Diurnal Cycles of Precipitation and Lightning in the Tropics Observed by TRMM3G68, GSMaP, LIS, and WWLLN

SHOSHIRO MINOBE

Department of Earth and Planetary Sciences, Faculty of Science, and Department of Natural History Sciences, Graduate School of Science, Hokkaido University, Sapporo, Japan

JUN HYOCK PARK

Department of Natural History Sciences, Graduate School of Science, Hokkaido University, Sapporo, Japan

KATRINA S. VIRTIS

University of Alabama in Huntsville, Huntsville, Alabama

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ABSTRACT

Diurnal cycles of precipitation and lightning are investigated by analyzing rain rates of the TRMM3G68 dataset, consisting of Precipitation Radar and Microwave Imager data only; rain rates of Global Satellite Mapping of Precipitation (GSMaP), for which infrared (IR) data are also used; lightning flash rates observed by TRMM Lightning Imaging Sensor (LIS); and lightning stroke rates of World Wide Lightning Location Network (WWLLN) over the tropics. Diurnal amplitudes relative to averages are generally larger for lightning than for precipitation. Over ocean, relative amplitudes are stronger in the stratocumulus deck region in the southeast Pacific than those over typical ocean regions. The phase of GSMaP is substantially delayed to TRMM3G68 due to the phase-delay problem of IR-based estimation. The diurnal peaks tend to occur between 1400 and 1800 LST over the continent after spatial averaging with a phase leading order of TRMM3G68, LIS, and WWLLN, and between 0000 and 0700 LST over oceanic regions where diurnal cycles are prominent in all datasets. Off-equatorward phase propagations are found in the precipitation in the Pacific and Indian Oceans. Over selected coastal regions, all data exhibit consistent oceanward phase propagation with the longest, medium, and shortest phase propagation distances for TRMM3G68 precipitation, WWLLN lightning, and LIS lightning, respectively, with a phase leading order of LIS, WWLLN, and TRMM3G68. The summertime diurnal cycle over the Gulf Stream also exhibits oceanward phase propagation, but with strong amplitude enhancement over the Gulf Stream. Diurnal cycle amplitude is also enhanced over the Kuroshio in the East China Sea in the baiu–mei-yu rainy season.

1. Introduction

The diurnal cycle is a major atmospheric variation in conditions including temperature, wind, precipitation, and lightning. Diurnal precipitation and lightning are closely related because they are both associated with convection. Advances in observational technologies, particularly satellite remote sensing, have revealed

global spatiotemporal structures in diurnal precipitation cycles, including distinct features over land and over tropical open oceans. Ground-based observations have shown that the rain rate generally reaches its maximum from afternoon to early evening over land, due to convection caused by daytime solar heating (e.g., Wallace 1975; Oki and Musiak 1994). Land topography can cause more complex diurnal precipitation structures associated with mountain–valley breezes (Yang and Slingo 2001). Over open tropical oceans, the diurnal cycle tends to reach its maximum from midnight to early morning (e.g., Janowiak et al. 1994; Yang and Slingo 2001; Nesbitt and Zipser 2003; Dai et al. 2007; Kikuchi and Wang 2008). Several mechanisms for the diurnal

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Corresponding author: Shoshiro Minobe, minobe@sci.hokudai.ac.jp

cycle over oceans have been proposed [see the summary of Yang and Smith (2006)], and the following mechanisms explain the observed diurnal phases: destabilization and restabilization due to radiative cooling and heating of the top of clouds (Kraus 1963; Randall et al. 1991) or the top of the boundary layer (Kubota et al. 2004), and moistening leading to condensation due to radiative cooling (Tao et al. 1996; Sui et al. 1997).

Diurnal precipitation cycles in some coastal regions exhibit features different from those in open ocean and interior land. In tropical coastal regions, where the land–sea breeze plays an important role, diurnal phases propagate in the oceanward direction over ocean and in the opposite landward direction over land (e.g., Yang and Slingo 2001; Mori et al. 2004; Kikuchi and Wang 2008; Rauniyar and Walsh 2011). These types of propagation are found near the Maritime Continent, the Bay of Bengal, the Pacific Ocean off Mexico, and the Atlantic Ocean off western Africa and are caused by gravity waves and density currents (Yang and Slingo 2001; Mapes et al. 2003; Kodama et al. 2015). Although diurnal precipitation cycles are not prominent over most midlatitude oceans, an exceptionally strong diurnal cycle occurs over the Gulf Stream in summer and over the Kuroshio in the East China Sea in June, which is the baiu–mei-yu rainy season in that region (Minobe and Takebayashi 2015; Virts et al. 2015). These western boundary currents transport warm water from the tropics poleward, resulting in sea surface temperatures (SSTs) warmer than 26°C, the threshold of deep convection over the ocean under the current climate (Graham and Barnett 1987; Waliser et al. 1993). The warm SST allows tropical-like atmospheric convection associated with the air–sea interaction with these currents (Minobe et al. 2008; Minobe et al. 2010; Sasaki et al. 2012).

Satellite sensors and ground-based networks have advanced global-scale lightning observations. The Optical Transient Detector (OTD) on the *Microlab-1* satellite and the Lightning Imaging Sensor (LIS) on board the Tropical Rainfall Measuring Mission (TRMM) satellite detect cloud brightness changes associated with intracloud and cloud-to-ground lightning flashes (Christian et al. 2003). Because these satellites observe only a small fraction of Earth at once, it takes a long time to obtain representative diurnal climatology (Cecil et al. 2014). In contrast, the ground-based World Wide Lightning Location Network (WWLLN) monitors very low-frequency (VLF) radio waves for lightning sferics globally and simultaneously. WWLLN preferentially detects strong cloud-to-ground lightning strokes (Hutchins et al. 2012). Hence, LIS/OTD and WWLLN measure different aspects of lightning. Climatological LIS/OTD lightning flash density is several times larger than WWLLN lightning stroke density, especially over continents (Virts et al. 2013a; Thompson

et al. 2014; Bürgesser 2017). Abarca et al. (2010) reported substantial differences between diurnal cycles from WWLLN and the U.S. National Lightning Detection Network and suggested that biases in WWLLN may arise from lower efficiency in daytime detection or WWLLN's preference for strong stroke detection. However, WWLLN captures features of diurnal lightning cycles that are consistent with those of precipitation in several regions over the globe (Kucieńska et al. 2012; Virts et al. 2013a,b; Venugopal et al. 2016).

There are close relationships between the diurnal cycles of lightning and precipitation. Tropical and regional mean diurnal lightning observed by LIS shows an afternoon or early evening peak in lightning over land and an early morning peak over ocean (Liu and Zipser 2008; Sen Roy and Balling 2013; Ávila et al. 2015; Chronis and Koshak 2017). Venugopal et al. (2016) showed good agreement between diurnal peak timing over tropical continental and coastal regions by comparing precipitation estimates from TRMM3B42, a rain rate dataset over the global tropics estimated from TRMM and other satellites, including infrared (IR) observations of geostationary satellites, with WWLLN lightning stroke data. In coastal regions of Borneo and equatorial America, they confirmed the evening maximum of lightning over the continent and oceanic oceanward and terrestrial landward phase propagations consistent with those of precipitation. They also found that when there is a phase difference longer than 3 h (i.e., the temporal resolution of the TRMM3B42 dataset), lightning tends to lead precipitation, and they interpreted this feature as consistent with the persistence of precipitation after vigorous convection has weakened. Similarly, combined analysis of TRMM3B42 and WWLLN for southern Mexico and the adjacent Pacific Ocean showed a consistent relationship between lightning and precipitation diurnal cycles in summer, including oceanward propagation (Kucieńska et al. 2012). In addition, strong lightning diurnal cycles occur over the Gulf Stream and its extension, leading the precipitation diurnal cycle of TRMM3B42 by several hours (Virts et al. 2015). Consequently, lightning and precipitation exhibit similar peak timing over land and coastal ocean regions, and when there is a phase difference, lightning tends to lead precipitation.

Although these previous studies provided interesting and useful information about precipitation and lightning, further studies of the diurnal cycles are needed. These studies used the IR-based TRMM3B42 rain rate, and the IR-based precipitation estimates tend to be delayed by 3–4 h compared with ground-based radar and rain gauge data (e.g., Houze and Betts 1981; Kubota and Nitta 2001; Ohsawa et al. 2001; Dai et al. 2007). Kikuchi

and Wang (2008) and Rauniyar and Walsh (2011) reported that the diurnal cycle of TRMM3B42 lags by about 3 h compared with the more accurate TRMM3G68 dataset, which is produced using only the TRMM Precipitation Radar (PR) and TRMM Microwave Imager (TMI) with no IR data. This artificial phase delay of TRMM3B42 may explain the diurnal phase delay between precipitation and lightning, as discussed by Kucieńska et al. (2012). Therefore, to understand the phase relation between lightning and precipitation better, it is important to use precipitation estimations based on precipitation radars and microwave imagers, such as the TRMM3G68 dataset. This dataset is now available for the full 18 years of service of the TRMM satellite, double the data length used by Kikuchi and Wang (2008). Furthermore, the previous studies that compared precipitation and lightning used WWLLN data; however, it is also worth comparing precipitation with LIS lightning observations. In particular, an hourly high-resolution ($0.1^\circ \times 0.1^\circ$) diurnal climatology of LIS has recently become available (Albrecht et al. 2016a). As noted above, LIS and WWLLN measure different aspects of lightning, and thus the relationships among LIS, WWLLN, and TRMM3G68 data may shed new light on our understanding of diurnal variability. In this paper, we intend to obtain a clearer, more systematic understanding of the diurnal cycles of lightning and precipitation. To this end, we analyze the diurnal climatology of TRMM3G68, LIS, and WWLLN. We also compare TRMM3G68 data with an IR-based precipitation estimation by Global Satellite Mapping of Precipitation (GSMaP) version 7, for which a more advanced method than TRMM3B42 is used for combining IR, microwave, and PR data, to determine whether the advanced method reduces the diurnal phase bias.

The rest of this paper is organized as follows. In section 2, two precipitation datasets, TRMM3G68 and GSMaP version 7, and two lightning datasets, LIS and WWLLN, are described. In section 3, diurnal cycles of precipitation and lightning are examined on large scales over the global tropics. In section 4, precipitation and lightning diurnal cycles are studied for coastal regions and warm western boundary currents, namely, the Gulf Stream and the Kuroshio in the East China Sea. The discussion, including implications of the present results for future modeling studies, and summary are presented in section 5.

2. Data and methods

We analyze the rain rate estimation in the TRMM3G68 dataset as our main precipitation dataset. These rain rates are estimated based on TRMM PR and TMI combined between December 1997 and March 2015. The data are

gridded on an hourly $0.5^\circ \times 0.5^\circ$ grid. Sanderson et al. (2006) showed that the phase difference between the TRMM PR-only estimation and TRMM PR–TMI combined estimation is generally small. We exclude the rain rates estimated using fewer than 100 total pixels, following Kikuchi and Wang (2008), and calculate an hourly climatology for each calendar month. The resultant hourly climatology for each month is available at the corresponding author's home page.¹ In addition, as one of the latest rain rate datasets produced using IR data, we use GSMaP MVK version 7 (Ushio et al. 2009). The rain rates in this dataset are estimated using a Kalman filter from multiple microwave satellites combined with an IR dataset provided by the National Oceanic and Atmospheric Administration/Climate Prediction Center. The IR data are used to generate moving vectors of estimated precipitation and to estimate the precipitation itself from brightness temperatures. In GSMaP version 7, data from the Global Precipitation Measurement Mission/Dual-Frequency Precipitation Radar are included. We use GSMaP data between March 2014 and August 2018 on an hourly $0.1^\circ \times 0.1^\circ$ grid.

For lightning, we analyze two data products. One is the hourly climatology of the LIS flash rate, the number of lightning flashes per unit area per unit time, for the period 1998–2013 (Albrecht et al. 2016a). The data are gridded to $0.1^\circ \times 0.1^\circ$ with a smoothing 1° boxcar moving average. Even though the effective resolution is 1° , it is still a much higher resolution than LIS/OTD climatology with a resolution of 2.5° (Cecil et al. 2014). The 2.5° LIS/OTD diurnal climatology was used by Virts et al. (2013a) for diurnal cycle analysis over the Maritime Continent, but the coarse resolution does not allow close examination of complex diurnal structures in the coastal ocean regions. The $0.1^\circ \times 0.1^\circ$ LIS climatology is used for analysis of the diurnal cycle at the global lightning hotspot (Albrecht et al. 2016b). The other lightning dataset used in this study is WWLLN diurnal climatology of stroke rates, number of lightning strokes per unit area per unit time, for the period from 2006 to 2015, which is updated from Virts et al. (2013a). As described in section 1, several studies reported that the diurnal lightning cycles captured by this dataset are consistent with diurnal precipitation variability in several regions.

For GSMaP, we calculate the hourly diurnal climatology for each calendar month on the original grid, and then spatially average the monthly climatologies onto the $0.5^\circ \times 0.5^\circ$ grid of TRMM3G68. Similarly, WWLLN climatology on the $0.25^\circ \times 0.25^\circ$ grid (Virts et al. 2013a)

¹ http://www.sci.hokudai.ac.jp/~minobe/data_by_minobe/TRMM3G68_diurnal_clim/.

TRMM3G68, Annual

FIG. 1. Global distribution of the (a) average, (b) amplitude, (c) relative amplitude, and (d) phase of the first harmonic of the annual mean diurnal cycle of precipitation for TRMM3G68. The phases are shown as the LST at which the diurnal component reaches its maximum.

is averaged over the TRMM3G68 grid. For the LIS climatology, which is gridded on a $0.1^\circ \times 0.1^\circ$ grid with smoothing by a 1° boxcar filter, we resample the data to the $0.5^\circ \times 0.5^\circ$ grid.

We focus on the first harmonic component of the diurnal cycle. This is because the diurnal component is generally stronger than the semidiurnal and other components, and this approach reduces the problem of noise in the diurnal climatologies. As a measure of the relative importance of the diurnal component to the

total precipitation, we use relative amplitude, which is defined as

$$R(x, y) = \frac{A(x, y)}{E(x, y)}, \quad (1)$$

where x and y are longitude and latitude, R is the relative amplitude, E is the time average, and A is the amplitude of the diurnal first harmonic component (Easterling and Robinson 1985; Dai et al. 2007; Minobe and

FIG. 2. As in Fig. 1, but for GSMaP rain-rate climatology. The upper limit of the color bar for (a) (0.5 mm h^{-1}) is larger than that of Fig. 1a (0.4 mm h^{-1}).

Takebayashi 2015). If the diurnal cycle consists only of the first harmonic diurnal component and the time average with a minimum at zero, the relative amplitude is unity (100%). If the diurnal cycle has a narrow peak, the relative amplitude can be larger than 100%.

Easterling and Robinson (1985) categorized the case where $50\% < \text{relative amplitude} < 100\%$ as a diurnal cycle with a clear peak, and $100\% < \text{relative amplitude}$ as a well-developed diurnal cycle with a prominent peak.

FIG. 3. Hourly diurnal climatology of rain rate over (left) land and (right) ocean between 20°S and 20°N as a function of LST with a low-pass filter that retains 3-h or longer period components. The land or ocean averages are calculated using grid points that have more than 99% of the area within $\pm 5.0^{\circ}$ in longitude and latitude as land or ocean, respectively, based on a 1-min topography dataset.

3. Results

a. Basin-scale relation between precipitation and lightning diurnal cycles

Figure 1 shows the global distribution of the amplitudes, relative amplitudes, and phases of the annual mean of the diurnal first harmonic component of precipitation in TRMM3G68, and their time averages. The phases are shown as the local solar time (LST) at which the diurnal component reaches its maximum, and LST is calculated from coordinated universal time with a longitudinal distance between each grid point and 0° . The diurnal amplitudes are generally large in the regions where time averages are large, including the intertropical convergence zone (ITCZ) and South Pacific convergence zone (SPCZ). However, the relative amplitudes are large where the averages and amplitudes are small, including semiarid areas over land and stratocumulus decks in the Pacific and Atlantic Oceans, accompanied by well-organized phase distributions. This is consistent with Dirmeyer et al. (2012), who reported the relative amplitude map of TRMM3B42 in boreal summer. The phase distribution shows the well-known overall contrast between land and ocean; the diurnal precipitation peak occurs mainly from afternoon to early evening over land (yellow and red), whereas it occurs from midnight to early morning over ocean (dark and light blue), including stratocumulus deck regions in the Pacific and Atlantic Oceans. Exceptional morning maxima of land

precipitation are found to the east of the Andes and south of the Tibetan Plateau, and the Andes maximum is consistent with ground observation and numerical modeling associated with moisture convergence of the low-level jet (Nicolini and Saulo 2006). Consistent with earlier studies discussed in section 1, phases in some coastal regions are different from nearby open oceans, including the Maritime Continent, the Bay of Bengal, the Pacific Ocean off Mexico, and the Atlantic Ocean off western Africa. The diurnal cycles over the coastal regions are closely examined in the section 3b. Another interesting feature is that the phases in the open ocean are not uniform, but they exhibit a basin-scale pattern characterized by relatively uniform zonal bands of phases with differences in the meridional direction. This feature will be discussed further below.

GSMaP version 7 generally exhibits structures for averages, diurnal amplitudes, and relative amplitudes similar to those of TRMM3G68, but shows systematic phase delays with respect to TRMM3G68 (Fig. 2). The average rain rates of GSMaP are slightly larger than those of TRMM3G68, but the diurnal amplitudes are similar, resulting in slightly smaller relative amplitudes than TRMM3G68. The GSMaP phases generally lag those of TRMM3G68, consistent with the phase delay problem of IR-based precipitation estimation discussed in section 1.

To know major features of TRMM3G68 and GSMaP precipitation over land and over ocean not only for the first

FIG. 4. As in Fig. 1, but for LIS lightning density climatology. Missing values for relative amplitude and phase, shown in gray, occur at grid points where climatologies are zero over 24 h.

harmonic component, we plot diurnal cycle climatology averaged in respective domains (Fig. 3). In the both domains, diurnal cycles of TRMM3G68 rain rate lead those of GSMaP. This indicates that the latest precipitation estimation of GSMaP version 7 still suffers from the time-delay bias. Furthermore, the afternoon peak observed by TRMM3G68 over land is much narrower than that by GSMaP. Thus, the problem in diurnal cycle for IR-based rain rate estimation is not simple parallel time shifts.

Diurnal cycles of lightning are shown for the LIS flash rate (Fig. 4) and WLLN stroke rate (Fig. 5) and their

time averages. As previously reported, climatological mean lightning densities exhibit a wider range of magnitudes than those in precipitation, and maxima occur mainly over land with smaller increases than precipitation in the ITCZ and SPCZ (Figs. 1a and 2a; see also Virts et al. 2013a; Albrecht et al. 2016b). These features are also seen in the diurnal amplitude; that is, the diurnal lightning amplitudes have larger ranges of magnitudes and are more concentrated over land than precipitation. The land–ocean magnitude difference both for the average and diurnal amplitudes is larger for LIS than

FIG. 5. As in Fig. 1, but for WWLLN lightning stroke climatology.

WWLLN. WWLLN's larger relative amplitude over the ocean may be due to intense cloud-to-ground flashes striking the ocean possibly related to the high conductivity of the underlying saltwater (Lyons et al. 1998; Hutchins et al. 2013). The relative lightning amplitudes of LIS and WWLLN are generally larger than those of precipitation, and LIS has larger relative amplitudes

than WWLLN. This indicates that the diurnal cycle plays a more important role in lightning than in precipitation, especially for intracloud lightning, which is better captured by LIS than by WWLLN. The diurnal lightning phases over land peak from afternoon to early evening, consistent with precipitation. The lightning phases over open oceans are generally noisy, especially

FIG. 6. As in Fig. 3, but for LIS lightning flash rates (red), WWLLN lightning stroke rates (blue), and arbitrarily normalized TRMM3G68 rain rate (green).

for LIS, but well-organized phases, which have similar values in nearby grids, are observed in coastal ocean areas such as the Maritime Continent, Bay of Bengal, the Pacific Ocean off Mexico, the Gulf of Mexico, and the Atlantic Ocean off western Africa.

Figure 6 shows the diurnal cycles of LIS and WWLLN lightning averaged over land and ocean, respectively, along with TRMM3G68 rain rate for a comparison. In both regions, the trough–peak contrast is stronger for lightning data than precipitation, consistent with the larger relative amplitudes in lightning than precipitation shown in Figs. 1, 4, and 5. Over land, the precipitation peak leads the LIS lightning peak, which in turn leads the WWLLN lightning peak, while over ocean the lead–lag order of peaks is reversed. The lead–lag relation over land is consistent with analysis of MacGorman et al. (2011) for lightning over the United States; that is, intracloud lightning proceeds to cloud-to-ground lightning.

To examine the relationship between TRMM3G68 precipitation and LIS and WWLLN lightning more closely, we plot the area-averaged diurnal climatology in $10^\circ \times 20^\circ$ bins (Fig. 7). In most of the land areas and their vicinity, the diurnal climatologies of lightning and precipitation are characterized by narrow peaks and wide troughs. Additionally, in those boxes, the normalized minima of three datasets have a systematic order, with the lowest for LIS, followed by WWLLN, and the highest for TRMM3G68, indicating that the contrasts between the minimum and maximum are the largest, middle, and smallest for LIS, WWLLN, and TRMM3G68, respectively. This is consistent with the differences in

relative amplitudes between lightning and precipitation and between LIS and WWLLN. Over the ocean, diurnal cycles are less prominent, but all three datasets exhibit consistent diurnal cycles in the equatorial central-eastern Pacific (10°S – 10°N , 180° – 100°W) and tropical south Indian Ocean (20°S – 0° , 60° – 100°E).

The timing of the diurnal peak of TRMM3G68 precipitation and LIS and WWLLN lightning in the $10^\circ \times 20^\circ$ boxes is shown in Fig. 8. In continental land areas, the peaks of all three datasets tend to occur between 14:00 and 18:00 LST. The phase relations differ among continents—over Africa, TRMM3G68 precipitation and LIS lightning occur simultaneously, and tend to lead WWLLN lightning by 1–2 h, whereas in South America TRMM3G68 tends to lead LIS and WWLLN lightning. Assuming that the time difference between WWLLN and LIS comes from WWLLN’s preference for large cloud-to-ground lightning over intracloud lightning, the phase relationship implies that over Africa diurnal peaks of precipitation and intracloud lightning occur roughly simultaneously and are followed by cloud-to-ground lightning. In contrast, in South America the precipitation peak occurs earlier than intracloud and cloud-to-ground lightning. The difference between Africa and South America might be related to the difference of altitudes; longer lead time of intracloud lightning proceeding to the cloud-to-ground lightning in high plains than in low-altitude regions (MacGorman et al. 2011) is consistent with the LIS lightning leading WWLLN lightning in Africa, for which altitudes are generally higher than South America. Furthermore, Houze et al. (2015) showed several difference in the character of convection

FIG. 7. Hourly diurnal climatology of LIS lightning flash rate (red curves), WWLLN lightning stroke rate (blue curves), and TRMM3G68 rain rate (green curves) as a function of LST (0–24 h, horizontal axes) with a low-pass filter that retains 3-h or longer period components averaged over 10° latitude and 20° longitude bins. Climatology is shown as a solid curve if the primary peak of the climatology is larger than the secondary peak by 20% (i.e., the secondary peak divided by the primary peak is smaller than 0.8). Otherwise, the climatology is shown as a dashed curve. Each diurnal climatology time series is scaled such that the bottom of the box is zero and the top of the box is 1.5 times the maximal values, which are shown in the box with the units in the top of the figure. The white, orange, and gray backgrounds of each bin indicate ocean, land, and mixed areas, respectively. Ocean and land are defined if 90% of the area of each bin is ocean or land based on a 1-min topography dataset.

between Africa and South America, but whether and how those differences are related to the difference of diurnal cycles is not known.

For ocean boxes, peak hours tend to occur between midnight and the early morning (Fig. 8). In particular, for the aforementioned ocean boxes in which all three datasets have strong diurnal cycles in the tropical central-eastern Pacific and tropical south Indian Ocean, the peak tends to occur between 0000 and 0700 LST. In most of these boxes, WWLLN peaks occur earlier than peaks of other data (e.g., 10°S – 0° , 180° – 120°W), consistent with that over the ocean domain WWLLN lightning peak leads the peaks of LIS lightning and rain rate shown in Fig. 6. It is noteworthy that over the stratocumulus cloud deck region in the tropical southeastern Pacific, WWLLN's phases after spatial averaging are generally consistent with TRMM3G68 rain rate (Fig. 8), suggestive of the importance of the diurnal cycle. Consistently, area-averaged diurnal climatology over 25° – 5°S , 110° – 85°W exhibits a stronger relative peak–trough contrast (Fig. 9) than the typical oceanic diurnal cycle shown in Fig. 6b both for WWLLN lightning and TRMM3G68 rain rate; the peak value divided by the

trough value in Fig. 9 is 1.8 and 1.4 times larger for WWLLN and TRMM3G68 than those in Fig. 6b, respectively. This means that diurnal cycle plays a relatively more important role in stratocumulus cloud decks than other ocean regions. The maxima in Fig. 9 occur in early morning, consistent with diurnal cycles of clouds (e.g., Wood 2012; Burleyson and Yuter 2015) and ship-based precipitation observation (Burleyson et al. 2013) in the southeastern Pacific.

In some other Pacific boxes in Fig. 8 (most of 180° – 120°W , 30° – 10°S and 10° – 20°N), the WWLLN peaks often occur between 1600 and 1800 LST, contrary to the general tendency for oceanic peaks to occur between the midnight and the early morning. LIS lightning peak follows this general tendency, for bins where LIS peak times are identified. The cause of discrepancy is unknown. Previous studies have suggested that diurnal cycles of WWLLN can be biased due to stronger attenuation of VLF in daytime than in nighttime (Pessi et al. 2009; Abarca et al. 2010). On the other hand, LIS may suffer from noise in daytime associated with bright background sunlight (Boccippio et al. 2002). Further studies are needed to clarify the reasons for the discrepancy.

FIG. 8. LST of the primary peak of hourly diurnal climatologies, which are shown in Fig. 7. A peak time is not shown if the primary peak is not greater than 20% higher than the secondary peak (dashed curves in Fig. 7).

The diurnal precipitation phases exhibit meridional phase changes (Figs. 1d and 2d) without similar phase distribution in lightning (Figs. 4d and 5d). Thus, we examine the meridional phase variations of precipitation more closely. Figure 10 shows the zonally averaged reconstruction of the diurnal first harmonic component for the TRMM3G68 rain rate in the Indian and Pacific Oceans, normalized by the amplitudes at each latitude in the respective basins. Off-equatorward phase increases, starting from the equator as shown by the propagation of the locations of maxima, are commonly found in both basins. Near the equator, the diurnal component reaches its maximum at about 0200 LST in the Indian Ocean and between 0100 and 0200 LST in the Pacific Ocean. The maxima occur in later hours, around 10°S in the Indian Ocean at about 0500 LST, and around 10°S and 7°N in the Pacific Oceans between 0600 and 0700 LST. The off-equatorward phase propagation is also confirmed by an analysis of GSMaP (not shown).

The present interpretation of off-equatorward propagation is different from the previous interpretation of a standing oscillation associated with the regime for the convergence zones (ITCZ and SPCZ) and the regime for the equatorial region between the convergence zones (Kikuchi and Wang 2008). The continuous phase changes shown in Fig. 10 are more consistent with the present interpretation of the off-equatorward propagation rather than the interpretation of two regimes. Furthermore, if the diurnal phases are dominated by

regimes with and without the convergence zone, the western equatorial Pacific should be governed by convergence zone regime, because SPCZ covers there (Fig. 1a). However, even in that region diurnal phases are the same as those in the equatorial eastern Pacific (Fig. 1d), thereby supporting the off-equatorward phase propagation. Further studies are needed to confidently conclude which interpretation is more appropriate and to understand the mechanisms.

FIG. 9. As in Fig. 3b, but for TRMM3G68 rain rate and WWLLN stroke counts averaged over the southeastern Pacific (25°–5°S, 110°–85°W).

FIG. 10. (a),(b) Zonally averaged and normalized diurnal component reconstructions and (c),(d) zonally averaged time mean rain rate for the (a),(c) Indian Ocean 60°–90°E and (b),(d) Pacific Ocean 170°E–120°W.

b. Regional-scale relationships in coastal regions

In this subsection, we examine the relationship between precipitation and lightning in coastal regions, where the behavior of the diurnal cycles is different from that in open ocean and interior land, as reported previously (section 1). First, we examine coastal ocean regions in the tropics for the Maritime Continent, the Pacific Ocean off Mexico, and the Atlantic Ocean off Africa. In addition, we examine the diurnal cycle over the Gulf Stream and over the Kuroshio in the East China Sea, where strong diurnal cycles were reported to

be associated with the air–sea interaction of these western boundary currents (Minobe and Takebayashi 2015; Virts et al. 2015).

Figure 11 shows the amplitudes of the diurnal first harmonic component of TRMM3G68 precipitation, and LIS and WLLN lightning over the Maritime Continent, the Pacific Ocean off Mexico, and the Atlantic Ocean off Africa. All datasets have stronger amplitudes over land than over ocean, and LIS has the strongest land–sea amplitude contrast, as found in the global analysis in section 3a. The regions in which the largest amplitudes occur are different among datasets.

FIG. 11. Amplitudes of the annual mean of the diurnal first harmonic component of (a),(d),(g) TRMM3G68 precipitation, (b),(e),(h) WWLLN lightning, and (c),(f),(i) LIS lightning (a)–(c) over the Maritime Continent, (d)–(f) around Mexico, and (g)–(i) around western Africa.

TRMM3G68 generally has larger amplitudes over the Maritime Continent compared with the other two regions. WWLLN amplitudes are large over the Maritime Continent and around Central America, but small over western Africa and the adjacent North Atlantic where the network's detection efficiency is lower (Hutchins et al. 2012). In contrast, the LIS amplitudes have similar magnitudes in all three regions.

The phases of the diurnal first harmonic (Fig. 12) generally indicate that the diurnal maxima occur over land in a narrow time range from late afternoon to early evening and over ocean in a wider time window from the midnight to late morning. The phases of TRMM3G68 precipitation apparently lag those of LIS lightning in most regions. The lightning–lead precipitation relationship is also seen between TRMM3G68 precipitation and WWLLN lightning around central America and over the North Atlantic off Africa, but not clearly over the Maritime Continent and the South Atlantic off Africa. The oceanward phase propagations are observed for all datasets in the Indian Ocean off Sumatra, the

South China Sea off Borneo, the Pacific Ocean off New Guinea, the Pacific Ocean off central America, and the South Atlantic off Africa. In North Atlantic off Africa, oceanward propagation is prominent in TRMM3G68 precipitation but not in LIS and WWLLN lightning.

To compare the phase propagation in coastal regions, we estimate the phases of the first diurnal component that are averaged in the direction parallel to the coastline over the boxes in Fig. 12 (Fig. 13). Nocturnal oceanward phase propagation is commonly observed in all data and in all regions, except for the lightning in the North Atlantic off Africa, where the phases of lightning are roughly uniform. The propagation distance, which is the distance over which prominent oceanward propagation occurs, is the shortest for the LIS lightning, middle for the WWLLN lightning, and the longest for the TRMM3G68 precipitation in each region. Among the regions, the propagation distance for precipitation is longest over the Pacific off Mexico (about 900 km) and shortest in the Indian Ocean off Sumatra (about 400 km). For an offshore distance of between 100 and 400 km, we

FIG. 12. As in Fig. 11, but the phase is shown as the LST of the maxima of the diurnal first harmonic component. The phases are plotted only at grid points where corresponding amplitudes in Fig. 11 are larger than the color bar value next to zero (e.g., 0.02 mm h^{-1} for TRMM3G68 precipitation). The pink rectangles indicate the area over which phases as a function of distance from the coast are shown in Fig. 13.

calculate the phase velocity for precipitation, which has a longer propagation distance than lightning allowing a stable estimation, and obtain the velocities range from 15 m s^{-1} off Sumatra to 28 m s^{-1} off Mexico. The different propagation speeds can be due to different gravity wave speeds and/or background winds. The diurnal maximum of precipitation between 100 and 400 km from the coast occurs between 0400 and 1300 LST, which is generally later than the precipitation phase maximum of open ocean (0000–0700 LST) shown in Fig. 8. Regarding the phase relationships among datasets, LIS lightning leads or is concurrent with WWLLN lightning, and WWLLN lightning leads or is concurrent with TRMM3G68 precipitation. The phase difference between WWLLN lightning and TRMM3G68 precipitation is mostly within 2 h, and they are almost in phase in the Pacific off New Guinea, whereas the phase difference between LIS and TRMM3G68 is 2–4 h. Therefore, the phase difference between precipitation and lightning is generally between 0 and 4 h. The phase difference between lightning and precipitation appears to be shorter than in previous studies (Kucieńska et al. 2012; Venugopal

et al. 2016) because those studies used the IR-based TRMM3B42 dataset.

Figure 14 shows the amplitudes and phases of the diurnal first harmonic of precipitation and lightning in summer over the Gulf Stream. Strong diurnal cycles of precipitation and lightning were reported in this region in summer (Minobe and Takebayashi 2015; Virts et al. 2015). Because the Gulf Stream Extension is not fully covered by TRMM3G68, results from GSMaP version 7 are also shown in this figure. Furthermore, the LIS lightning climatology is limited to the annual mean, and thus it is not shown here. Strong diurnal amplitudes occur along the Gulf Stream and its extension with a clear gap in small amplitudes between the Gulf Stream and continent (Figs. 14a–c). However, there is no gap for the tropical coastal oceans (Fig. 11), indicating the active role of the Gulf Stream in modulating the diurnal cycles associated with high SSTs as explained in section 1. The phase distributions of all data over the Gulf Stream south of Cape Hatteras hint at oceanward phase propagation (Figs. 14d–f), which is more clearly seen in the phase of the diurnal harmonic averaged in the direction

FIG. 13. Phases of diurnal first harmonic components averaged in the direction parallel to the coast in the boxes in Fig. 12 for the (a) Indian Ocean off Sumatra, (b) Pacific off New Guinea, (c) Pacific off Mexico, (d) North Atlantic off Africa, and (e) South Atlantic off Africa for TRMM3G68 precipitation (red), LIS lightning (blue), and WWLLN lightning (green). The origin of the horizontal axis corresponds to the line inside the boxes in Fig. 12 (approximately the local coastline); land is to the left of the origin and ocean to the right.

FIG. 14. (top) As in Fig. 11 and (bottom) as in Fig. 12 but for the Gulf Stream region during June–August. The green contours show a surface geostrophic current velocity of 50 cm s^{-1} provided by AVISO (<https://www.aviso.altimetry.fr/en/data/product-information.html>), indicating the mean position of the Gulf Stream.

parallel to the coastline (Fig. 15). The phase propagation of precipitation was reported by Minobe and Takebayashi (2015), who analyzed IR-based GSMaP version 5. The present analysis indicates that phase propagation also occurs in the lightning stroke rate observed by WWLLN. The phases of WWLLN lightning lead TRMM3G68 precipitation by 1 or 2 h between 100 and 300 km from the coast.

Although the amplitude enhancement of the diurnal cycle of precipitation over the Kuroshio in the East China Sea in June (i.e., the baiu–mei-yu rainy season) has been reported previously (Minobe and Takebayashi 2015), the diurnal cycle of lightning in this region has not been studied. Figure 16 shows that the diurnal amplitudes of WWLLN lightning are also enhanced over the Kuroshio in the East China Sea. The amplitude enhancement over the Kuroshio is not clear in either TRMM3G68 or GSMaP version 7, probably because data accumulation may not be sufficient for correct detection of the diurnal cycle in a single month with limited data under the TRMM orbit for TRMM3G68 and with

4-yr data of GSMaP version 7. By using 11-yr data of GSMaP version 5, Minobe and Takebayashi (2015) reported diurnal amplitude enhancement over the Kuroshio and this feature can be obscured by the baiu–mei-yu rainband distributing in a wider area without a strong diurnal component. Figure 17 shows that the southeastward phase propagation, which was reported for GSMaP version 5, is also seen in GSMaP version 7 and to some extent in the WWLLN data but not in the TRMM3G68 phases, which are roughly uniform in the East China Sea. Further studies are needed to conclude whether propagation plays an important role in the diurnal cycle in the East China Sea.

4. Discussion and conclusions

We investigated the diurnal cycles of precipitation and lightning using the datasets of TRMM3G68 rain rate, GSMaP version 7 rain rate, LIS lightning flash rate, and WWLLN lightning stroke rate. The distributions of

FIG. 15. As in Fig. 13, but for the Gulf Stream coastal region shown in Fig. 14 for TRMM3G68, GSMaP precipitation, and WWLLN lightning.

the diurnal cycle amplitudes of all datasets follow their time mean magnitudes; diurnal precipitation amplitudes are large in convergence zones (Figs. 1 and 2), whereas the lightning amplitudes are large over land, with smaller amplitude enhancement in convergence zones, especially for the LIS data (Figs. 4 and 5). Relative amplitudes, defined as the amplitude divided by time mean, are generally larger for lightning than precipitation. The relative amplitudes of precipitation and lightning are large over semiarid areas and over stratocumulus decks over the Pacific and Atlantic Oceans (Figs. 1, 2, 4, 5, and 9). In the stratocumulus deck region over the tropical southeast Pacific, relatively prominent diurnal cycles are found for TRMM3G68 rain rate and WWLLN lightning (Fig. 9). The diurnal phases of TRMM3G68 lead those of GSMaP (Figs. 1–3), indicating that the latest IR-based precipitation estimation still has a phase bias problem, as found in the older TRMM3B42 dataset by previous studies (Kikuchi and Wang 2008; Kucieńska et al. 2012). Spatially averaged diurnal cycles in $10^\circ \times 20^\circ$ bins indicate that the differences between the diurnal minimum and maximum are the largest for LIS, middle for WWLLN, and the shortest for TRMM3G68 (Fig. 7). The diurnal peaks over land tend to occur between 1400 and 1800 LST, with a phase leading order of TRMM3G68, LIS, and WWLLN when there is a phase delay between datasets, and between 0000 and 0700 LST over ocean in

the $10^\circ \times 20^\circ$ bins where diurnal cycles are prominent in all datasets (Fig. 8). The phases of WWLLN in some regions of the Pacific Ocean are between 1600 and 1800 LST, largely different from those of LIS, and further studies are necessary to identify the reason for this difference. Interesting off-equatorward phase propagations are common in TRMM3G68 and GSMaP in the North and South Pacific and the south Indian Ocean with minimum phases near the equator (Fig. 10), suggesting that the precipitation diurnal cycle is influenced by the latitudinal difference of the Coriolis parameter. The off-equatorward propagation was also found in the diurnal cycles of near-surface winds observed by buoys (Deser and Smith 1998), but it remains unknown whether the precipitation and wind propagation are related.

Diurnal cycles over tropical coastal regions, namely the Maritime Continent, around central America, and western Africa and the adjacent Atlantic Ocean, are closely examined as well as two midlatitude western boundary current regions, namely the Gulf Stream and the Kuroshio in the East China Sea. The amplitude patterns in each region are similar among datasets, but are different among regions depending on the dataset which region has overall large or small amplitudes (Fig. 11). Oceanward phase propagations are common in those tropical coastal oceans (Fig. 12), and the propagation distance is the longest for TRMM3G68 precipitation, followed by the WWLLN lightning, and is the shortest for the LIS lightning (Fig. 13). For these propagations, the LIS lightning phase tends to lead WWLLN lightning, which tends to lead TRMM3G68 precipitation. The phase difference between lightning and precipitation is generally less than 4 h and that between WWLLN lightning and precipitation is less than 2 h. The summertime diurnal cycle over the Gulf Stream near the coast south of Cape Hatteras also exhibits oceanward phase propagation similar to those found over the tropical coastal oceans, but with strong amplitude enhancement over the Gulf Stream (Fig. 14). The enhancement of the diurnal cycle amplitude is also found in WWLLN lightning over the Kuroshio in the East China Sea in June, during the baiu–mei-yu rainy season (Fig. 16), consistent with the enhancement of precipitation diurnal cycle reported by Minobe and Takebayashi (2015).

The two lightning datasets used in this study have different characters. As mentioned in introduction, LIS can observe a narrow region at once, and requires a long time to obtain representative diurnal climatology. The required time becomes long for weak signals. This may explain why diurnal climatology of LIS lightning is not well defined over the stratocumulus decks compared to WWLLN lightning (Figs. 4 and 5) in association with weak diurnal amplitudes in this region. On the other

FIG. 16. As in Fig. 14, but for the Kuroshio region in June. The green contours show a surface geostrophic current velocity of 50 cm s^{-1} , indicating the mean position of the Kuroshio.

hand, although WWLLN monitors lightning globally and simultaneously, its sensors do not distribute uniformly across the globe. The distribution is relatively sparse around Africa (Fig. 1 of Virts et al. 2013a), resulting in relative detection efficiency as small as about 50% (Fig. 6 of Hutchins et al. 2013). Thus, the average and diurnal amplitude of WWLLN lightning shown in Figs. 5 and 11h are probably underestimated around Africa. On the other hand, the spatially varying detection efficiency may not affect phase distributions documented in this paper. Thus, the phase relations between LIS lightning and WWLLN lightning probably reflect the different phase relations between intracloud lightning and cloud-to-ground lightning. Future studies are necessary to clarify the cause of the phase relationship found in this paper.

There is room for further development of diurnal cycle studies including regional-scale analyses in specific seasons, which are mostly untouched in this paper. To facilitate those studies, as mentioned in section 2 we have made available the hourly climatology of TRMM3G68 rain rate estimation in each month for the research

community. The TRMM3G68 rain rate is better than the IR-based rain estimate including TRMM3G42 as reviewed in section 1 and GSMaP version 7 as shown in the present study. Although TRMM-PR would be more accurate than TMI within the footprint of PR, the much narrower footprint of PR than that of TMI probably results in a noisier diurnal cycle of PR than that of PR-TMI combined TRMM3G68 on regional scales. Indeed, this is confirmed by a comparison between the diurnal phase distribution of TRMM-PR (Fig. 18 of Kodama et al. 2015) and that of TRMM3G68 (not shown). Therefore, TRMM3G68 is a reasonable choice for diurnal cycle studies.

Numerical modeling studies also need accurate observational estimation of diurnal cycles, but some numerical studies used IR-based data such TRMM3B42 for model-observation comparison (e.g., Dirmeyer et al. 2012; Noda et al. 2012; Birch et al. 2015; Xie et al. 2019). The phase delay problem of IR-based rain estimate hinders accurate model-observation comparison. This problem becomes more serious for advanced models, for which closer comparisons are required. For example,

FIG. 17. As in Fig. 15, but for the Kuroshio region in the East China Sea shown in Fig. 16.

the Nonhydrostatic Icosahedral Atmospheric Model (NICAM) can reproduce the major features of the diurnal cycles over the global tropics (Sato et al. 2009; Noda et al. 2012; Kodama et al. 2015). The diurnal peak of NICAM with 3.5-km grid spacing over land slightly (1–2 h) delays with regard to TRMM-PR peak, but conversely leads TRMM3B42 because of phase-delay problem of this dataset. A 20-yr integration of 14-km NICAM can capture the oceanward propagation over ocean around the Maritime Continent and Central America but with a 2–4-h phase delay relative to TRMM-PR (Kodama et al. 2015). Although analyses of Kodama et al. (2015) for diurnal cycles are limited only to these phase propagations, many aspects of diurnal cycles of this long integration of NICAM are worth being examined.

Recently, the first global lightning simulation of the diurnal cycle was conducted (Field et al. 2018). In this simulation, the lightning total flash rate was statistically parameterized based on the upward flux of the graupel mass and total ice water path using a model grid spacing of about 15 km at the equator. The simulation captured the lightning peak activity in the late afternoon and early evening over land. Over ocean, the simulated peak times occurred typically between 0200 and 0800 LST (Fig. 5 of Field et al. 2018), and this is in good agreement with our LIS analysis in Fig. 8 over the open ocean. However, the phase propagation features in several coastal regions

documented in this paper are not evident from their global phase map.

We documented the diurnal climatology of precipitation and lightning on the global scale and on regional scales in coastal areas. These results may be used as basic information for further refining observational studies and for comparisons with numerical models. Future studies will answer questions that arise from the present study. For example, what is the mechanism of the poleward propagations from the equator in the Pacific and Indian Oceans? Why are the phase lags between precipitation and lightning different among land regions and among coastal ocean regions? Answers to these questions will advance our understanding of the diurnal cycles in the atmosphere.

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