2.7 SEASONAL AND DIURNAL VARIATIONS OF CLOUD PROPERTIES DERIVED FOR CERES FROM VIRS AND MODIS DATA

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1. INTRODUCTION

Cloud optical and physical properties are essential for linking the hydrological cycle with the Earth's radiation budget (ERB). Simultaneous measurements of cloud properties and broadband radiative fluxes provide the empirical basis for accurate modeling of both processes in climate models. The Clouds and Earth's Radiant Energy System (CERES) project is designed to provide such measurements by matching very consistent cloud properties with radiation budget data for several different satellites. CERES is currently using two multispectral imagers, the Visible Infrared Scanner (VIRS) on the Tropical Rainfall Measuring Mission (*TRMM*) satellite and the Moderate Resolution Imaging Spectroradiometer (MODIS) on *Terra*, to remotely sense a wide range of cloud properties on a global basis at different times of day coincident with the CERES broadband flux data. These cloud properties have already been used to develop a host of new models that characterize the anisotropy of the radiation field exiting the Earth leading to improved estimates of the ERB from radiance measurements like those from CERES (Loeb et al. 2002; Gambheer et al. 2002). They will also be valuable for relating the hydrological cycle and the ERB and for improving climate model processes. This paper presents the results from the analysis of VIRS data and compares the VIRS and initial MODIS results to determine the consistency of the cloud products.

2. DATA & METHODOLOGY

The *TRMM*, launched during late 1997, continues to provide coverage at all local hours between 37°N and 37°S over a period of 46 days, while *Terra*, operating since Spring 2000, has a 1030 LT equatorial crossing time providing twice-per-day coverage in the Tropics and midlatitudes and higher temporal sampling in polar regions. Minnis et al. (2002) found that the VIRS calibrations were steady during the first 4 years of operation, except for the 1.6-µm channel gain, which appears to be degrading. The MODIS thermal channel brightness temperatures were all within $\pm$ 0.7 K of their VIRS counterparts and the MODIS VIS reflectance was 3% greater (less) than the corresponding VIRS reflectance at the high (low) end of the range. Each 2-km VIRS or 1-km MODIS pixel is first classified as clear or cloudy using updated versions of the pixel classification schemes outlined by Trepte et al. (1999) and Trepte et al. (2001) that rely on the radiances taken at 0.64 (visible), 1.6 (near infrared), 3.7 (solar infrared), 11 (infrared), and 12 (split window) µm. Cloud temperature T_c, height z_c, phase, effective droplet radius r_e or effective ice crystal diameter D_e, optical depth τ, and water path *WP* are derived from these same radiances using one of three methods. The visible infrared solar-infrared split-window technique (VISST), an updated version of the 3-channel daytime method described by Minnis et al. (1995), is used during daytime, defined as the time when the solar zenith angle *SZA* is less than 82°. At night, the solar-infrared infrared split-window technique (SIST) is used to determine all of the parameters. The SIST, an improved version of the 3-channel nighttime method described by Minnis et al. (1995), uses thermal infrared data only. Thus, its retrievals are valid only for optically thin clouds. For clouds with $\tau < 8$ at night, default values are used for all parameters except phase, T_c, and z_c. The third method, the solar-infrared infrared near-infrared technique (SINT), was adapted from the method described by Platnick et al. (2001) and is only applied to MODIS data during the daytime for clouds over snow or ice backgrounds. The determination of the background surface as snow or ice can either come from the scene classification for adjacent clear pixels or from the snow and ice maps used in the CERES data stream. All of the methods compute ice and liquid water solutions that simultaneously determine T_c, τ, and particle size by matching the observed radiances to emittance and reflectance parameterizations that account for atmospheric attenuation and surface reflectance and emission. The cloud reflectances and emittances are included in the parameterizations using updated lookup tables for each specific channel (Minnis et al. 1998).

The pixel-level data are convolved into the footprint (10-20 km) of each CERES radiance to provide the link between clouds and the radiation budget. These single-scanner footprint (SSF) products include the cloud fraction and mean associated properties for up to two cloud layers. Edition-2 VIRS cloud products are available for January 1998 - August 2001. Production of CERES Edition-1 MODIS cloud properties has just begun. Analysis of both VIRS and MODIS data is proceeding to provide a continuous long-term record.

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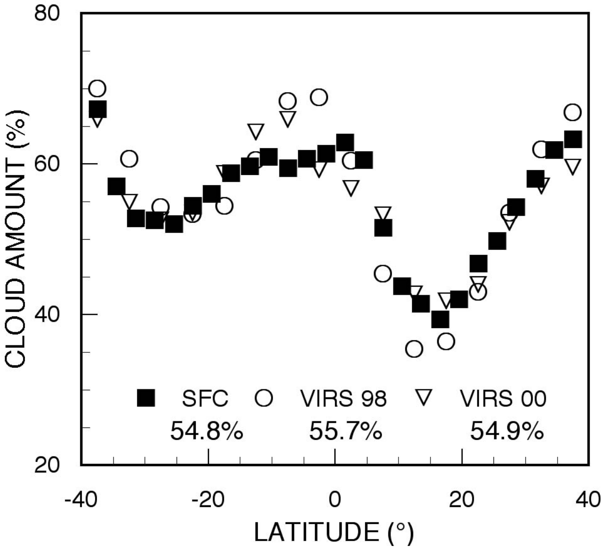

Fig. 1. Mean March cloud amounts from surface observations (1971-1996) and VIRS (1998 and 2000).

3. VALIDATION & CONSISTENCY

A variety of methods are being used to verify the results including climatology, surface data, and other satellite observations. The mean zonal cloud amounts from VIRS for March 1998 and 2000 and from surface observations taken between 1971 and 1996 (Hahn et al. 1999) in Fig. 1 agree well in magnitude and distribution. Exceptions include the southern equatorial belt where VIRS detects more clouds and the northern subtropics where fewer clouds are detected by VIRS during the 1998 El Nino. These same areas are sparsely sampled at the surface relative to the other zones. The results in Fig. 1 are typical for the other months. The VIRS-derived mean cloud amounts follow the same trends, but are typically 7-8% less than those from the 1984-1991 International Satellite Cloud Climatology Project (ISCCP; Rossow and Schiffer, 1999) D2 dataset.

The VIRS-derived cloud products were also compared with similar quantities retrieved from simultaneous surface-based radar, lidar, and radiometer measurements at the Atmospheric Radiation Measurement (ARM) site in Oklahoma. Dong et al. (2002) found that, for 25 stratus cloud cases, the instantaneous VIRS-derived values of τ, r_e, and liquid WP (LWP)are within -2% $\pm$ 21%, 6% $\pm$ 20%, and 16% $\pm$ 35% of the surface-based averages during daytime. The effective cloud heights from VIRS nearly always fell within the cloud boundaries determined from the radar for all cloud types. On average during daytime, for optically thin clouds (τ < 5), z_c is 1.1 km below the center height of the cloud, but above the base height. For thicker clouds, z_c is 0.4 km above (below) the cloud center (top). For some low-level stratus, z_c is greater than the cloud top because the boundary-layer inversion was not resolved in the temperature profiles. At night, z_c is 0.7 km (0.5 km) above (below) the cloud center (top) for thin clouds and 1.6 km (0.4 km) above (below) the cloud center (top) for thick clouds. No more than 41 (49) samples were available for any of the daytime (night) height comparisons. Initial comparison of the LWP derived from the *TRMM* Microwave Imager for Jan. - Aug. 1998 indicates that, on average for warm overcast clouds over ocean, the VIRS-derived LWP is only 2% less than the microwave-based retrievals. Examination of the cirrus properties is underway.

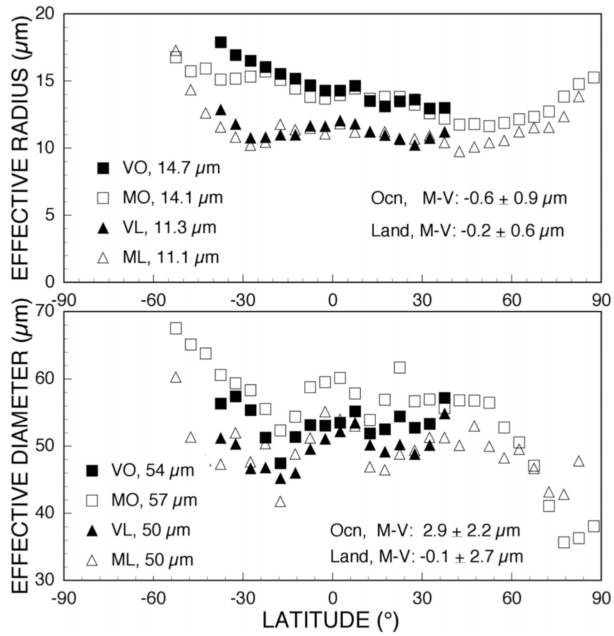

Fig. 2. Mean effective cloud particle sizes for VIRS (June 2001) and MODIS (week 1, June 2001). VIRS (V), MODIS (M), ocean (O), land (L).

CERES analyzes all cloudy pixels. In 3% of the cases, cloud properties cannot be retrieved because the no match can be found between the modeled and observed radiances. Some of those pixels are reclassified as clear. The remainder are not included in the SSF convolution. Such pixels cannot be processed for a variety of reasons relating to errors in clear-sky radiances, 3-D cloud structure, partially filled pixels, and errors in the parameterizations. Other errors not assessed in the comparisons between the surface and satellite data include those due to overlapped and broken clouds. Thin cirrus over low-level water clouds will often cause an underestimate of the cirrus altitude. If identified as ice (τ of upper-level cloud likely to exceed 2), such pixels will likely yield an underestimate of D_e and τ and an overestimate of WP. If identified as a water cloud, r_e, τ, and WP will be overestimated (Kawamoto et al. 2002). Pixels with only partial cloud fraction tend to underestimate τ and overestimate r_e.

To measure the consistency between the CERES VIRS and MODIS retrievals, zonal means were computed for each parameter for June 2001. Only 1 week of CERES MODIS results were available for this comparison. Figure 2 plots the zonal mean effective cloud particle sizes from the two instruments and shows the averages for ice and water clouds over land and water separately. Effective radii from MODIS are roughly 0.5-µm smaller than their VIRS counterparts. The mean values of D_e are the same over land, but D_e from MODIS is 4-µm larger than that from VIRS over

Table 1. Mean difference between MODIS and VIRS zonal averages for June 2001. Only 1 week of MODIS data used.

Parameter	Ocean	Land
cloud amount (%)	-2.0	-0.6
z_c, ice (km)	0.3	0.3
z_c, water (km)	0.2	0.4
τ, ice	1.4 $\pm$ 2.2	0.4 $\pm$ 5.5
τ, water	-0.2 $\pm$ 1.5	0.4 $\pm$ 2.8
LWP (gm^{-2})	-0.11	3.1
IWP (gm^{-2})	40	19

ocean. The values of r_e are generally larger than those reported from earlier studies, however, these results include all water clouds. Removal of overlapped and broken clouds would reduce the derived values of r_e by 0.5 to 2.0 µm. Table 1 summarizes the differences between VIRS and MODIS for many of the remaining parameters. In general, these results are very consistent. Some of the outstanding differences may be due to the different time sampling because VIRS samples all times of day while MODIS only measures during late morning. Other differences may arise from discrepancies in the angular sampling by each instrument (e.g., Heck et al. 2002) or from spectral and calibration differences not taken into account by the retrievals.

4. RESULTS

Zonal means were computed for each parameter and season using VIRS results from 1998-2001. The seasonal variation of liquid and ice water cloud fractions are shown in Fig. 3. Over ocean, the liquid water clouds oscillate seasonally with a range between 0.05 and 0.12. Greatest values in the northern hemisphere (NH) occur during winter and spring and, in the southern hemisphere (SH), more clouds are detected during the boreal summer and fall. The seasonal changes in liquid clouds over land are less significant. Seasonal variations in ice cloud coverage are more striking because of the shifts in midlatitude storm tracks and in the tropical convergence zones. Ice clouds are observed least often over land and ocean at 15°S during the boreal summer, while the opposite is true at 15°N. Ice clouds account for about half of the clouds over land and for only about one third of the cloud cover over ocean. The mean cloud heights (Fig. 4) also vary seasonally. Over ocean, mean water cloud heights vary by only 0.1 to 1.0 km, while the ice cloud altitudes change by up to 2 km during the year. The seasonal changes are most dramatic in the midlatitudes where z_c varies with the tropopause height. Over land, mean z_c can vary by almost 2 km (at 15°S) for water clouds and by nearly 3 km for ice clouds. Little change is evident in the equatorial ice cloud heights.

The variations in cloud microphysics are less regular than those for the cloud macrophysical properties. Maritime liquid cloud optical depths (Fig. 5) peak during the boreal winter in the NH and SH, except for latitudes

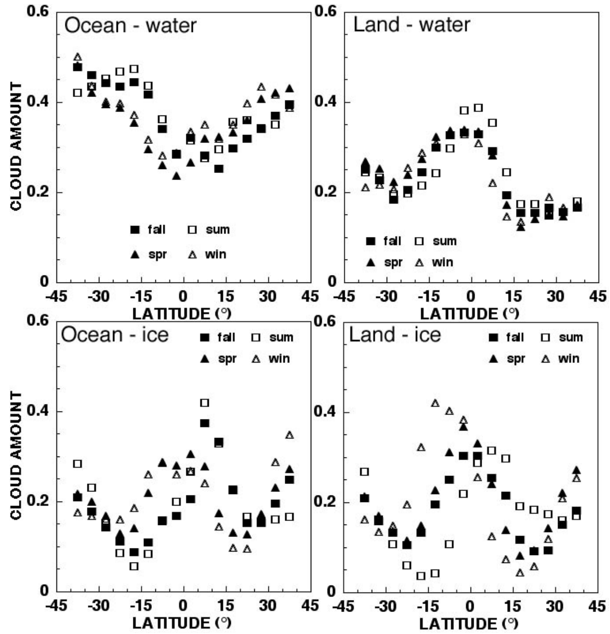

Fig. 3. Mean cloud fraction by phase for 1998-2001.

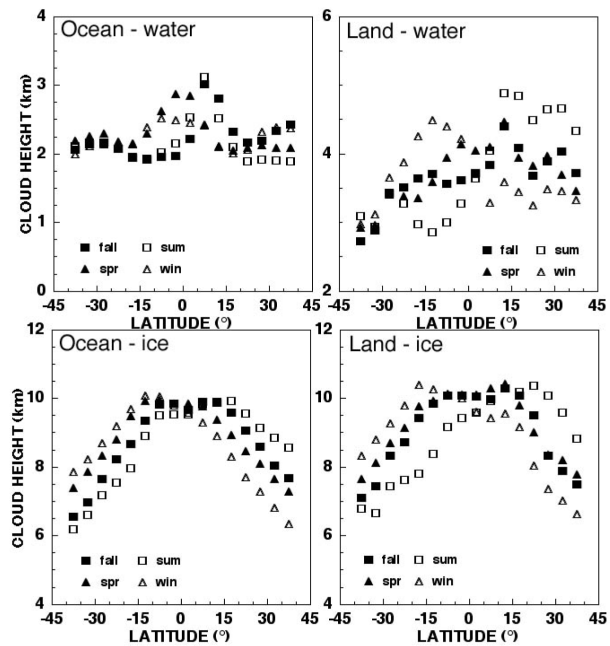

Fig. 4. Mean cloud height by phase for 1998-2001.

south of 30°S. Over land, τ for liquid water clouds reaches a maximum during winter in the NH and during summer for the SH. The seasonal variation in τ is considerably greater in the NH than in SH over both ocean and land areas. Ice cloud optical depths also vary more with season over NH ocean regions than their SH counterparts (not shown). Seasonal changes in mean τ for ice clouds over land are similar over both hemispheres.

Cloud droplet sizes also change with the seasons. Over ocean, r_e varies by up to 4 µm, on average, during the year over zones in the SH (Fig. 6). The smallest SH ocean values occur during the boreal summer when air

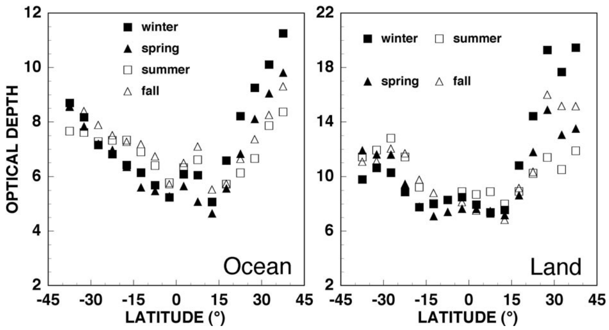

Fig. 5. Zonal mean liquid cloud optical depth, 1998-2001.

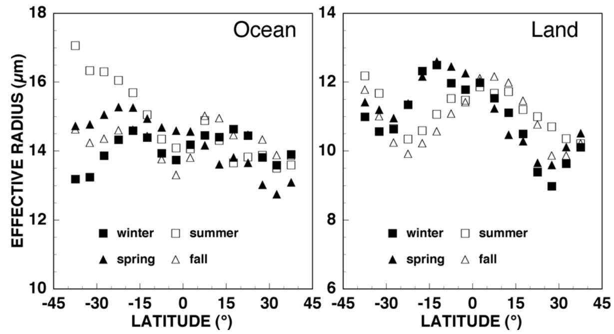

Fig. 6. Zonal mean effective droplet radius, 1998-2001.

from polar regions is more likely to influence the SH boundary layer clouds. Droplet radius varies by 1 μm or less north of 15°S over ocean. Over land, the variation in r_e is more regular with a winter-spring minimum at 25°N and a summer-fall minimum at 25°S. Droplet radius is smaller on average over the NH than over the SH and is larger over ocean (14.3 μm) than over land (11.0 μm). Mean ice crystal size (not shown) varies seasonally over oceans by up to 5 μm in a given zone between 20°S and 15°N, but changes minimally poleward of 25° latitude. More variability occurs over land areas. On average, D_e is smaller over land (50 μm) than over ocean (54 μm).

5. CONCLUDING REMARKS

The comparisons with independent data indicate that the cloud property data being retrieved from VIRS and MODIS for CERES are, so far, quite reasonable in terms of accuracy and are consistent from one satellite to the other. Validation studies are continuing so that the uncertainties in this unique dataset can be determined for all cloud types and conditions. Because of the VIRS sampling pattern, diurnal and angular biases affecting the seasonal variations are minimized for the zone from 37°N - 37 °S. When combined with retrievals from MODIS, the CERES data will provide a unprecedented global picture of clouds and radiation.

The results of these analyses should be valuable for studying the variation of clouds and radiation at many different spatial and temporal scales over the globe. The VIRS data are currently available for studies of cloud processes, climatology, and aerosol-cloud interactions. The MODIS results will become available during July 2002.

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