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Determination of ice water path in ice-over-water cloud systems using combined MODIS and AMSR-E measurements

Jianping Huang,[1] Patrick Minnis,[2] Bing Lin,[2] Yuhong Yi,[3] T.-F. Fan,[4] Sunny Sun-Mack,[4] and J. K. Ayers[3]

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[1] To provide more accurate ice cloud microphysical properties, the multi-layered cloud retrieval system (MCRS) is used to retrieve ice water path (IWP) in ice-over-water cloud systems globally over oceans using combined instrument data from *Aqua*. The liquid water path (LWP) of lower-layer water clouds is estimated from the Advanced Microwave Scanning Radiometer for EOS (AMSR-E) measurements. The properties of the upper-level ice clouds are then derived from Moderate Resolution Imaging Spectroradiometer (MODIS) measurements by matching simulated radiances from a two-cloud-layer radiative transfer model. The results show that the MCRS can significantly improve the accuracy and reduce the over-estimation of optical depth and IWP retrievals for ice-over-water cloud systems. The mean daytime ice cloud optical depth and IWP for overlapped ice-over-water clouds over oceans from *Aqua* are 7.6 and 146.4 gm^{-2}, respectively, down from the initial single-layer retrievals of 17.3 and 322.3 gm^{-2}. The mean IWP for actual single-layer clouds is 128.2 gm^{-2}.
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1. Introduction

[2] Distributions of ice cloud microphysical properties are needed to accurately characterize global hydrological and radiation budgets. Their estimation from satellites is often exacerbated by the presence of water clouds underneath the ice clouds. Satellite cloud retrieval techniques have typically relied on the assumption that all clouds are homogeneous in a single layer, despite the frequent occurrence of overlapped cloud systems. Overlap can produce large errors in many retrieved cloud microphysical properties, such as IWP, cloud height, optical depth (τ), phase, and particle size. The influence of liquid water clouds and precipitation on the radiances observed at the top of the atmosphere (TOA) is one of the greatest impediments to accurately determining cloud ice mass for multi-layered systems with ice clouds above water clouds. The optical depth derived from the reflected visible radiance represents the combined effects of all cloud layers. When the entire reflected radiance is interpreted with an ice cloud model, the optical depth of the ice cloud can be severely over-estimated because the underlying water cloud can significantly increase the reflectance. It is clear that the underlying clouds must be properly characterized for a more accurate retrieval from overlapped cloud systems.

[3] Methods for direct retrieval of ice cloud microphysical properties using millimeter and sub-millimeter-wavelength measurements have been developed [*Liu and Curry*, 1998, 1999; *Weng and Grody*, 2000; *Zhao and Weng*, 2002] but have seen only limited use. The discrepancy between cloud-top pressure derived from a CO_2-slicing retrieval and the infrared (IR)-based cloud pressure has been exploited to detect overlapped clouds and retrieve the properties of each layer over a large portion of the Earth [*Chang and Li*, 2005a, 2005b]. These recent ventures into passive remote sensing of multi-layered clouds are encouraging, but the accuracy of these retrievals and their limitations are poorly understood.

[4] Over ocean regions, the use of combined microwave (MW), visible (VIS), and IR retrievals shows potential for improving multi-layered cloud retrievals. These retrievals have generally consisted of deriving the total cloud water path (TWP) by interpreting the entire cloud as ice cloud with the VIS and IR data, retrieving the LWP with the MW data, and finally estimating the IWP as the difference between the two quantities (that is, TWP-LWP). This approach has been implemented by combining data sets from different satellite platforms [*Lin and Rossow*, 1996; *Lin et al.*, 1998] and by using well-matched data on the same platform, e.g., the Visible Infrared Scanner (VIRS) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data [*Ho et al.*, 2003]. Recognizing that the radiances emanating from combined ice and water cloud layers are not equivalent to those from a simple addition of the IWP and LWP to obtain the TWP, *Huang et al.* [2005] developed a more rigorous multilayer cloud retrieval system (MCRS). The MCRS explicitly uses the lower layer cloud as part of the background radiation field and the ice-cloud contribution to the TOA radiance to estimate IWP. The initial version of the MCRS has been upgraded using lookup tables of reflectance based on advanced radiative transfer calculations of combined ice and water clouds and applied to the matched VIRS and TRMM data to obtain a more accurate assessment of tropical IWP (P. Minnis et al., Ice cloud properties in ice-over-water cloud systems determined from matched TRMM VIRS and TMI data, submitted to *Journal of Geophysical Research*, 2006, hereinafter referred to as Minnis et al., submitted manuscript, 2006). In the revised MCRS, the background in the two layer

[1]College of Atmospheric Sciences, Lanzhou University, Lanzhou, China.
[2]NASA Langley Research Center, Hampton, Virginia, USA.
[3]Analytic Services & Material, Inc., One Enterprise Parkway, Hampton, Virginia, USA.
[4]Science Applications International Corporation, One Enterprise Parkway, Hampton, Virginia, USA.

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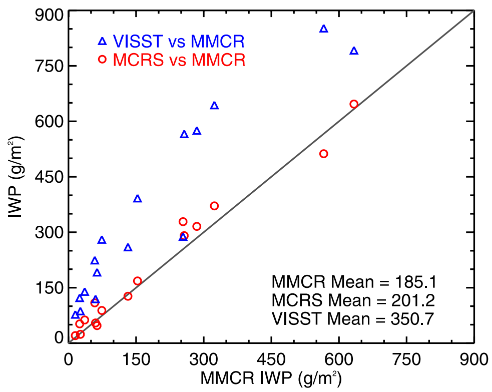

Figure 1. Comparison of VISST and MCRS IWP retrievals with simultaneous IWP retrievals using the MMCR reflectivity data over the ARM TWP Manus site (December 2004–February 2005).

radiative transfer model is either land or ocean surface. This enhanced version is more accurate and applicable to a broader range of boundary conditions.

[5] In this study, the updated MCRS is applied to estimate IWP for multi-layered clouds globally over ice-free oceans. The MW-VIS-IR (MVI) algorithm [*Lin et al.*, 1998] is used to first identify the overlapped clouds. Ice cloud optical depth and IWP, in the ice-over-water cloud systems, are then retrieved with the MCRS. The IWP retrievals are validated by comparison to IWP retrievals from millimeter wave cloud radar (MMCR) over the Atmospheric Radiation Measurement (ARM) Program Tropical Western Pacific (TWP) site on Manus Island [*Ackerman and Stokes*, 2003]. The variability and global distribution of cloud IWP is further analyzed.

2. Data

[6] The MCRS is applied to the daytime matched data from the MODIS and the AMSR-E on *Aqua* taken over oceans from December 2004 through February 2005. The 1-km MODIS data are analyzed for CERES using the VIS-IR-Solar-infrared-Split-window Technique (VISST) [*Minnis et al.*, 1995, 1998] to retrieve single-layer (SL) cloud microphysical properties for each pixel. The CERES MODIS (CM) cloud microphysical properties [*Minnis et al.*, 2004], including phase, cloud optical depth (τ), cloud effective temperature (Tc), effective ice crystal diameter (*De*) and IWP or LWP, are combined with the original MODIS radiances at 0.64, 2.1, 3.8, 10.8, and 12.0 μm for each pixel. The CM pixel-level results are then convolved into the AMSR-E footprints as in *Ho et al.* [2003]. The cloud LWP and cloud water temperature (Tw) are retrieved from the AMSR-E MW data at the 36.5-GHz 12-km field of view (FOV) by matching the multi-spectral MW data to MW radiative transfer model (RTM) calculations [*Lin et al.*, 1998].

3. IWP Retrieval

[7] For each convolved CM-AMSR-E FOV, the MVI technique [*Lin et al.*, 1998] is used to detect overlapping clouds based on the difference between *Tw* retrieved from AMSR-E and *Tc* derived from VISST. The next step is to estimate the optical depth (τ_w) of the lower-layer water cloud, which can be written as

$$\tau_w = 0.75\, Q_{vis}(r_e) LWP / r_e, \tag{1}$$

where

$$r_e = r_0 + r_1 * LWP, \tag{2}$$

and $Q_{vis}(r_e)$ is the extinction efficiency for a given effective droplet radius (r_e). Equation (2) is derived from the statistical analysis of single-layer water clouds. Over oceans, r_0 = 12 and r_1 = 0.0186. The uncertainty of LWP derived from the satellite microwave measurements is ±40 gm^{-2} [*Lin et al.*, 1998]. Based on that uncertainty, *Huang et al.* [2005] made sensitivity retrieval tests for LWP ±40 gm^{-2}. Overall, the ice cloud properties are more sensitive to an underestimated LWP than to overestimates. The optical depth increases about 10% for 40 gm^{-2} underestimated LWP compared to only 2% for 40 gm^{-2} overestimated LWP. The ice crystal size is only affected by ±2%, while the LWP uncertainty translates to an uncertainty of −7.6% to 3% in IWP. Also, the sensitivity is larger for smaller values of IWP. These values of r_e and τ_w are used to select the proper set of lookup tables (LUT). The TOA radiances are then computed for every combination of r_e and τ_w and upper-layer ice clouds and matched to the observed 0.64 μm radiances as in the work by Minnis et al. (submitted manuscript, 2006). The retrieval follows the VISST procedure resulting in the selection of *De*, τ, and IWP for the upper layer ice cloud.

4. Results

[8] The MCRS was used to retrieve ice cloud microphysical properties for detected overlapped cloud pixels for the period from December 2004 through February 2005. To validate the MCRS IWP retrievals, the ground-based IWP is derived from MMCR radar reflectivity using the algorithm of *Liu and Illingworth* [2000] and averaged over a 20-minute period centered on the Aqua overpass time at the ARM TWP Manus site (2.006°S, 147.425°E). The averaged MMCR IWP results are compared with IWP values derived from Aqua MODIS using VISST and from the convolved CM-AMSR-E data using the MCRS (shown in Figure 1). Sixteen matching ice-over-water cases were identified during the 3 months. The VISST and MCRS IWP retrievals in Figure 1 are averaged for the pixels over the ocean within a 0.5° box centered on the coastal Manus site. In all cases, the MCRS yields values of IWP that are close to those from the MMCR retrieval. On average, the MCRS and MMCR IWPs differ by only 16.1 gm^{-2} (9%). This difference is much smaller than the difference between the mean VISST (350.7 gm^{-2}) and mean MMCR (185.1 gm^{-2}) values and is probably within the error of the MMCR method and data, which were taken at a single point on the coast. Minnis et al. (submitted manuscript, 2006) also found good agreement between the updated MCRS IWP and millimeter cloud radar (MMCR) retrievals of the same quantity over Oklahoma. It is clear from these comparisons that the MCRS provides a remarkable improvement over the VISST IWP retrieval.

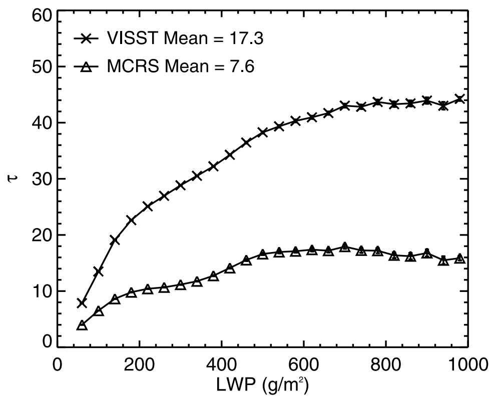

Figure 2. Comparison of ice cloud optical depths derived from VISST and MCRS as a function of LWP for ice-over-water cloud pixels over global ocean (December 2004–February 2005). The tiny vertical bars on the curves represent the standard errors ($\sigma/\sqrt{N}$, where σ is the standard deviation and N is the number of FOVs).

[9] Figure 2 shows a comparison of mean ice cloud optical depth and standard error derived from the VISST and MCRS as a function of LWP for all overlapped cloud retrievals during the analysis period. The standard error gives a rough measure of the variability of the means. For the VISST retrievals, the optical depth increases monotonically with rising LWP as expected because thin water clouds under the ice clouds should not cause large VISST retrieval errors (e.g., Minnis et al., submitted manuscript, 2006). The reflectance increases with increasing LWP and causes the current satellite retrievals to overestimate τ when a lower-level cloud is present. The effects of the lower-level cloud, however, are nearly removed by the MCRS. There is only a slight upward trend in the MCRS τ associated with increasing LWP. On average, the mean ice-cloud optical depth drops from 17.3 to 7.6 when the lower-level water cloud is taken into account. Figure 2 also shows that the standard errors are quite small and the mean differences in τ are significant at the 99% level for all LWP bins.

[10] The frequency histograms of IWP derived from VISST, MVI, and MCRS for ice-over-water clouds and the IWP derived from VISST for single-layer ice clouds (SICE) are shown in Figure 3. As expected, the mean IWP values derived from the MCRS are considerably less than those derived from VISST. The mean IWP decreases from 322.3 to 146.4 gm^{-2}, a value only slightly greater than the single-layer ice cloud mean value (128.2 gm^{-2}). The close agreement in the frequency distribution between IWP derived from the MCRS and those from VISST single-layer ice cloud retrievals, for all bins, clearly demonstrates the improvements provided by the MCRS. For the lowest IWP category (IWP < 100 gm^{-2}), the frequency from the MCRS is only 10% greater than that for single-layer ice clouds. Multi-layered cloud pixels with IWP < 100 gm^{-2} comprise more than 65% of the data for the MCRS retrievals compared to only 38% for VISST retrievals. The mean MCRS IWP is roughly half of the VISST derived and the mean MVI IWP is about 17% greater than the MCRS value. The MVI IWP mean is significantly affected by the retrieval of negative IWP values which are eliminated by the MCRS.

[11] The global distribution of the seasonal (December 2004–February 2005) mean IWP derived from VISST and MCRS and the differences between them are shown in Figure 4. The seasonal means were only computed for overcast ice-over-water clouds. Thus, these results are a subset of the entire VISST dataset. Figure 4 indicates that the MCRS improves the IWP retrieval over all global oceans. For almost all regions, the IWP derived from the MCRS is less than the VISST derived values. The IWP is found to be most pronounced, with VISST values up to 500 gm^{-2}, in the 40°–60° latitude bands where baroclinic systems are common (Figures 4a and 4b). The major differences between VISST and MCRS retrievals (Figure 4c) are also found in these bands. In the Southern Hemisphere, the large IWP means are nearly continuous throughout the temperate zone, while in the Northern Hemisphere, they are confined primarily to the western sides of the oceans. A relative maximum difference follows the northward shift of the inter-tropical convergence zone (ITCZ) where both thin cirrus and thick anvil clouds generated by deep tropical convection are frequently observed.

5. Conclusions and Discussion

[12] Large-scale satellite retrievals are critical for both verifying and improving general circulation model (GCM) parameterizations of clouds and radiation for climate prediction. The global distribution of IWP, while available from a variety of current satellite analyses, is highly uncertain because of the bias caused by the presence of liquid water clouds under the ice clouds. *Chang and Li* [2005a] addressed this issue with a combined VIS-IR-CO_2 technique that is nominally applicable over all surfaces, but their method requires that the upper-layer ice cloud be optically thin. This study has provided an improved estimate of IWP in multi-layered cloud systems for both thin and thick non-precipitating ice cloud systems, but only over global oceans. The current MCRS algorithm only works for non-precipitating cloud systems. The effect of precipitation

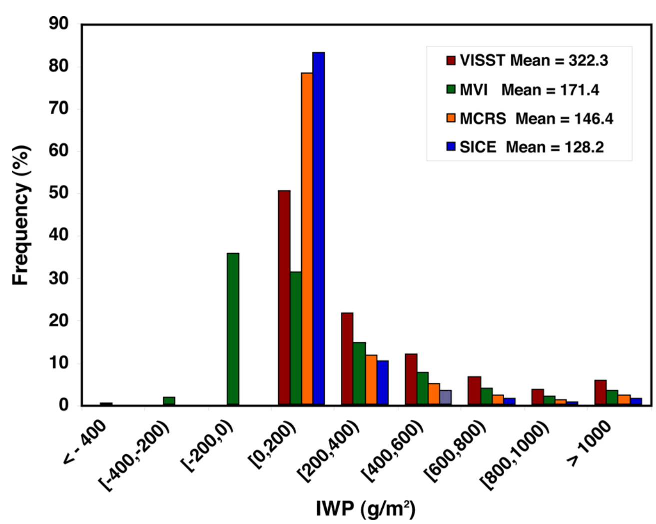

Figure 3. Histograms of IWP derived from VISST, MVI and MCRS for ice-over-water clouds, and IWP derived from VISST for single-layer ice clouds (SICE) over global oceans (December 2004 to February 2005).

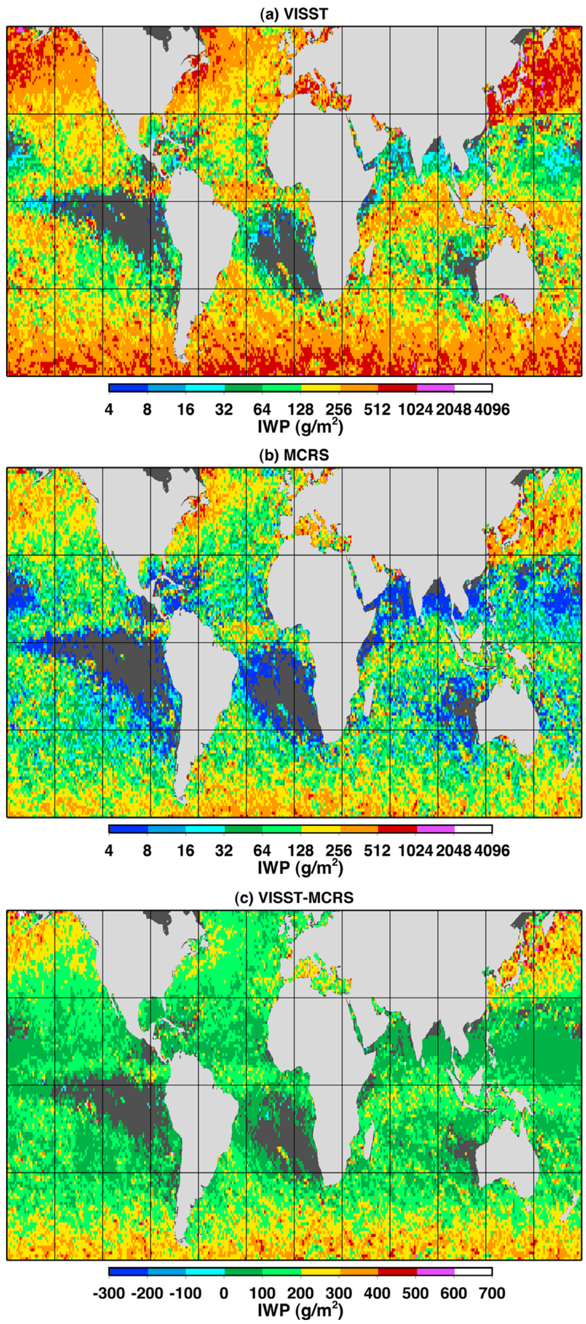

Figure 4. Global distribution of seasonal (DJF) mean IWP derived from *Aqua* data using (a) VISST and (b) MCRS and (c) the difference between VISST and MCRS means.

on the microwave radiances is significant and depends on wavelength, particle size, shape, phase, and the LWP and IWP of precipitating hydrometeors due to absorption, emission and scattering by these large particles. Since ice phase particles have little absorption and emission, the scattering from upper-layer large ice crystals (> 200 μm), snowflakes and hailstones reduces TOA observed microwave radiation from the lower layers of precipitating systems, while raindrops and graupel have both emission and scattering effects on the radiation. The net changes in TOA brightness temperatures due to precipitation can be as large as 50K [*Lin and Rossow*, 1997]. Therefore, the MCRS requires ice effective particle size less than 200 μm for successful satellite remote sensing (such as AMSR-E). The MCRS attempts a more realistic interpretation of the radiance field than earlier MVI-like methods because it explicitly resolves the radiative transfer that would produce the observed radiances at all relevant wavelengths. Using the MCRS to derive IWP in overlapped clouds represents a first step toward constructing a more reliable global IWP climatology. Based on comparisons with the MMCR retrievals for multi-layered clouds and with VISST retrievals for single-layer ice clouds over global oceans, these initial results are very encouraging. The development of an accurate oceanic climatology of IWP from *Aqua* and TRMM data is now quite feasible.

[13] In the short term, this MCRS method will be extremely valuable for climate research by providing more accurate retrievals of IWP than previously possible. Future research should develop an advanced retrieval method for multi-layered clouds over land. Over land, the variability in surface emissivity renders the microwave approach nearly useless. Thus, surface radiometers like those at the ARM sites are the only data source for application of this technique. With further validation using radar retrievals and perhaps aircraft in situ data, this method could be used as reference source for other available techniques or for those under development which use other spectral radiance combinations. Because this technique does not require the presence of cloud radar, and may be applied at any location with a microwave radiometer, it provides the opportunity for validating other methods in many more conditions than possible using radar retrievals. Ultimately, it could be combined with methods like the VIS-IR-CO_2 technique to provide a comprehensive characterization the IWP over the entire globe.

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J. K. Ayers and Y. Yi, AS & M, One Enterprise Parkway, Hampton, VA 23666, USA.

T.-F. Fan and S. Sun-Mack, SAIC, One Enterprise Parkway, Hampton, VA 23666, USA.

J. Huang, College of Atmospheric Sciences, Lanzhou University, Lanzhou 730000, China. (hjp@lzu.edu.cn)

B. Lin and P. Minnis, NASA Langley Research Center, Mail Stop 420, Hampton, VA 23681, USA.