

## Implications of the differences between daytime and nighttime CloudSat observations over the tropics

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[1] Using 1 year of CloudSat level 2B Cloud Geometrical Profile product, the vertical structures, geographical distributions, and seasonal variations of cloud occurrence at the daytime (1330 LT) and the nighttime (0130 LT) overpasses and their differences over tropical land and ocean are presented separately. The differences between the cloud and precipitation occurrence at 0130 and 1330 LT and the 24 h mean are quantitatively evaluated using climatologies of diurnal variation from 9 years of TRMM observations. Then the vertical structures, geographical distributions, and seasonal variations of cloud and precipitation near the two CloudSat overpass times are generated from 9 years of TRMM observations and compared to those from CloudSat. Larger differences between cloud and precipitation occurrences at 0130 LT and those at 1330 LT were found at high altitudes because the amplitude of diurnal variation increases with height. Cloud and precipitation occurrences show day versus night differences which are opposite with respect to each other in the upper troposphere over the tropics. For example, near 1330 LT over tropical oceans, there are more clouds, but less precipitation at 13–14 km than near 0130 LT except over Panama. This may be explained with the phase lags between precipitation and clouds in the life cycles of the convective systems over land and ocean. The differences between the seasonal cycles of cloud and precipitation sampled at the 0130 and 1330 LT A-Train overpass times and the seasonal cycles generated from full day samples are shown.

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### 1. Introduction

[2] As an important member of the A-Train satellites [Stephens *et al.*, 2002], CloudSat has provided valuable observations of clouds and precipitation globally since its April 2006 launch [Haynes and Stephens, 2007; Mace *et al.*, 2007; Zhang *et al.*, 2007]. Like other A-Train satellites, CloudSat's Sun-synchronous orbit passes over the tropics near 0130 and 1330 local time (LT). It is well known that there are strong diurnal cycles of precipitation and clouds over the tropics [e.g., Gray and Jacobson, 1977; Augustine, 1984; Janowiak *et al.*, 1994; Hall and Vonder Haar, 1999; Yang and Slingo, 2001; Dai, 2001; Dai *et al.*, 2007]. Because of observations from the Tropical Rainfall Measuring Mission (TRMM [Kummerow *et al.*, 1998]), the diurnal variations of cloud and precipitation properties and vertical structure are known in greater detail [Imaoka and Spencer, 2000; Sorooshian *et al.*, 2002; Nesbitt and Zipser, 2003; Liu and Zipser, 2008]. Because of the diurnal cycles of clouds and precipitation, large differences between the CloudSat daytime (1330 LT) and nighttime (0130 LT) observations are expected. In addition to finding explan-

ations for these differences, a more immediate question is how different the climatologies of precipitation and clouds generated from the CloudSat observations are from climatologies produced from full day samples.

[3] An example of the climatology of diurnal variation of tropical precipitation echoes from TRMM [Liu and Zipser, 2008] is shown in Figure 1. Over tropical land, the A-Train satellites do not capture the strongest or most frequent afternoon convective period (Figure 1a). Over tropical oceans, the early morning precipitation maximum is also not captured (Figure 1b). Because the amplitude of the diurnal cycle of precipitation increases with height over both tropical land and ocean, the differences between the daytime and nighttime precipitation observations of CloudSat are expected to be larger at higher altitudes. Therefore, if observations from CloudSat and other A-Train Satellites are to be used to understand the role of clouds and precipitation in the diabatic heating of the atmosphere, it is important to understand the implications of the subsampling of the full diurnal cycles.

[4] In this study, we focus on presenting and interpreting the differences between the daytime and nighttime observations from CloudSat over the tropics. The questions addressed include the following:

[5] 1. What are the differences from the climatologies of total amount of cloud and precipitation of CloudSat, which samples only at two specific times of the day, to the climatologies from the full day?

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[6] 2. What are the differences of CloudSat observed clouds and precipitation between day and night over the tropics? How may we interpret these differences?

[7] 3. What are the seasonal cycles of CloudSat-observed clouds and precipitation observed during the daytime and the nighttime? Are they similar? How different are they from the seasonal cycles generated from the TRMM full day samples?

[8] First TRMM observations at A-Train observation times are compared with the full day sample of TRMM observations. Then day-night differences of vertical structure, geographical and seasonal distributions of cloud and precipitation from CloudSat over the tropics are presented. Next we interpret these differences by using the climatologies of diurnal variation of cloud and precipitation generated from 9 years of TRMM observations.

## 2. Data and Methods

### 2.1. CloudSat Data

[9] One full year (July 2006 to June 2007) of CloudSat level 2B Cloud Geometrical Profile (2B-GEOPROF) data [Mace *et al.*, 2007; Marchand *et al.*, 2008] is used in this study. In the CloudSat Profiling Radar (CPR) [Im *et al.*, 2006] reflectivity, clouds are identified with a cloud mask. In this study, CloudSat observations flagged as significant with the CloudSat cloud mask [Marchand *et al.*, 2008] and CPR reflectivity greater than  $-20$  dBZ are considered as cloud (hereafter referred to as cloudy pixels). Pixels with CPR reflectivity greater than  $0$  dBZ are considered as thick cloud with precipitation particles (referred to as precipitation from now on). The occurrence frequencies of cloud and precipitation are presented vertically, geographically, and seasonally over the tropics from  $20^{\circ}\text{S}$  to  $20^{\circ}\text{N}$ .

[10] To calculate these frequencies, the total number of sampled pixels (cloudless and cloudy), and total number of cloud and precipitation pixels, and the total number of pixels with a reflectivity greater than or equal to the thresholds of  $-20$ ,  $-10$ ,  $0$ , and  $10$  dBZ are accumulated monthly into  $1$  km bins from  $0$  to  $20$  km in  $1^{\circ} \times 1^{\circ}$  boxes globally from daytime and nighttime observations separately. Then the vertical profiles of occurrence frequency of cloudy pixels and a reflectivity greater than or equal to  $-20$ ,  $-10$ ,  $0$  and  $10$  dBZ are calculated by dividing the accumulated cloudy and precipitation pixels with the total sampled pixels in the boxes for daytime and nighttime over land and oceans in the tropics, separately. The geographical distributions of the occurrences of precipitation pixels and reflectivity greater than or equal to  $10$  dBZ are generated by summarizing the occurrences on a  $5^{\circ} \times 5^{\circ}$  grid.

### 2.2. TRMM Data

[11] The TRMM satellite has a non-Sun-synchronous  $35^{\circ}$  inclination orbit covering the tropics and subtropics, with instruments for observing precipitation, clouds, and lightning [Kummerow *et al.*, 1998]. Given enough observation time, TRMM data provides detailed information about the diurnal cycles of precipitation and clouds [Negri *et al.*, 2002; Nesbitt and Zipser, 2003; Liu and Zipser, 2008]. This study uses the TRMM Precipitation and Cloud Feature (PF) database created from 9 years of TRMM observations. The database includes more than one hundred million PFs defined by grouping the near surface raining area observed

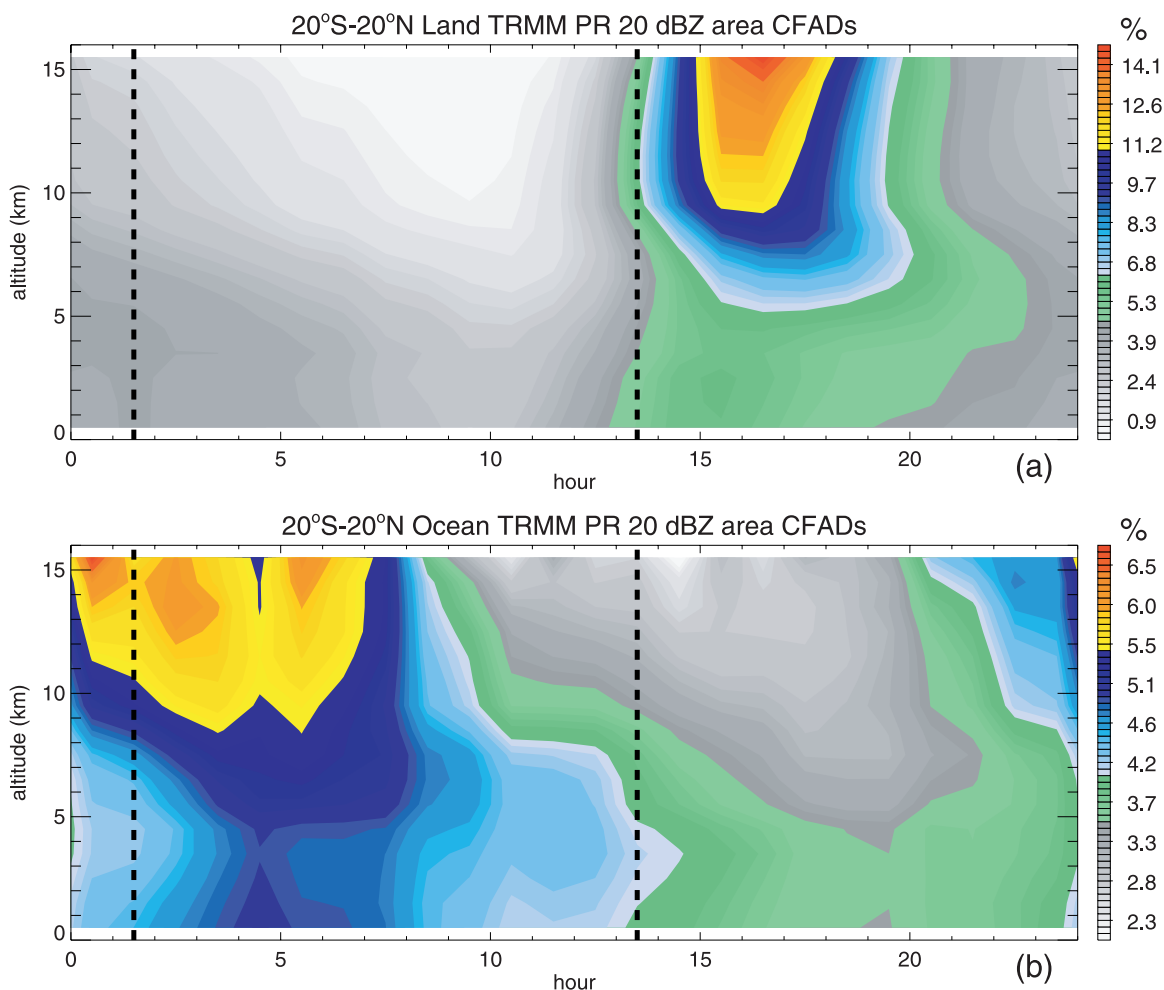
by the TRMM Precipitation Radar (PR), area projected from the pixels with PR  $20$  dBZ, or cloud area with the Visible Infrared Scanner (VIRS)  $10.8 \mu\text{m}$  brightness temperature ( $T_{\text{B11}}$ ) colder than  $235$  K [Liu *et al.*, 2008]. For each one of these PFs, the area of  $20$  dBZ at different altitudes, area of cloud with  $T_{\text{B11}} < 210$  K and  $235$  K, and flash counts are summarized. Here we present the occurrence of precipitation, clouds colder than  $210$  K and  $235$  K, and lightning flash counts at the A-Train observation times and their contributions to the full day average.

## 3. Results and Discussion

### 3.1. Occurrence of TRMM Precipitation and Cloud at A-Train Observation Times

[12] Before presenting the differences between daytime and nighttime CloudSat observations, it is important to know the contribution of precipitation and clouds at the A-Train observing times compared to the full day average. By dividing the TRMM precipitation occurrence at  $0100$ – $0200$  and  $1300$ – $1400$  LT by the  $24$ -h mean, the deviation of the precipitation occurrences at the A-Train times from the mean at different altitudes are calculated and shown in Figure 2. Over tropical land (Figure 2a), precipitation occurs more frequently during the daytime and less frequently during the night overpasses than the mean above  $8$  km. During the day the discontinuity at midlevels from  $5$  to  $8$  km matches up well with the discontinuity at midlevels in Figure 1a. Below  $5$  km, precipitation at both overpass times occurs more frequently than the mean. The averaged precipitation occurrence from the day and night observations is about  $10\%$  more than the mean below  $2$  km, and  $20\%$  less than the mean above  $14$  km. Over tropical oceans (Figure 2b), precipitation occurs more frequently during the night and less frequently during the daytime overpasses than the mean. The deviations from the mean at both daytime and nighttime are near  $0$  at  $5$  km, but up to  $35\%$  at high altitudes. However, the average of precipitation occurrences from the two CloudSat overpass times is very close to the  $24$ -h mean with about  $5\%$  overestimation above  $8$  km.

[13] TRMM observations also provide information on the diurnal cycles of clouds and lightning [Liu and Zipser, 2008]. By dividing the 9 years of TRMM observations of near surface volumetric rain, clouds with  $T_{\text{B11}} < 210$  K and  $235$  K, population of PFs, and flash counts at  $0100$ – $0200$  and  $1300$ – $1400$  LT by the  $24$ -h mean, the deviations of the total precipitation, occurrence of cold clouds, population of precipitation systems and flashes at A-Train times from the mean are calculated and listed in Table 1. Over land, there are larger populations of PFs with more flashes and with larger volumetric rainfall, but fewer clouds colder than  $210$  K and  $235$  K in the daytime than at night. This can be explained by the phase lags of the diurnal cycles of the convective systems over land [Hong *et al.*, 2006; Liu and Zipser, 2008]. At  $1330$ , most of the convective systems are still in the developing stage and have high flash rates, high rainfall intensity, but do not have large areas of cold clouds. However, at  $0130$  LT, most of the convective systems over land have completed their life cycles, but large areas of cold clouds generated by a small number of long-lived mesoscale convective systems (MCSs) may still exist. Over ocean, there are more PFs with more rainfall, clouds with  $T_{\text{B11}} < 210$  K and flashes at the



**Figure 1.** Contoured frequency-by-altitudes diagrams (CFADs [Yuter and Houze, 1995]) of diurnal variation of precipitation area with TRMM PR reflectivity greater than or equal to 20 dBZ over 20°S–20°N (a) land and (b) ocean. Units are in %. Vertical dashed lines are the A-Train satellite observations around 0130 and 1330 local time.

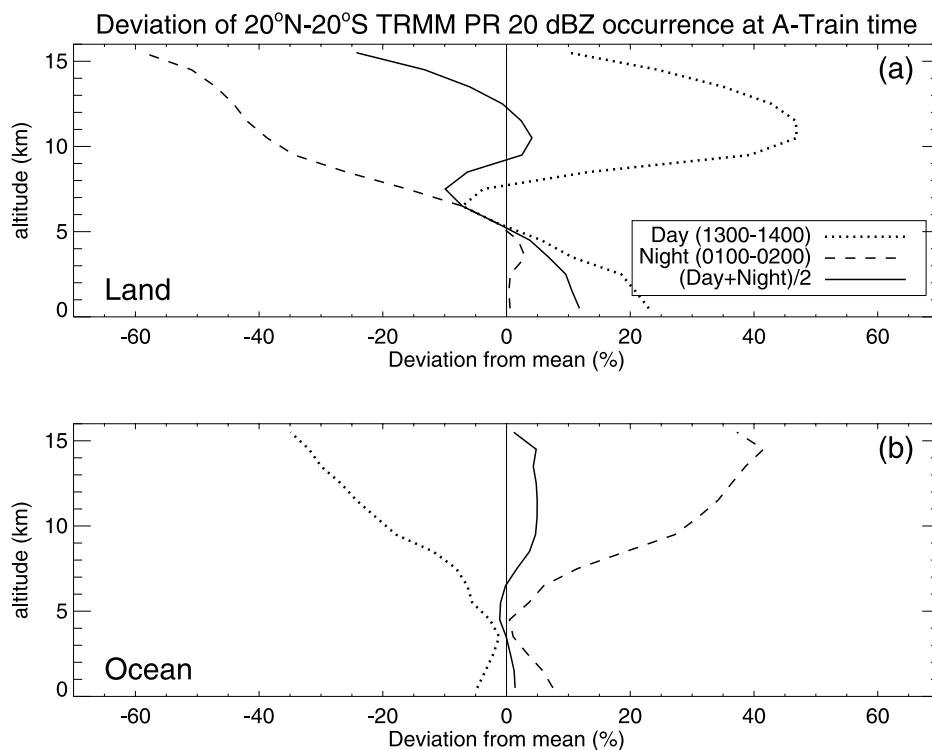
nighttime overpasses than the mean, and fewer PFs with less rainfall, clouds with  $T_{B11} < 210$  K and flashes at the daytime overpasses than the mean. The only exception is the area of clouds with  $T_{B11} < 235$  K, which is greater during the day. This may be an effect of daytime cirrus clouds. After averaging both the day and the night data, the values of near surface volumetric rain, cold clouds, and population of PFs are close to the mean, with less than 5% overestimation.

[14] The geographical distribution of the ratio of the occurrence of PR 20 dBZ at 14 km and VIRS  $T_{B11} < 235$  K at the 1300–1400 and 0100–0200 LT observation times and their average to the mean of all day samples is shown in Figure 3. Large fractional differences from the occurrence of PR 20 dBZ at 14 km at daytime and nighttime to the mean of full day samples are obvious over central Africa and the Amazon in Figures 3a and 3b. The average occurrence of the daytime and nighttime values is greater than the mean of full day samples over most of the Amazon and southern Africa, but less than the mean over the Sahel (Figure 3c). Consistent with Figure 2b, the Tropical Ocean has a large area with higher occurrence of 20 dBZ at 14 km at nighttime than the mean of full day samples. Generally

there are fewer clouds colder than 235 K over tropical land at both daytime and nighttime than the mean of full day samples (Figures 3d and 3e). Even though the average of the daytime and nighttime occurrences of cloud colder than 235 K over the entire tropical ocean is only about 4% different from the mean of full day samples (Table 1), there are some regional variations shown in Figure 3f. The daytime and nighttime average is larger than the mean over most of the Atlantic and the East Pacific, but less than the mean over about half of the West Pacific and the Indian Ocean.

### 3.2. Cloud and Precipitation Vertical Structure From CloudSat

[15] The daytime and nighttime vertical profiles of the occurrence of CloudSat CPR pixels with cloud mask,  $-20$ ,  $-10$ ,  $0$ , and  $10$  dBZ, as well as the occurrence of TRMM PR 20 dBZ at 0100–0200 and 1300–1400 LT with a vertical bin size of 1 km are shown for land and ocean separately in Figures 4a and 4b. The ratio of the occurrence during the daytime to the occurrence during the nighttime from Figure 4 is shown in Figure 5. The low occurrence of the CPR 10 dBZ below the melting level in Figures 4a and 4b is due to radar attenuation. In Figure 4a, CloudSat



**Figure 2.** Percentage differences from occurrence of TRMM PR 20 dBZ around the A-Train observing daytime (0100–0200 LT) and the nighttime (1300–1400 LT) to the all day mean occurrence over 20°S–20°N (a) land and (b) ocean.

detects more clouds at 10–13 km than other altitudes during both day and night over land. Clouds and precipitation occur more frequently in the daytime below 3 km. In the mid troposphere (4–8 km), up to a 20% higher occurrence of clouds and high reflectivity exists during the night than during the day (Figures 4a and 5a). In the upper troposphere (9–12 km), clouds (<–10 dBZ) happen more frequently during the night, but precipitation (>0 dBZ) happens more frequently during the day (Figures 4a and 5a). In the day, most of the convective systems over land are in an early development stage. There is more shallow precipitation, and more clouds with high reflectivity reaching high altitudes in deep convective cells [Liu and Zipser, 2005]. In the night, most of the convective systems that remain are in the dissipating stage, or are large MCSs with large stratiform fractions. There is much less deep convection [Nesbitt and Zipser, 2003].

[16] Over ocean, more clouds are detected below 2 km and at 10–13 km than at other altitudes by the CPR (Figure 4b). More clouds and precipitation are below 7 km during the night

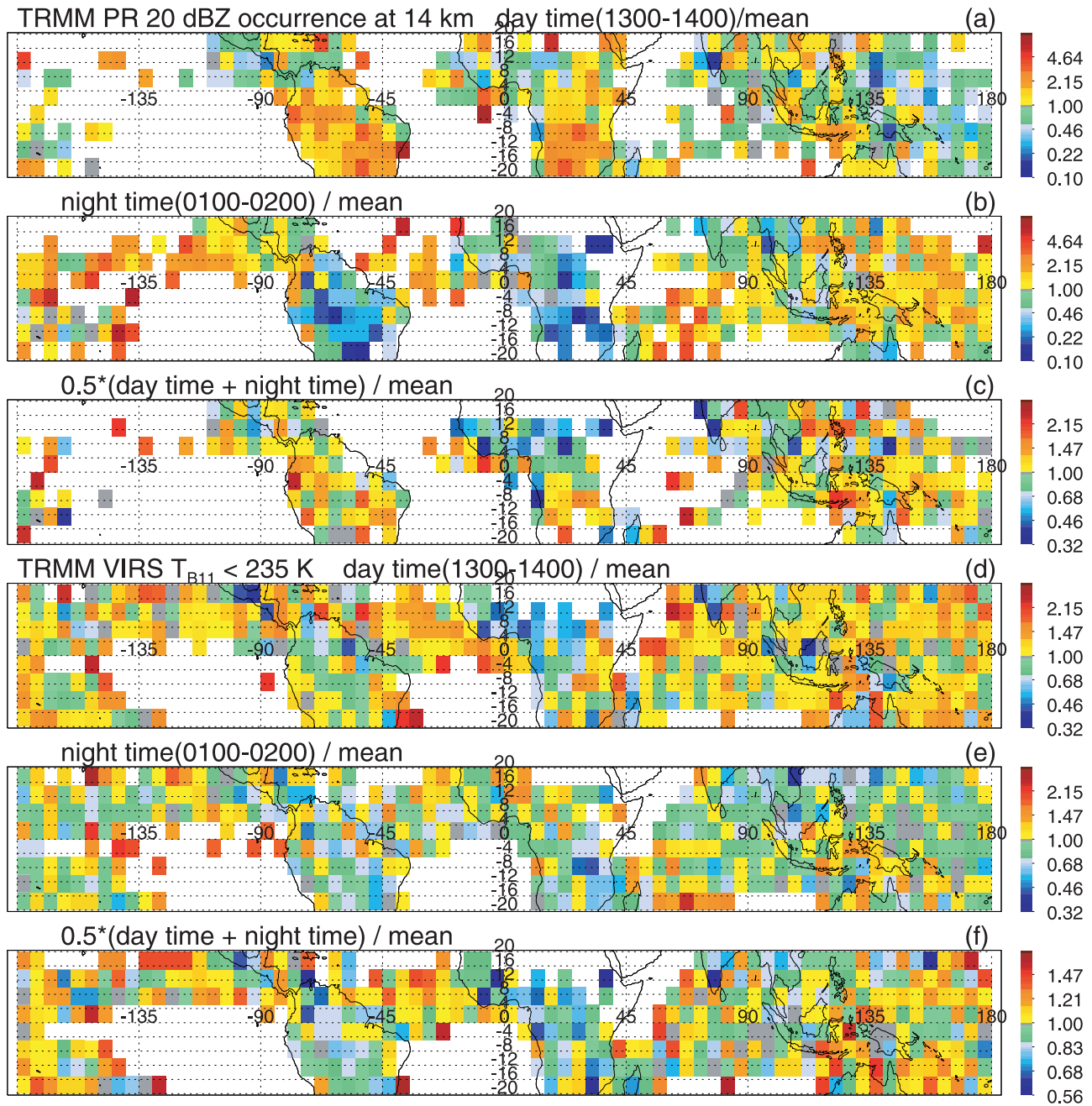
than during the day. However, more cloud pixels (including those <–10 dBZ), but less thick precipitating cloud pixels (>0 dBZ) are above 10 km during the day than at night. It seems possible that the greater occurrence of daytime high clouds can be residual cirrus clouds with low reflectivity (<10 dBZ) from early morning convection. However, diurnal cycles of precipitation and clouds over tropical oceans may include contributions from nocturnal convection, early morning convective showers, and shallow early afternoon showers [Sui *et al.*, 1997; Pereira and Rutledge, 2006; Liu and Zipser, 2008]. It may be premature to explain the differences between the day and nighttime cloud and precipitation statistics as a simple function of the life cycles of the early morning convective systems, thus further investigation is warranted.

### 3.3. Geographical Variation

[17] Several studies have shown the geographical distribution of clouds from CloudSat [e.g., Mace *et al.*, 2007]. Here we focus on the differences between the CloudSat CPR detected clouds and precipitation with reflectivity greater or equal to 10 dBZ in the upper tropical troposphere at 13–14 km during the 1330 and 0130 LT observation times. As shown in Figures 6a, 6b, and 6e, precipitation is more frequent over the ocean at 0130 LT and over land at 1330 LT at 13–14 km. Figures 6c, 6d, and 6f show that high clouds occur more frequently over the west Pacific, Africa, Panama, and Amazon at both 1330 and 0130 LT observation times. Consistent with Figure 4, in general high clouds are more frequent over the ocean at 1330 LT and over land at 0130 LT. The most noticeable exception is over Panama,

**Table 1.** Percentage Deviation of the TRMM Precipitation Volume, Area of Cold Clouds, Flashes, and Population of Precipitation Systems at 0100–0200 and 1300–1400 LT From the Mean Over Tropics (20°S–20°N)

	Land			Ocean		
	Day	Night	Average	Day	Night	Average
Population of PFs	58	–18	20	–10	16	3
Volumetric rain	29	–5	12	–6	8	1
Area of $T_{B11} < 210$ K	–31	–11	–21	–18	14	–2
Area of $T_{B11} < 235$ K	–18	–8	–13	15	–7	4
Flashes	12	–38	–13	–29	45	8

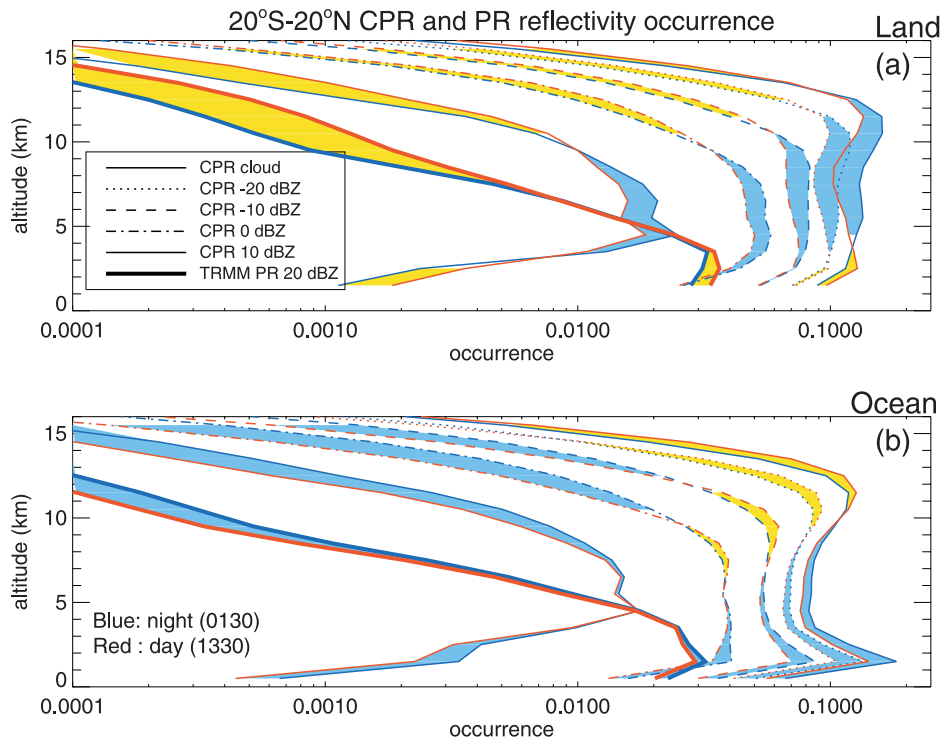


**Figure 3.** (a) Ratio of the occurrence of TRMM PR 20 dBZ at 14 km at 1300–1400 LT to the mean from 9 years of full day samples, only shown for  $5^\circ \times 5^\circ$  boxes with at least 10 pixels with 20 dBZ. (b) same as Figure 3a but for occurrence at 0100–0200 LT. (c) same as Figure 3a but for occurrence of averaging 0100–0200 and 1300–1400 LT, only shown for  $5^\circ \times 5^\circ$  boxes with at least 10 pixels with 20 dBZ at both 1300–1400 and 0100–0200 LT. (d) Ratio of the occurrence of TRMM VIRS  $T_{B11} < 235$  K at 1300–1400 LT to the mean from all day samples, only shown for  $5^\circ \times 5^\circ$  boxes with at least 10000 pixels with  $T_{B11} < 235$  K. (e) same as Figure 3d but for ratio of occurrence at 0100–0200 LT to the mean. (f) same as Figure 3d but for ratio of occurrence of averaging 0100–0200 and 1300–1400 LT to the mean.

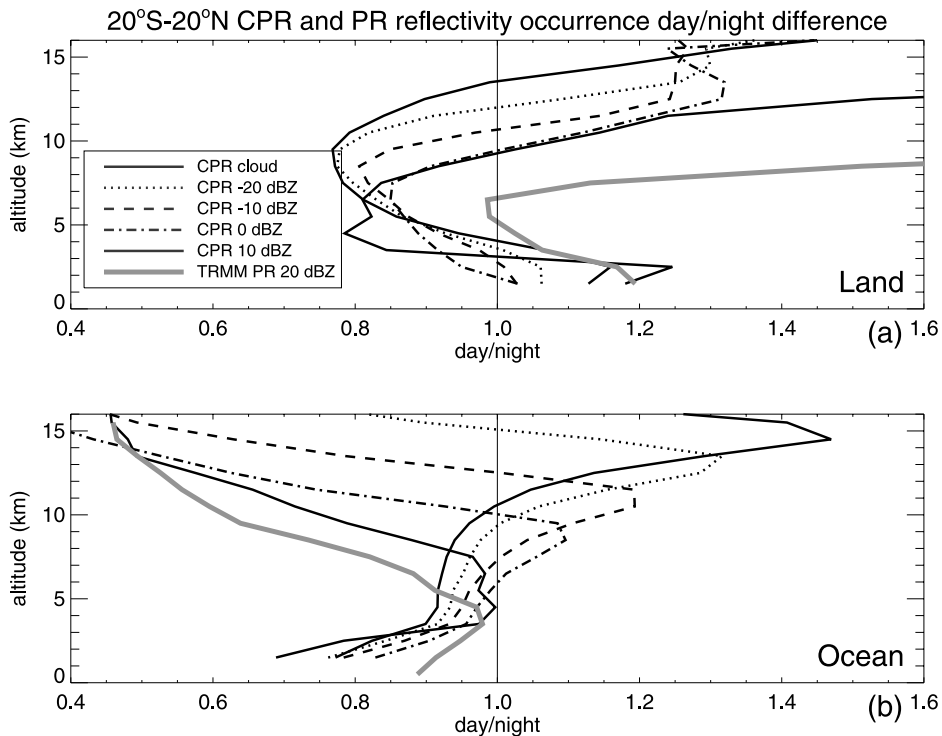
where there are more high clouds during the day, but more precipitation at night.

[18] For comparison, the occurrences of TRMM 20 dBZ at 14 km and cloud with  $T_{B11} < 235$  K during 0100–0200 and 1300–1400 LT and their differences are shown in Figure 7. The geographical distributions of precipitation from the TRMM PR and cloud from infrared images in

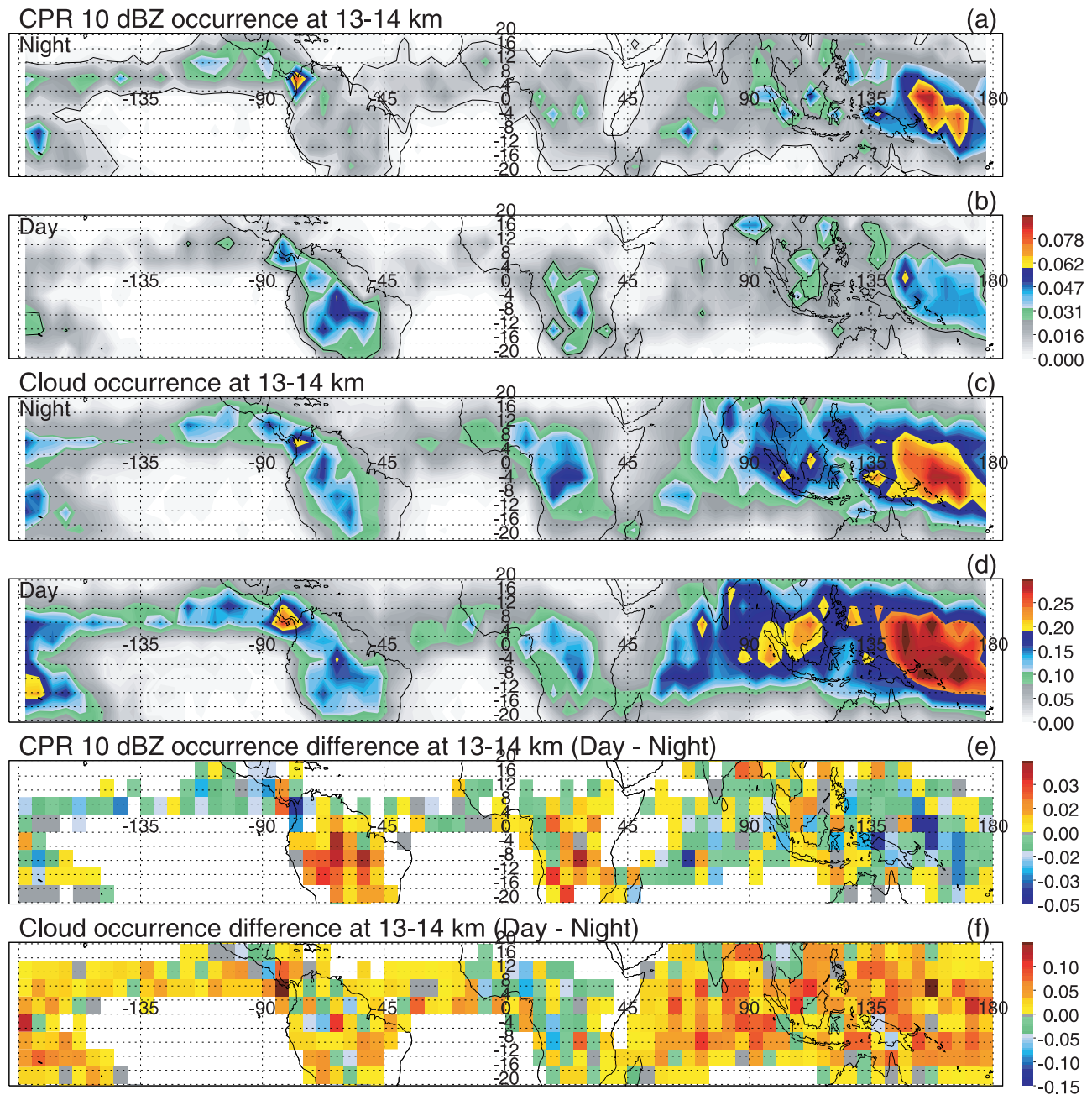
Figures 7a–7d are close to those shown in Figures 6a–6d, with the exception that TRMM PR 20 dBZ occurs less frequently over ocean than CPR 10 dBZ. The patterns of the differences between the daytime and the nighttime precipitation with TRMM PR  $>20$  dBZ at 14 km in Figure 7e and cold clouds in Figure 7f are consistent with Figures 6e and 6f, including the exception over Panama.



**Figure 4.** Occurrence (fraction) of sampled pixels with cloud mask,  $-20$ ,  $-10$ ,  $0$ , and  $10$  dBZ observed by CloudSat CPR and  $20$  dBZ observed by TRMM PR at different altitudes over tropical (a) land and (b) ocean ( $20^{\circ}\text{S}$ – $20^{\circ}\text{N}$ ) at the A-Train day ( $1330$  LT) and night ( $0130$  LT) observation times. Here TRMM PR occurrences are summarized from the observations during  $0100$ – $0200$  and  $1300$ – $1400$  local time. The vertical bin size is  $1$  km. Light blue (yellow) filled areas indicate differences when nighttime occurrence is greater (less) than that of daytime.



**Figure 5.** Ratios from the daytime to the nighttime CPR and PR reflectivity occurrences over (a) land and (b) ocean in Figure 3.



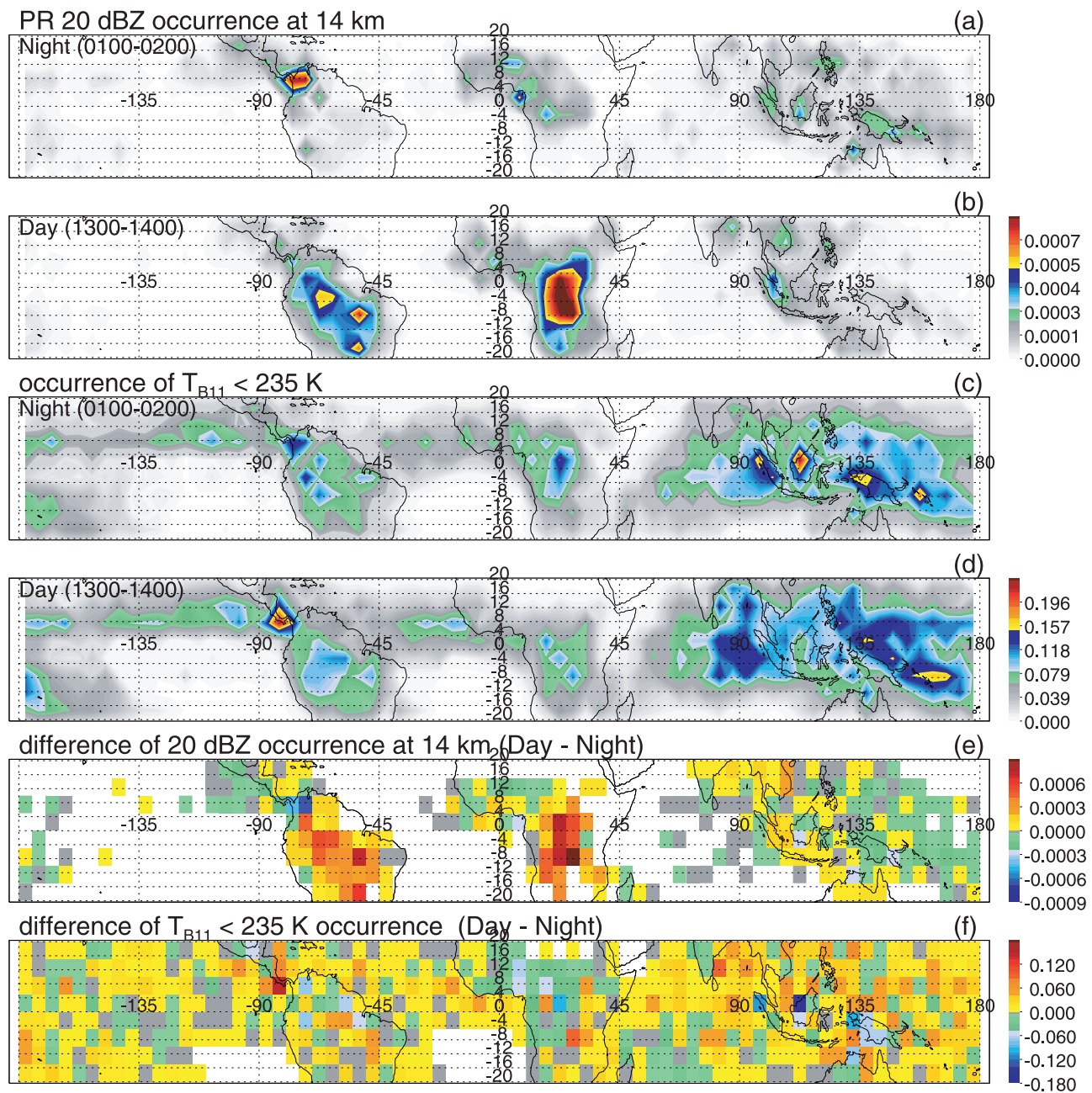
**Figure 6.** (a) Occurrence (fraction) of CloudSat CPR reflectivity greater or equal to 10 dBZ at 13–14 km at nighttime. (b) Same as Figure 6a but for daytime. (c) Occurrence of clouds detected by CloudSat CPR at 13–14 km at nighttime. (d) Same as Figure 6c but for daytime. (e) Differences between daytime and nighttime CPR 10 dBZ occurrences restricted to  $5^\circ \times 5^\circ$  boxes with at least 1000 pixels with 10 dBZ in both Figures 6a and 6b. (f) Differences between daytime and nighttime CPR cloud occurrences restricted to  $5^\circ \times 5^\circ$  boxes with at least 1000 pixels with cloud mask in both Figures 6c and 6d.

### 3.4. Seasonal Variation

[19] Large deviations between the amounts of precipitation and clouds observed at the A-Train observation times and the amounts from the full day average were shown in section 3.1. In this section we try to show how different the seasonal cycles of precipitation and clouds sampled at A-Train times are from the seasonal cycle from the full day samples. The normalized seasonal variation of the occurrence of CloudSat CPR cloud and precipitation with 10 dBZ or greater at 13–14 km over tropical land and ocean are shown in Figures 8a–8d. There are

some differences between the seasonal variation of the high clouds and precipitation at 1330 LT and those from the seasonal variations at 0130 LT. Over land, large differences occur in July–August, due to a larger contribution of high cloud at 0130 LT. In November there is a larger contribution of high cloud at 1330 LT (Figures 8a and 8c). Over ocean, the seasonal variation of high clouds at 1330 LT and at 0130 LT show large differences in July and October (Figures 8b and 8d).

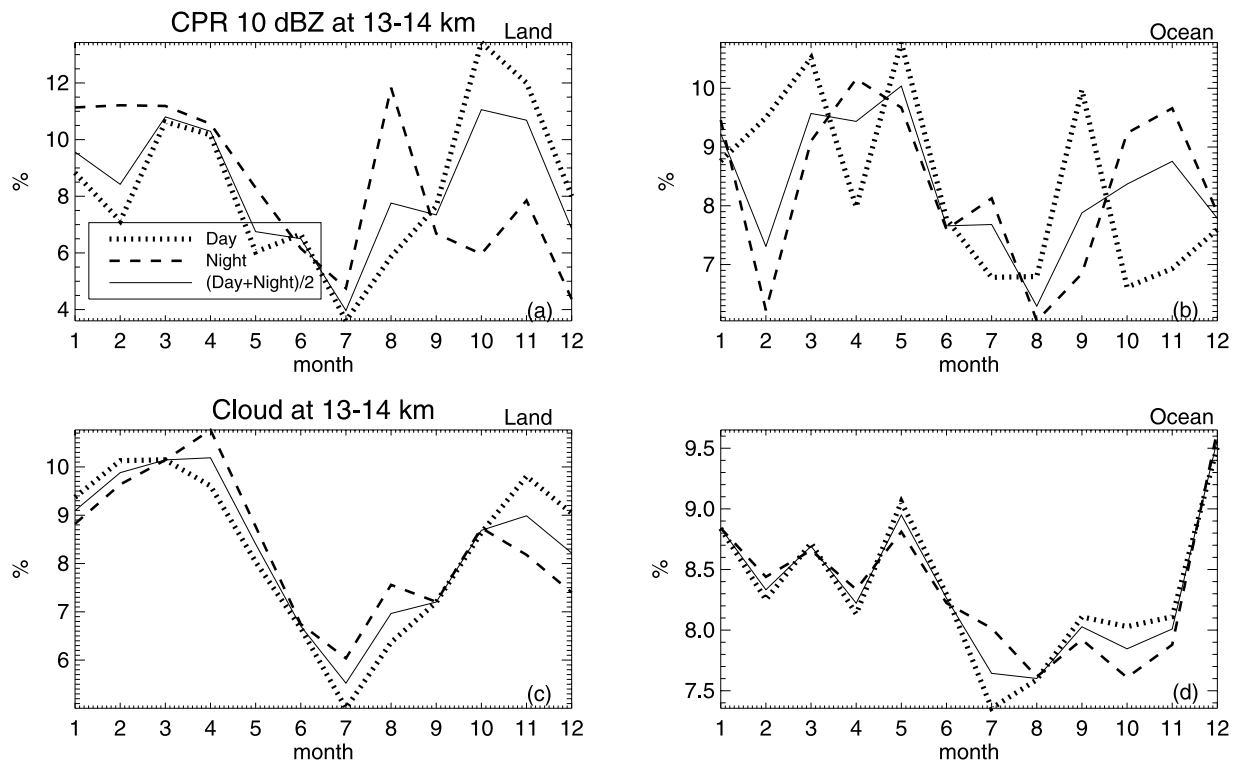
[20] For comparison, the seasonal variations of the occurrence of TRMM PR 20 dBZ at 14 km, and cloud with



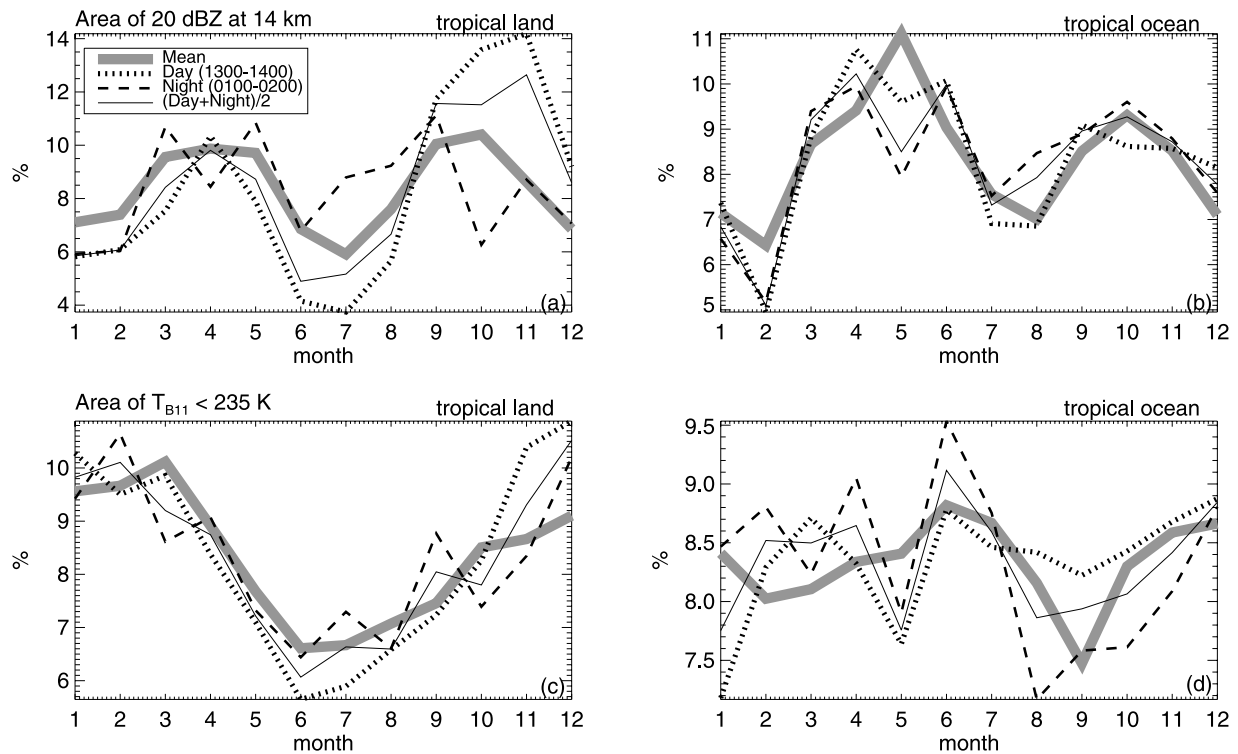
**Figure 7.** (a) Occurrence of TRMM PR reflectivity greater or equal to 20 dBZ at 14 km for nighttime (0100–0200 LT). (b) same as Figure 7a but for daytime (1300–1400 LT). (c) Differences between daytime and nighttime. (d) Occurrence of TRMM VIRS  $T_{B11} < 235$  K for nighttime (0100–0200 LT). (e) Differences (Figures 7a and 7b) between daytime and nighttime occurrence of PR 20 dBZ at 14 km restricted to  $5^\circ \times 5^\circ$  boxes with at least 10 pixels of 20 dBZ in both Figures 7a and 7b. (f) Differences between daytime and nighttime occurrence of cloud colder than 235 K restricted to  $5^\circ \times 5^\circ$  boxes with at least 1000 pixels of cloud colder than 235 K in both Figures 7a and 7b.

VIRS  $T_{B11} < 235$  K at 0100–0200 and 1300–1400 LT are shown in Figure 9. Because of interannual variability, some differences between the seasonal variation of cloud and precipitation from the 9 year TRMM database in Figure 9 and those from 1 year of CloudSat data in Figure 8 are to be expected. Here we focus on the differences between the seasonal cycles of cloud and precipitation generated from the daytime and the nighttime. The differences between the daytime and the nighttime high clouds from TRMM VIRS

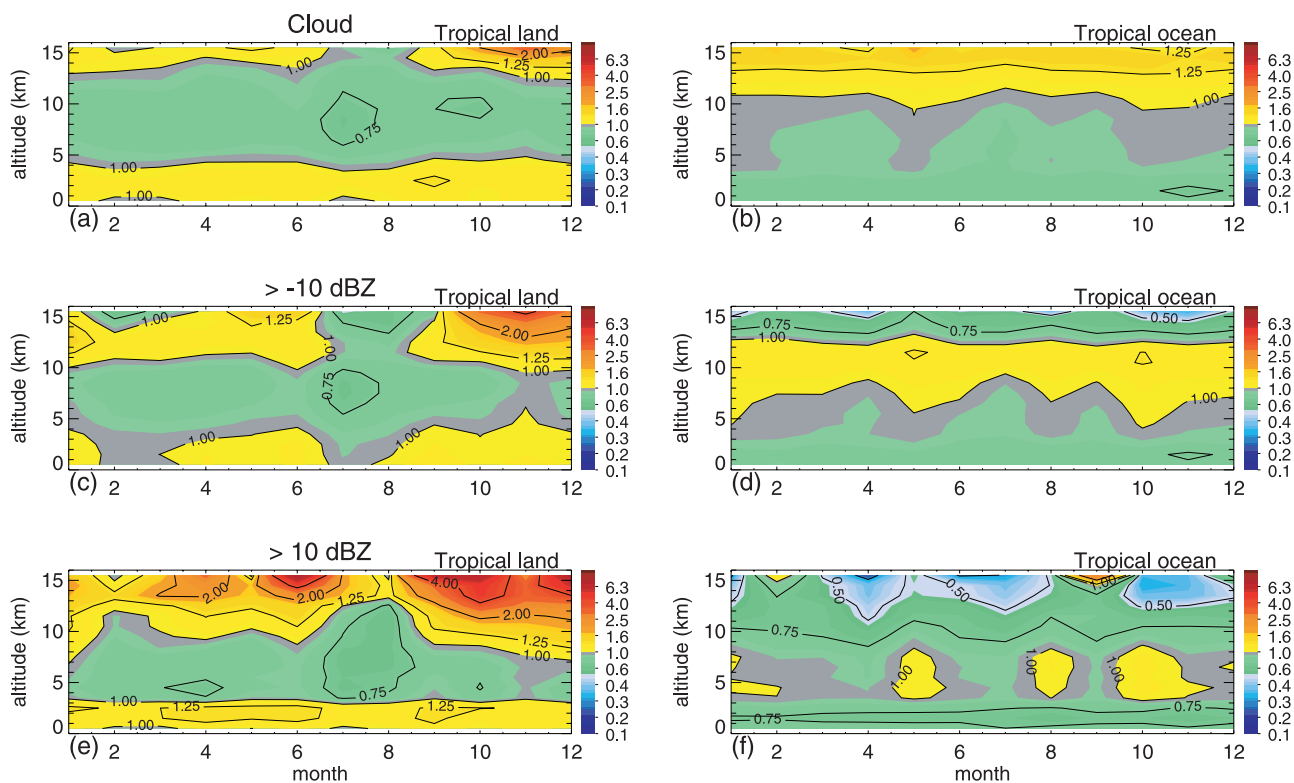
in Figures 9a–9d closely resemble the patterns of the differences from the CloudSat observations as shown in Figures 8a–8d. It is important to note that neither the seasonal cycles of high clouds at 1330 LT nor at 0130 LT can well represent the seasonal cycle derived from the mean of full day samples (thick gray line in Figure 9), especially over tropical oceans (Figures 9b and 9d). This suggests large seasonal variations in the diurnal cycles of cloud and precipitation over some parts of the Tropics.



**Figure 8.** Seasonal variation of (a and b) occurrence of CPR 10 dBZ at 13–14 km and (c and d) occurrence of CloudSat CPR clouds at 13–14 km over tropical land and ocean (20S°–20N°). The mean values for month 1–6 are from data in 2007, and the mean values for month 7–12 are from data in 2006.



**Figure 9.** Seasonal variation of area of (a and b) PR 20 dBZ reaching 14 km and (c and d)  $T_{B11} < 235$  K from all the TRMM observations and from only the TRMM observations during 0100–0200 and 1300–1400 local time over tropical land and ocean (20°S–20°N).



**Figure 10.** Seasonal variation of ratios of occurrences of (a and b) CloudSat cloud, (c and d) CPR reflectivity  $> -10$  dBZ, and (e and f) CPR reflectivity  $> 10$  dBZ in the daytime to those at night over land and ocean. The mean values for month 1–6 are from data in 2007, and mean values for month 7–12 are from data in 2006.

[21] As shown in Figure 10, the day to night ratios of cloud and precipitation occurrence vary seasonally at different altitudes. This is caused by the seasonal variation of the amplitude or phase of the diurnal cycles of cloud and precipitation. Consistent with Figures 4a and 5a, precipitation over land occurs more frequently at the daytime and clouds occur more frequently at the nighttime at 10–13 km during most of the year with the exception that both clouds and precipitation occur more frequently during the night in July and August at these levels. Large differences among the vertical structures of day versus night ratios of occurrence of CPR pixels with cloud mask,  $-10$  dBZ and  $10$  dBZ exist over the ocean. Consistent with Figure 8b, May, July and October (Figure 10f) show large day versus night differences in clouds and precipitation. Further investigations of these variations are needed to properly interpret the day-night seasonal differences of clouds.

### 3.5. Sample Size

[22] Because only 1 year of CloudSat data is used in the above discussion, a large enough sample size is important for the robustness of the statistics. This discussion focuses on the sample size of the geographical distribution of cloud and precipitation occurrence shown in Figures 6 and 7 because it has a smaller sample size than the seasonal and vertical distributions shown in Figures 4, 5, 8 and 9.

[23] The mean of the total number of sampled columns in a  $5^\circ \times 5^\circ$  box in  $20^\circ\text{S}$ – $20^\circ\text{N}$  from 1 year of CloudSat data is approximately 37,500. Since pixels are accumulated in each

column at a 1 km vertical interval, and considering each CloudSat column has a  $\sim 240$  m vertical resolution, more than 150,000 pixel samples are in a  $5^\circ \times 5^\circ$  box at each 1 km vertical interval. A CPR cloud or precipitation pixel represents  $\sim 6.6 \times 10^{-6}$  fractional occurrence. This is at least three orders of magnitude lower than the occurrences shown in Figures 6a, 6b, and 6e, and about four orders of magnitude lower than the occurrences shown in Figures 6c, 6d, and 6f. Therefore, the fractional occurrences shown in Figure 6 are in no way near the margins of sampling.

[24] Compared to the CloudSat CPR, the TRMM PR samples about four times less frequently along the orbit because of its larger footprint, although it samples 49 times more frequently at each scan across the orbit swath. Since only 1/24 of the samples are used to match CloudSat overpass times, even with 9 years of TRMM PR data, only  $\sim 670,000$  samples are in a  $5^\circ \times 5^\circ$  box in Figure 7. A pixel with 20 dBZ represents about  $1.5 \times 10^{-6}$  fractional occurrence. This is about two orders of magnitude lower than those shown in Figures 7a, 7b, and 7e, and four orders of magnitude lower than those shown in Figures 7c, 7d, and 7f. To avoid regions with marginal sample size, the occurrence differences in Figure 7e and Figures 3a–3c are only shown for boxes with at least 10 pixels of 20 dBZ.

[25] In Figure 9, we did not use seasonal cycles from the same time period of TRMM PR data as CloudSat. This is because there would be serious diurnal sampling biases if we subsample at CloudSat overpass times from only a

month of TRMM PR data to generate the seasonal cycles [Negri et al., 2002; Fisher, 2007].

#### 4. Summary

[26] 1. Substantial differences in the climatologies of cloud and precipitation sampled at the A-Train overpass times exist when compared to the daily average climatologies. The difference is larger over land than over ocean, especially at higher altitudes where the diurnal cycle has larger amplitudes.

[27] 2. Cloud and precipitation show different day versus night occurrence frequencies in the upper troposphere over tropical land and ocean at A-Train overpass times. High clouds are found to occur much more frequently during the daytime overpass time. This may be due to the phase lags between precipitation and clouds in the life cycles of the convective systems over land and ocean.

[28] 3. There are differences between the seasonal cycles of cloud and precipitation over the tropics sampled at 0130 LT and those sampled at 1330 LT. Simulation of sampling at A-Train overpass times using TRMM data suggests that the seasonal variations of clouds sampled at A-Train overpass times are different from the seasonal cycles of clouds derived from full day averages. This may be explained by the seasonal variation of the diurnal cycles over tropics.

[29] These results suggest the importance of interpreting the CloudSat and other A-Train observations at 1330 and 0130 LT as independent samples at their respective times within the diurnal cycle. This is especially important if the data are to be used for climate model validation. Unfortunately, most climate models currently generate output statistics only every 3 h. It is clear that the vertical structure of precipitation and clouds vary significantly on this time scale (Figure 1). Therefore, it is important that models are sampled in ways that account for the physical processes that drive the diurnal cycle of the tropical atmosphere if comparisons to observations are to be beneficial.

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