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Comparison of in situ and satellite-derived cloud properties during SUCCESS

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Abstract. The validation of cloud microphysical properties derived from satellite data with in situ observations is generally difficult due to the spatial and temporal variability of observed clouds. Two missions during SUCCESS concentrated on orographic wave clouds that exhibited relative spatial and temporal homogeneity. A comparison has been made of effective ice particle diameters derived from multi-spectral satellite data with in situ measurements from the MASP and PVM instruments aboard the DC-8 aircraft. For both days, the satellite-derived effective diameters fall well within the bounds of the in situ data.

Introduction

The microphysical properties of a wide array of cirrus clouds were sampled in situ during the spring 1996 NASA Subsonic Clouds and Contrails Effects Special Study (SUCCESS) conducted under the auspices of the NASA Subsonic Assessment Program and First ISCCP Regional Experiment (FIRE). These measurements provide the resources for addressing one of FIRE's objectives, the validation of satellite-retrieved microphysical properties. A methodology [*Minnis et al.*, 1995] and models of cloud optical properties [*Minnis et al.*, 1997a] have recently been developed for retrieving cloud microphysical properties from all types of clouds using multispectral data from the Geostationary Operational Environmental Satellite (GOES) multispectral imager, the NOAA Advanced Very High Resolution Radiometer (AVHRR), and other similar instruments. This paper uses a subset of the SUCCESS data to begin the process of validating the retrieval methodology and models.

Two wave cloud cases are the focus of this investigation because they were extensively sampled in situ during SUCCESS near the overpass of NOAA-14 and showed more uniformity than most cirrus clouds. Model studies [*Eric Jensen, personal communication*] suggest that wave clouds tend to be vertically uniform in particle size. This minimizes one of the factors, vertical inhomogeneity, that complicates the comparison of in situ and satellite retrievals. Thus, it should be possible to draw more definitive conclusions concerning the validity of the satellite results for wave clouds.

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Data and Methodology

The in situ data were collected with the multi-angle aerosol spectrometer probe (MASP) [*Baumgardner et al.*, 1998] and the particulate volume monitor (PVM) [*Gerber et al.*, 1998] flown on the NASA DC-8 during SUCCESS. These instruments measure the ice particles optically and assume spherical particles when determining the particle sizes. The size range of the MASP extends from 0.3 μm to 40 μm. The PVM size range extends to 50 μm. For this study, estimates of effective diameter from these instruments are made once every 5 seconds from MASP and once every second for PVM.

Both 1-km and 4-km NOAA-14 AVHRR and the 4-km, GOES-8 imager data were analyzed pixel by pixel in a box containing the selected DC-8 flight tracks for the two cases, April 30 and May 2, 1996. The AVHRR visible (VIS; 0.65 μm), solar infrared (SI; 3.7 μm), and infrared (IR; 10.8 μm) data and the nearest coincident GOES VIS, SI (3.9 μm), and IR (10.9 μm) pixels were analyzed with the VIS-SI-IR technique (VIST) [*Minnis et al.*, 1995] to derive effective ice particle diameter D_e, VIS optical depth τ, and cloud temperature T_c. The VIST uses an iterative technique to simultaneously determine values for each parameter given the observed VIS reflectance ρ, and the SI and IR brightness temperatures and estimates of the clear-sky reflectance ρ_s, and SI and IR clear-sky brightness temperatures T_{SI} and T_{cs}. Temperatures and reflectances for a range of particle sizes and optical depths are computed for the given solar zenith, viewing zenith, and relative azimuth angles, θ_o, θ, and ψ, respectively, using the cloud emittance and reflectance parameterizations of *Minnis et al.* [1997a] and a VIS surface-atmosphere-cloud reflectance parameterization [*Minnis et al.*, 1995]. The cloud parameters are determined by iteratively solving for the best match between the observed and modeled temperatures and reflectances.

The reflectances for the AVHRR and GOES are computed as

$$\rho = \frac{\pi L_V}{526.9 \cos\theta_o \delta(d)}, \tag{1}$$

where the observed radiance is $L_v = a_0 + a_1\, CT$, CT is the 10-bit count, d is the day of the year, and δ is the Earth-Sun distance correction factor. The calibration coefficients a_0 and a_1 are -4.93 and 0.120 for AVHRR and -19.2 and 0.674 for GOES-8, respectively. The nominal calibrations were used to convert IR counts to temperatures. The reflected solar component was determined using SI solar constant values

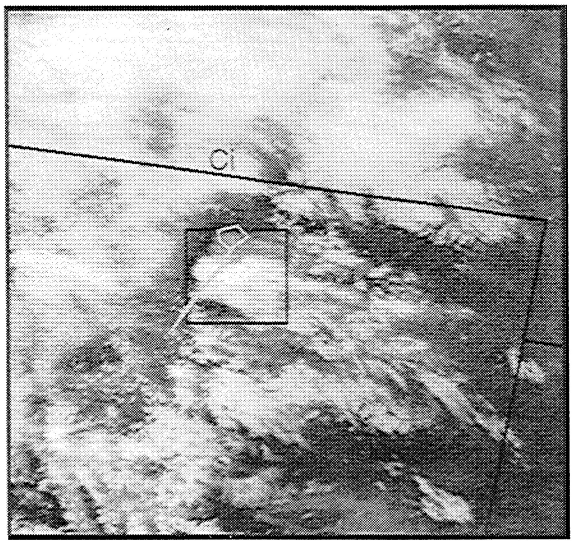

Figure 1. AVHRR IR imagery of the wave cloud over Colorado, 20.56 UTC, May 2, 1996. The gray line denotes the DC-8 flight track for 20.37 - 20.65 UTC.

equivalent to T_{SI} = 357.3K and 338.0K for AVHRR and GOES-8, respectively. Soundings from National Weather Service stations at Albuquerque, NM (April 30) and Denver, CO (May 2) from 1200 UTC were used to convert temperature to altitude and adjust for the effects of humidity on the IR radiances.

Effective ice particle diameter for the particle distributions used in the VIST models are calculated by:

$$D_e = \frac{\int_{L_1}^{L_2} D^2 LN(L)dL}{\int_{L_1}^{L_2} DLN(L)dL} \qquad (2)$$

where L is the particle length, D is the particle width, and N is the normalized number of particles in a size bin. Effective diameters are calculated from the in situ data using equation (2) and assuming spherical particles ($D = L$).

Results and Discussion

May 2, 1996

A wave cloud located east of the Front Range of the Rocky Mountains was sampled by the NASA DC-8 between 19.6 and 21.8 UTC, 2 May 1996. Figure 1 shows this cloud in the 20.56 UTC NOAA-14 IR image. The box in the image indicates the area analyzed by VIST using data from both AVHRR and GOES. The DC-8 flight track for 20.37 - 20.65 UTC is also shown. The northeast-southwest leg of the DC-8 flight between the times of 20.55 - 20.61 UTC matches the NOAA-14 overpass time of 20.56. Essentially the same area was sampled earlier between 20.43 - 20.49 on the same path while the aircraft traveled to the northeast.

During these passes the DC-8 flew near the top of the cloud (~11.8 km) at an ambient temperature of 209 K. ER-2 lidar data indicate that this cloud extended vertically from 12 km to at least 9.8 km [*Spinhirne et al.*, 1998]. The true bottom of the cloud is unknown since the lidar signal was attenuated by the cloud. Although this was an optically thick cloud, no temperatures below 219 K were observed in the 1 km resolution AVHRR data. This suggests that the majority of the cloud mass is beneath the DC-8 altitude and that the satellite observed properties from a lower portion of the cloud.

Cloud properties derived from the 1-km resolution AVHRR data are shown in Figure 2 for the area in the box in Figure 1. Pixels classified by VIST as clear are indicated in black. Gray pixels denote data that cannot be fit with consistency by the VIST algorithm and are reported as "no retrieval." To eliminate lower clouds from the comparisons, the area of the wave cloud is defined as the portion of these fields where the emittance exceeds 0.8 and T_C < 250 K. The central portion of the cloud is nearly thermally black (cloud emittances, ε > 0.95). Throughout most of the cloud, τ ranges from 4 - 20. The particle sizes are consistently small, ranging between 10 - 25 µm in the main body of the cloud.

This scene was also analyzed using the 4-km AVHRR and GOES data from 20.75 UTC. Because these data have poor resolution compared to the 1 km AVHRR, care must be taken in comparisons to avoid cloud edge contamination. All comparisons were performed using only those pixels with retrieved ε > 0.85. These results are summarized in Table 1.

The agreement between D_e retrieved from the two satellites is quite good. Particle sizes range from 17.9 ± 2.1 from GOES to 19.7 ± 3.9 for the lower resolution AVHRR. Also, the AVHRR data indicate that particle sizes sampled along the flight track are representative of the cloud as a whole. There is, however, some discrepancy among the retrieved values of τ and T_C. The optical depth comparison can be difficult when using data with varying spatial resolution. The comparison is much better if the 4-km AVHRR and the GOES data are

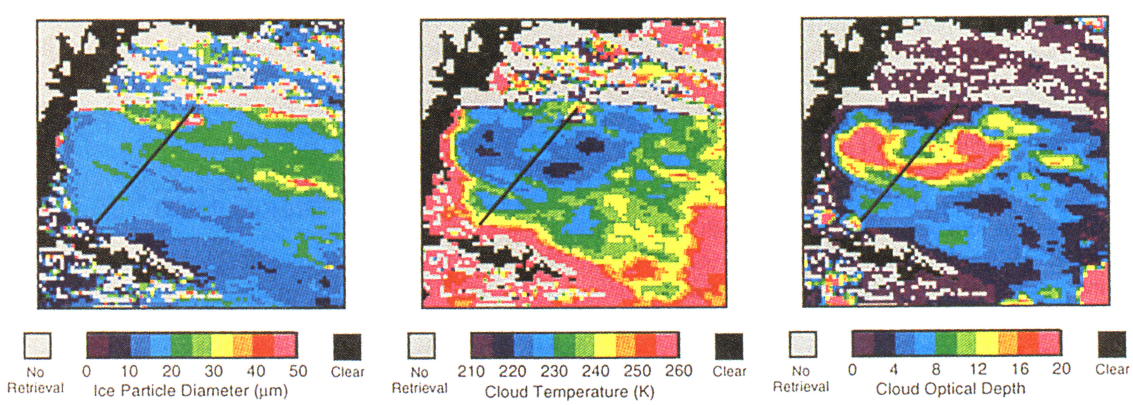

Figure 2. Cloud properties retrieved using VIST from 1-km AVHRR data, 20.56 UTC, May 2, 1996. The region corresponds with the box in Figure 1. The solid line indicates the location of the DC-8 flight track from 20.55 - 20.61 UTC.

Table 1. Derived Cloud Properties from May 2, 1996.

Data	D_e (µm)	$\sigma(D_e)$ (µm)	Optical Depth	T_{cloud} (K)
1 km AVHRR (entire region)	18.3	3.8	10.3	232.4
1 km AVHRR (flight track)	18.7	2.3	9.6	228.7
4 km AVHRR	19.7	3.9	6.8	226.6
4 km GOES 20.75 UTC	17.9	2.1	4.3	230.9
MASP 20.55 - 20.61 UTC	15.5	1.6	-	-
MASP 20.43 - 20.49 UTC	16.4	2.5	-	-
PVM 20.55 - 20.61 UTC	11.8	1.6	-	-
PVM 20.43 - 20.49 UTC	12.7	2.1	-	-

restricted to pixels with $\varepsilon > 0.95$. For these data, the AVHRR optical depth increases to 9.1, which is in much better agreement with the 1-km data. The GOES optical depth also increases (to 5.5), but not as much. This may indicate some inconsistency in the relative visible calibrations, although the GOES calibration was based on coincident April 1996 GOES and AVHRR data. The temperatures are all consistently greater than the temperature at the DC-8 flight level. This is caused largely by the satellite seeing the optical center of the cloud. However, the mean value of T_c may also be biased too high due to the effects of partial cloudiness near the cloud edges.

Data from the PVM and MASP instruments were averaged for the 20.55 - 20.61 UTC time period and compared with a two-pixel-wide swath of satellite data taken along the flight track, as indicated by the black line in Figure 2. For this region, the VIST retrieves D_e = 18.7 ± 2.3 µm. The MASP data averages to 15.5 ± 1.6 µm, while the PVM measured 11.8 ± 1.6 µm. During the earlier flight leg (20.43 - 20.49 UTC) the MASP and PVM measured effective diameters of 16.4 µm and 12.7, respectively. The frequency distributions of D_e are compared in Figure 3. The in situ distribution shows the time variability of D_e, while the spread in the VIST data is indicative of spatial variation along the track at 20.56. The VIST, MASP, and PVM distributions show similar relative distributions, although there are differences in the mean diameters. Significantly, both the satellite retrievals and in situ measurements show the uniformly small particles expected in this type of cloud. In contrast, D_e retrieved from AVHRR data

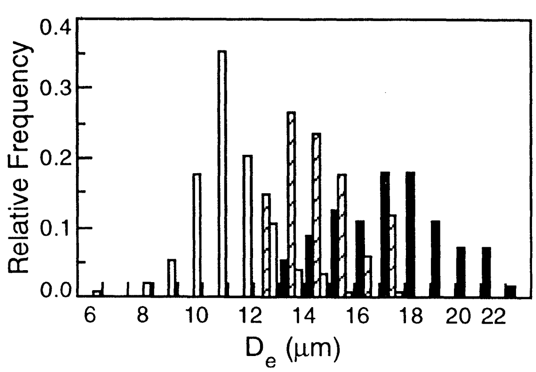

Figure 3. Comparison of the distribution of effective ice particle diameters derived along the DC-8 flight track on May 2 from VIST (black), MASP (white) and PVM (hatched).

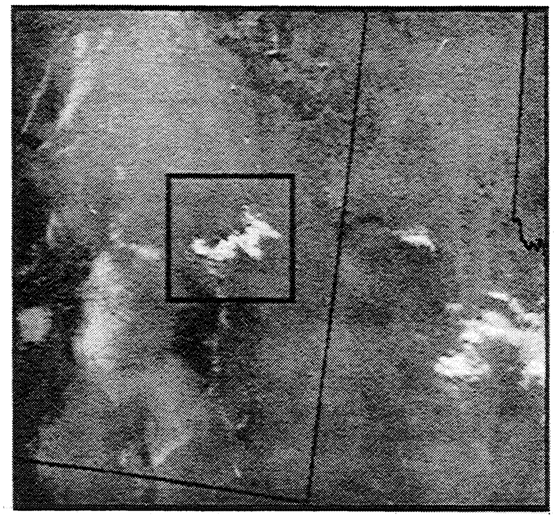

Figure 4. AVHRR IR imagery of the wave cloud over New Mexico, 20.92 UTC, April 30, 1996.

for the non-orographic cirrus cloud to the north (labeled Ci in Figure 1) are 61 ± 14 µm, values more typical for cirrus. For example, a global VIST analysis found a mean global value of 58 µm for ice clouds over land [*Minnis et al.*, 1997b].

To understand the significance of the distributions observed in the wave cloud, correlations of the time series along the second flight leg were performed. The correlation between the VIST and PVM particle sizes is low (R ~ 0.15), as is the correlation between the two in situ measurements (R ~ 0.17). Much of the poor correlation is due to the homogeneity of the wave cloud as demonstrated by the low standard deviations. Because of the low variance in the data sets and the high frequency of the variations, shifting the time series slightly can change the correlations somewhat (to maxima of 0.40 and 0.46, respectively) indicating some possible spatial variability. The largest source of variation though, is most likely noise in the measurements. This suggests that this case provides an excellent estimate of the error range in the VIST retrieval for clouds of this type. Additional studies are needed to reconcile the differences in the in situ measurements [see *Gerber et al.*, 1998; *Jensen et al.*, 1998]. However, the satellite-derived values of effective particle size are well within the bounds of the in situ observations.

Table 2. Derived Cloud Properties from April 30, 1996.

Data	D_e (µm)	$\sigma(D_e)$ (µm)	Optical Depth	T_{cloud} (K)
1 km AVHRR (entire region)	19.8	5.4	6.4	252.5
4 km AVHRR (e > 0.75)	23.4	8.8	4.0	256.8
4 km AVHRR (e > 0.90)	20.8	3.9	5.7	255.4
4 km GOES (e > 0.75)	22.8	9.9	2.7	259.7
4 km GOES (e > 0.90)	14.2	1.1	5.6	259.7
MASP (20.0 - 20.8 UTC)	16.0	3.1	-	-
MASP (20.8 - 21.5 UTC)	17.2	3.3	-	-
PVM (20.0 - 20.8 UTC)	17.1	2.9	-	-
PVM (20.8 - 21.5 UTC)	16.9	2.4	-	-

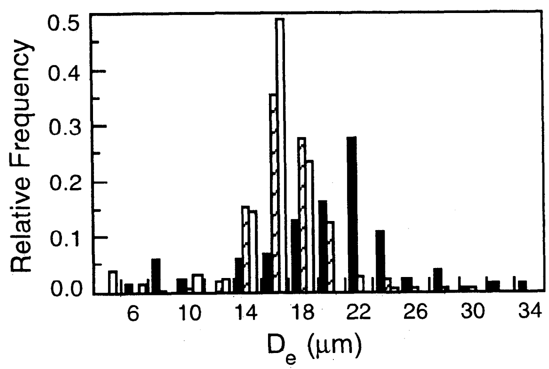

Figure 5. Comparison of the distribution of effective ice particle diameters derived in the April 30 wave cloud from VIST (black), MASP (white) and PVM (hatched).

April 30, 1996

A wave cloud located east of the Rocky Mountains in New Mexico was sampled by the DC-8 between 19.3 and 21.3 UTC, April 30, 1996. The DC-8 flew numerous passes through the cloud at an altitude of 8.5 - 9.0 km at an ambient temperature of ~236 K. Figure 4 shows the 20.92 UTC NOAA-14 AVHRR IR image. This relatively isolated wave cloud consisted of several sections over sloping terrain having a steep gradient in surface temperature. The wide variation in the surface background and the cloud create a more difficult situation for deriving cloud properties using satellite data. The satellite overpass time of 20.92 UTC occurs in the middle of a time period when the DC-8 was out of the cloud (20.74 - 21.2 UTC). Therefore, comparisons for this day are not as direct as those for May 2.

Table 2 summarizes the results of VIST retrievals. The variable nature of this cloud is apparent in the increase in the standard deviations of D_e. The results for the 4-km data are also much more sensitive to changes in the cloud emittance cut-off used to define the central portion of the cloud. Partial cloudiness near cloud edges generally causes an increase in D_e and T_c, as is seen here. Using a more stringent condition of $\varepsilon > 0.90$ results in more consistent satellite retrievals. In contrast with the May 2 data, the optical depths derived from GOES and AVHRR are roughly equivalent when only the highest emittance data are considered. Once again, T_c appears to be quite warm compared with the cloud top temperature because the satellite data are seeing further into the cloud.

Figure 5 shows the distribution of particle sizes derived from VIST, MASP, and PVM. The in situ data from 20.0 - 20.8 UTC are compared to the 1-km AVHRR data. Although the satellite data demonstrates greater variability, the three data sets agree well with D_e = 19.9 ± 5.4 μm, 16.0 ± 3.1 μm, and 17.1 ± 2.9 μm for VIST, MASP, and PVM, respectively. Table 2 also includes mean particle sizes for MASP and PVM for the later time period of 20.8 - 21.5 UT.

Conclusions

Wave cloud properties have been derived from satellite data using the VIST multi-spectral technique. In general, there is very good agreement between the effective ice particle diameters and cloud temperatures derived from GOES and AVHRR data, even when viewing conditions vary. Derived optical depths are less consistent, possibly due to calibration errors. Derived cloud temperatures are higher than the ambient temperature of the in situ instruments since the DC-8 flew near cloud top and the location of the cloud radiating center is well below the top in cirrus clouds. Some additional bias in temperature may be due to cloud-edge effects which can also cause an overestimate in the particle sizes for low resolution data. Biases in particle size can also be caused by insufficient calibration of the SI channels [*Minnis et al.*, 1995].

Comparisons of the particle size distributions with in situ measurements shows that the satellite-derived diameters are quite reasonable. For the May 2 case when there is almost complete temporal and spatial simultaneity, each data set exhibits particle size distributions expected for wave clouds The cloud variability and lack of temporal simultaneity of the April 30 case causes more noise in the comparisons. On this day, the VIST results compare better with the PVM data, although all three data sets are in fairly good agreement. Overall, the uncertainty in the satellite retrieved particle sizes appears to span the range of the in situ data measured by the different instruments, providing a degree of confidence in the VIST retrievals for small ice-crystal clouds.

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