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Research Article

Dependence of Warm Season Cloud-to-Ground Lightning Polarity on Environmental Conditions over Sichuan, Southwest China

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The effects of thermodynamic and moisture factors on cloud-to-ground (CG) lightning polarity in the warm season were discussed. Small convective available potential energy (CAPE) represents relatively shallow convection, which is beneficial to the generation of positive lightning. Large vertical wind shear results in the displacement of upper-level positive ice crystals and promotes the initiation of +CG lightning from positive ice crystals. The dry low- to midlevel troposphere and the high cloud base in the plateau region favor +CG lightning, while the strong thermodynamic conditions in the basin region offset the influence of these moisture factors. In the plateau region, due to the limited cloud thickness, high total column liquid water may mean high cloud water content in the warm cloud region rather than high liquid water content in the mixed-phase region, which is unfavorable for the middle-level positive graupel and thus is unfavorable for the initiation of +CG lightning. In the basin region, the cloud thickness is relatively thicker, the high total column liquid water means that the liquid water content in the warm cloud and the mixed-phase region is both high, which is conducive to the middle-level positive graupel and the +CG lightning.

1. Introduction

The local thermal, dynamic, and microphysical conditions affect the polarity of cloud-to-ground (CG) lightning by synergistically affecting the structure of the thunderstorm and the processes of electrification and discharging [1–7]. Lightning polarity depends on the vertical charge distribution of the thunderstorm [8–13]. The normal charge structure is that the upper level of the thunderstorm is a positive charge zone, the lower part is a negative charge zone, and the discharge process transfers the negative charge to the ground and forms a −CG lightning flash. The anomalous charge structure, inverted polarity, refers to a thunderstorm with a negative charge zone at the upper level and a positive charge zone at the lower level, and there is usually a small negative charge zone below the positive charge zone [14]. The discharge process transports the positive charge to the ground and forms a +CG lightning flash. Negative leaders are more likely to be generated by thunderstorms with inversed polarity, while positive leaders are more likely to be generated by thunderstorms with normal polarity [14].

Although the physical factors controlling the polarity of lightning are not very evident, the meteorological environment still partly explains the electrification, charge structure, and the generation of +CG and −CG lightning through regional differences. The studies on the influence of environmental factors on lightning polarity were generally based on a hypothesis supported by laboratory and observational studies [12, 15–19]. The hypothesis is that the high liquid water content in the mixed-phase region represents the high rime accretion rate of graupel particles, which leads to the positive charge carried by graupel particles, which leads to the generation of the inverted charge structure and the increase in the ratio of +CG lightning [20, 21].

Smith et al. [22] found that areas with large surface equivalent potential temperature gradients were high in +CG lightning during tornadic outbreaks in Kansas and Illinois. Severe thunderstorms dominated by +CG lightning were closely related to the equivalent potential temperature gradient and equivalent potential temperature bridge in the Contiguous United States [23]. Kalb [24] suggested that equivalent potential temperature, convective available potential energy (CAPE), mean relative humidity, precipitable water, freezing level, and vertical wind shear did not have a significant effect on +CG lightning, while the lower cloud base heights and warm cloud depth and higher dew points were conducive to the occurrence of +CG lightning in the central United States. Carey and Buffalo [20] suggested that positive thunderstorms were related to the dry low- to midlevel troposphere, and the strong conditional instability, high cloud base height, thin warm cloud thickness, and large wind shear were all conducive to the transportation of liquid water to the mixed-phase region and then the occurrence of +CG lightning in Southern Great Plains of the United States. MacGorman et al. [21] and Eddy [25] also found that the above factors had a stimulation effect on +CG lightning, but the excitation effect had prominent regional differences, and the strong thermodynamic parameters offset the influence of microphysical factors on +CG lightning to some extent throughout the Contiguous United States. The relative frequency of +CG lightning is lower than that of −CG lightning, but the peak current generated by positive return stroke is obviously larger than that of negative one, so the threat of +CG lightning to ground objects is more prominent [26–29].

The topography of Sichuan is very complex, located on the east side of the Tibet plateau. The eastern part of Sichuan is the plateau terrain, the western part is the basin terrain, and the surrounding areas are mountainous terrain with an average elevation of 3 km. The effects of the environmental factors on lightning polarity have obvious regional differences and uncertainty. This study focuses on discussing the dependence of lightning polarity on thermodynamic and moisture factors in this complex topography and comparing the similarities and differences between the dependence in the plateau region and the basin region.

2. Data and Methodology

2.1. CG Lightning. The CG lightning data were obtained from the Sichuan Lightning Detection Network, which consists of 25 ground-based Advanced Time of Arrival and Direction (ADTD) system CG lightning detection sensors with a detection efficiency of ~90% [30–32]. The location of the lightning detection sensors and the topography of Sichuan are shown in Figure 1. According to previous studies [33, 34], data quality control was processed, the flashes with +CG lightning peak currents less than 15 kA were eliminated to avoid the contamination of intracloud lightning flashes.

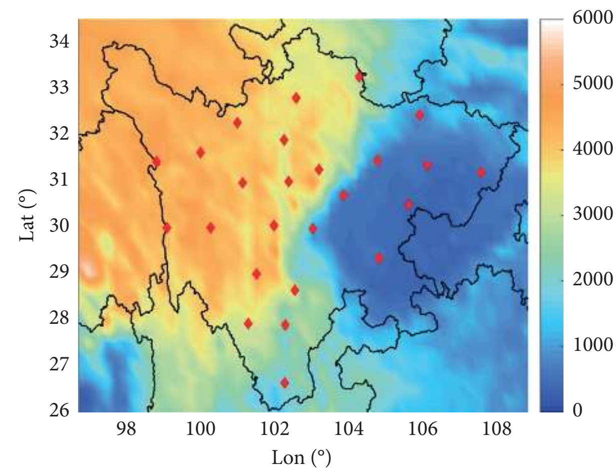

Figure 1: Lightning detection sensor location and topography (unit: m) in Sichuan.

To match the temporal and spatial resolution of the environmental factors data from ERA5, the warm season CG lightning data from 2005 to 2017 were processed into monthly average data with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$. The relative frequency of +CG and −CG lightning is defined as the number of +CG or −CG lightning flashes divided by the number of total CG lightning flashes:

$$\text{Raletive Frequency} = \frac{\pm\,\text{CG flashes}}{\text{Total CG flashes}} \times 100\%. \quad (1)$$

2.2. Environmental Factors. Previous studies [20–24] indicated that a variety of environmental factors, such as CAPE, vertical wind shear, potential temperature, relative humidity, cloud base height, warm cloud thickness, and freezing level height, have significant effects on lightning polarity. Twelve environmental factors in the warm season classified as thermodynamic factors and moisture factors were selected to discuss the dependence of lightning polarity on environmental factors. Environmental factors' data were obtained from ERA5 reanalysis single-level and pressure-level monthly averaged data sets [35]. In this study, the selected monthly averaged data range was from 2005 to 2017, with a spatial resolution of $0.25^{\circ} \times 0.25^{\circ}$.

The ERA5 pressure-level data are not suitable for analyzing the vertical distribution of environmental factors due to the large topographic fluctuation in Sichuan. We used the barometric formula [36] and Digital Elevation Model (DEM) data to process the pressure levels into the geometric-altitude-levels Above Ground Level (AGL) and interpolated the data into the geometric-altitude-level AGL. The thermodynamic factors included CAPE, surface pressure (SP), potential temperature (THETA), vertical wind shear between 0 and 3 km (SHEAR-3 km), vertical wind shear between 0 and 5 km (SHEAR-5 km), and vertical velocity at 3 km (VV-3 km). Moisture factors included dew point depression (DPD), average relative humidity between

3 km and 5 km (RH), cloud base height (CBH), zero-degree height (ZDH), total column liquid water (TCLW), and total column ice water (TCIW). THETA is calculated from SP and 2 m temperature, given as

$$\text{THETA} = T_{2m}\left(\frac{P_0}{P}\right)^{0.286}, \quad (2)$$

where $T_{2\text{m}}$ is 2 m temperature, P_0 is SP, and P is 1000 hPa. SHEAR-3 km and SHEAR-5 km are calculated similarly and given as

$$\text{SHEAR} = \sqrt{(u_1 - u_0)^2 + (v_1 - v_0)^2}, \quad (3)$$

where u_1, u_0, v_1, and v_0 are zonal and meridional wind speeds at two geometric-altitude levels, respectively. DPD is the difference between 2 m temperature and 2 m dew point temperature, given as

$$\text{DPD} = T - T_d. \quad (4)$$

3. Results and Discussion

3.1. Relative Frequency of CG Lightning Polarity. Figure 2 shows the spatial distribution of the relative frequencies of −CG and +CG lightning, the spatial distribution of +CG lightning density, and the monthly distribution of +CG lightning relative frequency in Sichuan. There were significant differences in the relative frequency between the basin region in the east of Sichuan and the plateau region in the west of Sichuan. For −CG lightning (Figure 2(a)), the relative frequency in the basin region was significantly higher than that in the plateau region, which was about 70–90%, and that in the plateau region was about 50–70%. While, for +CG lightning (Figure 2(b)), the relative frequency in the plateau region was about 30–50%, and the relative frequency in the basin region was about 10–30%, the relative frequency in the plateau region was higher than that in the basin region. In Yunnan province, south of Sichuan province, the annual average +CG lightning ratio was about 3–20%, which was close to that in the basin region in this study but significantly lower than that in the plateau region [37]. This may be related to the particularity of convective clouds caused by the topographic compression of the plateau [38]. Qie et al. [39] found that the ratio of +CG lightning in different thunderstorms in the Chinese Inland Plateau ranges from 6.5% to 100%, with an average ratio of ~15.3%.

In the warm season, the +CG lightning density in the basin region and the southern part of Sichuan is higher than that in the plateau region, with a maximum lightning density of approximately 0.4 flashes km^{-2} year^{-1} in the plateau region and approximately 0.2 flashes km^{-2} year^{-1} in the plateau region (Figure 2(c)). In the summer with active lightning activity, the relative frequency of +CG lightning was lower than that of other months in the warm season (Figure 2(d)). The monthly distribution characteristics of the relative frequency of +CG lightning in Sichuan were consistent with those in other parts of China such as northern China, southern China, Yangtze river basin, and southwest mountains regions [31, 32], but the average relative frequencies of +CG lightning in these areas were less than 10% in summer, which were significantly lower than those in the western Sichuan plateau region in this study.

3.2. Correlation between Lightning Polarity and Environmental Factors. It is generally acknowledged that +CG lightning accounts for about 10% of the total CG lightning [5]. Due to its relative rarity, the understanding and research on it are relatively not in-depth. The active +CG lightning is mainly concentrated in the cold season and the dying stage of thunderstorms, and its great destructive power on the ground objects highlights its importance [5, 40]. Figure 3 shows the correlation between the relative frequency of +CG lightning and the thermodynamic factors in Sichuan during the warm season. Over the whole Sichuan region, CAPE (Figure 3(a)) and THETA (Figure 3(c)) show a significant negative correlation with the relative frequency of +CG lightning, indicating that the strong thermal conditions in the warm season are not conducive to the occurrence of +CG lightning. Previous studies [20–22] indicated that strong conditional instability is conducive to the generation of +CG lightning through case studies, mainly because the strong updraft transports a large amount of liquid water to the mixed-phase region, which is favorable for graupel particles to carry positive charges. In this study, the strong thermal instability conditions were not conducive to the +CG lightning, which mainly reflects that weaker thunderstorms are more likely to produce positive lightning [41]. The thermal conditions are weak, while the proportion of the +CG lightning is high [5, 42–44]. In other words, the weaker the thunderstorm, or the dissipating stage of the storm, the more +CG lightning it tends to produce. Vertical wind shears (Figures 3(d) and 3(e)) were positively correlated with +CG lightning, especially in southern Sichuan and plateau region, suggesting that an increase in vertical wind shear triggers the occurrence of +CG lightning. The strong vertical shear in the thunderstorm will lead to the tilt of the cloud, which is conducive to the tilt of the main positive charge region in the upper level of the thunderstorm to avoid the block of the negative charge region in the lower part. In this way, it is conducive to the transmission of positive charge to the ground from the thunderstorm, forming +CG lightning. A previous study [45] found that the displacement of upper-level positive ice crystals caused by wind shear is an important cause of positive lightning. It is worth noting that SP (Figure 3(b)) was negatively correlated with the relative frequency of +CG lightning in the plateau region and positively correlated with it in the basin region. VV_3 km (Figure 3(f)) was positively correlated with the +CG lightning in southern Sichuan, while the correlation was not significant in other areas of Sichuan.

Laboratory and observational studies [12, 15–19] have found that high liquid water content in the mixed-phase region leads to the positive charge carried by the middle-level graupel particles, which is conducive to the generation of +CG lightning. This indicates that the moisture parameters related to liquid water have a potential influence on +CG lightning. Figure 4 shows the correlation between the

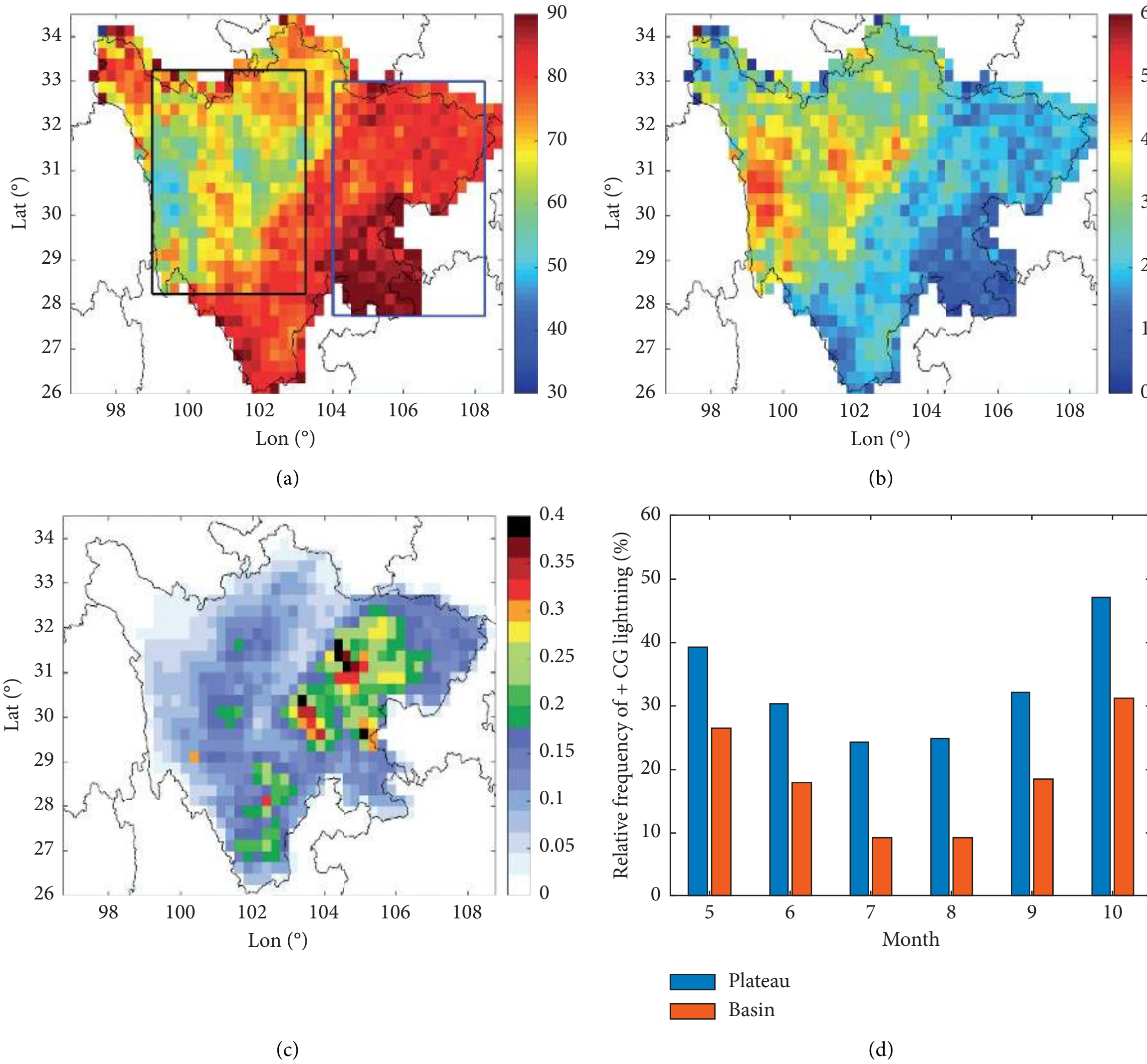

FIGURE 2: Relative frequency (unit: %) of (a) –CG and (b) +CG lightning during the warm season in Sichuan, (c) +CG lightning density (unit: flashes km^{-2} $year^{-1}$), and (d) monthly distribution of +CG lightning relative frequency. The plateau region and the basin region are outlined by black and blue rectangles, respectively, in the left panel.

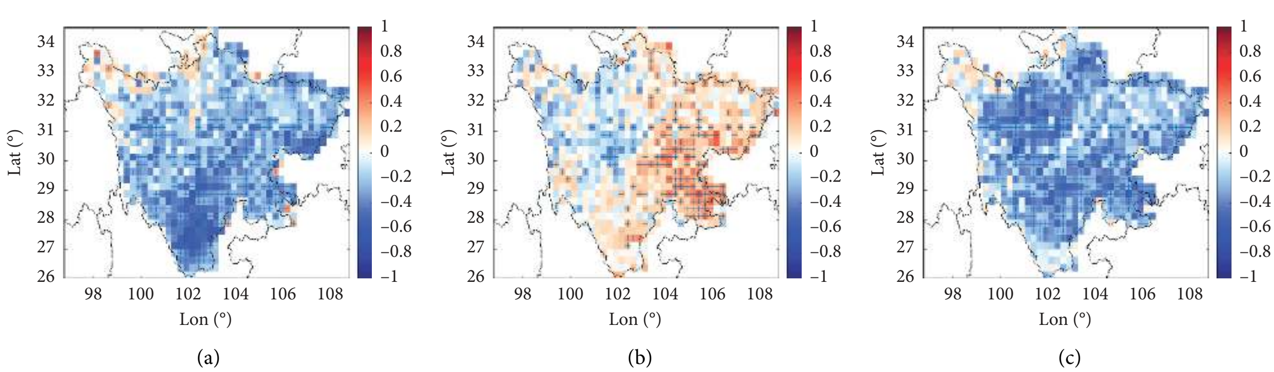

FIGURE 3: Continued.

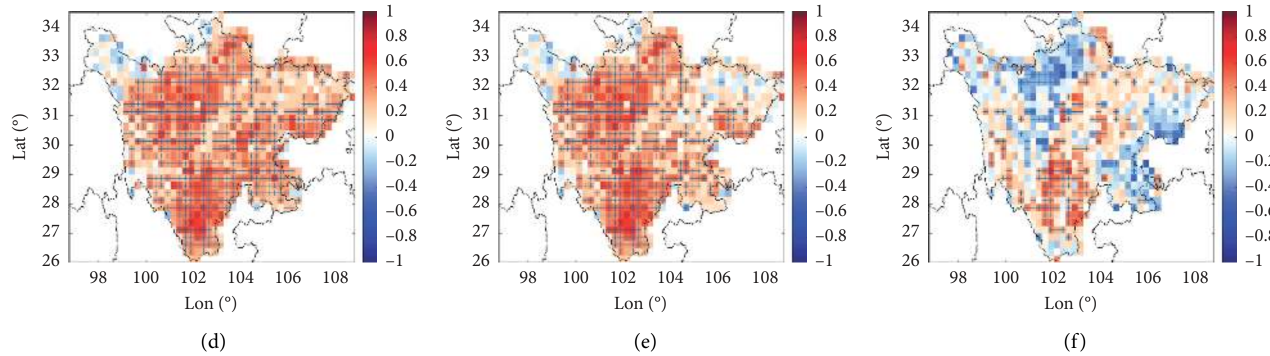

Figure 3: Pearson's correlation coefficients between relative frequency of +CG lightning (unit: %) and (a) CAPE (unit: J kg^{-1}), (b) SP (unit: hPa), (c) THETA (unit: K), (d) SHEAR-5 km (unit: m s^{-1}), (e) SHEAR-3 km (unit: m s^{-1}), and (f) VV-3 km (Pa s^{-1}) during warm season. The correlation coefficient in each grid box was calculated from 78 months of monthly data, and the cross symbol in the grid box indicated that the grid passed the significance test at a 95% confidence level.

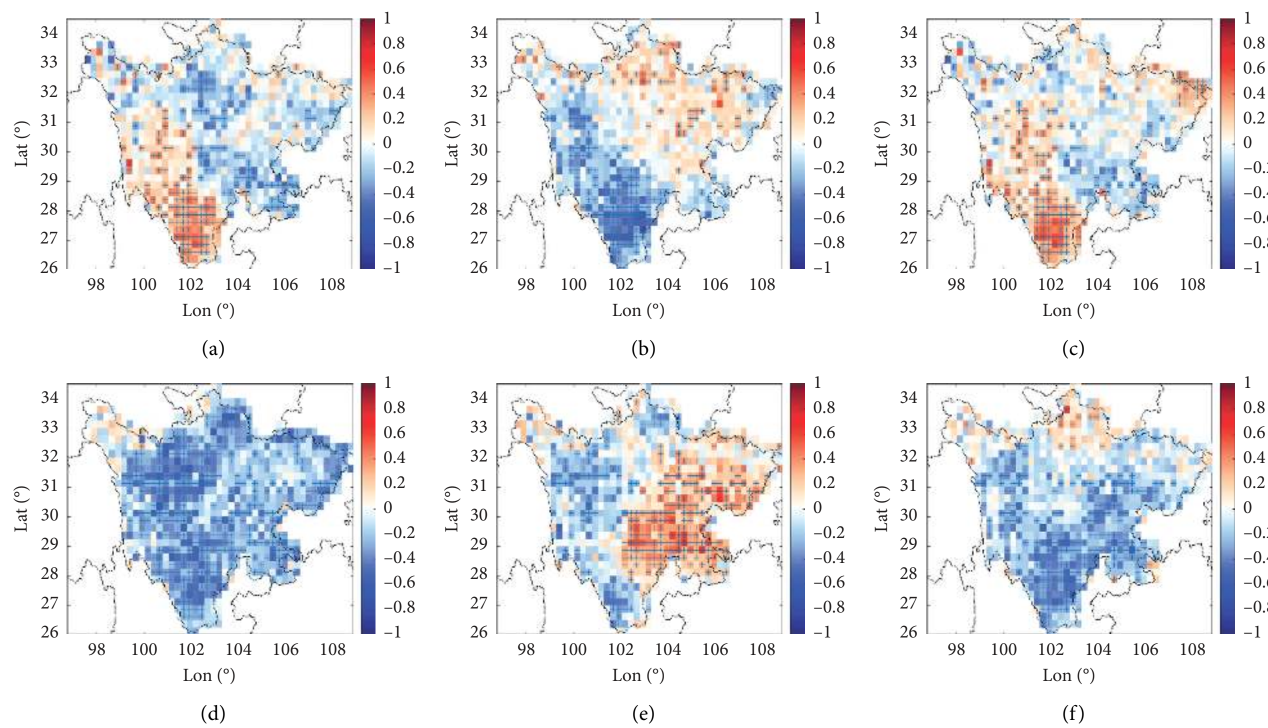

Figure 4: Pearson's correlation coefficients between the relative frequency of +CG lightning (unit: %) and (a) DPD (unit: K), (b) RH (unit: %), (c) CBH (unit: m), (d) ZDH (unit: m), (e) TCLW (unit: kg m^{-2}), and (f) TCIW (unit: kg m^{-2}) during warm season. The correlation coefficient in each grid box was calculated from 78 months of monthly data, and the cross symbol in the grid box indicated that the grid passed the significance test at a 95% confidence level.

moisture factors and the relative frequency of +CG lightning in Sichuan. DPD (Figure 4(a)) and RH (Figure 4(b)) characterized the humidity in the low-to midlevel troposphere, respectively. In southern Sichuan and the plateau region, the humidity in the low-to the midlevel troposphere was negatively correlated with the +CG lightning, which indicated that the dryer low-to the midlevel troposphere is conducive to the +CG lightning [20]. In the plateau region, CBH (Figure 4(c)) showed a significant positive correlation with the relative frequency of +CG lightning in southern Sichuan and the plateau region. CBH has a significant linear correlation with the updraft [46], and a higher CBH means a stronger updraft, which is conducive to transporting liquid water to the mixed-phase zone. Besides, a higher CBH also means a thinner thickness of the warm cloud (below the freezing level), which is not conducive to the occurrence of warm rain process, and the cloud water is more likely to be transported to the zone above the freezing level [6, 47]. In the basin region, the correlation between CBH and the relative frequency of +CG lightning was not significant. The influence of CBH on +CG lightning had an obviously regional difference, and the influence of strong thermodynamics on lightning polarity offset the influence of CBH [21]. In the whole Sichuan, ZDH and TCIW were negatively correlated with the relative frequency of +CG lightning. This may be because a higher ZDH means a thicker warm cloud, which is not conducive to the existence of a large amount of liquid water in the mixed-phase region. A larger TCIW may indicate that the ice-phase process in the cloud is more active than the liquid-phase process. All the above conditions were not conducive to the positive charge carried by graupel particles in the thunderstorm. It is noteworthy that TCLW (Figure 4(e)) was negatively correlated with +CG lightning in the plateau region and positively correlated with +CG lightning in the basin region. In the plateau region, the topography-induced compression effect on the cloud makes both average cloud thickness and warm cloud depth thinner than those in other regions [38]. The topography-induced compression effect means that the high topography of the plateau and tropopause has a certain compression effect on the convective clouds so that the convective clouds in this region are shallower than those in other regions of the same latitude. An increase in TCLW tended to lead to an increase in warm cloud depth rather than an increase in supercooled water content. However, in the basin region, an increase in TCLW may indicate an enhancement in convection and an increase in liquid water content in the mixed-phase zone.

3.3. Lightning Polarity in Environmental Factors Bins. To further analyze the influence of environmental factors on the relative frequency of +CG lightning, all the thermodynamic factors and moisture factors were divided into 5 bins, to discuss the various characteristics of the relative frequency of +CG lightning with the variation in environmental factors. According to the division of the plateau and the basin in Figure 2, we discussed the plateau region and the basin region, respectively. Figure 5 shows the variations of the relative frequency of +CG lightning with the thermodynamic factors in the plateau region. +CG lightning relative frequency showed a quasi-linear decreasing trend with the increase in CAPE and THETA in the plateau region. The relative frequency of +CG lightning decreased first and then increases with the increase of SP. With the increase of SHEAR-5 km and SHEAR-3 km, the relative frequency of +CG lightning showed a significant upward trend. For VV_3 km, weak updraft and downdraft were more conducive to +CG lightning. The weaker convective activities are more favorable to the occurrence of +CG lightning, which is consistent with previous studies [20, 21], suggesting that the excessively strong updraft is conducive to the development of the ice-phase process, but not conducive to the transport of liquid water to the mixed-phase zone of the thunderstorm.

Figure 6 shows the changes in +CG lightning relative frequency with moisture factors in the plateau region. Carey and Buffalo [20] found that the dry low-midlevel troposphere is conducive to the generation of +CG lightning of the thunderstorm. The +CG lightning frequency did not change significantly with the increase of DPD and TCLW in the plateau region. The relative frequency of +CG lightning decreased with the increase of RH; in particular, when the RH increased from 51% to 63%, the decreasing trend of +CG lightning was more significant. When the CBH increased from 560 m to 880 m, the +CG lightning frequency did not change significantly. When the CBH increased from 880 m to 1200 m, the +CG lightning frequency tended to increase. The variation of the relative frequency of +CG lightning with RH and cloud base height suggested that the drier low-troposphere is favorable for +CG lightning, which is consistent with the study of Carey and Buffalo [23]. The changing trend of +CG lightning with ZDH and TCIW was close to each other, both of which decreased obviously at first, and then showed an insignificant change trend. In the plateau region, due to the compression effect of the terrain on the clouds, the mix-phase and electrification regions of convective clouds are thinner than those in the low-altitude region of the same latitude [38]. Therefore, high ZDH and TCIW mean less liquid water content in the mixed-phase region, which is not conducive to graupel particles being positively charged in this region and thus is not conducive to the generation of positive lightning.

Figure 7 shows the variation characteristics of the relative frequency of +CG lightning with the thermodynamic factors in the basin region. The CAPE and THETA of the basin region were larger than those in the plateau region. In the basin region, as in the plateau region, the +CG lightning relative frequency showed a decreasing trend with the increase in CAPE and THETA, but the decreasing trend was less obvious than that in the plateau region, where lightning was more sensitive to CAPE than in other regions [48]. The influence of SP on the relative frequency of +CG lightning was more prominent in the basin region than that in the plateau region, and the +CG lightning increases with the increase in SP, indicating that near-surface convergence, which is beneficial to the development of convection, is not conducive to +CG lightning. In the basin region, the +CG lightning increased monotonously with the increase in SHEAR-5 km and SHEAR-3 km, like the trend of increasing first and then decreasing in the plateau region (Figure 5). In the plateau region, due to topography-induced compression of cloud [38], both the cloud thickness and electrification region in the plateau region should be thinner than those in the basin region, so the responses of liquid water in the mixed-phase region and +CG lighting in the plateau region were more sensitive to dynamic factors than those in the basin region.

Figure 8 shows the changes in the relative frequency of +CG lightning with moisture factors in the basin region. Compared with the plateau region, the relative frequency of +CG lightning showed irregular and insignificant changes with the increase in RH and CBH, which may be due to the influence of strong thermodynamic factors on the relative frequency in the basin region to offset the influence of these moisture factors on the relative frequency of +CG lightning, which is in line with the study of MacGorman et al. [21]. The

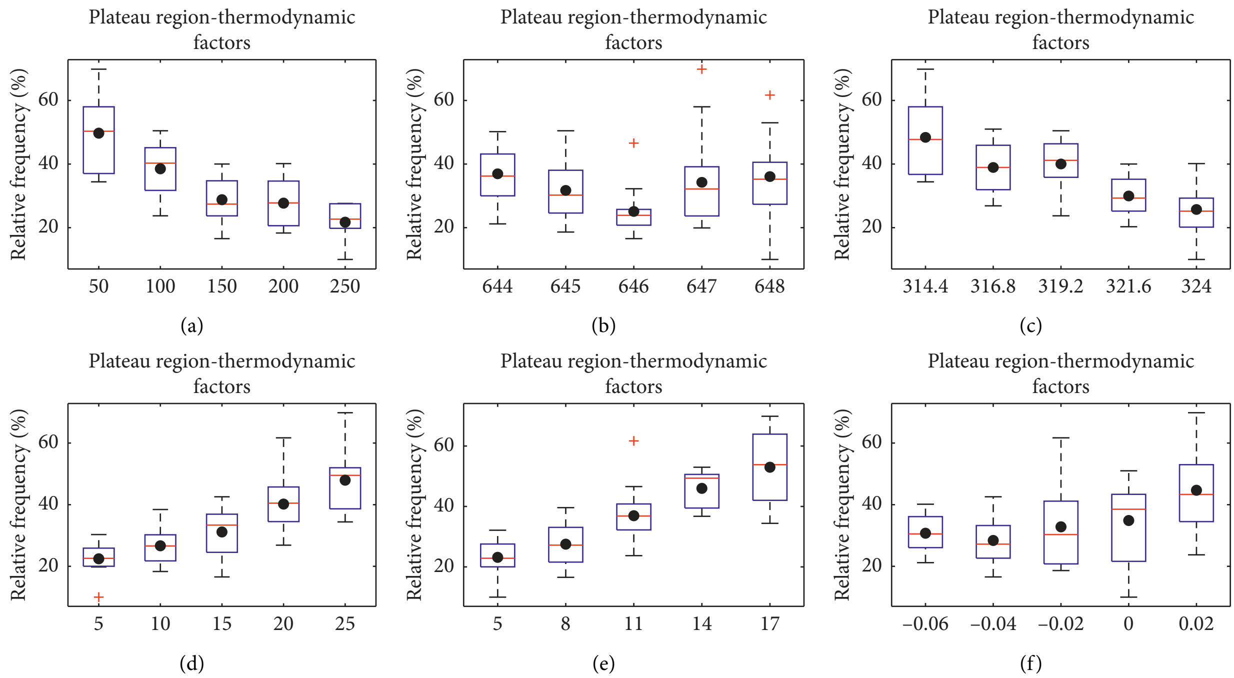

FIGURE 5: Relative frequency (unit: %) of +CG lightning in each bin of (a) CAPE (unit: J kg^{-1}), (b) SP (unit: hPa), (c) THETA (unit: K), (d) SHEAR-5 km (unit: m s^{-1}), (e) SHEAR-3 km (unit: m s^{-1}), and (f) VV-3 km (Pa s^{-1}) in the plateau region.

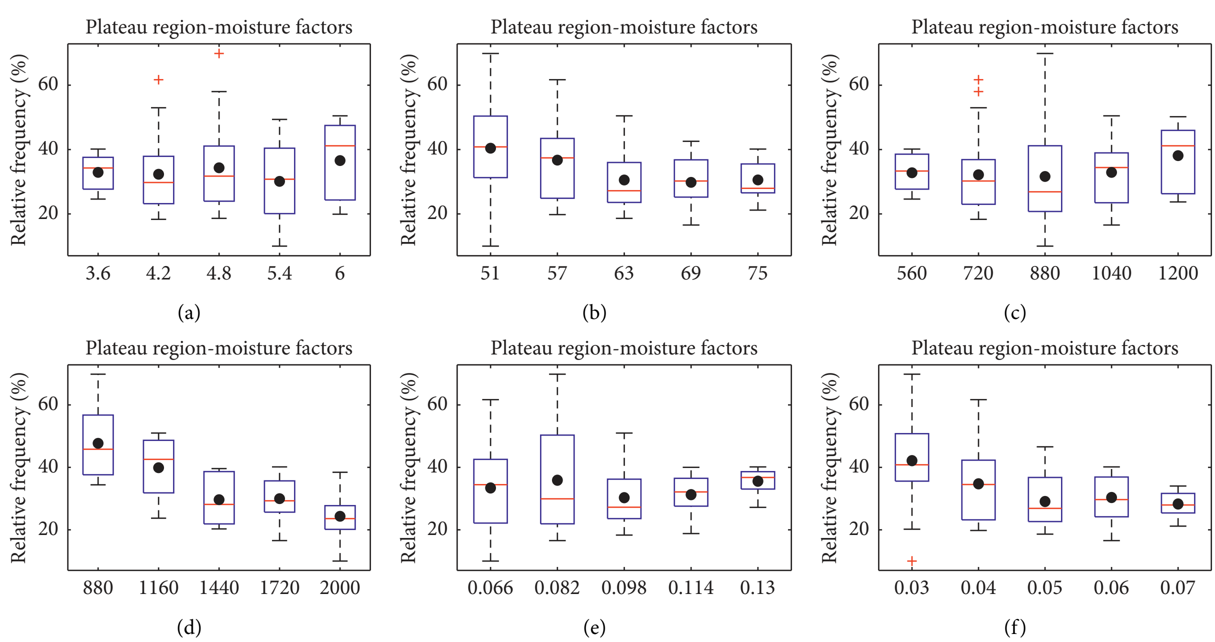

FIGURE 6: Relative frequency (unit: %) of +CG lightning in each bin of (a) DPD (unit: K), (b) RH (unit: %), (c) CBH (unit: m), (d) ZDH (unit: m), (e) TCLW (unit: kg m^{-2}), and (f) TCIW (unit: kg m^{-2}) in the plateau region.

+CG lightning relative frequency showed a steady decreasing trend with the increase in ZDH and TCIW, suggesting that the increase in ZDH in the basin area means the increase in the warm cloud thickness, and the increase in TCIW indicates that the development of the ice-phase process in the cloud is more vigorous than the development of the mixed-phase process, which is not conducive to the formation of +CG lightning [19]. +CG lightning tended to increase stably with the increase in TCLW, suggesting that the increase in TCLW in the basin region may be caused by the increase in cloud water in the warm-phase region and liquid water in the mixed-phase region, which is conducive

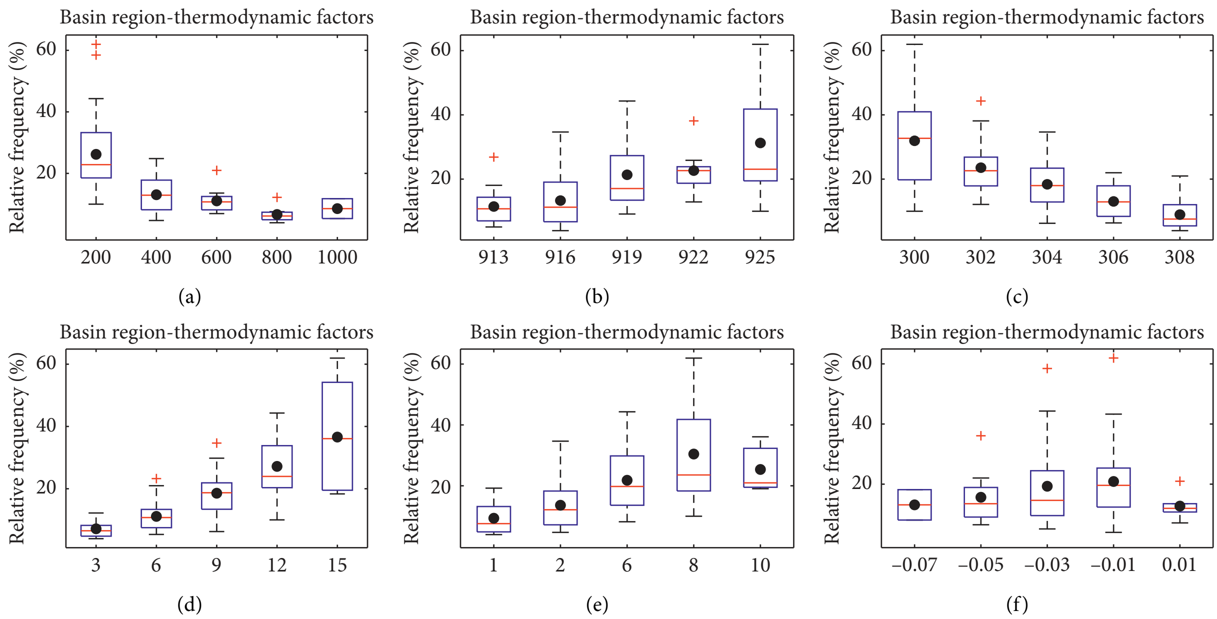

Figure 7: Relative frequency (unit: %) of +CG lightning in each bin of (a) CAPE (unit: J kg^{-1}), (b) SP (unit: hPa), (c) THETA (unit: K), (d) SHEAR-5 km (unit: m s^{-1}), (e) SHEAR-3 km (unit: m s^{-1}), and (f) VV-3 km (Pa s^{-1}) in the basin region.

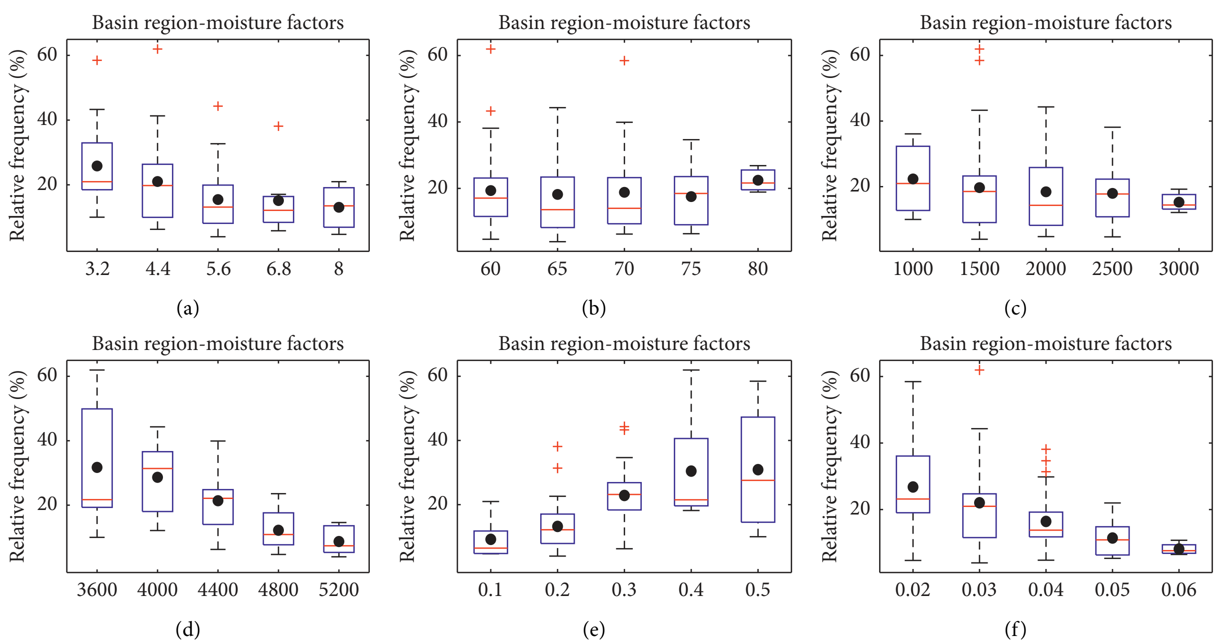

Figure 8: Relative frequency (unit: %) of +CG lightning in each bin of (a) DPD (unit: K), (b) RH (unit: %), (c) CBH (unit: m), (d) ZDH (unit: m), (e) TCLW (unit: kg m^{-2}), and (f) TCIW (unit: kg m^{-2}) in the basin region.

to the formation of inverted charge structure [12, 15, 16, 19, 49].

3.4. Joint Effects of Environmental Factors on the Lightning Polarity. The thermodynamic factors and moisture factors control the intensity and polarity of lightning through the synergistic effect [6, 47, 50]. Figure 9 shows the joint effects of CAPE, SHEAR-5 km, ZDH, TCLW, and TCIW on the relative frequency of +CG lightning in the plateau region. Because a small CAPE indicates a weak convective intensity, the relative frequency of +CG lightning was higher in the case of a small CAPE. The high +CG lightning relative frequencies were mainly concentrated in a range of less than 100 J·kg^{-1} for CAPE. Under the condition of a fixed CAPE, small TCIW and ZDH were conducive to the occurrence of

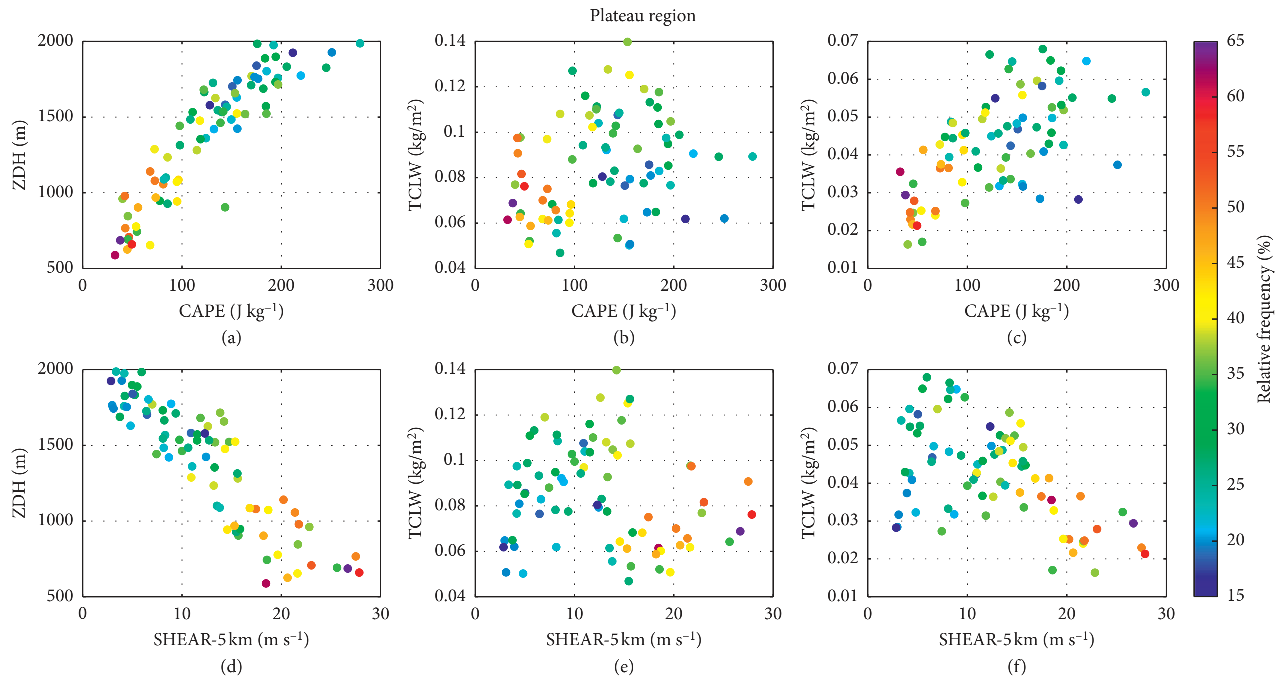

FIGURE 9: Scatter plots of +CG lightning relative frequency between thermodynamic factors (CAPE and SHEAR-5 km) and moisture factors (ZDH, TCLW, and TCIW) in the plateau region.

+CG lightning. When ZDH was less than 1000 m and TCIW was less than 0.04 $kg{\cdot}m^{-2}$, +CG lightning occurred more frequently. The high topography in the plateau region results in significantly greater wind shear in this region than that in the basin region. The increase in vertical wind shear resulted in the decrease in ZDH and TCIW, suggesting that the high vertical wind shear in the plateau region is disadvantageous to the development of ice-phase processes. Strong wind shear condition was accompanied by a relatively high relative frequency of +CG lightning. When SHEAR-5 km was fixed at 20–30 $m{\cdot}s^{-1}$, high relative frequencies of +CG lightning were mainly concentrated in the range of 500–1000 m for ZDH and 0.02–0.04 $kg{\cdot}m^{-2}$ for TCIW.

Figure 10 shows the joint effects of CAPE, SHEAR-5 km, ZDH, TCLW, and TCIW on the relative frequency of +CG lightning in the basin region. In the basin region, the high relative frequency of +CG lightning mainly occurs when CAPE was less than 250 $J{\cdot}kg^{-1}$, and ZDH and TCIW showed an increasing trend with the increase in CAPE. The increase in wind shear in the basin region led to the decrease in ZDH and TCIW and the increase in TCLW, which indicates that the large vertical wind shear is not conducive to the development of the ice-phase process but is conducive to the development of the warm-phase or mixed-phase process. The occurrence of +CG lightning was favored by the larger vertical wind shear, which was mainly concentrated in the range of wind shear of 10–15 $m{\cdot}s^{-1}$. In the case of fixed vertical wind shear, the high relative frequency of +CG lightning was mainly concentrated in the range of 3500–4000 m for ZDH, 0.2–0.4 $kg{\cdot}m^{-2}$ for TCLW, and 0.015–0.04 $kg{\cdot}m^{-2}$ for TCIW. In the basin region, the influence of TCLW on +CG lightning frequency was more prominent than that in the plateau region. The high TCLW in the basin region indicated the high content of supercooled water in the mixed-phase region in the cloud, which was conducive to the positive charge carried by graupel particles and thus to the generation of +CG lightning.

4. Summary and Conclusion

CG lightning relative frequency and ERA5 reanalysis data from 2005 to 2017 were used to discuss the impact of environmental conditions on lightning polarity in Sichuan. Environmental conditions were classified as thermodynamic factors and moisture factors. The thermodynamic factors included CAPE, SP, THETA, SHEAR-5 km, SHEAR-3 km, and VV-3 km. The moisture factors included DPD, RH, CBH, ZDH, TCLW, and TCIW.

The spatial distribution of lightning polarity is significantly distinct over Sichuan. In the plateau region of the western plateau of Sichuan, the relative frequency of +CG lightning is higher, which was 30–50%. In the basin region of eastern Sichuan, the relative frequency of +CG lightning was relatively lower, which was 10–30%. The +CG lightning in Sichuan was mainly concentrated in the cold season, which is consistent with the previous research on other areas [5, 42–44]. To eliminate seasonality interference with the dependence of lightning polarity on environmental factors, we focused on +CG lightning in the warm season, when lightning activity is most frequent and more representative.

We discussed the influence of environmental conditions on lightning polarity based on the hypothesis of previous studies [20, 21, 51]. The hypothesis is that the liquid water content in the mixed-phase region determines the lightning polarity, and the high liquid water content leads to the positive charge carried by graupel particles, which forms a

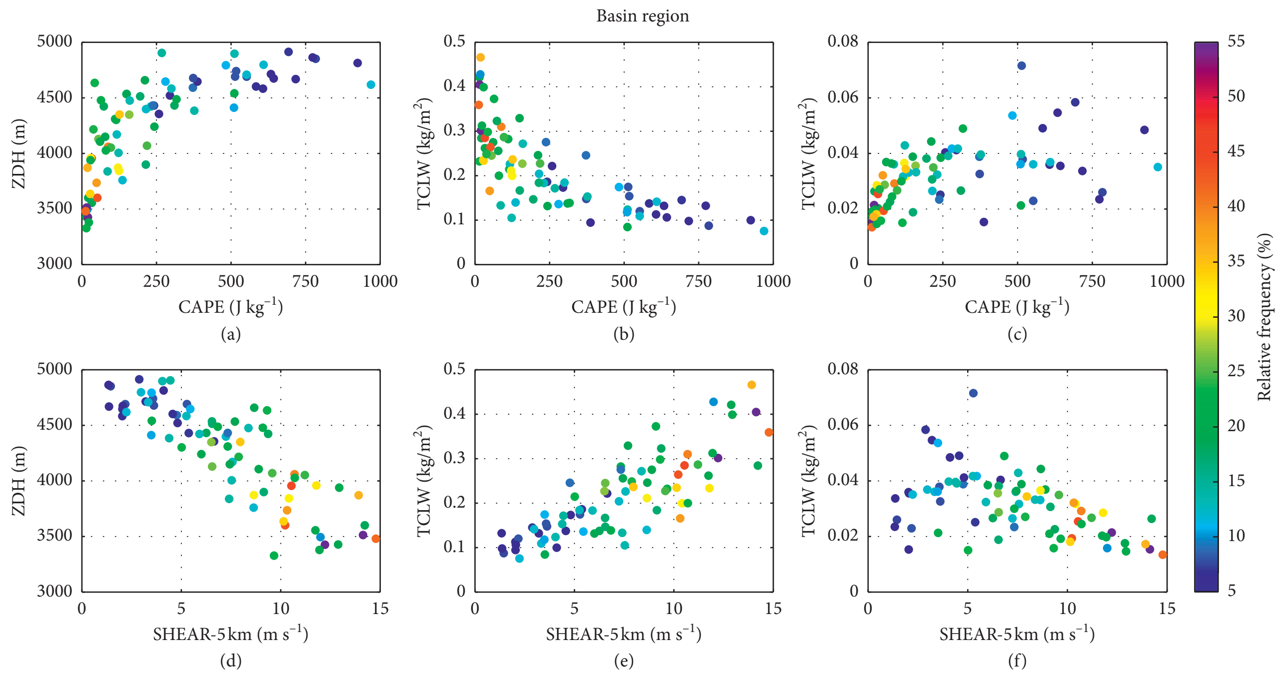

FIGURE 10: Scatter plots of +CG lightning relative frequency between thermodynamic factors (CAPE and SHEAR-5 km) and moisture factors (ZDH, TCLW, and TCIW) in the basin region.

positive charge zone in the lower part of the thunderstorm, which is conducive to the generation of +CG lightning. Another hypothesis for producing +CG lightning is that, in relatively narrow convective clouds, positive lightning is triggered by positive ice crystals in the upper level, which are displaced by wind shear and downdrafts [41]. This means that positive lightning in weaker convection is triggered by positive ice crystals in the upper layers.

In the thermodynamic factors, the lightning polarity is more dependent on CAPE, THETA, SHEAR-3 km, and SHEAR-5 km, while, in the moisture factors, the lightning polarity is more sensitive to ZDH, TCLW, and TCIW. CAPE and THETA were negatively correlated with the +CG lightning relative frequency in Sichuan, which indicated that the relatively shallow convection is favorable to the initiation of positive lightning from the upper-level positive ice crystal. Vertical wind shear was positively correlated with the relative frequency of +CG lightning. Large vertical wind shear results in positive ice crystal displacement in the upper level, which is favorable for positive lightning [41, 45]. In the plateau region, the dry low- to midlevel troposphere and high CBH were conducive to +CG lightning. In the basin region, these moisture factors are not significantly correlated with +CG lightning, especially for DPD, RH, and CBH, which may be offset by the strong thermodynamic factors [21]. ZDH and TCIW had a significant negative correlation with +CG lightning in Sichuan, suggesting that the ice-phase process in the cloud is more vigorous than the warm-phase process or the mixed-phase process, which is not conducive to the existence of liquid water in the mixed-phase region and thus is not conducive to the middle-level positive graupel to initiate positive lightning [20, 21]. TCLW was negatively and positively correlated with +CG lightning in the plateau region and the basin region, respectively. This suggests that the cloud thickness in the plateau region is relatively thin due to topographic compression [38], and high TCLW may be related to the cloud water content in the warm cloud rather than the liquid water in the mixed-phase region, while high TCLW in the basin region means high liquid water content in both the mixed-phase region and warm-phase region.

Many environmental factors affected the lightning polarity by affecting the intensity of convection and the liquid water content in the mixed-phase region, and the factors also have synergistic effects. In the plateau region, the +CG lightning relative frequency was high under the conditions of high vertical wind shear and low ZDH, CAPE, and TCIW. In the basin area, the +CG lightning relative frequency was high under the conditions of high vertical wind shear and TCLW and low CAPE, ZDH, and TCIW. To further reveal the dependence of positive lightning on environmental factors, more radiosonde observations and simulation studies are necessary in the future.

Data Availability

The data are available by contacting the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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