P7.20 DEVELOPMENT OF A GLOBAL MULTILAYERED CLOUD RETRIEVAL SYSTEM

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1. INTRODUCTION

The accurate quantification of ice cloud properties is essential for the characterization of global hydrological and radiation budgets. It is often complicated by the occurrence of multi-layer and overlapped clouds. Current satellite cloud retrievals are usually based on the assumption that all clouds are a homogenous single-layer, despite the frequent occurrence of overlapped cloud systems. Cloud overlap can introduce large errors in the retrieval of many cloud properties such as ice water path (*IWP*), cloud height, optical depth, phase, and particle size. For multi-layered systems with ice clouds above water clouds, the influence of the 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. 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 can be underestimated significantly because the same reflectance from a water cloud typically corresponds to a much greater optical depth (Minnis et al. 1993). Surprisingly, the resulting IWP would be overestimated as a result of the larger ice crystal particle sizes. It is clear that the underlying clouds must be properly characterized for a better retrieval of the overlapped cloud system.

Over ocean regions, the use of combined microwave (MW), visible (VIS), and infrared (IR) retrievals has been promising. These have generally consisted of deriving the total cloud water path (*TWP*), generally by interpreting the entire cloud as ice particles with the VIS and IR data, retrieving the liquid water path (*LWP*) with the MW data, and estimating the IWP as the difference between the two quantities. This approach has evolved from using data from two different satellites on a monthly average (Lin and Rossow, 1996) and on an instantaneously matched (Lin et al., 1998) bases to well-matched instantaneous Visible Infrared Scanner (VIRS) and Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data on the same *TRMM* satellite (Ho et al., 2003). Recognizing that the radiative effects of combining an ice and a water cloud layer are not equivalent to a simple addition of the IWP and LWP to obtain the TWP, Huang et al. (2004) developed a more rigorous multilayer cloud retrieval system (MCRS) that explicitly treats the low-level cloud as part of the background radiance field in order to retrieve the IWP from ice-cloud contribution to the TOA radiance.

The initial version of the MCRS (Huang et al., 2004) used a parameterization of the adding-doubling (AD) radiative transfer method by combining the low-layer cloud with the surface to produce a background radiance for the retrieval of the ice cloud properties. In this paper, the MCRS is upgraded using a more explicit radiance-based retrieval based on calculations of combined ice and water clouds and using only the surface and atmosphere as the background in the radiative transfer model parameterization. This enhanced version should be more accurate and applicable to any region covered with water.

Table 1. Summary of zenith angles and optical depths.

$\theta_{0,}\theta$	0.0, 18.19, 25.84, 31.78, 36.87, 41.41, 45.57, 49.4653.13, 56.63, 60.0, 63.27, 66.42, 69.51, 72.54, 75.52, 78.46, 81.37, 84.26, 87.13, 90.0
ψ	0.0, 2.5, 5.0, 10,15,25,35, 45, 55,65,65,75,85,95, 105,115,125, 135,145,155165, 175, 180
τ_I	0.0, 0.25, 0.5, 1, 2, 3, 4, 8, 16, 32, 64,128
τ_w	0.0, 0.10, 0.20, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90, 1.00, 1.20, 1.40, 1.60, 1.80, 2.00, 2.50, 3.00, 3.50, 4.00, 5.00, 7.50, 10.0, 15.0, 20.0, 25.0, 30.0

2. TWO-LAYER CLOUD RT MODEL

A two-layer cloud model is used to characterize the reflectance fields for multilayered clouds. The upper and lower layers consist of ice particles and water droplets, respectively. The visible reflectances at particular solar zenith (θ_0), viewing zenith (θ), and relative azimuth (ψ) angles (Table 1.) were computed with the AD model for $\lambda = 0.65$ μm using 11 ice cloud models and 7 water cloud models (Minnis et al., 1998) for ice cloud optical depths (τ_I) ranging from 0 to 128 and for water cloud optical (τ_W) ranging from 0 to 30. The computed reflectances were compiled in type-specific lookup tables. The reflectance at any specific set of angles, optical depths, and lower-cloud *re* are estimated from the lookup tables using nearest-node values and interpolations with various combinations of linear and Lagrangian methods. Given the *LWP* and *re* of the lower layer, a set of TOA VIS (0.65 μm) reflectances can be easily computed from the parameterization of Arduini et al. (2002) using the multilayer cloud reflectance lookup tables for each of optical depth nodes and ice particle sizes.

An example of the effect of combining the cloud layers is given in Figs. 1 and 2. The VIS reflectance at $\theta_0 = 45^o$ is shown in Fig. 1 as a function of viewing and

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illumination from adding-doubling RTM calculations with fixed upper layer ice cloud optical depth ($\tau_I = 8$), particle size ($De = 67$ μm), and *IWP* =160 gm^{-2} over water clouds with four different *LWPs*. As expected, the reflectances increase with as *LWP* increases from 0 to 150 gm^{-2} and the reflectance field becomes more isotropic. The anisotropy is different, however, from that expected for a pure ice cloud with the same albedo. The anisotropic difference and reflectance increase causes the current satellite retrievals to overestimate *IWP* and *TWP* when a lower cloud is present, due to the one-layer assumption. Figure 2 shows the reflectances for the same conditions except that the *TWP* is fixed at 200 gm^{-2} and *LWP* and *IWP* are varied as indicated in the plots. Figures 1a and 2a are similar in pattern because both have no water influence. However, Figs. 1c and 2d are quite similar despite the former having a value of *TWP* that is 60 gm^{-2} greater than that in the latter plot. These plots illustrate how important it is to properly treat the reflectance field in multilayered conditions. For example, in Fig. 2c at $\theta = 60°$ and $\psi = 45°$, the reflectance is 0.74. A single-layer ice cloud with the same amount of *TWP* would produce a reflectance of 0.65. A retrieval from the VIS reflectance for the cloud system in Fig. 2c using the assumption that the entire cloud is ice phase would yield *IWP* = *TWP* = 345 gm^{-2}. In this case, the retrieved *IWP* and *TWP* are greatly overestimated by 245 gm^{-2} and 145 gm^{-2}, respectively.

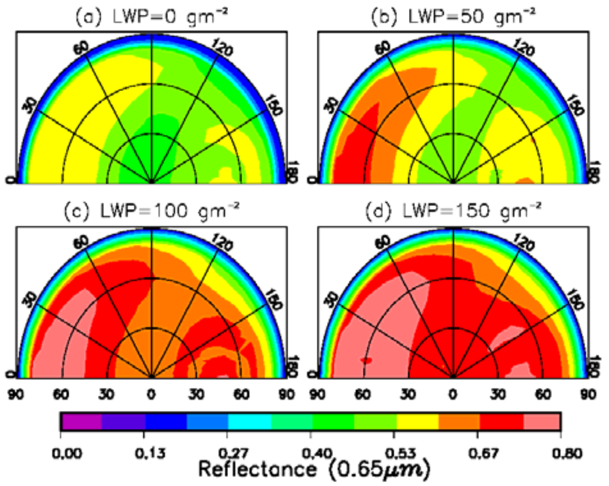

Fig. 1. Combined ice and water cloud VIS reflectance at θ_o = 45° and IWP = 160 gm^{-2} as function of θ (radial) and ψ (circular) coordinates.

3. MULTILAYERED CLOUD RETRIEVAL SYSTEM

To improve the accuracy of ice cloud property retrievals, a global multilayered cloud system (MCRS) is proposed. A schematic view of this system is outlined in Fig. 3. Initially, the Visible Infrared Solar-infrared Split-window Technique (VISST; see *Minnis et al.* 2001) retrieval is used to detect cloud existence and estimate the cloud properties by treating each cloudy pixel as a single-layered cloud. Next, overlapped cloudy pixels are detected using various methods. Over ocean, the MW, VIS, and IR (MVI) method (Lin et al. 1998) whenever both MW data and VISST retrievals are collocated. The MVI technique detects cloud overlapping by using the difference between the value of cloud water temperature *Tw* retrieved from MW data and the cloud effective temperature *Tc* derived from VISST (*Lin et al.* 1998). Over land, the vertical profile of relative humidity and temperature can used to estimate the probability of a cloud beneath the upper layer cloud (Yi et al., 2004). When both sounder and imaging channels are available, CO_2 slicing and spatial coherence methods (Baum et al. 1994), brightness temperature differences (e.g., Kawamoto et al. 2002), or VISST and CO2-slicing results can be used to detect thin cirrus over thick water clouds.

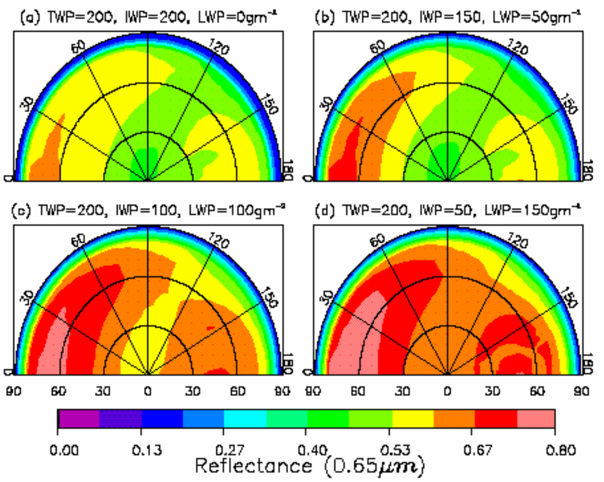

Fig. 2. Same as Fig. 1, but for fixed *TWP*, variable *IWP* and *LWP*.

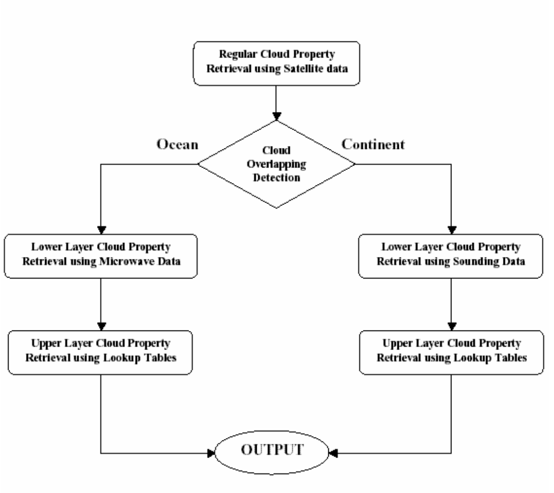

Fig. 3 Schematic view of global multilayered cloud retrieval system (MCRS).

For multilayered clouds over ocean, the MW retrieval is used to derive liquid water path (LWP_{MW}) and cloud water temperature (*Tw)* for the low-layer cloud. The optical depth of the low-level water cloud can be estimated as

$$\tau_{low} = 0.75\ Q_{vis}(r_e)\ LWP_{MW}\ /\ r_e. \qquad (1$$

where $Q_{vis}(r_e)$ is the extinction efficiency at a given effective droplet radius. In this study, r_e is assumed to be 6μm. These values of *re* and τ_W are then used to select the proper lookup tables and the TOA radiances are computed for every combination of that low-level cloud and the ice clouds. The retrieval then follows the VISST procedures resulting in the selection of the effective ice crystal diameter *De*, τ_I, and *IWP* for the upper-layer cloud. This algorithm, in which the lower layer cloud properties are retrieved using microwave, is defined as MCRS-MW.

Over land, the variability in surface emissivity renders MW retrievals nearly useless. Therefore a parameterization scheme is used to estimate the cloud liquid water path (LWP_{SD}) and the temperature of the lower level cloud instead of the microwave retrievals. The LWP_{SD} is given by

$$LWP = \int_{Z_B}^{Z_T} \eta(RH,T) * LWC(Z)dZ\ , \qquad (2)$$

where Z_B , Z_T, respectively, are the cloud base and top heights, $\eta(RH,T)$ is the weighting function that can be determined from relative humidity (RH) and temperature (T) as in Chin et al. (2000). *LWC* is the adiabatic liquid water content and is given by

$$LWC(Z_{i+1}) = LWC(Z_i) + \overline{\rho_Z} C_p \int_{Z_i}^{Z_{i+1}} \frac{\Gamma_d - \Gamma_s}{L_v} dZ \qquad (3)$$

where $\overline{\rho_Z}$ and C_P are the constant; Γ_d and Γ_s are the dry and moist adiabatic lapse rates, respectively. L_v is the latent heat of evaporation. This algorithm is defined as the MCRS-SD.

Table 2. Viewing, illumination, and scattering angles for GOES-8 and the surface at the SCF during 2000.

Case	Month /Date	Time (UTC)	θ_o (°)	ϕ (°)	Scattering Angle (°)
1	03/22	1445	64.1	144.5	146.92
2	03/22	1515	58.6	150.2	154.21
3	03/22	1545	53.4	156.7	161.34
4	06/27	1745	16.9	173.5	148.00
5	06/27	1945	20.4	90.92	128.56
6	06/27	2015	25.7	79.37	122.37
7	06/27	2045	31.3	71.10	115.98
8	06/27	2152	37.2	64.67	109.41
9	07/03	1545	38.8	133.4	146.92
10	07/03	1615	33.0	139.5	149.88

Preliminary validation of the MCRS-MW and MCRS-SD retrievals are accomplished by comparing with simultaneous retrievals using the Millemeter Cloud Radar (MMCR) radar at the Atmospheric Radiation Program (ARM) Southern Great Plains Central Facility (SCF) in Oklahoma. Table 2 shows the times and sun-view angles for 10 examples of multilayered clouds over the SCF during 3 different days in 2000 for the Geostationary Operational Environmental Satellite (GOES-8) imager. These times were selected because the multi-layering conditions met the criteria for retrieving the ice cloud properties using the method of Mace et al. (2002). As indicated in Table 2, these cases cover a wide range of viewing, illumination, and scattering angles. The value of θ is constant at 47.64°.

Figure 4 shows a comparison of *IWP* derived from the GOES-8 and MW data using the MCRS and VISST, and from the MMCR using the algorithm of Mace et al. (2002). For the MCRS-MW retrieval, the LWP_{MW} is estimated from the ARM microwave radiometer measurements (Liljegren et al., 1999; Clothiaux et al., 2000). The LWP_{SD} is estimated from ARM SFC sounding measurements for the MCRS-SD retrieval. Both MCRS-MW and MCRS-SD consistently produce smaller values of *IWP* than the VISST. In all of the cases, both MCRS-MW and MCRS-SD yield values of *IWP* that are close to those from the MMCR retrieval.

Table 3. Comparison of the mean and standard deviation of IWP derived from VISST, MCRS and MMCR

	VISST	MCRS-MW	MCRS-SD	MMCR
MEAN	158.8	74.3	59.7	65.1
STD	71.5	43.56	44.03	27.3

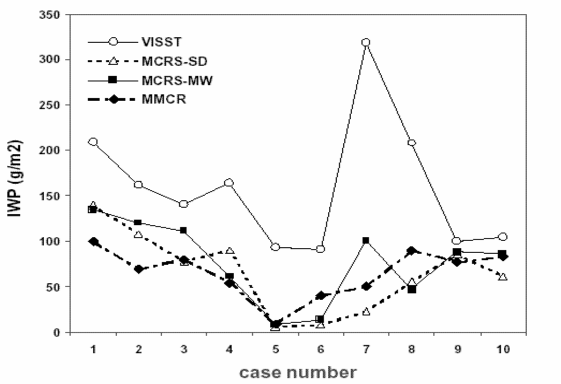

Fig. 4. Comparison of *IWP* derived using four different methods for the 10 cases shown in Table 2.

The differences are greatest for case 7 when *IWP* (MCRS-MW) is around 218 gm^{-2} less than the VISST retrievals. On average, for these cases, the difference between the MCRS-MW and MMCR *IWP*s is 9 gm^{-2}, which is 13.8% of the mean MMCR value of 65 gm^{-2} (see Table 3). The difference is almost 3.5 times smaller than the mean VISST-MMCR difference. Thus, it is clear from these results that the MCRS, in either form, represents a marked improvement over the single-layer VISST retrieval. The MCRS reduces the *TWP*, on average, because it generates a new value of *IWP*. The mean MCRS-SD *IWP* (59 gm^{-2}) is smaller than both the MCRW-MW and MMCR values. This underestimate suggests that adiabatic approach overestimates LWP_{SD}. Thus, some method for improving the estimate of LWP_{SD} is needed.

4. CONCLUSIONS AND DISCUSSION

A more rigorous multilayered cloud retrieval system has been developed to improve the determination of high cloud properties in multilayered clouds. 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. A two-layer cloud model was used to simulate multilayered cloud radiative characteristics. Despite the use of a simplified two-layer cloud reflectance parameterization, the MCRS clearly produced a more accurate retrieval of ice water path than simple differencing techniques used in the past. More satellite data and ground observation have to be used to test the MCRS. The MCRS methods are quite appropriate for interpreting the radiances when the high cloud has a relatively large optical depth ($\tau_I > 2$). For thinner ice clouds, a more accurate retrieval might be possible using infrared methods. Selection of an ice cloud retrieval and a variety of other issues must be explored before a complete global application of this technique can be implemented. Nevertheless, the initial results look promising.

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