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Research Article

Five-Year Analysis of Lightning Activities in Different Climatic Regions of Sichuan Province, China

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Sichuan is a high-incidence area of thunderstorm activity in China. Based on the data of the total lightning location system from 2018 to 2022, the total lightning, cloud-to-ground (CG) lightning, and intracloud (IC) lightning activity regularity for the Sichuan province (SC) and its three climate subregions: Sichuan Basin (SB), Panxi district (PD), and West Sichuan Plateau (WSP) are analyzed, and the influences of different climate and topography conditions on lightning activities are also discussed. The results show that (1) for the whole province, the annual mean value of total lightning is about 850 thousand. The SB has the most lightning occurrences, and the WSP has the largest IC and +CG proportion. The southwest of PD, the north-center of PD, and the southeast of SB are the three high-value centers of lightning density. (2) For SB, the better thermodynamic and moisture conditions account for the most lightning occurrences. For PD, the lightning distribution is attributed to the joint effect of specific meteorological conditions and mountainous topography. For WSP, the convections are weak and shallow, which lead to high IC and +CG proportion. (3) The IC lightning mainly occurs below 12 km, and the IC height is much lower on WSP. The spatial and seasonal variation of IC height corresponds well to the cloud base height (CBH) and cloud top height (CTH). (4) The seasonal lightning frequency distribution in the three regions is similar, but the diurnal variation is quite different. The lightning activity mainly occurs between 1400 and 2200 LT on WSP but shows obvious nocturnal in SB. (5) Most CG intensity concentrates in the range below 50 kA, and IC concentrates in the range below 75 kA.

1. Introduction

Lightning is a random, strong, and destructive discharge phenomenon in the atmosphere, and it has been listed by the United Nations as one of the ten most severe natural disasters [1–5]. Due to its extreme heat and mechanical and electromagnetic radiation effects, not only the direct lightning strikes can cause serious casualties and property losses but also the indirect lightning strikes can be a great threat to electronic equipment and aerospace-sensitive electrical equipment [6–9]. According to the different types of discharge, lightning is mainly divided into cloud-to-ground (CG) lightning and intracloud (IC) lightning. To better understand the characteristics of lightning activities and issue more accurate lightning warnings, many countries or districts have established ground-based lightning location systems (LLSs) in recent years. However, so far, except for some areas, most operational LLS can only detect the CG return stroke information and lack of IC detection capability.

By analyzing the lightning detection data in different climate zones of the world, many scholars have achieved meaningful results and further deepened people's understanding of lightning activity regularity. For example, Christian et al. [10] analyzed 5 years of optical transient detector (OTD) lightning data and found that the global lightning frequency per second is approximately 44 ± 5 fl/s (lightning per second), which also has periodic variational regularity. Approximately 78% of lightning events occur within the 30° north and 30° south latitude region, and the average lightning ratio of land is about 10 times larger than that of the ocean. Orville et al. [11–14] analyzed the distribution characteristics of lightning density and the current intensity of positive and negative lightning strikes in the United States recorded by the National Lightning Detection Network (NLDN). Yang et al. [15] analyzed the spatiotemporal distributions of CG lighting across China from 2010 to 2013 and found that high lightning density areas are mainly located in southern China, the Sichuan Basin, and the south of Jiangsu Province. Xie et al. [16] and Chai and Sun [17] analyzed the spatiotemporal distribution and the peak currents of the CG lightning of Yunnan and Hubei provinces of China, respectively. Zhao et al. [18] investigated the impact of environmental conditions on positive CG distribution of the warm season in Sichuan Province. Hui et al. [19] analyzed the spatiotemporal distribution of CG lightning over the Qinghai-Tibetan Plateau and further discussed their dependence on meteorological factors.

Most of the existing research studies mainly focus on the CG lightning, and in recent years, more lightning detection sensors with the ability to detect IC lightning have been developed and put into operation in some regions. Thus, some scholars have studied IC characteristics during some severe weather systems. Carey and Rutledge [20] pointed out that IC frequency was 20 to 70 times higher than that of CG frequency in a supercell thunderstorm case. Qie et al. [21] studied an isolated convective storm on the Tibetan Plateau, they found that IC lightning occurs earlier than CG lightning, and most CG occurs at the end of an IC phase of the discharge. Qie et al. [22] studied the electrical characteristics of thunderstorms in four plateau regions of China and found that the IC discharge height is located at about 3.3–5.6 km and 6.8–7.7 km above the sea level (asl). Macgorman et al. [23] found that the IC lightning occurs earlier than CG lightning in most of the thunderstorms, even though some thunderstorms only occur in IC lightning, without CG lightning.

Sichuan Province (hereinafter abbreviated as SC) is located in southwestern China, and it has complex terrain and climate conditions. Based on the different altitudes, terrain, radiation, and hydrothermal conditions, the SC can be divided into three typical climate regions: Sichuan Basin (SB), Panxi district (PD), and West Sichuan Plateau (WSP). The maximum elevation difference between the WSP and the SB is close to 7000 m. The weather system affecting Sichuan mainly includes plateau vortex, plateau shear line, southwest vortex, and Sichuan Basin inverted trough. Such complex geographical and meteorological conditions led SC to become one of the thunderstorm centers in China [15]. Hence, SC suffered many serious lightning disasters in recent years. Only in the first half of 2023, three lightning igniting forest fires occurred in Ganzi Prefecture, Aba Prefecture, and Liangshan Prefecture, leading to economic losses of over 20 million RMB Yuan. To ensure public safety and accurate monitoring of convective systems, the SC and its surrounding provinces have established a total lightning detection network (ADTD-2C), which has the ability to detect both CG and a portion of IC lightning. By far, the LLS has collected a relatively complete dataset containing 5 years of lightning location data (CG + IC) from 2018 to 2022.

For Sichuan Province and its adjacent areas, some studies mentioned above [15, 16, 18] mainly focus on the CG lightning, lacking the IC lightning activity regularity, which is more important to aviation and electronic equipment safety. Some studies [21, 22] are mainly concerned about the IC lightning characteristics in some special thunderstorms, but the analysis of long-term IC lightning activity characteristics is lacking. Therefore, in order to investigate the characteristics of the lightning distributions in SC more scientifically, this paper analyzes the spatial, annual, monthly, diurnal, and the current intensity of the CG and IC lightning for SC and the three subregions. The influence of different climatic and terrain conditions on the lightning activity regularity is also investigated. The results will provide more accurate and scientific references for lightning nowcasting and lightning protection over the SC region.

2. Data and Methods

2.1. Division of the Study Area. Figure 1 shows the geographical scope of the study area (26.0°–34.28°N, 97.37°–108.57°E) and the location of lightning detection stations (ADTD-2C). Previous studies [15, 24, 25] indicated that Sichuan Province is a high occurrence area of lightning in China, and the lightning activity regularity is quite different from other areas. Meanwhile, forest fires and casualties caused by lightning are more serious. From the topography of the province, the SC is bounded by the Qinghai-Tibet Plateau to the west, the Qinling Mountains to the north, the Yunnan-Guizhou Plateau to the south, and the Qinba Mountains to the east. The terrain of SC has the characteristics of being low in the west and high in the east, tilting from northwest to southeast. The terrain and climate conditions of three typical climate regions are presented as follows.

Sichuan Basin (SB) is located in the eastern part of Sichuan, and the altitude is about 200–750 m. Sichuan Basin belongs to the subtropical humid climate zone, warm and moist throughout the year. The average annual temperature is 16–18°C, and annual precipitation is 1000–1200 mm, more than 50% of precipitation is concentrated in summer and often rainy at night.

Panxi District (PD) is located in the southern part of Sichuan, and the altitude is about 2000-3000 m. Panxi district belongs to the subtropical subhumid climate zone, and the temperature is high throughout the year. The average annual temperature is 12–20°C, and the annual precipitation is 900–1200 mm; 90% of precipitation is concentrated in May to October.

The West Sichuan Plateau (WSP) is a part of the southeast edge of the Qinghai-Tibet Plateau and the Hengduan Mountains, and the altitude is above 3000 m. The plateau belongs to a high and cold climate zone with insufficient water and heat conditions. The average annual temperature is 4–12°C, and the annual precipitation is 500–900 mm.

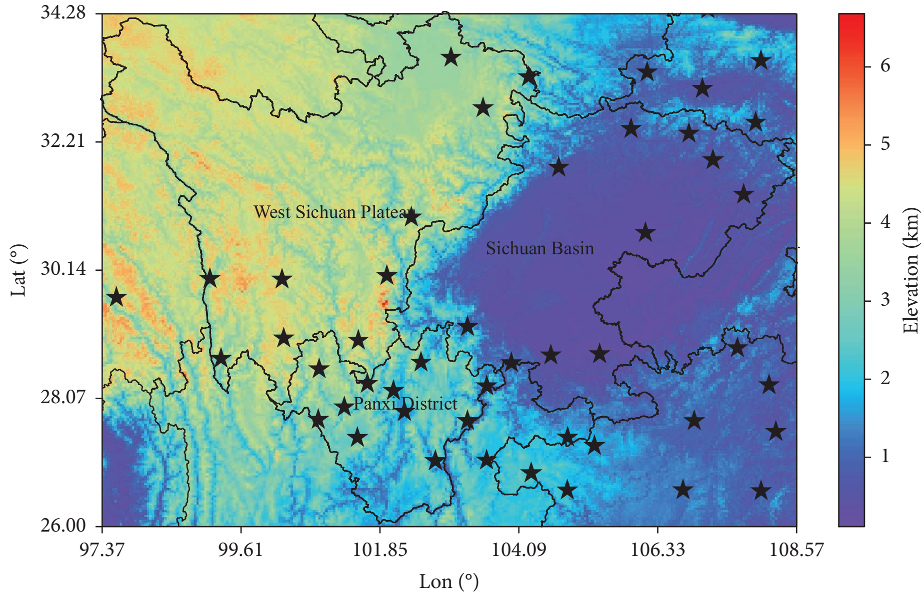


Figure 1: The location of the three climate regions and the distribution of total lightning location sensors (black star).

2.2. Total Lightning Location Data. Until now, Sichuan and its adjacent provinces have established 50 total lightning detection stations (ADTD-2C), represented by the stars in Figure 1. The ADTD-2C lightning detection sensor mainly detects the VLF/LF (3–300 kHz) signals produced by the intensity intercloud discharge process or return stroke of CG. So, the IC detection efficiency is much lower than the VHF lightning sensors which can detect the intercloud prebreakdown process. However, we still believe that our lighting dataset can reflect the activity patterns of IC lightning. The baseline of the ADTD-2C stations is about 100–300 km, and the location error and the detection efficiency strongly depend on the station density and terrain variations.

Previous studies [15, 18] indicated that one lightning flash usually contains one or more return strokes' processes, and the return strokes with a time interval of 0.5 s and a distance interval of 10 km should be classified as one lightning flash. The ADTD location results are the discrete return strokes radiation information, which contains the information of the occurrence time, latitude, longitude, type, location mode, polarity, and intensity of each source pulse. First, in order to eliminate the interference from nonlightning signals or the incorrect location results, the data quality control must be performed by the following steps: (1) remove the data only detected by two stations for CG and three stations for IC, (2) remove the data of pulse intensity of less than 2 kA or larger than 500 kA, and (3) remove the data of positive CG pulse intensity of less than 15 kA. Second, in order to obtain the lightning location results, all the discrete lightning pulse radiation data should be clustered. The clustering criteria is that the radiation points with the same type and polarity belong to the same lightning event if their distance is within 10 km and the time difference is within 0.5 s. After quality control and clustering, we achieved a high-quality lightning location dataset of Sichuan Province from 2018 to 2022.

2.3. Meteorological Data. Research has demonstrated the apparent dependence of lightning activity on climatic and geographic conditions in different regions [18, 19, 26, 27]. Therefore, we selected four typical thermodynamic and moisture factors which are closely related to lightning formation, namely, 2 m temperature, average relative humidity between 3 km and 5 km (3–5 km RH), convective available potential energy (CAPE), and convective inhibition (CIN). The abovementioned factors are obtained from ERA5 reanalysis of single-level and pressure-level monthly averaged datasets from 2018 to 2022, with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. Since more than 80% of the lightning occurs between April and October, so we also adopt the meteorological factors from the same month period for analysis.

2.4. CALIPSO Cloud Data. Cloud base height (CBH) and cloud top height (CTH) are very helpful for analyzing the characteristics of thunderstorms and the vertical distribution of IC lightning. The CBH and CTH data are obtained from the CALIPSO level 2 daily products from 2018 to 2022, with a spatial resolution of 1 km × 1 km [28, 29]. Since the CBH and CTH are mainly used for interpreting the seasonal variation of the IC height, so for computational convenience, we reduced the data resolution to $1.2^{\circ} \times 1.2^{\circ}$ and aggregated the daily data into seasonal average data.

3. Results and Discussion

3.1. Overall Characteristics of Lightning in SC. Table 1 shows the number of total lightning, CG, IC, and the proportion of IC to total lightning for SC and its three subregions. The 5-year mean numbers of total, IC, and CG lightning for SC are 857734, 522330, and 335404, and the mean proportion of IC to total lightning is 0.39. The reason for the relatively low IC proportion is that the Sichuan LLS operates in the

Table 1: The number of total, CG, and IC lightning in Sichuan Province from 2018 to 2022.

Year	District	Total	CG	IC	IC/total
2018	Sichuan Province	1042205	532926	509279	0.49
	Sichuan Basin	593451	334896	258555	0.44
	Panxi District	243716	128896	114820	0.47
	West Sichuan Plateau	205038	69134	135904	0.66
2019	Sichuan Province	818387	534529	283858	0.35
	Sichuan Basin	346242	236321	109921	0.32
	Panxi District	216466	150844	65622	0.30
	West Sichuan Plateau	255679	147364	108315	0.42
2020	Sichuan Province	744796	486963	257833	0.35
	Sichuan Basin	280174	192830	87344	0.31
	Panxi District	194893	138290	56603	0.29
	West Sichuan Plateau	269729	155843	113886	0.42
2021	Sichuan Province	801372	511082	290290	0.36
	Sichuan Basin	372318	251319	120999	0.32
	Panxi District	189208	121745	67463	0.36
	West Sichuan Plateau	239846	138018	101828	0.42
2022	Sichuan Province	881918	546154	335764	0.38
	Sichuan Basin	303109	183949	119160	0.39
	Panxi District	275437	181130	94307	0.34
	West Sichuan Plateau	303372	181075	122297	0.40
Mean	Sichuan Province	857734	522330	335404	0.39
	Sichuan Basin	379058	239863	139195	0.37
	Panxi District	223944	144181	79763	0.35
	West Sichuan Plateau	254732	138286	116446	0.46

VLF/LF (3–300 kHz) band, with a low ability to detect the lightning initial breakdown process in clouds. In the last 5 years, the maximum number of total and IC lightning that occurred in 2018 was 1042205 and 509279. However, the maximum number of CG lightning that occurred in 2022 was 546154. Except for 2018, the proportion of IC to total lightning for Sichuan Province varied from 0.35 to 0.39. For SC, the numbers of total IC lightning generally showed a decreasing trend from 2018 to 2022, but CG lightning did not change much. However, it is worth noting that after 2020, total, CG, and IC lightning all showed an increasing trend. The annual variation of lightning frequency in SB is similar to that of the SC. For PD and WSP, the total and CG lightning generally shows an increasing trend from 2018 to 2022 and the IC lightning does not change much.

For the three subregions, the SB has the most lightning occurrences and the IC proportion varies from 0.3 to 0.4. For PD and WSP, the lightning occurrences are relatively small, but the IC proportion of the West Sichuan Plateau is obviously larger than the other two regions. This phenomenon is similar to previous studies, where Qie et al. [21] indicated that the cloud base height (CBH) is generally about 1 km above ground and the convective available potential energy (CAPE) is usually low on the plateau region, even though the thunderstorm activities are frequent, but its intensity is small, and the duration is short, resulting in quite low lightning occurrences. The weak convections are very conducive to the generation of IC lightning.

Table 2 shows the number and the intensity of −CG and +CG lightning and the proportion of + CG to CG lightning for SC and its three subregions. For SC, the 5-year mean

Table 2: The mean number and the current intensity of +CG and −CG in Sichuan Province from 2018 to 2022.

District	CG type	Counts	Intensity (kA)	+CG/CG
Sichuan Province	−CG	392897	−30.34	0.25
	+CG	129433	53.75	
Sichuan Basin	−CG	180649	−33.37	0.25
	+CG	59214	51.51	
Panxi District	−CG	118485	−24.13	0.18
	+CG	25695	44.03	
West Sichuan Plateau	−CG	93762	−32.36	0.32
	+CG	44524	62.35	

number of −CG lightning is more than the +CG lightning, and the mean intensity of the +CG lightning is larger than the −CG lightning. Previous research [11, 14, 30, 31] also found that most of the +CG lightning only contains one return stroke process, and the proportion of +CG lightning that contains more than two return strokes is very low. However, more than 80% of −CG lightning contains more than two returns. Therefore, the quantity of charge released by a single discharge process is large. By observing the summer thunderstorms of the inland plateau of China, Qie et al. [32] found that during the same thunderstorm, the amount of charge transferred by a +CG and its continuous current process transfer is about 70°C, which is 7-8 times larger than the amount of charge transferred by multiple −CG lightning. For WSP, the mean value of +CG proportion is 0.32, which is similar to the one reported by Zhao et al. [33], after they analyzed 12 thunderstorms in the Nagqu area of the Qinghai-Tibet Plateau.

Same as Tables 2 and 3, Table 1 shows the number and the intensity of IC and +IC lightning and the proportion of +IC to IC lightning. Consistent with CG lightning, the number of negative IC lightning is more than that of the positive IC lightning, and the mean intensity of the positive IC lightning is larger than that of the negative IC lightning. In the clustering process of our lightning dataset, we also find that the number of +IC lightning that only contains one pulse source is larger than the −IC lightning that only contains one pulse source, which explains the higher intensity of +IC lightning compared to the −IC lightning. The positive IC proportion does not show obvious regularity, and the value is always around 0.4.

Table 3: The mean number and the current intensity of +IC and −IC in Sichuan Province from 2018 to 2022.

District	IC type	Counts	Average intensity (kA)	+IC/IC
Sichuan Province	−IC	203415	−37.97	0.39
	+IC	131989	46.08	
Sichuan Basin	−IC	87596	−31.06	0.37
	+IC	51599	37.55	
Panxi District	−IC	46934	−27.22	0.41
	+IC	32828	31.11	
West Sichuan Plateau	−IC	68883	−54.08	0.40
	+IC	47563	65.66	

3.2. The Spatial Distribution of Lightning. The study area (Figure 1) is divided into $0.01^{\circ} \times 0.01^{\circ}$ grid cells (approximately $1\,km \times 1\,km$), and the number of lightning occurrences is counted within the grid cells. The lightning density is obtained by dividing the lightning numbers by the grid area (approximately $1\,km^2$). Figure 2 shows the mean value of total lightning density distribution in Sichuan Province. As seen from Figure 2, the spatial distribution of total lightning density varies greatly and the 5-year mean and maximum values of total lightning density are 1.90 lightning $km^{-2}\cdot yr^{-1}$ and 25.8 lightning $km^{-2}\cdot yr^{-1}$. Three high-value centers of total lightning density are located in the southwest of PD (mainly Panzhihua city), north-center of PD, and southeast of SB, and the maximum density value of 25.8 lightning $km^{-2}\cdot yr^{-1}$ occurs in the southwest of PD. The WSP is a low-value area for the lightning density, and the value is less than 2 flashes $km^{-2}\cdot yr^{-1}$ in most areas. Due to the lower latitude and higher altitude, the southwest and north-center of PD have good solar radiation conditions; hence, the atmosphere with large convective available potential energy (CAPE). Meanwhile, the abovementioned two regions are mainly mountainous areas, so the unstable atmosphere conditions and mountainous terrain jointly lead to high lightning occurrences. Another high-value center is located to the southeast of SB, but the coverage and density are smaller than the above two mentioned high-value centers. This area mainly includes parts of Yibin city and Luzhou city. Yibin is the confluence of the Jinsha River, the Minjiang River, and the Yangtze River. So, the area has good hydrothermal conditions and is very conductive to thunderstorm formation. Besides, in certain years, we also find that the lightning density distribution is not entirely consistent with that shown in Figure 2 due to the climatic anomaly. For example, the central part of the SB is also a high incidence area of lightning in the years of 2019 and 2021.

Figure 3 shows the 5-year mean value of CG, −CG, and +CG lightning density distribution in SC. As seen in Figure 3(a), the mean and maximum values of CG lightning density are 1.23 flashes $km^{-2}\cdot yr^{-1}$ and 19.0 flashes $km^{-2}\cdot yr^{-1}$, respectively. The high-value centers of CG are mainly located in the southwest and north-center of PD, but the coverage and density are much lower than that of total lightning, especially obvious in the north-center of PD. In Figure 3(b), the −CG lightning density distribution is basically consistent with CG lightning and the 5-year mean and maximum values of −CG lightning density are 1.0 flashes $km^{-2}\cdot yr^{-1}$ and 17.2 flashes km^{-2}, respectively. In Figure 3(c), due to the low frequency of occurrence, the +CG lightning density is generally low in the whole province and the 5-year mean and maximum values of +CG lightning density are 0.41 flashes $km^{-2}\cdot yr^{-1}$ and 3.8 flashes $km^{-2}\cdot yr^{-1}$, respectively. Yang et al. [15] also found that the SB has a large CG lightning density (>4 flashes $km^{-2}\cdot yr^{-1}$), while the minimum CG density (<0.05 flashes $km^{-2}\cdot yr^{-1}$) is located in WSP. For +CG lightning density, Zhao et al. [18] found that the maximum lightning density is about 0.4 flashes $km^{-2}\cdot yr^{-1}$ in the SB and about 0.2 flashes $km^{-2}\cdot yr^{-1}$ in the WSP. In Yunnan province [16], the mean +CG density is in the range of 0.06–0.15 flashes $km^{-2}\cdot yr^{-1}$. In Canada and the central United States [11, 14], the mean +CG density is found to be less than 0.3 flashes $km^{-2}\cdot yr^{-1}$ and in the range of 0.5–0.7 flashes $km^{-2}\cdot yr^{-1}$, respectively. The reason for a higher +CG density value in this paper is due to the use of a more finer lightning grid resolution ($0.01^{\circ} \times 0.01^{\circ}$), and when we reduce the grid resolution as the previous studies [11, 14, 16, 18] to $0.2^{\circ} \times 0.2^{\circ}$, we find that the mean and maximum values of +CG lightning density are 0.13 flashes $km^{-2}\cdot yr^{-1}$ and 0.42 flashes $km^{-2}\cdot yr^{-1}$, respectively.

Figure 4 shows the mean value of IC, −IC, and +IC lightning density distribution in SC. Due to the LLS's low detection efficiency for IC lightning in this study, the IC lightning density is low in most areas. The 5-year mean values of IC, −IC, and +IC lightning density are 0.81 flashes $km^{-2}\cdot yr^{-1}$, 0.56 flashes $km^{-2}\cdot yr^{-1}$, and 0.42 flashes $km^{-2}\cdot yr^{-1}$, respectively. The maximum values of IC, −IC, and +IC lightning density are 7.8 flashes $km^{-2}\cdot yr^{-1}$, 5.4 flashes $km^{-2}\cdot yr^{-1}$, and 3.8 flashes $km^{-2}\cdot yr^{-1}$, respectively. From Figure 4(a), we can still find that the IC density is relatively high in the southwest and north-center of PD.

For climate subregions, different terrain and climate conditions tend to produce different types of thunderstorms with different charge structures and further affect the lightning activity characteristics. The spatial distribution of 5-year average values of 2 m temperature, 3–5 km RH, CAPE, and CIN is shown in Figure 5; although the CIN values are missing in some plateau areas and the 3–5 km RH has outliers along the boundary between the basin and the plateau, we still believe that these two factors can reflect the general distribution of CIN and 3–5 km RH in Sichuan Province.

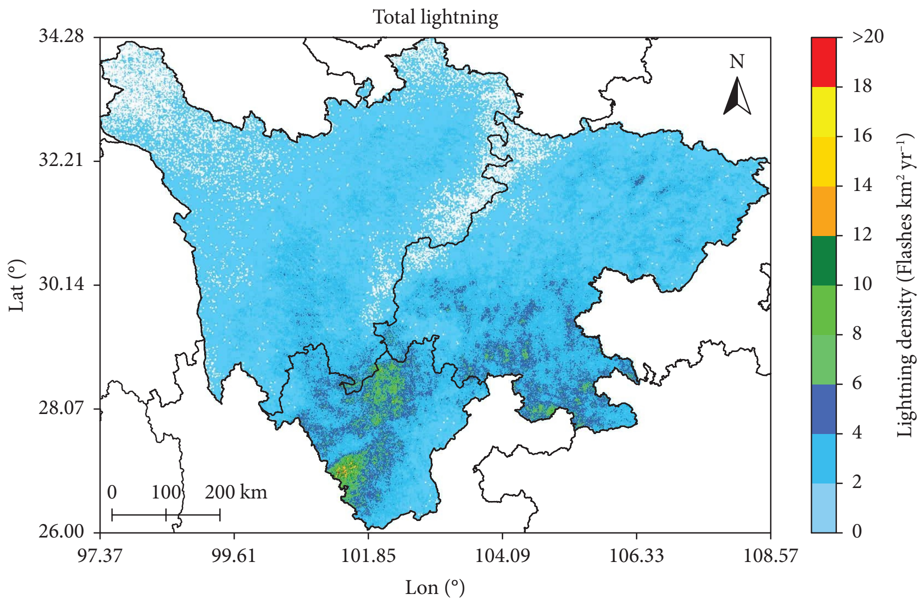


Figure 2: The 5-year mean value of total lightning density in Sichuan Province.

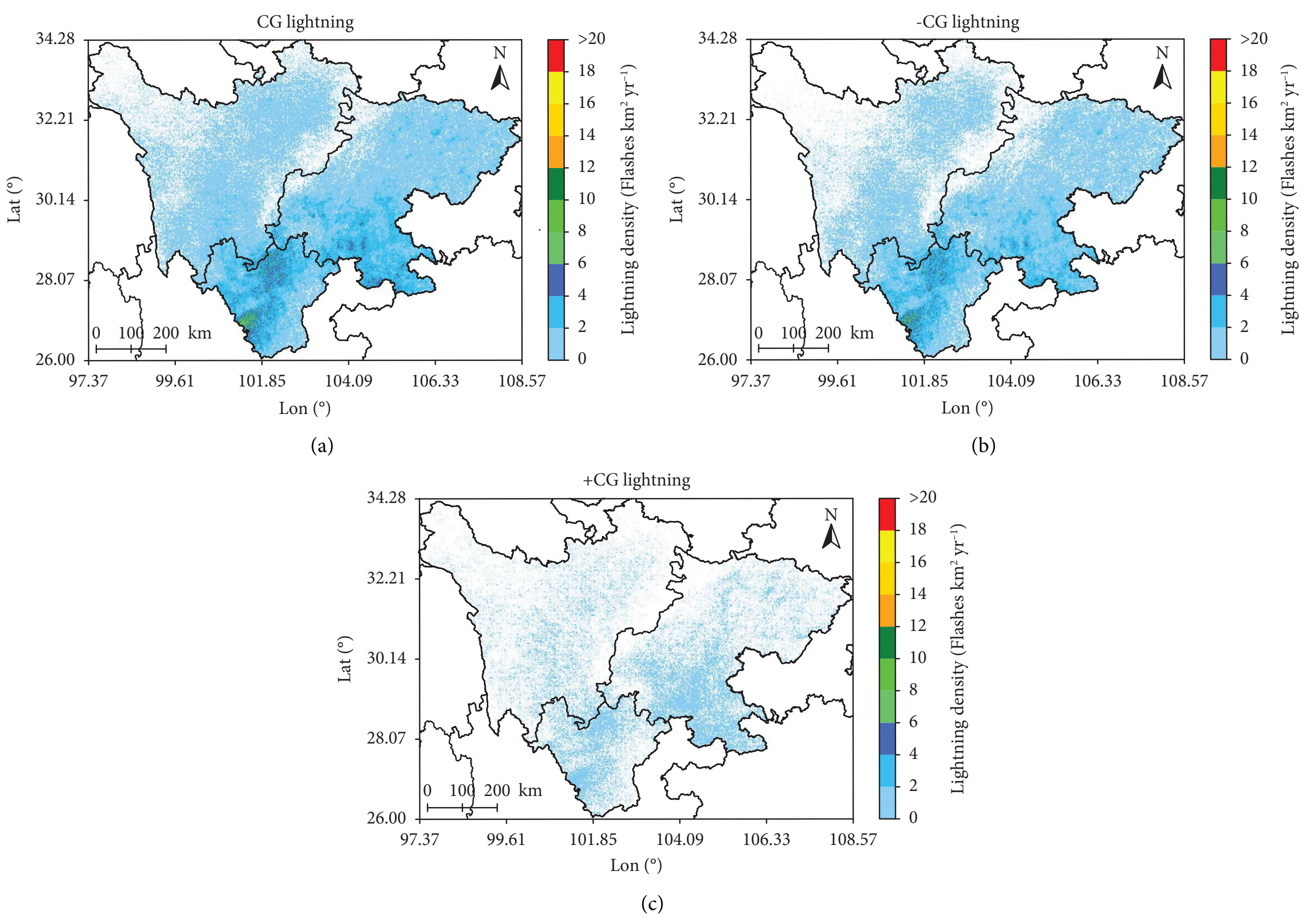


Figure 3: The 5-year mean value of (a) CG, (b) −CG, and (c) +CG lightning density distribution in SC.

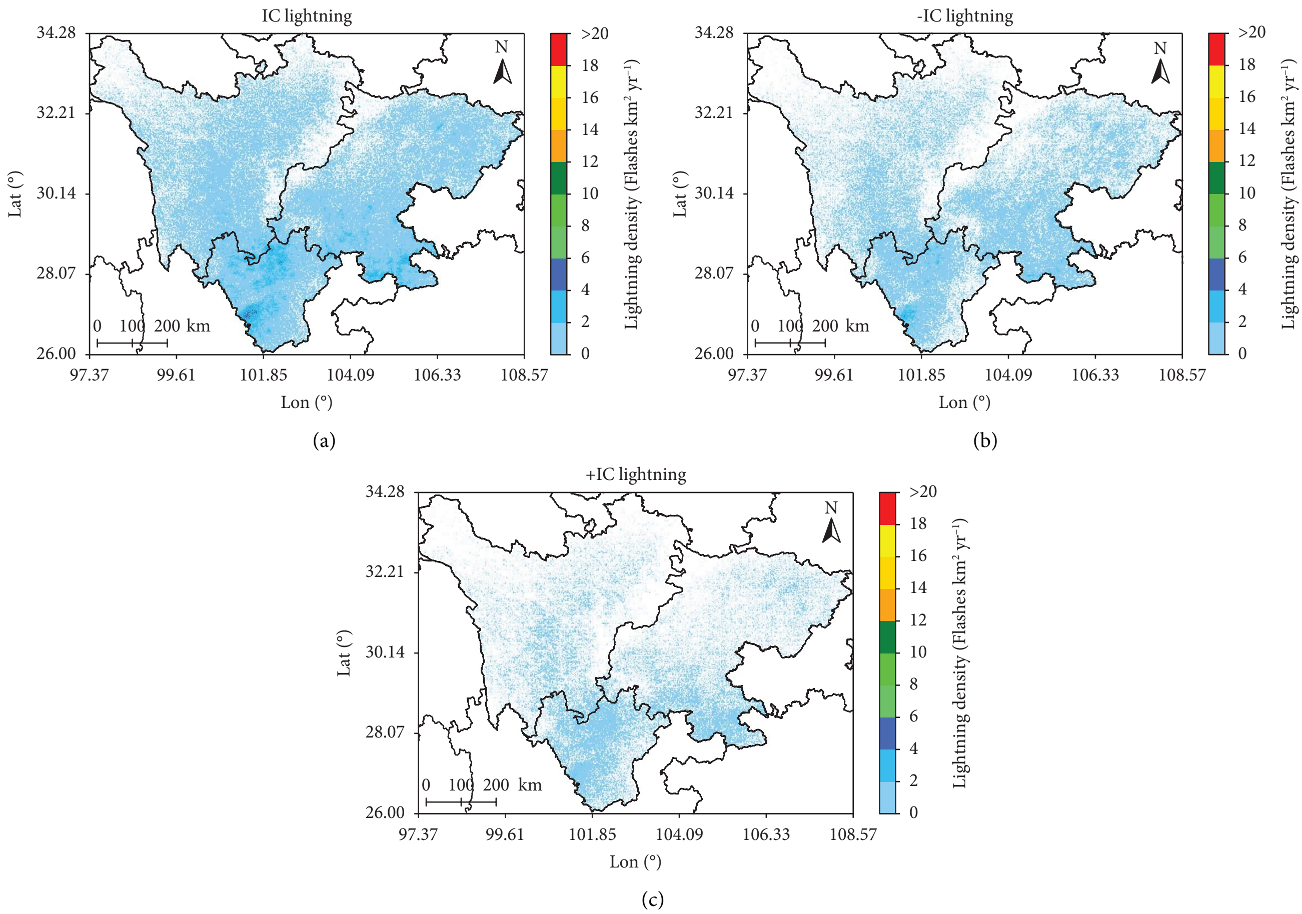


Figure 4: The 5-year mean value of (a) IC, (b) −IC, and (c) +IC lightning density distribution in SC.

As seen from Figure 5, the values of 2 m temperature (Figure 5(a)) and CAPE (Figure 5(c)) are obviously larger in the SB and southwest of PD but are much lower in WSP. In the north-center of PD, although the value of 2 m temperature and CAPE is not the highest, but the value is still at a relatively high level. Thus, the strong thermodynamic conditions are beneficial for the occurrence of thunderstorms. Figure 5(b) shows the distribution of 3–5 km RH, and it can be seen that the value of 3–5 km RH is much lower in the central parts of the WSP and southwest of PD. In SB, the RH conditions are better than WSP and PD and the RH value in the southeast of SB is larger than 80%. Sufficient moisture conditions are very crucial for the formation and maintenance of hydrometeors of the ice phase in convections. Figure 5(d) shows the distribution of CIN, and it can be seen that the value of CIN is relatively low in most areas of WSP and PD, while the value of CIN is higher in SB. For the formation and maintenance of the convections, the value of CIN needs to be within an appropriate range. A large CIN value is unfavorable for the formation of convections, and a small CIN value makes it difficult for energy to accumulate in lower layers, and convective adjustment occurs easily; thus, the convection is difficult to develop to a strong level.

For the three climate subregions, the SB has better thermodynamic and moisture conditions and the CIN condition is appropriate, so the basin is easier to undergo convection weather and has the most lightning occurrences. The middle atmosphere moisture condition in the southeast of SB is higher than in other parts of the basin; thus, the lightning density is also higher. In the southwest and north-center of PD, the thermodynamic conditions are obviously better, but the moisture conditions are worse, which indicates that the convection type is different from that in the basin. The strong thermodynamic conditions and insufficient moisture conditions can also form the higher concentrations of ice phase in convection systems, which are conducive to lightning occurrence, but it cannot be sustained for a long time. From Figures 1 and 2, it can be seen that the lightning is mostly concentrated in mountainous areas in PD, which is consistent with the results proposed by Lin-Lin et al. [8]. The uplift effect of mountainous terrain is favorable for the convection systems' formation. Therefore, the high-value centers of lightning density in PD are the result of specific meteorological conditions and topography. For WSP, it is obvious to find that the thermodynamic and moisture conditions are worse, combined with the topography-induced compression effect on the cloud, so the

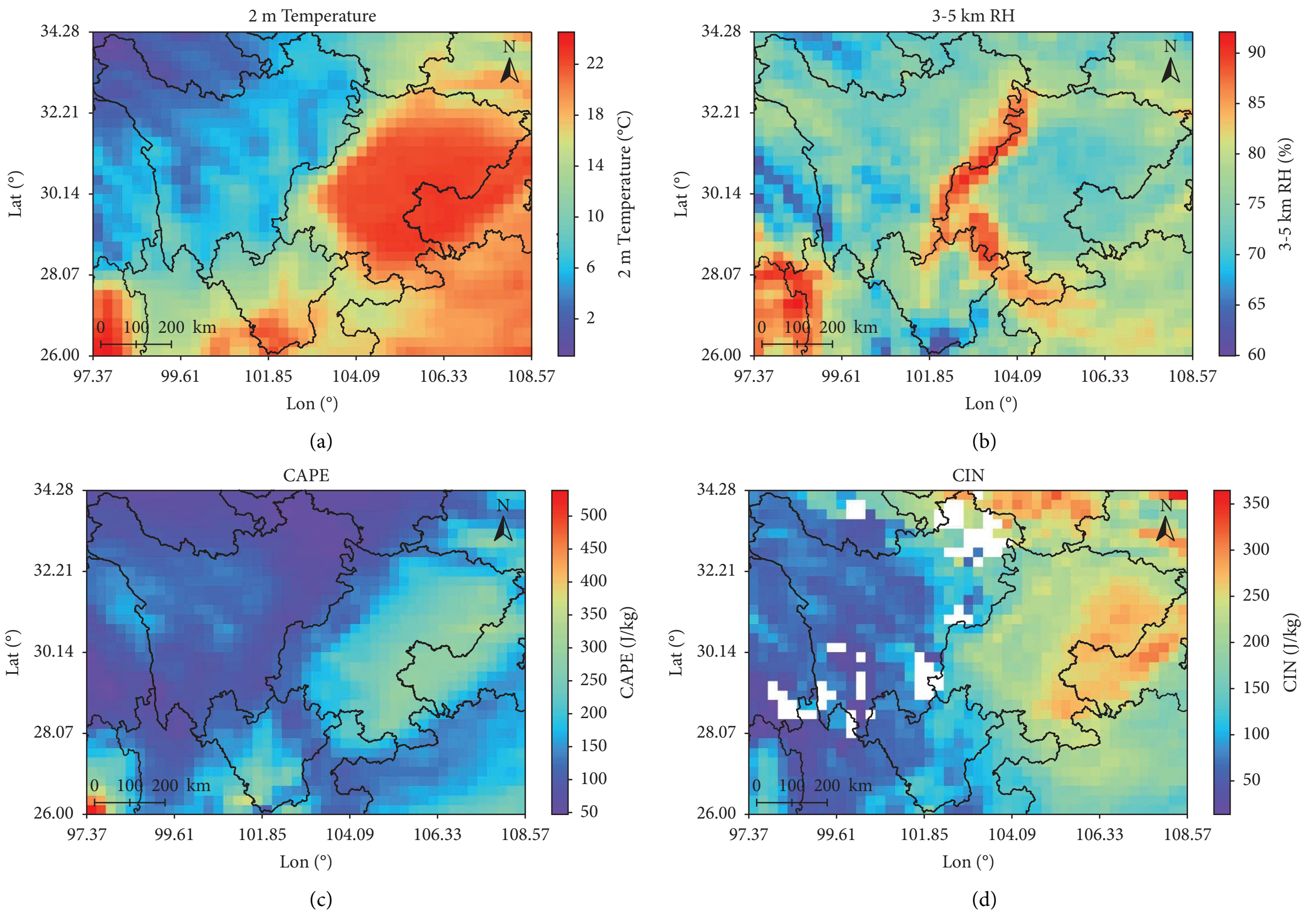


Figure 5: The 5-year mean value of (a) 2 m temperature, (b) 3–5 km RH, (c) CAPE, and (d) CIN distribution in SC.

convections generated in the plateau are shallow and weak. Existing studies [18, 21, 25] showed that the shallow and weak convections have fewer lightning occurrences but are very conducive to the generation of IC lightning and +CG lightning, as shown in Tables 1–3. The abovementioned analysis further indicates that the different meteorological conditions and topography can greatly affect the lightning activity characteristics.

3.3. Vertical Distribution of IC Lightning. The annual and seasonal variations of IC height for Sichuan and its three subregions are shown in Figure 6. Figure 6(a) shows that the 5-year mean IC lightning heights of SC, SB, PD, and WSP are 7.76 km, 7.83 km, 7.42 km, and 5.31 km, respectively. It is obvious to find that IC height is much lower for WSP. Figure 6(b) shows the seasonal variation of IC lightning height, for the whole province, and the maximum height occurs in summer, with an average height of 7.85 km, followed by autumn, with an average height of 7.73 km. The highest season (summer) is about 0.78 km higher than the lowest season (winter).

Figure 7 shows the frequency of IC lightning and the average IC lightning intensity in different height intervals for Sichuan and its three subregions. For all cases, the number of −IC frequency is always larger than +IC, and the IC lightning mainly occurs below 12 km, accounting for almost 80% of all IC records. The IC frequency is the most when the height is in the range of 3–6 km. The IC initiation altitude depends on the height of the charge zone in thunderstorms. Carey and Rutledge [20] analyzed a typical three-polarity thunderstorm and found that the upper positive charge zone is located at the height of about 9.5 km (−35°C), the middle negative charge zone is located at the height of about 7 km (−17°C), and the lower positive charge zone is located at the height about 4.5 km (3°C).

Figure 7(a) also shows that, for SC, the +IC intensity is always larger than −IC and the maximum values of +IC and −IC intensity both occur in the range of 3–6 km. When the height is in the range of 6 km−12 km, the +IC intensity roughly decreases with height, and the −IC intensity roughly increases with height. For SB (Figure 6(b)), the +IC intensity is obviously larger than the −IC when the height is below 9 km. When the height is larger than 12 km, the −IC intensity starts to exceed +IC, but the difference is not significant. A similar phenomenon is also found in PD (Figure 6(c)), and the −IC intensity starts to exceed +IC when the height is larger than 9 km. For the WSP (Figure 6(d)), the +IC intensity is in the range of 55 kA–75 kA and the −IC intensity is in the range of 45 kA–55 kA. Obviously, in all height intervals, both +IC and −IC are much larger than

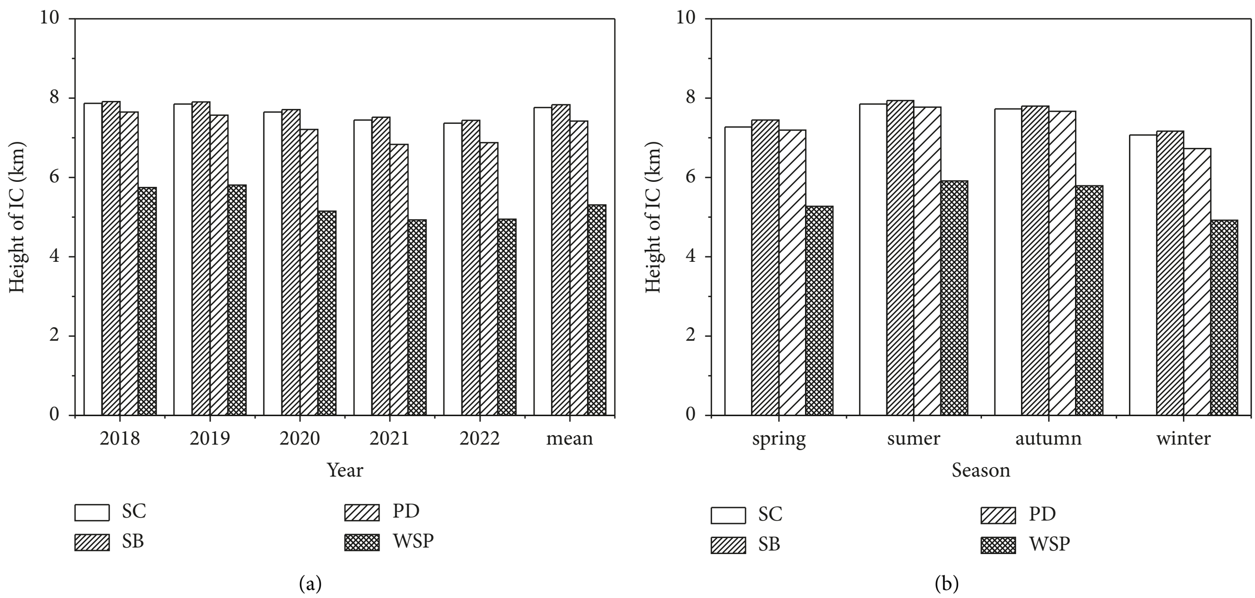


Figure 6: (a) Annual and (b) seasonal variation of IC height for Sichuan and its three subregions.

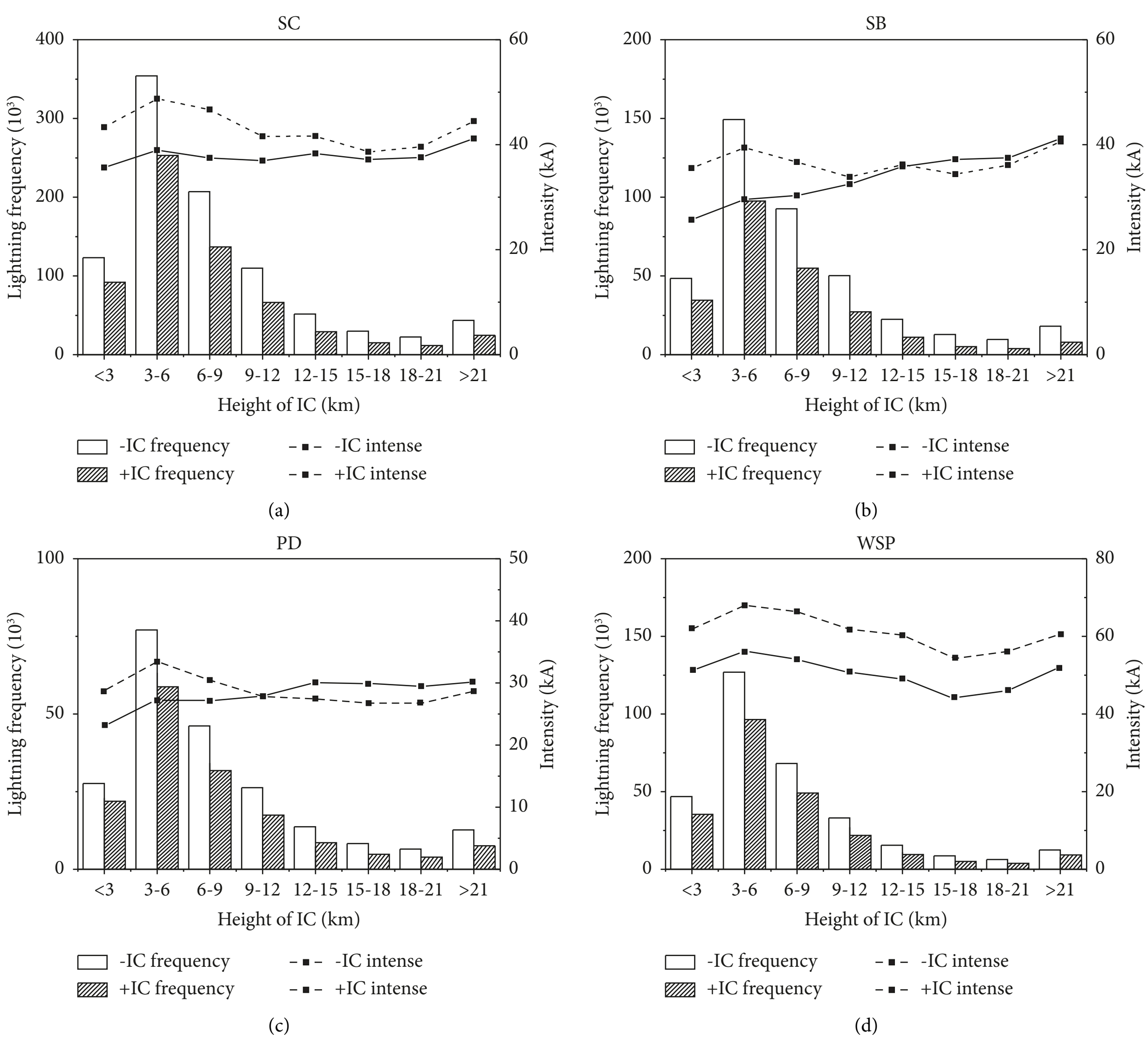


Figure 7: The IC lightning frequency and the average lightning intensity in different height intervals for (a) SC, (b) SB, (c) PD, and (d) WSP.

SB and PD. Different from SB and PD, the +IC intensity is always larger than −IC and the intensity difference is about 10 kA.

To further discuss the physical processes that cause the seasonal variation of IC height, we employ the cloud base height (CBH) and cloud top height (CTH) data from the CALIPSO satellite to explain this issue. The seasonal distribution of cloud base height and cloud top height is shown in Figures 8 and 9. Obviously, the IC height corresponds well to the CBH and CTH, and most of the IC lightning occurs at the height between CBH and CTH. In each season, the SB has the largest CBH and CTH, while the WSP has the lowest CBH and CTH. Large CBH and CTH represent the large strength of updraft, which is beneficial to processes of electrification and discharging. Therefore, the SB has the most lightning occurrence and the WSP has the least lightning occurrence. The seasonal variation of IC lightning height is consistent with the seasonal variation of CBH and CTH. In summer and autumn, the more favorable thermodynamic and moisture conditions make the convective clouds grow up higher. In SB and PD, the seasonal mean IC height is almost the same, with the value of approximately 7.8 km, which corresponds to the height of the mixed-phase region in thunderstorms where the noninductive electrification process occurs. In WSP, the seasonal mean IC height is obviously lower, with the value of approximately 5.3 km. This phenomenon can be explained by the topography-induced compression effect. The high-altitude terrain makes convective clouds that are shallower than those in other regions of the same latitude [18, 21, 25], which is also confirmed by the lowest CBH and CTH in WSP.

3.4. The Temporal Distribution of Lightning

3.4.1. Seasonal Distribution of Total, CG, and IC Lightning. The criteria for seasonal division are spring (March-May), summer (June-August), autumn (September-November), and winter (December-February the next year). Figure 10 shows the seasonal variation of lightning frequency for Sichuan Province and its three subregions. It can be seen that most lightning occurs in summer for all regions, far more than in other seasons. During the 5 years, the total lightning frequency exceeded 500 thousand in summer. Since during the northern hemisphere summer, the thermodynamic conditions are favorable and moisture conditions are more sufficient than other seasons; hence, they are conductive to convection system formation and lightning occurrence. For SB, the total lightning frequency in spring is slightly larger than that in autumn, but for PD and WSP, the total lightning frequency in autumn is slightly larger than that in spring. In spring and summer, the SB accounts for the most total lightning occurrences, but in autumn and winter, the WSP and PD account for the most total lightning occurrences, respectively.

For CG and IC, the seasonal variation is consistent with total lightning. The mean CG lightning frequency for spring, summer, autumn, and winter was 65380, 387194, 83211, and 728. In summer, the mean CG lightning frequency for SB, PD, and WSP was 185356, 99726, and 88016. In autumn, the WSP had the largest CG lightning frequency with a value of 35546. In winter, the PD had the largest CG lightning frequency with a value of 448. The mean IC lightning frequency for spring, summer, autumn, and winter was 40510, 241955, 52498, and 521. In summer, the mean IC lightning frequency for SB, PD, and WSP was 108821, 56281, and 76853. In autumn, the WSP had the largest IC lightning frequency with a value of 27189. In winter, the PD had the largest IC lightning frequency with a value of 306.

3.4.2. Diurnal Distribution of Total, CG, and IC Lightning. Figure 11 shows the diurnal variation of lightning frequency for Sichuan Province and its three subregions. For SC, Figure 11(a) shows that the diurnal variations of the total, CG, and IC lightning have "single peak and single valley" characteristics, with a main peak at 1700 LT and a valley at 1100 LT. The lightning frequency increases rapidly from 1300 to 1700 LT and then decreases slowly after 1700 LT. Until 0500 LT, the lightning frequency still remains at a high level. From 0600 LT to 1200 LT, the lightning frequency is low because the convective activity is weak in this period.

Figures 11(b)–11(d) show that the diurnal variation is quite different for the three climate subregions. For SB, the lightning frequency increases rapidly from 2100 LT, reaching the maximum at 0000 LT, and then decreases from 0000 LT to 0500 LT, which shows the obvious nocturnal character. For PD, the lightning activity mainly concentrates between 16:00 and 03:00 for the next day, with the maximum occurring at 2100 LT. For WSP, the lightning activity mainly concentrates between 14:00 and 23:00, and the maximum occurs at 1700 LT. For the three regions, the minimum value always occurs at 1000 LT–1100 LT. The diurnal variations of CG and IC are consistent with total lightning. The difference in diurnal variation in the three subregions is possibly due to the joint effect of the diurnal cycle of insolation, the large-scale circulation, and the topographic feature.

3.5. Intensity Distribution Characteristics of Lightning

3.5.1. Intensity Distribution Characteristics of CG Lightning. Figure 12(a) shows the frequency of CG lightning in different intensity ranges. The intensity of CG lightning is mainly concentrated in the range below 50 kA, accounting for 81% of the total CG records. Among them, the most CG lightning occurs in the range of 0~25 kA, accounting for 45% of the total CG records. The CG intensity larger than 100 kA rarely occurred. When CG intensity is below 50 kA, the number of −CG lightning is much larger than that of the +CG lightning. The number of −CG lightning starts to exceed +CG lightning when the intensity is larger than 75 kA, but the frequency difference is small.

Figure 12(b) shows the monthly variation of CG intensity, and the 5-year mean intensity of +CG and −CG lightning is 53.75 kA and −30.34 kA. The maximum intensity of +CG and −CG occurs in September, with values of 58.6 kA and −33.4 kA. The minimum intensity of +CG and −CG occurs in January and May, with values of 42.8 kA and

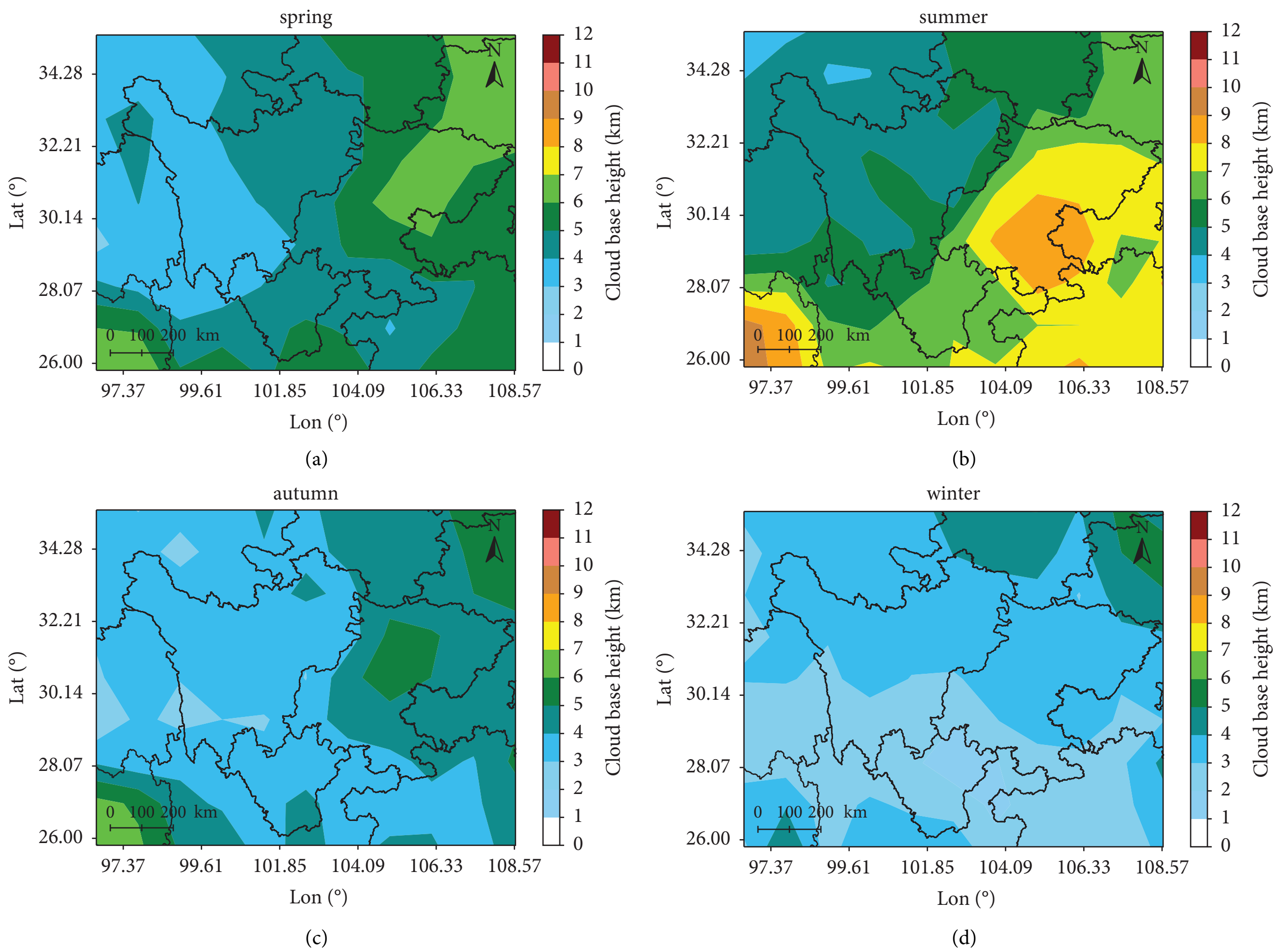


FIGURE 8: Spatial distribution of CBH for SC in (a) spring, (b) summer, (c) autumn, and (d) winter.

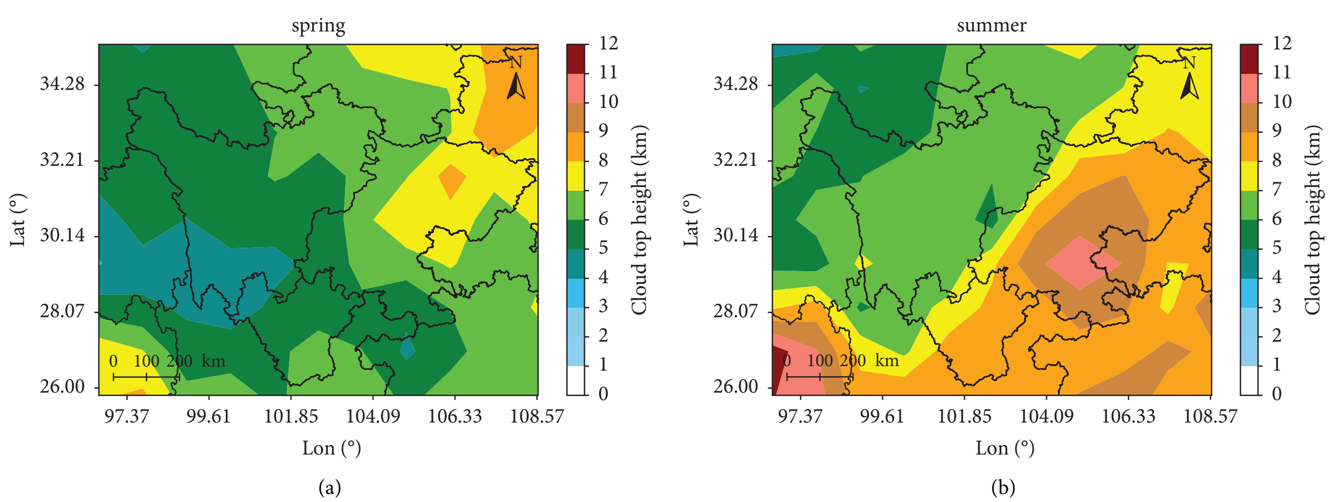


FIGURE 9: Continued.

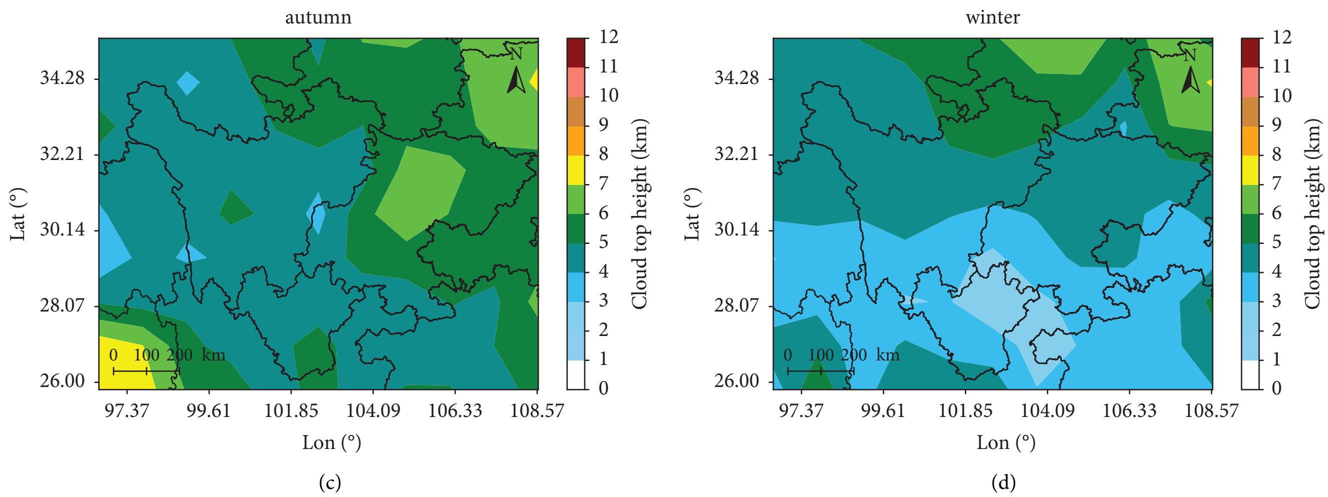


FIGURE 9: Spatial distribution of CTH for SC in (a) spring, (b) summer, (c) autumn, and (d) winter.

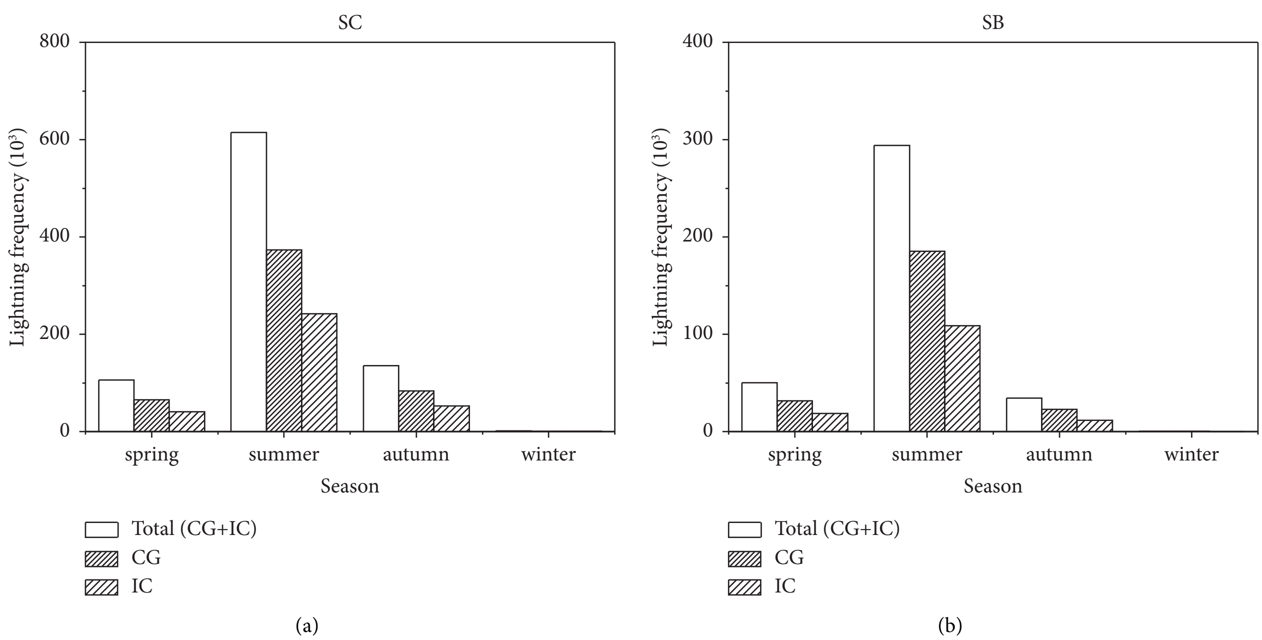
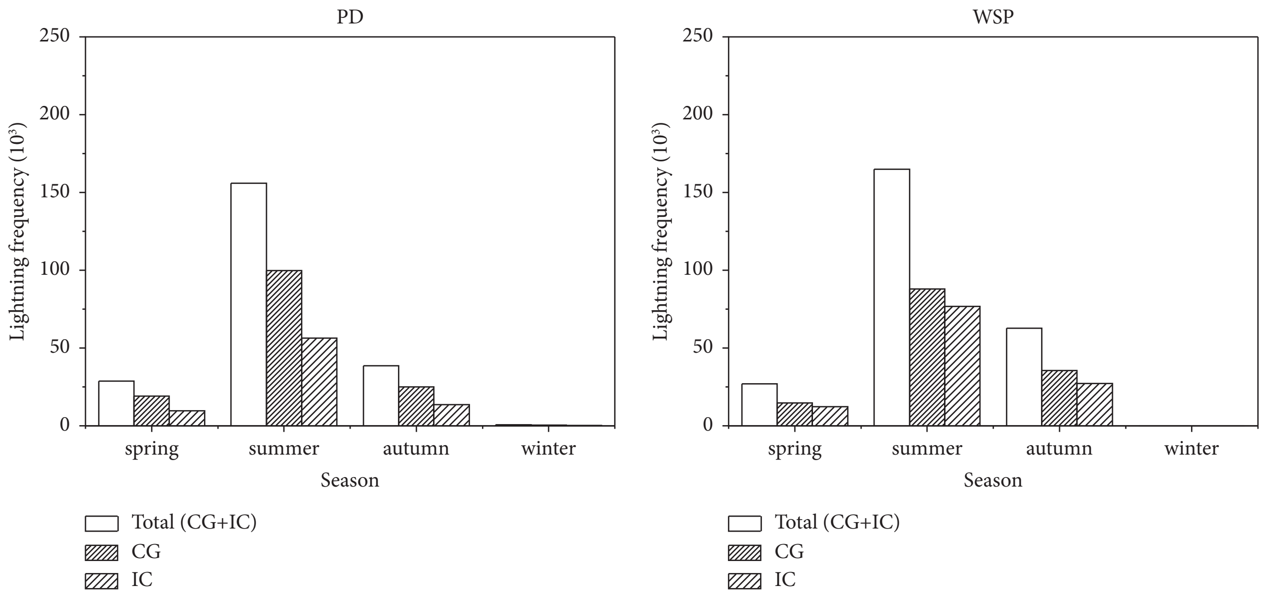
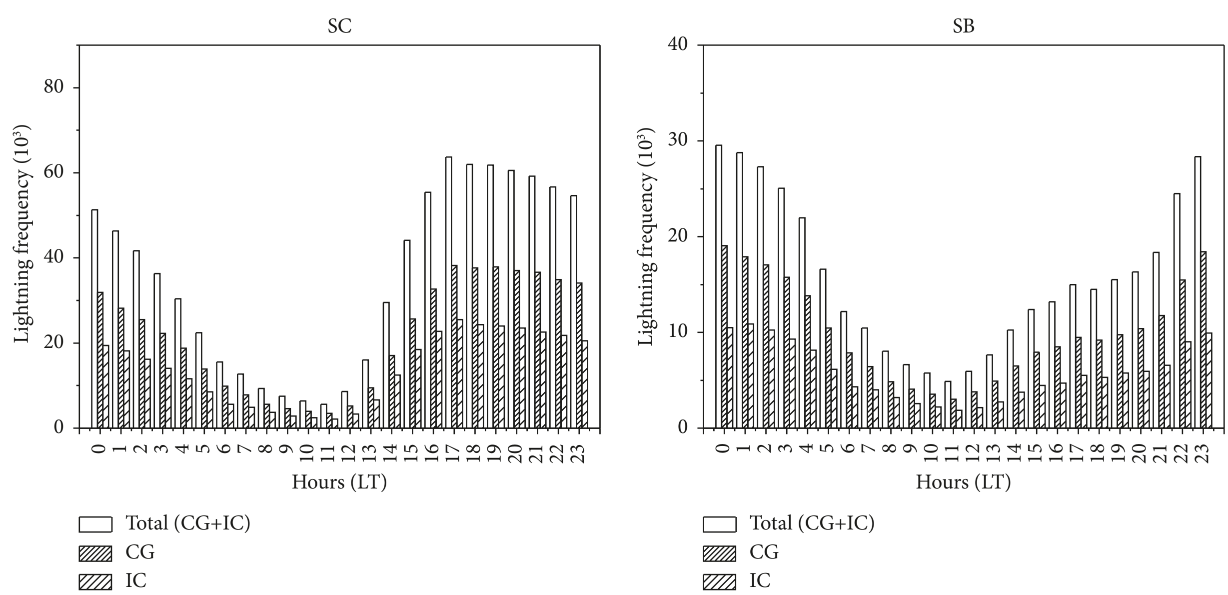


FIGURE 10: Continued.



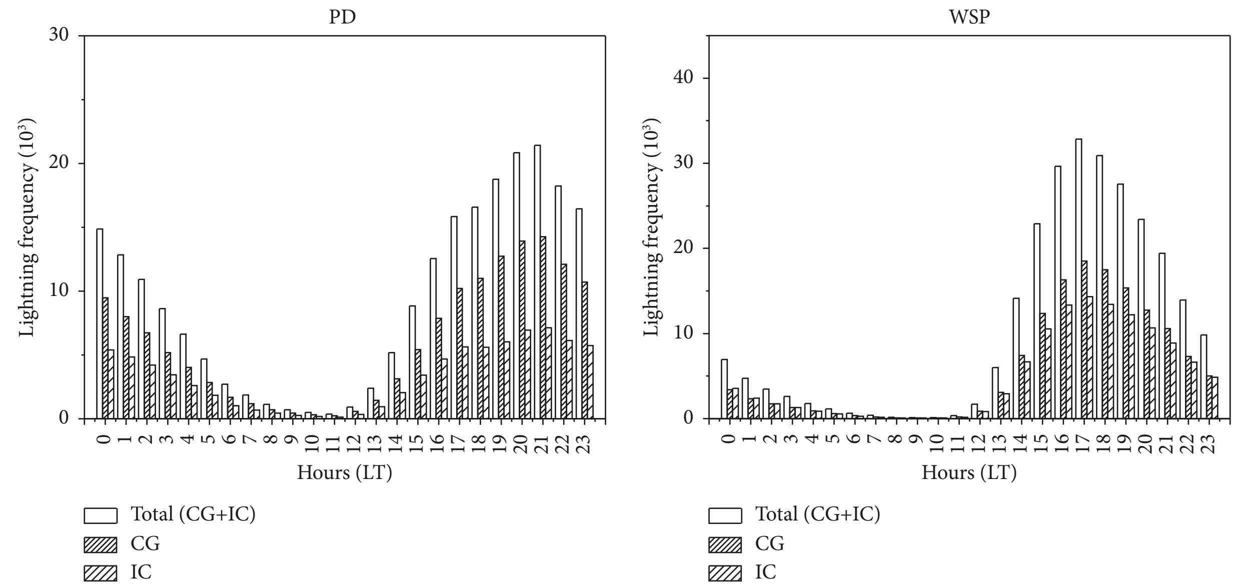
(c) (d)

Figure 10: Seasonal distribution of total, CG, and IC lightning frequency for (a) SC, (b) SB, (c) PD, and (d) WSP.



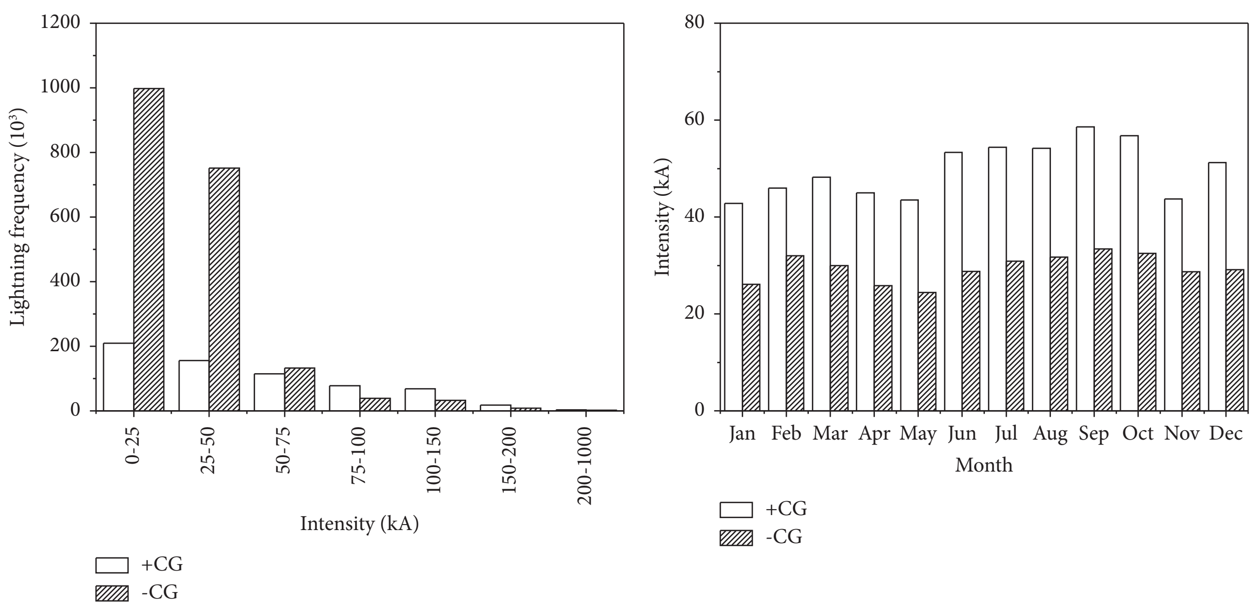
(a) (b)

Figure 11: Continued.



(c) (d)

Figure 11: Diurnal distribution of total, CG, and IC lightning frequency for (a) SC, (b) SB, (c) PD, and (d) WSP.



(a) (b)

Figure 12: (a) CG lightning frequency in different intensity ranges and (b) monthly variation of CG intensity.

−24.4 kA. The lightning intensity from June to September is slightly greater than that in other months. In each month, the intensity of +CG lightning is obviously larger than that of −CG lightning.

3.5.2. Intensity Distribution Characteristics of IC Lightning. Figure 13(a) shows the IC lightning frequency in different intensity ranges. The intensity of IC lightning is mainly concentrated in the range below 75 kA, accounting for 85% of the total IC records. Among them, the most IC lightning occurs in the range of 0~25 kA, accounting for 44% of the total IC records. When IC intensity is below 50 kA, the number of −IC lightning is much larger than the +IC lightning. The number of −IC and +IC lightning is almost the same when the intensity is larger than 50 kA.

Figure 13(b) shows the monthly variation of IC intensity, and the 5-year mean intensity of +IC and −IC lightning is −37.97 kA and 46.08 kA. For both +IC and −IC, the intensity value varies a little from month to month. The maximum intensity of +IC and −IC occurs in September and January,

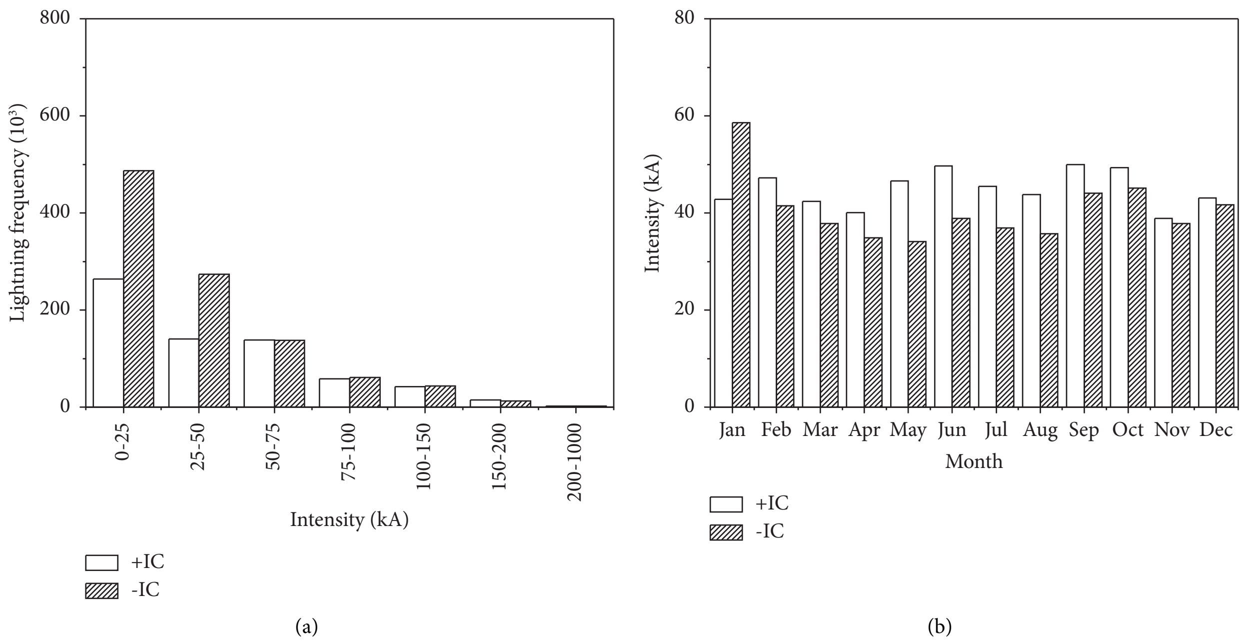


FIGURE 13: (a) IC lightning frequency in different intensity ranges and (b) monthly variation of IC intensity.

with values of 50.0 kA and −58.6 kA. The minimum intensity of +IC and −IC occurs in November and May, with values of 42.8 kA and −34.1 kA. Except for January, the intensity of +IC is larger than the −IC in each month, but the difference in intensity is relatively less than CG lightning.

4. Conclusion

In this paper, we analyze the spatiotemporal distribution and current intensity characteristics of total lightning, cloud-to-ground lightning (CG), and intracloud lightning (IC) for the whole Sichuan Province and its three climate subregions. The influence of different climate conditions on lightning activities is also discussed. The results are as follows:

(1) For the whole province, the annual mean value of total lightning is about 850 thousand and the mean IC proportion is about 0.39. The SB has the most lightning occurrences, accounting for 44% of the dataset. For WSP, the IC proportion, +CG proportion, and the lightning intensity are obviously larger than the other two regions.

(2) For the spatial distribution, the mean and maximum values of total lightning density are 1.90 flashes $km^{-2}{\cdot}yr^{-1}$ and 25.8 flashes $km^{-2}{\cdot}yr^{-1}$. Three centers of high lightning density are observed in the southwest of PD (mainly Panzhihua city), the north-center of PD, and the southeast of SB. The WSP is a low value (<2 flashes $km^{-2}{\cdot}yr^{-1}$) area for the lightning density. The spatial distribution of CG and IC is similar to the total lightning.

(3) The SB has better thermodynamic and moisture conditions, which is favorable for the occurrence of convection weather and has the most lightning occurrences. In PD, the thermodynamic conditions are better, but the moisture conditions are worse. Lightning is mostly concentrated in mountainous areas in PD, which is attributed to the joint effect of specific meteorological conditions and mountainous topography. For WSP, due to the worse hydrothermal conditions and the topography-induced compression effect, the convections are shallow and weak, which are very conducive to the generation of IC lightning and +CG lightning.

(4) The 5-year mean IC lightning heights of SC, SB, PD, and WSP are 7.76 km, 7.83 km, 7.42 km, and 5.31 km, respectively. The maximum IC height occurs in summer (7.85 km), and the minimum value occurs in winter (7.07). The seasonal variation of IC height corresponds well with the seasonal variation of CBH and CTH, and most of the IC lightning occurs at the height between CBH and CTH. The IC lightning mainly occurs below 12 km, accounting for 80% of all IC records, which corresponds to the IC discharge between the main charge centers in thunderstorms. The IC height is much lower on WSP, and the variation rule of current with height is different from that of the SB and PD.

(5) In terms of seasonal variations, the highest frequency of CG and IC lightning all occurs in summer, followed by autumn, and the seasonal variation of IC frequency is closely related to the seasonal thermodynamic and moisture conditions. The diurnal variation is quite different in the three regions. For SB, the lightning frequency increases rapidly from 2100 to 0000 LT and then decreases from 0000 LT to 0500 LT, which shows obvious nocturnal character. However, for WSP, most lightning occurs between 1300 and 2300 LT, and the peak value occurs at 1700 LT.

(6) Most CG intensity concentrates in the range of below 50 kA, and IC concentrates in the range of below 75 kA. For CG and IC, the maximum frequency occurs in the range of 0–25 kA. Below 50 kA, the frequencies of −CG and −IC are obviously larger than +CG and +IC, respectively. When larger than 50 kA, such frequency difference reduces a lot. In each month, the intensity difference between +CG and −CG is significant, but the difference between +IC and −IC is relatively less.

Data Availability

The total lightning location data (ADTD-2C) used to support the findings of this study are available from the corresponding author upon request. The ERA5 reanalysis data were downloaded from ECMWF website (https://cds.climate.copernicus.eu). The CALIOP products were downloaded from the Atmospheric Science Data Center (https://earthdata.nasa.gov).

Conflicts of Interest

The authors declare that there are no conflicts of interest.

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