JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, D16211, doi:10.1029/2007JD009481, 2008

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Global characterization of cirrus clouds using CALIPSO data

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Received 9 October 2007; revised 21 April 2008; accepted 12 May 2008; published 28 August 2008.

[1] A global and seasonal distribution of cirrus clouds is presented herein on the basis of measurements made by the lidar aboard the Earth-orbiting Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite launched in April 2006. The latitude-longitude and vertical distributions of occurrence frequency of cirrus clouds measured by CALIPSO from June 2006 to June 2007 are presented. The investigation of top-layer cirrus clouds shows maximum-occurrence frequency of up to 70% near the tropics over the 100°–180°E longitude band. The results show large latitudinal movement of cirrus cloud cover with the changing seasons. The examination of the vertical distribution of cirrus clouds shows the maximum of cirrus top-altitude occurrence frequency of approximately 11% at 16 km in the tropics. There are no significant differences in vertical distributions of occurrence frequency of cirrus clouds in the Northern and Southern hemispheric midlatitudes. At latitudes 20°N to 60°N, the maximum frequency of the cirrus top and base altitudes is about 5.1% at 11 and 8 km, respectively.

Citation: Nazaryan, H., M. P. McCormick, and W. P. Menzel (2008), Global characterization of cirrus clouds using CALIPSO data, *J. Geophys. Res.*, *113*, D16211, doi:10.1029/2007JD009481.

1. Introduction

[2] Cirrus clouds play a significant role in the energy budget of the earth-atmosphere system by their effects on the transfer of radiant energy through the atmosphere [*Hansen et al.*, 1997], and they are critical to understanding feedback processes that regulate or modulate the climate response to forcing. Unlike many low clouds that have a cooling effect on solar radiation through scattering, high thin cirrus clouds scatter only a small amount of solar radiation and prevent a large quantity of long-wave radiation from leaving the earth-atmosphere system [*Liou*, 1986]. They usually exert a net radiative heating on the system rather than cooling like lower altitude clouds [*Hartmann et al.*, 1992; *Liou*, 1986].

[3] Cirrus clouds are one of the most important and yet uncertain components in weather and climate studies [*Liou*, 1986; *Lin and Zhang*, 2004; *Li et al.*, 2005]. Advances in modeling capabilities to predict climate change require improved representations of cloud processes in models and decreased uncertainties in parameterizations of cloud-radiation interactions. Cloud parameterizations in climate models need to account properly for the temporal and spatial distributions of high cloud properties [*Tselioudis and Jakob*, 2002; *Ringer and Allan*, 2004; *Lin and Zhang*, 2004; *Li et al.*, 2005]. Thus a thorough description of global cloudiness and its associated properties is essential.

[4] Cirrus clouds normally exist in the upper troposphere and sometimes extend into the stratosphere. According to *Wylie and Menzel* [1999] the highest frequency of upper tropospheric clouds occurs most often in the intertropical convergence zone and midlatitude storm belts, with lower concentrations over subtropical deserts and oceanic subtropical highs. Cirrus clouds are globally distributed and are composed almost exclusively of non-spherical ice crystals. The Geoscience Laser Altimeter System (GLAS) data, carried on board the Ice, Cloud, and land Elevation Satellite (ICESat) [*Spinhirne et al.*, 2005], showed that maxima in thin near-tropopause cirrus (TNTC) tend to occur over regions of intense convective activity like equatorial Africa and South America, where vigorous continental convection occurs, and in the western Pacific, where significant oceanic convection occurs [*Dessler et al.*, 2006].

[5] Several investigations on the development of cirrus cloud climatologies have been accomplished recently. A number of field campaigns have provided valuable information on cirrus cloud properties like the First International Satellite Cloud Climatology Project (ISCCP) Regional Experiment (FIRE) [see *Starr*, 1987], and the Subsonic Aircraft: Contrail and Cloud Effects Special Study (SUCCESS) [*Toon and Miake-Lye*, 1998]. The overall ISCCP [*Rossow and Schiffer*, 1999] has produced over twenty years of cloud products that contain various cloud optical and microphysical parameters. *Hahn and Warren* [1999, 2003] provided a high-quality cloud record by gathering and editing surface synoptic weather reports that cover the years 1952–1995 for ocean and 1971–1996 for land.

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0148-0227/08/2007JD009481$09.00

[6] Satellite remote sensing is the only practical means of observing cloud and climate variables such as aerosols on a global scale. However, most satellite analysis only sample the optically thick and usually highest-altitude clouds and it is difficult to determine from satellite imagery how deep a cloud extends into the atmosphere regardless of its optical depth [*Wang et al.*, 1996]. Active sensors like airborne lidar and surface-based radar [*Mace and Benson-Troth*, 2002] can effectively determine multilayer clouds, but are limited to a few ground locations, or using an airborne lidar, to the flight region. Satellite lidar has the ability to profile multilayer cloud structures on a much more global scale, spatially and temporally, and it is particularly useful for the detection of subvisual cirrus. With passive sensors, it is difficult to detect thin cirrus clouds (optical depth less than 0.4), and as a result there are few quantitative, global analyses of them [*Dessler and Yang*, 2003; *Dessler et al.*, 2006]. *Woodbury and McCormick* [1983] reported the spatial extent and frequency of cirrus clouds analyzed from the solar occultation SAGE extinction data over a 15-month period extending from February 1979 to April 1980. The analysis separates cirrus cloud observations into cirrus and thin cirrus on the basis of the observed extinction values from the satellite experiment. *Woodbury and McCormick* [1986] extended their analysis to cover the time period from February 1979 to November 1981 and to provide zonally-averaged cirrus cloud cover and a cirrus global distribution.

[7] However the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite mission provides comprehensive observations of cloud vertical structure on a near global scale [*Winker et al.*, 2003]. CALIPSO was developed within the framework of collaboration between NASA, France's Centre National d'Etudes Spatiales (CNES), and Hampton University [*Winker et al.*, 2003; *McCormick et al.*, 2002, *McCormick*, 2004], and was launched on 28 April 2006 into a sun-synchronous 705-km circular polar orbit with an ascending node equatorial crossing time of 13:30 local time. Further, and importantly, CALIPSO flies in formation as part of the A-Train constellation, which consists of the Aqua, Aura, CALIPSO, CloudSat, and PARASOL satellites. The CALIPSO orbit is controlled to provide a space-time near coincidence with measurements from the other satellites of the constellation.

[8] The CALIPSO payload consists of three nadir-viewing instruments: the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), the French-built Imaging Infrared Radiometer (IIR) and the Wide Field Camera (WFC). CALIOP is a three-channel lidar system (1064 nm and 532 nm parallel and perpendicular) with a 1 m receiving telescope [*McCormick*, 2004]. The IIR is a non-scanning imager and provides calibrated radiance measurements at 8.65 μm, 10.6 μm, and 12.05 μm, having a 64 km by 64 km swath width. Both the infrared emissivity and particle size of thin cirrus cloud particles can be estimated employing the three IIR channels. The WFC provides meteorological context for the lidar measurements and is used during daytime only. The CALIPSO data products are archived with a vertical resolution of 30 m from 0 to 8 km, and 60 m from 8 to 20 km.

[9] *McGill et al.* [2007] compared the measurements from CALIPSO and Cloud Physics Lidar (CPL) [*McGill et al.*, 2002] flown on the NASA ER-2 from 26 July to 14 August 2006. Their study showed a good agreement between these two instruments in cloud layer identification, cloud layer base retrievals for optically thin clouds, and cloud top determinations.

[10] The objective of this study is to use data provided by CALIOP on CALIPSO to investigate the occurrence frequency of cirrus clouds on a near global scale. *Wylie et al.* [1994] reported the frequency, geographical distribution, and seasonal changes of observations of upper tropospheric clouds from 1989 to 1993. *Wylie and Menzel* [1999] compiled the frequency and location of high-cloud observations from 1989 through 1997 using multi-spectral High-Resolution Infrared Radiation Sounder (HIRS) data from the National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. Their study showed that clouds with optical depths greater than 0.1 cover 69% of the earth between 65°N and 65°S. High clouds were found more often in the tropics than in the northern and southern mid-latitudes.

[11] During our investigation of cirrus clouds we follow the *World Meteorological Organization* [1987] and assume the following definition: layer, band or filament clouds composed primarily of ice crystals. In this work, we do not make any distinction between cirrus, cirrocumulus, or cirrostratus, or any of the many subspecies.

[12] In our study we employ the 5-km (horizontal resolution) cloud layer data product from CALIPSO. We use the Feature Classification Flags reported in the CALIPSO data set to identify cloud layers. We use only those cloud layers from the CALIPSO data record that are identified by the CALIOP cloud-aerosol discrimination algorithm as clouds with high level of confidence (i.e., "Feature Type QA" parameter equals 3).

[13] *Dowling and Radke* [1990] reported that the measured thickness range of cirrus clouds is from 0.1 to 8 km. Thus in our study we consider only those clouds with thickness less than 8 km. *Dowling and Radke* [1990] also obtained the range of measured heights for cirrus clouds to be from 4 to 20 km. Previous studies [see *Sassen et al.*, 1985] showed that supercooled water droplets are occasionally found in cirrus during formation. However they are not encountered or reported routinely at cirrus altitudes or temperatures [see *Dowling and Radke*, 1990]. *Lynch et al.* [2002] gave an overview on cirrus cloud definition and pointed out that a cloud classification could be devised and formalized on the basis of ice content. In the troposphere, altitude is correlated with temperature and we employ a threshold for the base altitude of high clouds, such that the corresponding temperature is generally cooler than -41°C at those altitudes and homogeneous nucleation takes place. We use the same bottom threshold as in investigation by *Eguchi et al.* [2007] that uses ICESat/GLAS observations to characterize cirrus clouds. During our study, we examine clouds with Cloud Layer Base (CLB) altitude higher than 8 km in the tropics (15°S–15°N) and higher than 5 km in the 15°–85°S and 15°–85°N latitude bands. At these altitudes, temperatures are so cold that clouds are composed primarily of ice crystals.

[14] Previous studies have shown that lidar measurements of depolarization ratio can be used to determine cloud ice-water phase [*Sassen*, 1991]. The spherical particles in water clouds have very small depolarization values, while the

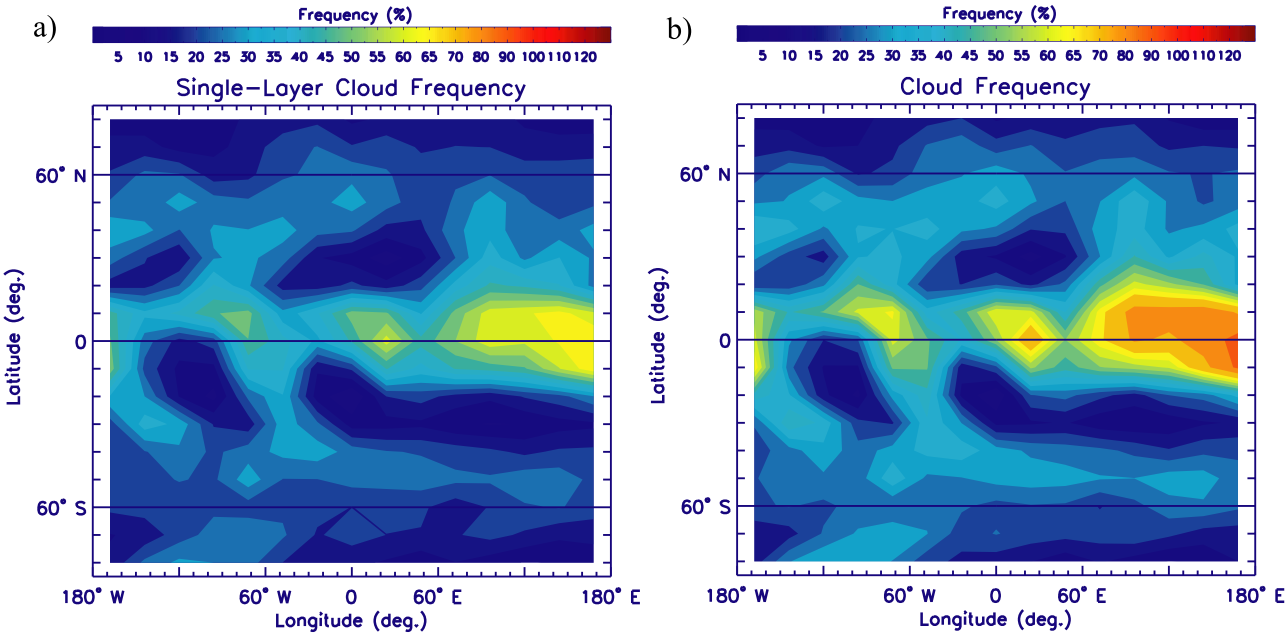

Figure 1. Latitude-Longitude distribution of the CALIOP cirrus cloud occurrence frequency over the period of June 2006 to June 2007 for (a) single-layer and (b) multilayer clouds.

randomly oriented crystals in ice clouds introduce significant depolarization. However, this assumption is applicable only when the signal is dominated by single scattering. Because of the large footprints of space base lidars such as CALIPSO, multiple scattering effects on lidar measurements can be significant and water clouds may show strong depolarization signal. We also note that many ice clouds contain horizontally oriented ice plates that can generate near-zero depolarization ratios at nadir incidence. *Sassen and Benson* [2001] studied the variability of the lidar linear depolarization ratio δ with height and temperature, and its dependence of the lidar pointing angle for zenith (<1.5°) and off zenith (>2.5°, >4.0°) lidar measurements. For midlatitude cirrus clouds, they reported that the average value of depolarization ratio for all zenith data points is 0.33 ± 0.11.

[15] During our investigation the Integrated Volume Depolarization Ratio (VDR) of cloud layers retrieved by CALIOP is compared to a threshold value to determine its ice-water phase. We examine only clouds with Integrated Volume Depolarization Ratio (VDR) greater than 0.2 (greater than 20%) to study clouds mostly composed of non-spherical ice crystals. We take into account only those clouds for which the cloud layer base is reported in the data set and either the surface or a lower cloud layer is detected.

[16] Thus we use certain thresholds values to study high-level ice clouds, which can be considered typical for cirrus clouds. We define the cloud occurrence frequency as the ratio of the number of retrieved cirrus cloud layers to total number of observations by CALIOP.

[17] We investigate the occurrence frequency of cirrus clouds measured by CALIOP as a function of time, latitude, and altitude [*Wang et al.*, 1996; *Wylie et al.*, 2005]. In particular, we examine the latitude-longitude and vertical distributions of cirrus clouds, including their seasonal behavior.

2. Latitude-Longitude Distribution of Cirrus Cloud Frequency

[18] Horizontal cloud cover is very important in the radiation field of the earth-atmosphere system and, hence, in weather and climate processes. To investigate the zonal

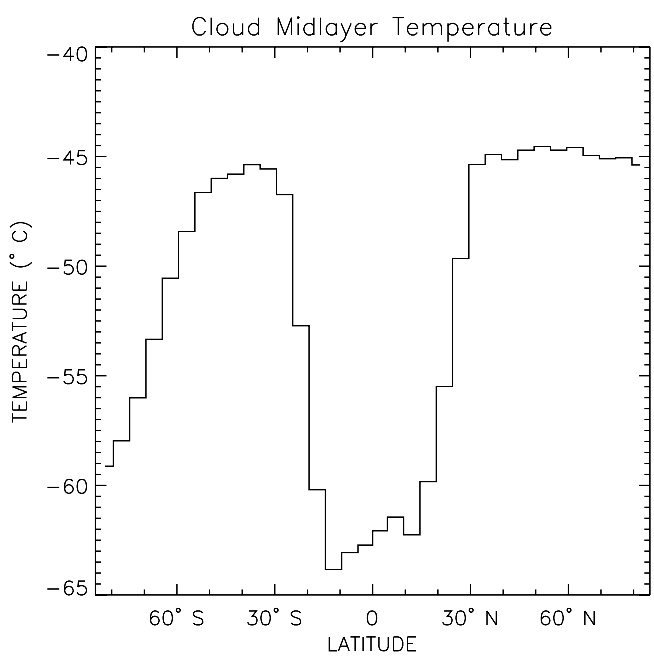

Figure 2. Zonal mean distribution of cirrus cloud midlayer temperature as a function of latitude from June 2006 to June 2007.

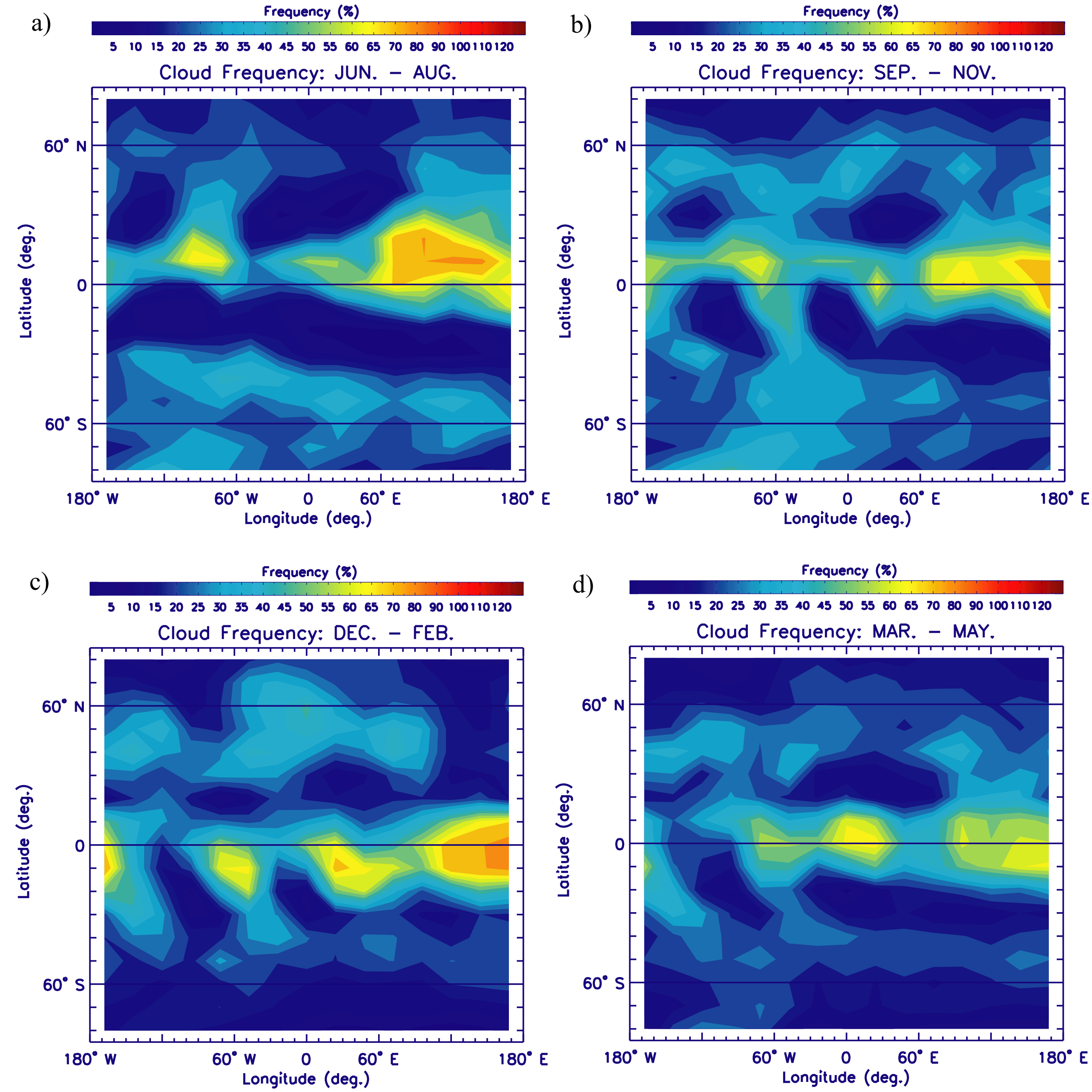

Figure 3. Seasonal variations of the latitude-longitude distributions of the CALIOP cirrus cloud occurrence frequency of the top-layer clouds from June 2006 to May 2007.

variability to cloud occurrence, the CALIOP measurements are grouped into 10° latitude by 24° longitude bins. Our calculations of cirrus cloud occurrence frequency take into account only the top-layer clouds and obtain the cirrus cloud occurrence frequency distribution for single-layer clouds (see Figure 1a) using the following formula:

$$\textit{Single Layer Frequency} = \frac{N_S}{N_T} \cdot 100\%,$$

where N_S is the number of the retrieved top-layer cirrus clouds, and N_T is the number of total observations. Next we calculate the average frequency for each 10° latitude and 24° longitude bin as shown in Figure 1a. Our results show maximum-occurrence frequency of up to 70% of top-layer cirrus clouds near the tropics over the 100°–180°E longitude band. Cirrus clouds most often occur over western Pacific ocean, Micronesia, central Africa, and the northern part of South America in the 20° S to 20°N latitude band. The cloud system in the tropics is associated with deep convective activities in the Intertropical Convergence Zone (ITCZ). The cloud occurrence in the middle and high latitudes (especially in the northern hemisphere) may be related to the frontal systems.

[19] CALIOP is capable of retrieving multilayer clouds, thus revealing the vertical structure of cirrus cloud distri-

butions. Figure 1b shows the latitude-longitude distribution of occurrence frequency of multilayer cirrus clouds using the criteria introduced earlier for minimum height and depolarization. Thus during our analysis we take into account not only the top-level clouds, but also the lower-level, overlapped cirrus clouds, employing the following formula:

$$Occurrence\ Frequency = \frac{N_M}{N_T} \cdot 100\%,$$

where N_M is the number of all retrieved cirrus clouds. For the multilayer clouds, the cirrus occurrence frequency may be higher than 100%, since individual lidar returns may provide information about multiple layers of clouds within each lidar profile. Hence the number of retrieved clouds N_M may be larger than the number of observations N_T. We obtain maximum-occurrence frequency of multilayer cirrus clouds of up to 94% near the tropics over the 100° – 180°E longitude band.

[20] Multi-layer clouds have been a major issue in climate studies owing to a lack of reliable information. Comparison of the Figures 1a and 1b shows that the multilayer clouds are fairly common near the tropics and in the midlatitudes. Hence satellite systems with retrieval methods that assume single-layer cloud (see Figure 1a) and do not provide information concerning the presence of a lower-layer clouds beneath the top-level cirrus cloud, largely underestimate the cirrus cloud occurrence frequency (see Figure 1b). In particular, the current MODIS product only provides the location of the top of the highest cloud viewable from space, which may not account for multilayer clouds. According to *Chang and Li* [2005], use of these cloud-top data would underestimate low clouds by about 30% if there were cirrus overlapping and the optical depths of overlapped cirrus clouds would be overestimated by a factor of 7 because of the optically thicker water clouds underneath.

[21] We obtain that the differences between occurrence frequencies of top-level single-layer cirrus clouds and multilayer clouds are highest in the tropical region and may reach up to 23.5% (see Figure 1).

[22] The CALIPSO data set also contains information on temperature at the geometric midpoint of the layer in the vertical dimension. These values were derived from the Goddard Earth Observing System (EOS) Data Assimilation System (GEOS-4) data product. We examine the midlayer temperature of the clouds under consideration. Figure 2 reveals that the zonal mean of the cirrus clouds midlayer temperature is between about −44° and −64°C from June 2006 to June 2007. This confirms the fact that the clouds considered in this study are indeed composed almost exclusively of ice crystals.

[23] To investigate the seasonal behavior of the cloud frequency distributions, CALIOP data are further grouped according to season. Figures 3 and 4 show seasonal variations of the latitude – longitude distributions of the CALIOP cirrus cloud occurrence frequency for single-layer (top-level) and multilayer clouds, respectively, for the following four seasons: (a) June–August of 2006; (b) September–November 2006; (c) December 2006–February 2007; and (d) March–May 2007. For June–August (northern summer), Figure 3 shows high frequency of cirrus clouds up to ~80% from 10°S to 25°N latitude over 60°–180°E longitude bands. This maximum frequency of occurrence moves south from September through the southern summer of December–February, where the maximum extends poleward to only about 15°S, much less than its north poleward extent in northern summer. The peak frequency over Africa (0°–20°S latitude and 0° – 60°E longitude), however, is much more pronounced in southern summer than the equivalent weaker maximum at 0–10°N latitude and 0°–60°E longitude during northern summer. The latitudinal movements of the maximum occurrence of cirrus clouds near the tropics are in agreement with the seasonal shift of the ITCZ.

[24] For multiple layered clouds, Figure 4 reveals similar seasonal behavior but with overall higher frequencies over broader areas, especially in the tropics. CALIOP provides us a unique opportunity to study cirrus clouds near the poles, and Figure 4 shows high-occurrence frequency of up to 65% throughout September–November extending from South Pole to about 50°S in the 160°W–0° longitude band.

[25] There were several studies of the seasonal variation of cirrus clouds using passive remote sensors on a global scale. *Wylie and Menzel* [1999] reported large latitudinal movement in cloud cover with the changing seasons using the HIRS data. While HIRS is sensitive to detecting cirrus clouds, it does not detect low cloud obscured by cirrus clouds. *Wang et al.* [1996] developed a climatology of cloud occurrence frequency on the basis of the solar occultation observations of the Stratospheric Aerosol and Gas Experiment (SAGE) II between 1985 and 1990. They examined the seasonal variations of zonal mean cloud occurrence and reported that the cloud occurrence in the subtropical regions has a distinct seasonal variation, with the maximum frequency in local summer and the minimum during local winter. Since there were no SAGE II data poleward of about 55° during local winter, the results of the 6-year zonal average at high latitudes above 55° were slightly biased toward the summer season [*Wang et al.*, 1996]. The solar occultation technique with its two measurements per orbit (sunrise and sunset) repeats its retrievals at a given latitude with a frequency of about a month. The SAGE II observations [*McCormick*, 1987] did not contain information concerning changes in cloud distributions with shorter frequencies. Hence the seasonal cloud frequency derived from the SAGE II data could be biased. CALIOP, however, has measurements with higher vertical resolution, shorter sampling frequency, and extend to the Polar Regions.

[26] According to the CALIPSO data quality statements (release v1.10) the detection of cloud layers during the nighttime portion of the orbits is more reliable than during the daytime. The noise levels in the daytime measurements are larger than those at night, because of solar background signals.

[27] Figure 5 shows the differences between the occurrence frequencies of cirrus clouds measured by CALIOP during day and night from June 2006 to June 2007. The mean (night-day) difference, calculated over all latitude and longitude bins, is about −2.1% for the top-layer cloud frequencies. Near the tropics and Polar Regions, the CALIOP nighttime measurements generally reveal up to 15%

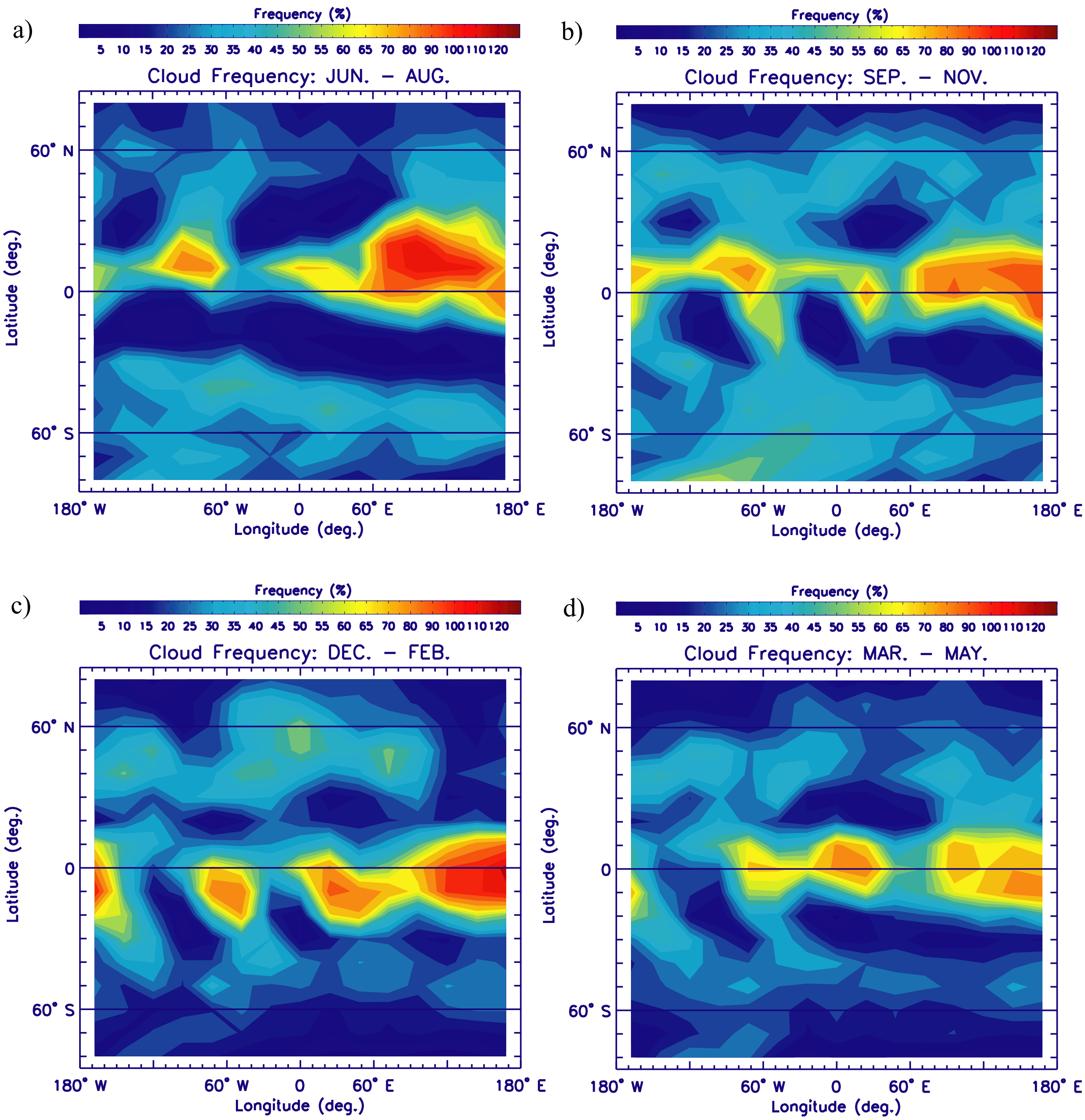

Figure 4. Seasonal variations of the latitude-longitude distributions of the CALIOP cirrus cloud occurrence frequency of multilayer clouds from June 2006 to May 2007.

more clouds compared to the daytime retrievals (see Figure 5a). On the other hand, daytime estimates in the 30°S–65°S and 30°N–65°N latitude bands show up to 14% more top-layer cirrus clouds than the nighttime measurements.

[28] The occurrence frequency (night - day) differences are much larger for the multilayer cloud case (see Figure 5b). The daytime estimates near the tropics over the 60°–180°E longitude band show up to 25% more multilayer cirrus clouds than the nighttime measurements. The average (night-day) difference for the multilayer cloud frequencies is about −8.4%. The nighttime frequency values are generally larger by up to 8.1% near the tropics over the 90°W–50°E longitude band.

[29] These large differences between the daytime and nighttime retrievals for multilayer clouds may be due to larger noise levels in the daytime measurements. According to the CALIPSO data quality statements (release v1.10) some portions of dense aerosol layers are labeled as cloud. This may affect occurrence frequency estimates during daytime. It was also reported (see data v1.10 release statements) that portions of the bases of some cirrus clouds are

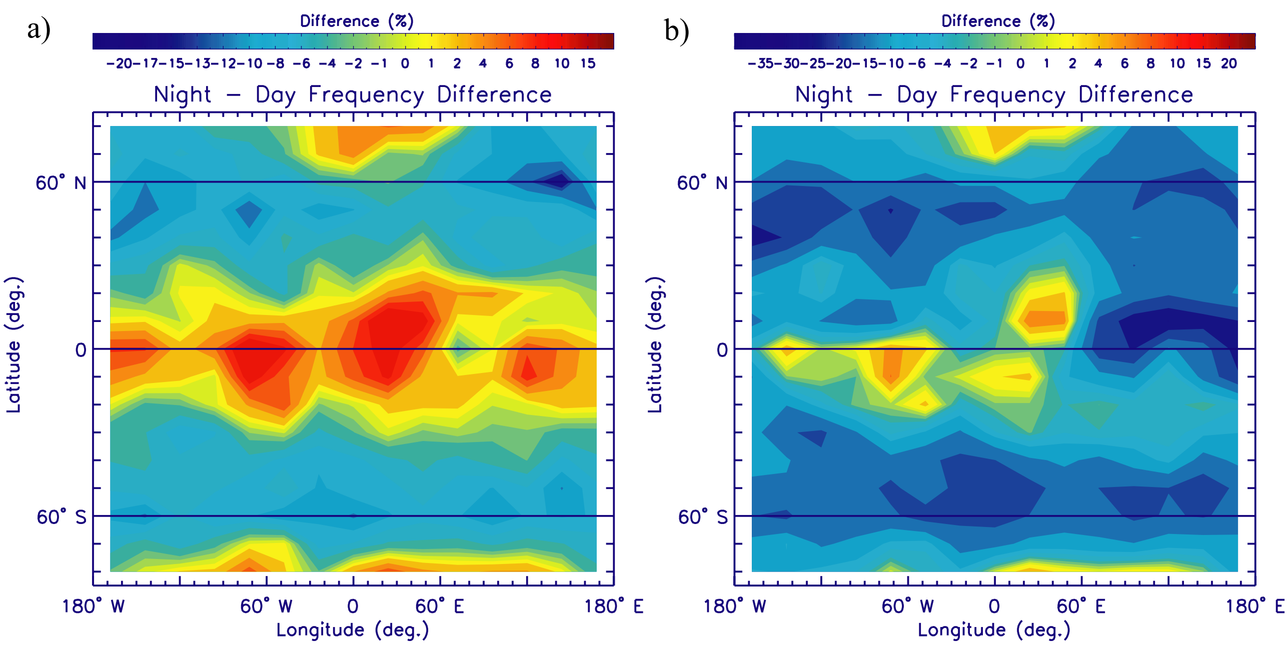

Figure 5. Latitude-Longitude distribution of the differences between the occurrence frequencies of cirrus clouds measured by CALIOP during day and night over the period of June 2006 to June 2007 for (a) single-layer and (b) multilayer clouds. Note the change of scale in Figure 5b.

mislabeled as aerosol, which may also cause some discrepancies in frequency calculations.

3. Vertical Distribution of the Cirrus Clouds

[30] The global distribution of cloud vertical structure is essential for climate studies because of its impact on both the magnitude and sign of the net cloud radiative forcing and latent heating profiles of the atmosphere, which in turn influences both small-scale dynamics and the atmospheric general circulation [*Ramaswamy and Ramanathan*, 1989; *Randall et al.*, 1989; *Chang and Li*, 2005]. The largest sources of uncertainty in estimating long-wave radiative fluxes within the atmosphere are connected with difficulties in determining the vertical distribution of multilayer clouds [*Stephens et al.*, 2004].

[31] Figure 6 shows the vertical distribution of the frequency of cirrus cloud top and base altitudes measured by CALIOP. The ratio of the number of cirrus cloud layers to the total number of observations by CALIPSO from June 2006 to June 2007 is calculated for each 1 km altitude step. Hence the occurrence frequency of cloud top altitude depicted in Figure 6 at 10 km level, for example, represents the frequency of cloud top altitudes between 9.5 and 10.5 km. We observe the maximum of cirrus cloud top-altitude occurrence frequency to be about 11% at 16 km over 20°N–20°S. The maximum of cirrus cloud base altitude occurrence frequency near the tropics is about 8.5% at 14 km. The results show that for 20°N to 60°N the maximum-occurrence frequency of the cirrus top and base altitudes is about 5.1% at 11 km and 8 km, respectively. There are no significant differences in absolute value in vertical distributions of occurrence frequency of cirrus clouds at latitude bands 20°S–60°S or 20°N–60°N. From 60°N to 82°N, the maximum-occurrence frequency of the cirrus top (base) altitudes is about 4.5 (5) % at 9 (7) km. The values for 60°S–82°S are within about 1% in absolute value.

[32] We also investigate the vertical distribution of cirrus clouds in the region near Indonesia (latitude 15°S – 15°N and longitude 90°E–180°E). We obtain that the maximum-occurrence frequency of the cirrus top (base) altitudes is about 21 (14) % at 16 (14) km. We note that this is the region where the frequency of cirrus cloud occurrence is highest (see Figure 1).

[33] During our study we also calculate the fraction $N_{Detected}/N_{Total}$ for each 10° latitude and 24° longitude bin, where $N_{Detected}$ is the number of clouds whose base altitude is detected by the CALIOP retrieval algorithm. N_{Total} is the total number of cloud layers reported in the CALIOP data set. Our analysis shows that the 5-km horizontal resolution cloud layer data product from CALIPSO reported the cloud bottom altitudes for about 99.8% of cloud layers under consideration.

[34] *Eguchi et al.* [2007] using the GLAS data, for the period 1 October to 18 November 2003, also found similar values to ours for the vertical distribution of cirrus frequencies in the tropics and in northern midlatitudes. They reported maximum frequencies of the cirrus cloud top (bottom) in the tropics 13 (8) % at 16.5 (14.5) km, whereas using one year of CALIOP data we found 11% (top) at 16 km and 8.5% (bottom) at 14 km.

[35] We also examine the zonal mean distribution of the cirrus cloud layer top altitudes and layer base altitudes measured by CALIOP for each 5° latitude bin. Figure 7a shows that the yearly averaged zonal mean top (base) altitudes of cirrus cloud layers are less than 15 (13.3) km and 9.5 (7.8) km near the equator and in the Polar Regions, respectively. We obtain that the zonal mean values of cirrus

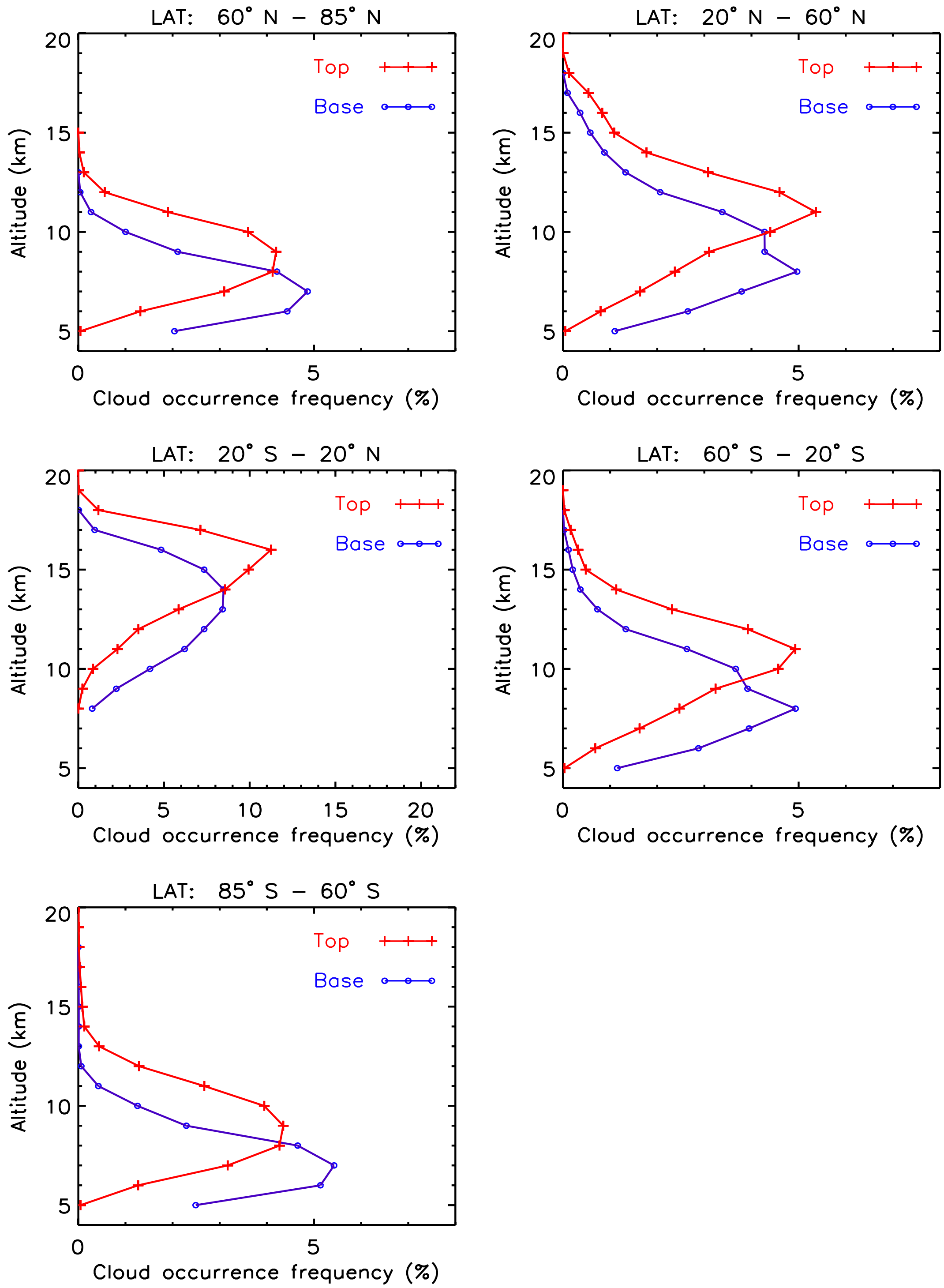

Figure 6. Vertical distribution of the frequency of the cloud layer top altitudes (plus signs) and layer base altitudes (circles) from the CALIOP data set from June 2006 to June 2007.

cloud layer top altitudes in the Antarctic region are generally larger than the values observed in the Arctic from June 2006 to June 2007.

[36] Figures 7b and 7c show the seasonal variations of the zonal mean distribution of the cirrus cloud layer top altitudes and layer base altitudes. Our investigation reveals that the zonal mean top altitudes south of 70°S are higher than the mean top altitudes north of 70°N from June to August 2006. A reverse of this pattern is observed from December 2006 to February 2007 (northern winter) with higher zonal mean top altitudes poleward of 60°N, and lower top altitudes near the Antarctic region.

[37] Figure 7 also shows the zonal mean height of the tropopause corresponding to cirrus clouds for each 5° latitude bin. Thus whenever we observe a cirrus cloud layer in the CALIPSO data set we also take into account the tropopause height reported in the data set at that location and calculate the zonal mean of the tropopause height

corresponding to cirrus clouds. Figure 7 shows that the zonal mean altitudes of the tropopause are higher than the zonal mean cloud top altitudes calculated for each 5° latitude bin.

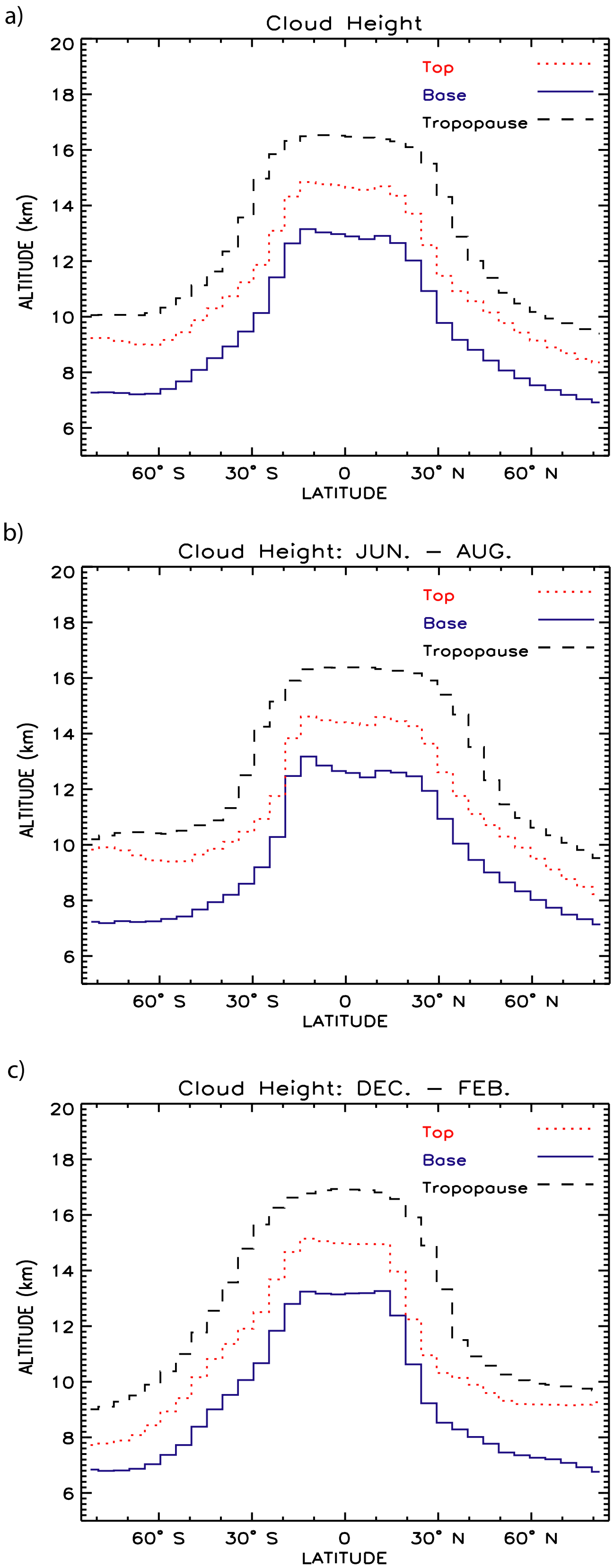

Figure 7. Zonal mean distribution of the cirrus cloud layer top altitudes (dotted line) and layer base altitudes (solid line) measured by CALIOP as a function of latitude: (a) from June 2006 to June 2007, (b) from June to August of 2006, and (c) from December 2006 to February 2007. The dashed line is the average height of the tropopause corresponding to observed cirrus clouds for each latitude bin.

[38] The (night - day) differences of the cirrus cloud layer heights retrieved by CALIOP from June 2006 to June 2007 for each 5° latitude bin are depicted in Figure 8. First we study the zonal mean distribution of the cirrus cloud layer top altitudes and base altitudes for nighttime and daytime separately. Our calculations of the difference reveal that the cloud layer top altitudes measured by CALIOP during nighttime are higher than the daytime estimates by up to ~1 km. The cloud base altitudes from the nighttime data are lower than the daytime base altitudes by up to about 0.5 km.

[39] Larger differences between the cloud top and base altitudes in the Polar Regions from June to August 2006 and from December 2006 to February 2007 depicted in Figures 7b and 7c, respectively, suggest a concentration of relatively thicker clouds near Arctic and Antarctic during local winter.

[40] Study by *Yamanouchi and Charlock* [1997] showed that the Antarctic cloud cover have large impact on the surface radiation budget. According to *Liou* [1986] thick cirrus clouds appear to behave like a water cloud in the thermal infrared region, and the presence of thick cirrus clouds may produce cooling in the atmosphere.

[41] Our investigation shows that the zonal mean of the cirrus clouds midlayer temperature is between about −55° and −65°C over the 60°S – 82°S latitude band from June to August 2006. Hence the very cold temperatures may be the cause of the high thickness values of cirrus clouds in the Antarctic region. However, we also note that the CALIPSO data set contains much more nighttime observations in the Antarctic region than north of 60°S during the one year period under consideration. As we mentioned above, nighttime data set reveals higher cloud top-altitude values and lower base altitude values than the daytime data (see Figure 8). If there are more CALIOP nighttime observations in certain regions (e.g., Antarctica) than daytime observations, then the combined average will show relatively thicker clouds in those regions. Hence the cirrus cloud layer top and base altitude values depicted in Figures 7a and 7b near the South Pole may be due to cold temperatures and the combination of sampling issues with daytime – nighttime differences. Improvements of CALIPSO cloud retrieval algorithm are underway and we will continue to investigate the cloud thickness values as more data becomes available.

4. Summary

[42] In our study we used the 5 km horizontal layer CALIOP cloud product to analyze the latitude-longitude distribution of the cirrus cloud occurrence frequencies from June 2006 to June 2007. Our investigation of the top-level (single-layer) and multilayer cirrus clouds showed maximum-occurrence frequencies of up to 70% and 93.5%, respectively, near the tropics over the 100°–180°E longitude band. We also studied the seasonal variation of the

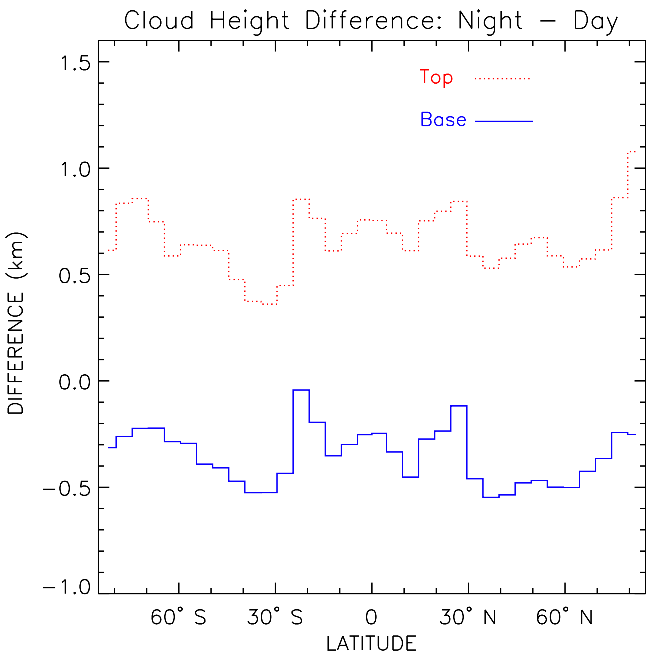

Figure 8. Zonal mean distribution of the (night - day) differences of the cirrus cloud layer heights retrieved by CALIOP from June 2006 to June 2007.

horizontal distribution of cirrus cloud occurrence frequency and our results showed large latitudinal movement of cirrus cloud cover with the changing seasons, which is in agreement with previous studies [*Wang et al.*, 1996; *Wylie and Menzel*, 1999].

[43] Examination of the vertical distribution of occurrence frequency of the cirrus cloud top and base altitudes observed by CALIPSO revealed that the maximum of cirrus top (base) altitude occurrence frequency in the 20°N–20°S latitude band was about 11 (8.5) % at 16 (14) km from June 2006 to June 2007.

[44] We also investigated the differences between the occurrence frequencies of cirrus clouds measured by CALIOP during daytime and nighttime. The average (night-day) difference, calculated over all latitude and longitude bins, for the multilayer cloud frequencies was about −8.4%. The daytime retrievals near the tropics over the 60° – 180°E longitude band showed up to 25% more multilayer cirrus clouds than the nighttime measurements. We have also calculated the zonal mean distribution of the cirrus cloud layer top altitudes and base altitudes for nighttime and daytime separately. The cloud top altitudes from the nighttime data were higher than the daytime top altitudes on average by 0.66 km. These differences may be caused by larger noise levels in the daytime data.

[45] Different cloud studies report different frequencies of clouds because of the differences in spatial sampling and their ability to detect clouds. The ISCCP data can confuse some lower-level broken clouds with high-level transmissive clouds, while the HIRS CO_2 – slicing analysis does not [*Jin et al.*, 1996]. According to *Wylie et al.* [2005], HIRS finds more upper tropospheric clouds than ISCCP. SAGE II had higher sensitivity to thin cirrus clouds than HIRS. *Wylie and Wang* [1997] compared the HIRS and SAGE II cloud data and reported that SAGE II generally observed even more cloud cover than HIRS. The principal disadvantage of the SAGE II data was that their sampling was limited because of occultation geometry, and their measurements were averaged over horizontal length scales of hundreds of kilometers. As we have discussed above, there have been a number of investigations dedicated to cirrus clouds that use satellite data. Most of the measurement systems employed in those investigations use passive remote sensing and therefore have limitations, as do all remote sensors. However passive sensors have particular difficulty in resolving multilayer clouds.

[46] CALIOP measures clouds with an unprecedented vertical and horizontal resolution, especially high clouds. Our examination of high-clouds provides additional information on the distribution of cirrus clouds on a near global scale. We plan to continue our quest for the construction of a cirrus cloud climatology as more and more data become available using the unique opportunity provided by CALIPSO. We also plan to study the cirrus cloud characteristics provided by CloudSat and MODIS, and to compare the cirrus cloud climatologies obtained from the CALIPSO, CloudSat, and MODIS data sets in our future studies.

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