Atmos. Meas. Tech. Discuss., doi:10.5194/amt-2016-380, 2017
Manuscript under review for journal Atmos. Meas. Tech.
Discussion started: 19 April 2017

Atmospheric Measurement Techniques Discussions

Lightning Data Analysis of the CMA Network in China

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Abstract

Based on analysis and evaluation of the 2009 to 2013 national lightning monitoring data, the average lightning detection station distance is approximately 170 kilometers in China, and the average operational availability **(AO)** exceeds 90%. Lightning detection systems use a hybrid location method of direction finding (DF) and the time difference of arrival (TOA). The stations use four localization algorithms, including two-station mixing, three-station mixing, four-station mixing and two-station amplitude. Among them, the four-station method has the highest positioning accuracy, i.e., close to 50%. The statistical results show that lightning occurrences in China have increased, especially negative cloud-to-ground (-CG) flashes because positive cloud-to-ground (+CG) flashes account for only 5.1% of the total. In china, most of lightning currents range are in the -60~+60kA, Lightning current between -10~+10kA

[1]Sponsored by the Meteorological support project for disaster prevention and control of geological disasters.

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only accounted for small proportion of 0.6%.The average intensity of positive flashes is 64.2kA, the average intensity of negative flashes is -40.28kA. The average +CG intensity is higher than that of -CG flashes, which is consistent with statistical results of other Lightning detection network. Lightning frequency has obvious regional differences across the country; the high density lightning area is mainly distributed in south-central China, the south-central Yangtze River region and the eastern part of southwestern China. Seasonal variation in lightning activity is well defined, with few lightning occurrences in winter and a gradual but significant increase from spring to autumn in the middle and lower reaches of the Yangtze River to the north, south and southwest. The ratio of positive to negative flashes is highest in winter.

Key words: lightning detection; localization algorithm; statistical features

1. Introduction

Lightning is a discharge phenomenon that commonly occurs in the development phase of strong cumulonimbus clouds, and it is often accompanied by strong wind gusts and rain and occasionally hail and tornadoes (Chen Weimin. 2006; Xu Xiaofeng et al.2003). The electric current of lightning is generally tens of thousands to hundreds of thousands of amperes, and the discharge process takes less than 60 microseconds (Qie Xiushu et al. 2013). The strong current, high temperature, violent wave, electromagnetic field change, strong electromagnetic radiation and other properties of lightning can cause fatal injuries. Lightning affects aerospace (Nie Ying et al. 2008), communication (Wang ShunXiang. 2013), power (Hu XianNiu. 2003), forests (Wu

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ShuSen et al. 2010), buildings (Hou AnXiao. 2014), national defense and the economy. Statistics show that there are, on average, tens of thousands of lightning-related incidents, more than 800 lightning casualties, and billions of Yuan in direct economic losses each year in China.

China is located in temperate and subtropical regions; therefore, thunderstorm activity is frequent. The 21 provincial capital cities experience more than 50 thunderstorm days each year, with as many as 134 days in some cities. The casualties, economic losses and social effects caused by lightning are becoming increasingly serious (China Meteorological Administration. 2008). Therefore, there is an urgent need to effectively monitor the occurrence, development and evolution of lightning. The thunder and lightning monitoring and location systems produced at the end of the 20th century and beginning of the 21th century can detect lightning discharges more accurately, providing powerful data support to thunder and lightning monitoring, protection and research (Lin Jian et al. 2008).

In order to monitor and prevent lightning events, since late twentieth Century, a number of lightning monitoring network were established in the world , such as the United States National Lightning Detection Network (NLDN) (Cummins K L etal 1998a), European lightning detection network (LINET) (Betz H-D,2009)and the global lightning location network (WWLLN)(Dowden RL etal,2002), the network constantly were updated technology, improved localization algorithm, the detection efficiency continuously to improve (Rakov V A, 2013), which play an important role in the research of lightning technology and lightning monitoring and warning operation.

In 2004, China began constructing a national lightning detection network that includes unified comprehensive data processing and positioning calculation. Based on the 2009 to 2013 national lightning monitoring data, this paper analyzes the operation of the Chinese lightning detection network and explores the temporal and spatial distribution of lightning, which is expected to provide a reference for domestic lightning monitoring and forecasting.

2. Lightning Detection Network

2.1 Network Operation Stability

Construction of China's lightning detection network began in the early 21st century and was initiated by the Chinese Academy of Sciences and the China Meteorological Administration (CMA). The CMA has more than 170 deployments, while the Chinese Academy of Sciences has approximately 50. After 2008, most of the lightning detection equipment was under the unified management of the CMA. Thus, the national lightning detection network formed and began operation. The number of national lightning detection network observation stations reached 275 at the end of 2009, with 265 stations being built by the CMA and only 10 stations by other ministries. From 2010 to 2013, the network continued to expand and increased by 10% per year. The number of stations reached 347 at the end of 2013, and the detection coverage increased by 30% compared to 2008. The average distance between stations is approximately 170 kilometers, approximately 300 kilometers in western China and 150 kilometers in eastern China. The network station layout is

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shown in Figure 1. The detection accuracy is approximately 500 meters.

Figure 1 about here

The CMA observation center evaluates the operation ability of the lightning detection network every year. The operation availability (AO) is used as an evaluation index. The specific algorithm is the sum of the time that all equipment was in normal operating or suspicious conditions (the device self-deviation or crystal deviation value is greater than the specified value, but it is still working to get data) divided by the total the equipment operation time. The index reflects the stability of the overall operation of the observation network.

$$\mathbf{AO} = \frac{Normal\ status\ running\ times + suspicious\ status\ runing\ time}{total\ running\ time} \times 100\% \quad (1)$$

Among them, the total running time includes the normal running time, suspicious state running time and equipment failure time. But it is also different from the full year, the full year is equal to the sum of the total running time and maintenance time (According to the regulation, each equipment needs to be shut down for a certain period of time to carry out routine maintenance to prevent the failure).

The results show that China's annual average operational availability of the lightning network was 89.68%, 91.19%, 95.39%, 96.30%, and 94.41% in 2009, 2010, 2011, 2012, and 2013, respectively, which shows that the overall stability of the lightning observation network is Credible and satisfactory in China.

2.2 Lightning Location Method

The national lightning observation network primarily uses the ADTD model lightning detector, which is based on the VLF/LF time difference direction hybrid positioning technique. The device was developed by the Chinese Academy of Space Science and Application Research Center and was certified by the CMA in 2003. The detector can simultaneously detect the cloud-to-ground lightning electromagnetic field azimuth and the time of arrival. Then, an appropriate positioning algorithm can be chosen according to the number of stations that actually detect a lightning electromagnetic wave. Four types of localization algorithms, namely two-station hybrid, three-station hybrid, four-station hybrid and two-station amplitude (referred to as M1, M2, M3, and M4), are used to determine the location of lightning according to the site distribution and detected data.

The M1, M2, and M3 algorithms are hybrid location methods that comprehensively utilize direction finding (DF) and the time difference of arrival (TOA). The principle is that each lightning detector can detect the hit back azimuth and the time of return stroke radiation of electromagnetic waves that reach the detection station. If two detectors receive the electromagnetic wave signal, the lightning position can be calculated using a hyperbolic function of the TOA and the two azimuth angles. If three detectors receive the electromagnetic wave signal, the time difference method is used in the double solution region; in the non-dual solution region, the double solution is obtained using the time difference method. False solutions are removed from the double solution using the direction-finding method. If four or more detectors receive the wave, the TOA least squares method is used to calculate the best lightning position.

The multi-station network (more than four stations) mainly uses the TOA data to locate lightning. **Then, the TOA localization results are used for systematic error correction of the DF data to improve the positioning accuracy of the two-station and three-station hybrid methods.** The TOA and DF hybrid lightning location system can ensure positioning results for networks with fewer detectors with high positioning accuracy, which is a more practical lightning monitoring and positioning system. According to domestic and international research, its general positioning accuracy is between a few hundred meters to 2-3 kilometers, for example, U.S. National Lightning Detection Network(NLDN) location error is about 308m(Nag et al.2011), LINET location error is 100~200m(Betz et al, 2009) , World Wide Lightning Location Network(WWLLN) location error was estimated to be 4-5km (Abarca et al. 2010). Recently, Wang Yu et al. (2015) study on Beijing Lightning NETwork (BLNET) and point out its location error was less than 200 m within the network and 3 km at the range of 100 km outside the network. The M3 method has the highest efficiency in actual operation (Shao Liang-qi,2007). It can not only ensure that a small number of detection stations to participate in the positioning of the calculation, save computing resources and time, but also to ensure a high positioning accuracy, is a more practical lightning monitoring and positioning method. Its frequency of use is **also high,** which can be seen in the following analysis.

The amplitude method is mainly used to detect cloud-to-ground flashes and near-distance in-cloud flash. Its main principle is that according to the attenuation relationship between the intensity and the distance of the lightning radiation field, a standard intensity value is obtained to determine the approximate distance of lightning. Its relative error is mainly determined by the dispersion and propagation error of lightning intensity (Zhang W J et al. 2009).

Figure 2 shows the usage frequency for the four lightning positioning algorithms (M1, M2, M3, and M4) from 2009 to 2013. The M3 algorithm is used most often, accounting for nearly 50% of lightning detection results, and its usage has continuously increased since 2009. M1 was used approximately 30% of the time, and M2 was used approximately 20% of the time. M4 was used least often and was decommissioned in 2012-2013. The results show that 40%-50% of lightning strikes can be measured using M3 in China. This result also reflects the high sensitivity of the ADTD detector; in the event of a lightning strike, multiple adjacent stations can simultaneously capture the corresponding electromagnetic wave signal. Therefore, the positioning precision is also high. After 2012, M4, which has a lower detection accuracy, was eliminated; this outcome also verifies that the detection ability of China's lightning network is constantly improving.

Figure 2 about here

Figure 3 shows the cumulative frequency distributions of the detection algorithms from 2009 to 2013. The M3 algorithm has the highest frequency, especially in Sichuan, Yunnan, Guizhou, Hubei, the Yangtze and Huai River Basins, regions south of the Yangtze River and southern China, i.e., 6000 to 10000. Figure 3 also shows that the detector density is reasonable. Moreover, thunder and lightning events that can be detected in these regions using the multi-detector approaches. The

M1 algorithm is primarily used in the Sichuan Basin, western Sichuan Plateau, the border between the Yunnan and Guizhou provinces, the eastern mountain area south of the Yangtze River, and the eastern and southern hilly and mountainous areas of southern China, suggesting that the detection environment is poor in these areas, and the lightning signal tends to be detected by only a few stations.

Furthermore, the M2 algorithm is used less often than M1 and is concentrated in the Sichuan Basin and Guangdong's Zhujiang River delta. M4 has the lowest usage frequency, i.e., less than 1000, and is concentrated west of Guizhou, in Chongqing, and in the southern part of the region south of the Yangtze River. According to the principle of lightning detection and local convective weather and climate characteristics, it can be assumed that more cloud flashes occur in these regions, which are easily detected by the two-amplitude method, although its overall frequency is much less than the number of cloud-to-ground flashes (Yu Min, et al 2015). Overall, the detection algorithm distribution is consistent with lightning locations, and the M3 algorithm (multi-station method, high accuracy, and high sensitivity) is generally used in areas prone to lightning, while the M4 algorithm is used less often. Additionally, the various detection algorithms are mainly concentrated in eastern China and are rarely used in western regions and Inner Mongolia. This conclusion may be related to climate or the lack of detectors in these areas.

Figure 3 about here

3. Lightning Statistics

3.1 Temporal Changes in Lightning Features

Occurrence number of detected lightning increased each year from 2009 to 2013 in China (Figure 4). This increase is, on the one hand, related to improvement in lightning detection equipment and the monitoring network and, on the other hand, may be related to climate change in China. According to monitoring statistics, there were 49772855 (cloud-to-ground) lightning events from 2009 to 2013 in China; 47245362 of these were negative lightning strikes, accounting for 94.9% of the total. There were 589149 positive lightning strikes, accounting for 5.1% of the total. This finding is consistent with the positive lightning ratio of 4-5% in the United States reported by Xu Xiaofeng et al. (2008) for the period 1992-1994. The seasonal differences in lightning frequency are significant (Fig. 4). Winter (December to February) lightning occurs less frequently; fewer than 1% of lightning occurrences are observed in winter. Moreover, the lightning frequency increases each month after May, reaching a peak in August (average of 3070865, accounting for 30% of the annual total). Lightning that occurs from June to September accounts for approximately 83% of the annual total. The finding that summer is an active lightning season, which may be related to the enhanced warm moist air flow and strong convective activity in summer (Lin Jian, et al. 2008), is consistent with satellite observations (Yuan Tie, et al. 2004).

Figure 4 about here

3.2 Spatial Distribution Characteristics

3.2.1 Annual Average Distribution

According to the average lightning distribution for the period of 2009 to 2013 (Fig. 5), the number of lightning events has well-defined regional differences. For example, northern China, the middle and lower reaches of the Yangtze River, Yunnan, Guizhou, and Sichuan provinces, and the eastern coastal areas have frequent lightning activity. Moreover, a lightning-prone area is also found over south-central China, the central region south of the Yangtze River and in southwestern China. Northwest China has relative fewer lightning events.

Figure 5 about here

3.2.2 Seasonal Variation

The monthly and seasonal average lightning distribution differences are also significant. In the first and fourth quarters, there are significantly fewer lightning strikes than in the second and third quarters. Moreover, lightning occurs over a much smaller region in the first and fourth quarters. The lightning occurrence area of the third quarter is the most extensive, and the lightning activity is the most frequent. The lightning occurrence area expands after February, with lightning-prone areas showing an irregular hook-shaped distribution in March that extends from south-central China to the eastern region of southwestern China and to the northern region south of the Yangtze River. In May, the lightning-prone areas expand to all of southern China; lightning in Guangdong province increases significantly, and lightning activity in the western region of Xinjiang begins to appear. In June, northern and northeastern China's lightning activity increases significantly, lightning in the western Xinjiang region continues to expand eastward, and the frequency increases significantly across

China. In July and August, the lightning activity reaches its peak across China in terms of both the spatial extent and frequency of occurrence. The lightning activity in September decreases significantly, especially north of the Yangtze River; the lightning-prone areas become confined to the southwest and south of the Yangtze River and southern China.

Previous research has shown that seasonal changes in the distribution of lightning activity are affected by variability in the western Pacific subtropical high. Because of the relatively warm and moist air located northwest of the subtropical high, this area prone to instability. As a result, extensive lightning activity occurs in this region when a low-pressure system, upper-level trough, shear line, or vortex interact with the warm and moist air. However, the separate weather system effects result in thunderstorm activity; thus, the occurrence of thunder and lightning is not entirely consistent with the movement of the subtropical high (Xu Xiaofeng et al. 2003; Qie Xiushu. 2013).

Figure 6 about here

3.3 Ratio of Positive and Negative Lightning and Intensity Features

Statistics show that negative flashes are dominant on an annual basis. The 5-year average of the positive to negative flash ratio is 0.0557; the highest ratio occurred in 2010, reaching 0.0628, while the lowest occurred in 2013 (0.0495). The positive lightning frequency in winter was significantly higher than that in the other seasons, with the highest occurrences in December and January. These findings demonstrate that the total number of positive lightning events was lower in seasons with higher temperatures (and vice versa).

2009~2013, the lightning current intensity that are detected in China are general whthin -300~300kA. Most of them currents range are in the -60~+60kA, accounting for 84.8% of the total number of lightning. The average intensity of positive flashes is 64.2kA, the average intensity of negative flashes is -40.28kA. the average +CG intensity is higher than that of -CG flashes, which is consistent with the results of Williams E et al (2007) research. Similar to the results of other lightning detection network (Abarca S F et al, 2010), lightning current between -10~+10kA only accounted for small proportion of 0.6%. Figure 8 shows the proportion of different intensities of lightning, negative flashes with -20~-30kA current are the highest proportion, while for the positive flash,30~40kA intensity is the highest proportion.

Figure 7 and 8 about here

4. Summary and Conclusions

There are approximately 350 lightning detectors with an average station distance of 170 kilometers in China. The average **operation availability** exceeds 90%, and the operation stability has been high over the past 5 years.

China's lightning detection technology is based on LF and VLF technology. The lightning location methods are primarily based on DF and TOA hybrid methods. According to the data, the four algorithms (two-station hybrid, three-station hybrid, four-station hybrid and two amplitude) have similar practical operation capabilities. The four-station hybrid method is used approximately 50% of the time, while the low-accuracy two-amplitude method was removed from operation in 2012, demonstrating that lightning detector accuracy continues to improve in China.

The statistics show that the number of lightning strikes in China remained steady from 2009 to 2013; negative flashes account for the majority of strikes, and positive lightning flashes account for approximately 5.1% of all strikes. These results are consistent with statistical results from the United States [2]. The lightning distribution has well-defined regional differences. For example, in northern China, the middle and lower reaches of the Yangtze River coastal region, Yunnan, Guizhou, and Sichuan provinces, and eastern coastal areas, lightning activity is frequent. A lightning-prone area extends over south-central China, and there is relatively less lightning activity in the eastern area south of the Yangtze River and southwest regions and northwest China. Lightning has seasonal variations and rarely occurs in winter, although the proportion of positive lightning strikes peaks in winter. In china, most of lightning currents range are in the -60~+60kA, accounting for 84.8% of the total number of lightning. Lightning current between -10~+10kA only accounted for small proportion of 0.6%. The average intensity of positive flashes is 64.2kA, the average intensity of negative flashes is -40.28kA, the average +CG intensity is higher than that of -CG flashes.

Acknowledgments

The author is grateful to Dr. Li Yan, Mrs. Wu Lei, Xu MingYi and ZhouWei from the MOC of the CMA for assistance with the lightning data processing and diagram creation.

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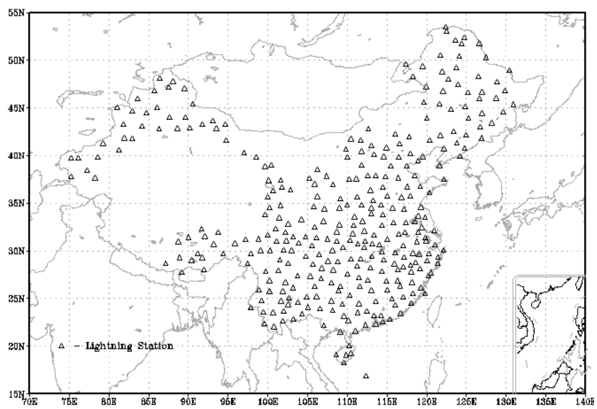

Fig. 1 Lightning detection network layout in China.

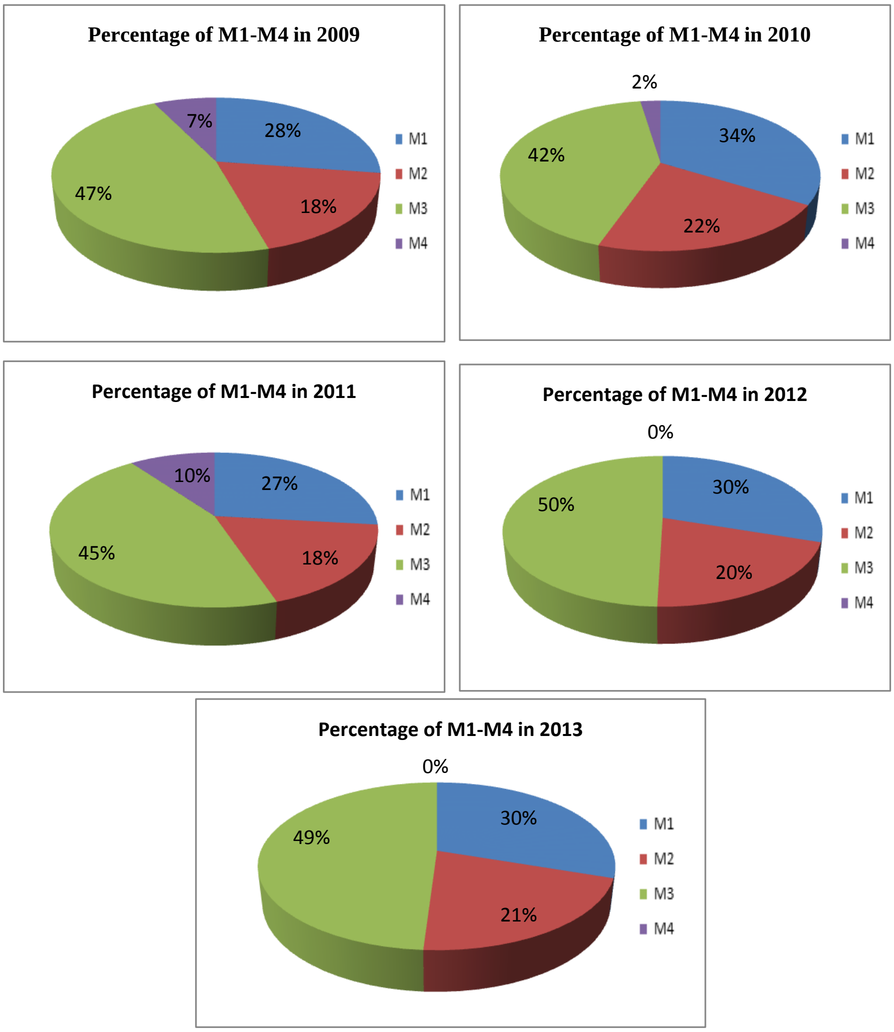

Fig. 2 The usage frequency of the four location methods (M1: blue, two-station hybrid; M2: red, three-station hybrid; M3: green, four-station hybrid; and M4: purple, two-station amplitude) used during the period 2009-2013 in China.

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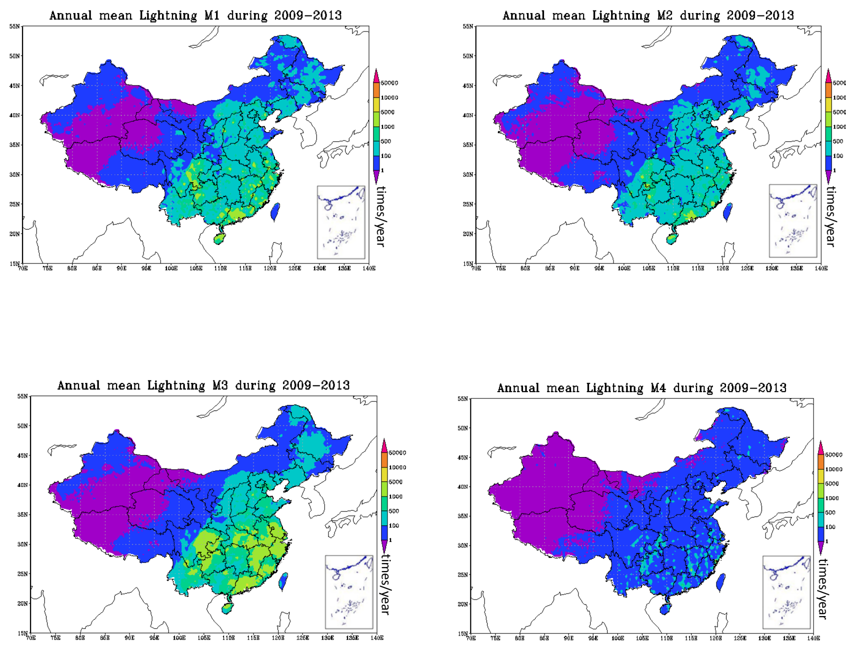

Fig. 3 Four location methods annual mean usage number distribution during the period from 2009 to 2013 in China (Color coded represents usage number, unit: times/year).

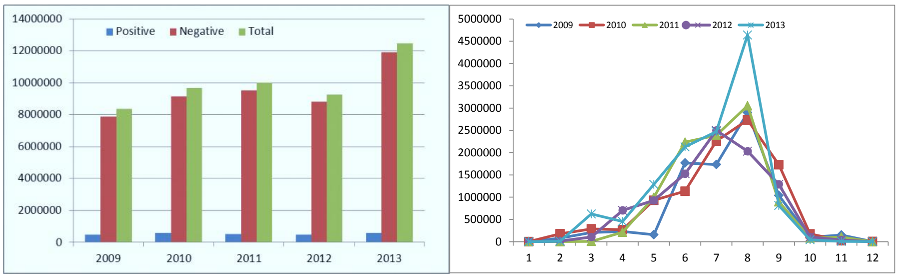

Fig. 4 Annual (left) and monthly (right) lightning number variations from 2009 to 2013.

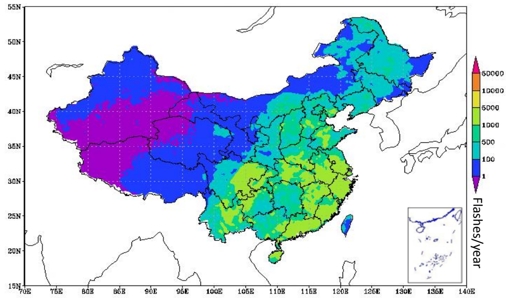

Fig. 5 Annually averaged lightning frequency distribution for the period from 2009 to 2013 in China.

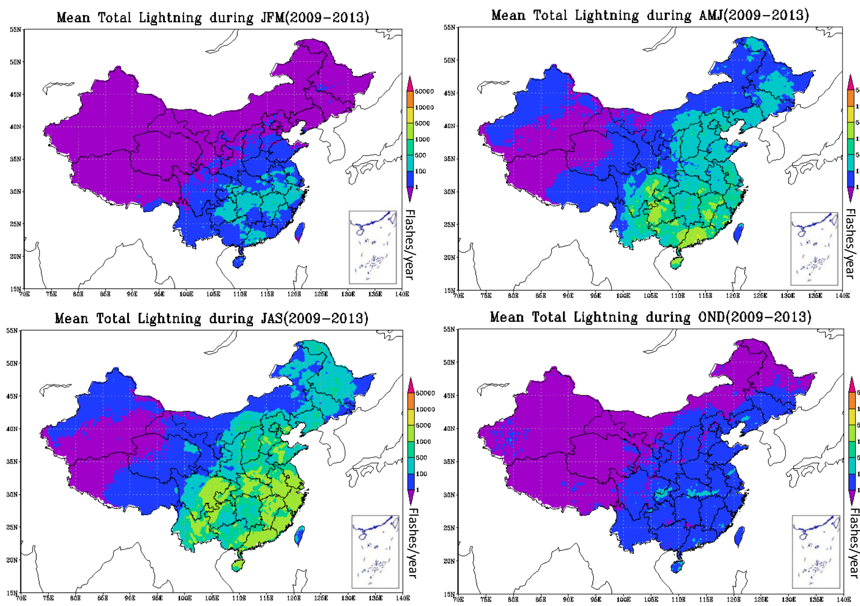

Fig. 6 Seasonal lightning activity in China over the period from 2009 to 2013 (JFM stands for January, February, March; AMJ for April, May, June; JAS for July, August and September; OND for October, November, December).

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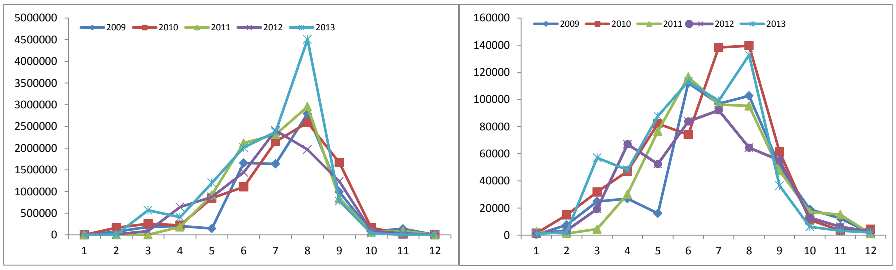

Fig. 7 Monthly change in negative (left) and positive (right) lightning strikes from mean for 2009 to 2013 in China.

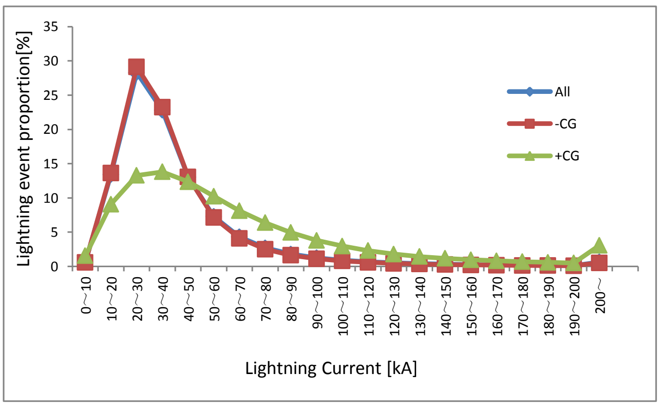

Fig.8 Percentage of lightning with different intensities base on annual average (2009~2013) lightning data