Remote sensing of three-dimensional inhomogeneous cirrus clouds using satellite and mm-wave cloud radar data

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Received 1 February 2002; revised 26 March 2002; accepted 27 March 2002; published 15 May 2002.

[1] We have innovated a remote sensing methodology involving the retrieval of three-dimensional ice water content and ice crystal mean size of cirrus clouds based on a unification of satellite and ground-based cloud profiling radar observations. This methodology has been applied to AVHRR/NOAA satellite data and mm-wave cloud radar data obtained from the DOE's ARM program in northern Oklahoma. The three-dimensional cloud parameter fields thus constructed are assessed with ice crystal size distributions independently derived from measurements by optical probes on board the University of North Dakota Citation. The retrieved three-dimensional ice water contents and mean effective ice crystal sizes involving an impressive cirrus cloud occurring on April 18, 1997, are shown to be comparable to those derived from the analysis of collocated and coincident in situ aircraft measurements. *INDEX TERMS:* 0320 Atmospheric Composition and Structure: Cloud physics and chemistry; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing

1. Introduction

[2] Cirrus clouds are globally distributed, being present at all latitudes and in all seasons with a global cloud cover of about 20–30% and more than 70% in the tropics [*Wylie et al.*, 1994]. The effects of cirrus clouds on the radiation budget of the earth and the atmosphere and, hence, their impact on weather and climate processes have been articulated by *Liou* [1986, 1992]. Satellite mapping of optical depth in midlatitude and tropical regions has illustrated that cirrus clouds are frequently finite in nature and display substantial horizontal variability. Vertical inhomogeneity of the ice crystal size distribution and ice water content (IWC) has also been shown in balloon-borne replicator sounding observations [see, e.g., *Ou et al.*, 1995], as well as the numerous series of backscattering coefficients derived from lidar returns [*Sassen*, 1991]. However, the mapping of three-dimensional (3D) inhomogeneous clouds in space and time based on observational data has not been developed at this point.

[3] In line with our previous work on radiative transfer and satellite remote sensing involving ice crystal clouds, we have innovated a remote sensing methodology for the retrieval of IWC and mean effective ice crystal size of cirrus clouds in 3D space based on a unification of satellite and ground-based 35 GHz mm-wave cloud profiling radar (mmCR) observations. We first present the conceptual approach of 3D remote sensing, followed by its implementation and validation using collocated and coincident satellite, radar, and in situ ice crystal microphysics data gathered by the Department of Energy's Atmospheric Radiation Measurement (ARM) program in the northern Oklahoma area.

2. Conceptual Approach to Three-Dimensional Remote Sensing

[4] Recent advances in the satellite remote sensing of cirrus clouds have demonstrated that their optical depth and mean effective ice crystal size, defined as the ratio of volume to area weighted size distributions, can be retrieved from the operational NOAA AVHRR channels and the MODIS channels on board the NASA EOS/TERRA satellite. *Ou et al.* [1995] developed an infrared technique based on the thermal component of 3.7 μm and 10.9 μm radiance to infer the optical depth and mean effective ice crystal size of cirrus clouds using AVHRR data. Furthermore, using MODIS Airborne Simulator (MAS) data, *Rolland and Liou* [2001] have shown that cirrus optical depth and mean effective ice crystal size can be determined from the correlation of 0.63/1.6 and 0.63/2.13 μm reflectances. However, neither the 1.6 μm nor the 2.13 μm channel is available on operational satellites at present. Our recent work in this area has extended the correlation approach to the AVHRR 0.63 μm and 3.7 μm (total radiance) channels to retrieve cirrus cloud optical depth and mean effective ice crystal size [*Ou et al.*, 1999]. Remote sensing from satellites using the preceding visible and near infrared channels can only produce the vertically integrated cloud parameters in a horizontal plane and does not provide the variability of clouds in the vertical direction.

[5] One of the co-authors of this paper [*Mace et al.*, 2002] developed a technique for the retrieval of IWC and ice crystal size parameters of cirrus clouds based on the reflectivity and Doppler velocity of 35 GHz Doppler radar. In this approach, the ice crystal size distribution is assumed to conform to a modified Gamma distribution consisting of hexagonal columns from which the Rayleigh-Gans theory is used to determine the backscatter and to estimate the fall velocity. Of course, other ice crystal size distributions and shapes could also be used as initial conditions for the retrieval purpose. Although the backscattering technique from mm-wave cloud radar is still evolving, it suffices to demonstrate that the vertical profile of cloud parameters can be retrieved, particularly in connection with cloud horizontal mapping from satellites. Furthermore, lidar backscatter returns have provided accurate vertical and horizontal boundaries of cirrus clouds as well as their extinction coefficient profiles [*Sassen*, 1991]. This information can assist in the construction of 3D cloud fields as presented in the following.

[6] We first let the horizontal distribution of the optical depth and mean effective ice crystal size retrieved from satellite data be denoted by $\tau(x, y)$ and $\mathrm{DE}(x, y)$, respectively. As noted above, both are vertically integrated parameters. Second, from the cloud radar backscatter data and based on the local sounding wind profile, we can convert $\mathrm{IWC}(z, t)$ and $\mathrm{DE}(z, t)$ in the time-height domain to a two-dimensional space domain, $\mathrm{IWC}(x, z)$ and $\mathrm{DE}(x, z)$. We may use the relationship $x = u\Delta t$, where the coordinate axis

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0094-8276/02/2002GL014846$05.00

x is defined in the along-wind direction, u is the wind speed at the cloud level, and Δt is the time difference between the radar measurement and the satellite overpass. For the present analysis, the mean wind speed in the cloud layer is employed to transform time to space.

[7] The optical depth is a function of DE and the ice water path (IWP), which is the product of the vertically averaged IWC and cloud thickness Δz. Based on the parameterization of light scattering by ice crystals [*Liou*, 1992, p. 308], we may relate the optical depth, IWC, Δz, and DE as follows:

$$\tau(x,y) \cong \mathrm{IWC}(x,y)\Delta z(x,y)[a + b/DE(x,y)], \tag{1}$$

where a and b are certain coefficients. Based on satellite and lidar backscattering data, pronounced variation of the cloud thickness Δz has been shown along the x-direction, the direction of the prevailing winds. Moreover, inspection of the AVHRR visible reflectance for cirrus and the local wind pattern from radiosonde also reveals more variability in the along-wind direction than in the cross-wind counterpart. Thus, the vertically integrated IWC(x, y) in a horizontal plane can be determined from the optical depth and ice crystal size retrieved from satellites and the cloud thickness inferred from lidar data.

[8] As noted above, the vertical profiles of IWC and ice crystal size, which can be converted to the parameters defined for satellite retrieval, can be inferred from cloud radar backscattering and Doppler shift spectra and are denoted by IWC(x, z) and DE(x, z). To merge these values with those retrieved from satellites so as to construct a 3D cloud field, we may define the normalized quantities such that IWC*(x, z) = IWC(x, z)/[IWC(x)] and DE*(x, z) = DE(x, z)/[DE(x)] where [IWC(x)] and [DE(x)] are the ice water content and mean effective ice crystal size averaged along the vertical direction and are functions of the direction of the prevailing winds. It follows that the 3D IWC and DE fields may be defined by

$$\mathrm{IWC}(x,y,z) = \mathrm{IWC}(x,y) \bullet \mathrm{IWC}*(x,z), \tag{2a}$$

$$\mathrm{DE}(x,y,z) = \mathrm{DE}(x,y) \bullet \mathrm{DE}*(x,z). \tag{2b}$$

The 3D cloud field so constructed will then have the horizontal and vertical resolutions corresponding to AVHRR/MODIS pixels, (~1 km by 1 km) and 35 GHz cloud radar backscattering profiles (~90 m).

[9] The conceptual approach for the remote sensing of 3D cloud fields presented above is based on a number of physical assumptions and obviously requires independent validation. In the following, we present a case study where collocated and coincident satellite, radar, and lidar data were available over a mesoscale domain for the remote sensing of 3D IWC and ice crystal size. In addition, we also present the cirrus cloud microphysics data that were collected from aircraft during the same time period and locality for an independent check of retrieval results.

3. Application to DOE/ARM Spring 1997 Cloud-IOP Measurements

[10] In conjunction with the test of the conceptual approach for 3D cloud remote sensing described above, we have selected collocated and coincident AVHRR/NOAA and DOE/ARM cloud radar data gathered at the SGP-CART site in the northern Oklahoma area for a single-layer cirrus occurring on April 18, 1997, during the ARM Cloud-IOP. Using these data, retrieval and analyses were carried out to construct 3D IWC and DE fields, which were then compared to collocated and coincident in situ measurements of the ice crystal size distribution and IWC independently derived from the optical probes on board the University of North Dakota Citation. To ensure the compatibility of the retrieved cloud parameters and in situ aircraft microphysics measurements, we selected all the relevant local data that were within one hour of the satellite overpass. The airborne optical probes for measuring the ice crystal size distributions involved the imaging of the cross section of ice particles in the forward direction using a laser beam. These instruments generally sample ice particles larger than about 20 μm.

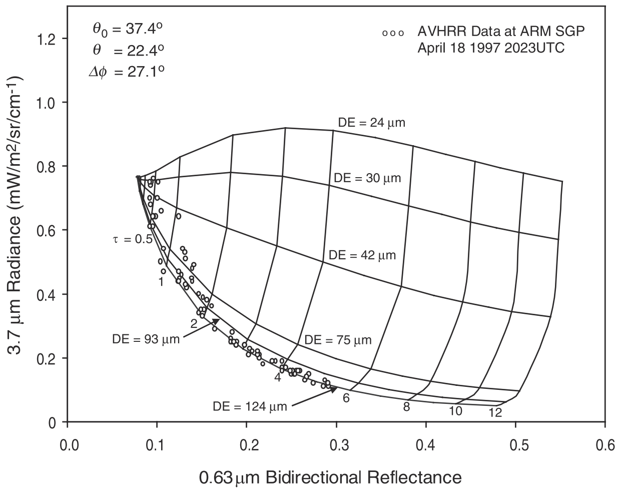

Figure 1. Display of a correlation diagram for the 0.63-μm reflectance and 3.7-μm total radiance in terms of six mean effective ice crystal sizes (24 ~ 124 μm) and a range of optical depths from 0.5 to 12. Overlapped are a scan line of AVHRR/NOAA-14 data over the central region of the ARM-SGP CART site at 2023 UTC, April 18, 1997.

[11] Figure 1 displays a correlation diagram for the 0.63 μm reflectance and 3.7-μm total radiance as functions of reference optical depth and DE constructed from radiative transfer calculations [*Ou et al.*, 1999]. Subsequently, a two-dimensional reflectance-radiance correlation diagram based on these look-up tables was charted in terms of curves of constant optical depth and mean effective ice crystal size. The 0.63-μm reflectances are primarily dependent on the optical depth, as evidenced by its nearly vertical curves of constant value. The 3.7-μm radiances, however, are functions of both the optical depth and DE for optically thin and moderately thick cirrus clouds, as illustrated by the sloping curves of constant DE values. For optically thick clouds, the 3.7 μm radiances approach asymptotic values, which are dominated by DE, as indicated by its nearly horizontal curves of constant values. Overlapped with these curves are NOAA-14 AVHRR LAC data points for a section of a scan line between 96.5°W and 98.5°W near the central region of the ARM SGP-CART site at 2023 UTC on April 18, 1997. It is noted that the curves of constant reference optical depth and DE form a two-dimensional correlation mesh. For each satellite data point that falls within this mesh, a unique set of the optical depth and DE can be determined by using a numerical interpolation-iteration method which searches through a look-up table for the optimal combination of these two parameters that minimizes the differences between computed and observed reflectance/radiance values [*Ou et al.*, 1999]. In this diagram, we see that the distribution of data points reveals that the detected cirrus pixels consist of a variety of optical depths (0–5) and DEs (30–124 μm).

[12] For brevity of presentation, the time series of IWC and DE as functions of height between 1900 and 2130 UTC for the cirrus case are not displayed here. It suffices to point out that the thickness of this mushroom-shaped cirrus cloud varied from about 1 to 3 km over a time period of ~1 hour. The cloud top heights are

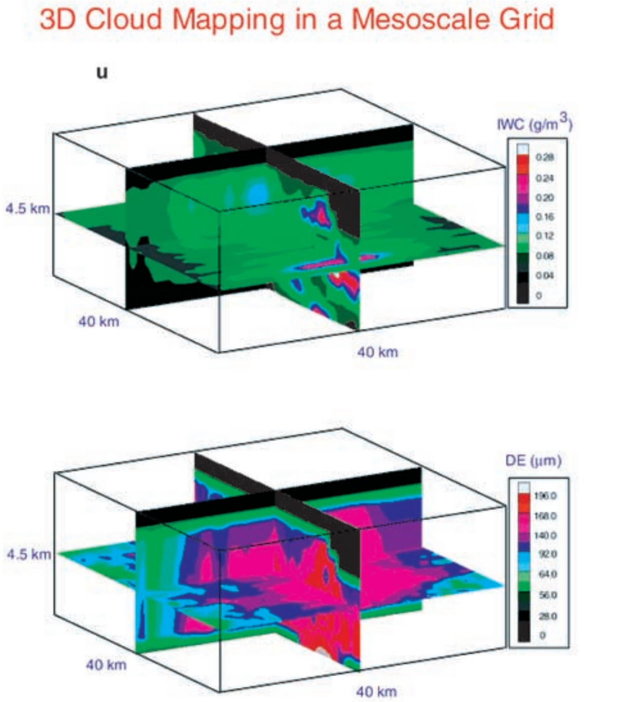

Figure 2. Three-dimensional ice water content (IWC, 0–0.28 g/m^3) and mean effective ice crystal size (DE, 0–196 μm) determined from a unification of the optical depth and DE retrieval from the 0.63 and 3.7 μm AVHRR channels aboard the NOAA-14 satellite and the IWC and DE retrieved from the 35 GHz cloud radar over the ARM-SGP CART site at 2023 UTC on April 18, 1997. The 3D IWC and DE results are presented in *xy*, *yz*, and *xz* planes over a 40 km × 40 km × 4.5 km domain.

nearly constant (∼10–11 km), but the cloud base heights varied drastically and extended downward to about 8 km. The retrieved IWC and DE values were 0–0.3 g m^{-3} and 0–170 μm, respectively, while the inferred extinction coefficients were 0–0.01 m^{-1}.

[13] Using the aforementioned satellite and cloud radar data and following the unification approach outlined in the previous section, 3D IWC and DE fields were constructed and are shown in Figure 2. For illustration purposes, the 3D IWC and DE results are presented in the *xy*, *yz*, and *xz* planes over a 40 km × 40 km × 4.5 km AVHRR data domain, corresponding to cloud radar measurements between 2000 and 2050 UTC. Substantial variabilities in IWC and DE are shown in the *xz* plane as compared to those in the *yz* plane, because the prevailing wind direction was designated in the *x*-direction. Also noted is the increasing DE toward the cloud base. The black areas indicate that data was not available.

[14] The 3D IWC and DE fields determined from satellite and cloud radar data were compared to the ice crystal size distribution and IWC independently derived from the simultaneous in situ measurements by 2D probes on board the University of North Dakota Citation. The flight track between 2018 and 2100 UTC consisted of a racetrack pattern in six ascending legs centered around the ARM central facility site near Lamont, Oklahoma. A leg was defined as the section of the flight track, for which the variation of flight height is less than a small value (e.g. ∼10 m), as shown in the upper panel of Figure 3. This period coincided with the NOAA-14 AVHRR overpass (∼2023 UTC). The sampling of ice crystal sizes was taken every 5 sec. Following the method described in *Ou et al.* [1995], we computed the average in situ IWC and DE, and their associated standard deviations for each of the six legs. Based on the soundings of local wind speed and direction, we also determined the latitude and longitude of the satellite's pixels (∼275) that corresponded to the location of each in situ sampling. For comparison purposes, we extracted IWC and DE values from the 3D cloud fields retrieved from AVHRR and cloud radar using the latitude and longitude of AVHRR pixels and the flight height. We then calculated mean values and standard deviations for the pixels associated with each aircraft leg.

[15] The lower panel of Figure 3 illustrates comparison of the mean (symbols) and standard deviation (bars) as functions of the aircraft leg height. The retrieved mean DEs varied between 60 and 120 μm, generally larger than those derived from in situ measurements by less than 10 μm. Also, the retrieved mean IWCs varied between 0 and 0.1 g m^{-3} in general agreement with those derived from in situ measurements in terms of both magnitude and the vertical pattern. Differences in the 3D IWC and DE values between retrieval and in situ analysis could be attributed to a number of approximations made in the development of the remote sensing algorithm as well as the inherent uncertainty in geographical collocation and temporal coincidence between two data sources. Nevertheless, the similarity between the retrieved and in situ

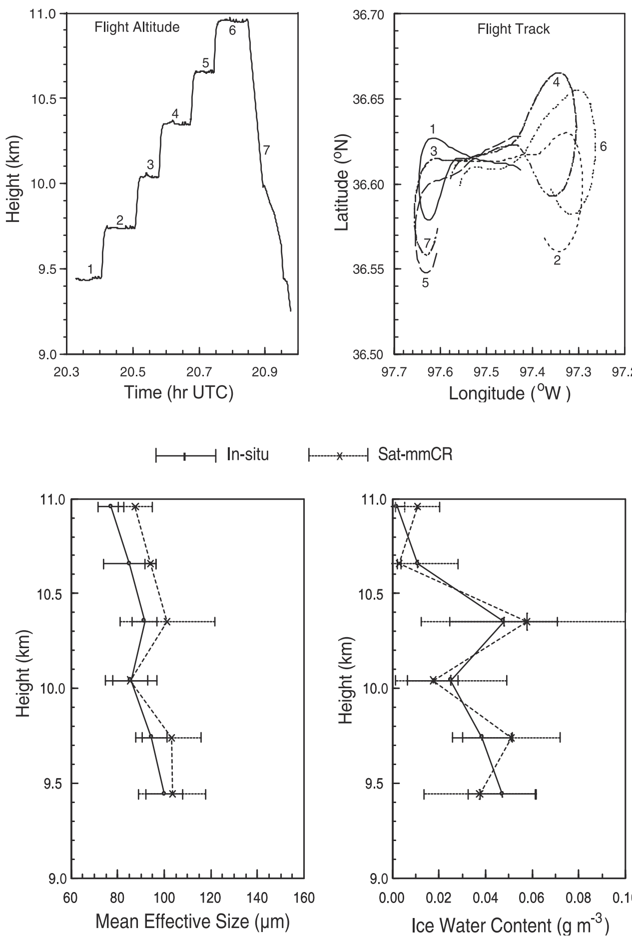

Figure 3. Time series of the flight altitude and the position of the flight track of the North Dakota Citation over the ARM-SGP CART site on April 18, 1997 (upper panel). Comparison of the mean (symbols) and standard deviations (bars) of the retrieved IWC and DE values from the unification approach involving satellite and cloud radar observations derived from in situ measurements taken on board the University of North Dakota Citation, as functions of aircraft leg height (lower panel).

derived IWC and DE values is quite encouraging. Finally, we wish to point out that because of the limitations of in situ observation of small ice crystals [see, e.g. *Kristensson et al.*, 2000] and of satellite retrievals of thin optical depths [*Rolland and Liou*, 2001], the 3D remote sensing technique developed herein is most applicable to cirrus clouds containing ice crystals larger than about 20 μm and with vertical optical depths greater than about 0.5.

4. Concluding Remarks

[16] We have innovated an approach for the determination of 3D IWC and DE fields of cirrus clouds based on a unification of satellite and ground-based cloud radar measurements. Satellite retrieval yields vertical integrated cloud parameters in a horizontal plane, whereas cloud radar produces cloud parameters in a vertical plane. To test the validity of this approach, we selected collocated and coincident AVHRR/NOAA and DOE/ARM mmCR data available from the SGP-CART site in the northern Oklahoma area for an impressive cirrus cloud occurring on April 18, 1997, during the ARM Cloud-IOP.

[17] To map the horizontal distribution of optical depth and DE, the correlation technique involving the AVHRR 0.63/3.7 channel radiances was followed. Based on the physical principle of radiative transfer, IWC can be determined from optical depth, DE, and the information of cloud thickness, which can be precisely inferred from lidar backscattering measurements. The horizontal distributions of IWC and DE are then merged with values retrieved from cloud radar to produce 3D fields. We demonstrated that the 3D IWC and DE fields so constructed are physically reasonable and we performed validation employing independent in situ measurements of ice crystal size distributions by optical image probes on board an aircraft.

[18] The remote sensing of clouds from satellite radiometry is presently limited to the mapping of horizontal variation of the cloud field. However, the vertical inhomogeneity of clouds appears to be a critical parameter from the vantage point of understanding the cloud radiative forcing in realistic atmospheres. It is also important to the understanding of the heating rate profiles produced by inhomogeneities that may impact the numerical simulations of atmospheric parameters in climate models [*Gu and Liou*, 2001]. The 3D cloud parameters constructed from a combination of satellite and cloud radar measurements presented in this paper can provide valuable datasets to assist in the computation of heating rate and flux fields in 3D clouds and cloudy atmospheres, on the one hand, and in the development of the parameterization scheme for inhomogeneous clouds in climate models on the other.

[19] **Acknowledgments.** Research reported in this paper has been supported by DOE Grant DE-FG03-00ER62904, NSF Grant ATM-9907924, and NASA Grant NAG5-7123.

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