Determination of 3-D Cloud Ice Water Contents by Combining Multiple Data Sources from Satellite, Ground Radar, and a Numerical Model

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ABSTRACT

This study aims at determining the 3-dimensional distribution of ice water content over a broad area near the Atmospheric Radiation Measurement Southern Great Plain site, where cloud radar and meteorological observations have been routinely conducted. Together with wind fields from other measurements, the ice water content retrievals can be used to derive cloud ice water advective tendency terms needed for single-column model simulations. In this study, a Bayesian retrieval algorithm has been developed, which combines multiple data sources from satellite high-frequency microwave radiometry and ground cloud radar observations, and mesoscale numerical model analysis. The cloud radar observations allow us to infer the characteristics of vertical ice water content structures. The numerical model data are used to locate the cloud height. The satellite data provide information on the integrated ice water path, its horizontal distribution over a broad area, and, to a lesser extent, the vertical structure of ice water content. Our approach is to retrieve the 3-dimensional cloud ice water content in a 10° by 10° area surrounding the cloud radar site by combining all the information contained in the above datasets through a Bayesian framework. Validation of the algorithm has been done by comparing the retrievals with measurements from two ground radars. The comparison shows that the mean ice water content profiles and the 2-dimensional (height-ice water content) probability density functions retrieved for 19 coincident cases agree fairly well with the validation data. However, the retrieved ice water contents generally lack of detailed vertical structures due to the low sensitivity of satellite data to the vertical variation of cloud ice.
1. Introduction

One of the scientific foci of the Atmospheric Radiation Measurement (ARM) program is to develop and test the radiative and cloud microphysical parameterizations used in general circulation models by the means of single column modeling (SCM) (Randall et al. 1996). As forcing terms, SCMs require horizontal advection tendencies of cloud condensates in addition to the advections of heat, moisture and momentum. However, because surface-based radar observations from the millimeter-wave cloud radar (MMCR) are point measurements, they do not provide the horizontal advection of cloud condensates. This poses a significant problem when testing physical parameterizations (Randall et al. 1998). Satellite observations normally cover a large area within a short time and are therefore potentially useful for retrieving the horizontal distribution of cloud condensates required for calculating advective tendencies. As a first step in deriving the advection of cloud ice water, we have developed an ice water path (IWP) retrieval algorithm by combining ground cloud radar and satellite high-frequency microwave measurements (Seo and Liu 2005). In this previous study, the surface cloud radar provides statistics for the vertical distribution of ice water content, then the satellite retrievals use those statistics to broaden a point measurement to an areal measurement. Using this algorithm, IWPs have been retrieved over an area of 10° x 10° centered at the ARM southern great plain (SGP) site where the cloud radar operates. However, to derive the advection tendency of cloud ice water, the integration and the vertical distribution of cloud ice water contents are needed. Toward this goal, in this study we take one step further to explore the feasibility of retrieving the vertical distribution of ice water content (IWC) in order to derive a 3-
dimensional ice water content around the ARM SGP site by combining data from satellite, ground radar, and numerical model analysis.

Based on satellite and airborne radiometer measurements, several studies on cloud ice water retrievals were conducted by previous investigators. Minnis et al. (1993) developed a method to retrieve cirrus cloud properties from satellite-observed visible and infrared radiances. By combining visible and microwave measurements, ice water amount was extracted from total condensed water amount (Lin and Rossow 1996). Meanwhile, using high-frequency microwave channels, the reduction of upwelling radiation due to scattering by ice particles was related to IWP (Liu and Curry 1998; 2000; Zhao and Weng 2002). Skofronick-Jackson and Wang (2000) and Skofronick-Jackson et al. (2003) estimated microphysical profiles using multichannel microwave observations. In addition, Evans et al. (1998; 2002; 2005) modeled the radiative properties of cirrus clouds, especially at submillimeter wavelengths.

In our previous study (Seo and Liu 2005), an IWP retrieval algorithm was developed by combining ground radar MMCR and satellite AMSU-B (Advanced Microwave Sounding Unit – B) measurements. The algorithm was based on Bayes’ theorem in which an *a priori* database linked brightness temperatures ($T_B$) at AMSU-B frequencies to IWPs of ice clouds. The *a priori* database was constructed by conducting radiative transfer model simulations using the MMCR measured cloud IWC profiles as input. The radiative transfer model adopted the most recently documented ice microphysics (Heymsfield and Miloshevich 2003; Heymsfield 2003ab) and single-scattering properties of nonspherical ice particles (Liu 2004). In the present study, we use the same *a priori*
database to retrieve IWC profiles but add an ice cloud top constraint from analysis data of the Rapid Update Cycle, version 2 (RUC-2) modeling system (Benjamin et al. 1998). The rest of this paper is arranged as follows. Section 2 describes the data used in this study. Section 3 contains sensitivity studies of the AMSU-B $T_B$ to IWC profiles. Section 4 describes the retrieval algorithm. Section 5 presents validation using two ground radars.

2. Data

Datasets used in this study include: brightness temperatures from AMSU-B, radar reflectivities from MMCR and Next Generation Radar (NEXRAD), and cloud water analysis from the RUC-2 model during the March 2000 ARM cloud Intensive Observation Period (IOP) over a $10^\circ \times 10^\circ$ box centered at the ARM SGP site.

a. AMSU-B

AMSU-B is a cross-track and continuous line scanning radiometer aboard the National Oceanic and Atmospheric Administration (NOAA)-15 and later polar orbiting satellites. It provides measurements of scene radiance in five channels. Two of the channels are centered at 89 and 150 GHz. The other three channels are centered near the 183.3 GHz water vapor line at 183.3±1, 183.3±3 and 183.3±7 GHz. The relative sensitivities of all five frequencies to the vertical structures of ice water content are discussed in the next section. The antenna beamwidth is a constant 1.1 degrees (at the half power point) for all channels, resulting in a spatial resolution at nadir of ~16 km at a nominal satellite altitude of 850 km. Each scan consists of ninety contiguous cells, covering $\pm 48.95^\circ$ from nadir.
AMSU-B brightness temperature data are provided by the NOAA National Environmental Satellite, Data, and Information Service.

b. MMCR

The MMCR operating at the ARM SGP site in Oklahoma (36.6167° N, 97.5° W) is a zenith-pointing 35 GHz Doppler radar (Moran et al. 1997). It reports radar reflectivities and Doppler velocities of up to 20 km, although only reflectivity data are used in this study. The accuracy of radar reflectivity is ~0.5 dBZ with a minimum detectable value of ~-50 dBZ at 5 km. The vertical resolution and sampling interval depend on the radar’s operational mode. During March 2000, most data had a vertical resolution of 90 m and a sampling rate of 9 seconds. Radar reflectivities from the MMCR are used to derive IWC profiles.

To convert radar reflectivity (Z) into IWC, the following relationship derived by Seo and Liu (2005) is used; it is based on the average of the six Z-IWC relationships for two types of snowflakes and four types of rosettes:

\[ IWC = 0.078Z^{0.79}, \]

where IWC is in g m\(^{-3}\) and Z in mm\(^6\) m\(^{-3}\). The IWCs are averaged vertically to obtain IWC profiles of 300 m in vertical resolution in order to construct database of the retrieval algorithm.

c. RUC-2 Model

The analyzed data from the RUC-2 (Benjamin et al. 1998) are used to constrain the top height of ice water content profiles. The cloud top height level defined here is the
highest level where the sum of cloud liquid and ice water mixing ratios exceeds $10^{-3}$ g kg$^{-1}$.

The spatial and temporal resolutions of the data are 40 km and hourly, respectively. The key features of the RUC-2 include assimilation of data from: wind profiles, rawinsondes and special dropsondes, National Weather Service's weather surveillance Doppler radars, total precipitable water estimates from satellites, and high-density visible and IR cloud drift winds, etc.

d. **NEXRAD**

Level II data from the NEXRAD (operating at a wavelength of 10 cm) located in Tulsa, Oklahoma (36.175°N, 95.5647°W) have been used for algorithm validation. To convert NEXRAD radar reflectivity into IWC, a Z-IWC relationship for 10 cm radar is derived following the method of Seo and Liu (2005). The averaged Z-IWC relationship for the six types of ice particles at 10 cm wavelength is determined to be

$$IWC = 0.070Z^{0.74},$$

where IWC is in g m$^{-3}$ and Z in mm$^6$ m$^{-3}$.

3. **Sensitivity of AMSU-B Channels to IWC Vertical Structure**

We first investigate the response of brightness temperatures at AMSU-B frequencies to the variation of IWC profiles through radiative transfer modeling. The model used here is the 4-stream discrete ordinate model developed by Liu (1998) with single-scattering properties of nonspherical ice particles parameterized by Liu (2004). In the model simulations, all surface and atmospheric properties except for IWC remained fixed. IWC at each ice cloud layer is then perturbed $N (=26)$ times in the range of 0.005 to 18 g m$^{-3}$.
from its base IWC value. The sensitivity \( r(i, j) \) of the brightness temperature at the \( i \)th channel to IWC at the \( j \)th layer is then defined by

\[
r(i,j) = -\frac{1}{N}\sum_{n=1}^{N}(T_b'(i,j) - T_b(i))/(IWP'(j) - IWP),
\]

where \( T_b \) and \( IWP \) denote brightness temperature and ice water path, respectively, corresponding to the base IWC profile, and \( T_b' \) and \( IWP' \) represent those for the perturbed IWC profiles. The sensitivity defined here has similar meanings to the weighting functions used in satellite soundings for atmospheric temperature profiles. That is, the sensitivity indicates the change in brightness temperature for a given change of IWC at a certain layer.

The computed sensitivity for clouds with several different base IWC profiles is shown in Fig. 1. The base IWC profiles corresponding to Figs. 1a-f are vertically uniform, while the IWC profile corresponding to Fig. 1g decreases linearly with height. Figures 1a-c exhibit the results for clouds with relatively low IWPs (4 and 388 g m\(^{-2}\)). When the ice clouds are located at high altitude layers (8.5 – 10.5 km, Figs. 1a,b), sensitivities show little vertical variation except at the 183.3±1 channel, although the magnitude of the sensitivities increases with IWP. Therefore, it seems to be difficult for AMSU-B observations alone to resolve the vertical variation of IWCs in these high clouds with low IWPs. If the cloud is formed at lower altitude layers (4.5 – 6.5 km, Fig. 1c), the sensitivity profiles vary across channels, particularly so for the three water vapor channels. Thus, more vertical structure information is contained in the satellite observed \( T_B \).

For deeper clouds with moderate to high IWPs (Figs. 1d-f), the sensitivity profiles show clear differences among the AMSU-B channels. All channels show the greatest
sensitivity to ice water at the cloud top and the rate of change of sensitivity with height varies from the smallest at 89 GHz to the largest at 183.3±1 GHz. In other words, the 89 and 150 GHz channels are sensitive to the IWC changes in the entire cloud layer, while the water vapor channels are sensitive to the IWC changes mostly in the upper portion of the cloud. This sensitivity difference allows us to determine the IWC vertical structures from brightness temperature observations. For most of the deep clouds with high IWPs, IWC generally decreases with altitude. The sensitivity for such a cloud is investigated by using a base IWC profile that decreases linearly with height. The result in Fig. 1g exhibits that the two channels near the water vapor absorption line center (183.3±1 and 183.3±3 GHz) are the most sensitive to the top portion of the cloud and the other three channels are the most sensitive to the bottom portion of the cloud. This contrast in the location of the maximum sensitivity among different channels is the most useful information in determining IWC vertical structures.

In summary, the AMSU-B channels show different vertical sensitivity distributions to IWCs of mid and deep clouds. Often, the two channels close to the water vapor absorption line center, 183.3±1 and 183.3±3 GHz, have maximum sensitivity near the cloud top, the 89 GHz and 150 GHz channels have a relatively uniform sensitivity pattern, and the 183.3±7 GHz channel exhibits a sensitivity profile that varies according to the IWC profile. Therefore, it appears that the AMSU-B data contain three pieces of independent information on vertical IWC distributions in addition to the information on integrated ice water amount (i.e., IWP). Nevertheless, satellite observations alone cannot resolve the finer details of vertical IWC structures due to their limited information contents. Therefore, we
will develop the IWC retrieval algorithm by combining satellite data with a database of IWC profiles derived from ground cloud radar and cloud top information from a numerical model.

4. Retrieval Algorithm

The algorithm is based on Bayes’ theorem in which retrievals are derived from a combination of the information contained in current observations and the past knowledge on the related variables in an *a priori* database. In this study, the current observations are satellite high-frequency microwave brightness temperatures from AMSU-B. The *a priori* database used for the retrieval is built in two steps. First, a parent database is constructed from a great variety of IWC profiles. Then, based on the cloud top height given by the RUC-2 model, a subset of the parent database’s profiles is selected to serve as as the *a priori* database for the retrieval.

a. *Database relating ice clouds and brightness temperatures*

The parent database used in this study was constructed by Seo and Liu (2005). In constructing their database, an EOF analysis was first performed on the ARM SGP MMCR radar reflectivity profiles during the entire month of March 2000 (refer to Biggerstaff et al. 2005; Seo and Biggerstaff 2005). The leading 4 principal components of the EOFs were used to create a collection of reconstructed radar reflectivity profiles. IWC profiles were derived from the reconstructed profiles using a Z-IWC relation (1). Together with other atmospheric and surface observations, these IWC profiles were then used to calculate brightness temperatures at AMSU-B frequencies with a radiative transfer model (Liu 1998).
This radiative transfer model adopted the recently available ice microphysical properties from *in situ* observations (Heymsfield and Miloshevich 2003; Heymsfield 2003a,b) and ice particles’ single-scattering properties were calculated based on discrete dipole approximation simulations of realistic nonspherical ice particles (Liu 2004). By differently combining 3000 IWC profiles, 160 sounding profiles, and 5 sets of ice particle type and size distributions, their parent database containing approximately 8 million combined T_B-IWC profiles was constructed.

A subset of the parent database becomes the *a priori* database used for the IWC retrieval. In forming the subset, cloud top height produced by the RUC-2 model is used; this cloud top height is defined as the highest height at which the combined cloud liquid and ice mixing ratio exceeds 10^{-3} g kg^{-1}. Those profiles in the parent database with a cloud top height within 1.5 km of RUC-2 cloud top height compose the *a priori* database. The 1.5 km tolerance accounts for both the RUC-2 model error and the inhomogeneous distribution of the AMSU-B brightness temperatures within the RUC-2 grid (40 km in horizontal).

*b. Bayesian retrieval method*

Based on Bayes’ theorem, the expected vector \( \hat{E}(x) \) of \( x \) (the atmospheric state; in this study, IWC profiles) given a set of \( y_0 \) (the observed state; in this study, brightness temperatures) under an assumption that the errors in the observation and simulations are Gaussian and uncorrelated, is expressed in a discrete form (Lorenc 1986; Kummerow et al. 1996; Olson et al. 1996; Evans et al. 2002) by

\[
\hat{E}(x) = \sum_j x_j \exp\left\{-0.5\left[y_0 - y_s(x_j)\right]^T (O + S)^{-1} \left[y_0 - y_s(x_j)\right]\right\} / \hat{A},
\]  

(4)
where $\mathbf{O}$ and $\mathbf{S}$ are the observation and simulation error covariance matrices, respectively; $\hat{A}$ is a normalization factor and $\mathbf{y}_s$ is the radiative transfer model simulated brightness temperature vector. In this study, we use the departure ($\Delta T_b$) of brightness temperature from background brightness temperature of clear sky for $\mathbf{y}_o$ and $\mathbf{y}_s$. We use [4 K, 2 K, 2 K, 2 K, 2 K] for $|\Delta T_b| < 25$ K and [5 K, 3 K, 3 K, 3 K, 3 K] for $|\Delta T_b| \geq 25$ K as observation plus simulation errors in the diagonal terms of the matrix $(\mathbf{O} + \mathbf{S})^{-1}$ for the five AMSU-B frequencies. All off-diagonal terms are set to be zero due to the lack of information on the correlation of errors between the different channels. Additional details of the retrieval algorithm can be found in Seo and Liu (2005).

One way to test the performance of the Bayesian retrieval method is to consider some of the a priori database points as “observations”. Since the IWC profiles are known for these data points, we can compare the “retrieved” versus original IWC profiles by this exercise. This test was performed using about 3000 data points selected from the a priori database, designating them as “observations”. For the retrievals, the observation points were excluded from the a priori database. Results were classified into three categories by their IWP values: $< 500$ g m$^{-3}$, 500 - 5000 g m$^{-3}$, and $> 5000$ g m$^{-3}$. The contoured frequency by altitude diagrams (CFADs; Yuter and Houze 1995) of the retrieved and “observed” profiles as well as their means are shown in Fig. 2. The CFADs provide the frequency distribution of IWC in the vertical, facilitating comparison between the retrieved and the “observed” IWC profiles. Figure 2 shows that the CFADs of the “observed” and retrieved IWC profiles are quite similar in general for all three categories, while detailed
comparison indicates that the retrieved IWCs are in a narrower range than those “observed”, especially for the low IWP cases. The narrower range in the retrieved IWC profiles than the “observed” profiles might be due to an inherent problem in using Bayesian retrieval method in the form of (4), as explained below. The retrieval based on (4) is essentially the product of a Gaussian weighting function (determined by the distance between modeled and observed brightness temperatures and the error covariance) and the probability distribution function (PDF) of IWC. The natural PDF of IWC is a heavily skewed distribution with much greater density at the lower end of IWC. Therefore, the contribution to the IWC retrieval from the lower side of the true IWC value is more substantial than that from the higher side, yielding a smaller expected value than the true value. This problem is the most serious when IWC is low because of the heavy skewness of IWC distribution at low IWCs.

For the mean IWC profiles, the retrievals are quite close to the “observations”. This performance test using ideal cases demonstrates that the retrieval algorithm captures the principal structure of IWC profiles, while there are inconsistencies between “observed” and retrieved IWC characteristics for low IWC cases.

5. Validation

The ice water amount retrieved from the AMSU-B measurements using the Bayesian retrieval algorithm is examined with two independent observations. First, the horizontal distributions of AMSU-B-derived IWP are compared to those of NEXRAD-derived IWP. To calculate the NEXRAD IWP, IWCs are first derived from radar reflectivities using (2) and then integrated vertically to obtain IWP. It is noted that we use
the NEXRAD-derived IWP only as proxy of cloud ice water path, since the 10-cm radar is sensitive only to large precipitating ice particles, and has a very coarse vertical resolution and an increasingly large sampling volume with range from the radar. Therefore, the intention of the comparison is only to assess if the retrieval algorithm can produce an IWP horizontal distribution that agrees qualitatively with NEXRAD observations. AMSU-B brightness temperatures from NOAA-16 satellite are available in the vicinity of the ARM SGP site approximately twice a day. Of all the observations during March 2000, we choose three cases on 2, 22, and 18 March 2000, representing clouds with thick, moderately thick, and thin optical depths, respectively. Figure 3 shows the 150 GHz $T_B$ and the IWP distributions derived from the NEXRAD and retrieved from the AMSU-B measurements via the Bayesian algorithm. On the whole, the horizontal IWP structures from the two measurements are in a good agreement; the satellite retrievals capture the main features of the cloud systems shown by the NEXRAD. On the other hand, the NEXRAD shows greater IWPs than the AMSU-B at locations of optically thick clouds, while it misses ice clouds in the surrounding areas of the cloud systems where usually only thin clouds exist. This discrepancy may partially be explained by the large field of view of satellite measurements and the NEXRAD insensitivity to cloud ice and its vertically coarse resolution at its far range.

The distance-height cross section of satellite retrieved IWCs along the line shown in Fig. 3 (pass over SGP site) are shown in Fig. 4 along with the time-height cross section of MMCR derived IWCs. Note that the satellite retrievals are shown in the W-E distance domain while the MMCR retrievals are shown in the time domain. The scales of the x-axes
in the plots are arranged such that the W-E distance scale is congruous with the time scale if the cloud system moves from west to east with a speed of about 15~20 m s\(^{-1}\). For the case on 2 March 2000, the distance scale along the cross section is about 450 km and the time scale is about 6.5 hours (Figs. 4a,d). Overall vertical IWC structures of the cloud system retrieved from these two measurements are quite similar to each other with respect to an anvil in front of the cloud system, followed by convective clouds and trailing stratiform clouds. The amounts of IWC retrieved from the satellite observations are larger than those converted from the MMCR observations in cloud columns between 50 km and 200 km. This can be partly attributed to intensification of some cells in the cloud system after passing through the SGP site. The evolution of this system over time, observed by the NEXRAD radar (not shown), supports this interpretation. The second case on 22 March 2000 has radar echoes confined in low-to-middle layers in the MMCR observations. The time scale (about 2.5 hours) is relatively short compared to the event on 2 March 2000 (Figs. 4b,e). Hence, the comparisons between the satellite and MMCR retrievals appear to be better for detailed structures of ice cloud cells. The retrieved IWCs exhibit quite similar cloud structures, having maximum IWCs at lower-to-mid layers in the distance range of 15-70 km from SGP site in the satellite retrievals and during 1340-1300 UTC in the MMCR retrievals. Also, the middle layer IWC maximum is well matched between 70-140 km in the satellite retrievals and during 1300-1210 UTC in the MMCR retrievals. The third case has low MMCR derived IWCs confined in relatively lower levels. The satellite retrieved IWCs extend to higher altitude than the MMCR IWCs, but the high IWCs are in similar altitudes (4-6 km) (Figs. 4c,f). To investigate whether or not the RUC cloud top heights in this case
have misled the satellite retrieval whose cloud tops are much higher than the MMCR-derived cloud top heights, a fixed cloud top height (about 6 km derived from the MMCR data) was used as a constraint instead of using the RUC data. This exercise indicates that more correct cloud top height data improve the IWC retrieval (not shown here). Another possible explanation for the difference in Figs. 4c,f can be attributed to the insensitivity of the AMSU-B channels to low IWCs and the algorithm uncertainty for the high altitude clouds. Despite the ambiguity involved in the comparisons between quantities in space and time, the results above indicate that the vertical structures retrieved by our algorithm capture the main characteristics retrieved by the surface cloud radar.

Similar to Fig.2, we next compared the CFADs of satellite retrieved versus MMCR measured IWCs. During the month of March 2000, there were 19 coincident cases between AMSU-B and MMCR, for MMCR IWPs > 10 g m\(^{-2}\). To compare IWC profiles over comparable scales, the satellite retrievals were averaged over an area within 0.25° radius centered at the radar site, and the MMCR retrievals were averaged over 90 minutes centered at the satellite passing time. Using these coincident data, the CFADs and the means of IWC profiles from the MMCR and satellite retrievals are plotted in Fig. 5. Between 2 and 9 km, the CFADs of the two measurements have similar patterns although some differences exist in detail. Above 9 km, the satellite retrievals show more frequent low-IWC occurrences, while the MMCR retrievals show more high-IWC occurrences with less frequency. This difference may be attributed to the difference between satellite observing from the top-down and ground radar observing from the bottom-up. Particularly, attenuation to radar returns by clouds/precipitation in the lower atmosphere may have
prevented MMCR from detecting cloud ice in the upper levels. Additionally, validating satellite retrievals by surface observations is challenging because of the spatial/temporal mismatches between the two datasets (e.g., Smith et al. 1998). The mean IWC profiles derived from satellite and MMCR are compared as shown in Fig.5c. While details of IWCs differ between the two retrievals at some levels, overall the mean profiles agree reasonably well. In Fig.5c, we also plotted the mean IWC profiles retrieved from satellite without using RUC model cloud top height in the retrieval algorithm as a test of the role of cloud top information in the retrieval algorithm. The results indicate that the mean MMCR profile has a better match with the mean retrieved profile with the RUC cloud top height as a constraint than that without the RUC data.

In summary, the results of this validation are encouraging in that the satellite retrievals are consistent with the main features of ice clouds identified from two different radars in both horizontal and vertical. On the other hand, retrieving optically thin clouds or detailed vertical ice water structure from the limited currently available AMSU-B channels is still quite challenging.

6. Conclusions

The objective of the study is to determine the 3-dimensional distribution of ice water content over a broad region near the ARM SGP site. In this study, a Bayesian retrieval algorithm to retrieve ice water content has been developed; it combines multiple data sources from satellite high-frequency microwave radiometry and ground cloud radar observations, and mesoscale model analysis.
The sensitivity of satellite AMSU-B channels to the vertical structure of ice water content has been investigated. The results show that the sensitivity profiles vary with channels for thick and low clouds, while they have no channel dependence for thin and high clouds. In other words, the satellite data contain more vertical structure information for thick and low clouds. For thin high clouds, the vertical structure information is solely based on the cloud top height from the numerical model and the statistical pattern of ice water content from long-term ground cloud radar observations. To characterize the vertical structure of ice water profiles near the ARM SGP site, an EOF analysis was conducted on cloud radar reflectivity profiles. The leading four principal components of the EOFs were used to create a collection of reconstructed radar reflectivity profiles. Ice water content profiles were derived from the reconstructed profiles. Together with other atmospheric and surface observations, these ice water content profiles were then used to calculate brightness temperatures at satellite AMSU-B frequencies by a radiative transfer model, which adopted single-scattering properties from discrete dipole approximation for realistic nonspherical ice particles. The brightness temperatures computed from the radiative transfer model and the ice water profiles from the MMCR constitute the parent database of the Bayesian retrieval algorithm. In the retrieval, a subset of the parent database with cloud top height within 1.5 km of that determined by a mesoscale numerical model was used as the \textit{a priori} database.

Validation of the retrieved ice water contents has been done by comparing them with measurements of two ground radars: the NEXRAD and MMCR. The comparison shows that the mean ice water content profiles and the 2-dimensional (height-ice water
content) probability density functions (generated for 19 coincident cases from the two measurements) agree fairly well. Therefore, our retrievals capture the general pattern of the vertical ice water content distribution. It is also suggested that inclusion of correct cloud top height in the algorithm is a critical factor in improving the retrieval of vertical structure of IWC. On the other hand, due to the lack of sensitivity of the currently available satellite channels to the vertical variation of cloud ice, retrieving the detailed structure of ice water contents still remains very challenging. Improving the retrievals for thin ice clouds by further combining visible and infrared observations is planned in the future.

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**FIGURE CAPTIONS**

Figure 1. Sensitivity of brightness temperature at the AMSU-B channels to a given layer's IWC. The number inside each panel denotes IWP corresponding to its base IWC profile.

Figure 2. CFADs of IWC profiles from the observations (the first column) and the retrievals (the second column) and mean vertical profiles (the third column) for the observations (cross) and the retrievals (circles).

Figure 3. Horizontal distributions of 150 GHz TBs and IWPs derived from the NEXRAD and the AMSU-B measurements at (a-c) 1450 UTC, 2 March, (d-f) 1404 UTC, 22 March, and (g-i) 1353 UTC, 18 March, 2000. The cross and asterisk in each panel represent the SGP site and the NEXRAD site, respectively. In the NEXRAD IWPs, white pixels inside cloud systems include radar reflectivity greater than 30 dBZ within their cloud column.

Figure 4. (a-c) the distance-height cross section of satellite retrieved IWCs along the line shown in Fig. 3 and (d-f) the time-height cross section of MMCR derived IWCs. The vertical solid lines in (a-c) and (d-f) represent, respectively, the SGP site in space and the AMSU-B satellite observation time at the SGP site. Circles in (a-c) denote the cloud top height in the RUC data.

Figure 5. CFADs of (a) the MMCR-, (b) the AMSU-B-based IWC profiles with the RUC data, and (c) mean MMCR- (crosses) and mean AMSU-B-based IWC profiles with (blue circles) and without (red circles) the RUC data, which are collocated at the
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