Remote Sensing of Cirrus Vertical Size Profile Using MODIS Data

X. J. Wang[1], K. N. Liou[1], S. C. Ou[1], G. Mace[2] and M. Deng[3]

[1]Department of Atmospheric and Oceanic Sciences, University of California, Los Angeles, Los Angeles, California; [2]Department of Meteorology, University of Utah, Salt Lake City, Utah; [3]Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming

Cirrus Vertical Structure and Motivation

Cirrus clouds are high clouds made of ice particles. The size and shape of the ice particles vary in the vertical direction. Two figures illustrate this phenomenon: Figure 1 shows ice particle effective diameter measured along a spiral aircraft flight track; Figure 2 is a replicator image profile taken during FIRE-II campaign. For typical mid-latitude cirrus clouds, ice particles vary from non-spherical small particles at cloud top to hexagonal ice crystals inside clouds to large irregular ice particles near cloud bottom.

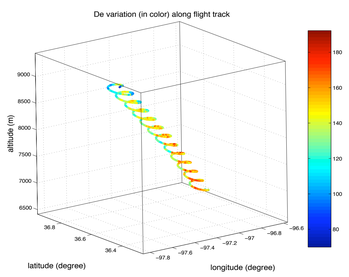

Figure 1: Effective Diameter D_e along the flight track compiled by in situ ice crystal measurements taken onboard the University of North Dakota Citation on Mar 9, 2000 over ARM-SGP CART site.

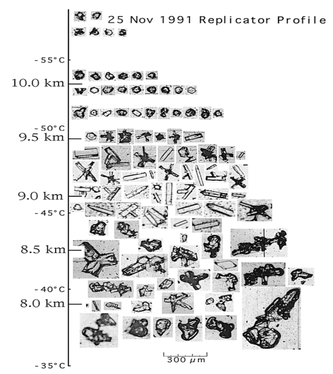

Figure 2: cirrus cloud replicator profile during FIRE-II campaign by Heymsfield & Iaquinta 2000

Cirrus vertical inhomogeneity of size and shape distribution has an effect on radiative heating/cooling rate calculation and thus knowing the vertical variability of cirrus microphysics properties is important to improve our understanding of cirrus clouds and their representation in GCMs. Satellite remote sensing seems to be the only way to establish a global data set of cirrus properties including vertical inhomogeneity.

We model the cirrus vertical profile of effective diameter as a linear function of cloud optical depth within clouds and explored the possibility of retrieving the vertical profile using MODIS 0.645, 1.64 and 2.13 and 3.75 μm channel reflectance/radiance. A numerical iterative Vertical Size Profiling (VSP) algorithm is developed to carry out the retrieval. For simplicity reason, the selected MODIS channels are referred to as channels 1~4.

Selected MODIS Channels & Weighting Function

As shown in Figure 3, 0.64 μm channel is non-absorptive, so this channel is used to retrieve cloud optical thickness. The rest three channels are size sensitive. Meanwhile, as wavelength increases, absorption due to cloud particles also increases, which means, 3.75 μm has more sensitivity to cloud top properties, while 1.64 μm channel carries relatively more information about cloud bottom than 3.75 μm channel. This is demonstrated by Figure 4, which shows the weighting functions of the three near-IR channels for the model cloud. The weighting function illustrates the contribution of individual cloud layers.

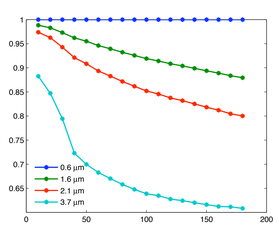

Figure 3: Single scattering albedo as a function of D_e at four wavelengths.

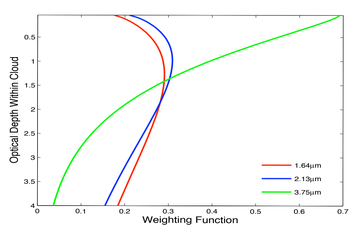

Figure 4: Weighting functions of the three near-IR channels calculated based on the maximum photon penetration principle for a model cloud with D_e=45 μm and τ=4.

Retrieval Algorithm and Sensitivity Study

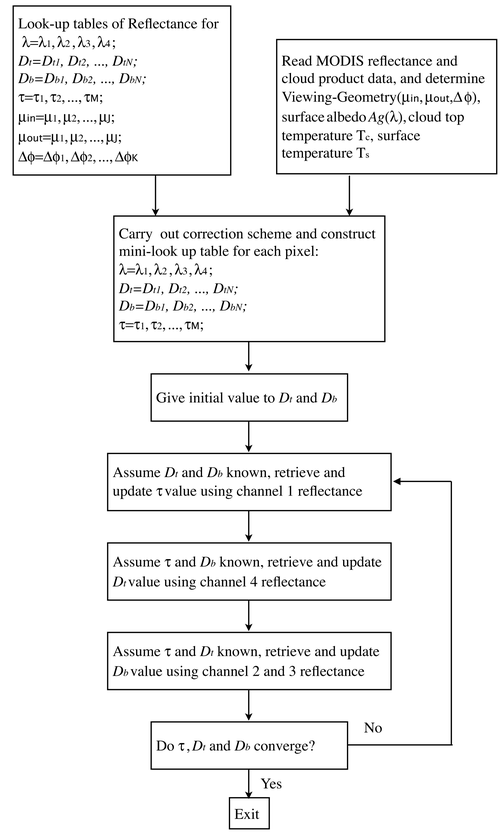

Figure 5: Flowchart of VSP algorithm.

A numerical iterative algorithm has been designed to search in the look-up library for the best match for given measurements. The flow chart is shown in Figure 5.

Synthetic retrievals have been carried out to study the effects of noise in the input parameters as well as in the measurements on the retrieval results. Channel 4 reflectance has the largest effect on the retrieval accuracy since channel 4 has the lowest Signal-to-Noise ratio. The statistics of retrieval errors are shown in Table 1, where $\Delta\tau_c$, ΔD_t and ΔD_b are the retrieval error in τ_c D_t and D_b

Table 1: Root-mean-square error of synthetic retrievals subject to perturbation to input parameters and instrument noise. The definition of the notations are: P_c: cloud top pressure, T_s: surface temperature, T_c: cloud temperature, A_g: surface albedo, R: measured reflectance.

Perturbed	$rms(\Delta\tau_c)$	$rms(\frac{\Delta\tau_c}{\tau_c}\cdot 100\%)$	$rms(\Delta D_t)$	$rms(\frac{\Delta D_t}{D_t}\cdot 100\%)$	$rms(\Delta D_b)$	$rms(\frac{\Delta D_b}{D_b}\cdot 100\%)$
P_c	0.016092	0.15728	2.5465	4.4792	3.0498	15.264
T_s	0.0072004	0.12083	3.5816	8.6382	4.8748	21.067
T_s	0.061167	0.65826	10.389	18.415	14.035	23.751
$A_{g,1}$	0.13819	3.1959	4.1298	9.0983	5.0602	19.414
$A_{g,2}$	0.029887	0.80291	5.9145	15.742	11.381	34.253
$A_{g,3}$	0.01784	0.49382	3.8677	10.04	7.3752	24.297
$A_{g,4}$	0.0038634	0.069966	2.6351	5.4108	3.3071	14.146
R_1	0.14362	1.599	2.7512	5.1562	3.5277	16.283
R_2	0.0078243	0.098226	2.5778	4.6727	3.2009	15.63
R_3	0.015499	0.17706	2.6491	5.0156	3.6182	16.259
R_4	0.16487	1.6528	20.263	46.453	28.159	59.872

Validation

One cirrus case has been selected to demonstrate the reliability of the retrieval algorithm. The cirrus scene was observed by MODIS onboard Terra over ARM-SGP site in central Oklahoma around 1736UTC on the 6th of March 2000. It was also observed by the MMCR at the Central Facility site (Lamont, 36.62˚N, 97.5˚W).

We first compare our retrieval against corresponding cloud parameters extracted from the MODIS cloud product (MOD06). The results are shown in Figure 6.

To compare satellite retrieval and ground-based MMCR retrieval, A time-space correlation relationship is established through wind speed and direction data in cloud layer. Pixels in black box of Figure 6 roughly corresponding to the stream of cloud that have passed over the MMCR in a ten-minute period centered at the MODIS overpass time. We compare the statistics in Fig 7. Our retrieval correlates well with MODIS retrieval, and qualitatively follows the trend of MMCR retrieval.

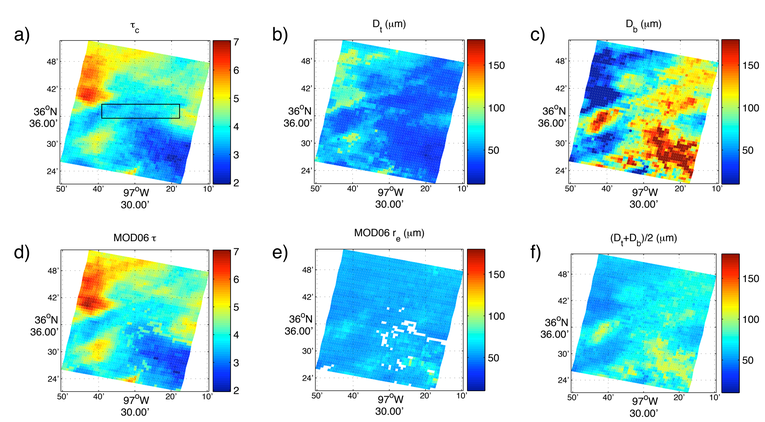

Figure 6: (a) VSP retrieved τ_c; (b)Cloud top effective diameter D_t (b) Cloud base effective diameter D_b (c) MOD06 τ_c ; (d) MOD06 r_e; (f) vertically averaged D_e from VSP

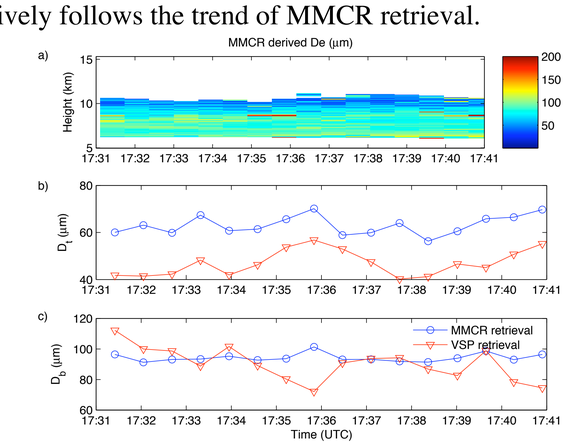

Figure 7: a) MMCR retrieved time series of vertical D_e profile. b). D_t time series from MMCR and from VSP retrieval. c) D_b time series from MMCR and from VSP retrieval.

Summary

We have developed a retrieval method to infer cirrus cloud vertical size profile information from four MODIS channel measurements. Validation with either ground based remote-sensing result or in-situ aircraft measurement shows qualitative agreement. Overall, the conceptual VSP retrieval algorithm represents a progress in the development of satellite cloud retrieval program in terms of its capability to determine the vertical cloud particle size profile.