Cloud Macro- and Microphysical Properties Derived from GOES Over the ARM SGP Domain

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Introduction

Cloud macrophysical properties such as fractional coverage and height z_c, and microphysical parameters such as cloud liquid water path (LWP), effective droplet radius (r_e), and cloud phase, are key factors affecting both the radiation budget and the hydrological cycle. Satellite data have been used to complement surface observations from the Atmospheric Radiation Measurement (ARM) Program by providing additional spatial coverage and top-of-atmosphere (TOA) boundary conditions of these key parameters. Since 1994, the Geostationary Operational Environmental Satellite (GOES) has been used for deriving at each half-hour over the ARM Southern Great Plains (SGP) domain: cloud amounts, altitudes, temperatures, and optical depths τ as well as broadband shortwave (SW) albedo and outgoing longwave (LW) radiation (OLR) at the TOA (see Khaiyer et al. [2001] for summary). A new operational algorithm has been implemented to increase the number of value-added products to include cloud particle phase and effective size (r_e or effective ice diameter D_e) as well as LWP and ice water path (IWP). Similar analyses have been performed on the data from the Visible Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission (TRMM) satellite as part of the Clouds and Earth's Radiant Energy System (CERES) project. This larger suite of cloud properties will enhance our knowledge of cloud processes and further constrain the mesoscale and single column models using ARM data as a validation/initialization resource. This paper presents the results of applying this new algorithm to GOES-8 data taken during 1998 and 2000. The global VIRS results are compared to the GOES SGP results to provide appropriate context and to test consistency.

Data

Half-hourly, 4-km GOES-8 imager pixels with reflectances at 0.65 visible (VIS) and brightness temperatures T at 3.9 (SI), 10.8 (IR), and 12.0 μm (WS) were analyzed over a domain covering the area between 32°N and 42°N and between 91°W and 105°W. The entire domain was used for data taken during the Spring 2000 Intensive Operational Period (IOP) from March 1 through April 6, 2000. Data for a 0.3° box centered on the ARM SGP Central Facility (CF) were analyzed for daylight, defined as solar zenith angle SZA < 78°, between January 1 and December 31, 1998. The GOES-8 VIS data were calibrated using coincident VIRS data (Minnis et al. 2001).

CERES Edition-1 average cloud properties derived from 2-km VIRS pixels were computed for a 0.3° box centered over the CF. The VIRS data were taken at different times of day that changed each day because of TRMM's precessing orbit. The CERES analyses use channels similar to those on GOES-8 and covered the first 8 months of 1998. For more details, see http://eosweb.larc.nasa.gov/PRODOCS/

Temperature and humidity profiles from the rapid update cycle (RUC) (Benjamin et al. 1994) analyses were used to correct the radiances for atmospheric absorption and to provide an initial guess at surface skin temperature for the GOES-8 analyses. The VIRS analyses used European Center for Medium-range Weather Forecasts (ECMWF) analyses for the same purposes.

Methodology

A 4-channel update, the Visible Infrared Solar-infrared Split-window Technique (VISST), of the multispectral method described by Minnis et al. (1995) using the models of Minnis et al. (1998) were used together with the technique of Minnis and Smith (1998) to derive cloud fraction, height, temperature, r_e, D_e, LWP, IWP, SW albedo, and OLR for each GOES-8 pixel. The combination of these parameters can also be used to determine which clouds are composed of supercooled liquid water (SLW). Surface emissivities were estimated for each thermal channel using an updated version of the method described by Smith et al. (1999). The values of r_e, D_e, τ, and water paths were found to agree well with both in situ (e.g., Young et al. 1998) and radar-radiometer retrievals (Mace et al. 1998; Dong et al. 2001) for single-layer clouds. Multi-layered clouds can produce significant errors, especially in the derived particle sizes (e.g., Kawamoto et al. 2001).

Results

Spring 2001 IOP

The mean gridded cloud amounts for the Spring 2001 IOP in Figure 1 show total cloud amounts ranging from 30 percent in the southwestern corner of the domain values as great as 69 percent in the northwestern corner. The areas with the greatest cloud amounts are dominated by ice clouds, while liquid water clouds are more prevalent elsewhere. A substantial portion of the liquid water clouds consist of SLW, at least in the part of the cloud viewed by the satellite. The mean cloud heights (Figure 2) reflect the relative distribution of ice and water with the greatest heights occurring in the northwestern part of the domain. In this case, the cloud center height refers to height of the effective radiating center of the cloud. For liquid-water clouds, this center is very close to the cloud top, while for ice clouds it may be 1 to 2 km below the top because of the relatively small optical depths in the tops of physically thick ice clouds. The mean ice cloud heights range from 5.5 to 8 km, while the liquid water cloud heights vary from 2 to 5 km. The SLW clouds are typically at higher altitudes, 3.5 to 5 km, than the average water cloud. This range of mean total cloud heights is typical for this domain although the pattern is not necessarily typical. Khaiyer et al. (2001) provide more details of the climatological values of these properties.

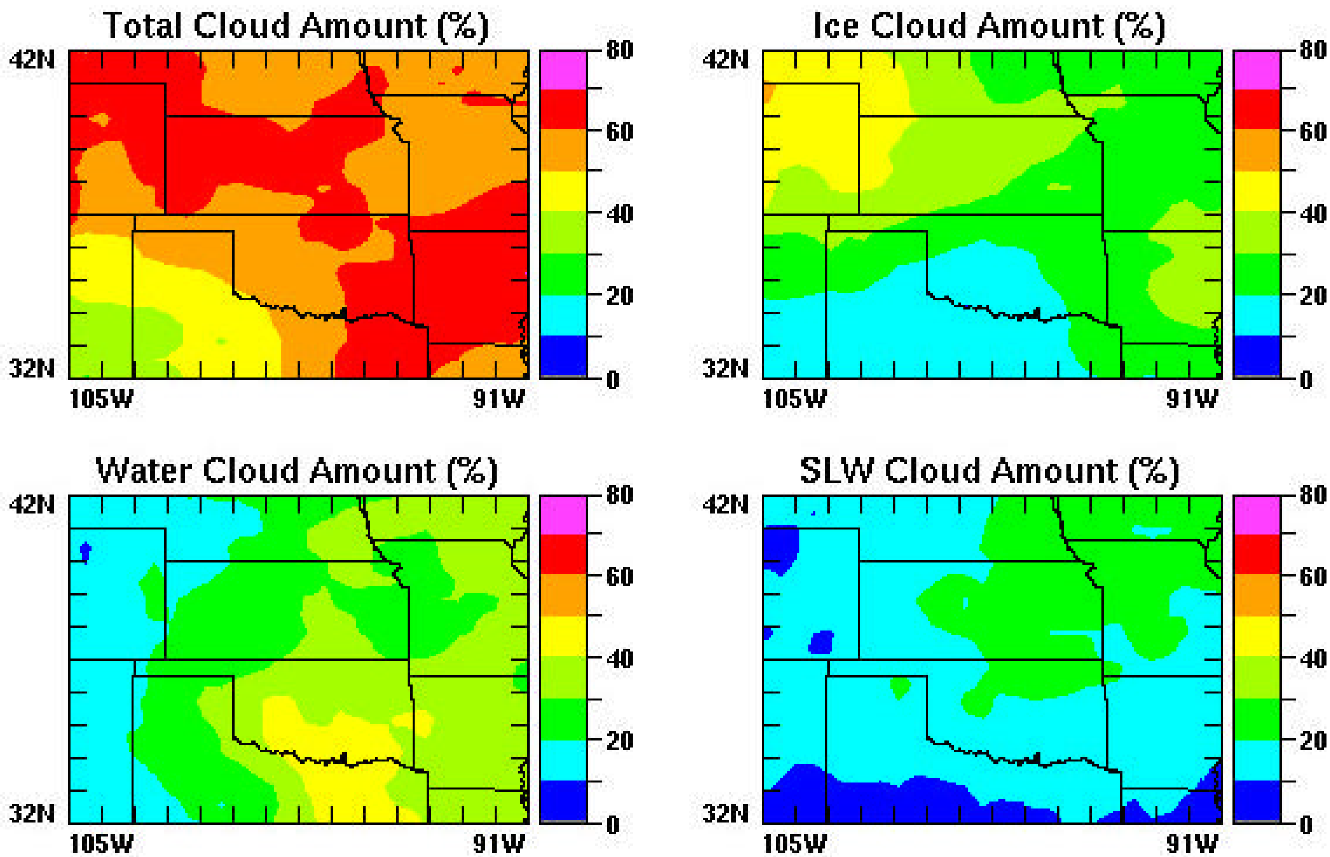

Figure 1. Mean daytime cloud amounts from GOES-8 during the Spring 2000 IOP.

Mean cloud optical depths (OD) are greatest over Oklahoma during the IOP with maximum values near 45 (Figure 3). Several cyclones developed and stalled over the state during the period resulting in the patterns seen here. The largest mean ODs were found in the SLW clouds. Larger instantaneous values probably occurred for the ice clouds. Mean ice cloud optical depths fell below 8 in the southwestern corner of the domain. Figure 4 shows the mean values of r_e for all liquid water clouds, SLW clouds only, and all water clouds that were observed in a grid box free from any pixels identified as ice clouds. Mean LWP values are also provided. For all cases, r_e varies from 10 to 15 µm over the domain. Similar values are observed for the SLW clouds. However, if the ice-contaminated boxes are removed, the range of r_e is reduced to values between 8 and 12 µm. The apparent 2-µm difference in mean r_e between all cases and the ice-free cases is probably due to multi-layered or mixed-phase clouds that tend to increase the derived particle size (e.g., Kawamoto et al. 2001). LWP varies from 100 to 350 gm^{-2} with the maximum values occurring in the same locations as the peak ODs. The mean ODs were unusually large over Oklahoma during the 2001 IOP.

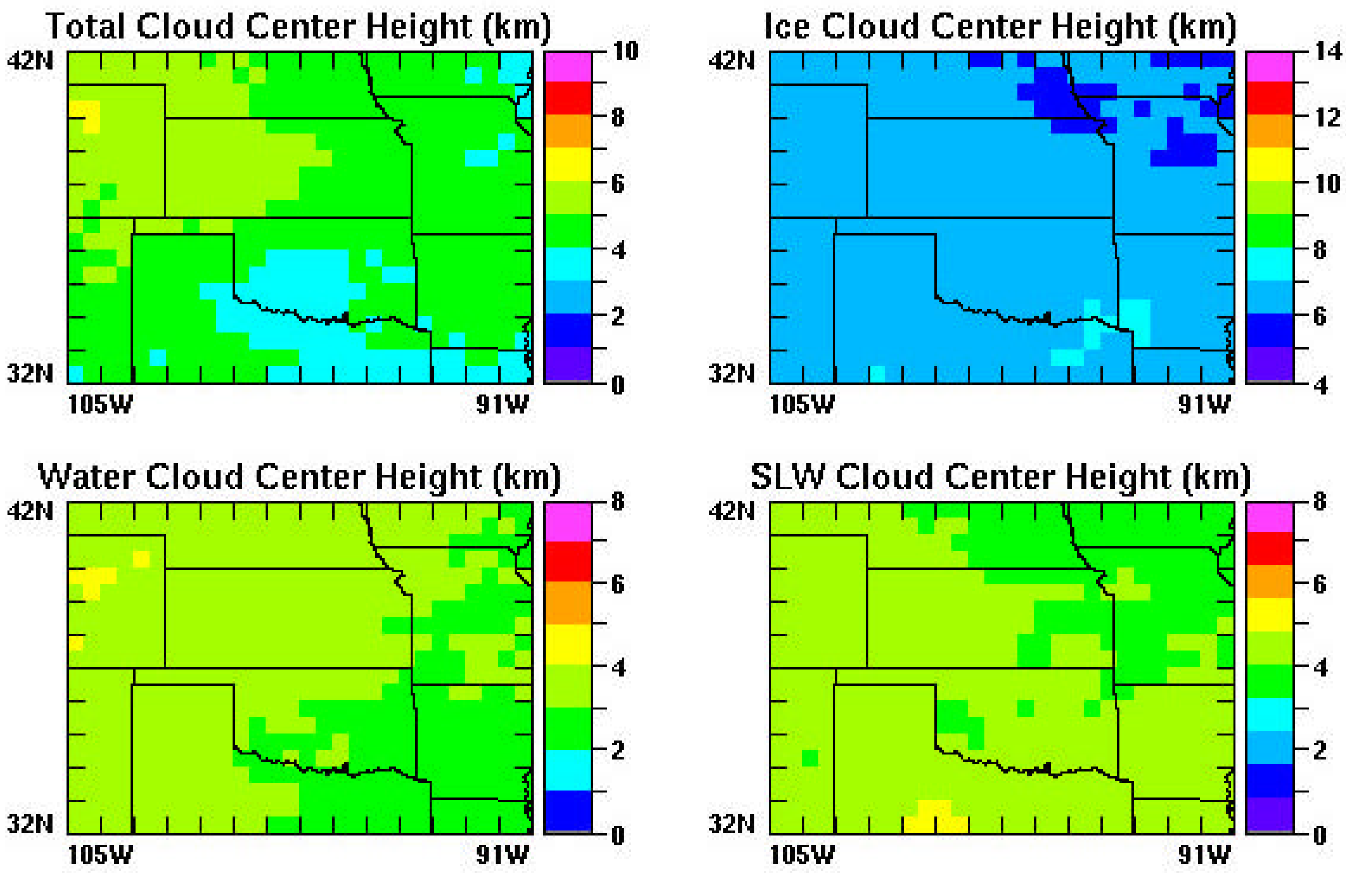

Figure 2. Same as Figure 1, except for mean cloud heights.

1998 CF Averages

The plots in this section denote the seasons as numerals with 1 and 4 representing winter and fall, respectively. The mean cloud amount over the CF in Figure 5 shows that the maximum coverage occurred during the fall in 1998 with a minimum during the summer. The average total cloud fraction for the year was 50 percent composed of roughly 40 percent ice and 60 percent water. Mean total cloud heights (not shown) were greatest during summer at 5.6 km and lowest during autumn at 4.4 km. Total optical depths were greatest during winter and least during summer, although the ice cloud OD was least during fall. Ice cloud OD was smaller than the water cloud value only during fall. Cirrus, defined as ice clouds having $\tau < 4$, coverage (not shown) was greatest during winter and fall. Mean cirrus heights varied from 6 km in winter to 8 km during the summer. Many cirrus overlapped lower clouds and, therefore, were not identified as such because the total OD exceeded 4 for those cases.

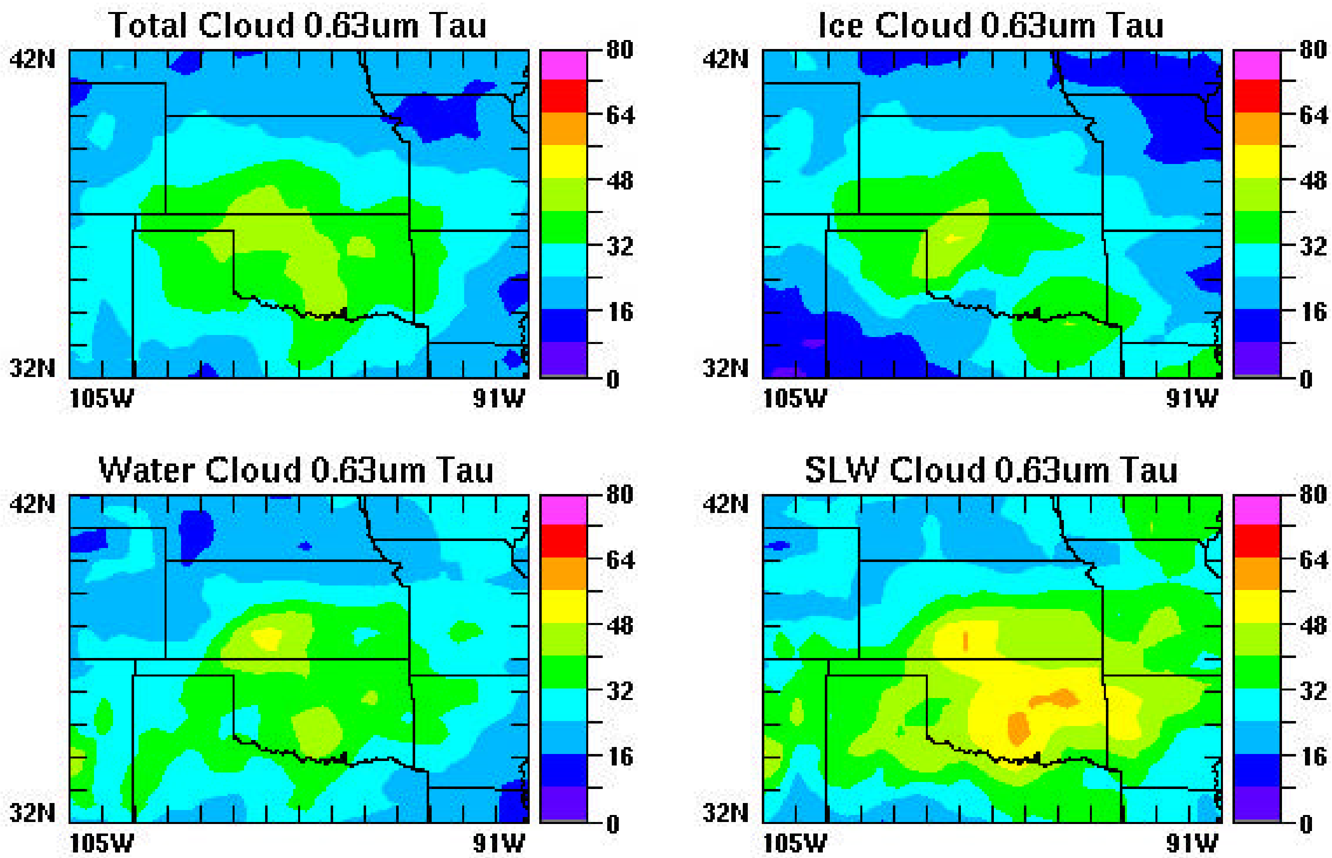

Figure 3. Same as Figure 1, except for cloud optical depths.

The mean cloud effective particle sizes (Figure 6) show a slight seasonal variation with minima in both r_e and D_e during the summer. The average annual values for these parameters are 10.8 and 56 µm, respectively. These values are typical of the global averages derived over land areas by CERES from VIRS data. Consistent with the variations in OD and particle size, the LWP and IWP values peak during winter and bottom out during the summer. The large mean values of IWP are dominated by the passage of deep cyclonic systems and convective storms.

VIRS Comparisons

In addition to comparisons with the reference datasets derived from in situ measurements and active remote sensors noted earlier, it is possible to assess an uncertainty in the satellite-derived cloud properties using comparisons with similar retrievals taken at other viewing angles. VIRS data is valuable for such comparisons because of the changing local time coverage. GOES-8 observes the CF at constant viewing zenith angle (VZA) of 53°, while VIRS has a VZA varying from 38° to 48° with azimuth angles that differ from GOES-8. The mean matched cloud fractions from GOES-8 for 1998 are 4 percent greater than those from VIRS with a root mean square (rms) difference of 20 percent. The magnitude of these differences is expected given the different VZAs and pixel resolutions.

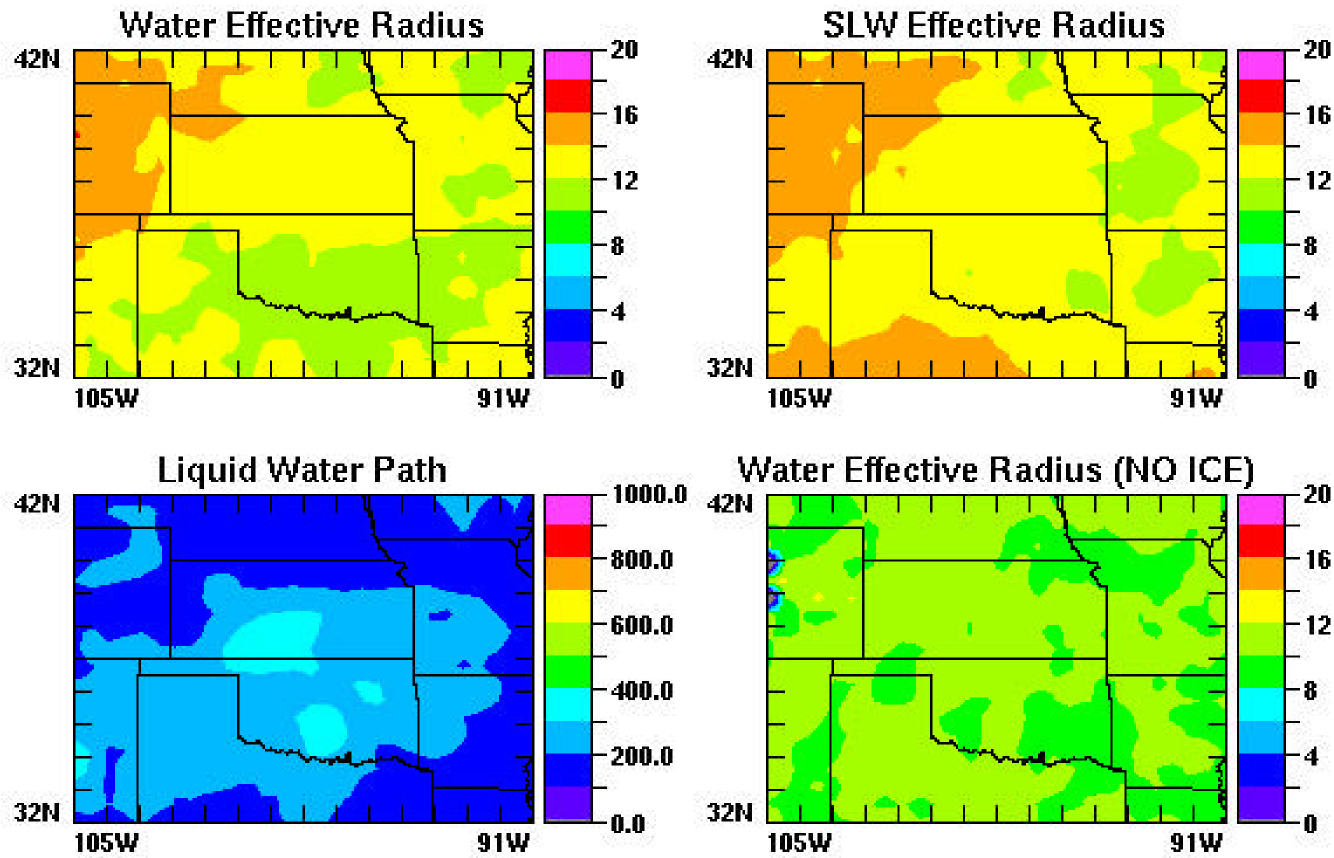

Figure 4. Same as Figure 1, except for cloud water droplet sizes and LWP.

Figure 7 shows the scatterplots of cloud heights derived from the two satellite instruments for mostly overcast and broken cloud cases separately. For the overcast (CLD > 95%) cases, the mean difference is only 0.2 km with a 0.8-km standard deviation (std). When only broken cloud cases are considered, however, the mean GOES-8 heights are 0.8 km higher than their VIRS counterparts with much greater variance. Several factors such as differences in the temperature profiles may be responsible for these discrepancies. For examples, the few GOES cloud heights below 2 km suggests that boundary layer inversions that typically accompany low stratus clouds may not be very well defined in the RUC analyses. For the broken cloud cases, nearly all of the GOES cloud heights exceed the VIRS values.

This bias may be due, at least in part, to the larger pixel size and greater VZA for GOES. The greater cloud fractions caused by these two factors would tend to decrease the apparent optical depth of the cloudiness in a given pixel resulting in a greater height correction than would be applied to the VIRS pixels for the same area. Further analyses are needed to better define the source of the differences. On average, the GOES-8 cloud heights are 0.4 km greater than VIRS with a standard deviation 1.0 km.

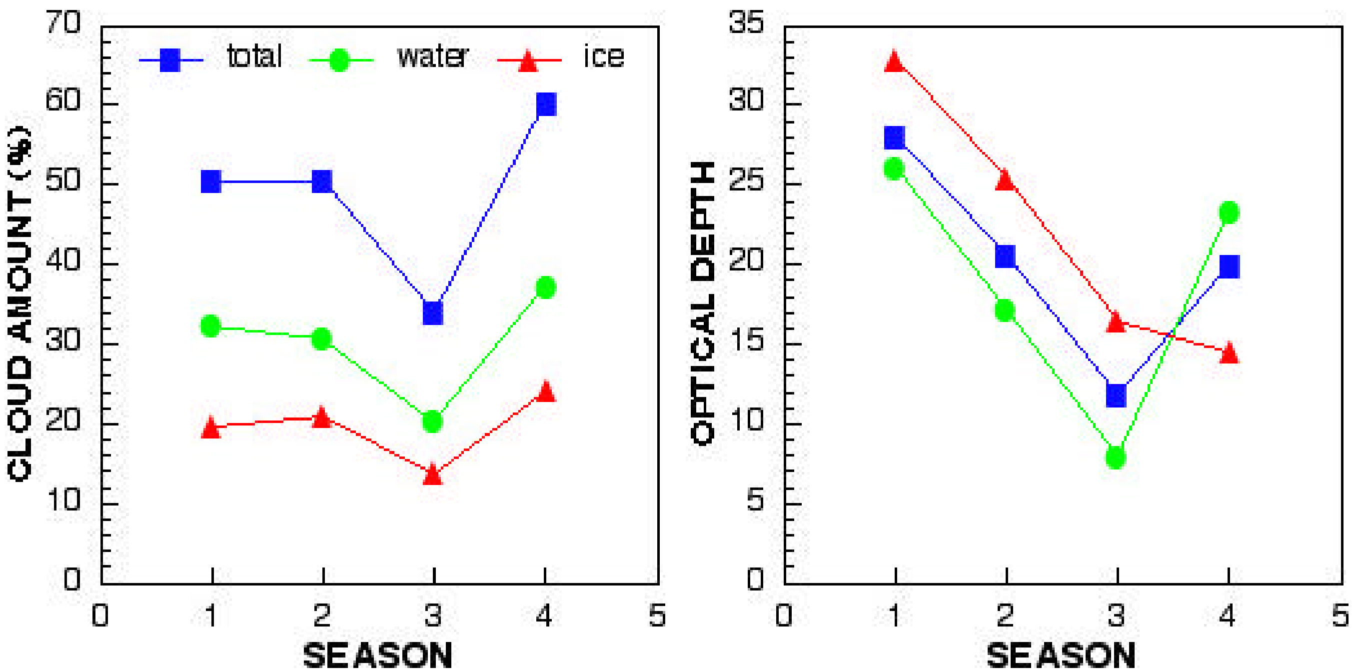

Figure 5. Mean seasonal cloud amounts and optical depths over the SGP CF from GOES-8, 1998.

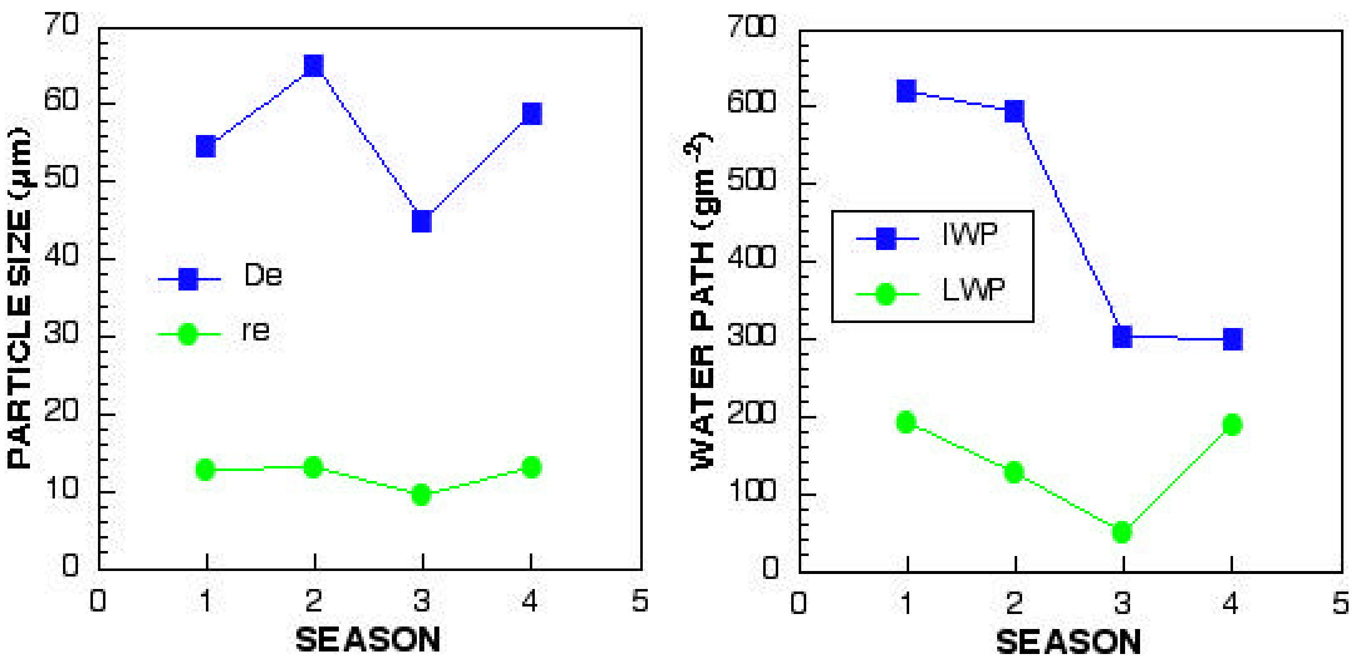

Figure 6. Same as Figure 5, except for cloud particle size and water path.

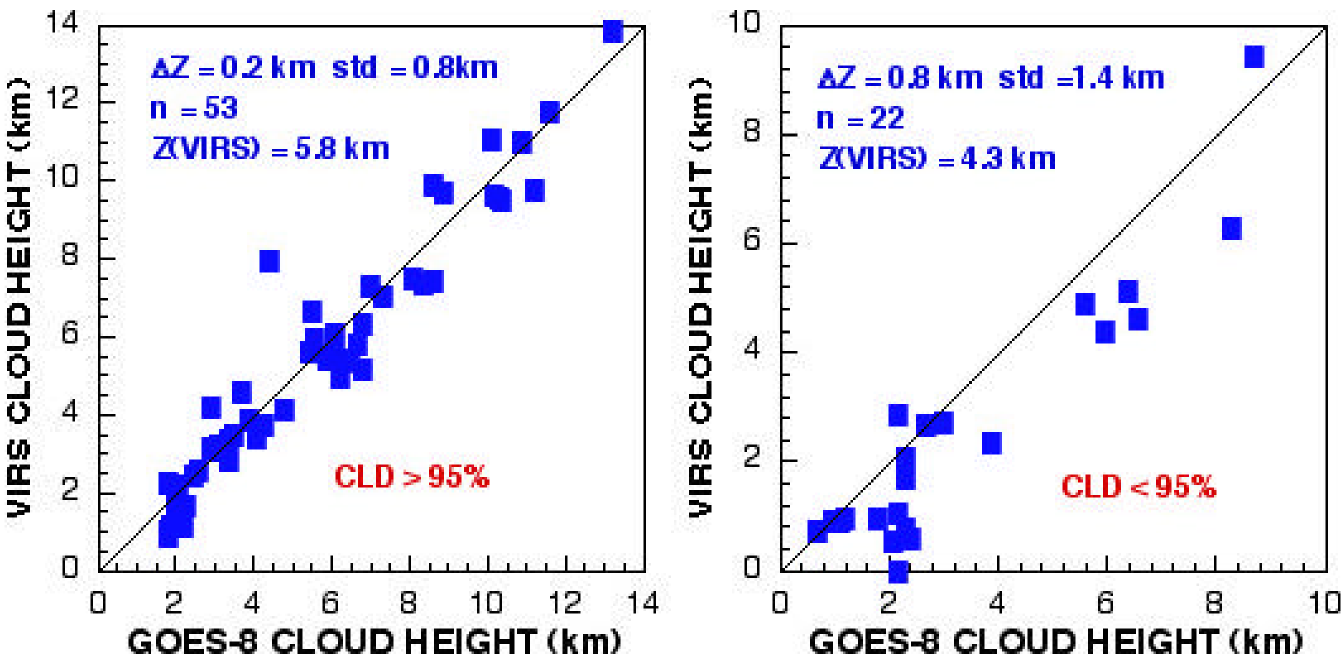

Figure 7. Comparison of daytime GOES-8 and VIRS-derived cloud heights during 1998 over the CF.

The VIRS ODs are slightly larger than those from GOES for all clouds, but are the same, on average, for ice-free clouds (Figure 8). The standard deviation for the pure ice clouds is only 20 percent compared to 67 percent for pure ice clouds. The mean VIRS ice cloud OD is 3.5 greater than its GOES counterpart, corresponding to a bias of ~16 percent. This difference is not particularly significant since there are only 17 samples. Removal of the most extreme sample reduces the bias to 0.6 or 3 percent. The mean difference for all cases is 1.5 or 10 percent with a standard deviation of 50 percent. These large differences for ice clouds may be indicative of discrepancies between the model crystal optical properties and the actual cirrus particles or they may be due to some errors in the parameterization of cloud reflectance as discussed later.

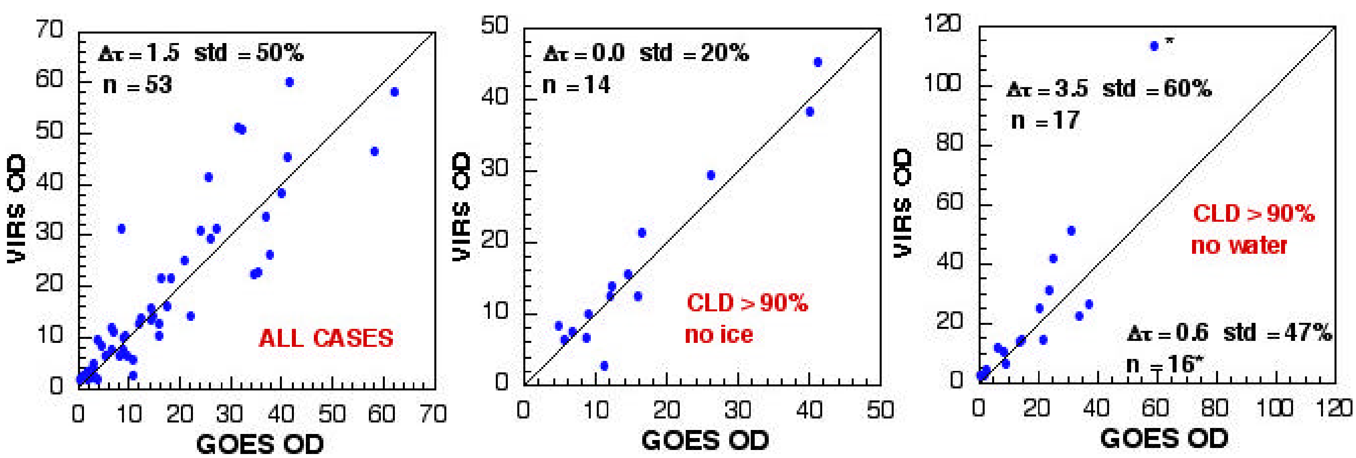

Figure 8. Comparison of daytime optical depths from GOES-8 and VIRS over the CF during 1998.

Cloud water droplet r_e values are compared in Figure 9 for all water clouds and for those that are nearly overcast and ice free. The mean difference in r_e is the same for both cases with GOES yielding droplets that are 1.2 μm larger than those from VIRS. However, the mean droplet size for the ice-free cases is more than a third smaller than for all water cloud cases. The discrepancies are most likely due to ice contamination or the impact of partly cloudy pixels that will yield an overestimate of r_e when the pixel is assumed to be overcast. The ice clouds seem to be less influenced by water droplet contamination (Figure 10) because the mean value of D_e is the same for both water-free and all cases. The lack of water clouds in the box, however, does not necessarily exclude the occurrence of overlapping ice and water clouds if the ice cloud covers the entire box. Thus, some of the ice crystal size retrievals may be affected by underlying water clouds. The mean value of D_e, 56 μm, is nearly identical to the near-global average from VIRS, but is less than that found by Kawamoto et al. (2001) for non-overlapped cases. Figure 10 shows that the range of D_e decreases when the possibility of water-cloud contamination is reduced.

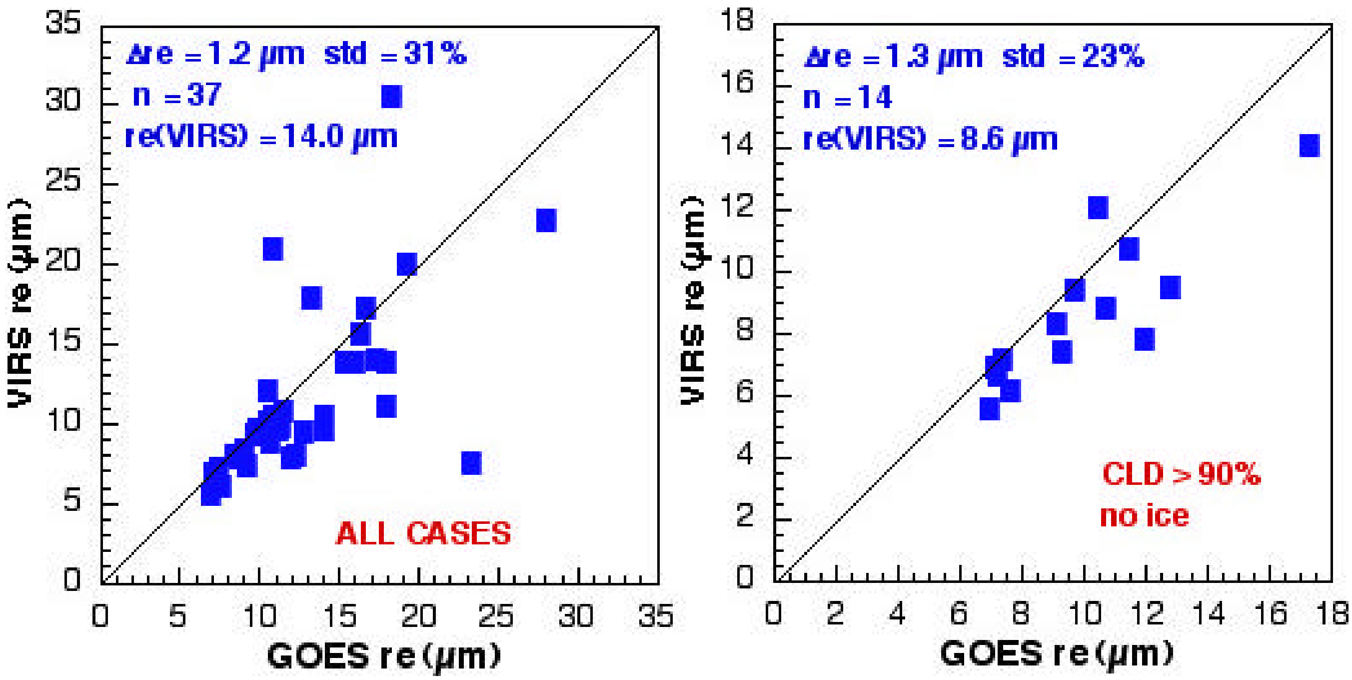

Figure 9. Same as Figure 8, except for cloud droplet r_e.

A closer examination of the VIS reflectance parameterization used to retrieve cloud optical depth and particle size from the VIS and SI data revealed angle-dependent errors relative to complete detailed radiative transfer computations. Although the rms errors in the parameterized reflectances are ~5 percent, the sign of the errors changes with VZA and SZA. Such errors also introduce even greater uncertainties in the derived ODs. Thus, the large variances and, perhaps, the mean OD differences in Figure 8 may be, in large part due to the parameterization, especially the outlier point for the ice cases. Nevertheless, the general agreement is good for the GOES and VIRS comparisons. A new parameterization has been developed that eliminates the angular dependencies and has an overall rms error of less than 1 percent relative to the complete radiative transfer results for a full range of surface albedos and cloud types and heights.

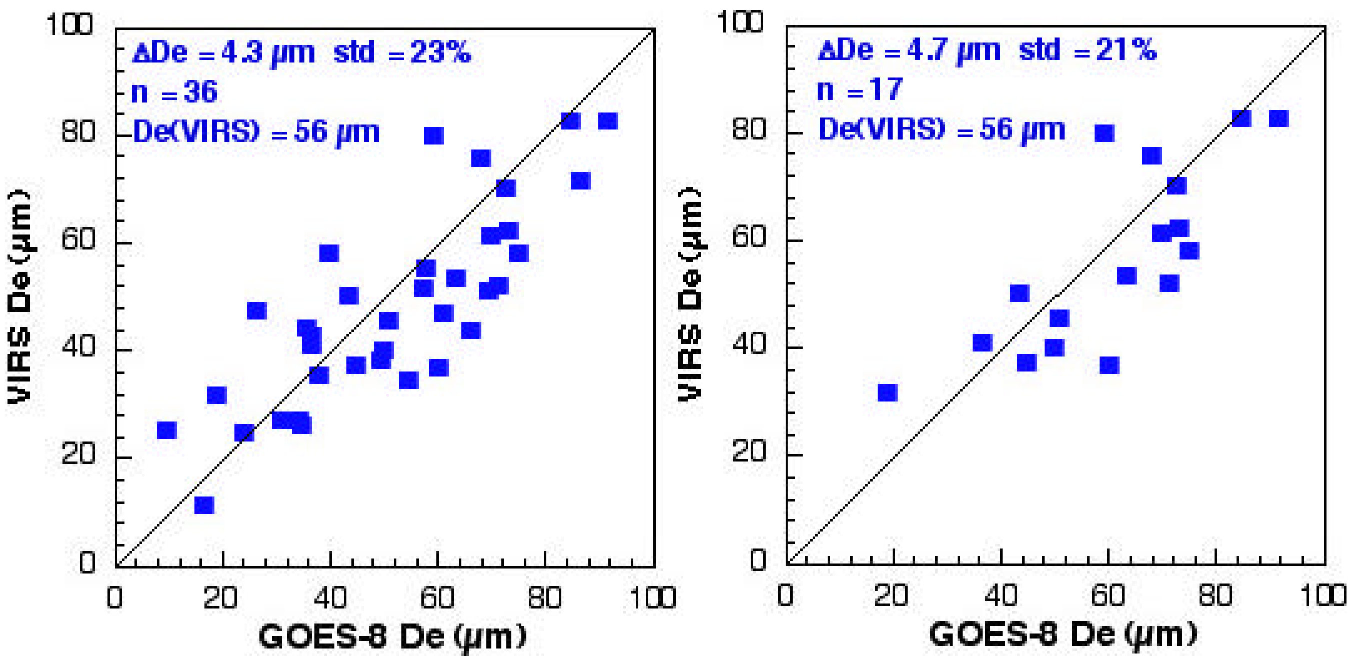

Figure 10. Same as Figure 8, except for cloud ice crystal effective diameter. All cases (left), ice only (right).

Concluding Remarks

Preliminary results of an analysis of cloud micro- and macrophysical properties over the SGP have been presented for a cloud IOP and for 1 year of GOES data. Although some viewing zenith angle effects are expected, especially for cloud amount, these results are consistent with similar retrievals from another satellite viewing the same area from other angles. Many of the inconsistencies are due to differences between the soundings used for the two satellites and to errors in the retrieval models. The effect of the soundings on cloud heights will be examined to determine if one set of temperature profiles is better than another for defining cloud height. Development of a multi-layer cloud detection algorithm will continue as the effects of overlapped clouds on the derived cloud properties are significant. Additionally, the analyses will be performed again using a new parameterization of cloud reflectance that should eliminate any model-induced angle dependencies. The resulting dataset should be valuable for studies relating surface and TOA radiation over the SGP and for cloud process modeling.

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