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Lightning activity in tropical cyclones and its relationship to dynamic and thermodynamic parameters over the northwest Pacific

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ABSTRACT

Tropical cyclones (TCs) over the northwest Pacific (NWP) Basin from 2005 to 2016 are used to investigate the characteristics of lightning activity and its relationship to environmental dynamic and thermodynamic parameters, which is based on lightning data from the World Wide Lightning Location Network (WWLLN), TC intensity and track, sea surface temperature (SST) and vertical wind shear (VWS) data. The highest lightning density in the inner core is found when TC is at tropical depression stage, whereas the secondary maximum occurs in super typhoon intensity stage. In the outer rainbands, lightning density changes slightly with TC intensity. The 6-hourly flash rate shows a distinctly positive correlation with the SST in the outer rainbands, and lightning activity in the inner core is less sensitive to the SST when the SST exceeds 27 °C. Asymmetric lightning distribution with respect to the VWS is observed. In the inner core, the asymmetric distribution of lightning activity is relative to the integrated effects of the VWS and TC motion vectors; however, the outer rainbands asymmetry is more sensitive to the VWS.

1. Introduction

Since frequent lightning flashes were detected during Hurricane Diana (1984) (Black and Hallett, 1986), lightning activity in tropical cyclones (TCs) has emerged as a significant research subject. Based on the National Lightning Detection Network (NLDN), Molinari et al. (1999) found two peak values of lightning flashes for nine Atlantic TCs during their hurricane stage, with the primary maximum > 200 km away from the storm center and a second maximum near TC center. The bimodal distribution pattern of flashes has been confirmed since then by more recent studies (e.g., Cecil et al., 2002; Pan et al., 2010; Abarca et al., 2011; Qie et al., 2014; Ranalkar et al., 2017).

Cecil et al. (2002) examined radial lightning distribution in 45 TCs by utilizing lightning data from the Lightning Imaging Sensor (LIS). They found that lightning density in the eyewall region and the outer rainbands was much larger than the inner rainbands. Using data from Guangdong Lightning Location System, Zhang et al. (2012) reported that radial distribution of lightning density varied with TC intensity when TCs landed in China, and the maximum of lightning density moved from the eyewall to the outer rainbands with TC intensity strengthening. Although detection efficiency (DE) is low, an obvious advantage of the world wild lightning location network (WWLLN) is that global and continuous lightning activity could be detected. Abarca et al. (2011) reported that radial distribution of lightning density detected by the WWLLN in 24 Atlantic TCs was consistent with the result from the NLDN. DeMaria et al. (2012) found that the average lightning density in Atlantic and Eastern North Pacific (ENP) TCs decreased with increasing distance from TC center when TC center was over the ocean. They considered that the disappearance of the minimum density in the inner rainbands was due to the overlap between the inner rainbands with small lightning flashes and the inner core of large TCs with high lightning density. Based on the data of the WWLLN, Pan et al. (2014) obtained similar result for the northwest Pacific (NWP) TCs regardless of TC intensity. Bovalo et al. (2014) examined lightning activity of TCs in the Southwest Indian Ocean by utilizing the WWLLN data and found that the radial distribution of lightning activity was relative to TC location and intensity.

The relationships between lightning activity in TCs and intensity change have received considerable attention in previous studies. Price et al. (2009) found that there was a significant correlation between flash rate and the maximum sustained wind (MSW) during intense hurricanes, and the MSW peaked about one day after the maximum

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flash rate. Using the WWLLN, Abarca et al. (2011) found that the lightning density of the inner core for 24 Atlantic TCs had a potential role in TC intensity forecasts, and this role was evident during the weaker intensity stages with the largest flash densities. DeMaria et al. (2012) showed that lightning outbreaks in the inner core were a signal that the intensification period of Atlantic TCs was nearly over; for rainbands in both the ENP and Atlantic TCs, the rapid intensification in the subsequent 24 h meant lightning density was higher. Pan et al. (2014) demonstrated that lightning activity was helpful to predict TC intensification due to strong relationships between lightning activity and the maximum wind speed over the NWP. Using data from optical transient detector (OTD), with high DE and discontinuous coverage of lightning activity, Cecil and Zipser (1999) found that most of the lightning flashes in the inner core occurred during weak TCs with the MSW between 17 and 23 $m\,s^{-1}$ and strong TCs (the MSW > 49 $m\,s^{-1}$), but a relationship between the lightning flash rate and TC intensification was not clear. Jiang and Ramirez (2013) found a positive (negative) correlation between total lightning densities and TC intensification in the outer rainbands (inner core) using 11 years of TRMM data. The above studies suggest that lightning activity in TCs could be useful for warnings of TC intensity changes.

In addition to lightning density and TC intensity, several authors have analyzed lightning outbreaks in TC eyewall region and found eyewall lightning outbreaks were often related to storm intensification (Stevenson et al., 2014). Molinari et al. (1994) stated that eyewall lightning outbreaks were related to the strengthening of Hurricane Andrew (1992), and these outbreaks were linked with the rapid growth of eyewall convection and increased liquid water content in the mixed phase region within updrafts. Further studies have shown that eyewall lightning outbreaks not only appeared at the time of intensity change but also during the eyewall replacement and TC recurvature (Squires and Businger, 2008; Zhang et al., 2015).

Compared with the spatial and temporal variations in TC lightning, studies on the relationship between lightning and the evolution of the convection, dynamic, and thermodynamic structures have received less attention. Abarca et al. (2011) studied the influences of the environmental vertical wind shear (VWS) and TC motion on lightning distribution using WWLLN and found stronger downshear left (right) asymmetric distributions for the inner core (outer rainbands) as the VWS strengthened, and the asymmetry caused by TC motion became less clear. In their study, lightning locations were described by icosagons around the TC center, and the sum of flashes was normalized to a range of 0–1. DeMaria et al. (2012) found that the structure of inner core lightning was influenced by the potential vorticity, while lightning activity in the outer rainbands was associated with the vertical circulations. Recently, Stevenson et al. (2016) conducted a similar study and presented that the environmental shear dominated the lightning asymmetric distribution; however, the TC motion vector, which is opposite of the shear, influenced the azimuthal distribution of the ENP TCs when the TC moves fast. Other regional lightning detection networks have been used, which restrict the study on TCs close to land. Corbosiero and Molinari (2002, 2003) linked the azimuthal distribution of lightning with the VWS in 35 Atlantic TCs by using data from the NLDN. They found that > 90% of flashes were located downshear when the VWS exceeded 5 $m\,s^{-1}$, and they considered this asymmetric distribution to be connected to the slantwise vorticity induced by the shear. Fierro et al. (2011) investigated the intracloud narrow bipolar events (NBEs) for Hurricanes Rita (2005) and Katrina (2005) using lightning data from the Los Alamos Sferic Array. The occurrence of NBEs and the maximum radar reflectivity in the northern area of the eyewall indicated that NBEs were related to the deep convective updraft in the eyewall region. The convective events in the eyewall region rotated around the eyewall for Rita and located at a fixed position for Katrina, which was likely due to different internal or external forcing mechanisms.

In recent years, TCs over the NWP Basin have been frequent and intense (Stowasser et al., 2007; Knutson et al., 2015). In 2013, there were four super typhoons that landed in this basin, which included Haiyan (2013), the most intense typhoon to make landfall in the Philippines, and this typhoon caused devastating damage and heavy casualties (Wang et al., 2016). Super typhoon Rammasun (2014), the most severe typhoon to make landfall in southern China since 1973, brought great disaster to the region. As a result of the frequent occurrence of intense TCs and the great disaster, knowledge of lightning activity for TCs in this basin is scientifically significant, which could provide useful information to TC path and intensity prediction (DeMaria et al., 2012; Zhang et al., 2015). However, research on lightning activity during TCs in this basin are still few (Zhang et al., 2012, 2015; Pan et al., 2014) compared to the Atlantic basin.

In this article, the intent is to examine the characteristics of lightning activity within TCs, as well as the relationship of lightning to dynamic and thermodynamic parameters over the NWP. The structure of this paper is as follows. Section 2 briefly introduces the data and analysis methods. Section 3 presents the characteristics of lightning activity with respect to TC intensity and SST, as well as the azimuthal distributions related to the shear and TC motion. The last section provides the conclusions.

2. Data and analysis method

2.1. Lightning data and correction

Twelve-years of lightning data from 2005 to 2016 are utilized in this work. The WWLLN, which is operated by University of Washington, consists of over 68 ground-based sensors installed across the globe to detect impulsive signals from lightning discharges (sferics) in the VLF band (3–30 KHz). These signals are obtained in real time and represent cloud-to-ground and intra-cloud lightning flashes that occur around the world (Rodger et al., 2009; Virts et al., 2013).

Since the WWLLN was established, the reliability of the network has been estimated using various methods (e.g., Rodger et al., 2005; Abreu et al., 2010; Virts et al., 2013; Soula et al., 2016; Srivastava et al., 2017). Pan et al. (2013) stated that the spatial and temporal distributions of lightning correlated well to those detected by the Lightning Imaging Sensor/Optical Transient Detector (LIS/OTD). Lightning distributions were also in agreement with the higher DE of the NLDN (Abarca et al., 2011). With the number of stations increasing and the location algorithm improved, the DE showed a large rate of increase. DeMaria et al. (2012) used lightning data from LIS/OTD to evaluate the DE of the WWLLN over the ENP and Atlantic Basins from 2005 to 2010, and found it ranged from 0.9% and 2.7% to 17.5% and 20%, respectively. Using the same measures, Bovalo et al. (2012) found that the DE increases from 2.0% in 2005 to 10.9% in 2013 over the southwest Indian Ocean. Zhang et al. (2015) found that the DE over the NWP more than doubled between 2005 and 2009. Consequently, the continuous evolution of convection and lightning distributions for TCs, which are far away from land, can be successfully described using the WWLLN.

As the WWLLN's DE has improved during this study, lightning data calibration is necessary for consistency. Because of the spatial variability of the WWLLN DE over the NWP Basin (0°–45°N, 100°–180°E) is small enough (Hutchins et al., 2013, as shown in Fig. 6), the DE could be considered identical in this region. Following the same procedure proposed by DeMaria et al. (2012), WWLLN data are calibrated before the analysis. The climatological mean flash rate from LIS/OTD lightning data on a 2.5° × 2.5° grid is used as the ground truth (Cecil et al., 2014; Yuan et al., 2016). The DE of the WWLLN is evaluated by dividing the annual WWLLN flash rate by the annual LIS flash rate over the NWP for each year, which is shown in Table 1. The result shows that the DE over the NWP Basin increases from 4.3% in 2005 to 19.1% in 2016, which is in line with the trend over different regions reported by other researchers (DeMaria et al., 2012; Bovalo et al., 2012; Zhang et al., 2015). The WWLLN data are corrected by multiplying by the annual