easters .

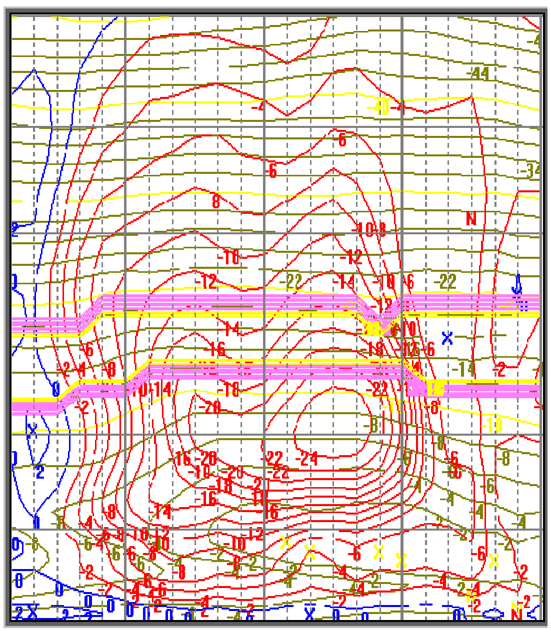

FIG 10. Time Section KCAR from the 12 UTC 2 February 2003 NAM showing area of UVV collocated with temperatures of -5^{o} Celsius during time of steadiest precipitation. Gray horizontal lines represent 5,000 Ft intervals.

February 02, 2003 NAM 12Z
Station ID: KCAR – Caribou, Maine

FHR	Tsfc	QPF	SR	QSF	STS	STP
01	27	0.01	9:1	0.1	0.1	0.01
02	29	0.03	10:1	0.3	0.4	0.04
03	29	0.05	11:1	0.5	0.9	0.09
04	30	0.08	11:1	0.9	1.8	0.17
05	30	0.09	10:1	0.8	2.6	0.26
06	31	0.09	11:1	1.0	3.6	0.35
07	30	0.12	13:1	1.5	5.1	0.47
08	30	0.13	12:1	1.5	6.7	0.59
09	29	0.12	13:1	1.6	8.2	0.71
10	28	0.12	13:1	1.5	9.8	0.83
11	28	0.11	12:1	1.3	11.0	0.93
12	28	0.09	11:1	1.0	12.0	1.03
13	27	0.09	11:1	1.0	13.0	1.12
14	27	0.09	13:1	1.1	14.1	1.20
15	27	0.09	13:1	1.2	15.3	1.29
16	28	0.11	14:1	1.5	16.8	1.40
17	28	0.11	15:1	1.6	18.4	1.50
18	28	0.09	17:1	1.6	20.0	1.60
19	27	0.07	19:1	1.3	21.3	1.67
20	27	0.05	21:1	1.0	22.3	1.71
21	27	0.02	24:1	0.5	22.8	1.74
22	27	0.00	0:1	0.0	22.8	1.74
23	26	0.00	0:1	0.0	22.8	1.74
24	26	0.00	0:1	0.0	22.8	1.74

Table 7: Example output from Perl version of snowfall algorithm based on 12Z 2003Feb02 NAM input. Columns same as Table 3.

5. SUMMARY AND FUTURE WORK

A simple snow ratio algorithm has been introduced that uses distributions of vertical motion, temperature, and humidity to produce up to hourly predictions of snow ratio. The algorithm has been shown to produce reasonable snow ratios for four common cases: UVV maximum above, below, collocated, and bridging the SPZ.

More cases need to be looked at to fully validate the utility of the algorithm. Additional assessment of the spatial accuracy, variability and coherence of the algorithm output via the GFE Smart Tool is also needed. The current plan is for algorithm testing to continue through the 2005-2006 winter season.

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