P3.26 DEVELOPMENT OF A SNOWFALL RETRIEVAL ALGORITHM USING DATA AT HIGH MICROWAVE FREQUENCIES

Yoo-Jeong Noh*, Guosheng Liu, and Eun-Kyoung Seo
Florida State University, Tallahassee, FL 32306, USA

1. INTRODUCTION

In the high latitudes during cold seasons, a substantial portion of precipitation falls in the form of snow. Measuring snow precipitation has many applications such as forecasting hazardous weather, understanding hydrological water budget and evaluating the cooling and freshening effects of snow onto ocean surface. But, ground-based snowfall measurements are difficult to make due to strong wind effects on snow gauges and melting/evaporating before measuring, and observation sites are very sparse in remote regions. Thus, satellite measurements have advantage for global snowfall observation. However, while satellite data have been extensively used in many cloud and rainfall studies, existing satellite remote sensing techniques have not been able to provide accurate snowfall retrievals. It is believed that there are two major reasons for this lag. First, the ice signature is indistinguishable from the liquid water signature at visible and infrared wavelengths, and the radiative signature of snow particles (scattering signature) is weak at low microwave frequencies (<90 GHz). This leaves high-frequency microwave as the best candidate for snowfall retrieval. But satellite observations with a reasonable spatial and temporal resolution at these frequencies were not available until recently when the Advanced Microwave Sounding Units – B (AMSU-B) onboard the NOAA-15 satellite. The second reason for this lag is the nonspherical shape of ice particles and snowflakes, whose radiative properties are much more complex than their liquid counterparts (water drops). Additionally, the thermal emission by water vapor and cloud liquid water has a masking effect on the snow scattering and reduces the snowfall signature (Liu and Curry, 1998).

The goal of this study is to develop a snowfall retrieval algorithm based on Bayes' theorem using high frequency microwave satellite data. An important component of the Bayesian algorithm is the *a-priori* database that connects brightness temperatures to snowfall rates. In constructing this database, we used a large number of snowfall profiles observed from both airborne and surface radars for shallow snow convections in the vicinity of Japan. We related these profiles to brightness temperatures with a radiative transfer model (Liu, 1998). Therefore, this algorithm is particularly applicable to snowfall associated with shallow convections. A new feature added to the radiative transfer model is single-scattering properties parameterized for nonspherical snowflakes (Liu, 2004). The Wakasa Bay 2003 field experiment (Lobl et al., 2005) that was recently conducted to validate satellite retrieval products from the Advanced Microwave Scanning Radiometer – EOS (AMSR-E) provides both remotely sensed and *in situ* data of snowfall events. The current study takes full advantage of this rich dataset for the purpose of snowfall retrieval algorithm development and validation

*Corresponding authors address : Yoo-Jeong Noh, Florida State University, Dept. of Meteorology, Tallahassee, FL 32306; e-mail: yjnoh@met.fsu.edu

2. DATA

In this study, the Wakasa Bay and its surrounding areas near the Sea of Japan are the main focus. In order to construct a database for snowfall retrievals, data collected during the Wakasa Bay 2003 field experiment (Lobl et al., 2005) are used. Of the various datasets collected in the experiment, the data from the following two remote sensors onboard a C-130 aircraft are analyzed: the Millimeter-Wave Imaging Radiometer (MIR) and the dual frequency Precipitation Radar (PR-2). The MIR is a total power, cross-track scanning radiometer that measures radiation at seven frequencies: 89, 150, 183.3±1, 183.3±3, 183.3±7, 220, and 340 GHz (Racette et al., 1996; Wang, 2003). The PR-2 operates at 13.4 GHz (Ku-band) and 35.6 GHz (Ka-band), and uses a deployable 5.3-m electronically scanned membrane antenna (Im, 2003). Besides the airborne remotely sensed data, nine upper air sounding profiles and *in situ* particle size distributions observed at Fukui airport (36.14°N, 136.22°E) during the field experiment are used. Data from a 3.2 cm Doppler radar were also used to build the *a-priori* database. The radar was operated at Obama (35.55°N, 135.74°E) in the coastal area of the western Japan from 2 to 17 February 2001.

The snowfall retrieval algorithm is applied to the NOAA-16 AMSU-B data. The AMSU-B has five channels: 89, 150, 183.3±1, 183.3±3, and 183.3±7 GHz (Zhao and Weng, 2002). Five of the seven MIR channels operate at the same frequencies as the AMSU-B. To validate the retrieved results, the AMeDAS (Automatic Meteorological Data Acquisition System) radar precipitation data are used. The AMeDAS (Oki et al., 1997) consists of radar and automatic rain gauge stations located all over Japan. The radar-AMeDAS data are 1-hr accumulated precipitation observations from gauge-calibrated radars.

3. THE BAYESIAN RETRIEVAL ALGORITHM AND BUILDING THE *A-PRIORI* DATABASE

An important component of a Bayesian retrieval algorithm is the *a-priori* database that connects the observations (brightness temperatures) with the parameters to be retrieved (snowfall rates); the probability density of a snowfall rate in the database should be consistent with the likelihood of the same snowfall rate occurring in actual snow events. To build such a database, we collect snowfall data from airborne and surface based radars. The radar reflectivity is converted to snowfall rate, and a radiative transfer model is used to link the snowfall rate to microwave brightness temperatures.

In an effort to accurately calculate the scattering parameters of snowflakes in radar equations and radiative transfer models, we performed DDA simulations using realistic snow particle shapes. The DDA (Draine and Flatau, 2000) is a general method for computing the scattering and absorption of arbitrarily shaped particles. It is useful in studying the scattering caused by complex particles like dendrites. Two types of snowflakes (sector and dendrite snowflakes) are considered in the DDA computations. The backscatter cross sections calculated from the discrete-dipole approximation (DDA) for snowflakes is used to develop the Z_e-S relationships to convert equivalent radar reflectivity of the PR-2 to snowfall rate, i.e.,

$$Z_e = 250S^{1.083} \quad \text{at 13.4 GHz} \qquad (1a)$$

$$Z_e = 88.97S^{1.04} \quad \text{at 35.6 GHz} \qquad (1b)$$

where Z_e is the equivalent radar reflectivity in mm^6 m^{-3}, and S is the snowfall rate in mm h^{-1}.

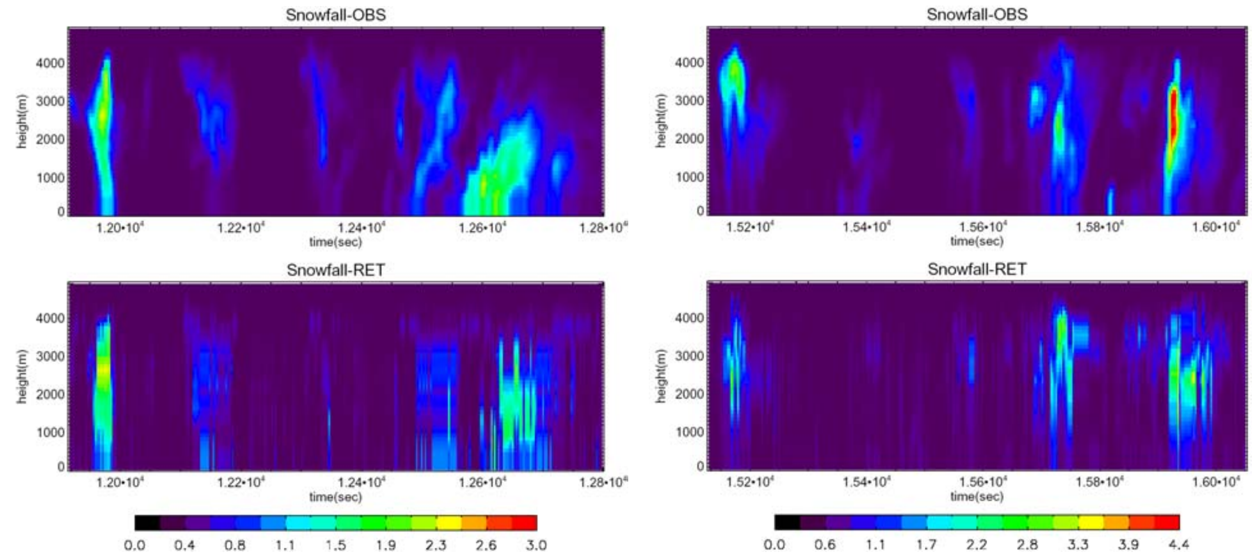
Since the *a-priori* database linking the brightness temperatures and snowfall rate will be constructed by radiative transfer calculations, it is essential that the radiative transfer model can produce brightness temperatures consistent with observations. This step is particularly important for the radiative transfer modeling of snowfall because the scattering properties of nonspherical snowflakes are not as well understood as those of raindrops. We simulate and compare the model brightness temperatures with those observed by MIR during the Wakasa Bay 2003 field experiment to ensure the validity of the radiative transfer model. The radiative transfer model used in the study solves the radiative transfer equation using the discrete ordinate method (Liu, 1998) and calculates the single-scattering properties of nonspherical snowflakes using the DDA based parameterization described by Liu (2004). It assumes the snowflakes are composed equally (by mass) of sector and dendrite particles with random orientations.

On 29 January 2003, strong northwesterly flow was dominant over the Sea of Japan, and extensive areas of snowfall were reported along the west coast of the main island of Japan. An aircraft flight observed the snowfall over ocean along several different flight legs. In this study, we use the brightness temperature depressions ($\Delta T_B = T_B - T_{B0}$, where T_B and T_{B0} are the cloudy and clear-sky brightness temperatures, respectively). The clear-sky brightness temperatures are derived from locations where no radar echo of PR-2 was observed. The depressions of brightness temperatures of MIR are significantly greater at 220 and 340 GHz than the other channels, and they reach about 80 K for the first cell. Among the three 183-GHz water vapor channels, 183±7 GHz is the most sensitive to the snowfall cells. The 89-GHz brightness temperatures in some convective cells are higher than clear-sky values; this implies rich cloud liquid water exists in these cells. While the increase in brightness temperature occurs at 150 GHz as well, the overall signature in this channel is of a depression corresponding to a snow cell. To take into account the emission from cloud liquid water, a layer of cloud liquid water is assumed between 3 and 3.5 km. The liquid water path (*LWP*, g m^{-2}) is determined by the brightness temperature increase at 89 GHz using $LWP = 0.84\,(\Delta T_{B89})^2$ that is derived by regressing radiative transfer model simulation results. Due to the uncertainties for input variables such as atmospheric water vapor profiles and snow particle size distributions, we choose to vary these variables in the radiative transfer model simulations.

In the radiative transfer simulations, we used the exponential form of the particle size distribution, $N(D) = N_0 \exp(-\Lambda D)$, but with two different parameterizations of the N_0 and Λ. First, the distribution of Sekhon and Srivastava (1970) was used. The second size distribution was derived from data by Dr. Muramoto's research team at Kanazawa University (http://sharaku.eorc.jaxa.jp/AMSR/data_val/, referred to as the Muramoto size distribution hereafter.), who analyzed images of snow particles observed at Fukui Airport every 10 minutes from 1600 LST 28 January to 0800 LST 29 January 2003.

Next, we use this model to link snowfall rate with brightness temperatures at high microwave frequencies. The snowfall profiles in the database are made using two sources: PR-2 data from the 2003 Wakasa Bay experiment and surface radar data from February 2001. The PR-2 snowfall rate profiles are derived from PR-2 observations made on 29 January 2003. Radar reflectivity is converted to snowfall rate using (1), and a liquid water cloud layer is inserted between 3 and 3.5 km with liquid water path calculated from 89 GHz ΔT_B. A total of 2201 snow profiles are generated from the PR-2 dataset. Surface radar data from two snowy days, 13-14 February 2001, are also used to enrich the database, which are using Aonashi et al. (2003)'s empirical Z_e-S relationships. To determine how much liquid water to include in each snowfall profile, we conducted an Empirical Orthogonal Function (EOF) analysis (von Storch and Zwiers, 1999) on the database from the Wakasa Bay 2003 field experiment. Using the EOF coefficients, the relationship between the vertical distribution of liquid water contents and snowfall profiles was obtained.

The derived liquid water contents of each snowfall profile in 2001 are combined with surface radar data to construct about 10000 snow cloud profiles.



(a) (b)

Figure 1. Comparisons of PR-2 observations at 35 GHz (upper) and retrieved snowfall rate (lower) along (a) leg1 and (b) leg3.

The *a-priori* database is then constructed through radiative transfer model simulation using all possible combinations of: 2201 Wakasa Bay (2003) snow cloud profiles, about 10000 surface radar (2001) snow cloud profiles, a total of 10 atmospheric sounding profiles (from observations at Fukui and the US standard mid-latitude winter atmospheric profile), and two types of particle size distributions. The total number of datum points in the database is about 260000.

A retrieval algorithm based on Bayes' theorem can be stated mathematically as follows (e.g., Olson et al., 1996; Evans et al., 1995, 2002). Let vector **x** represent snowfall rate profiles, and vector $\mathbf{y}_0$ represent available observations. The best estimate of **x,** given the observations $\mathbf{y}_0$, is assumed as the expected value, and in Bayes' theorem it can be written by the summation for a sufficiently large database,

$$\hat{\mathbf{E}}(\mathbf{x}) = \sum_j \mathbf{x}_j \frac{\exp\{-0.5[\mathbf{y}_0 - \mathbf{y}_s(\mathbf{x}_j)]^{\mathbf{T}} \times (\mathbf{O}+\mathbf{S})^{-1}[\mathbf{y}_0 - \mathbf{y}_s(\mathbf{x}_j)]\}}{\hat{A}}, \tag{2}$$

where the normalization factor is

$$\hat{A} = \sum_j \exp\{-0.5[\mathbf{y}_0 - \mathbf{y}_s(\mathbf{x}_j)]^{\mathbf{T}} \times (\mathbf{O}+\mathbf{S})^{-1}[\mathbf{y}_0 - \mathbf{y}_s(\mathbf{x}_j)]\} \tag{3}$$

where **O** and **S** are the observation and simulation error covariance matrices, respectively, and $\mathbf{y}_s(\mathbf{x})$ is simulations for the atmosphere state **x**. In the present study, the error covariance matrices, **O** and **S**, are set as follows similar to Olson et al. (1996). In the retrievals, we use (3 K, 1.2 K, 3 K, 3 K, 1.2 K) for $|\Delta T_B| \le 15$ K and (4.5 K, 1.8 K, 4.5 K, 4.5 K, 1.8 K) for $|\Delta T_B| \ge 15$ K, respectively, as observation plus simulation uncertainties for each frequencies for AMSU-B. The algorithm is then applied to the case of 29 January 2003 as an assessment of the algorithm's performance. Figure 1 shows the retrieved snowfall by applying the algorithm to MIR data measured for two different flight legs. The observed snowfall from PR-2 35 GHz (the upper panels) is compared with the retrievals. It appears that the retrieval algorithm captures well the basic features of the snow cloud cells, although differences exist in details between the observed and retrieved structures.

4. APPLICATION OF AMSU-B SNOWFALL RETRIEVAL

The snowfall retrieval algorithm is applied to the AMSU-B satellite data. Since there are no 220 and 340 GHz channels in AMSU-B, the AMSU-B version of the retrieval algorithm only uses data from five channels with frequencies from 89 to 183±7 GHz. Two snowfall cases are studied from 14 and 27 January 2001. These were located over Japan and its surrounding areas, and coincided with the field experiment "Winter MCSs Observations over the Japan Sea - 2001" (Murakami et al., 2001a, 2001b; Yoshizaki et al., 2001). During 12 to 19 of January, heavy snowfalls occurred mainly induced by quasi-stationary band-shaped snowfall systems elongated east and west along the southern coast of Japan. Meanwhile, on 27 January a synoptic cyclone developed and brought heavy snowfalls over the central Japan.

For 14 and 27 January 2001, figures 2-3 show the brightness temperature depressions at four of the five AMSU-B frequencies, the retrieved snowfall rates at 1.5 km, and the hourly-accumulated snow amount from the AMeDAS radar data. Note that the AMeDAS radar snow amount is the hourly-accumulated snow (in mm) averaged for 3 hours around the nearest time to the satellite passage or 1-2 hours after satellite passage, not instantaneous snowfall rate.

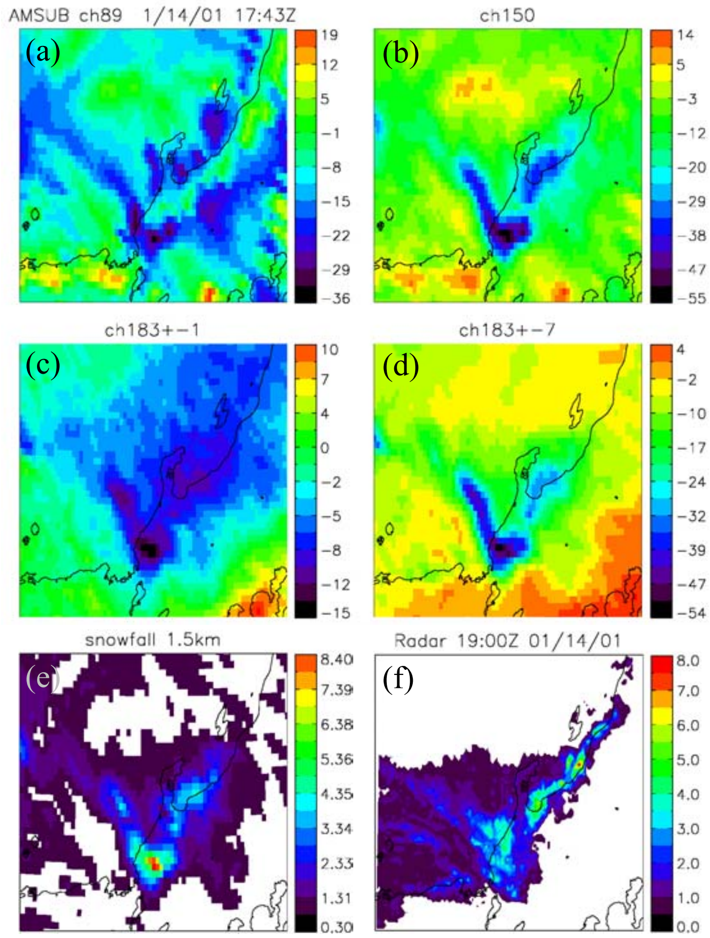


Figure 2. Comparisons of observations and retrieved results on 14 January 2001. (a-d) Brightness temperature depressions from the AMSU-B at 89, 150, 183±3, and 183±7 GHz, (e) retrieved snowfall at 1.5 km from the surface, and (f) hourly accumulated snow data (3-hr averaged) from the AMeDAS radar data.

Heavy snow bands are observed in the Wakasa Bay area on 14 January from the AMSU-B observations (Fig. 2a-d). The reduction of brightness temperature due to the scattering of snow appears much stronger at 150 GHz than at 89 GHz. The snow bands are also clearly resolved at 183±7 GHz frequency. The retrievals near the surface (Fig. 2e) are in good agreement with the AMeDAS radar observations. In particular, strong snow bands northeast of the Wakasa Bay are clearly reproduced in the retrievals. Despite the difficulty of direct quantitative comparison between surface radar data and retrievals from the satellite, the maximum snowfall region shows a similar magnitude and pattern.

In contrast to snow bands in the first case, an organized snow cloud system associated with a polar low on 27 January was observed. In the figure, we can see that clouds covered most of central Japan. The intense echo area was circular/spiral in shape and corresponded to the maximum depression of brightness temperature of about 70 K at 150 GHz (Fig. 3b). The AMSU-B snowfall retrievals show broad snow coverage over central Japan that compares well with AMeDAS snow accumulation about 2 hours after satellite passing time.

5. CONCLUSION

A snowfall retrieval algorithm has been developed based on Bayes' theorem using high frequency microwave radiometry observations. The *a-priori* database of the Bayesian algorithm is constructed using airborne and surface based radar measurements of snowstorms in the vicinity of Japan Sea. The relations between brightness temperatures and snowfall rates in the database are established by radiative transfer modeling. The algorithm is subsequently applied to airborne MIR and satellite AMSU-B measurements of snowfall near the Japan Sea, and the retrieved snowfall rates are compared with surface radar observations.

Since the *a-priori* database is an essential component of the Bayesian retrieval algorithm, special attention has been paid in this study to its construction. The backscattering of radar reflectivity and the single-

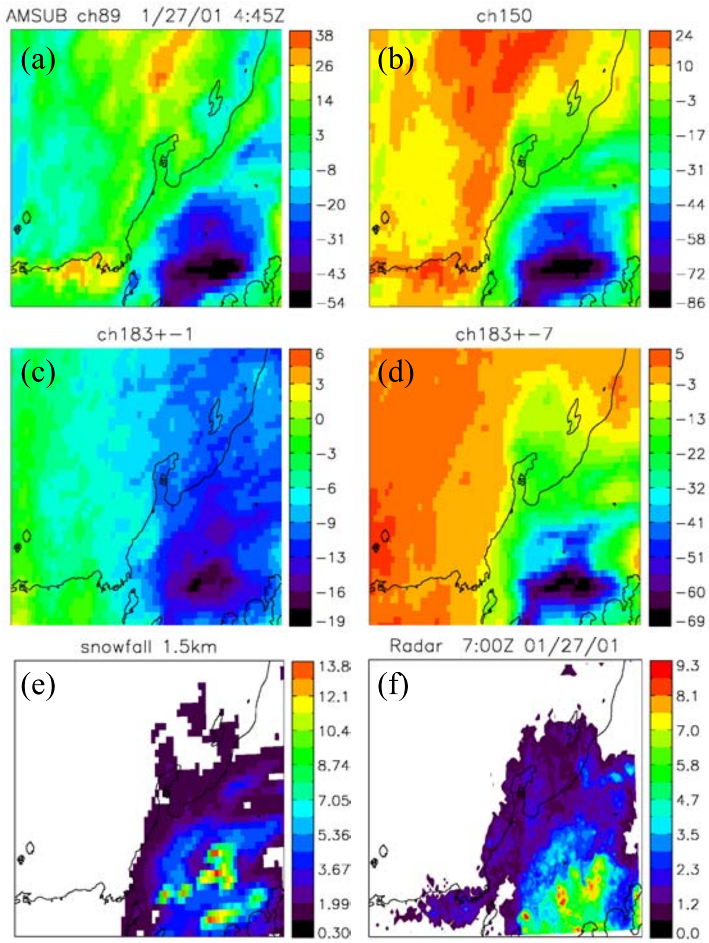


Figure 3. Same as Fig. 2, but for 27 January 2001.

scattering properties used in the radiative transfer model are calculated using a discrete dipole approximation for realistic nonspherical ice particles. Using the scattering properties from nonspherical particles, snowfall rates derived from radar reflectivities and brightness temperatures derived from radiative transfer models are expected to be more accurate than those computed from widely used spherical approximations. Second, the snowfall rate profiles used for building the database are from actual radar observations. The use of observational data instead of numerical model outputs ensures that the statistics of snowfall rate profiles in the database are consistent with those occurring naturally. To enrich the database, we included profiles from airborne radar and surface radar observations. Third, the diversity of the database is further enhanced by using two different types of particle size distributions: the widely used Sekhon and Srivastava (1970) distribution and the Muramoto distribution that was derived in the Japan Sea region using *in situ* ice particle measurements. Furthermore, embedded cloud liquid water layers and ten atmospheric sounding profiles are used as input for computing brightness temperatures with a radiative transfer model. The Bayesian snowfall retrieval algorithm was applied to satellite microwave AMSU-B data for two snowfall cases during January 2001 in the vicinity of the Japan Sea. The retrieved results are compared with the AMeDAS surface radar observations. Overall, the algorithm produces snowfall patterns in agreement with the radar data, especially within 1-2 hours after the satellite passage.

The database developed in this study is based on observations of snowfall events near the Japan Sea for the sole reason of data availability. Therefore, our algorithm is considered best suited for snowfall in this region. However, as more snowfall radar observations become available in the future, for example by CloudSat radar (Stephens et al., 2002), a global database can be constructed in a similar fashion, and the algorithm may be applied globally.

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