Determining Cloud Ice Water Path from High-Frequency Microwave Measurements

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Introduction

A better understanding of cloud water content and its large-scale distribution is important to climate research for improving our ability to parameterize and validate cloud/precipitation processes in global climate models. The goal of this study is to determine the distribution and large-scale advection of cloud ice/liquid water near the Atmospheric Radiation Measurement (ARM) Cloud and Radiation Testbed (CART) sites using satellite measurements. As the first step, we are developing and evaluating cloud ice water path (IWP) retrieval algorithms. The IWP retrieval algorithm is based on scattering signatures at high-frequency microwaves (~150 GHz and above) although lower frequency data are also used in the algorithm to determine cloud type and background radiation. High frequency microwave data are currently available from Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Water Vapor Sounder (SSM/T-2) and National Oceanic and Atmospheric Administration (NOAA) Advanced Microwave Sounding Unit – B (AMSU-B) satellite observations, as well as from NASA's airborne Millimeter-wave Imaging Radiometer (MIR) measurements during several field experiments. In this abstract, we first explain the retrieval method, and then show retrieval results from the tropics (near ARM Tropical Western Pacific [TWP] site) during 1992 and 1993 based SSM/T-2 and MIR observations, and preliminary results from AMSU-B data during March 2000 at ARM Southern Great Plains (SGP) site.

Retrieval Method

For high-frequency microwaves (>150 GHz), the existence of ice cloud reduces the upwelling radiation emitted from surface and lower atmosphere due to scattering by ice particles. The magnitude of the brightness temperature depression increases with the increase of cloud IWP. This scattering signature is the primary information we use to retrieve IWP.

Besides IWP, several other variables also contribute to the upwelling brightness temperature, such as surface emission, atmospheric temperature and humidity, cloud liquid water, and ice density and shape. To minimize retrieval uncertainties, we first determine the type of clouds, and then use different retrieval algorithm for different cloud type (Liu and Curry 1999). Clouds are divided into several types based on their top temperatures and microwave radiative properties. Radiative transfer model simulations are then performed for the different types to establish a relation between IWP and the depression of 150, 183 ± 1, 183 ± 3, and 183 ± 7 GHz (and 220 GHz for MIR observations) brightness temperatures. The retrievals have been compared with several other measurements including in situ microphysical measurements by PMS 2D-C probes and International Satellite Cloud Climatology Project (ISCCP) cloud optical depth analysis. Currently, we are comparing retrievals at the ARM CART sites (SGP and TWP) with ground-based cloud radar measurements.

Figure 1 shows the IWP retrievals for a thick cirrus case observed by MIR onboard NASA's ER-2 aircraft on February 1, 1992, over the TWP. In this figure, we show (a) satellite infrared image on the top, followed by (b) cloud top temperature, (c) 85 GHz brightness temperature, (d) 10.7 GHz brightness temperature, and (e) retrieved IWP along the flight line. The aircraft flight area is circled in the satellite image. Except for an isolated cumulonimbus (Cb) cell, 85 and 10.7 GHz brightness temperatures observed from a low-frequency microwave radiometer showed little response to the cirrus clouds. But the IWP retrieved from 150 and 220 GHz data of MIR indicates a broad area of ice cloud; the IWP values range from 10 to several hundreds g m^{-2}, except for at the location of the Cb cell where IWP reaches thousands g m^{-2}.

Results from Tropical Clouds

Validation has been conducted by comparing IWP retrieved from MIR data with in situ measurements by 2D-C probe (Figure 2a), and by comparing total water path retrieved from SSM/T-2 (ice water) and SSM/I (liquid water) with total water path derived from optical thickness in ISCCP DX data (Figure 2b). Seven cases are shown in the comparison between the MIR and the 2D-C in situ measurements, in which the MIR radiometer was onboard an aircraft flying above the cloud and the 2D-C probe was on another aircraft flying within the cloud. The in situ IWP is calculated by adding ice water content at all levels when the aircraft made a profiling flight pattern (spiral up or down). Except for case (d), which is a case near the eyewall of a tropical storm, the MIR retrieval compared reasonably well with the in situ measurements.

Because visible/infrared techniques cannot differentiate between liquid and ice water in a mixed phase cloud, the ISCCP water path is the total water path including both liquid and ice water. To make a compatible comparison to ICSSP water path, we added liquid water path (LWP) retrieved from SSM/I (Liu and Curry 1993) and IWP from SSM/T-2 to obtain a total water path. Figure 2b shows the comparison between ISCCP total water path and the total water path derived from this study averaged in each 20-g m^{-2} bin. Good comparisons are found for total water path below ~250 g m^{-2}, which corresponds to a visible optical thickness of ~35. The poor comparison for high water paths may be caused by the existence of precipitation, for which both ISCCP and our retrievals are subject to large errors.

By using collocated satellite (SSM/T-2) microwave and infrared data, the relations among IWP and other atmospheric hydrological properties including cloud-top temperature, LWP, rainfall rate, and precipitable water are investigated for the tropical region. The results are summarized in the following: IWP tends to increase with the decrease of cloud-top temperature and this correlation is particularly evident for precipitating clouds. LWP retrieved for nonprecipitating clouds has a similar tendency but only for those with cloud-top temperatures warmer than 0°C. There is no clear relation between IWP and LWP. The ratio of IWP to total condensed water (ice + LWP) for nonprecipitating clouds seems to be negatively correlated with cloud-top temperature on an average of a large data volume, but this relationship differs substantially among individual cases. Rainfall rate has a strong correlation with

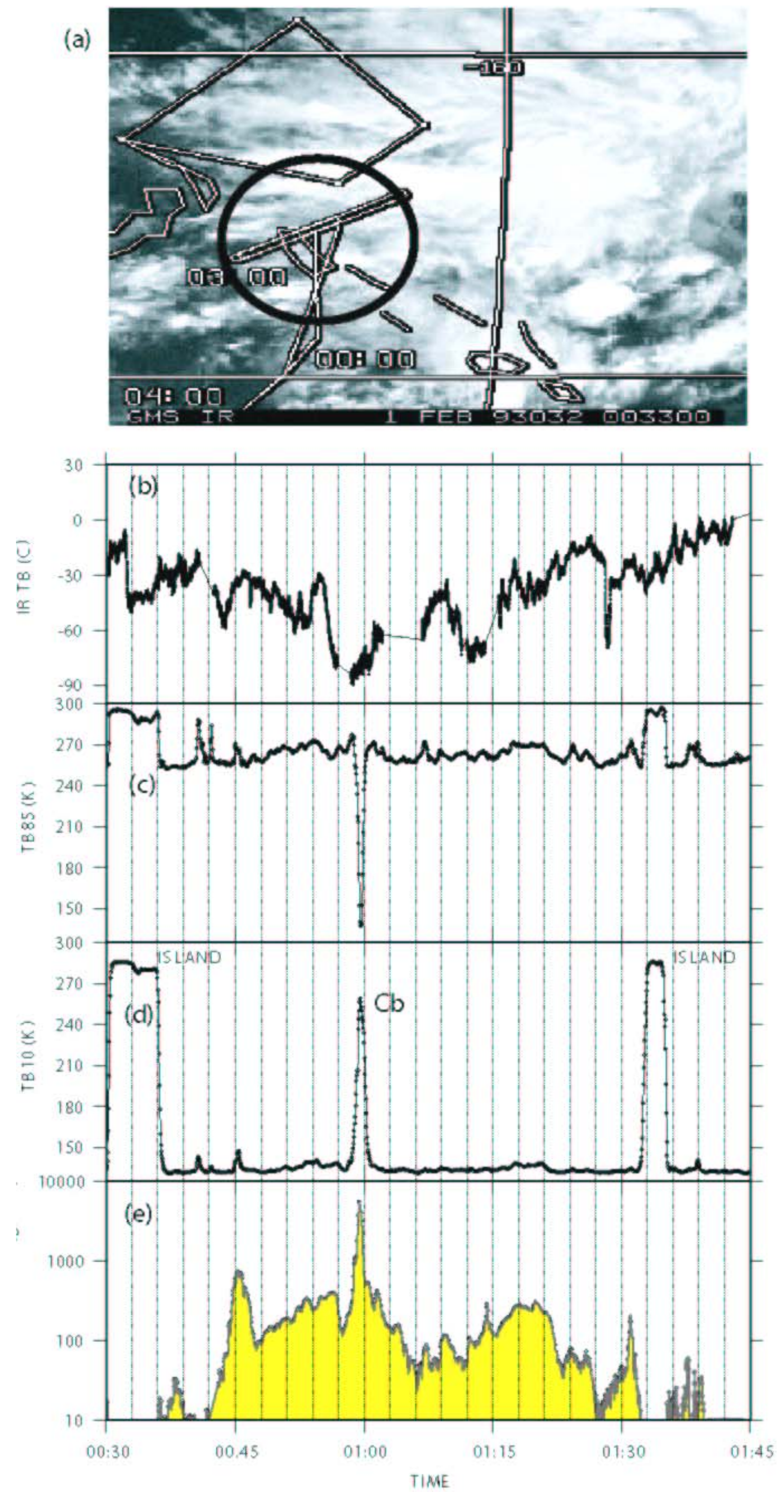
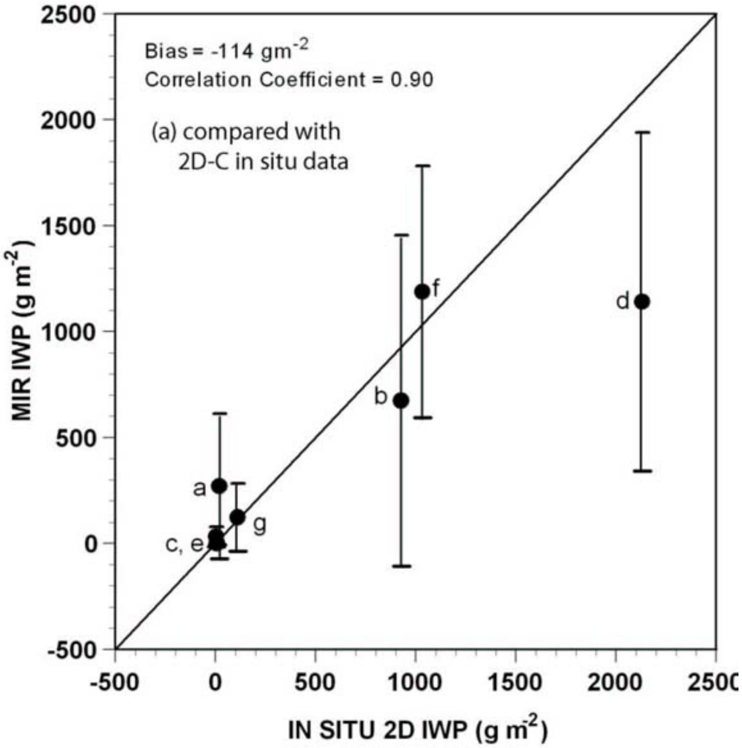


Figure 1. A thick cirrus case observed by satellite and instruments on ER-2 aircraft. (a) satellite infrared image. The area where the aircraft was flying was circled. (b) cloud top temperature. (c) 85 GHz brightness temperature. (d) 10.7 GHz brightness temperature. (e) IWP retrieved from MIR high frequency (150 and 220 GHz) observations.



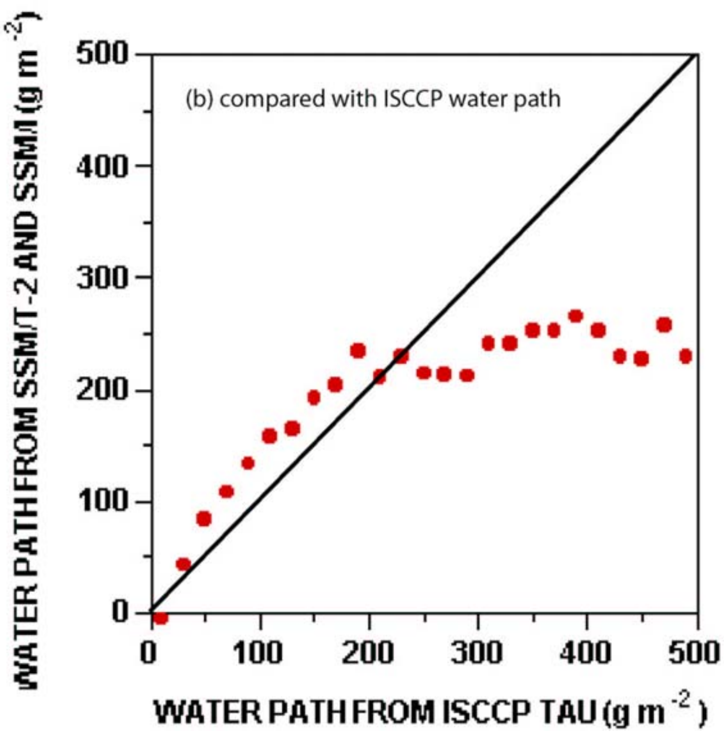


Figure 2. (a) IWP retrieved from an airborne high-frequency microwave radiometer (MIR: 91, 150, 220 GHz) compared with in situ measurements of a 2D-C PMS probe for seven tropical ice cloud cases. (b) Total water path (liquid + ice) retrieved SSM/I and SSM/T-2 data compared with total water path derived from ISCCP visible optical thickness.

IWP. The relation between condensed water and precipitable water is complicated: High values of IWP and LWP are always associated with high precipitable water while high precipitable water does not always correspond to high values of ice or LWP.

Preliminary Studies for March 2000 IOP Over SGP Site

We are currently analyzing data over the ARM CART SGP site collected during the March 2000 Intensive Observation Period (IOP). Figure 3 shows the time-height cross-section of cloud radar reflectivity at the top panel, together with satellite observed and radiative transfer model simulated

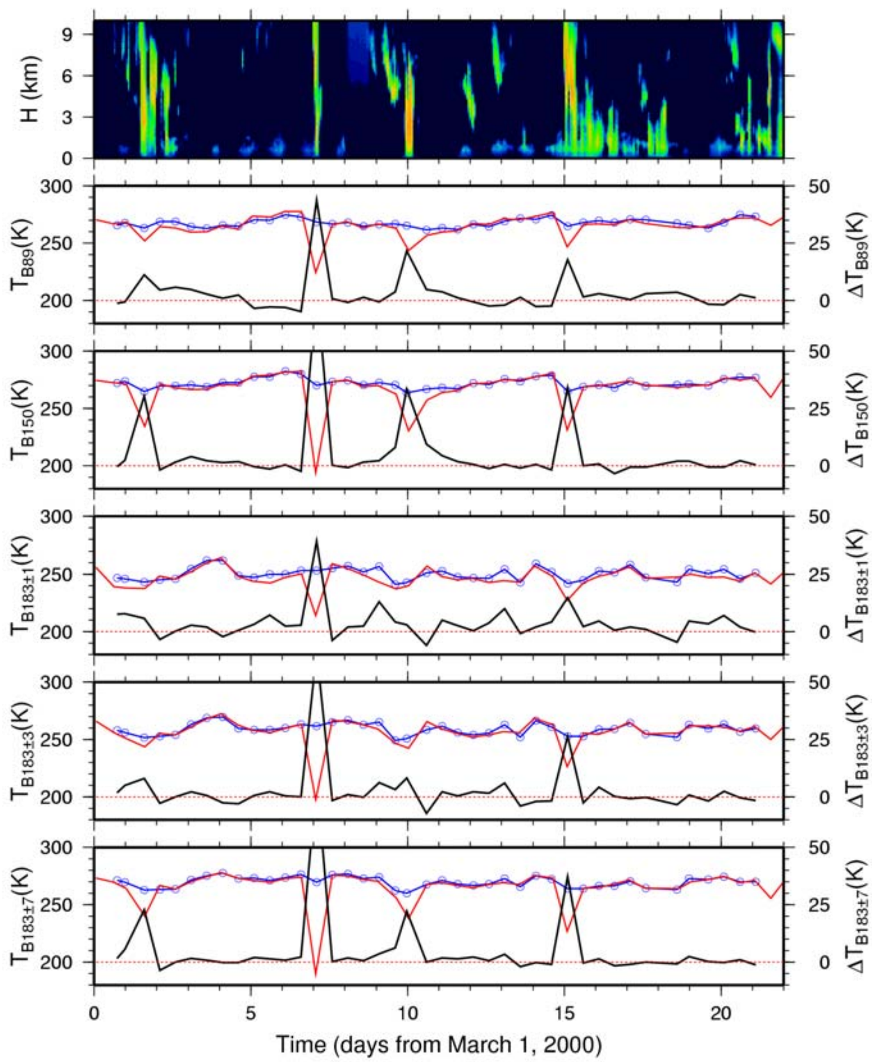


Figure 3. Top: Time-height cross-section of cloud radar reflectivity observed at SGP Central Facility during March 2000 IOP. Bottom five panels show AMSU-B observed brightness temperatures (red curves), radiative transfer model simulated "background brightness temperatures" (blue curves) and the difference of the above two temperatures (black curve). The circles in the blue curves indicate the time when satellite observations are available. The background brightness temperature is a virtual brightness temperature assuming all conditions being the same but without ice particles in the clouds.

background brightness temperatures for AMSU-B frequencies (89, 150, 183 ± 1, 183 ± 3, and 183 ± 7 GHz). The background brightness temperature is a virtual brightness temperature assuming all other conditions being the same but without ice particles in the clouds. It is calculated using a radiative transfer model by applying a surface emissivity to each channel, which is derived by matching to observed brightness temperatures at clear-sky conditions, and using the objectively analyzed atmospheric variables provided by Zhang et al. (2001).

The brightness temperature difference ($\Delta T_B = T_{B0}$-T_B) between the simulated background (T_{B0}) and the observed brightness temperature (T_B) is also shown in Figure 3 for the AMSU-B channels. Although all channels responded to the large cloud events on day 7 and day 15, data at 150 and 183 ± 7 GHz showed the best correspondence to upper level reflectivity of cloud radar when clouds are deep. The brightness temperature variations at 183 ± 1 and 183 ± 3 GHz also responded well to upper-level clouds near day 9 and day 13. During the 3 weeks, the radar cross-section almost continuously showed low-level (<2 km) clouds. These water clouds (below freezing level) had little impact on the high frequency microwave observations, which is the major advantage for using high-frequency microwave data to derive IWP.

The next step of this study is to convert the brightness temperature difference (ΔT_B) to IWP. Two major tasks are currently underway: (1) to build an ice cloud database for the mid-latitudes. We are primarily analyzing cloud radar and surface microwave radiometer data at the SGP central facility for this database. This database will enable us to constrain our retrieval algorithm; (2) to parameterize the single-scattering properties of non-spherical ice particles. This is done by using the Discrete Dipole Approximation method. This parameterization will be used in the radiative transfer model, which is then used to develop IWP retrieval algorithm.

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