Abstract

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Abstract—Cloud-to-ground (CG) lightning data and storm intensity and track data are combined with the data from a Doppler radar and the Tropical Rainfall Measuring Mission (TRMM) satellite to analyze the temporal and spatial characteristics of lightning activity in Typhoon Molave (0906) during different periods of its landfall (pre-landfall, landfall, and post-landfall). Parameters retrieved from the radar and the satellite are used to compare precipitation structures of the inner and outer rainbands of the typhoon, and to investigate possible causes of the different lightning characteristics. The results indicate that lightning activity was stronger in the outer rainbands than in the eyewall and inner rainbands. Lightning mainly occurred to the left (rather than "right" as in previous studies of US cases) of the moving typhoon, indicating a significant spatial asymmetry. The maximum lightning frequency in the tropical cyclone (TC) eyewall region was ahead of that in the whole TC region, and the outbreaks of eyewall lightning might indicate deepening of the cyclone. Stronger lightning in the outer rainbands is found to be associated with stronger updraft, higher concentrations of rain droplets and large ice particles at elevated mixed-phase levels, and the higher and broader convective clouds in the outer rainbands. Due to the contribution of large cloud nuclei, lightning intensity in the outer rainbands has a strong positive correlation with radar reflectivity. During the pre-landfall period (0300 Beijing Time (BT) 18 July 2009 to 0050 BT 19 July), the typhoon gradually weakened, but strong lightning still appeared. After the typhoon made landfall at 0050 BT 19 July, CG lightning density rapidly decreased, but the ratio of positive lightning increased. Notably, after the landfall of the outer rainbands at 2325 BT 18 July (approximately 1.5 h prior to the landfall of the TC), significantly higher ice particle density derived from the TRMM data was observed in the outer rainbands, which, together with strengthened convection resulted from the local surface roughness effect, might have caused the enhanced lightning in the outer rainbands around the landfall of Molave. Key words—Molave; typhoon; landfall; lightning; precipitation; structure I. INTRODUCTION Typhoon related disasters are one of the most severe natural disasters in the world and they often occur before and after landfall of the typhoon. Landfalling time is an important turning point during a typhoon's life cycle because the structure, strength, and track of the typhoon and associated precipitation distribution will all go through a series of changes. Prediction of local weather, flooding, and ocean waves associated with landfalling hurricanes and tropical cyclones (TCs) specifically within 48 h has been a challenging research topic [1]. With seven to eight typhoons making landfall each year, China is one of the countries with the most landfalled typhoons in the world, and their duration on land is on average 31 h [2]. Landfalling typhoons bring not only severe flooding, but also strong winds and storm surge to the coastal areas of China. Moreover, lightning activity in landfalling typhoons always causes severe damage. Therefore, it is important to investigate characteristics of landfalling typhoons. China has been constructing the national lightning detection network since the 1990s and we have now obtained ground-based lightning data for more than one decade. How to use these data to study the characteristics of lightning activity in connection with convective structures of landfalling typhoons is a fundamental research topic. In this study, we firstly use lightning data from a regional lightning detection network in South China, along with storm track and intensity data from the China Meteorological Administration (CMA), to study the characteristics of lightning activity in Typhoon Molave (0906) during different periods of its landfall. Secondly, we combine Doppler radar data with TRMM satellite observations to investigate the convective structure and precipitation characteristics in the inner and outer rainbands of Molave, and discuss the causes of distinct lightning characteristics in different typhoon regions. The results of this study will provide a better understanding of microphysical processes and electrification in TCs and may help improve assimilation of lightning data into TC forecasting models. II. DATA AND METHODS A. Lightning Data Lightning data are from the Guangdong Lightning Location System (GDLLS) in the grid of Guangdong Electric Power Company. The network consists of 16 sensors and provides real-time CG lightning locations for the whole Guangdong Province and its vicinity by the combined technique of magnetic direction finding (DF) and time of arrival (TOA). It provides information of date, time, latitude, longitude, peak current, polarity, and number of strokes per flash. Lightning data for Typhoon Molave span the period from 0300 Beijing Time (BT) 18 July 2009, 22 h prior to landfall of Molave, to 2000 BT 19 July 2009, 20 h after landfall. B. Tropical Cyclone Data Information on TC track and intensity are obtained from the Yearbook of Tropical Cyclone [3]. It gives the center latitude, longitude, maximum sustained surface wind speed, and minimum central pressure at 6-h intervals. Hourly TC center location and intensity are obtained by using spline interpolation. Figure 1 gives sensor locations of GDLLS and tracks of Molave during the periods when lightning data are examined. The storm region is divided into three sub-regions based on electrical characteristics: eyewall (within 60 km of the storm center); inner rainbands (100-200 km from the center); and outer rainbands, (200-500 km from the center). The motivation for dividing the storm is based largely on the work of [4] who found three broad categories of convection regimes in hurricanes on the basis of lightning activity. C. Radar Data Radar data are collected by the CINRAD-SA Doppler radar located in Guangzhou. Through using bilinear interpolation, polar coordinate reflectivity data were converted to rectangular
coordinate with a spatial resolution of 0.01°×0.01° and a vertical resolution of 25 layers. Radar data used in this study are from 1300 BT 18 July when the outer rainbands appeared within 300 km of the radar effective observation range and lightning started to be observed to 1000 BT 19 July when the storm center moved out of the radar effective observation range. For all radar images shown in this paper, lightning strokes that occurred 6 min after the radar scanning time and within 300 km of the effective observation range are overlaid on reflectivity. D. TRMM Data Two overpasses (orbit 66496 and 66501) of Typhoon Molave by the TRMM satellite are used in this study. Orbit 66496 viewed the storm at 1515 BT 18 July, 9.5 h prior to Molave landfall, and orbit 66501 viewed it at 2325 BT 18 July, 1.5 h prior to its landfall. Precipitation-processed ice concentrations (product 2A12) estimated by the TRMM Microwave Imager (TMI), and total lightning measured by the LIS are used to compare hydrometeor profiles of the storm at different stages. TMI and LIS are described in [6] [7]. III. LIGHTNING ACTIVITY DURING LANDFALL A total of 90233 CG flashes were detected by the DGLLS during the landfall of Typhoon Molave. The very low flash density in the eyewall and inner rainbands, and high flash density in the outer rainbands at the radii of 200 to 500 km from the center, are indicated clearly. The average flash density in the outer rainbands is 13.2 fl (10 km)-2, which is 4.7 and 9.1 times that in the inner rainbands and eyewall, respectively. A strong asymmetry is present in the figure with lightning flashes located mainly in the northwest quadrant, which is to the left of the moving typhoon during the Molave landfalling period. Figure 1 shows the evolution of lightning flash frequency superimposed on the minimum central pressure and maximum sustained wind speed of the storm. Lightning started to enhance since 1500 BT 18 July. The most frequent lightning occurred while the storm reached its maximum intensity at 2000 BT 18 July, with central pressure of 965 hPa and maximum wind of 38 m s-1. As the storm approached landfalling, lightning activity weakened sharply and gradually ceased. The variation of eyewall lightning demonstrates that: 1) eyewall lightning has a longer advanced warning period for the storm intensification than TC lightning. The peak of eyewall flash frequency occurred at 1600 BT 18 July, 4 h prior to the peak of TC flash and storm intensity; 2) eyewall flash outbreaks occurred during the storm rapid intensification. Molave produced a total of three eyewall flash outbreaks. The first burst (Burst ① at 1000 BT 18 July) occurred when the storm began to intensify, and the second burst (Burst ②, at 1300 BT 18 July) occurred 3 h later. The third eyewall outbreak (Burst ③, at 1600 BT 18 July) occurred 4 h before the storm reached its maximum intensity, and much larger than the first two in flash rate. In all time periods except for the outbursts, eyewall lightning was weak and the flash frequency was close to zero. 03 05 07 09 11 13 15 17 19 21 23 01 03 05 07 09 11 13 15 17 19 0 10 20 30 40 50 TCFlash(400*fl/hr) TC Flash Wind Eye Flash Pressure EyewallFlash(fl/hr) Pressure(hPa) 7/18 7/19 Landfall Burst① ② ③ BJ Time 950 960 970 980 990 1000 7/19 Fig. 1. Temporal evolution of lightning flashes superimposed on hourly interpolations of the minimum central pressure and maximum sustained wind speed. The three eyewall lightning outbreaks are indicated by arrows with serial numbers. IV. PRECIPITATION CHARACTERISTICS A. Lightning Activity and Radar Reflectivity Figure 2 presents variations of CG lightning frequency with maximum radar reflectivity in the inner and outer rainbands. The maximum radar reflectivity in the outer rainbands seems more correlated with the lightning time series than that in the inner rainbands. In the outer rainbands, the peak lightning frequency occurred 2 h after the peak maximum radar reflectivity and lightning activity steadily declined when the maximum reflectivity began to decrease. Moreover, larger values of maximum reflectivity appeared in the outer rainbands than in the inner rainbands. Strong reflectivity of 66 dBZ showed in the outer rainbands while the strongest echo in the inner rainbands was 54 dBZ. During the period of active lightning, the mean value of maximum reflectivity in the outer rainbands was 56 dBZ while that of the inner rainbands was 43 dBZ. Lightning activity is closely related to size distributions of cloud particles. Large particles produce strong radar reflectivity, so lightning frequency has a good correlation with maximum reflectivity. A better correlation was seen in the outer rainbands than in the inner rainbands due to the differences of precipitation structures. 13:00 15:00 17:06 19:06 21:00 23:06 1:06 3:06 5:06 7:06 9:12 0 100 200 300 400 500 Outer band: Flash rate Max reflectivity Inner band: Flash rate*10 Max reflectivity Max reflectivity(dBZ) Flash rate/(fl/min) BJ Time 20 30 40 50 60 70 80 Fig. 2. Temporal evolution of radar maximum reflectivity and lightning frequency in the inner and outer rainbands. B. Horizontal and Vertical Structures of Lightning Taking the height of 18-dBZ reflectivity echo as the cloud top height (CTH) and the grid cell area of CTH > 11 km as cloud horizontal scale, temporal evolutions of CTH, grid cell number, and lightning frequency in the rainbands are analyzed. The results show that lightning frequency in the outer rainbands were correlated with CTH. When CTH reached its peak, lightning flashes began to gradually increase. When CTH began to decrease, lightning frequency in the outer rainbands also began to drop. Lightning frequency also shows a good correlation with horizontal grid cell area in the outer rainbands. When lightning reached its maximum frequency, cloud horizontal area continued to increase, and lightning tended to stop when horizontal area rapidly decreased. Compared with the outer rainbands, lightning in the inner bands was more relevant to horizontal grid cell area than to CTH. The positive correlation of lightning frequency and cloud horizontal scale shows that intensive CG activity requires that strong convection in TCs reach not only a high level in the vertical but also a wide range in the horizontal. Because CG flash rate is positively correlated with convective cell area, it may be inferred that the larger the convective area, the larger the region of charge generation or the more efficient the charge separation process owing to stronger updrafts [8]. The above observational data analysis on Typhoon Molave indicates that the outer rainbands are featured with higher cloud top and larger convective area than the inner rainbands. Radar reflectivity analyses at 3, 8, and 12 km are performed to show the low-, mid-, and upper-level storm structures. Figure 9 gives temporal evolutions of lightning frequency and reflectivity area at these levels. At the low level (3 km), temporal variation of the 20-40-dBZ reflectivity area corresponded well to lightning frequency in the outer rainbands, except that the peak time of reflectivity was slightly ahead of the peak time of lightning. The peak time of strong reflectivity area (40 dBZ) is closer to the peak time of lightning frequency. However, reflectivity area has no correspondence with lightning activity at this level in the inner rainbands. At the mid level (5 km), the peaks of 20- and 30-dBZ reflectivity area in the outer rainbands lagged behind peaks of lightning frequency, but area of strong reflectivity ( ≥ 40 dBZ) was consistent with the variation
of lightning activity, because strong reflectivity at the mid level reflected the content of charged particles in the cloud. In the inner rainbands, reflectivity area of 30 dBZ had a better correspondence to lightning flash rate. At the upper level (12 km), strong reflectivity of 40 dBZ still had a certain area in the outer rainbands, but reflectivity of only 20 dBZ was observed in the inner rainbands. Reflectivity area of 20 30 dBZ had a good correspondence to lightning frequency in the outer rainbands, while in the inner rainbands changes of reflectivity area were different from variations of lightning activity, especially in the dissipation stage. V. PRECIPITATING PARTICLE DISTRIBUTIONS BEFORE AND AFTER LANDFALL OF THE OUTER RAINBANDS OF MOLAVE Figure 3 shows distributions of surface precipitation rate retrieved by TRMM/TMI and lightning detected by LIS at 1515 BT 18 July (9.5 h prior to landfall of Molave; Fig. 3a) and at 2325 BT 18 July (after landfall of the outer rainbands of Molave and 1.5 h prior to landfall of Molave; Fig. 3b). In Fig. 3a, the TC eye, the inner and outer rainbands of Molave were seen clearly and completely when the storm was over water. During this pre-landfall period, precipitation rate was low and evenly distributed in the inner and outer rainbands. Lightning activity was weak with only 7 total lightning detected by LIS in the 90-s viewing time. After the landfall of the outer rainbands of Molave, two convective cores and heavy rainfall appeared due to local land surface roughness effect and the influence of environmental airflow. Stronger lightning activity was observed, with an occurrence of 160 total lightning in the 90-s viewing time. Vertical profiles of various cloud particles (Fig. 4) show that the density of ice particle after landfall of the outer rainband was higher than that before, especially in the mixed-phase region of temperatures between -20 and -10 °C. The maximum value of PI in the mixed region was 1.4 g m-3 during post-landfall of the outer rainbands, which was 1.8 times the density before landfall of the outer rainbands. We infer that the increased density of ice particles in the mixed-phase region, together with intense convection, is the reason for stronger lightning activity around landfall of Molave. This is consistent with the results of previous studies [9] [10] [11]. Fig. 3. Distributions of surface precipitation rate retrieved by TRMM/TMI-2A12 and lightning detected by LIS during the (a) pre-landfall and (b) post-landfall of the outer rainbands of Molave. The rectangle denotes the study area. The symbol “+” indicates total lightning detected by LIS. The black dot gives the center location of Molave. 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 0 2 4 6 8 10 12 14 16 18 Orbit 66496 Outerband Water Content (g/m3) Height (km) -40°C -30°C -20°C -10°C 0°C 0°C Cld Wat. Prec. Wat. Cld Ice Prec. Ice 0 0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 0 2 4 6 8 10 12 14 16 18 Orbit 66501 Outerband Water Content (g/m3) Height (km) -40°C -30°C -20°C -10°C 0°C Cld Wat. Prec. Wat. Cld Ice Prec. Ice Fig. 4. Vertical profiles of the averaged particle density within cloud retrieved by TRMM/TMI-2A12 before (orbit 66496) and after (orbit 66501) landfall of the outer rainbands of Typhoon Molave. VI. SUMMARY With lightning data, storm intensity and track data, Doppler radar and TRMM satellite data, this study analyzes the temporal and spatial characteristics of lightning activity in Typhoon Molave (0906) around its landfall. Parameters retrieved from the radar and the TRMM satellite are utilized to compare the precipitation structures of inner and outer rainbands and to discuss possible causes of different characteristics of lightning activity. Preliminary results are summarized as follows. (1) Stronger lightning activity occurred in the outer rainbands than in the eyewall and inner rainbands during the landfall of Molave. Lightning flash density in the outer rainbands was 4.7 and 9.1 times the value in the inner rainbands and eyewall region, respectively. Lightning showed a significant spatial asymmetry and occurred mainly on the left side of the typhoon moving direction because of the land-sea distribution and the particular weather circulation pattern. Higher content of ice particles as well as stronger convection resulted from the local land surface condition may be the main cause of enhanced lightning activity in the outer rainbands around landfall of Molave. (2) When approaching landing, the storm gradually weakened, but strong lightning activity still occurred. After the landing, lightning density rapidly decreased. The maximum lightning frequency in the eyewall appeared prior to that of the whole TC lightning frequency. Three eyewall lightning outbreaks occurred before the storm reached its strongest intensity and the outbreaks of eyewall lightning may indicate deepening of the cyclone. (3) Characteristics of lightning activity are determined by convective structures and precipitation features in different regions of the typhoon. Strong lightning activity in the outer rainbands was caused by strong updrafts, large concentrations of precipitable particles and large-sized ice particle in the mixed-phase region, and higher and broader convective clouds. Statistics of the variables detected by the lightning detection system, radar, and satellite provides a summary about the convective characteristics of the inner and outer rainbands and the features of the strong lightning activity in the outer rainbands. (4) Typhoon Molave exhibited a complete structure of eye, inner and outer rainbands when it was over water, but with low precipitation rate and small lightning flash rate in this period. After the landfall of the outer rainbands, convective cores occurred in the outer rainbands and heavy rainfall and stronger lightning activity were observed. Vertical profiles of cloud particles reveal that the density of ice particles after landfall of the outer rainbands was significantly higher than pre-landfall of the outer rainbands, especially in the -20 to -10 °C mixed-phase region, and the maximum value of PI in the mixed-phase region during post-landfall of the outer rainbands was 1.8 times the value of that before landfall of the outer rainbands. When the outer rainbands of Molave landed, significantly higher ice particle density derived from the TRMM data was observed in the outer rainbands, which, together with strengthened convection resulted from the favorable local surface condition, might have caused the enhanced lightning in the outer rainbands around the landfall of Molave. REFERENCES [1] Marks, F. D., and L. K. Shay, 1998: Landfalling tropical cyclones: Forecast problems and associated research opportunities. Bull. Amer. Meteor. Soc., 79(2), 305–323. 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