



# Distribution Characteristics and Formula Revision of Lightning Current Amplitude and Cumulative Probability in Zhejiang Province

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The cumulative probability distribution of the lightning current amplitude can reflect the lightning activity and is important for the lightning protection engineering technology. Based on the lightning location data from 2009 to 2019, the distribution characteristics of the lightning current amplitude and cumulative probability are studied. The results show that a total of 8,634,858 lightning flashes occurred in Zhejiang province in last 11 years. Negative flashes are much more common than positive ones, accounting for 87.44% of the total. The percentage of the lightning current amplitude between 2 and 100 kA is 94.3%. The average amplitude of positive flashes is significantly higher than that of negative flashes. For the current amplitude of positive flashes, the peak occurs in March and gradually decreases with the increase of the month, reaching its lowest in December. But the monthly distribution of negative flashes is relatively concentrated, especially from February to October. When lightning current amplitude is higher than 25.5 kA, the cumulative probability of positive flashes is significantly higher than that of negative flashes and vice versa. The cumulative probability distribution of negative flashes is closer to that of total flashes and is significantly different from that of positive flashes. In order to get a more suitable cumulative probability formula of lightning current amplitude and corresponding parameters in Zhejiang province, the Levenberg–Marquardt method is used. By fitting the measured data with the formulas recommended by the Institute of Electrical and Electronics Engineers (IEEE) and Electric Power Industry Standard of China (Code for design of overvoltage protection and insulation coordination for AC electrical installations GB/T 50064-2014), respectively, the correlation coefficients of different polarities are obtained. By comparing the aforementioned two fitting results, it is found that the formula recommended by the IEEE can more objectively reflect the probability distribution characteristics in Zhejiang province, and the accuracy of the derived formula is verified by using the lightning current data in 2020. It shows that the curve based on the measured values is consistent with that fitted by the IEEE formula but quite different from that fitted by the GB/T 50064-2014 formula.

**Keywords:** lightning current amplitude, cumulative probability, characteristics, median current, the Levenberg–Marquardt method

## INTRODUCTION

As lightning discharges often lead to lightning disasters (Paisios et al., 2007; Ma et al., 2008; Chemartin et al., 2012), the study of lightning physical characteristics has become more and more important (Finke and Hauf, 1996; Christian et al., 2003; Pinto et al., 2003; Soriano et al., 2005; Fleenor et al., 2009). Lightning's current amplitude of return stroke is one of its important parameters, closely responding to the lightning disaster. The cumulative probability of the lightning current amplitude has been widely used in the lightning protection engineering technology, which represents the distribution of lightning current amplitude (Yue et al., 2013; Zhao et al., 2017). The precise expression is useful for studying lightning activity, protecting the transmission line, and assessing the lightning disaster risk (Metwally et al., 2004; Zhang et al., 2011; He et al., 2017).

At present, more researchers have been studying about lightning current amplitude (Borghetti et al., 2004; Chowdhuri et al., 2005). As early as the 1880's, Kohlrausch had carried out the work of measuring the lightning current amplitude (Kohlrausch et al., 1888). Pabolansky (1977) proposed a formula for calculating the cumulative probability of lightning current amplitude based on data in Europe, Australia, and the United States (Shim et al., 2002). Thereafter, considerable progress has also been made on proposing different calculation formulas based on data in different regions (Grant et al., 1985; Orville and Huffines, 1999). The approximate expression of the cumulative probability of the lightning current amplitude was first given by Anderson based on the data of Berger, which was later recommended by the IEEE (Anderson et al., 1980). In China, the regulation method is mainly used to calculate the cumulative probability of lightning current amplitude in the lightning protection engineering technology (Du., 1996; Li, R.F et al., 2011). The corresponding logarithmic expression is recommended by GB/T 50064-2014. In the early days, lightning data were lacking, and the parameters of the formula were obtained by inversion using the data recorded by the Xinhang line from 1962 to 1987 (Li et al., 2019). It is still in use today.

Due to the vast territory and environmental differences in China, using the identical parameters in different regions shows great uncertainty. For example, the calculation results indicate that the most prominent manifestation is not wholly accurate, and thus, it perhaps cannot accurately reflect the cumulative probability of lightning current amplitude in the area, which affects its application in engineering. With the widespread application of lightning location systems, most of the systems have been running for more than 10 years. A large amount of lightning data has been accumulated, and so it provides the basis for research on parameters of temporal and spatial differences, such as lightning current amplitude and its cumulative probability (Wang et al., 2016; Zhao et al., 2018; Li et al., 2019). Li, J.Q et al. (2011) found that significant differences lay in the distribution characteristics of the cumulative probability of lightning current amplitude with the polarity in Chongqing, and the cumulative probability formulas

recommended by the IEEE had better fitting effects than other formulas. Cheng et al. (2021) found that the cumulative probability curve of lightning current amplitude dropped faster in the interval of 20–50 kA and was consistent with the IEEE recommended formula in Liaoning. These research results provide the distribution characteristics of the lightning current amplitude and cumulative probability that are suitable for local use.

There is a subtropical monsoon climate with frequent lightning disasters in Zhejiang province, which lies in the central-eastern part of China. According to statistics, there were 9,728 recorded lightning disasters from 1998 to 2020, including 357 casualties, 282 injuries, and 307 deaths (Gu et al., 2021). The temporal and spatial characteristics of lightning activities have been mainly studied based on the lightning location system in Zhejiang province (Liu et al., 2009; Cui et al., 2021; Zhang et al., 2021). But the relevant research on lightning current amplitude and cumulative probability has not been carried out. Based on the lightning location system in Zhejiang province from 2009 to 2019, this article studies the characteristics of lightning current amplitude and localizes its parameters in the cumulative probability formula. The accuracy of the calculation results is helpful to the development of the lightning protection engineering technology.

## DATA AND METHODS

The data are collected by using the lightning location positioning system of the Meteorological Departments in Zhejiang province. The system is uniformly deployed by the China Meteorological Administration, and it has 11 substations in Zhejiang province, which are shown in **Figure 1**. Also, it has a monitoring accuracy of 300 m and a detection efficiency of over 85%. Based on the principle of magnetic field positioning and time difference positioning, the system can accurately determine the location and time of a lightning occurrence, using satellite positioning systems and geographic information systems. It is mainly used for the detection of cloud-to-ground flashes and provides basic data for the study of the physical characteristics of lightning current.

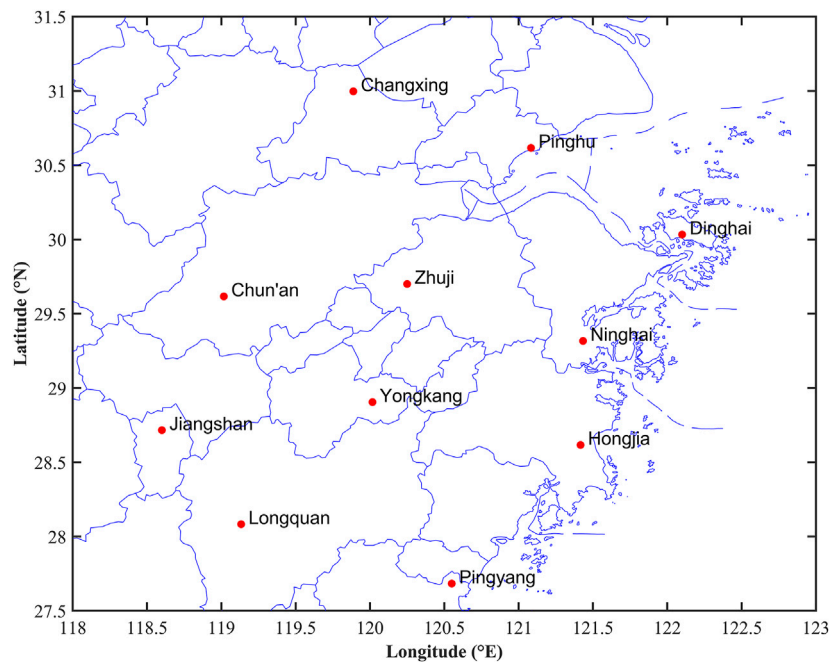
The cumulative probability formula for lightning current amplitude recommended by the IEEE is as follows:

$$P = \frac{1}{1 + (I/a)^b} \quad (1)$$

The cumulative probability formula for lightning current amplitude recommended by GB/T 50064–2014 is as follows:

$$\lg P = -\frac{I}{c} \quad (2)$$

where  $I$  is lightning current amplitude (kA),  $P$  is the cumulative probability that the lightning current amplitude is greater than  $I$ ,  $a$  is the median lightning current amplitude, and  $b$  is the degree of change in the cumulative probability curve. In **Eq. 1**, IEEE



**FIGURE 1** | Site distribution map for the lightning location system in Zhejiang province.

recommends  $a = 31$ ,  $b = 2.6$ , and  $I \in (2, 200]$ , and in Eq. 2, GB/T 50064–2014 recommends  $c = 88$ .

The parameters recommended by the IEEE are the average results of global lightning current amplitude, and lightning activities vary greatly with time and space, so it is not appropriate to use the average results directly in Zhejiang province, and for Eq. 2, the parameters were obtained by inversion using the data recorded by the Xinhang line from 1962 to 1987. Therefore, the accuracy needs further verification according to the lightning observed data. In order to obtain a more suitable cumulative probability formula of lightning current amplitude and corresponding parameters in Zhejiang province, the least squares criterion is often used, and the Levenberg–Marquardt method is a commonly used method.

The study counts the observed data of the lightning location system in Zhejiang province from 2009 to 2019 and carries out quality control. According to IEEE regulations, the application range of the current is defined as 2–200 kA. Therefore, records with lightning current amplitudes of less than 2 kA and greater than 200 kA are excluded. The lightning number is counted according to the rule, which is that the current amplitude starts at 2 kA, then 5 kA, and increases by 5 kA until 200 kA. According to the results, the distribution characteristics of the lightning current amplitude are analyzed. According to the definition of the cumulative probability of lightning current amplitude, the percentages of positive flashes, negative flashes, and total flashes are calculated, respectively, based on the above intervals. Finally, the statistical points of the cumulative probability distribution of positive flashes, negative flashes, and total flashes are obtained.

In order to get a more suitable cumulative probability formula of the lightning current amplitude and corresponding parameters in Zhejiang province, the Levenberg–Marquardt method is used to fit the measured data with the formulas recommended by IEEE and GB/T 50064–2014, respectively, and the correlation coefficients of different polarities are obtained. The Levenberg–Marquardt method is a commonly used method that solves the non-linear least squares problem. In order to strengthen the robustness of the algorithm, it adds a damping factor on the basis of the Gauss-Newton method. The following is an example:

The vector  $p$  is defined to consist of fitted parameters whose number is  $M$ , while the vector  $X$  and  $Y$  consists of horizontal and vertical coordinates of measured scatter points whose number is  $N$ , respectively. There is a corresponding residual between the measured value and the fitted function value at each observation point. The residual functions, which are  $N$  form vector, are shown in Eq. 3 and Eq. 4.

$$r_j(p) = Y_j - y(p, X_j), \tag{3}$$

$$r(p) = [r_1(p), r_2(p), \dots, r_N(p)]^T, \tag{4}$$

where  $y(p, X_j)$  is the value substituted  $p$  and  $X_j$ ,  $r_j(p)$  is the fitted residual function at the scatter point  $j$ , and  $r(p)$  is the residual function vector.

The objective function  $F(p)$  is defined as follows:

$$F(p) = \frac{1}{2} r^T(p) r(p) = \frac{1}{2} \sum_{j=1}^N (Y_j - y(p, X_j))^2. \tag{5}$$

**TABLE 1 |** Lightning Current Amplitude Statistics from 2009 to 2019.

Year	Lightning polarity	Lightning current amplitude/kA										
		2–20	20–40	40–60	60–80	80–100	100–120	120–140	140–160	160–180	180–200	Total
2009	Positive	1978	3,401	1854	1,453	1,126	852	639	479	353	281	12,416
	Negative	36,741	135,040	67,763	32,479	14,009	7,055	4,020	2,525	1,676	1,215	302,523
2010	Positive	3,408	9,984	9,065	6,672	4,642	2,870	1814	1,159	737	483	40,834
	Negative	85,010	413,549	218,787	84,831	35,673	17,547	9,025	4,723	2,770	1,718	873,633
2011	Positive	5,085	8,705	5,432	3,664	2,459	1,526	974	634	383	262	29,124
	Negative	104,815	383,527	180,347	71,655	30,706	14,747	7,436	3,920	2,259	1,377	800,789
2012	Positive	4,041	8,664	6,874	5,302	3,542	2,294	1,513	1,022	718	499	34,469
	Negative	84,062	298,838	138,407	53,682	24,171	12,387	6,662	3,664	2,302	1,433	625,608
2013	Positive	3,005	6,346	5,567	4,043	2,574	1,742	1,129	771	486	302	25,965
	Negative	84,423	257,990	111,096	40,089	17,627	9,022	4,945	2,779	1,731	1,101	530,803
2014	Positive	4,448	7,259	5,454	3,991	2,726	1,820	1,263	750	518	325	28,554
	Negative	113,638	287,108	124,881	50,420	23,583	12,756	7,688	4,983	3,276	2,204	630,537
2015	Positive	2,345	3,951	3,492	2,452	1,538	1,068	645	474	361	225	16,551
	Negative	51,038	89,793	39,004	16,530	9,073	5,760	3,564	2,511	1,745	1,282	220,300
2016	Positive	17,834	35,091	39,082	32,404	25,509	18,288	11,823	6,941	4,304	2,767	194,043
	Negative	133,069	343,428	166,380	63,990	29,171	15,985	9,828	6,341	4,134	2,703	775,029
2017	Positive	9,105	20,363	18,811	12,426	9,030	6,536	3,795	2,091	1,213	712	84,082
	Negative	96,739	294,593	140,968	52,229	22,166	11,518	6,761	4,061	2,403	1,501	632,939
2018	Positive	21,968	37,596	35,532	21,832	10,463	5,745	3,340	2,059	1,284	894	140,713
	Negative	134,246	455,124	227,914	84,956	35,452	17,659	10,043	6,180	3,825	2,430	977,829
2019	Positive	162,763	122,107	62,981	43,247	34,135	23,640	13,730	8,069	4,744	2,786	478,202
	Negative	280,119	466,658	236,105	95,354	44,804	24,873	14,297	8,739	5,548	3,327	1,179,824
合计	Positive	235,988	263,467	194,144	137,486	97,744	66,381	40,665	24,449	15,101	9,536	1,084,961
	Negative	1,203,900	3,425,648	1,651,652	646,215	286,435	149,309	84,269	50,426	31,669	20,374	7,549,897

Here  $r^T(p)$  is the transposition of  $r(p)$ . It can be seen that  $F(p)$  is exactly 1/2 of the sum of squares of the fitting residual  $R$ . Under the principle of least squares, the vector  $p^*$  with the smallest value  $F(p)$  is the optimal solution, and  $R$  is also the smallest.

The partial derivatives of the residual vector  $r(p)$  with respect to each variable in  $p$  form the  $N \times M$  order matrix. It is expressed as

$$J = \begin{bmatrix} \frac{\partial y_1}{\partial x_1} & \frac{\partial y_1}{\partial x_2} & \cdots & \frac{\partial y_1}{\partial x_M} \\ \frac{\partial y_2}{\partial x_1} & \frac{\partial y_2}{\partial x_2} & \cdots & \frac{\partial y_2}{\partial x_M} \\ \cdots & \cdots & \cdots & \cdots \\ \frac{\partial y_N}{\partial x_1} & \frac{\partial y_N}{\partial x_2} & \cdots & \frac{\partial y_N}{\partial x_M} \end{bmatrix}_{N \times M} \quad (6)$$

In this study, based on Eq. 1,  $p = [a, b]^T$  and  $M = 2$ . Based on Eq. 2,  $p = [c]^T$  and  $M = 1$ .

On the basis of the initial value  $p_0$ , a suitable increment  $\Delta p$  is found to make the objective function  $F(p)$  change in the direction of the decreasing value, and  $p = p + \Delta p$  is iterated until it approaches  $p^*$ ; then,  $F(p)$  reaches the minimum value.  $\Delta p$  is obtained by Eq. 7 and Eq. 8.

$$S(p) = J^T(p)J(p) + \mu \text{diag}(J^T(p)J(p)), \quad (7)$$

$$S(p)\Delta p = -J^T(p)r(p). \quad (8)$$

where  $\mu$  is the damping factor,  $\text{diag}(J^T(p)J(p))$  is the diagonal matrix consisting of main diagonal elements  $J^T(p)J(p)$ ,  $\Delta p$  is the iterative increment of  $p$ , and  $S(p)$  is the intermediate variable.

In each iteration, the Levenberg–Marquardt method can have various indicators to measure the quality of this iteration, and the

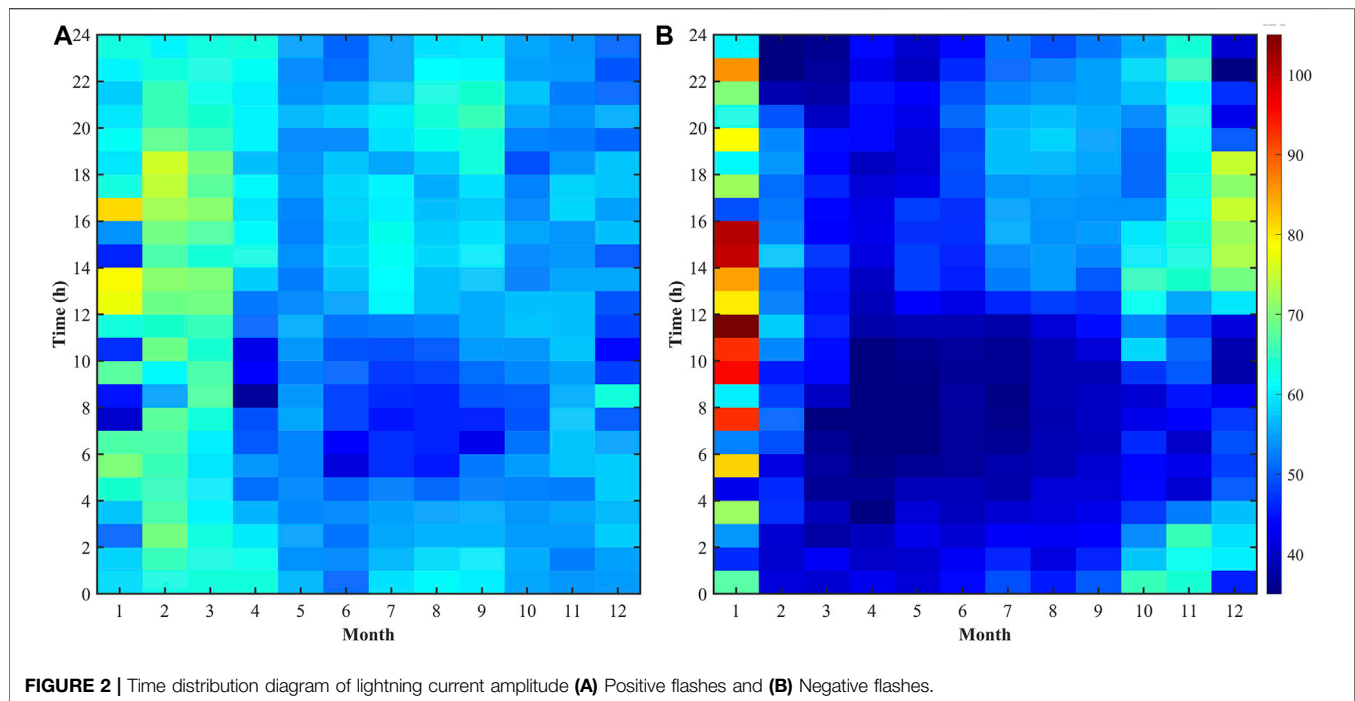
value of  $\mu$  is adjusted accordingly. In this study, the method is to decide whether  $\Delta p$  is acceptable or not by comparing the sizes of  $F(p + \Delta p)$  and  $F(p)$ .

In order to verify the effect of fitting, the median current method is applied to test the results by the Levenberg–Marquardt method.

## RESULTS AND ANALYSIS

### Analysis of the Characteristics of Lightning Current Amplitude

Table 1 indicates the counts of positive flashes, negative flashes, and total flashes from 2009 to 2019 in Zhejiang province. They are based on different intervals of 2, 5, 10, ... 195, and 200 kA. The total number of flashes is 8,634,858, with positive flashes of 1,084,961 and negative flashes of 7,549,897, accounting for 12.56 and 87.44%, respectively. Therefore, the number of negative flashes is far greater than that of positive flashes. For instance, the percentage of positive flashes is lower than what has been observed, in Belgium (Dieter 2014). For the average value of lightning current amplitude, it is 54.59 kA for positive flashes, and 41.39 kA for negative flashes. Lightning current amplitude is mainly concentrated in the range of 2–100 kA, with a total number of 8,142,671, accounting for 94.3%. In the range of 160–200 kA, the number becomes smaller, accounting for only 0.94%. Of the annual variations, the number of total flashes reached a maximum value of 1,658,026 in 2019, and a minimum value of 236,851 in 2015, and the average annual number of lightning strikes is 784,978, higher than that of Hubei province, which is 393,724 (Yu et al., 2021).



The monthly and hourly distributions of lightning current amplitude are shown in **Figure 2**. It is found that positive flashes greater than 60 kA account for 53.96% of the total and negative flashes account for 38.68% of the total in Zhejiang province. The average current amplitude of positive flashes is significantly higher than that of negative flashes, and the monthly distribution presents a significant shape of a single peak. January is the first month with high current amplitude, and the peak value is reached in February. After that, the current amplitude gradually decreases. For negative flashes, the monthly distribution is relatively concentrated, especially from February to October, showing a significant shape of downward convexity, and the high currents mostly occur from November to January of the following year. In Zhejiang province, **Figure 2** shows that positive flashes are frequent in spring, followed by winter, while negative flashes are mainly concentrated in summer and autumn. In winter, there are fewer lightning activities, but the average current intensity is stronger than in other seasons. This is basically consistent with the observed results in Beijing (Gao et al., 2019). In an hourly distribution, the current amplitude variation of positive flashes is more significant than that of negative flashes, while in spring high values are mainly concentrated in 12–19, in summer mainly in 12–18, in autumn mainly in 19–23, and in winter mainly in 12–14. Otherwise, for negative flashes, the hourly variation is more significant in winter, mainly concentrated in 09–20, and changes little in other seasons.

### Characteristics of the Cumulative Probability Distribution of Lightning Current Amplitude

For different polarities, the cumulative probability distribution curves of lightning current amplitude are shown in **Figure 3**,

which are quite different. The curve of negative flashes is steeper than that of positive flashes, that is, the cumulative probability distribution of negative flashes is more concentrated than that of positive flashes. When lightning current amplitude is higher than 25.5 kA, the cumulative probability of positive flashes is greater than that of negative flashes, and vice versa. The curve of negative flashes is closer to that of total flashes, especially due to the high proportion of negative flashes to total flashes (87.44%). Therefore, the cumulative probability distribution of lightning current amplitude of total flashes is mainly affected by negative flashes, which is consistent with the results of lightning current amplitude characteristics in Hubei province and Beijing (Wang et al., 2016; Gao et al., 2019).

When the cumulative probability of lightning current amplitude is 50%, the current of positive flashes, negative flashes, and total flashes is 44.4, 35.0, and 35.6 kA, respectively. It means that the median current of positive flashes, negative flashes, and total flashes in Zhejiang province is 44.4, 35.0, and 35.6 kA, respectively. The median current of total flashes (35.6 kA) is less than that in Guangzhou (36.7 kA) and greater than that in Liaoning (30.6 kA), which shows that the distribution in Zhejiang province is different from those in the southern and northern regions of China (Lu et al., 2009; Cheng et al., 2021). For the current amplitude of total flashes, which is higher than 80 and 100 kA, the corresponding cumulative probability is 10.15 and 5.7%, indicating that in Zhejiang province, less than 80 kA accounts for more than 89.85% and less than 100 kA accounts for more than 94.3%. It is similar to the result in Hubei province where lightning current amplitude is less than 100 kA, accounting for more than 98% (Wang et al., 2016). It is because the latitudes of Zhejiang and Hubei provinces are basically the same, and the water resources are relatively

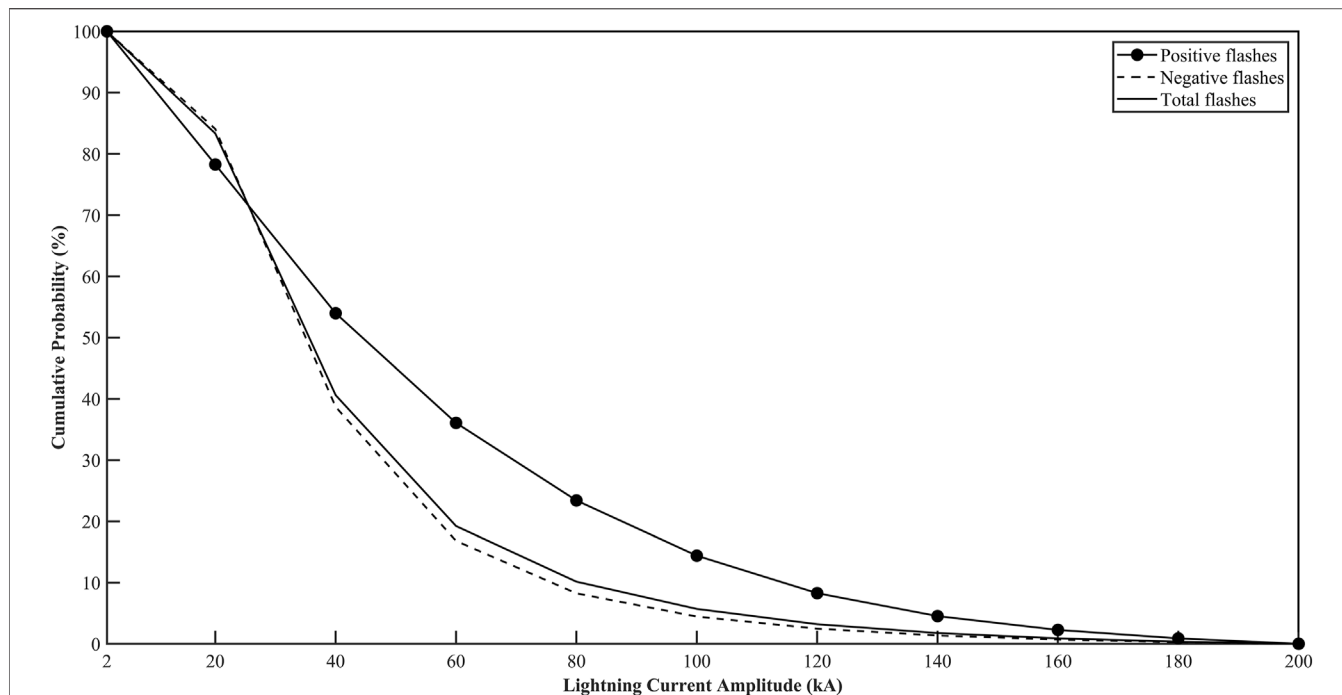


FIGURE 3 | Cumulative probability distribution curves of lightning current amplitude.

TABLE 2 | Fitting parameters recommended by the IEEE and GB/T 50064-2014.

Polarity	IEEE		GB/T 50064-2014
	a	b	c
Positive flashes	42.39	2.11	130.00
Negative flashes	34.60	2.97	97.20
Total flashes	35.30	2.77	100.88

TABLE 3 | Correlation coefficients between measured values and calculated values by the IEEE and GB/T 50064-2014.

Polarity	PIEEE (%)	P <sub>GB/T50064-2014</sub> (%)
Positive flashes	99.66	99.12
Negative flashes	99.99	98.41
Total flashes	99.98	98.72

abundant, which provides abundant water vapor for the breeding of lightning. Therefore, lightning activity occurs more frequently, and the distribution characteristics of lightning current amplitude are relatively similar.

### Formula Fitting

In order to calculate the exact parameters in the cumulative probability distribution formula of the lightning current amplitude for Zhejiang province, the Levenberg–Marquardt method is adopted. The data based on the lightning location system in Zhejiang province are fitted with the formula recommended by IEEE and GB/T 50064-2014, respectively.

Then, the parameters and correlation coefficients of different current polarities for Zhejiang province are obtained, which are shown in Tables 2 and 3.

For positive flashes, negative flashes, and total flashes, the trends of the fitting curves are more consistent with those recommended by the IEEE and quite different from those recommended by GB/T 50064-2014, which is shown in Figures 4 and 5.

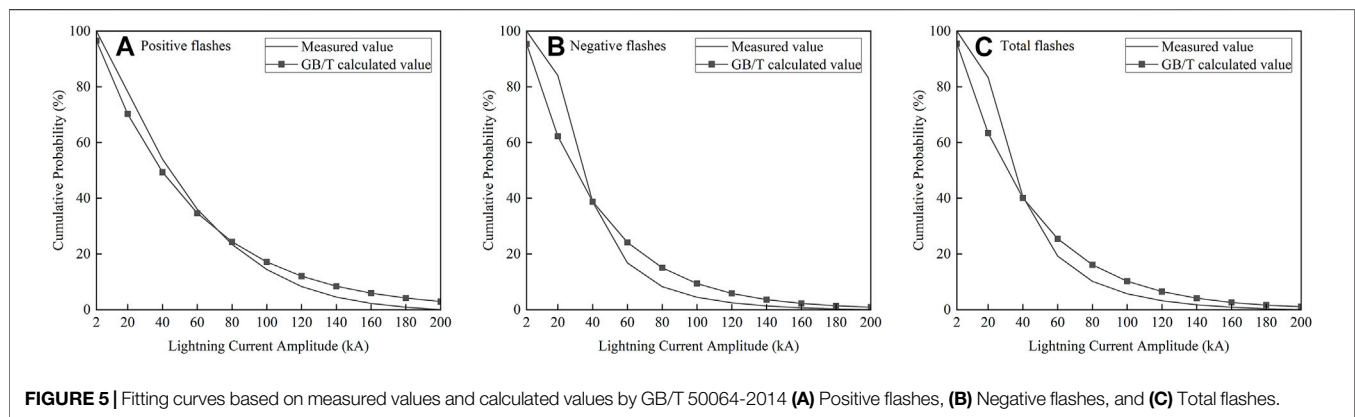
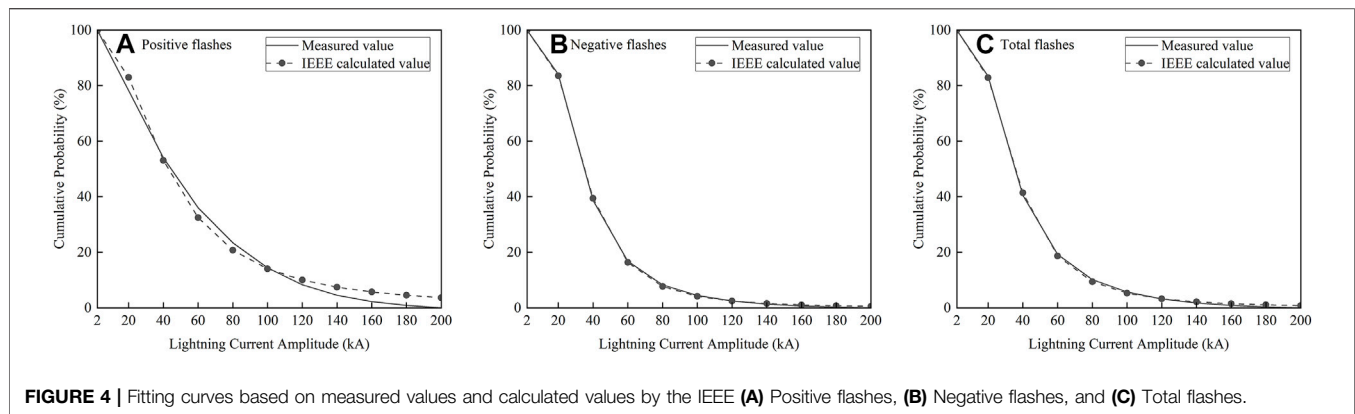
The correlation coefficients between the curves in Figure 4 are greater than those between the curves in Figure 5. It shows that the correlation between the curves based on the measured values and the ones based on the IEEE formula is higher for Zhejiang province. Therefore, to calculate the cumulative probability of lightning current amplitude in Zhejiang province, it is more appropriate to use the IEEE formula. This conclusion is basically consistent with the results in other regions in China, such as Beijing, Yan’an, and Hubei province (Wang et al., 2016; Gao et al., 2019; Li et al., 2019).

Based on the aforementioned method, the formula for the cumulative probability distribution in Zhejiang province is shown in Eq. 9, which applies to the calculation of positive flashes.

$$P_+ = \frac{1}{1 + (I/42.93)^{2.11}} \tag{9}$$

The formula is shown in Eq. 10, which applies to the calculation of negative flashes.

$$P_- = \frac{1}{1 + (I/34.60)^{2.97}} \tag{10}$$



**TABLE 4 |** Comparison of fitting results between the Levenberg–Marquardt method and the median current method.

Polarity	Levenberg–Marquardt method			Median current method		
	a	b	R <sup>2</sup>	a	b	R <sup>2</sup>
Positive flashes	51.19	2.28	0.9995	51.30	3.11	0.9989
Negative flashes	31.08	4.68	0.9997	30.54	4.28	0.9995
Total flashes	32.30	4.04	0.9993	31.57	3.78	0.9992

Eq. 11 applies to the calculation of total flashes.

$$P = \frac{1}{1 + (I/35.30)^{2.77}} \tag{11}$$

In order to test the accuracy of fitting results based on the Levenberg–Marquardt method, the median current method is used to test the fitting results. The test results are shown in Table 4. It is shown that the correlation coefficients ( $R^2$ ) used by the Levenberg–Marquardt method are greater than those based on the Median Current method, so the reliability of fitting results used by the Levenberg–Marquardt method is higher.

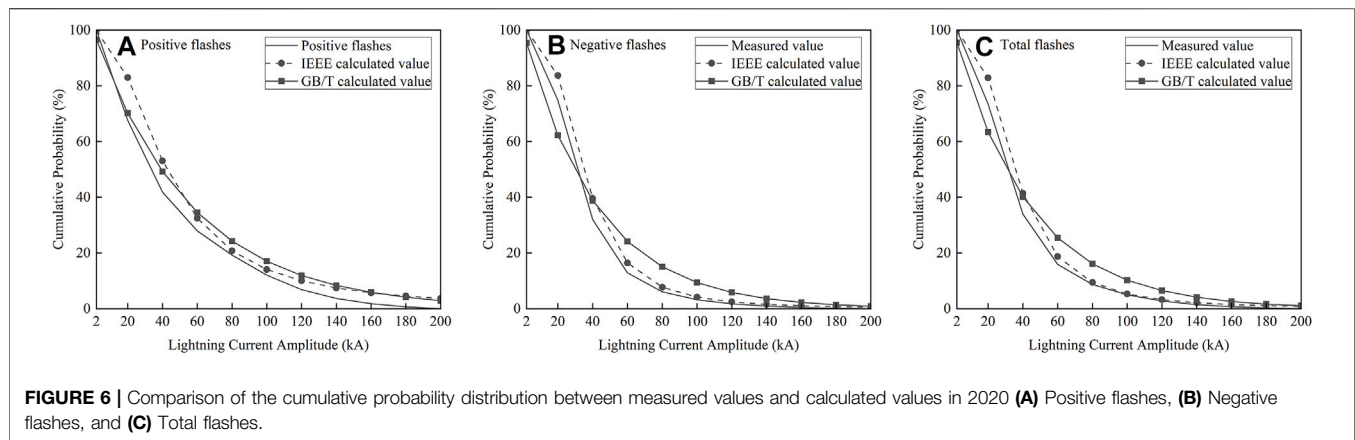
### Verification

In order to verify the accuracy of Eqs 9, 10, and 11, the data of lightning current amplitude in 2020 are taken as an example, and the results are shown in Figure 6. It clearly shows that compared to the formula recommended by GB/T50064-2014, the curves

based on Eqs 9, 10, and 11 are closer to those of the measured lightning data in 2020. For the measured value curve and the IEEE fitted curve, Figure 6A shows that the two curves are closer when lightning current amplitude is around 80 kA, and the others are slightly divergent. However, the basic trend is the same. In Figures 6B,C, the two curves have the same trend of change. As observed data increase, the fit of the two curves will be higher. Therefore, the fitted formulas in this study are more suitable for describing the distribution characteristics of the cumulative probability of lightning current amplitude in Zhejiang province.

### SUMMARY AND DISCUSSION

In this work, a total of 8,634,767 flashes are used to analyze the characteristics of lightning current amplitude and cumulative probability, based on the lightning data from 2009 to 2019. In



addition, the parameters in the formulas recommended by the IEEE are corrected, which can more objectively reflect the cumulative probability distribution of lightning current amplitude in Zhejiang province.

It is found that the number of negative flashes is far more than that of positive flashes in Zhejiang province. But the average current amplitude of positive flashes is significantly higher than that of negative flashes. Lightning current amplitude is mainly concentrated in the range of 2–100 kA, accounting for 94.3%. In the range of 160–200 kA, the number becomes smaller, accounting for only 0.94%. The seasonal characteristics are significant, and the monthly distribution of the positive lightning current amplitude has a unimodal distribution, while that of negative flashes is relatively concentrated. Positive flashes are frequent in spring, but summer is the season of negative flashes. The cumulative probability distribution of the negative lightning current amplitude is closer to that of total flashes and is significantly different from that of positive flashes. The variation law of total flashes is mainly affected by negative flashes. Based on the Levenberg–Marquardt method, the measured data are fitted with the formulas recommended by the IEEE and GB/T 50064-2014, respectively, and the parameters of different polarities are obtained. By analysis, the cumulative probability distribution formula recommended by IEEE is more suitable for Zhejiang province, which is basically consistent with the results in other regions in China.

In **Figures 6B and C**, the changing trend of the two curves basically coincides. But there are two intersections between the two curves in **Figure 4A**, and when the value is higher than 100 kA, the fit of the two curves becomes lower. In other words, for describing the distribution characteristics of the cumulative probability of lightning current amplitude in Zhejiang province, the formulas applying to negative flashes and total flashes are more realistic than those for positive flashes. With more lightning observation data, a subsection refinement of the cumulative probability of the lightning current amplitude can be carried

out in the following research, in order to obtain a more accurate cumulative probability formula.

## DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

## AUTHOR CONTRIBUTIONS

Data acquisition; LQ. Methodology; LX, FY and SN. Software; SN and GX. Validation; LY, LQ and GX. Investigation; LX and LY. Writing—original draft preparation, LX. Writing—review and editing; LX, SN, MP and GX. All authors have read and agreed to the published version of the manuscript.

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