7A.2

FORECASTING THE SOLID-TO-LIQUID RATIO OF PRECIPITATION IN A CLOUD-RESOLVING MODEL

J.A. Milbrandt[1], D. Jacob[2], R. McTaggart-Cowan[1]

[1]Numerical Weather Prediction Research Section, Environment Canada, Dorval, Québec, Canada
[2]National Laboratory for High Impact Weather, Montreal, Québec, Canada

1. INTRODUCTION

Increases in computer power in recent years have allowed for the use of more sophisticated cloud schemes in high-resolution atmospheric models. Consequently, bulk microphysics schemes (BMSs) play an increasingly important role in both research and operational numerical weather prediction (NWP) models. A BMS affects the model dynamics through latent heat release due to phase changes of water and through changes to buoyancy, it interacts with the radiation scheme through its production of hydrometeor fields, and it is responsible for the prediction of precipitation phase, type, and quantity. In support of the forecasting for the upcoming 2010 Winter Olympics in Whistler (Vancouver), Canada, the Canadian Meteorological Centre will be operating a special high-resolution forecast system. On 2.5-km and 1-km nested grids, a detailed double-moment BMS will be used. To our knowledge, this will be the first time that a fully double-moment bulk scheme will be used for an operational forecast system.

For the quantitative prediction of the depth of accumulated unmelted snowfall, most NWP systems predict the liquid-equivalent solid precipitation quantity and then multiply it by an assumed solid-to-liquid ratio. A new approach to explicitly forecasting this ratio, using information provided by the microphysics scheme, has been developed. In this abstract, the method is described and a case study of a heavy snowfall event is presented to demonstrate the potential forecast skill of the proposed approach.

2. OVERVIEW OF THE BULK MICROPHYSICS SCHEME

The microphysics parameterization used in this study is the multi-moment BMS described in Milbrandt and Yau (2005; hereafter MY). The scheme was originally designed as a research tool for cloud-resolving models. It has since been adapted for operational purposes.

The scheme includes six distinct hydrometeor categories: *cloud* (liquid droplets), *rain*, *ice* (pristine crystals), *snow* (large crystals/ aggregates), *graupel* (rimed crystals), and *hail* (high-density graupel/frozen drops). The size distribution of each category is represented by a complete 3-parameter gamma function of the form:

$$N(D) = N_{0x} D^{\alpha_x} e^{-\lambda_x} \qquad (1)$$

where $N(D)$ is the number concentration of particles of diameter D and N_{0x}, λ_x, and α_x are the "intercept", slope, and shape parameters, respectively, for category *x* (where x = *c*, *r*, *i*, *s*, *g*, *h*).

The full triple-moment version of the MY scheme includes prognostic equations for three moments of the size distribution of each category *x*: the mass mixing ratio q_x, the total number concentration, N_x, and the reflectivity, Z_x. The double-moment version predicts q_x and N_x while the single-moment version predicts just q_x. The single-moment version has been running in the quasi-operational Canadian 2.5-km limited-area model since April 2008 with the double-moment version being tested in the current (2009) prototype of the 2010 Winter Olympics high-resolution forecast system.

Several modifications have been made to the original scheme. Amongst these are changes which pertain to the treatment of the snow category. To reflect a modern understanding of the proper representation of ice crystal categories, the exponent in the mass-diameter (*m-D*) relation for snow has been changed from 3 to 2.078, with corresponding changes to the coefficient (e.g. Mitchell, 1996). This is similar to recent developments to the well-known Thompson BMS, used in the Weather Research and Forecasting (WRF) model and the Pennsylvania State University - National Center for Atmospheric

Corresponding author address:
Dr. Jason A. Milbrandt, 2121 Trans-Canada Highway, 5th floor, Dorval, QC, H9P 1J3 (Canada); e-mail: jason.milbrandt@ec.gc.ca

Research Mesoscale Model (MM5), described in (Thompson et al., 2008). An important implication of this change in exponent is that snow is no longer represented by spheres with a constant bulk density, as it is with an *m-D* exponent of 3. Rather, snow is now represented as particles whose density varies inversely with its maximum dimension. This characteristic of the snow category in the scheme is consistent with ground-based disdrometer measurements of real snow particles (Brandes et al., 2007). We exploit this characteristic in our proposed method to forecast the solid-to-liquid ratio of precipitating snow.

3. METHOD FOR PROGNOSTIC SOLID-TO-LIQUID RATIO

The instantaneous solid-to-liquid ratio of precipitating snow is equal to the ratio of the volume flux to the mass flux at the surface. With a constant bulk snow density, the fluxes are simply proportional to each other by a factor of the assumed density. Thus, for a snow density of 0.1 g cm^{-3}, for example, the solid-to-liquid ratio will be exactly 10-to-1. With a variable density, on the other hand, the ratio increases with the mean-mass diameter of the snow distribution. Thus, we are utilizing both the variable density with the new *m-D* relation plus the fact that a double-moment scheme can provide a better estimate of the mean-mass diameter than a single-moment scheme, since it explicitly models processes such as aggregation and size-sorting. Estimates of the densification of snow during melting are made.

For the calculation of the instantaneous solid-to-liquid ratio, we also apply the precipitation flux ratio for graupel, mass-weighted with that of snow. The effect of this is that the solid-to-liquid ratio can change with the environmental conditions. For example, if riming becomes important during a snowfall event, which is often the case in the mountainous coastal regions of the Vancouver area, there will be a shift from snow to graupel in the model which will be reflected by a decrease in the instantaneous solid-to-liquid ratio.

The solid-to-liquid ratio for the total accumulation of solid "snow" precipitation is equal to the ratio of the unmelted depth of total solid precipitation (excluding hail) to its melted (liquid-equivalent) depth. These depths are obtained by the time integration of the unmelted and melted volume fluxes (precipitation rates), respectively. The formal derivation follows.

The mass flux for hydrometeor *x* is given by:

$$F_{m\_x} = \rho q_x \overline{V}_{qx}, \qquad (2)$$

where $\overline{V}_{qx}$ is the mass-weighted mean fall velocity. These are the precipitation rates which are time-integrated to obtain the accumulated melted depth from that category.

The ratio of unmelted volume flux to the mass flux is computed as:

$$\frac{F_{V\_x}}{F_{m\_x}} = \frac{\int_0^\infty V(D)\cdot vol(D)\cdot N(D)dD}{\int_0^\infty V(D)m(D)N(D)dD} = \frac{\int_0^\infty V(D)\cdot \frac{m(D)}{\rho(D)}\cdot N(D)dD}{\int_0^\infty V(D)m(D)N(D)dD} \qquad (3)$$

For ice and graupel ($x = i, g$), the bulk densities are prescribed constants and thus:

$$\frac{F_{V\_x}}{F_{m\_x}} = \frac{\frac{1}{\rho}\int_0^\infty V(D)\cdot m(D)\cdot N(D)dD}{\int_0^\infty V(D)m(D)N(D)dD}, \qquad (4)$$

and,

$$F_{V\_x} = F_{m\_x}\cdot\frac{1}{\rho_x}. \qquad (5)$$

For snow, with a diameter-dependent density, the ratio of the fluxes is computed as:

$$\frac{F_{V\_s}}{F_{m\_s}} = \frac{\frac{ac}{e}\int_0^\infty D^{b+d-f}N(D)dD}{ac\int_0^\infty D^{b+d}N(D)dD} \qquad (6)$$

and hence,

$$F_{V\_s} = F_{m\_s}\cdot\frac{\lambda^f}{e}\frac{\Gamma(1+\alpha+b+d-f)}{\Gamma(1+\alpha+b+d)}. \qquad (7)$$

The liquid-equivalent volume flux for any category ($x = i, s, g$), which is used for the sedimentation rate for that category, is given by its mass flux divided by the density of water:

$$F_{Vle\_x} = \frac{F_{m\_x}}{\rho_L}. \qquad (8)$$

The unmelted and liquid-equivalent volume fluxes for the total solid "snow" precipitation (*i*, *s*, and *g*;

excluding *h*) is the sum of the individual fluxes, respectively:

$$F_{V\_sol} = F_{V\_i} + F_{V\_s} + F_{V\_g} \tag{9}$$

and

$$F_{Vle\_sol} = F_{Vle\_i} + F_{Vle\_s} + F_{Vle\_g} . \tag{10}$$

To account for the increase in density during melting, the liquid fraction of the partially melted total "snow" is approximated as the ratio of the rain mixing ratio to the sum of the mixing ratios of rain plus the individual solid precipitation categories. The assumption is that all rain present at that point, collocated with solid precipitation in the melting layer, is a surrogate for the amount of solid mass that has melted. Thus,

$$f_{liq} = \begin{cases} \dfrac{q_r}{q_r + (q_i + q_s + q_g)} & \text{for } T > 0^\circ\text{C} \\ 0 & \text{for } T \le 0^\circ\text{C} \end{cases} . \tag{11}$$

Using the flux above, the unmelted total volume flux is modified to tend it towards the liquid-equivalent total volume flux as the liquid fraction increases towards 1 to obtain the volume flux of partially melted (or unmelted) total solid (*i*+*s*+*g*) precipitation:

$$F_{Vpm\_sol} = (1 - f_{liq})F_{V\_sol} + f_{liq}F_{Vle\_sol} , \tag{12}$$

This flux gives the total solid (unmelted or partially-melted) precipitation rate which is time-integrated to obtain the final "snow depth" of accumulated solid precipitation.

For the accumulated precipitation amounts, the appropriate volume fluxes are integrated over time. For the liquid-equivalent quantities, the F_{V_x} values are used. The accumulated melted depths of ice, snow, and graupel are thus given by, respectively,

$$SN1^{t+1} = SN1^{t} + \Delta t \cdot F_{Vle\_i} , \tag{13}$$

$$SN2^{t+1} = SN2^{t} + \Delta t \cdot F_{Vle\_2} , \tag{14}$$

$$SN3^{t+1} = SN3^{t} + \Delta t \cdot F_{Vle\_g} , \tag{15}$$

with the total accumulated melted "snowfall" depth at any time given by,

$$SN = SN1 + SN2 + SN3 . \tag{16}$$

Likewise, the accumulated depth of unmelted total "snowfall" (with partial melting in air accounted for) is given by,

$$SND^{t+1} = SND^{t} + \Delta t \cdot F_{Vpm\_sol} . \tag{17}$$

With the melted and unmelted accumulated amounts of total snowfall, the solid-to-liquid ratio of the accumulated solid precipitation is simply,

$$S2L = \frac{SND}{SN} . \tag{18}$$

4. CASES STUDY

In order to examine the potential skill of the proposed method of forecasting snow depth, a case of a heavy snowfall event in eastern Canada was simulated on a 2.5-km grid using the Global Environmental Multiscale (GEM) model (Côté et al., 1998), the operational NWP model used by the Canadian Meterological Centre, with the double-moment MY scheme. Comparisons of simulated solid (unmelted) and liquid-equivalent snow depths were compared to observations in the Ontario-Quebec region.

Due to the difficulty in accurately measuring snow depths, the observations were carefully quality controlled. Consequently, the total number of reliable observations for this 48-h simulation was limited to 73 (total, for eight 6-h periods). Corrections were also made to account for undercatchment, following the method of McDonald and Polmeroy (2007).

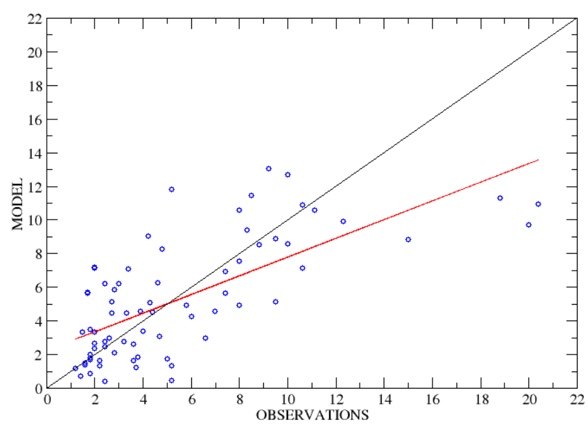

Fig. 1 Model vs. observed accumulated liquid-equivalent precipitation (mm) for eight 6-h periods between 0600 UTC 2 Dec – 0600 UTC 4 Dec 2007.

The quantitative precipitation forecast was reasonably good, as indicated by the scatter-plot of the observed to modeled liquid-equivalent precipitation quantities, shown in Fig. 1. Thus, it is reasonable to use this case to proceed to evaluate the simulated snow depth. The scatter-plot of the solid 6-h accumulated snow (Fig. 2) suggests that the proposed method may indeed exhibit some forecast skill for this quantity.

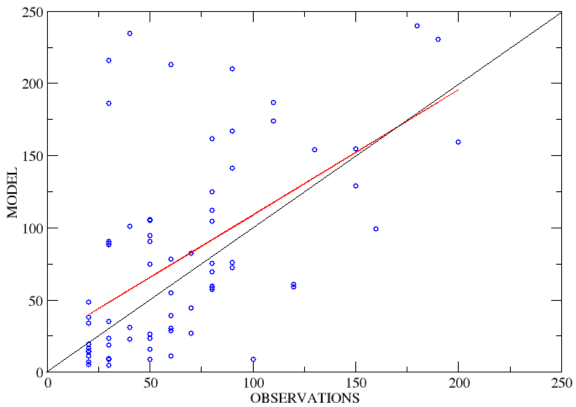

Fig. 2 As in Fig. 1 but for the accumulated snow depth (mm).

Closer examination of the actual solid-to-liquid ratios, on the other hand, indicates some potential problems with the evaluation of this case with the current data. Figure 3 shows the simulated solid-to-liquid ratio of the accumulated snow for a given 6-h period along with the observations that met the quality control criteria for that period. Overall, to simulated ratio values differ considerably from the observed values. The same comparison for a later 6-h period (Fig. 4), in contrast, indicates that the model does a better job reproducing the observations. It is clear that there is considerable variability, both spatially and temporally, for both the simulated fields and the observations. Thus, evaluation of the proposed method based on a single case may be of limited value, given the sparsity of the reliable observations.

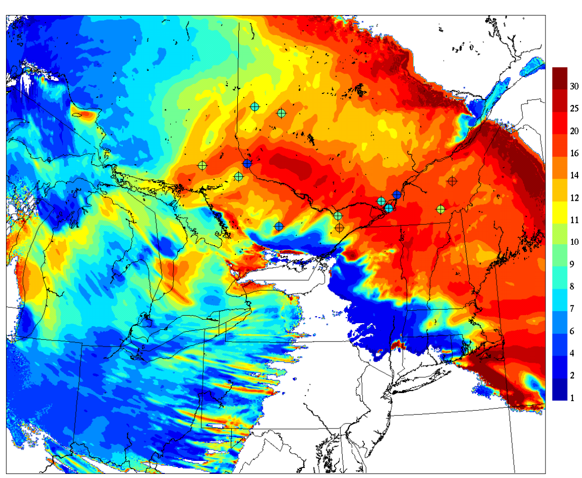

Fig. 3 Solid-to-liquid ratio for 6-h (0600 - 1200 UTC 3 Dec. 2007) accumulated precipitation from 2.5-km simulation (colored field) and station observations (circles; same color scale).

Nevertheless, comparison of the values of the simulated solid-to-liquid ratio over the entire model domain (420 000 points) to climatology suggests that the method produces realistic results. Figure 5 shows a histogram of the number of model points in the domain with a given solid-to-liquid ratio for the entire 48-h simulation. As an estimate of the expected values, we compare this to Fig. 6, which depicts a similar histogram for 1650 snowfall events over 28 stations in the central-eastern U.S. during the period from 1973-94, based on a climatology from Roebber et al. (2003). Although this is not a strictly valid comparison, and indeed the individual stations comprising the climatology vary from Fig. 6, it indicates, at the least, that the proposed method produces a realistic distribution of the values of the solid-to-liquid ratio.

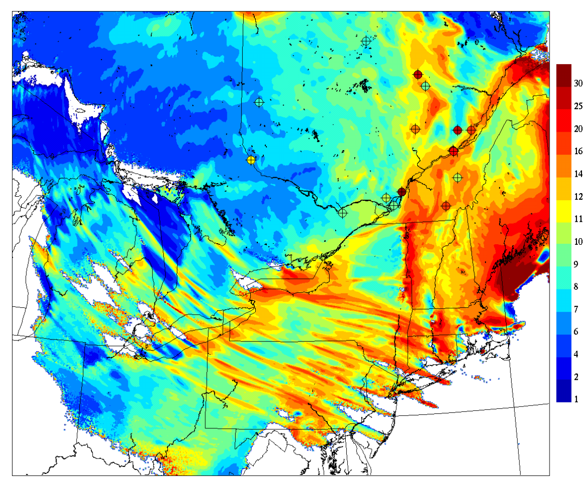

Fig. 4 As in Fig. 3 but for 1800 UTC 3 Dec – 0000 UTC 4 Dec 2007.

5. CONCLUSION

A method has been proposed to predict the snow depth, and thus the solid-to-liquid ratio of precipitating solid precipitation, in a cloud-resolving NWP model by which information given by the bulk microphysics scheme is used. Although the technique is inherently tied to assumptions made in the bulk scheme, it benefits from the fact that the model independently predicts the quantities of snow and graupel and exploits the characteristic of the snow category in which the new mass-diameter relation implies a size-dependent bulk density.

Verification of this forecast technique is challenging due to the difficulties in properly measuring accumulated snow quantities. Proper evaluation of the proposed method will require many case studies with observations that are rigorously quality controlled. Nevertheless, the preliminary results are encouraging since they produce a realistic distribution of values of the solid-to-liquid ratio.

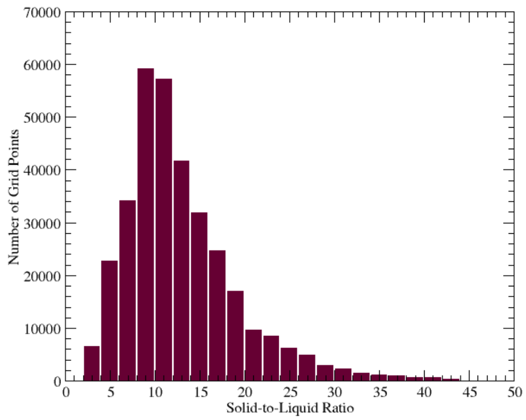

Fig. 5 Histogram of the solid-to-liquid ratio of the 48-h accumulated precipitation for each grid point in a 2.5-km simulation of a heavy snowfall case (2-4 December 2007) in eastern Canada.

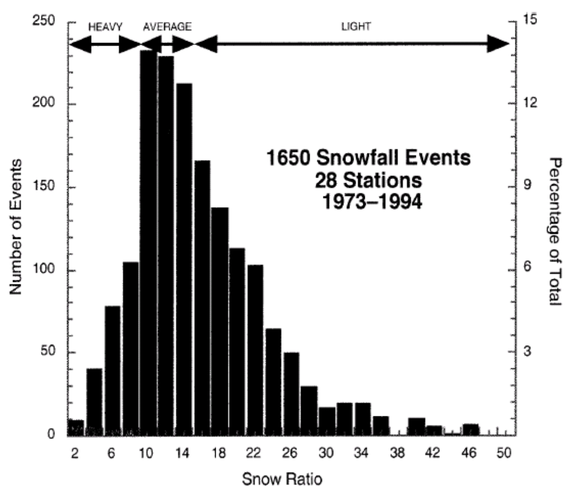

Fig. 6 Histogram of the solid-to-liquid ratio for 1650 snowfall events over 28 stations in the U.S. during 1973-94. (From Roebber et al., 2003.)

Further evaluation will be conducted on high-resolution (2.5-km) limited area domains in western Canada (British Columbia and Alberta) and eastern Canada (Ontario and Quebec) using the double-moment MY scheme in the 2009-10 winter as well as in the high-resolution forecast system during the upcoming 2010 Winter Olympics in Whistler, Canada.

REFERENCES

Brandes, E. A., K Ikeda, G. Zhang, M. Schonhuber, R. M. Rasmussen, 2007: A statistical and physical description of hydrometeor distributions in Colorado snowstorms using a video disdrometer. *J. App. Meteor. and Climatol.* **46**, 634-650.

Côté, J., S. Gravel, A. Méthot, A. Patoine, M. Roch, and A. Staniforth, 1998: The operation CMC-MRB Global Environmental Multiscale (GEM) model. Part I: Design considerations and formulation. *Mon. Wea. Rev.*, **126**, 1373-1395.

McDonald, J. P. and J. W. Polmeroy, 2007: Undercatch of two common snowfall gauges in a prairie environment. 64th *Eastern Snow Conference*, St. John's, Newfoundland, Canada, 2007.

Milbrandt, J. A. and M. K. Yau, 2005: A multimoment bulk microphysics parameterization. Part II: A proposed three-moment closure and scheme description. *J. Atmos. Sci.*, **62**, 3065-3081.

Mitchell, D. L., 1996: Use of mass- and area-dimensional power laws for determining precipitation particle terminal velocities. *J. Atmos. Sci.*, **53**, 1710-1723.

Roebber, P. J., S. L. Bruening, D. M. Schultz, and J. V. Cortinas Jr., 2003: Improving snowfall forecasting by diagnosing snow density. *Wea. and Forecasting*, **18**, 264-287.

Thompson, G., P. R. Field, R. M. Rasmussen, W. D. Hall, 2008: Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: Implementation of a new snow parameterization. *Mon. Wea. Rev.*, **136**, 5095-5114.