P1.29   Determination of Ice Water Path in Ice-Over-Water Cloud Systems Using Combined MODIS and AMSR-E Measurements

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1. Introduction

Distributions of ice cloud 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 homogenous in a single layer, despite the frequent occurrence of overlapped cloud systems. Overlap can produce large errors in many retrieved cloud properties such as ice water path (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 significantly overestimated 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. Methods for direct retrieval of ice cloud properties using millimeter and sub-millimeter-wavelength measurements in all conditions [*Liu and Curry* 1998, 1999; *Weng and Grody* 2000; *Zhao and Weng* 2002] are under development but have not yet been deployed on satellites. However, even for these newer techniques there are no cloud property estimates for the lower cloud layers in ice-over-water cloud systems.

Over ocean regions, the use of combined microwave (MW), visible (VIS), and infrared (IR) retrievals shows potential for improving retrievals. These retrievals have generally consisted of deriving the total cloud water path (TWP) by interpreting the entire cloud as either ice or water with the VIS and IR data, retrieving the liquid water path (LWP) with the MW data, and finally estimating the IWP as the difference

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between the two quantities. This approach has been used on data sets from different satellite platforms (Lin and Rossow, 1996; Lin et al., 1998) and on well-matched Visible Infrared Scanner (VIRS) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data (Ho et al., 2003). Recognizing that the radiative fields 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 low-level 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 (Huang et al., 2005) is upgraded using lookup tables of reflectance based on advanced radiative transfer calculations of combined ice and water clouds (Minnis et al., 2005). The background in the radiative transfer model is either a land or ocean surface. This enhanced version is more accurate and is applicable to a broader range of boundary conditions.

In this study, the updated MCRS is used to retrieve ice water path in ice-over-water cloud systems. The variability in IWP is further analyzed using cloud products derived for the Clouds and the Earth's Radiant Energy System (CERES) from Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) (Minnis et al., 2004). The IWP retrieval error is evaluated for ice-over-water multi-layered cloud systems using collocated MODIS and Advanced Microwave Scanning Radiometer for EOS (AMSR-E) data. The MVI algorithm (Lin et al. 1998) is used to identify the overlapped clouds and to estimate IWP values based on AMSR-E measurements. The IWP values of overlapped clouds are then evaluated by comparison to the single-layer cirrus clouds surrounding the observed overlapping systems. Correction models are also developed to improve the accuracy of the IWP estimates.

2. Data

The data used in this study are microwave, visible and infrared measurements taken by instruments aboard the *Aqua* satellite over global oceans during July 2004.

The AMSR-E is a conically scanning total power passive microwave radiometer sensing microwave radiation (brightness temperatures) at 12 channels and 6 frequencies ranging from 6.9 to 89.0 GHz. Horizontally and vertically polarized radiation are measured separately at each frequency. The AMSR-E antenna temperatures were converted to brightness temperatures Tb using the method of Wentz (1998). The plane-parallel microwave radiation transfer model (MWRTM) of Lin et al. (1998) was used to simulate Tb for all AMSR-E channels. A lookup table was derived for various atmospheric conditions including a range of cloud temperatures (Tw), liquid water paths (LWP), atmospheric column water vapor (WV), near-surface wind speed (WS), and sea surface temperature (SST). For each cloudy pixel, LWP and Tw can be retrieved from the lookup table simultaneously using SST, WS, WV, and bias-corrected values of Tb_{37H} and Tb_{85V}. Lin et al. (1998) showed that this simultaneous retrieval yields a bias error of about $\pm$ 10 gm^{-2} in LWP.

The 1-km MODIS pixel-level radiances and cloud products were collocated with AMSR-E measurements using the 36.5-GHz channel 14 km x 8 km footprint as the matching area. Since AMSR-E has a much larger footprint than MODIS, the MODIS cloud products were convolved with AMSR-E measurements to produce equivalent MODIS cloud retrievals within the AMSR-E footprint. Only the AMSR-E pixels containing more than 15% cloudiness from the convolved MODIS-AMSR-E data are used here. Because MODIS and AMSR-E are on the same spacecraft, the temporal and spatial mismatches between MODIS and AMSR-E measurements are negligible.

3. IWP Retrieval

Initially, the Visible Infrared Solar-infrared Split-window Technique (VISST; see Minnis et al., 1995) retrieval is used to detect cloudy pixels and estimate the cloud properties by treating each cloudy pixel as a single-layer cloud. Next, the combined microwave, VIS and IR (MVI) method (Lin et al., 1998) is used to detect overlapped cloudy pixels. The MVI technique detects overlapping clouds by using the difference between the values of cloud water temperature ($Tw)$ retrieved from TMI microwave data and the cloud effective temperature ($Tc)$ derived from VISST (*Lin et al.* 1998). The third step is to estimate the optical depth of the lower-layer water cloud. The optical depth (τ_w) of the lower-layer water cloud can be written as

$$\tau_w = 0.75 \ Q_{vis}(r_e) \ LWP/ \ r_e. \qquad (1)$$
$$r_{e\ =\ } r_0 + r_1 * LWP \qquad (2)$$

where $Q_{vis}(r_e)$ is the extinction efficiency for a given effective droplet radius. For the ocean, r_0 =12 and r_1 = 0.0186. These values of re and τ_w are derived from the statistics of single-layer water clouds using AMSR-E

data and are used to select the proper lookup table. The TOA radiances are then computed for every combination of the low-level water cloud and the upper-layer ice cloud. The retrieval follows the VISST procedure resulting in the selection of the effective ice crystal diameter ($De)$, τ, and IWP for the upper cloud.

4. Analysis Results

The MCRS was applied to July 2004 global ocean data to retrieve the ice cloud properties for the detected overlapped cloud pixels. Figure 1 shows a comparison of the optical depth derived from VISST and MCRS as a function of LWP. For the VISST retrievals, the optical depth increases linearly with rising LWP. This was expected because thin water clouds should not cause large VISST retrieval errors, which is also consistent with the RTM calculations (Huang et al., 2005, Minnis et al., 2005). The reflectance increases with increasing LWP and causes the current satellite retrievals to overestimate optical depth 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 retrieved optical depths associated with increasing LWP. This trend is apparent for LWP values larger than 110 gm^{-2}. The mean optical depth drops from 24.0 to 9.0. The comparison of ice cloud optical depths derived from VISST and MCRS as a function of cloud water temperature T_w, is shown in Figure 2. The ice cloud optical depths derived from the MCRS are significantly less than those derived from VISST for all T_w bins. The optical depth decreases with increasing T_w for both the VISST and MCRS derived optical depths suggesting that ice clouds are generally thicker in the ice-over cool water clouds than in ice-over warm water clouds. The optical depth derived from both algorithms varies with solar zenith angle (SZA) and the retrieval error is significant for solar zenith angles greater than 80° (Fig. 3). The smaller values for SZA < 30° are likely the result of fewer samples.
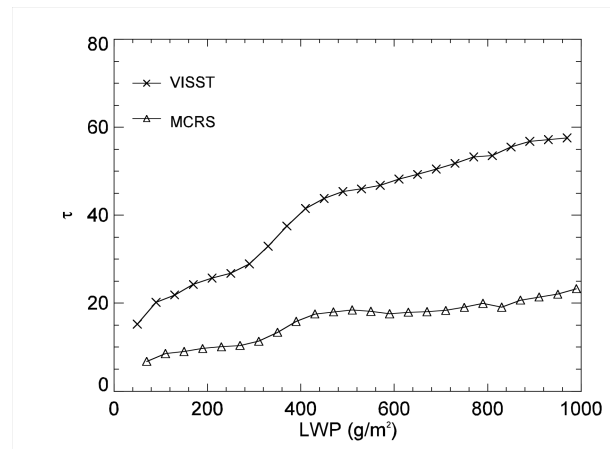

Figure 1. Mean ice cloud optical depths derived from VISST and MCRS as a function of LWP for ice-over-water cloud pixels over global ocean during July, 2004.
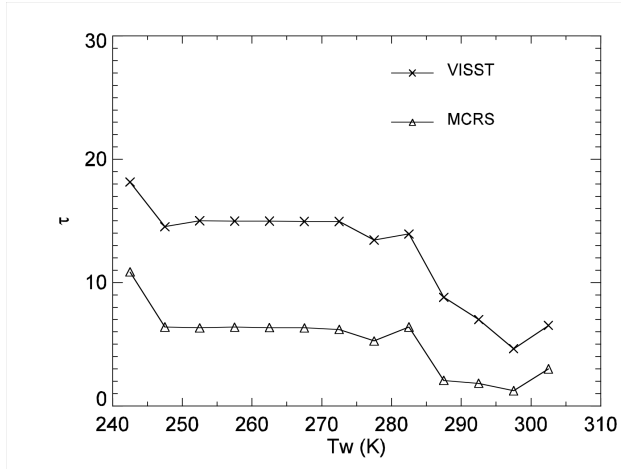
Figure 2. Same as Fig. 1, but as a function of *Tw*.

Figure 4. Histogram of the *IWP* derived from VISST, MVI and MCRS for ice-over-water cloud, and *IWP* derived from single-layer ice clouds

The frequency histogram of *IWP* derived from VISST, MVI, and MCRS for ice-over-water clouds and the *IWP* derived from VISST for single-layer ice clouds is shown in Figure 4. As expected, the mean *IWP* values derived from the MCRS are considerably less than those derived from VISST. The mean *IWP* decreases from 444 gm^{-2} to 217 mg^{-2}, a value only slightly less than the single-layer ice cloud mean value (242 gm^{-2}). The close agreement in the frequency distribution between the *IWP* derived by the MCRS and those from VISST single-layer ice cloud retrievals, for all bins, clearly demonstrates the improvements provided by the MCRS. The *IWP* values derived from the MCRS are significantly less than those derived from both VISST and MVI. The multilayered cloud pixels with *IWP* < 100 g/m^2 comprise more than 65% of the data for the MCRS retrievals compared to only 38% for VISST retrievals. The frequency distribution of the *IWP* derived from the MCRS for overlapped clouds is similar to the distribution of VISST retrievals
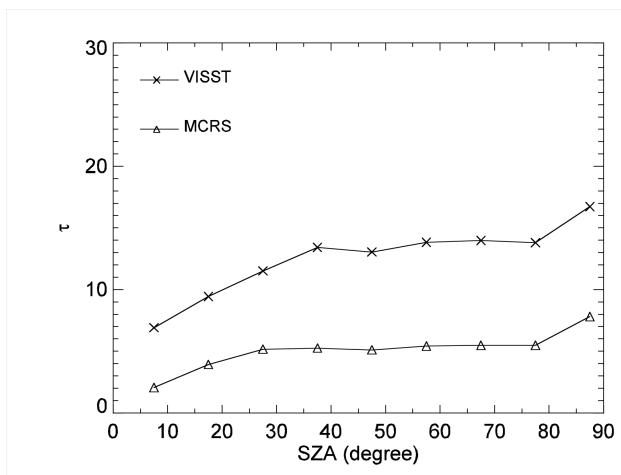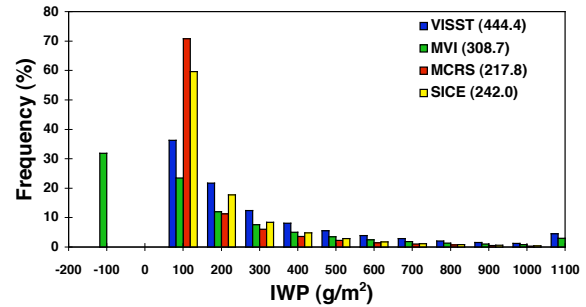
for single-layer ice clouds. For the lowest category of IWP (*IWP* < 100 gm^{-2}), the frequency from the MCRS is only 10% more than the frequency determined for single-layer ice clouds. The MCRS also eliminates the generation of negative values of *IWP* that sometimes occur in the MVI.

6. Conclusions and Discussion

This study has provided the basic framework for estimating ice water path in multi-layered cloud systems over global oceans using the MCRS. The MCRS attempts a more realistic interpretation of the radiance field than earlier methods because it explicitly resolves the radiative transfer that would produce the observed radiances. Using the MCRS to derive IWP in overlapped cases represents a first step toward constructing a more reliable global IWP climatology. The preliminary results are very encouraging when compared to the VISST for single-layer ice clouds over global ocean during July, 2004. In the short term, this method will be extremely valuable for climate research by providing more accurate retrievals of ice water path than previously possible. Future research should develop an advanced retrieval method for retrieval of multilayered 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 against radar retrievals and perhaps aircraft in situ data, this method could be used as reference source for other available techniques or those under development which use other spectral radiance combinations. Because this technique does not require the presence of a cloud radar it may be applied at any location with a microwave radiometer, providing the opportunity for validating other methods in many more conditions than possible using radar retrievals.

Figure 3. Same as Fig. 1, but as a function of solar zenith angle.

7. References

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