Land-sea contrast in the lightning diurnal variation as observed by the WWLLN and LIS/OTD Data

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Land-Sea Contrast in the Lightning Diurnal Variation as Observed by the WWLLN and LIS/OTD Data

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ABSTRACT

Data from the World Wide Lightning Location Network (WWLLN) for the period 2005–2011 and data composite of the Lightning Imaging Sensor/Optical Transient Detector (LIS/OTD) for 1995–2010 are used to analyze the lightning activity and its diurnal variation over land and ocean of the globe. The Congo basin shows a peak mean annual flash density of 160.7 fl km^{-2} yr^{-1} according to the LIS/OTD. The annual mean land to ocean flash ratio is 9.6:1, which confirms the result from Christian et al. in 2003 based on only 5-yr OTD data. The lightning density detected by the WWLLN is in general one order of magnitude lower than that of the LIS/OTD. The diurnal cycle of the lightning activity over land shows a single peak, with the maximum activity occurring around 1400–1900 LT (Local Time) and a minimum in the morning from both datasets. The oceanic diurnal variation has two peaks: the early morning peak between 0100 and 0300 LT and the afternoon peak with a stronger intensity between 1100 and 1400 LT over the Pacific Ocean, as revealed from the WWLLN dataset; whereas the diurnal variation over ocean in the LIS/OTD dataset shows a large fluctuation.

Key words: WWLLN, LIS/OTD, lightning activity, diurnal variation

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1. Introduction

The diurnal variation of lightning activity is an important part of the thunderstorm system. Over the past few decades, a series of studies have been devoted to understanding the lightning activity and its diurnal variation over land based on regional lightning networks (Maier et al., 1984; Reap, 1986; Lopez and Holle, 1986; Williams and Heckman, 1993; Westcott, 1995; Orville et al., 1997; Pinto et al., 1999; Orville and Huffines, 2001; Zajac and Rutledge, 2001; De Souza et al., 2009; Bourscheidt et al., 2009; Liu et al., 2011). However, few studies have focused on the lightning diurnal variations on the global scale.

Lightning activity is related to global temperature change (e.g., Williams, 1992, 1994) and it is also an important natural source of nitrogen oxide affecting the tropospheric ozone (e.g., Toumi et al., 1996; Nesbitt et al., 2000; Beirle et al., 2010). Obtaining the lightning distribution on the global scale is therefore important. Recent observations from the Optical Transient Detector (OTD) revealed a prominent land-sea contrast in lightning activity, and the land-ocean contrast can be found in the entire diurnal cycle (Christian et al., 2003). The satellite-based LIS (Lightning Imaging Sensor)/OTD and ground-based World Wide Lightning Location Network (WWLLN) data are suitable for studying the lightning activity over the globe.

Observations of the OTD and the LIS have also

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been widely used to analyze the global and regional lightning activities (e.g., Boccippio et al., 2000; Kandalgaonkar et al., 2003; Qie et al., 2003a, b; Ma et al., 2005; Dai et al., 2005; Yuan and Qie, 2008; Pan et al., 2010; Pan and Qie, 2010; Dai et al., 2009; Wang et al., 2009). The WWLLN was set up in 2004 and the data have been accumulated for more than 7 yr. Abarca et al. (2010) evaluated the WWLLN data by using the National Lightning Detection Network (NLDN) as ground truth and suggested that the WWLLN dataset has a strong potential for meteorological applications. Lay et al. (2007) suggested that the WWLLN data have the ability to address questions regarding land/ocean lightning differences in local time on any timescale in any location on the earth. In the present study, we use the WWLLN and LIS/OTD data to study the lightning activity and its diurnal variation over land and ocean on the global scale.

2. Description of the lightning data

The WWLLN provides real-time lightning locations by detecting the VLF (very low frequency; 3–30 kHz) radiation emanating from lightning discharges. For a lightning to be accurately detected, the radiation should be detected by at least 5 out of 60 stations. The efficiency and accuracy of the WWLLN has been estimated by many studies using regional lightning networks (e.g., Lay et al., 2004; Rodger et al., 2004, 2005, 2006; Jacobson et al., 2006; Abarca et al., 2010). The most recent work by Abarca et al. (2010) showed that the detection efficiency of the WWLLN of CG (cloud to ground) flashes has changed from 3.88% in 2006–2007 to 10.30% in 2008–2009.

The LIS/OTD lightning dataset obtained from the Global Hydrology and Climate Lightning Research Team at NASA's Marshall Space Flight Center is also used in this study. Both the products of Low Resolution Diurnal Climatology (LRDC) and High Resolution Full Climatology (HRFC) have been used. The LRDC is a 2.5°×2.5° gridded composite and HRDC is a 0.5°×0.5° gridded composite of total lightning bulk production as a function of local hour, expressed as a flash rate density. The 5-yr OTD (April 1998 to March 2000) and 8-yr LIS (Janurary 1998 to December 2010) missions are included in the dataset. The detection efficiency corrections and instrument cross-normalizations have been applied. The version 2.3 of the product is used in the present study.

3. Results

3.1 Global lightning distribution

The annual density of global lightning is shown in Fig. 1a. Flash rate is counted in unit of fl km^{-2} yr^{-1} based on the 0.5°×0.5° HRFC data. The flash density occurs in such regions as the Congo basin, south of the Mount Everest, Southeast Asia, Colombia, Paraguay, and Florida of the US. The result is similar to that in Christian et al. (2003) and Qie et al. (2003b). The maximum flash density over the Congo basin is about 160.7 fl km^{-2} yr^{-1}. The annual mean land to ocean flash ratio is 9.6:1. This ratio is consistent with the 5-yr OTD-based study by Christian et al. (2003), which showed a ratio of approximately 10:1 over land and ocean.

The global distribution of annual average total lightning from the 1°×1° WWLLN data is shown in Fig. 1b. Basically, the two datasets show similar lightning distribution patterns. However, the highest lightning density in the WWLLN data occurs in North America, while LIS/OTD data give the highest lightning density in Africa. This could result from the uneven distribution of WWLLN stations over the globe. Most of the WWLLN stations are located in North America, and only a limited number of stations are seen in Africa. Lightning density is far lower over ocean than over land. The maximum oceanic lightning density is observed in the Pacific, northern Atlantic, and northern Indian Ocean. Lightning is less frequent in the eastern Pacific, southern Indian Ocean, and southern Atlantic. The lightning density detected by the WWLLN is in general one order of magnitude lower than that of the LIS/OTD.

Figures 2a and 2b present zonal totals of annual average flash rate in one-degree bands. It is clear that most lightning events occur between 45°S and 45°N in both datasets. However, owing to the non-uniform distribution of WWLLN stations, most of the lightning activity is observed between 15°S and 30°N by the WWLLN, while most lightning events are observed between 30°S and 30°N by the LIS/OTD. 78.1% of the global lightning occurring within 30°S–30°N is detected by the LIS/OTD, which confirms the result of 78% by Christian et al. (2003) based on only 5-yr OTD data. The lightning occurring within 45°S–45°N in the LIS/OTD data accounts for 95% of the global

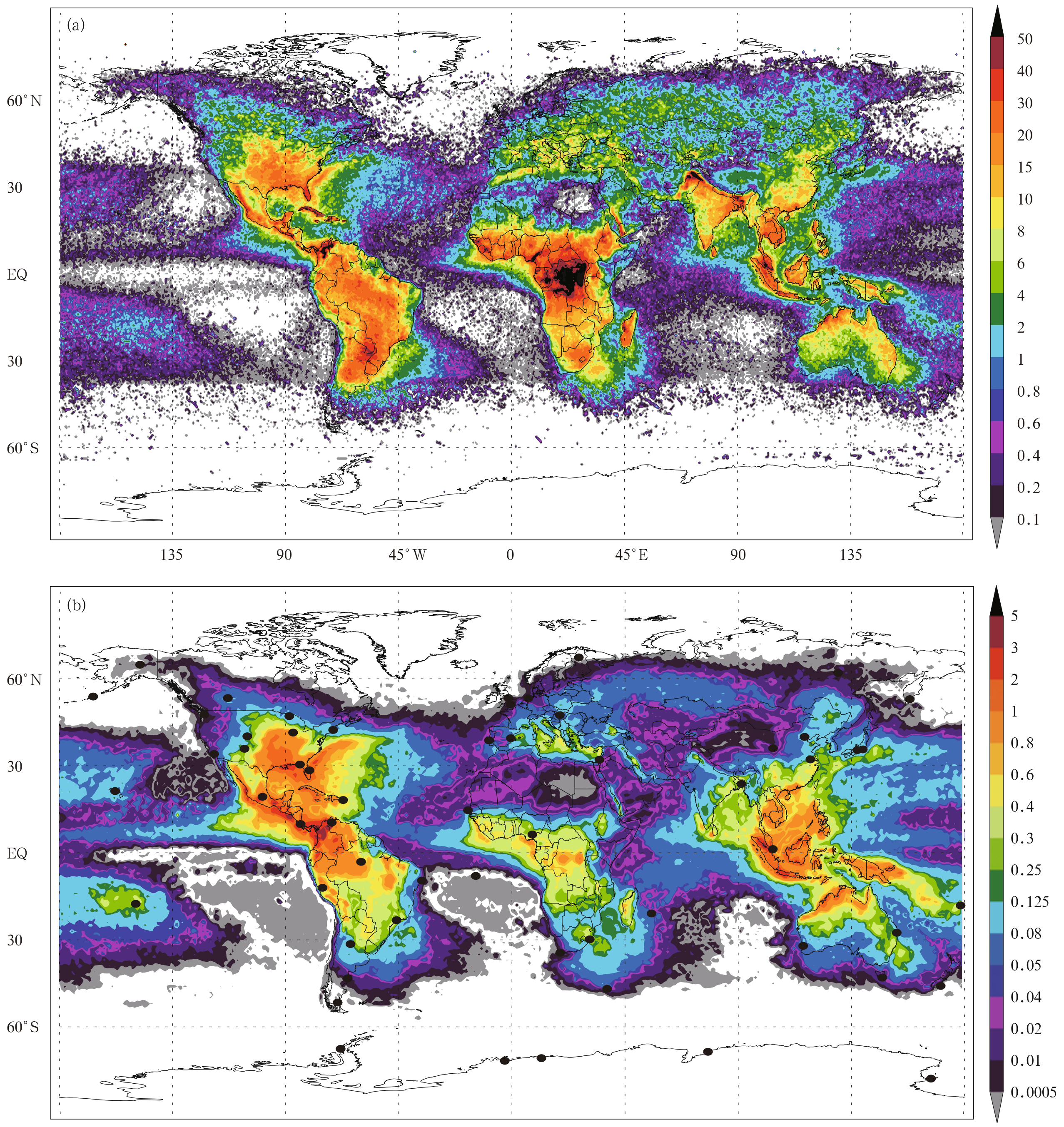

Fig. 1. Distributions of annual mean lightning density (fl km^{-2} yr^{-1}) using the (a) LIS/OTD and (b) WWLLN data. Black dots represent the WWLLN stations.

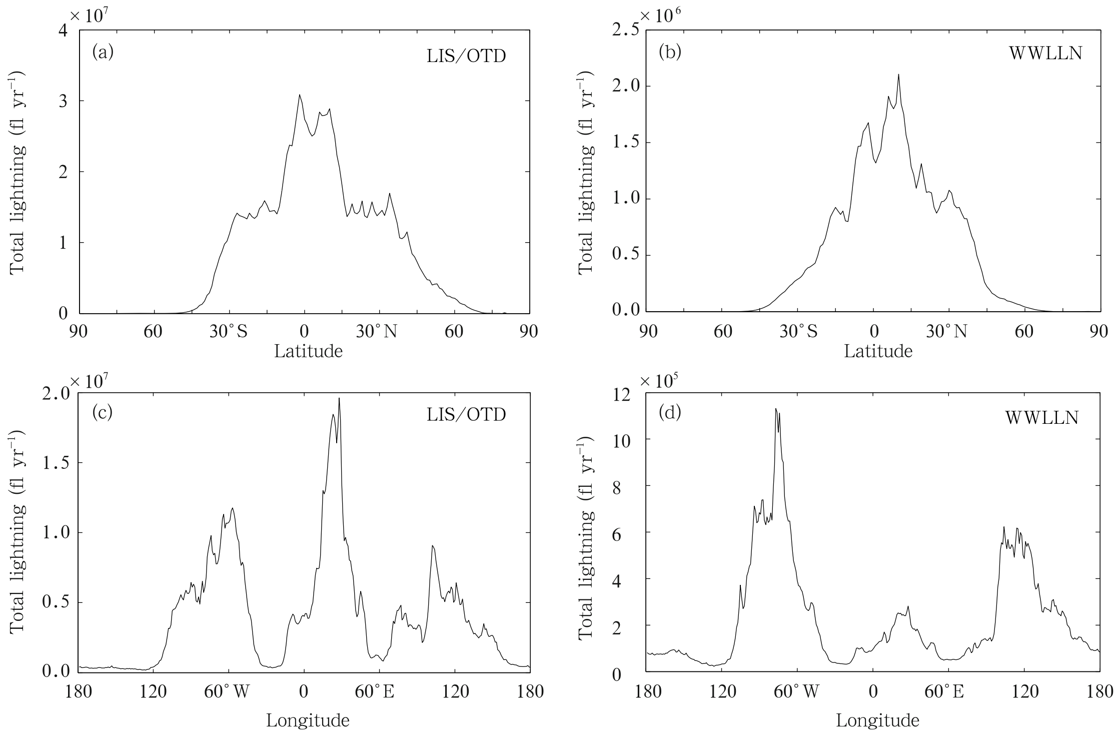

Fig. 2. (a, b) Zonal and (c, d) meridional distributions of total lightning rate (fl yr^{-1}) based on (a, c) LIS/OTD and (b, d) WWLLN data.

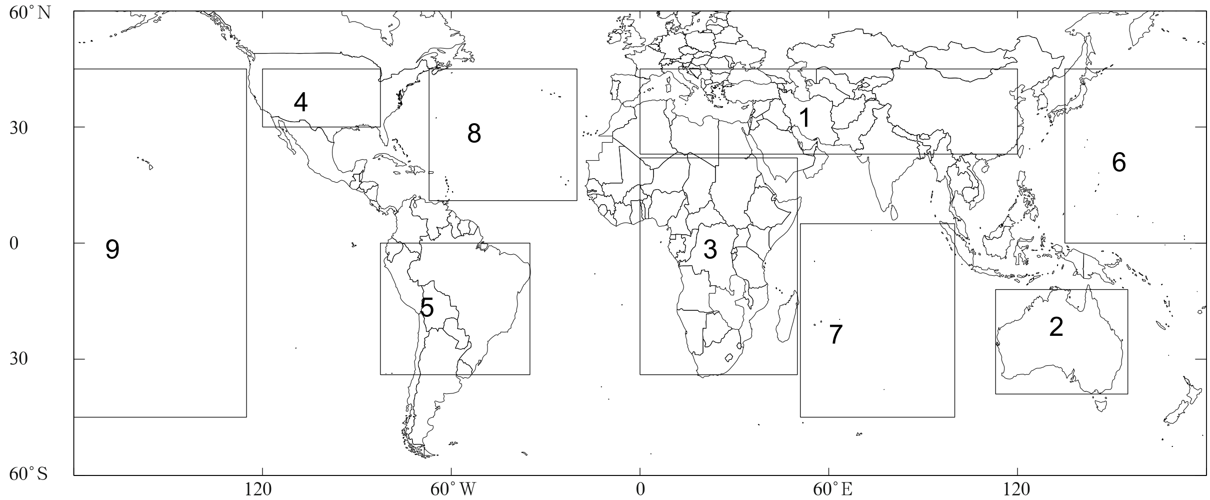

Fig. 3. Distribution of the 9 regions between 45°S and 45°N under study with 4 oceanic regions and 5 continental regions. The numbers 1–9 stand for Euro-Asia, Australia, Africa, North America, South America, western Pacific, Indian Ocean, North Atlantic, and East Pacific, respectively.

lightning production. In comparison, lightning activities detected by the WWLLN within 30°S–30°N and 45°S–45°N account for 82% and 97.6% of the global total lightning, respectively.

Figures 2c and 2d present meridional totals of annual average flash rate in one-degree bands. Given the dominance of continental effects on the global distribution, three peaks are found over the main continent of Africa, Americas, and Asia. The distribution pattern of lightning detected by the WWLLN is similar to that of the LIS/OTD, but the maximum peak does not occur in African regions in the WWLLN data.

3.2 Diurnal cycles of lightning activity

Based on the global distribution of lightning activity analyzed above, nine regions (Fig. 3) are selected to study the lightning diurnal cycles in detail, i.e., Euro-Asia, Australia, Africa, North America, South America, western Pacific, Indian Ocean, North Atlantic, and East Pacific. Each region represents a major continent or ocean. The regions are confined within 45°S–45°N.

3.2.1 Continental lightning cycle

Figures 4a–e show diurnal variations of the lightning activity over land based on the WWLLN and LIS/OTD data. The single peak over land from the WWLLN appears in all regions, but is shifted slightly for different regions. Lightning over Australia (Region 2) peaks around 1600 LT (Local Time), while lightning over Euro-Asia and South America occurs around

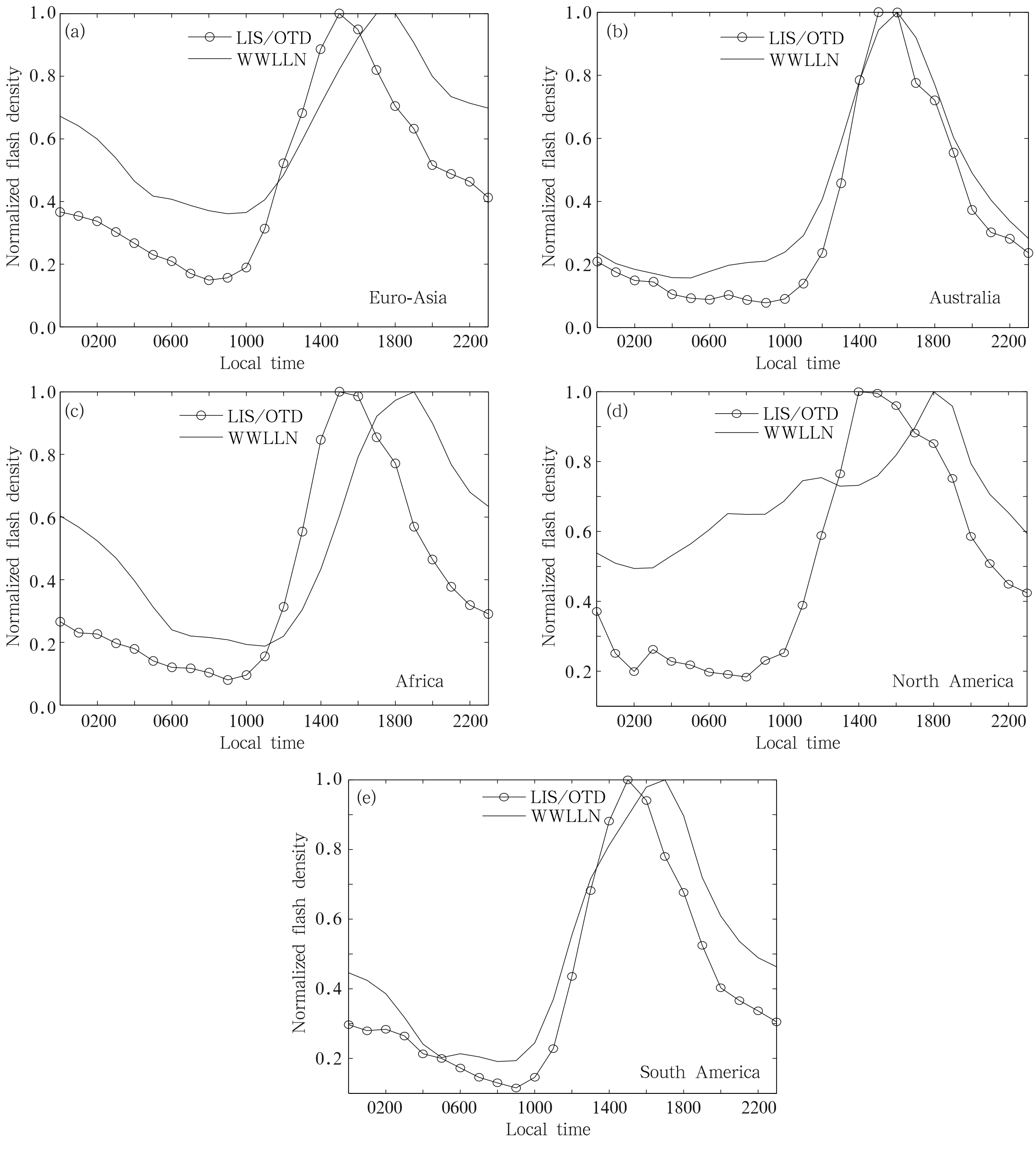

Fig. 4. Variations of lightning activity over five continental regions from the WWLLN (solid lines) and LIS/OTD (solid lines with circles) data. (a) Euro-Asia, (b) Australia, (c) Africa, (d) North America, and (e) South America.

1700 LT. The latest lightning peak over Africa (Region 3) occurs at 1900 LT. The diurnal structure of lightning over North America is very different, with two maxima: the largest at 1800 LT and a secondary and broader peak between 1100 and 1200 LT.

The diurnal variation patterns from the LIS/OTD are similar to those from the WWLLN. The lightning peak over North America occurs at 1400 LT, consistent with the result by Abarca et al. (2010), who showed a similar structure of the diurnal cycle with lightning peaking at 1600 LT according to the NLDN data. The lightning activity over the other 4 land regions peaks at 1500 LT. Abarca et al. (2010) used both WWLLN and NLDN datasets to study the diurnal cycle of lightning over North America. Their results showed that the diurnal cycle over land by the WWLLN exhibited two maxima: a main peak at 1900 LT and a secondary peak between 0800 and 1100 LT. They also found that the lightning peak detected by the WWLLN was lagging 3 h behind that from the NLDN. In our study, the lightning peak detected by the WWLLN is lagging 4 h behind that from the LIS/OTD in North America. The LIS/OTD and WWLLN are significantly different types of measurements, which could result in them detecting different components of the lightning behavior.

Details about diurnal variations of lightning in several main regions found in some recent literatures are summarized in Table 1.

Table 1. Comparison of the local diurnal variation of lightning activity with other studies found in the literature

Investigator	Lightning data	Region	Time of maximum activity in LT
This work	LIS/OTD (WWLLN)	Euro-Asia	1500 (1700)
		Australia	1500 (1600)
		Africa	1500 (1900)
		North America	1400 (1800)
		South America	1500 (1700)
De Souza et al. (2009)	BrasilDat/LIS/OTD	Southeastern Brazil	1700
Abarca et al. (2010)	NLDN	United States	1600
Kandalgaonkar et al. (2003)	OTD/LIS	Indian	1530
Qie et al. (2003a)	OTD/LIS	Tibetan Plateau	1500–1700
Williams and Heckman (1993)	LLP	Australia	1700

Note: LLP is an abbreviation of lightning location and protection.

The occurrence time of lightning peaks over most regions in this study is consistent with that of the previous studies. Therefore, the WWLLN data can be used to study the variations of lightning activity over the globe. It is also suggested that this network has a strong potential for weather system research.

3.2.2 Oceanic lightning cycle

The oceanic lightning diurnal cycle has a different structure from the continental one, and the amplitude of its diurnal variation is smaller than that of the continental counterpart. The diurnal variation over ocean shows a large fluctuation demonstrated by both the WWLLN and LIS/OTD datasets.

Figures 5a–d show the diurnal variations of the lightning activity over ocean based on the LIS/OTD and WWLLN data. There are two main lightning peaks over western Pacific (Region 6) in Fig. 5a from the LIS/OTD: the largest peak around 1400 LT and another peak around 0200 LT. The two associated minima occur at 1100 and 1900 LT, respectively. The maximum lightning activity occurs at 0300 LT and the minimum occurs at 1600 LT over the Indian Ocean (Region 7). Over North Atlantic (Region 8), the diurnal variation of lightning activity shows two maxima: a more intense peak at 0400 LT and a secondary one at 1300 LT while the minimum occurs at 1000 LT. Over East Pacific (Region 9), there are also two maxima: a broader and stronger peak occurs between 0100 and 0600 LT and a secondary peak at 1400 LT. The associated two minima occur at 0800 and 1700 LT, respectively.

The diurnal variation of lightning over most ocea-

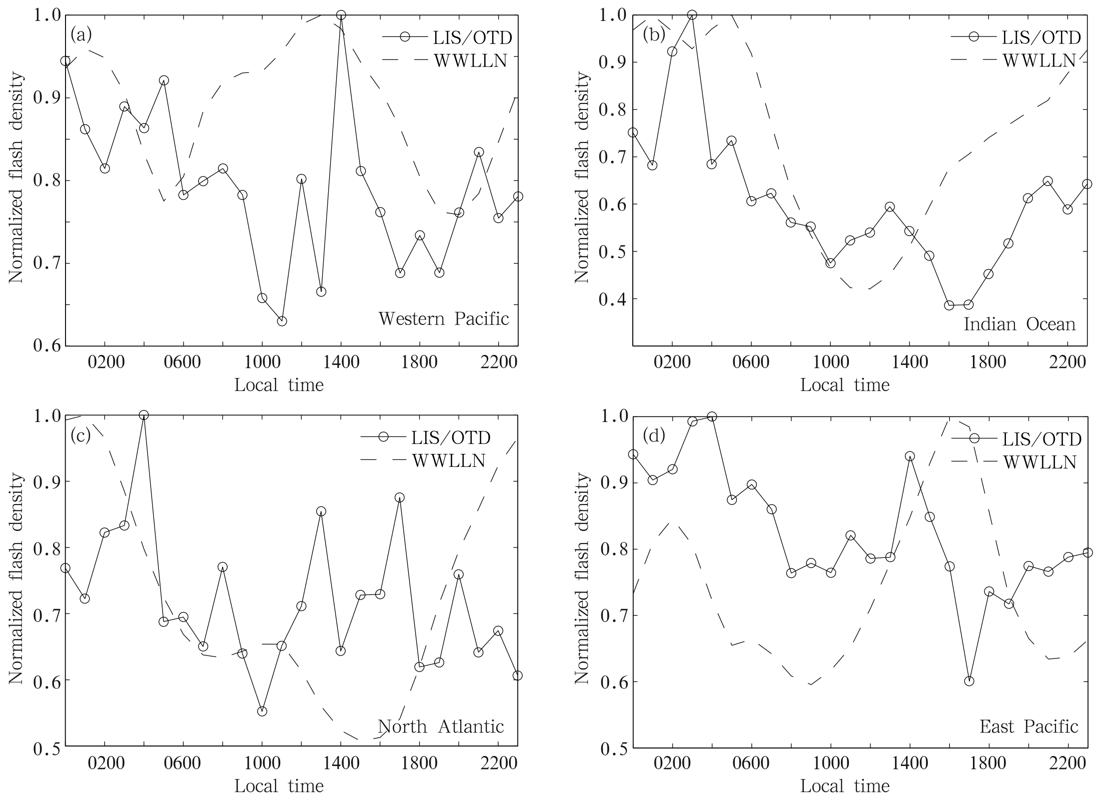

Fig. 5. Variations of the lightning activity over the four oceanic regions based on the WWLLN (dashed lines) and LIS/OTD (solid lines with circles) data. (a) Western Pacific, (b) Indian Ocean, (c) North Atlantic, and (d) East Pacific.

nic regions from the WWLLN dataset shows an early morning peak around 0100 LT. However, the diurnal cycle of lightning over the Pacific Ocean shows a stronger peak in the afternoon, with the lightning peaks over the western Pacific and East Pacific occurring at 1300 and 1700 LT, respectively. The lightning over the Atlantic shows a secondary peak at 1100 LT. The main lightning peak in the afternoon in the oceanic regions is induced by the changes of the net radiation: the low-level air is reheated by the ocean in the afternoon, which increases the atmospheric stratification instability, resulting in active convection and the other lightning peak.

3.2.3 Diurnal cycle of lightning in North America

Over North America, the diurnal cycle of lightning activity shows two maxima, but in the other four regions, only single peaks show up in the lightning diurnal cycle (Fig. 4). To find the reason for the two lightning maxima in North America in the WWLLN data, North America is divided into three strips for a detailed checking according to the time zone, i.e., W8: 112.5°–120°W; W7: 97.5°–112.5°W; and W6: 82.5°–97.5°W.

Figure 6 shows diurnal variations of the lightning activity over North America in the three time zones. The diurnal variations of the lightning activity in both regions W8 and W7 are characterized with a single peak at 1800 LT. However, a different diurnal structure happens in W6, in which two peaks occur with the first at 1100 LT and second at 1900 LT. The double peaks over North America are clearly contributed by the double peaks in W6. A number of factors may affect this double-peak diurnal cycle structure. The changing WWLLN stations, lightning from landfalling hurricanes, and the weather patterns in that small local region may alter this feature in certain years. Lay et al. (2007) studied the diurnal cycle of lightning over North America with 1-yr WWLLN data and found that only one peak of lightning took place around 1900 LT, which might be related to the low detection efficiency of the network in 2005. Abarca et al. (2010) analyzed the lightning diurnal cycle over the United States based on a 3-yr (2006–2009) WWLLN dataset, and found that the diurnal structure changed into double peaks.

Next, yearly lightning data are used to identify how increased detection efficiency could affect the diurnal cycle of the lightning.

Figure 7 shows diurnal variations of the lightning activity in the eastern North America for 7 individual years, and each line is independently normalized. The lightning diurnal cycle shows two peaks every year. The local afternoon peak is evident each year, but the morning peak shifts from year to year. From 2005 to 2008, the secondary peak occurred at 0700, 0800, 1000, and 1100 LT, respectively. The main peak occurred at 1100 LT and the secondary peak appeared at 1800 LT in 2009. Only one peak occurred at 1200 LT in 2010, and the afternoon peak was not apparent. As time advances, the diurnal variation shows a diminishment of the afternoon peak and an increase of the morning peak. The WWLLN afternoon peak was shifting to 1200 LT in 2010. However, the lightning peak shifted to 1800 LT in 2011, with the lightning flash rate kept at a high value from 0700 to 1900 LT. The changing WWLLN stations, upgrading of a new algorithm in 2007, and higher sensitivity to stronger lightning of the WWLLN may be responsible for the changing diurnal cycle structure from year to year in the eastern North America.

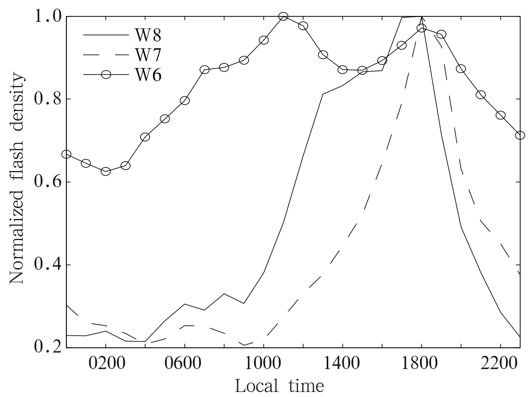

Fig. 6. Diurnal variations of the lightning activity over North America in three time zones W6, W7, and W8 (see text for specification of the zonal ranges).

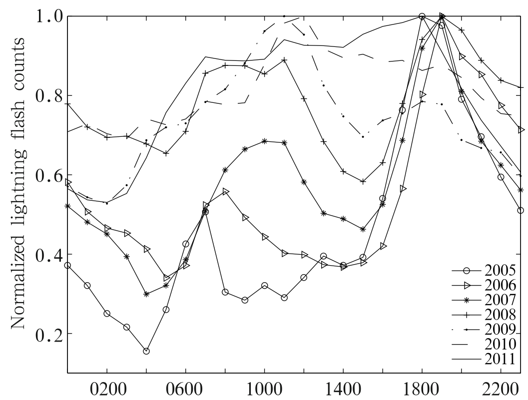

Fig. 7. Diurnal variations of the lightning activity in the eastern North America from 2005 to 2011.

4. Conclusions and discussion

Data from the WWLLN (2005–2011) and LIS/OTD (1995–2010) have been used to study the lightning activity on the global scale. The diurnal cycle of lightning activity over land and ocean is studied in detail in nine different geographical regions, with five continental and four oceanic regions.

The maximum flash density over the Congo basin is 160.7 fl km^{-2} yr^{-1}. The annual mean land to ocean flash ratio is 9.6:1. This result confirms the ratio of approximately 10:1 by Christian et al. (2003) using only 5-yr OTD data. However, the lightning density detected by the WWLLN is in general one order of magnitude lower than that by the LIS/OTD.

The diurnal variations over land in the WWLLN and LIS/OTD datasets show similar patterns, both with a local afternoon peak. In the WWLLN data, the diurnal cycle of lightning over land shows a single peak, with the maximum activity around 1400–1900 LT and a minimum in the morning. In the LIS/OTD data, the diurnal variation of lightning over land shows a narrow peak around 1400–1500 LT. The diurnal variation of lightning activity detected by the WWLLN over North America shows two maxima: a local afternoon peak and a secondary morning peak, and the morning peak shifts from year to year. However, the other four continental regions show only single peaks in the lightning diurnal cycle.

The lightning diurnal variation over ocean shows a large fluctuation demonstrated by the LIS/OTD dataset. In the oceanic regions, the diurnal variation of lightning shows two peaks: the early morning peak around 0100–0300 LT and the weaker peak between 1100 and 1400 LT by the LIS/OTD dataset. The curve of diurnal variation derived by the WWLLN data is smoother than that of LIS/OTD. The diurnal variations over the four oceanic regions based on the WWLLN data show an early morning peak around 0100–0300 LT. Besides the early morning peak, both of the western Pacific and East Pacific Ocean show a higher peak in the afternoon but none over the Indian Ocean. Over the Atlantic Ocean, a secondary peak occurs at 1100 LT. A comparison of the lightning diurnal variation over land and ocean by the WWLLN and LIS/OTD datasets suggests that both datasets have the ability to catch the diurnal variation of lightning over land; however, the WWLLN dataset is more suitable for study of diurnal variation of oceanic lightning. The smaller view time of the LIS/OTD may have possibly resulted in some of sparse lightning over ocean being missed out.

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