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On the Satellite Determination of Multilayered Multiphase Cloud Properties

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ABSTRACT

Conventional single-layer cloud assumptions lead to erroneous results in satellite retrieved cloud properties for multilayered multiphase cloud systems. The Cloud and Earth's Radiant Energy System (CERES) project strives to develop an exploratory multilayer cloud data product using the Moderate-resolution Imaging Spectro-radiometer (MODIS) data. The new MODIS multilayer cloud products will be available in the upcoming CERES Edition 3 version to provide cloud overlap information and retrieved upper- and lower-layer cloud properties that often consist of upper-ice and lower-water clouds. In this study, we present some preliminary comparisons of the multilayer cloud data between the CERES MODIS Edition-3 Beta version and two active sensing data from the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) (Winker et al. 2007) and the CloudSat (Stephens and Kummerow 2007).

1. INTRODUCTION

Clouds play a dominant role in Earth's climate and its change through their primary influences on the radiant energy and water cycle. Global climate and weather prediction models simulate cloud fractions and cloud water and ice contents at various horizontal and vertical levels. Different cloud parameterization and overlap schemes produce considerable variations in the model-simulated cloud feedback and climate sensitivity. Improved understanding and representation of cloud processes in climate models requires accurate long term satellite remote sensing of global cloud properties.

While operational satellites can provide a wealth of cloud property information on a large scale, most passive satellite cloud retrieval techniques have been designed for single-layered cloud systems. These methods are based on the interpretation of radiation reflected or emitted by clouds in different spectral channels. The application of these approaches to multilayer cloud conditions leads to erroneous results. For this reason, the CERES new Edition 3 version of cloud product has been developed using the MODIS data, which strives to identify multilayer clouds as well as to retrieve their properties, especially for an upper-level ice-phase cloud overlapping a lower-level water-phase cloud (Minnis et. al. 2010a). In this study, we investigate the multilayer cloud product from the CERES Edition 3 Beta version, a preliminary version, and compare the CERES multilayered multiphase cloud product to two active remote sensing products from the CALIPSO lidar (Winker et al. 2007) and the CloudSat radar (Stephens and Kummerow 2007).

CALIPSO and CloudSat are two experimental satellite active sensors launched by NASA in 2006 to provide the first satellite measurement of cloud vertical structure. While the two active sensors are ideal for accurately determining the vertical profile of clouds, the data are quite limited temporally or spatially due to their non-scanning, nadir-viewing only observations. Until the active sensing of clouds can overcome the challenges of providing large spatial scale and high temporal resolution of observations, it is necessary to develop and test new techniques for unscrambling the passively sensed radiances to retrieve more accurate cloud properties for both the single-layered and multilayer clouds.

2. THREE DIFFERENT MULTILAYER CLOUD DATA

This study uses 1 month, April 2007, of collocated and coincident Aqua MODIS, CALIPSO, and CloudSat data to compare the various satellite-determined multilayered, multiphase cloud properties. The three different satellite data products are briefly described below.

2.1 CERES MODIS Edition 3

The 1-km MODIS data matched with the CALIPSO and CloudSat footprints are used to retrieve single- and multi-layered cloud properties for the CERES project (Minnis et al. 2010a). The CERES Edition 2 cloud properties are retrieved by assuming single-layered clouds and, therefore, provide the cloud bulk properties, such as total optical depth, ice or liquid water path, and the effective cloud top properties, such as effective temperature, pressure, height and ice-crystal or water-droplet effective radius. However, the CERES Edition 3 products are designated to provide both the standard single-layered cloud properties and the exploratory multilayer cloud properties.

The CERES multilayer cloud retrieval algorithm uses a sequence of techniques to both detect and retrieve an overlapped cloud condition within every MODIS pixel. Figure 1 illustrates the sequence of the CERES MODIS multilayer cloud algorithm. Step 1 is to determine the presence of an upper tropospheric cloud layer above the 500-hPa level. The step is determined by applying the

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modified CO2 absorption technique (MCO2AT) as described in Chang et al. (2010a, b). If an upper tropospheric cloud above 500 hPa is retrieved, its cloud optical depth, Tau(MCO2AT), is inferred from the infrared radiative transfer calculations. If no cloud above 500 hPa is retrieved, no multilayer cloud is processed.

Step 2 is to determine the bulk cloud properties for the total atmospheric column by applying the Visible-Infrared-Solar-infrared-Split-window Technique (VISST) as described in Minnis et al. (2010b, c). In Step 2, the VISST-retrieved total-column cloud optical depth, Tau(VISST), is compared with the upper-layer Tau(MCO2AT) derived in Step 1 to determine the presence of overlapped upper and lower clouds. If the Tau(VISST) is significantly larger than Tau(MCO2AT), an overlap cloud is determined; otherwise, no overlap cloud is processed and the pixel is retrieved with single-layer properties.

Once cloud overlapping is determined, Step 3 retrieves separately the upper- and lower-layer cloud properties, such as temperature, pressure, height, emissivity, optical depth, and effective ice crystal or water droplet radius. This step is achieved by applying a technique similar to that described in Chang and Li (2005a, b). Figure 2 illustrates a CERES multilayer cloud retrieval case obtained on July 15, 2006, 15:45Z. Figure 2a shows the false-color RGB image; Figure 2b shows the MCO2AT retrieved upper-level cloud top heights (CTHs); and Figure 2c shows the CERES identified single-layer and multilayer cloud mask. In Fig. 2c, the magenta indicates confident multilayer clouds while the orange and red both indicate weak multilayer clouds but possible multiphase clouds.

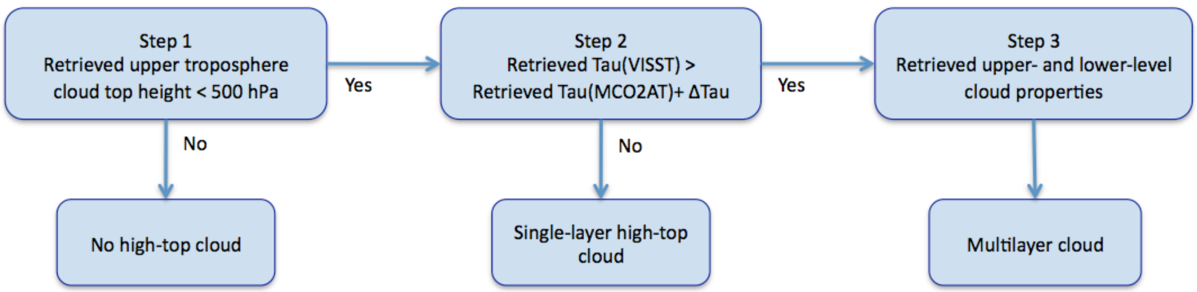

Figure 1. Schematic diagram for illustrating the CERES MODIS Edition 3 multilayer cloud retrieval algorithm.

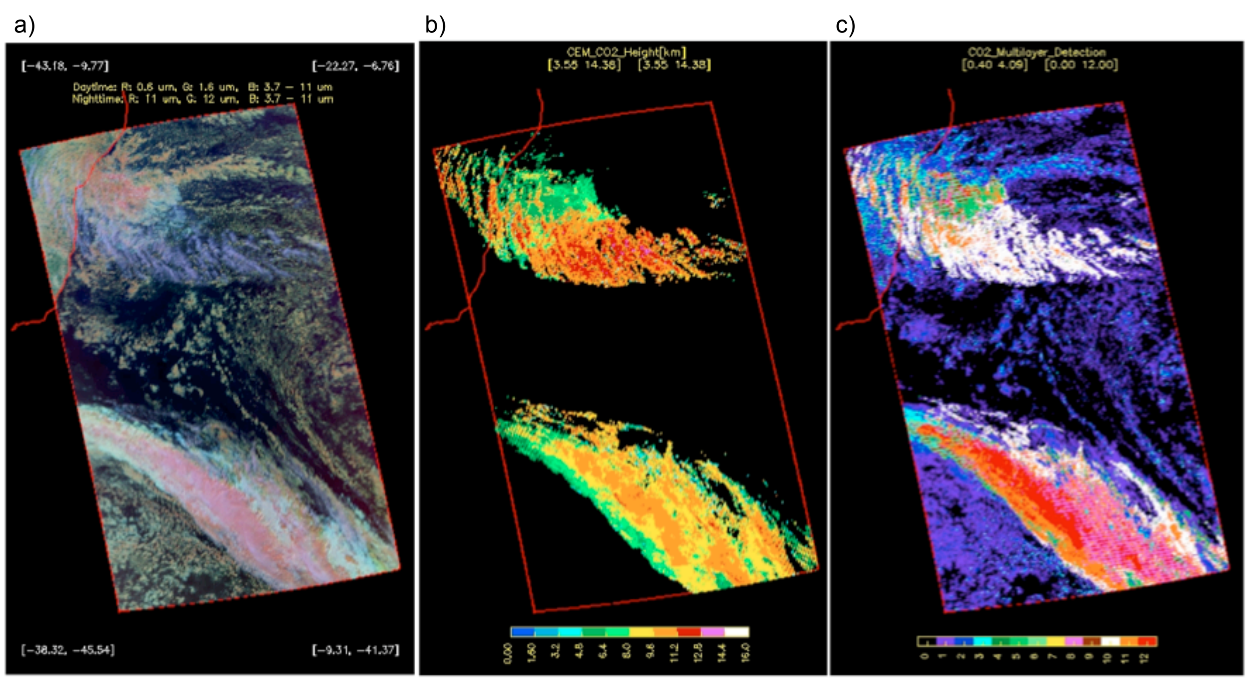

Figure 2. Illustrations of CERES MODIS Edition-3 multilayer cloud retrievals. a) MODIS RGB image, b) MCO2AT-retrieved upper-troposphere CTHs (km) and c) CERES single-layer and multilayer cloud identification mask. Magenta: confident overlapped clouds, orange and red: weak overlapped, possible multiphase clouds.

2.2 CALIPSO

The CALIPSO satellite data provide cloud vertical feature mask (VFM) products that are measured by the Cloud Aerosol Lidar with Orthogonal Polarization (CALIOP; Winker et al. 2007). The CALIOP is a nadir-pointing instrument that samples every 330 m with a spatial resolution or footprint of about 70 m. Vertical resolution of the VFM products is 60 m above and 30 m below the altitude of 8.2 km. The CALIOP data are only available around 0130 and 1330 LT at different locations each day. The instrument has 532 and 1064-nm lidars to profile the backscattering by clouds and aerosols and provide cloud top and bottom height information for each detected layer until the lidar beam is attenuated. The CALIPSO VFM version 2 products are used in this study.

2.3 CloudSat

The CloudSat satellite data provide cloud vertical mask products that are measured by the Cloud Profiling Radar (CPR). The CPR is a 94-GHz nadir-viewing radar, which measures the power backscattered by cloud hydrometeor particles as a function of distance from the radar. This study uses the 2B-CLDCLASS products, which have a uniform vertical resolution of 240 km. The horizontal resolutions in the cross-track and along-track directions are 1.4 and 1.8 km, respectively.

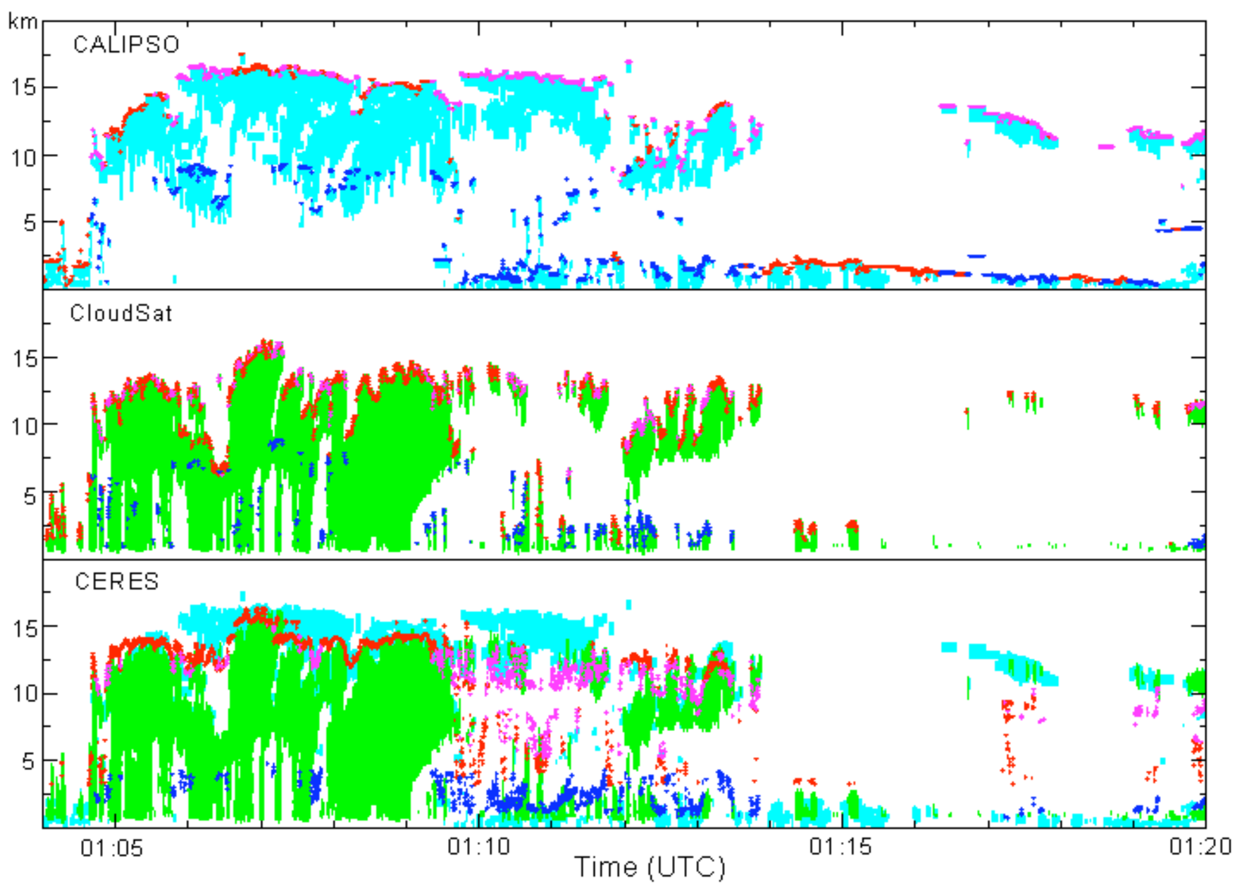

Figure 3. Comparisons of multilayer clouds and their upper- (magenta points) and lower-level (blue points) CTHs determined from the CALIPSO (cyan), CloudSat (green), and CERES MODIS (bottom panel) data.

3. RESULTS, DISCUSSIONS AND FUTURE WORK.

Figure 3 shows a case study for the three different multilayer cloud data and their corresponding upper-level and lower-level CTHs retrieved from the a) CALIPSO, b) CloudSat, and c) CERES MODIS data. The case is obtained from the Aqua A-Train satellites on 4 April 2007 over the tropical Pacific Ocean between 0105-0120 UTC. This typical case shows that CALIPSO retrieves significantly larger amounts of upper-tropospheric, optically thin cirrus clouds and that CloudSat is generally unable to detect such optically thin clouds. The upper-level CTHs from CloudSat are, thus, significantly lower than those from CALIPSO. On the other hand, the figure also shows that CALIPSO retrieves significantly smaller amounts of lower-tropospheric clouds when CloudSat is able to retrieve such clouds. These are due to the limitations of the CALIPSO lidar measurements that are saturated through a few cloud optical depths and the limitation of CloudSat radar measurements that are insensitive to optically thin clouds. The CERES MODIS retrieved upper- and lower-level CTHs appear to be closer to the CloudSat upper- and lower-level CTHs. However, the CERES MODIS data appear to have more cirrus retrievals than the CloudSat data, despite the CERES MODIS CTHs being lower than those from the CALIPSO.

Figures 4a-4c show preliminary comparisons of the upper-level high-top (< 500 hPa) cloud amounts retrieved from CALIPSO (4a), CloudSat (4b) and CERES MODIS (4c) during daytime for April 2007. Figures 4d-f show the multilayer cloud amounts retrieved from CALIPSO (4d), CloudSat (4e) and CERES MODIS (4f). It is found that upper-level high clouds and multilayer clouds occurred frequently on a global scale as revealed by the satellite observations. The occurrence frequencies of upper-level clouds are 44, 25 and 37% from CALIPSO, CloudSat and CERES MODIS, respectively, and the occurrences of multilayer clouds are 25, 4 and 8% from CALIPSO, CloudSat and CERES MODIS, respectively. CALIPSO data have the largest fractions of optically thin cirrus and multilayer clouds, whereas the CERES MODIS data have less and the CloudSat data have the smallest fractions among the three datasets.

For collocated multilayer clouds retrieved by both CALIPSO and CERES MODIS, Figures 5a-b show the distributions of upper-level CTHs retrieved by CALIPSO (5a) and CERES MODIS (5b) and Fig. 5c shows the scatter plot of CERES MODIS versus CALIPSO upper-level CTHs. Figures 5d-5e show the distributions of lower-level CTHs retrieved by CALIPSO (5d) and CERES MODIS (5e) and Fig. 5f shows the scatter plot of CERES MODIS versus CALIPSO lower-level CTHs. Likewise, Figures 6a-6f show the same comparisons as in Figures 5a-5f, except for collocated multilayer clouds retrieved by both CloudSat and CERES MODIS. The averaged upper-level CTHs were about 12.8, 10.9 and 10 km from CALIPSO, CloudSat and CERES MODIS, respectively. The averaged lower-level CTHs were about 3.6, 3.2, and 3.3 km for the CALIPSO, CloudSat and CERES MODIS, respectively. For upper-level CTHs, Figs. 5c and 6c show that the CERES MODIS CTHs are systematically lower than their CALIPSO and CloudSat counterparts by about 2.8 (5c) and 0.9 km (6c). For lower-level CTHs, Figs. 5f and 6f show that CERES MODIS values are biased high when lower-level CTHs < 2.5 km and biased low when lower-level CTHs > 2.5 km.

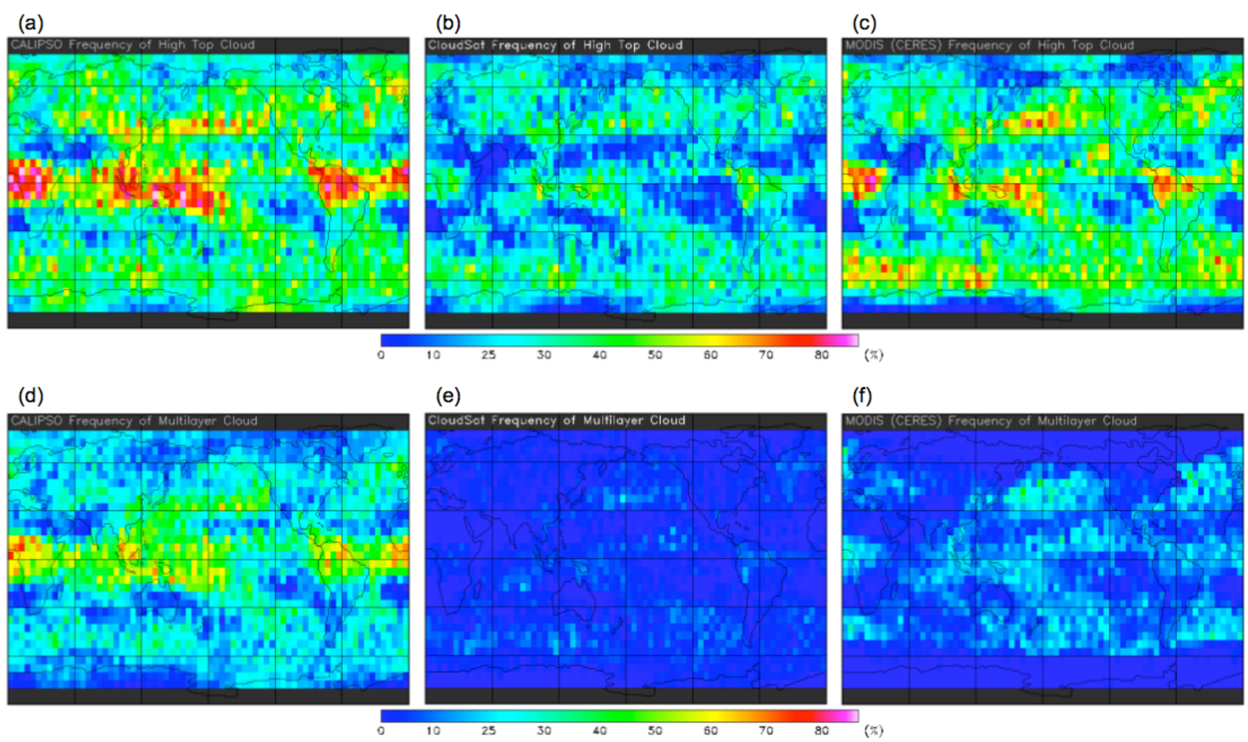

Figure 4. Occurrence frequencies of upper-level clouds (< 500 hPa) (a-c) and multilayer clouds (d-f) from collocated CALIPSO (a, d), CloudSat (b, e) and CERES MODIS (c, f) data. Results are obtained for April 2007.

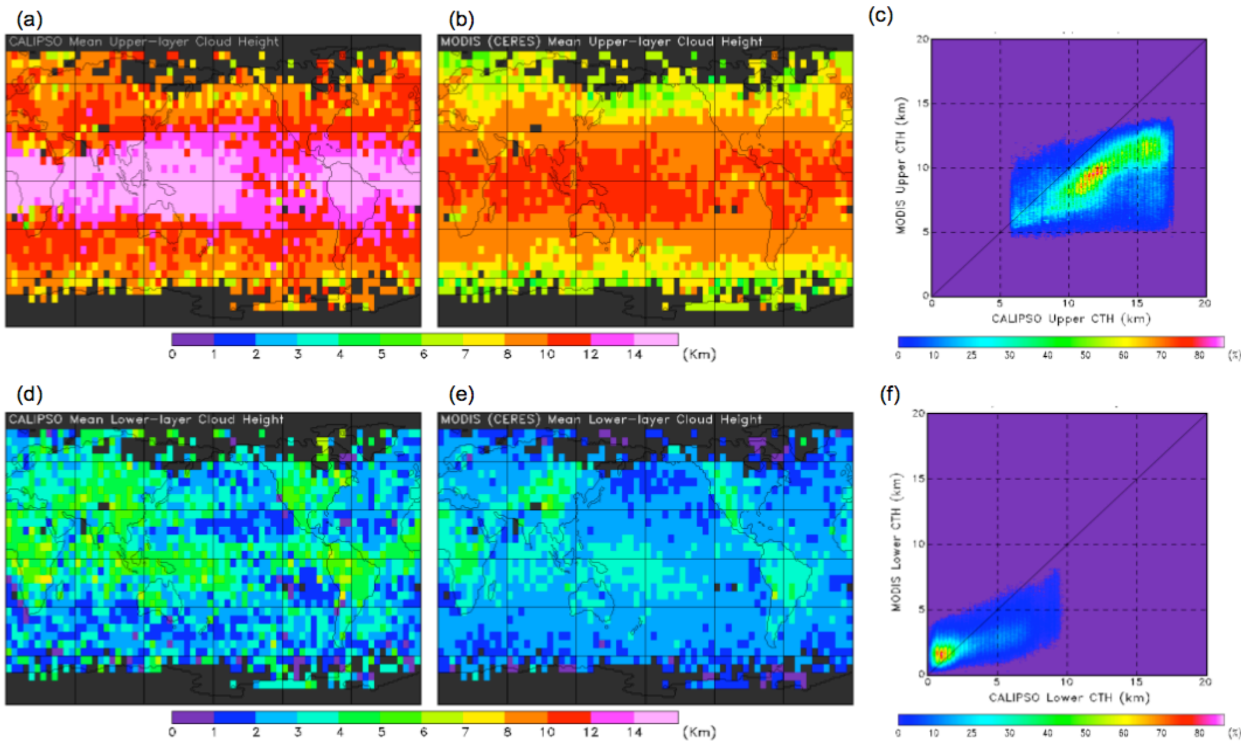

Figure 5. Distributions of upper-level (a, b) and lower-level (d, e) CTHs from collocated CALIPSO (a, d) and CERES MODIS (b, e) multilayer cloud data. Scatter plots (c, f) for the CTH comparisons of CERES MODIS versus CALIPSO data are shown in (c) for the upper-level CTHs from (a) and (b) and in (f) for the lower-level CTHs from (d) and (e).

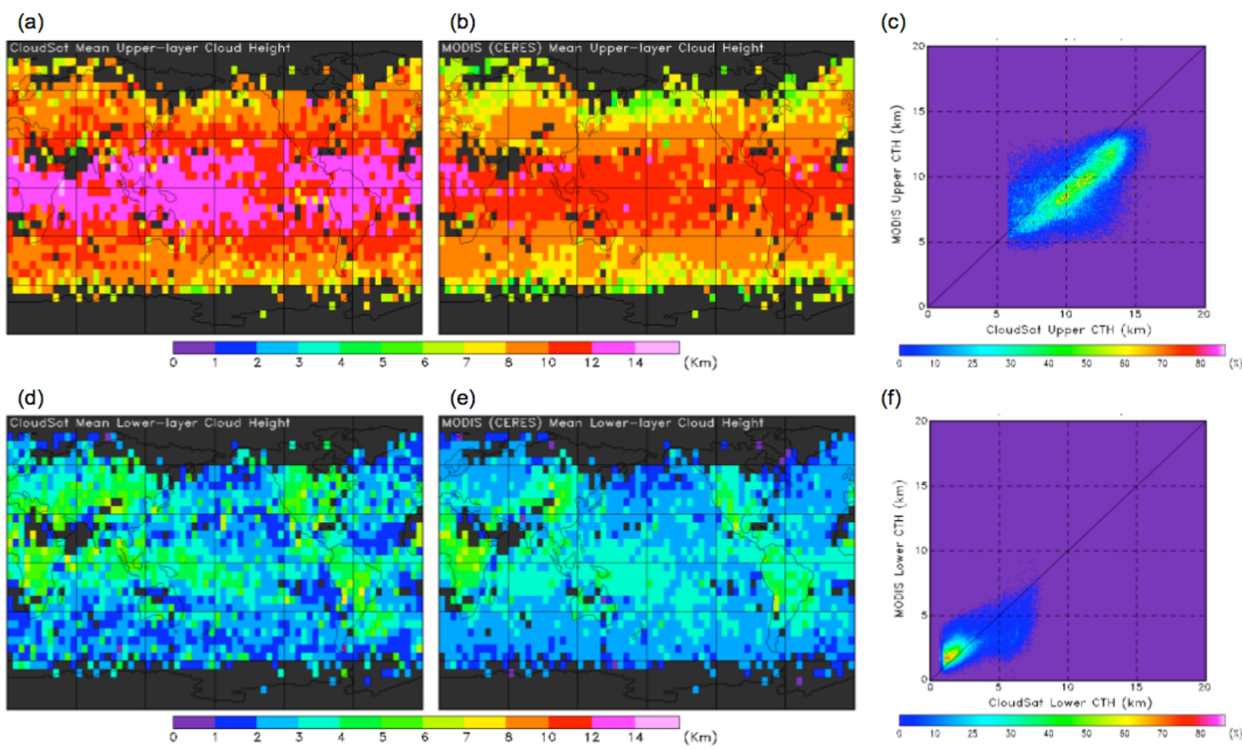

Figure 6. Same as in Fig. 5, except for the collocated CloudSat and CERES MODIS CTHs data.

Multilayer cloud systems in the tropics are primarily dominated by optically-thin cirrus clouds and optically-thicker lower-level water clouds. As a result, CloudSat systematically underestimates the upper-level thin cirrus clouds in the tropics. However, the CloudSat data reveal many multiphase clouds in mid- and high-latitude storm-track regions. Finally, Fig. 7 shows the distributions of multiphase clouds retrieved by CloudSat. To discriminate multilayer from single-layer clouds, Fig. 7a shows the occurrence frequencies of CloudSat multiphase clouds when CALIPSO retrieved multilayer clouds and likewise Fig. 7b shows the frequency of occurrences of CloudSat multiphase clouds when CALIPSO retrieved only single-layer clouds. On average, less than 10%, relatively, had CloudSat multiphase clouds when CALIPSO retrieved multilayer clouds whereas more than 30% of CloudSat multiphase clouds were found to have CALIPSO-retrieved single-layer clouds.

Based on the comparisons of upper-level thin cirrus and multilayer multiphase cloud properties retrieved from the passive sensing CERES MODIS data and active sensing CALIPSO and CloudSat data, more rigorous efforts for accurately retrieving more optically thin cirrus clouds and, therefore, retrieving more accurately multilayer and multiphase cloud properties are needed. The comparisons with collocated CALIPSO and CloudSat data performed in this study are helpful for improving the CERES MODIS multilayer cloud retrieval algorithms that are under enhancement and final testing by the CERES Cloud and Radiation Research Group in striving to provide the climate science community reliable CERES Edition 3 cloud and radiation products.

4. ACKNOWLEDGEMENTS

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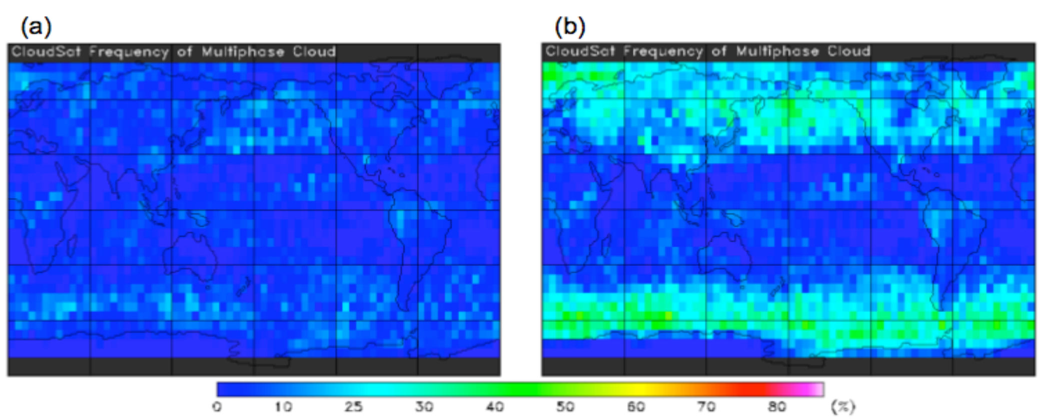

Figure 7. Occurrence frequencies of CloudSat retrieved multiphase clouds (a) when CALIPSO retrieved multilayer clouds and (b) when CALIPSO retrieved single-layer clouds.