Millimeter-wave Measurement of Frozen Hydrometeors during the 2003 Wakasa Bay Field Experiment

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1. INTRODUCTION

Snowfall is an important part of the Earth’s precipitation and hydrological cycle. Remote measurements of frozen hydrometeor properties have been limited because coincident measurements of microphysical and electromagnetic properties of snowfall have not been available. Ground-based radars have been widely used to monitor snowfall intensity, but even those measurements are difficult to relate to water equivalent of snow because of the vast diversity of snow habits, density, and size distributions. Moreover, the spatial coverage of radar networks is limited over most regions other than the U.S.A., Europe, and Japan.

Snowfall measurement from space has been suggested as a solution to overcome this limitation. If the precipitating clouds contain a sufficient density of ice water equivalent from snow crystals, graupel, or both, then depressed Tbs (Tbs) at 85 GHz is likely (Bennartz and Petty, 2001). However, if the precipitation is more of local nature or is shallow (4 km or less), the depression at 85 GHz may not be as apparent. Interest has focused on frozen hydrometeor measurements at millimeter-wavelengths that are short enough to react with frozen hydrometeors and for which water vapor obscures the variable emission from the underlying snow covered surface. Fortunately, the NOAA Advanced Microwave Sounding Unit (AMSU) has given us the opportunity to examine the possibility to measure snowfall over land using millimeter-wave radiometry.

This study analyzes the millimeter-wave radiometric measurements of frozen hydrometeors during the field experiment that was held in Wakasa bay of Japan in January 29, 2003. The MM5 cloud simulation is employed to provide temperature and humidity profiles for the radiative transfer calculations.

Parameterizations to represent the electromagnetic scattering properties of snow at millimeter-wave frequencies are applied to the hydrometeor profiles derived by airborne radar measurements. Calculated brightness temperatures, radar reflectivity are compared with the millimeter-wave measurements.

2. WAKASA BAY FIELD EXPERIMENT

The U.S. AMSR-E and Japanese AMSR teams implemented a field experiment for Jan/Feb 2003 over Wakasa Bay, Japan (Wilheit et al. 2002). During the field experiment, the NASA P3 aircraft carried the dual frequency precipitation radar (PR-2) operating at 14 and 35 GHz; a cloud radar operating at 94 GHz (ACR); a passive microwave sensor (PSR) that simulates the AMSR observations; a high frequency passive microwave imaging radiometer (MIR) covering from 90 to 340 GHz; and an upward looking radiometer at 21 and 37 GHz (AMMR). The Japanese contribution to the experiment consists of a dual-polarized ground-based radar and supporting surface observations that allow us to put the aircraft observations into the larger meteorological context.

Wakasa Bay, on the eastern end of the Sea of Japan, has a strongly predictable cold air outbreaks in which cold air from the Eurasian continent blows over the relatively warm Sea of Japan. These storms generally produce rainfall near the surface, where warm boundary layer air mixes with the cold air aloft. The depth of the rain layer, however, is typically very shallow and in some cases, the snowfall reaches all the way to the surface.

There were 12 flights during this field experiment between January 14 and February 3 but only one case had heavy dry snow precipitation on January 29th, 2003. Since the dielectric constant of liquid water is much different from air and ice, the melting snow (air, ice, and water mixture) exhibits more complicated electromagnetic (EM) behavior than dry snow (air and ice mixture). As a first step to understand the EM scattering properties of
snowfall, we therefore confine this study to dry snow retrieval only.

Figures 1(a) and 1(b) show the IR Tb from the GMS satellite and radar reflectivity observed at 04 UTC in January 2003. It has been reported that the center of low pressure that had been just west of Hokkaido had moved northwards to the middle of Sakhalin Island and deepened to 979 mb. Strong northwesterly flow over all of the Sea of Japan produced extensive areas of snow off the coast of Honshu and the western side of the Japanese Alps.

Fig. 1 (a) IR brightness temperature from the GMS satellite and (b) radar reflectivity observed at 04 UTC in January 2003.

Figure 2 shows that air temperature near the ground measured at a ground-based observation site during the field experiment. The figure shows that the air temperature dropped below 0°C after 23 UTC January 28th causing dry snowfall.

Fig. 2 air temperature near the ground measured at a ground-based observation site (Fukui Airport, 36.14N, 136.22 E)

Figure 3 shows the MIR measured Tbs at 89, 150, 183±1, ±3, and ±7, 220, 340 GHz and the PR2 measured radar reflectivity at 14 and 35 GHz, and the ACR measured radar reflectivity at 95 GHz between 03 UTC and 04 UTC in January 29th 2003. The MIR Tb depression at frequencies greater than 183 GHz is well correlated with the ACR and PR2 radar reflectivity, overall. Brightness temperatures at 89 GHz and 150 GHz also show the weak depression over the precipitation region while showing contamination by the surface effect.

Fig. 3 (a) The PR2 measured radar reflectivity at 14 GHz and 35 GHz, (b) the ACR measured radar reflectivity at 95 GHz, and (c) MIR Tbs measured at 89, 150, 183±1, ±3, and ±7, 220, and 340 GHz along nadir between 03:18 UTC and 03:40 UTC in January 29th 2003.

3. SNOW MICROPHYSICS DATA

The snow microphysics variables were measured by Kanazawa University at the ground truth site (Fukui Airport, 36.14N, 136.22 E) during the field experiment. Figure 4 shows the snow particle size distributions (PSD) between 01-04 UTC in January 29th, 2003. The average diameters of measured snow particles range between 1 mm and 2 mm during January 28th-29th snow event.

Fig. 4 The snow particle size distributions measured by Kanazawa University at the ground truth site (Fukui Airport, 36.14N, 136.22 E) during the field experiment at (a) 01 UTC, (b) 02 UTC, (c) 03 UTC, and (d) 04 UTC in January 29th, 2003.

The most popularly used PSD distribution for falling snow is the gamma distribution given by

$$N(D) = N_D D^\alpha \exp(-D/D_g)$$

where $D_g$ is one fifth of the mass-weighted mean diameter of equivalent spheres. However, this function cannot
represent the fast drop of particle numbers for sizes greater than the size where the number concentration peak occurs. Therefore, we tested with the modified gamma functions given by

$$N(D) = N, D^k \exp(-(D/D_0)^{\alpha})$$  \hspace{1cm} (2)

using various k values greater than 1 to find the best fit function to represent the snow PSDs observed during the Wakasa bay field experiment. The optimization was implemented by matching the 1st, 2nd, and 3rd moment of size distributions. Even after relaxing the power inside the exponential function, the optimized PSD function cannot satisfactorily represent the observed PSD. The lognormal distribution given by

$$N(D) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{(\log D - \mu)^2}{2\sigma^2}\right)$$  \hspace{1cm} (3)

also tested with optimization by matching the 1st and 2nd moment of size distributions. The result shows that the lognormal function represents the consistent PSD with the observations. Figure 5 compares observed PSD with the optimized lognormal PSD with $D_0=1.6$ and $\sigma=0.5$.

5. SNOWFALL RETRIEVAL METHODOLOGY

This study seeks to derive characteristics of snow whose electromagnetic properties are consistent with microwave Tbs at several frequencies provided by the MIR sensors and the radar reflectivity measured by PR-2 and ACR radars. We have parameterized the electromagnetic scattering properties of nonspherical snow particles and preliminary results are presented in Kim et al. (2004a,b). The snowfall retrieval methodology employing those parameterizations is presented in this section. Following Kim et al. (2004c), Tbs are computed from the Eddington approximation of the second kind. The radiative transfer model employs information from the Pennsylvania State University-National Center for Atmospheric Research (PSU–NCAR) fifth-generation Mesoscale Model (MM5). Figures 6(a) and 6(b) show the MM5 forecasted 1hr precipitation accumulation and total precipitation (rain+snow+graupel) mixing ratio at 04 UTC, January 29th 2003. It should be noted that the almost 100% of precipitation in Figure 6(b) is in snow. In addition, the MM5 simulated cloud top height shown in Figure 6(b) is very consistent with the ACR radar reflectivity shown in Figure 3.

![Fig 5 Comparisons of snow particle size distributions (PSD) with (a) the optimized gamma PSD function and (b) the optimized lognormal PSD function.](image)

In addition to the fractional surface snow cover ($f$) to adjust the surface emissivity, these MM5 profile distributions form the basis of parameters determining the relative humidity profile ($r$) and the snow mass profile ($M_s$) used as input for forward radiative transfer calculations with an Eddington 2nd approximation with delta-scaling (Kim et al. 2003, Skofronick-Jackson et al. 2004). These three parameters, along with assumption of the fixed temperature profile and snow size distribution given by Eqn.(3), produce snow cloud characteristics used to generate Tbs that would be observed at the MIR frequencies using forward radiative transfer calculations. The optimal estimate of the snow parameters is derived from the best match between computed and measured Tbs at all MIR frequencies and radar reflectivity provided by PR2 and ACR. When additional information about the snow or other aspects of the storm conditions become available, these can be included in to further constrain the optimization.

The greatest challenge of this study is determining the electromagnetic properties of the wide variety of shapes and sizes of snowflakes. Comparing the Discrete-Dipole Approximation (DDA) method calculated single scattering properties for nonspherical particles (hexagonal column, hexagonal disks, sector plates, planar rosette, and spatial rosette), Kim et al. (2004) showed that equal-V/A and equal-V spheres can reasonably well present the extinction efficiency while equal-V/A spheres (equal-V and equal-A spheres) show significantly smaller (larger) asymmetry factor than the DDA results. The study also found that the dielectric mixing approaches employed by O’Brien and Goedecke (1988) for a dendritic seem not applicable to generate reasonable single scattering properties especially for complex snow flakes including large fraction of air inside due to significantly underestimated extinction efficiency and overestimated asymmetry parameters at millimeter-frequencies. The inappropriateness of applying effective medium mixing theories to irregularly shaped
hydrometeors with size parameter of large structural inhomogeneities was also addressed by Shivola (1989).

Although the DDA method can be used to compute the scattering characteristics of non-spherical particles, the shape of the frozen crystal habit can only be crudely or sometimes impossible to estimate so that a simpler parameterization is necessary.

Figure 7 shows the single scattering properties for randomly oriented hexagonal columns (left panels) and spatial rosettes (right panel) calculated by the DDA method. Three equivalent sphere approaches (equal-volume (V), equal-area (A), equal-V/A spheres) are compared. To average over the resonant peaks in the phase functions, the scattering results for 14 large dimensions ranging 0.25 mm to 3 mm are normalized using the optimized snow PSD function given by Eqn.(3). The DDA calculated the extinction cross-sections are between values calculated with the equal-V and equal-V/A spheres. All of equivalent spheres show significantly less asymmetry factor than the nonspherical particles calculated with the DDA method at frequencies greater than 140 GHz. Equal-V and equal-A spheres overestimated backscattering cross-sections while equal-V/A spheres underestimated.

6. FUTURE WORK

The MM5 cloud simulation is employed to provide temperature and humidity profiles for the radiative transfer calculations. Parameterizations to represent the electromagnetic scattering properties of snow at millimeter-wave frequencies will be applied to the hydrometeor profiles derived by airborne radar measurements. Calculated Tbs, radar reflectivities will be compared with the millimeter-wave measurements.

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Fig. 7 Comparisons of single scattering properties calculated by the DDA method, equal-volume sphere, equal-area sphere, and equal-volume/area spheres. (a) and (b) shows extinction cross section, (c) and (d) shows the asymmetry factor, (e) and (f) shows the backscattering cross section for hexagonal column and spatial rosette, respectively.