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Diurnal cycles of precipitation, clouds, and lightning in the tropics from 9 years of TRMM observations

Chuntao Liu[1] and Edward J. Zipser[1]

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[1] The diurnal cycles of surface rainfall, population of precipitation systems, deep intense convection reaching near the tropopause, lightning flash counts, cold clouds, and vertical structure of precipitation are analyzed over the tropics, using 9 years of TRMM Precipitation Radar, Visible and Infrared Scanner, and Lightning Imaging Sensor measurements. The diurnal cycles over land include a late afternoon maximum of precipitation systems, with phase differences among cloud, precipitation, flash counts, and radar echo at different altitudes. Over ocean, the diurnal cycles are interpreted as having contributions from nocturnal precipitation systems and early afternoon showers. There are double peaks of radar reflectivity above 12 km near 0230 and 0530 local time over oceans. The oceanic clouds with infrared brightness temperature < 235 K have two peaks, one during the night and the other in early afternoon. **Citation:** Liu, C., and E. J. Zipser (2008), Diurnal cycles of precipitation, clouds, and lightning in the tropics from 9 years of TRMM observations, *Geophys. Res. Lett.*, *35*, L04819, doi:10.1029/2007GL032437.

1. Introduction

[2] Before the launch of the Tropical Rainfall Measuring Mission (TRMM) satellite [*Kummerow et al.*, 1998] in late 1997, most studies of the diurnal cycle of tropical convective clouds used infrared data only [e.g., *Fu et al.*, 1990; *Janowiak et al.*, 1994; *Garreaud and Wallace*, 1997]. A typical metric would be the area covered by clouds whose outgoing long wave radiation (or IR brightness temperature) was less than some specified value [e.g., *Hall and Vonder Haar*, 1999; *Yang and Slingo*, 2001]. The area covered by cold cloud was often used as a proxy for coverage of deep or intense convection, or for rainfall. The association is a logical one, because high cold clouds are usually anvil clouds produced directly by deep precipitating convective clouds.

[3] Using the Precipitation Radar (PR), the Visible and Infrared Scanner (VIRS), and the Lightning Imaging Sensor (LIS) on the TRMM satellite, it is possible now to separate information on clouds, precipitation, and lightning, and to demonstrate the intensity of the precipitating convection, and do so globally [*Nesbitt and Zipser*, 2003; *Cecil et al.*, 2005; *Liu et al.*, 2007]. The vertical structure of the precipitating systems can be revealed by TRMM PR measurements [e.g., *Heymsfield et al.*, 2000].

[1]Department of Meteorology, University of Utah, Salt Lake City, Utah, USA.

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[4] The motivation of this work is to address the following questions: (1) How does the vertical structure of precipitating systems vary diurnally? (2) What are the differences among the diurnal cycles of the cloud, precipitation and lightning in tropics (20°N–20°S)? And how they are related to the life cycles of the precipitating systems?

[5] To answer these questions, first we demonstrate the diurnal variations of precipitation occurrences at different altitudes using 9 years of TRMM PR observations. Then we generate the diurnal cycles of selected parameters representing deep convection, precipitation, cold clouds, and lightning from 9 years of PR, VIRS and LIS observations. The phase and amplitude of the diurnal cycles of these parameters are compared over land and ocean, and the results interpreted with respect to the life cycles of individual precipitation systems.

2. Data and Methods

[6] The occurrence of 20 dBZ reflectivity at different altitude levels is used to demonstrate precipitation occurrence as a function of height. To generate the diurnal variation of precipitation occurrence, first the pixels with PR reflectivity $\geq$ 20 dBZ and the total PR samples are summarized in $1^\circ \times 1^\circ$ grid boxes in 24 1-hour local time bins at 1-km altitude bins from 1 km to 16 km using 9 years (1998–2006) TRMM PR data. Then the 20 dBZ occurrences in the selected regions are calculated by dividing the total number of 20 dBZ pixels in the grid boxes within each region by the total samples within each region. In this paper, we only show the results of 20 dBZ occurrence over land and ocean regions between 20°N–20°S.

[7] To demonstrate the diurnal cycles of cloud, precipitation, intense convection and lightning, we have chosen six parameters (listed in Table 1) representing total precipitation, population of the precipitation systems, deep convection reaching to near the tropopause, cold clouds and lightning. The diurnal cycles of these parameters are generated by accumulating each parameter in 24 1-hour local time bins over selected regions from 9 years of PR, VIRS and LIS observations. Then we normalize the diurnal variation of each parameter and generate the percentage distribution in hourly bins so that amplitudes and the phases of diurnal cycles of all parameters can be compared together.

3. Results

3.1. Diurnal Variation of Vertical Structure of Precipitation

[8] Diurnal variations of 20 dBZ occurrences over land and ocean from 20°S–20°N are shown in Figure 1. Consistent with past studies [e.g., *Hall and Vonder Haar*, 1999; *Yang and Slingo*, 2001; *Tsakraklides and Evans*, 2003;

Table 1. Parameters Representing the Cloud, Precipitation, and Lightning

Parameters	Definitions
Total precipitation	Volumetric near surface rainfall retrieved from PR [*Iguchi et al.*, 2000]
Population of precipitation systems	Population of precipitation features defined by grouping raining pixels by PR [*Nesbitt et al.*, 2000; C. Liu et al., A cloud and precipitation feature database from 9 years of TRMM observations, submitted to *Journal of Applied Meteorology and Climatology*, 2007].
Deep convection reaching to near the tropopause	Area with PR 20 dBZ at 14 km [*Liu and Zipser*, 2005]
Very cold cloud	Area with VIRS infrared cloud top brightness temperature (T_{B11}) < 210 K
Cold cloud	Area with VIRS T_{B11} < 235 K
Lightning	Total LIS flash counts

Nesbitt and Zipser, 2003], there is stronger diurnal variation over land than over ocean. The daytime maximum 20 dBZ occurrence over land is greater than the night time maximum 20 dBZ occurrence over ocean. Note that the 20 dBZ occurrence is underestimated below 2 km over land and below 1.5 km over ocean due to contamination from ground clutter.

[9] To demonstrate the amplitude of the diurnal variations of precipitation at different altitudes, 20 dBZ occurrences in Figure 1 are normalized at each altitude and the 20 dBZ frequency is contoured with altitude vs. time in Figure 2. Two immediate conclusions can be drawn from the Figure 2. First, amplitudes of the diurnal variations of precipitation occurrences increase with height. Second, precipitation occurrence maximizes at different times at

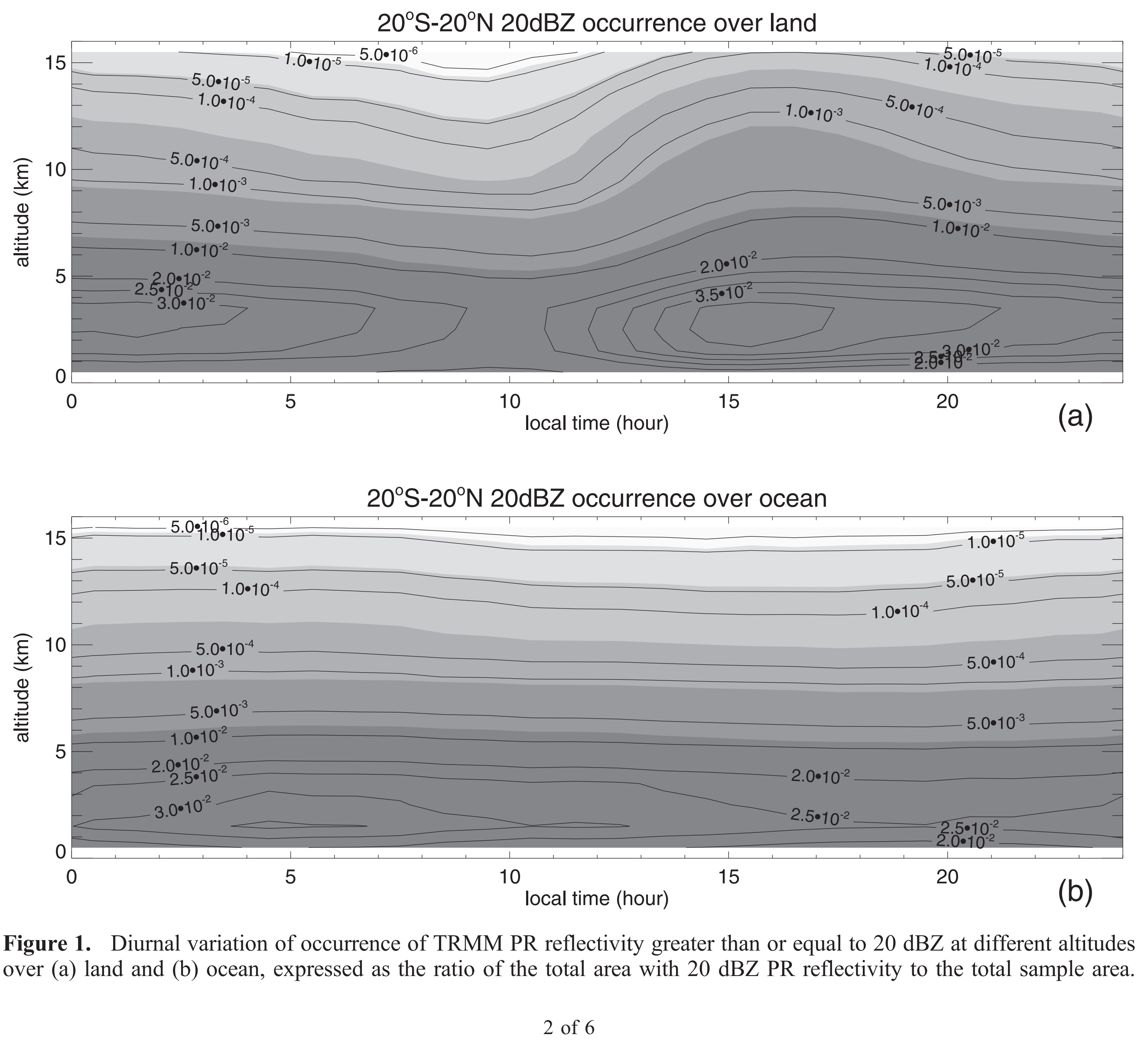

Figure 1. Diurnal variation of occurrence of TRMM PR reflectivity greater than or equal to 20 dBZ at different altitudes over (a) land and (b) ocean, expressed as the ratio of the total area with 20 dBZ PR reflectivity to the total sample area.

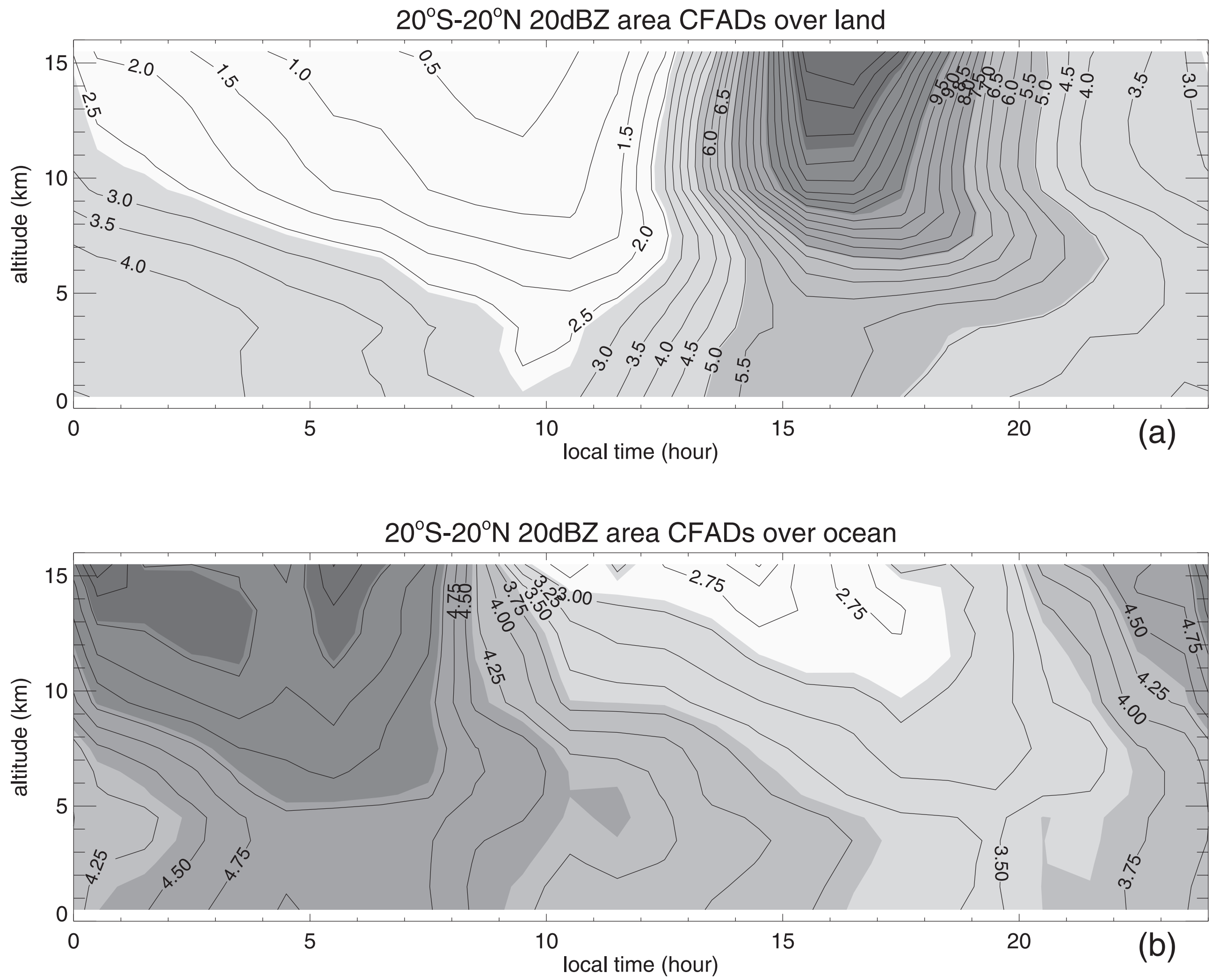

Figure 2. Contoured frequency of area with PR reflectivity greater than or equal to 20 dBZ with altitude vs. time over (a) land and (b) ocean. Units are in %.

different altitudes. Over tropical land, the 20 dBZ occurrence maximizes around 1500–1700 (only local time used in this paper) above 10 km. 1–2 hours later, the 20 dBZ occurrence maximizes in the mid troposphere from 5 km to 9 km. Over tropical ocean, it is interesting that there are two peaks of 20 dBZ occurrence above 12 km around 0230 and 0530. 20 dBZ in the mid troposphere from 5 km to 9 km occurs mainly from 0400–0700. There is an extended tongue of high 20 dBZ occurrence around 4 km to early afternoon over ocean. Some of the detailed features in Figure 2 are not as apparent in Figure 1 is because the absolute values of 20 dBZ occurrence decrease dramatically with height. To clarify the possible impact of coastal systems, we have done the similar analysis for the selected oceanic regions far from land. The two peaks of high altitude 20 dBZ occurrences and the high early afternoon 20 dBZ occurrence around 4 km were also found (figures not shown).

3.2. Differences Among Diurnal Cycles of Cloud, Precipitation, and Lightning

[10] The diurnal cycles of six parameters representing precipitation volume, population of precipitation systems, deep convection reaching to near the tropopause, cold clouds, and lightning over land and ocean from 20°N–20°S are shown in Figure 3. The diurnal cycle of total precipitation confirms *Nesbitt and Zipser*'s [2003] results even without covering the subtropical regions. Obviously, there are large differences among the amplitudes and phases of diurnal cycles of these parameters. To quantitatively compare the amplitudes and phase lags among them, Diurnal cycles of all six parameters are calculated in the selected regions using harmonic analysis. The first harmonic (S1) phase and amplitude are listed with the maximum and minimum phases in Table 2. Notice that S1 phases are not necessarily consistent with the phases of absolute maxima for all variables.

[11] Over land, S1 phases are found 0.5 ~ 1 hour later than the phases of the maxima variously for each parameter. But they can still be used as fair indicators for the phase lags in different variables. Firstly, the population of precipitation systems reaches its maximum late afternoon, followed in quick succession by the development of deep intense convection with 20 dBZ reaching 14 km accompanied with maximum flash counts and surface rainfall. After gradual spreading of anvil clouds, the amount of 210 K (~13.5 km)

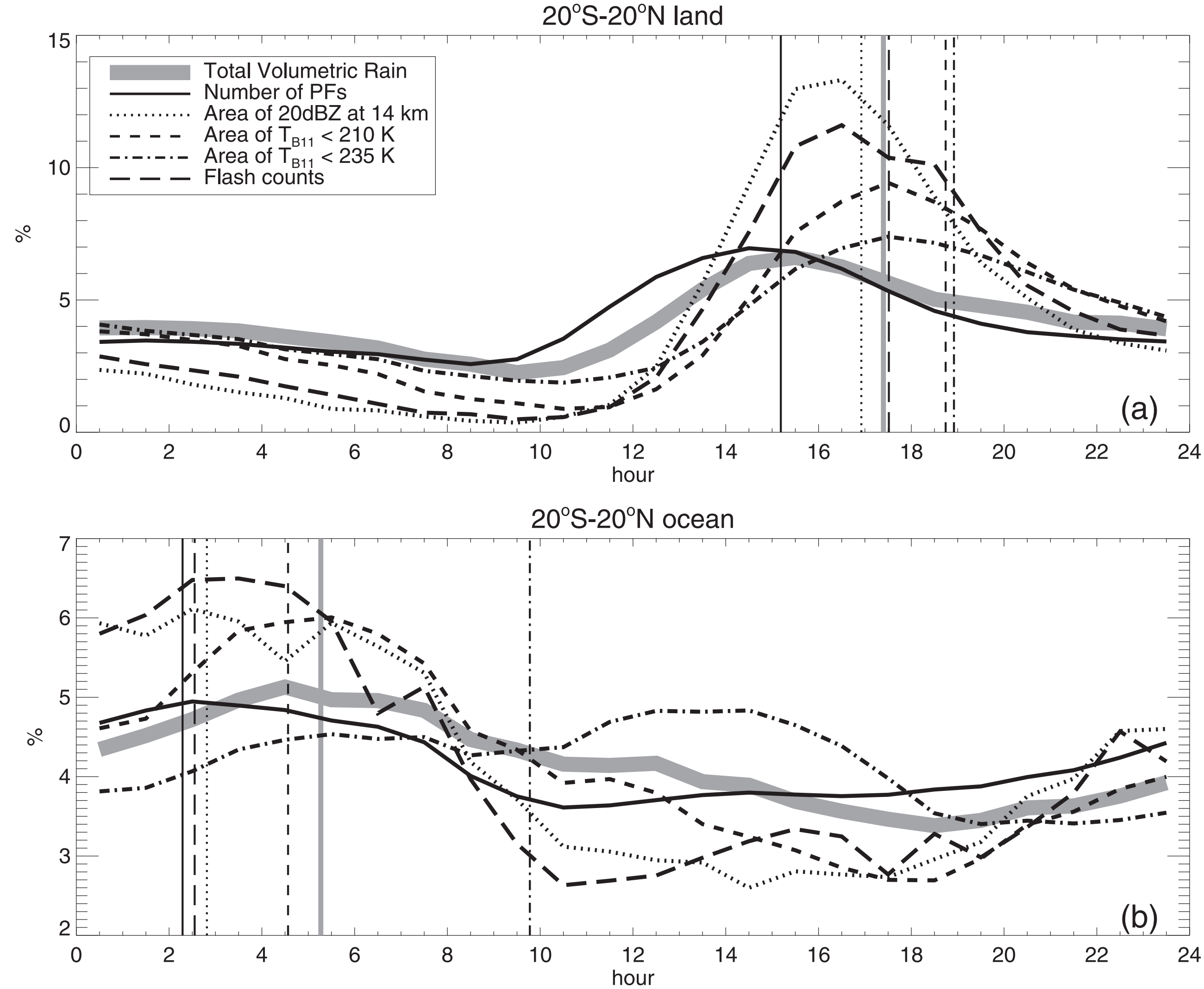

Figure 3. Diurnal variation of total volumetric rainfall, population of precipitation systems, area of 20 dBZ reaching 14 km, area of cold clouds with $T_{B11} < 210$ K and 235 K, and flash counts over (a) land and (b) ocean in 20°S–20°N. The vertical lines represent the location of the diurnal harmonic phase (S1). Diurnal cycles over land are stronger than over ocean with a larger scale range in Figure 3a.

and 235 K (~10.3 km) clouds increase to a maximum in 2–3 hours. This similar pattern can be found for different tropical land regions (Table 2, figures not shown), although there are regional differences in the phase lags. For example, convection over Indonesia has the latest and longest life cycle of the three tropical land regions.

[12] Over oceans, S1 phases cannot indicate the phase lags among the diurnal variations of different variables because of the multiple modes in the variations, especially for cold cloud with infrared brightness temperature (T_{B11}) < 235 K (Table 2, Figure 3). Deep intense convection reaching near the tropopause, area of very cold clouds with $T_{B11} < 210$ K, and flash counts show stronger diurnal variation than the -diurnal variations of area of $T_{B11} < 235$ K and the population of precipitation systems. There are two peaks of area of $T_{B11} < 235$ K, one during the night and the other in early afternoon. The two-peak patterns over the east and west Pacific, and the north Atlantic suggest that the early afternoon maxima are not related to coastal effects (figures not shown). In general, precipitation systems have peak occurrence near 0230, followed in quick succession by deep intense convection with flashes, if any (oceanic lightning is rare [*Cecil et al.*, 2005]), and then very cold clouds (<210 K), with heavy precipitation, in the early morning. During the early afternoon, there is a weak second peak of precipitation systems under a larger area of 235 K clouds.

4. Summary and Discussion

[13] The composite life cycle of tropical precipitation systems are demonstrated both by diurnal cycle of precipitation occurrence at different altitudes and by the phase lags among the diurnal cycles of deep convection, precipitation, cloud and lightning over tropics using a large volume of data. Over land, consistent with earlier research [e.g., *Gray and Jacobson*, 1977; *Augustine*, 1984; *Nesbitt and Zipser*, 2003], diurnal cycles of cloud, precipitation and lightning

Table 2. Maximum Periods, First Harmonic Phases, and Amplitudes of the Diurnal Cycles of Precipitation Population, Flashes, 20 dBZ Reaching 14 km, Area of 210 K, 235 K Clouds, and Rain Volume Over Different Tropical Regions[a]

Regions		Population	Flashes	20 dBZ at 14 km	Rain Volume	210 K Clouds	235 K Clouds
All land	Maximum time	14:00–15:00	16:00–17:00	16:00–17:00	15:00–16:00	17:00–18:00	17:00–18:00
180°W–180°E 20°S–20°N	Minimum time	08:00–09:00	09:00–10:00	09:00–10:00	09:00–10:00	10:00–11:00	10:00–11:00
	Harmonic phase	15:10	17:30	16:55	17:23	18:44	18:55
	Amplitude (%)	19	52	58	16	38	27
Congo	Maximum time	15:00–16:00	15:00–16:00	15:00–16:00	15:00–16:00	17:00–18:00	17:00–18:00
15°–32°E 10°S–5°N	Minimum time	09:00–10:00	09:00–10:00	09:00–10:00	10:00–11:00	11:00–12:00	10:00–11:00
	Harmonic phase	15:35	17:17	16:30	16:21	18:25	19:01
	Amplitude (%)	16	47	58	9	39	26
Amazon	Maximum time	14:00–15:00	16:00–17:00	15:00–16:00	14:00–15:00	17:00–18:00	17:00–18:00
54°–75°W 12°S–3°N	Minimum time	08:00–09:00	08:00–09:00	09:00–10:00	10:00–11:00	10:00–11:00	09:00–10:00
	Harmonic phase	14:00	16:22	16:04	14:18	17:23	17:53
	Amplitude (%)	26	52	64	13	41	27
Indonesia	Maximum time	14:00–15:00	16:00–17:00	16:00–17:00	15:00–16:00	18:00–19:00	17:00–18:00
90°–170°E 10°S–10°N	Minimum time	08:00–09:00	10:00–11:00	08:00–09:00	09:00–10:00	11:00–12:00	09:00–10:00
(land only)	Harmonic phase	15:35	17:47	17:35	18:19	19:56	19:36
	Amplitude (%)	20	54	54	23	33	23
All ocean	Maximum time	2:00–3:00	3:00–4:00	2:00–3:00	4:00–5:00	5:00–6:00	14:00–15:00
180°W–180°E 20°S–20°N	Minimum time	10:00–11:00	10:00–11:00	14:00–15:00	18:00–19:00	18:00–19:00	19:00–20:00
	Harmonic phase	2:17	2:33	2:48	5:16	4:30	9:46
	Amplitude (%)	7	21	21	9	17	7
West Pacific	Maximum time	2:00–3:00		1:00–2:00	4:00–5:00	4:00–5:00	15:00–16:00
90°–170°E 15°S–15°N	Minimum time	10:00–11:00		14:00–15:00	18:00–19:00	18:00–19:00	19:00–20:00
(ocean only)	Harmonic phase	3:05		2:20	5:31	4:54	9:30
	Amplitude (%)	3		22	11	18	7
East Pacific	Maximum time	1:00–2:00		1:00–2:00	4:00–5:00	5:00–6:00	12:00–13:00
90°–180°W 2°–13°N	Minimum time	09:00-10:00		13:00–14:00	21:00–22:00	13:00–14:00	21:00–22:00
	Harmonic phase	1:19		2:37	5:39	3:42	10:22
	Amplitude (%)	4		18	6	18	6
Atlantic	Maximum time	2:00–3:00		0:00–1:00	5:00–6:00	3:00–4:00	13:00–14:00
15°–45°W 0–10°N	Minimum time	09:00–10:00		18:00–19:00	18:00–19:00	17:00–18:00	18:00–19:00
	Harmonic phase	1:17		2:45	5:08	2:44	8:10
	Amplitude (%)	4		17	8	23	6

[a]First harmonic, S1; Amplitude is calculated by amplitude of S1 / Amplitude of S0 and in unit %. Phase and amplitude of flashes are not analyzed for individual ocean regions because of the small sample sizes.

can be easily interpreted, with life cycle of precipitation systems dominated by the afternoon convection.

[14] Over ocean, the diurnal cycles of precipitation and lightning may be interpreted in terms of the life cycles of nocturnal convective systems and early afternoon showers in general. However, there are two aspects of diurnal cycles of precipitation and clouds need further understanding.

[15] (1) First, in Figure 2b, there are double peaks of high occurrences of precipitation area above 12 km over ocean. The first peak near 0230 is accompanied with relatively less surface precipitation than the second peak near 0530 (Figure 2). From the literature, this may be explained by deep convection inside the nocturnal convective systems, and the morning cumulus over the West Pacific [*Sui et al.*, 1997], or under different synoptic wind regimes over East Pacific [*Pereira and Rutledge*, 2006].

[16] (2) The amplitude of the double peak of tropical oceanic clouds with $T_{B11} < 235$ K is much stronger than the signal of two peaks of tropical oceanic precipitation. This may help explain the reports of double peaks of oceanic rainfall retrieved from IR images [e.g., *Augustine*, 1984]. The oceanic afternoon convective showers are evident from the extension of the high 20 dBZ occurrence around 5 km in early afternoon. However, these convective showers are relatively weak without radar echo at high altitudes and very cold clouds (Figures 2b and 3b). Why are there large amounts of cold clouds with $T_{B11} < 235$ K in early afternoon? We speculate that some cirrus clouds may appear as relatively warmer clouds due to penetration of the longwave radiation from below. This assumes that there are indeed large amounts of daytime cirrus clouds over tropical oceans, which needs to be verified.

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C. Liu and E. J. Zipser, Department of Meteorology, University of Utah, 135 S 1460 E Room 819, Salt Lake City, UT 84112-0110, USA. (liu.c.t@utah.edu)