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Lightning Stroke Strength and Its Correlation with Cloud Macro- and Microphysics over the Tibetan Plateau

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Abstract: Lightning stroke strength, characterized by energy and peak currents, over the Tibetan Plateau (TP), is investigated by utilizing datasets from the World Wide Lightning Location Network and the Chinese Cloud-to-Ground Lightning Location System during 2016–2019. Focused on the south-central (SC) and southeast (SE) of the TP, it reveals that SE-TP experiences strokes with larger average energy and peak currents. Strong strokes (energy ≥ 100 kJ or peak currents $\geq |100|$ kA), exhibiting bimodal distribution in winter and summer, are more frequent and have larger average values over the SE-TP than the SC-TP, with diurnal distribution indicating peaks in energy and positive strokes in the middle of the night and negative strokes peaking in the morning. Utilizing the ECMWF/ERA-5 and MERRA-2 reanalysis, we find that stronger strokes correlate with thinner charge zone depths and larger CIWCFs but stable warm cloud depths and zero-degree levels over the SC-TP. Over the SE-TP, stronger strokes are associated with smaller CIWCFs and show turning points for warm cloud depths and zero-degree levels. Thicker charge zone depths correlate with stronger negative strokes but weaker positive strokes. Generating strokes of similar strength over the SC-TP requires larger CIWCFs, thinner warm cloud depths, and lower zero-degree levels than over the SE-TP.



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Keywords: stroke strength; cloud microphysics; cloud macrophysics; Tibetan Plateau; the World Wide Lightning Location Network; the Chinese Cloud-to-Ground Lightning Location System

1. Introduction

Lightning discharges represent highly powerful sources of electromagnetic energy covering a broad bandwidth [1,2], with a predominant concentration in the very-low-frequency (VLF) band, specifically below 30 kHz, and they generate high currents. Thus, their strength is generally characterized by the values of either energy or peak currents from ground-based lightning detection systems.

Strong lightning strokes, characterized by their large energy (e.g., $>10^3$ kJ for superbolts) or peak currents (e.g., >75 kA or >100 kA) [3–5], were commonly believed to be associated with discharge events initiating in the upper atmosphere, like elves, sprites, halos, and terrestrial gamma-ray flashes [6–12]. This highlights the potential impact of strong lightning strokes on aerospace, communication, etc., which are associated with the electromagnetic environment in the upper atmosphere. Therefore, studying the distribution of lightning stroke strength can advance our knowledge of upper atmospheric discharges, enabling the examination and mitigation of the potential hazards associated with them.

Lightning stroke strength exhibits significant spatiotemporal variations. In contrast to the finding that lightning occurs more frequently over land than over oceans [13], the overall energy of lightning over land is weaker than that over oceans [14]. The distribution of sprites, which are associated with large lightning stroke energy, also occurred more

frequently over oceans than over land [15]. Based on the World Wide Lightning Location Network (WWLLN) detection, superbolts (with lightning energies exceeding 10^6 J) mainly occurred over extratropical waters [16]. A higher proportion of strong lightning energy (>90% percentile of total energy) in lightning was observed in the northern waters of Japan (>30% in its current region) than in its eastern region, where the Kuroshio Current is located [17]. Regional differences in lightning strength are also evident over land. The return-stroke peak current in the eastern United States increases with decreasing latitude, suggesting larger peak currents occur closer to the equatorial region [18]. Observations from the U.S. National Lightning Detection Network indicated that large peak currents in negative cloud-to-ground (CG) lightning are concentrated over the coastal waters of the Gulf of Mexico and the southeastern United States, while those in positive CG lightning predominantly occur in the central United States, with a much higher proportion (30%) compared to other regions in the United States (4.5%) [19]. Zheng et al. [20] found that in Guangdong Province and its adjacent waters, the density of large peak current positive CG lightning near the coastline is higher than inland during the rainy season, while its distribution is reversed during the nonrainy season. There is no significant difference in the distribution of large peak current negative lightning between rainy and nonrainy seasons. Wang et al. [21] revealed the characteristics of large peak current CG lightning flashes in China's most populous areas and determined that the number of large peak current negative CG flashes with peak currents within 100–200 kA in southwest China is evidently greater than that within the lower peak current range, which is different from other regions of China. Furthermore, they found that the peak current distribution of large peak current positive CG flashes in most of China's mainland was distinct from those shown in other regions of the world. This is confirmed by Xu et al. [22]; in their study, they found the CG stroke peak current values in China are larger than those in America and Europe.

The Tibetan Plateau (TP) is the highest plateau in the world, with an average elevation of over 4 km above sea level. Lightning activities over the TP primarily occur during the summer [23–25]. Qi et al. [26] indicated that lightning activities concentrate over the eastern TP in the pre-monsoon, extend across the entire TP during the monsoon, and retreat eastward as the monsoon weakens. Compared to surrounding regions, the TP experiences fewer lightning activities, with shorter lightning length and weaker lightning optical radiation energy [27–31]. In contrast to the distribution of lightning activities and optical radiation energy, there is a higher occurrence ratio of lightning strokes with large energy over the TP than in other regions in China (as depicted in Figure 1 of Holzworth et al. [16]). Additionally, elves, sprites, and halos were observed over the TP, with the elves' parent strokes displaying higher average energy than those observed over the eastern plains [32], which seems to indicate a negative correlation between lightning energy and frequency [33,34]. However, the distribution of lightning strength over the TP has not been systematically investigated. Understanding the distribution of lightning strength is critical to better describe the lightning characteristics over the TP and may have implications for lightning protection.

Cloud microphysics, such as ice particle concentration, liquid water content, etc., was found to have indicative effects on lightning physical characteristics, such as lightning rate and strength [35–39]. Ice particles contribute to electricity in the mixed-phase region of clouds. The relationship between cloud ice fraction and lightning rate was found by Han et al. [40] on a global scale related to cloud type. In liquid clouds, lightning rate increases with the increase in cloud ice fraction and decreases in ice clouds. Supercooled water content increased by strong updrafts leads to an increasing lightning rate [41]. Lightning activity is also influenced by cloud macrophysics, such as cloud base height [42] and warm cloud depth [43,44]. The factors influencing the strength of lightning strokes, particularly those contributing to strong strokes, remain a subject of ongoing research. Kamra [45] proposed that weaker lightning tends to occur in conditions of higher air conductivity, achieved by reducing breakdown voltage through increased precipitation intensity, liquid water content, electric field, and particle charge. Zheng et al. [20] found that high current

CG flashes are more likely in thunderstorms with relatively weaker convection and larger precipitation areas in southern China. Laboratory studies on superbolts led Asfur et al. [46] to suggest that their lightning stroke strength increases with soil salinity. However, this explanation does not adequately explain the similar occurrence frequencies observed over the Mediterranean and North Sea. Yair et al. [47] and Pizzuti et al. [48] proposed that aerosols play a role in promoting convective activation and enhancing cloud electrification, explaining the high frequency of superbolts in the Mediterranean region and parts of Europe. However, Efraim et al. [49] suggested that aerosols have no significant effect on lightning strength. Instead, they highlighted a primary correlation with the zero-degree level. These studies collectively indicate that the factors affecting lightning strength exhibit regional variations.

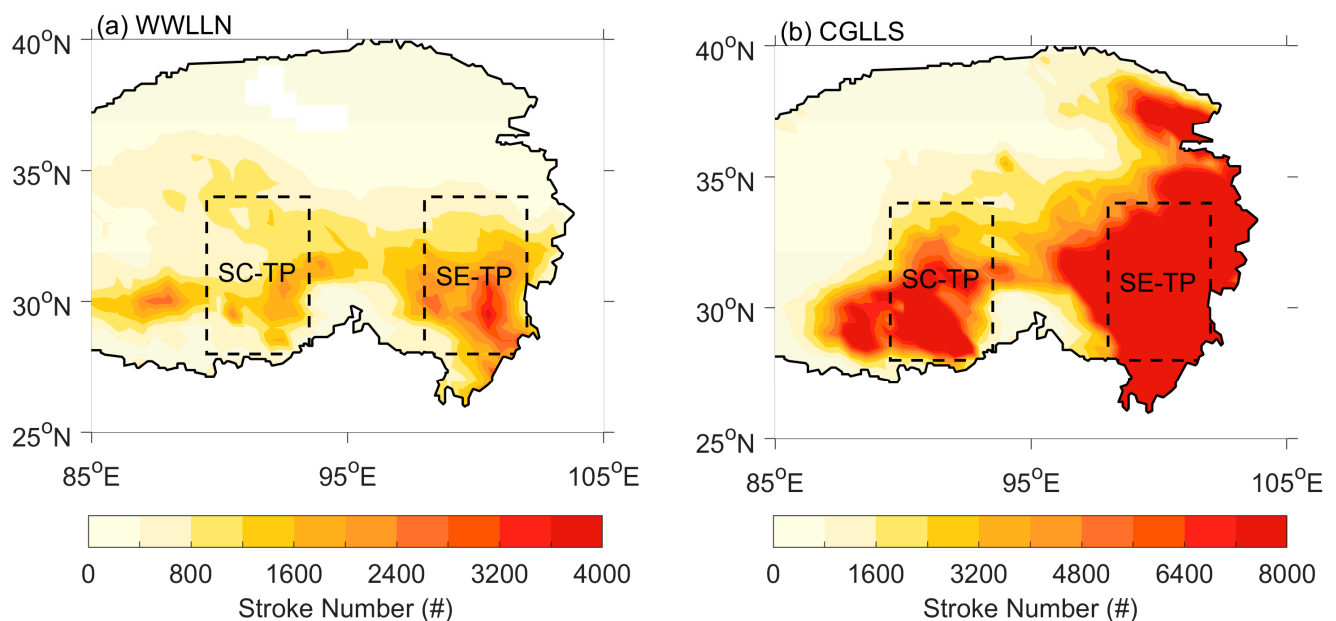


Figure 1. The spatial distribution of stroke numbers detected by (a) the World Wide Lightning Location Network (WWLLN) and (b) the Chinese Cloud-to-Ground Lightning Location System (CGLLS) during 2016–2019. The stroke numbers are the total strokes within $0.5^\circ \times 0.5^\circ$ grid cell. The two dotted rectangles represent the regions of interest for south-central (SC-TP) and southeast (SE-TP) of the Tibetan Plateau (TP). The black solid line delineates the 3 km contour of the TP.

Based on four-year concurrent detections (2016–2019) from two lightning location systems, the WWLLN and the Chinese Cloud-to-Ground Lightning Location System (CGLLS), this study investigates the distribution of lightning stroke strength (indicated by energy and peak currents) over the TP. Given that frequent lightning activities are concentrated over the central and southern regions of the TP, this study focuses specifically on the south-central and southeast regions of the TP. This is the first systematic investigation into the strength of lightning strokes over the TP, containing the distribution of both lightning stroke strength and strong lightning strokes. It could be used to evaluate the distribution of discharge phenomena in the middle and upper atmosphere over the TP [10]. Electrification in clouds occurs during the collision process of ice crystals and graupel particles in the mixed-phased zone, which indicates the great impact of clouds on lightning. Therefore, this research integrates cloud macrophysics (e.g., the charge zone depth, warm cloud depth, and zero-degree level) and microphysics (e.g., the cloud water content) obtained from the reanalysis data of ERA5 and MERRA-2 to examine their impact on the strength of lightning strokes over the study regions by following the method of Efraim et al. [49]. The results could help to improve the prediction of lightning properties by establishing the relationship between lightning strength and cloud parameters.

2. Materials and Methods

This study utilizes data on lightning strokes concurrently detected by the ground-based WWLLN and the Chinese Cloud-to-Ground Lightning Location System (CGLLS) from 2016 to 2019 to investigate the distribution of energy and peak currents over the TP. Meteorological and thunderstorm properties analyzed in this study are sourced from the fifth-generation reanalysis of the European Center for Medium-Range Weather Forecasts (ECMWF-ERA5) and Modern-Era Retrospective Analysis for Research and Applications, Version 2 (MERRA-2). Further details are provided in the following sections.

2.1. WWLLN

The WWLLN monitors very-low-frequency (VLF, 3–30 kHz) radio waves (sferics) emitted from lightning strokes and has employed the time-of-group arrival technique to locate lightning strokes since 2004 [50]. VLF propagates with low attenuation in the atmosphere, allowing for the detection of VLF signals spanning thousands of kilometers from the source. It utilizes the radiation energy in the VLF range to locate the information of lightning strokes and record the electric field waveform in uncalibrated sound card units (SCUs), which can be converted to volts per meter over the triggering window of 1.33 ms to calculate the radiated energy of each detected stroke [51–53].

Compared to regional/local lightning detection systems, such as the Los Alamos Sferic Array (LASA) [54], New Zealand Lightning Detection Network (NZLDN) [55], and Beijing Lightning Network (BLNET) [56], the detection efficiency (DE) of the WWLLN is relatively low and exhibits uneven spatial distribution [52]. It is well-established that the DE for strong lightning strokes is higher than for weaker ones, and the WWLLN cannot differentiate the lightning types (intracloud/cloud-to-ground lightning, IC/CG lightning) and polarity. The average location accuracy of the WWLLN over the TP was ~10 km [57]. Over the midsouthern TP, the DE for CG and total flash were, respectively, 9.37% and 2.58% during 2013–2015 and continuously increased after 2015 [57,58]. Fan et al. [57] also found that the CG flash data made up 71.98% of all the WWLLN flash data. In addition, Ma et al. [58] showed that the DE of the WWLLN over the TP is generally even. Therefore, the DE and the CG percentages over the TP are similar to those over the midsouthern TP. The lightning strokes between two regions over the TP in this study can be reliably compared, and the CG lightning data from the Chinese CGLLS will be used simultaneously.

This study uses time, location, and energy parameters from the WWLLN data collected between 2016 and 2019. Datasets meeting the following conditions are considered to ensure data accuracy [16]:

- (1) The value of energy is larger than 0;
- (2) The number of participating WWLLN stations in the location fit is at least seven;
- (3) The energy uncertainty is less than 50% of the energy.

2.2. The Chinese CGLLS

Due to a limitation in the WWLLN datasets, this study incorporates CG lightning information on peak currents and polarity from the Chinese CGLLS. The energy and the peak current of lightning both reflect the characteristics of lightning strength. In Hutchins et al. [53], the power of lightning stroke is expressed exponentially by peak current, and the energy is calculated by power multiples current triggering window time set at 1.33 ms. Therefore, the energy is the cumulative power of currents over a period of time.

The Chinese CGLLS uses both magnetic detection and time-of-arrival (TOA) location methods to locate the lightning strokes by monitoring 100–500 MHz radio waves from lightning strokes. The dataset contains information on detected lightning strokes, such as the precise time, latitude, longitude, peak current, return stroke number, and lightning polarity. The peak current is retrieved by the voltage signal measured by the detection station and the distance between the return point and the station [59]. The relative deviation of the peak return current is between 0.4% and 42%, and the arithmetic mean and median of the relative deviation are 16.3% and 19.1%, respectively [60]. The peak current of

lightning strokes serves as an indicator of the strength of positive and negative lightning strokes. Concurrent with the time frame of the WWLLN dataset used in this study (4 years, 2016–2019), the Chinese CGLLS datasets were examined to conduct a comprehensive analysis of lightning stroke strength.

To avoid the potential misinterpretation of intracloud lightning flashes with a positive peak current lower than 10 kA [57,58,61], strokes with a positive peak current lower than 10 kA were excluded. To reduce the impact of detection errors, only stroke information detected by at least four stations was considered. The stations are predominantly concentrated east of 85°E, and our study focuses on this region of the TP (85–102°E, 25–40°N).

2.3. Reanalysis Data

To investigate the characteristics of thunderclouds, four parameters from the ECMWF-ERA5 reanalysis were used in this study: the cloud base height, zero-degree level, specific cloud ice water content, and specific cloud liquid water content. The cloud base height is the height of the base of the lowest cloud layer above the ground surface. The zero-degree level is the height where the air temperature reaches 0 °C and marks the point where cloud liquid water begins to freeze. The specific cloud ice water content represents the average mass of cloud ice particles per kilogram of the total mass of moist air (including dry air, water vapor, cloud liquid, cloud ice, rain, and falling snow) within a grid with a resolution of $0.25^\circ \times 0.25^\circ$. Similarly, the specific cloud liquid water content is analogous to the specific cloud ice water content but pertains to cloud liquid water droplets. The ERA5 reanalysis data had a horizontal resolution of 0.25° , with hourly fields on 137 vertical levels. For detailed information, refer to the ECMWF website (<https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=overview>, accessed on 20 December 2023).

As cloud electrification occurs in the charging zone (above the zero-degree level), and there is an obvious negative correlation between stroke energy and the distance from the charging zone to the surface [49], the characteristics of this zone may affect charge and discharge processes. Charge zone depth is defined as the depth of the zone of lightning generation, representing the vertical distance between the cloud top and the zero-degree level (or the cloud base height, when the cloud base height is higher than the zero-degree level). The cloud top height is calculated by the cloud top temperature from the MERRA-2 reanalysis data. The MERRA-2 contains atmospheric components, meteorology characteristics, aerosols, and atmospheric chemical constituents. The data are presented at a spatial resolution of 0.5° latitude $\times$ 0.625° longitude $\times$ 72 vertical levels, with a temporal resolution of 1 h for the meteorological data [62]. The warm cloud depth has a great impact on the development and temporal evolution of deep convective clouds and lightning [44,63–66] and is defined as the vertical distance between the zero-degree level and the cloud base. We interpolated the spatial resolution of the MEERA-2 data into $0.25^\circ \times 0.25^\circ$.

To connect the parameters from the reanalysis data with the lightning data, in this paper, we found the nearest grid in distance and time to the lightning strokes. Specifically, from the ERA5 and MERRA-2 reanalysis data, we looked for the grids that lightning strokes located within $\pm 0.125^\circ$ of their latitude and longitude. The time resolutions of the reanalysis data are one hour, and the times of the grids we matched with the lightning records are the hours before the lightning records.

3. Results

3.1. The Distribution of Stroke Number and Strength over the Study Regions

The spatial distribution of stroke numbers detected by the WWLLN and the Chinese CGLLS is shown in Figure 1. Most strokes are concentrated over the central and southern regions of the TP, particularly in the southeast. Recognizing the detection efficiency of the WWLLN and the Chinese CGLLS, the two regions of interest on the TP were identified: south-central (SC-TP, 28–34°N, 89.5–93.5°E) and southeast (SE-TP, 28–34°N, 98–102°E). These regions were chosen to investigate the characteristics of lightning strength with

energy and peak currents. From 2016 to 2019, the WWLLN-detected average stroke density is 0.08 and 0.14 strokes/ km^2 /year over the SC-TP and SE-TP, respectively. Additionally, the Chinese CGLLS recorded average CG stroke density of 0.49 and 1.68 strokes/ km^2 /year over the SC-TP and SE-TP, respectively. The results indicate a higher number of strokes detected over the SE-TP compared to the SC-TP from both lightning detection systems, which is consistent with the yearly distribution of stroke numbers during 2016–2019 (Figure S1). Over the SE-TP, the stroke numbers increase from one year to another during the research period (Figure S1). Over the SC-TP, the stroke number decreases from 2016 to 2017 and increases from 2017 to 2019 (Figure S1), which agrees with the yearly variation in Ma et al. [58]. It is shown in Hutchins et al. [52] that the detection efficiency of the WWLLN over the SE-TP and SC-TP shows little difference. The minimum detectable peak currents for the Chinese CGLLS over these two regions are the same, relating to negligible differences in the detection efficiency between the two regions. The terrain's effect may, in part, contribute to the difference in the stroke numbers over the two regions of interest. The altitude of SE-TP is lower than that of SC-TP, which may cause a higher lightning rate [67]. Discrepancies in stroke numbers between the two lightning detection systems may, in part, be attributed to their different detection efficiencies [57]. The percentage of strokes detected by the WWLLN matched with those detected by the CGLLS is about 7.78% in the two regions of interest, similar to 7.30% over the midsouthern area of the Tibetan Plateau during 2013–2015 in Fan et al. [57].

Moreover, the monthly and diurnal distribution of stroke numbers detected by the WWLLN and the Chinese CGLLS over the regions of interest is shown in Figure 2. Both datasets display that most of the strokes over the regions of interest occur from June to September, although their months of maximum value slightly differ (Figure 2a). The WWLLN detects the monthly maximum value in September (September), while the Chinese CGLLS identifies it in June (July) over the SE-TP (SC-TP). This suggests a prevalence of large numbers of strong strokes over the two regions of interest in September and large numbers of CG lightning strokes over the SE-TP (SC-TP) in June (July). The diurnal distribution from both datasets exhibits consistency (Figure 2b), i.e., both datasets show large values at 1600–1900 BJT (Beijing Time) over the regions of interest, peaking at 1800 BJT and 1900 BJT, respectively.

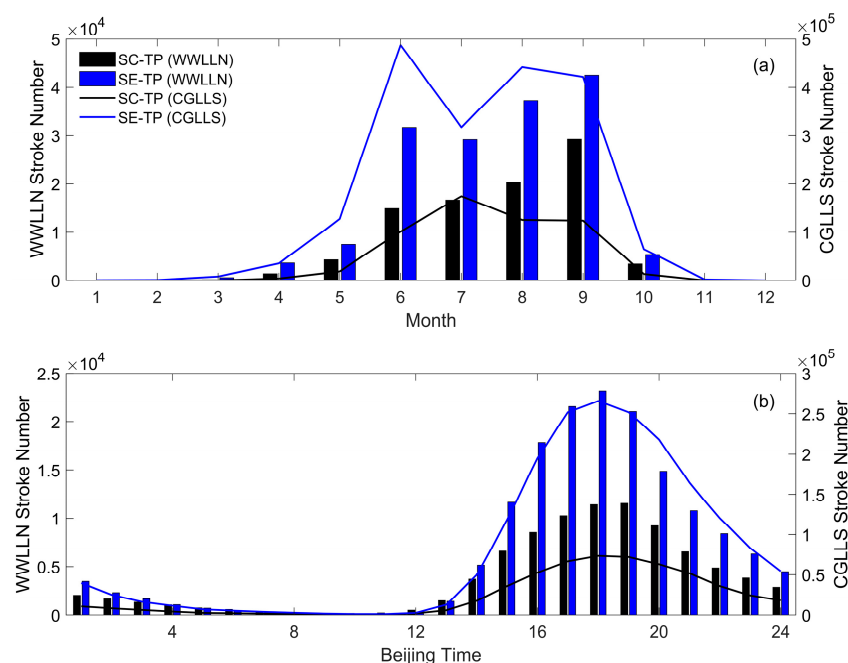


Figure 2. The (a) monthly and (b) diurnal (in Beijing time) distribution of stroke numbers detected by the WWLLN (in histograms) and the Chinese CGLLS (in line charts) over the two regions of interest.

Figure 3 displays the probability distribution functions (PDF) of stroke energy and peak currents over the two regions of interest. The lightning energy over the regions of interest ranges from 0.03 kJ to 817.2 kJ (Figure 3a). In the energy range of 7.4 kJ to 35.7 kJ, the values of stroke PDFs over the SC-TP exceed those over the SE-TP, while for energy levels surpassing 35.7 kJ, the reverse is observed. On average, the lightning energy over the SC-TP is 9.4 kJ, and over the SE-TP is 10.2 kJ. The Kullback-Leibler divergence (KL divergence) estimates the differences in energy/peak current probability distribution between the two regions of interest. The KL divergence of lightning energy is ~ 0.015 , while the maximum PDF is ~ 0.064 , indicating a significant difference in lightning energy probability between the two regions of interest.

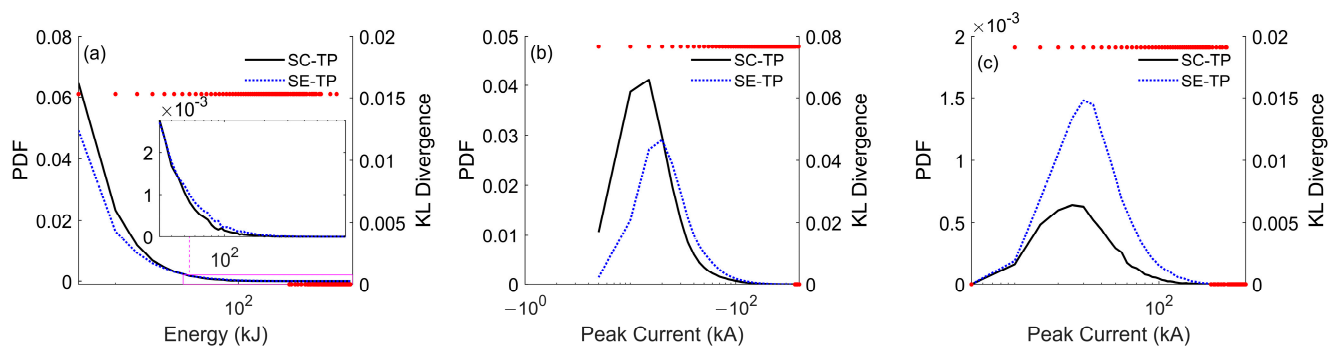


Figure 3. The probability distribution functions (PDF, left y-axis) of stroke (a) energy (in every 5 kJ), (b) negative peak current (in every 5 kA), and (c) positive peak current (in every 5 kA) over the two regions of interest. The Kullback-Leibler divergence (KL divergence) between the two regions of interest is depicted on the right y-axis as red dots. There aren't any red lines but red dots. The PDFs over the SC-TP are shown by solid black lines, and those over the SE-TP are shown by dotted blue lines. The probability distribution of stroke energy larger than 35 kJ is zoomed in subgraph in (a).

In Figure 3b,c, the distribution of peak currents appears to be lognormal [68], and there is a higher PDF of negative CG strokes (Figure 3b) compared to positive ones (Figure 3c) over both regions of interest. Over the SC-TP, the maximum PDFs for negative CG and positive CG strokes occur at -15 kA and 25 kA, respectively. Those over the SE-TP are -20 kA and 30 kA. Notably, the maximum PDFs at peak current values over the SC-TP are 15 kA lower than those over the SE-TP. This indicates that the peak current distribution over the SC-TP, for both positive CG and negative CG strokes, is generally smaller than that over the SE-TP. The peak currents from the Chinese CGLLS are estimated without considering the terrain effect, which may result in the overestimation of peak currents over the two regions of interest [69,70]. For the higher altitude of the SC-TP, the peak currents of lightning strokes over the SC-TP may be more overestimated than those over the SE-TP. There will be little influence on the comparison. Moreover, the PDFs of negative CG strokes over the SE-TP are larger than those over the SC-TP when the peak currents of strokes are larger than 20.5 kA, while the percentage of positive CG strokes over the SE-TP is larger than that over the SC-TP. The KL divergences of negative and positive strokes are 0.077 and 0.019 , respectively, while their maximum PDFs are 0.041 and 0.001 . Therefore, the peak current of CG strokes over the SE-TP is larger than that over the SC-TP, aligning well with the findings in energy distribution.

3.2. Strong Lightning Strokes over the Study Regions

The CG lightning with large peak currents mentioned in previous studies are those > 175 kA or 100 kA [7,10,71–73], and the average energy associated with elves over the southeastern TP is about 97 kJ [32]. Referring to these studies, this research focuses specifically on lightning strokes with energy ≥ 100 kJ and peak currents ≥ 100 kA to investigate the distribution of strong strokes over the two regions of interest (Figure 4a,b). Noted herein, according to the equations delineated in Hutchins et al. [53] for the relation-

ship between energy, power, and peak currents, strokes with peak currents of ≥ 100 kA generally exhibit stronger than those with an energy of 100 kJ. To account for the impact of uneven lightning stroke numbers, the percentage distribution of strokes within the energy and peak current value range is normalized by the total stroke number in each grid ($0.5^\circ \times 0.5^\circ$).

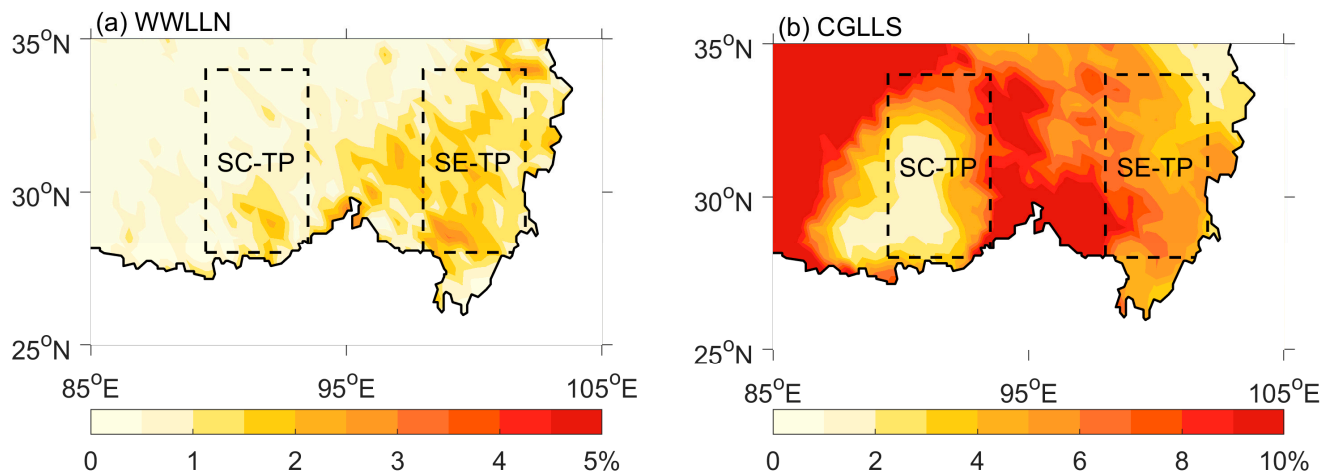


Figure 4. The spatial distribution of the stroke percentage for (a) energy (≥ 100 kJ) and (b) peak currents (≥ 100 kA). The two dotted rectangles represent the two regions of interest. The black solid lines show the 3 km contour of the TP.

As shown in Figure 4a, the percentage of large energy strokes over the SE-TP ranges from 0.26% to 3.06%, while that over the SC-TP varies from 0.08% to 2.20%. The mean percentages are 0.57% and 1.32% over the SC-TP and the SE-TP, respectively. Notably, there is a higher probability distribution of strong stroke energy (≥ 100 kJ) over the SE-TP compared to the SC-TP. Meanwhile, the median percentage of large peak current strokes over the SE-TP (5.31%) is larger than that over the SC-TP (4.03%) (Figure 4b), aligning well with the distribution of large energy strokes. Given the higher frequency of observed elves over the SE-TP [32], the distribution of high energy and peak currents over the two regions of interest correlates well with these findings.

The monthly and diurnal distribution of strong strokes (energy ≥ 100 kJ and peak currents ≥ 100 kA), along with their average values, is shown in Figure 5. The strong stroke number for each month (hour) is normalized by the total monthly (hourly) stroke number, presented as a percentage. In Figure 5a, it is evident that there are two peaks exhibited over the regions of interest. The majority of strong strokes are concentrated in the summer season; specifically, they are present in June and July over the SC-TP ($\sim 1.5\%$, ~ 161 kJ) and June to August over the SE-TP (~ 1.5 – 2.5% , ~ 174 kJ), which is in line with prior research findings (e.g., [23,74,75]). Notably, high percentages of strong strokes and average energy values are observed in February ($\sim 4.9\%$, with an average energy of ~ 182 kJ) and March ($\sim 0.7\%$, with an average energy of ~ 202 kJ) over the SE-TP, with their average energy values even larger than those recorded in summer. Due to the limited occurrence of lightning activities during winter over the TP [23,24] and considering that the WWLLN has higher detection efficiency for lightning strokes with high energy, the energy of lightning strokes detected in winter over the TP results in a high percentage and large average energy values of strong strokes in winter. The monthly distribution of strong strokes is consistent with and corroborates the elves' distribution presented in Xu et al. [32].

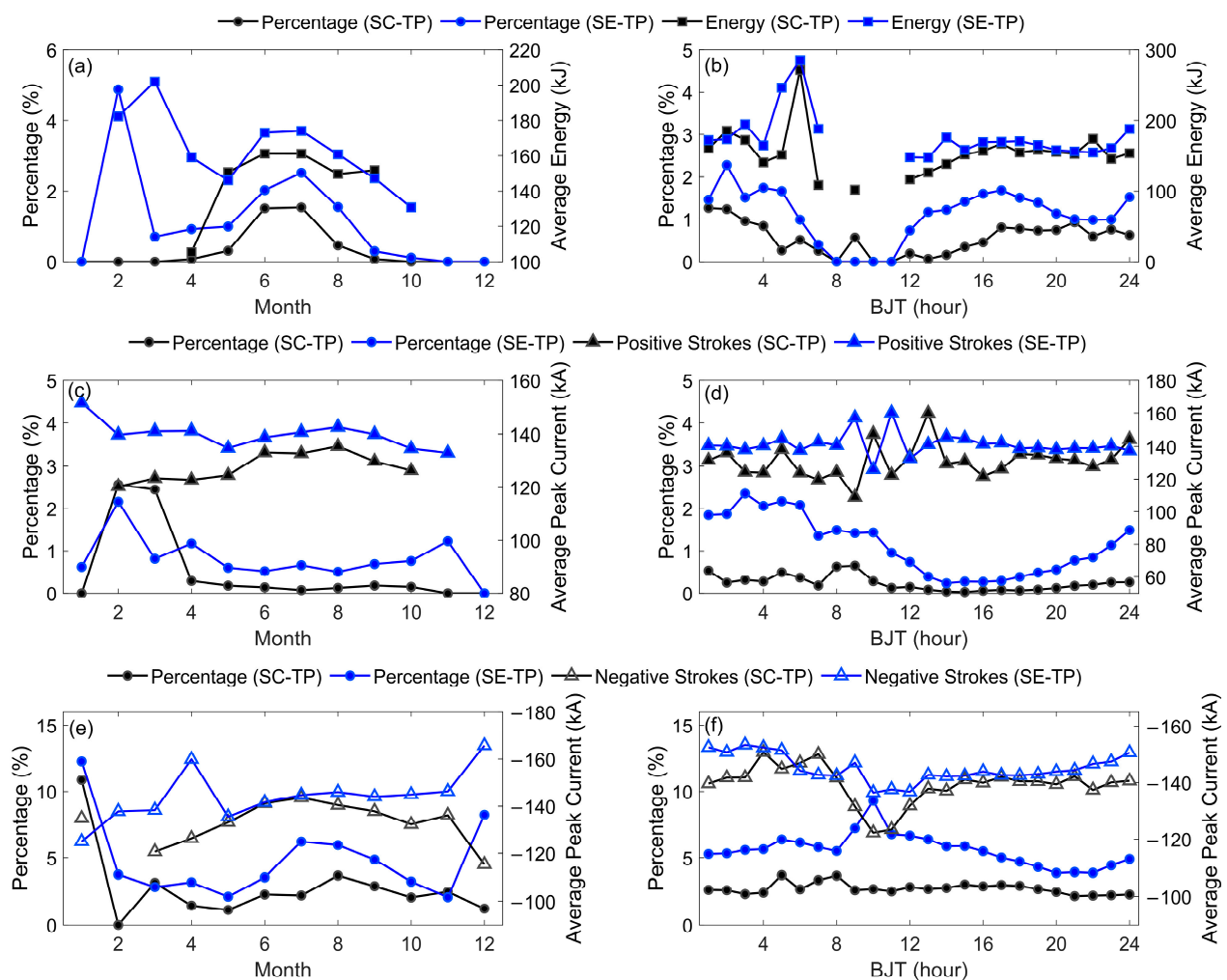


Figure 5. The monthly (left column, (a,c,e)) and diurnal (right column, (b,d,f)) distribution of the strong stroke percentage (depicted by filled circles on the left y-axes), average energy (depicted by squares on the right y-axes, top row) for stroke energy ≥ 100 kJ, average positive and negative peak currents (depicted by filled and hollow triangles, respectively, on the right y-axes, bottom row) for CG stroke peak currents $\geq |100|$ kA over the SC-TP (in black) and the SE-TP (in blue).

The percentages of strong negative CG strokes are larger than those of strong positive CG strokes, noting a higher occurrence of strong negative CG strokes over the two regions of interest (Figure 5c,e). Large percentages of strong positive CG strokes are evident in November and February over the SE-TP and February and March over the SC-TP, with values larger than those in the summer (Figure 5c). This is consistent with the findings of Yang et al. [76], who determined that the percentage of positive CG in a cold season is considerably greater than in a warm season. There are no discernible differences in the average peak currents for positive CG strokes across the months. For negative CG strokes, large percentages of strong strokes occur during both winter and summer over the regions of interest, displaying larger percentages and average values over the SE-TP than the SC-TP (Figure 5e).

The energy diurnal distribution of strong strokes displays large percentages from 1200 to 0600 BJT the next day. In both regions of interest, there is a peak in the afternoon (~ 1700 BJT) and another in the middle of the night (~ 0200 BJT over the SE-TP and ~ 0100 BJT over the SC-TP). The percentage of peaks in the middle of the night is the largest during the day (Figure 5b). The distribution of average energy value generally follows a similar pattern to those of their percentages, but notable peaks in average energy occur at 0600 BJT over the two regions of interest. Regarding the peak current diurnal distribution of strong positive

CG strokes (Figure 5d), different from those of energy, a large percentage is additionally observed in the morning (at 0600–1100 BJT) over the SE-TP. The diurnal variation in strong positive CG strokes over the SE-TP displays a similar variation to that in Guangdong Province, with a different peak at 0900 BJT [20]. Figure 5f shows that negative CG strokes over the SE-TP occur with a higher frequency in the morning, peaking at 1000 BJT, while those over the SC-TP show no significant variations. Their average peak current values demonstrate inverse variations to the percentage over the SE-TP, with the lowest values at 1000 BJT.

3.3. The Factors That Impact on Lightning Stroke Strength

As most lightning strokes over the two regions of interest were detected in summer (Figure 2, with fewer than 2000 strokes over the SE-TP and 170 strokes over the SC-TP over 4 years in winter according to the Chinese CGLLS), and considering the differences in cloud physics between summer and winter over the TP [77,78], this study explores the role of cloud physics on the strength of lightning strokes in summer, focusing on the charge zone depth, warm cloud depth, zero-degree level, and cloud ice water content fraction (CIWCF). Additionally, a much lower stroke number was detected by the WWLLN compared to that of the CGLLS, and this section displays the cloud micro- and macrophysics related to stroke peak currents.

Figure 6a shows that stronger positive strokes generally correspond to thinner charge zone depths over the SC-TP and for those with peak currents > 37.9 kA over the SE-TP. Stronger negative strokes correspond to thinner charge zone depths over the SC-TP for those with average peak currents in the range of $|9.9| - |40.2|$ kA. Over the SE-TP, stronger negative strokes correspond to thicker charge zone depths. The charge zone depths over the SC-TP (5.7–5.9 km) are thinner than those over the SE-TP (5.9–6.2 km) for positive strokes and negative strokes with peak currents larger than $|15.0|$ kA. It reveals that a thicker charge zone depth is required over the SE-TP than over the SC-TP to generate strokes of equivalent strength.

The variation in peak currents over the SC-TP does not show significant relevant changes in the warm cloud depth and zero-degree level (Figure 6b,c). Over the SE-TP, stronger positive strokes correspond to thicker warm cloud depths and higher zero-degree levels when their average peak currents are < 37.9 kA and < 32.8 kA, respectively. For average peak currents > 37.9 kA, stronger positive strokes correspond to thinner warm cloud depths. For average peak currents > 32.8 kA, stronger positive strokes correspond to lower zero-degree levels. The turning point values of negative strokes for warm cloud depths and zero-degree levels are $|25.5|$ and $|45.8|$ kA, respectively (Figure 6b,c). Regardless of strokes with negative or positive peak currents, the warm cloud depths and zero-degree levels over the SC-TP are both ~ 0.5 km lower than those over the SE-TP. Warm cloud depths are thinner than charge zone depths over the regions of interest, indicating a larger amount of ice particles participating in electrification than liquid particles in the thunderclouds.

Larger cloud ice content and flash rates are expected in deeper cloud depths, promoting cloud electrification and enhancing charge separation (e.g., [79–81]). Therefore, a CIWCF above the zero-degree level was investigated, which was calculated using the cloud ice water content (CIWC) and cloud liquid water content (CLWC) in the charge zone, i.e., $CIWCF = CIWC / (CIWC + CLWC)$, resulting in a $CIWCF > 0.5$. Figure 6d shows that stronger strokes generally correspond to larger CIWCFs over the SC-TP. In contrast, over the SE-TP, stronger strokes correspond to smaller CIWCFs. CIWCFs obtained over the SE-TP are smaller than those over the SC-TP, implying that a larger CIWCF is required to produce a stroke of the same strength over the SC-TP than over the SE-TP.

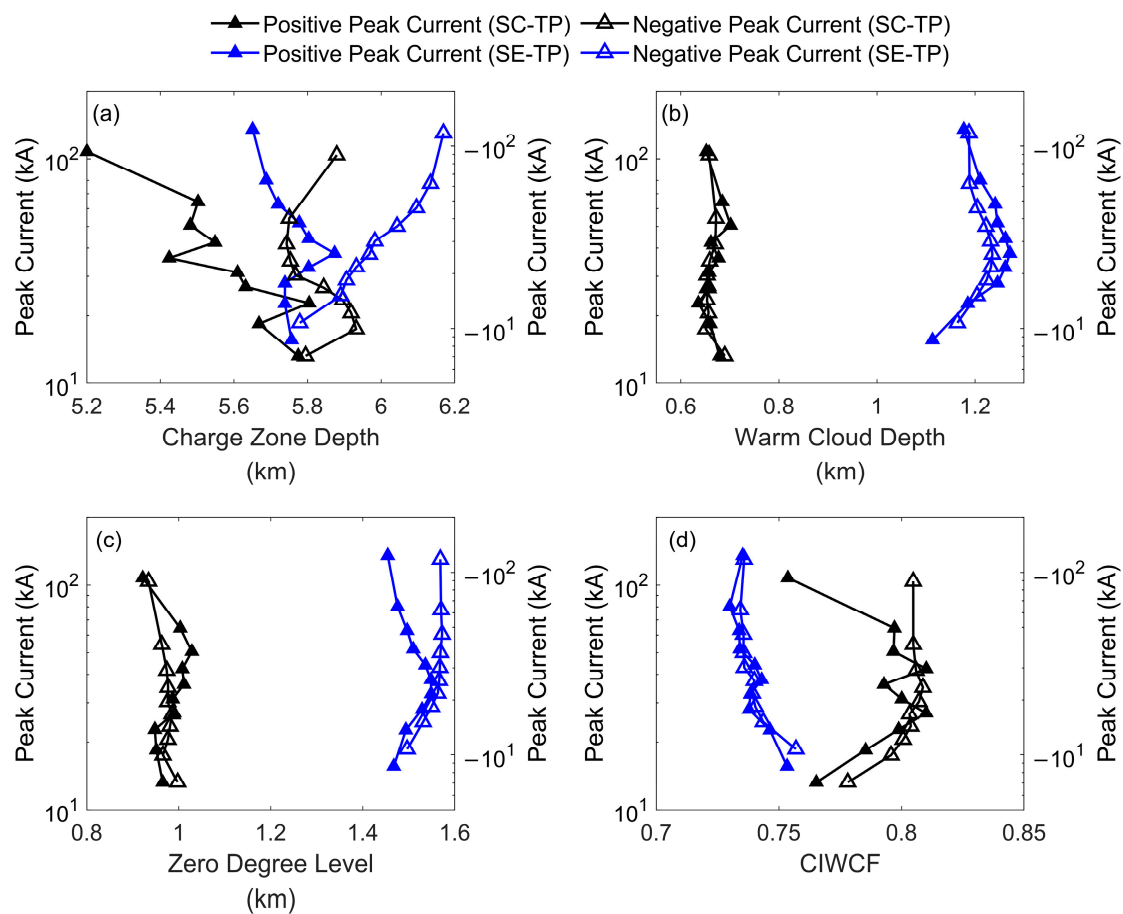


Figure 6. The mean stroke positive (depicted by filled triangles) and negative (depicted by hollow triangles) peak currents as a function of (a) charge zone depth, (b) warm cloud depth, (c) zero-degree level height, and (d) cloud ice water content fraction (CIWCF) in the charge zone over the SC-TP (in black) and the SE-TP (in blue) in summer. The left y-axes show the mean positive stroke peak currents, and the right ones show the mean negative stroke peak currents. The lightning cases are grouped into intervals of 10 percentiles of energy or peak currents over the two regions of interest.

4. Conclusions

In this study, we investigated the characteristics of lightning stroke strength over two regions of interest in the TP (SC-TP and SE-TP), where lightning strokes are concentrated. The stroke strength is indicated by energy and peak currents, which are obtained via ground-based lightning detection from the WWLLN and the Chinese CGLLS. Both datasets display that lightning stroke activities over the SE-TP are more than those over the SC-TP, and both regions of interest show peak values in summer and in the late afternoon. These results are in line with previous studies [58,75,82]. Compared to those over the SC-TP, the average energy and peak currents of lightning strokes over the SE-TP are larger.

Considering the probability of strong lightning strokes (energy ≥ 100 kJ, peak currents ≥ 100 kA) and their average values, both are larger over the SE-TP than the SC-TP. The monthly distribution of strong lightning strokes shows peaks in winter and summer. In comparison to other seasons, winter lightning exhibits a higher percentage of strong CG lightning. The peak occurrences of strong negative CG strokes are during both winter and summer, and they are higher than those of strong positive CG ones over the regions of interest. The diurnal distribution of strong lightning strokes displays peaks in the middle of the night for energy and positive peak currents over the regions of interest and in the morning for negative peak currents over the SE-TP. It indicates that strong lightning strokes are likely to occur in the middle of the night and in the morning. The peak values of average energy occur in spring and at 0600 BJT, but the distribution of average positive peak current

shows no noticeable changes. The variation in average negative peak currents is opposite to the variation in negative CG percentages over the SE-TP, contrary to the finding that peak currents increase between late night and early morning and decrease during the afternoon [33]. These results contribute to our understanding of lightning strength over the TP.

This analysis of cloud macro- and microphysics aimed to explore their impact on lightning stroke strength in summer. The relationships between stroke peak currents and cloud macro-/microphysics are different over the two regions of interest. Over the SC-TP, stronger strokes were found to correlate with thinner charge zone depths and larger CIWCFs but with no significant changes for warm cloud depths and zero-degree levels. Over the SE-TP, stronger positive strokes were associated with thinner charge zone depths and smaller CIWCFs, while stronger negative strokes were associated with thicker charge zone depths and smaller CIWCFs. The relationship between stroke peak currents and warm cloud depths/zero-degree levels changes over the SE-TP. For positive (negative) strokes, the turning points of warm cloud depths and zero-degree levels are 37.9 (−25.5) and 32.8 (−45.8) kA, respectively. Larger CIWCFs, thinner warm cloud depths, and lower zero-degree levels were required to produce lightning strokes of the same strength over the SC-TP than over the SE-TP, which may result in the lower percentage of strong lightning strokes detected over the SC-TP. The results reveal the relationship between lightning strength and cloud parameters, which could contribute to the prediction of lightning strength using cloud characteristics over the TP.

5. Discussion

In our study, 83% and 91% of CG lightning strokes are identified as negative CG over the SC-TP and SE-TP during winter, aligning with the findings of Ma et al. [83], using ADTD CG lightning data. The high percentages of strong CG lightning during winter are consistent with observations in various regions of China and the United States, with maximum mean percentages in January and December, respectively [76,84]. We suggest that the limited occurrences of lightning during winter resulted in a high percentage in winter. Previous studies mostly found a high percentage of positive CG in winter, and those were attributed to a strong shear, which transforms the charge structure of thunderstorms, and differences in the average cloud tops [84–86]. However, due to the lack of the monthly distribution of negative CG lightning percentages in previous studies, we cannot determine the contribution of negative CG lightning and positive CG lightning to the high percentage during winter, and this needs further research.

Even though we used hourly reanalysis data here to study the impact of cloud parameters on lightning strength, the temporal resolution is too low to accurately describe the cloud microphysics before lightning strokes. With the finding that there were no distinct environment parameter changes in the ERA5 data before storms [87], a very minor impact may affect the results. However, Wu et al. [87] also found the environmental parameters gradually increase from 30 min to 10 min before storms. Therefore, improving the resolution of cloud data is an inevitable necessity for future work. Considering that the lightning rate decreases as the ice fraction increases when the ice fraction is beyond the critical value (~ 0.3 over the continental regions [40]), this suggests a lower lightning rate when the lightning strength is stronger. The negative relationship between the lightning rate and lightning strength may explain the high peak percentages in winter and in the middle of the night/morning. This will be further studied using additional datasets (e.g., satellite cloud data, radar data, etc.) at a thunderstorm scale in subsequent research. Although the role of aerosols in impacting lightning strength is acknowledged, this study did not examine aerosol effects due to similar aerosol distribution over the south-central and southeast regions of the TP [88]. This element could be investigated in future studies by considering various aerosol types and concentrations in different regions.

The ISUAL serves as a payload for investigating global TLE occurrences but is limited to premidnight regions (passing over the central and eastern TP at ~ 1600 UTC, i.e.,

~2400 BJT), with the observable regions monitored only ~4.5 min per day (as it is onboard a Sun-synchronized orbit satellite, FORMOSAT-2) [89]. ASIM follows a similar observation shortage (e.g., [90]). Børge-Engeland et al. [10] highlighted that elves consistently occurred when their parent lightning stroke's peak current was ≥ 120 kA. To address the limitation of satellite observation, the distribution of peak currents ≥ 120 kA could be considered to estimate the number of elves' events. Across the regions of interest in this study, an average of ~18,000 lightning strokes with peak currents ≥ 120 kA occurs per year, whereas only ~four elves per year were observed by the ISUAL [32]. The ground-based lightning data can be used to estimate the elves' numbers over the TP and supplement the observation of the ISUAL.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/rs16050876/s1>, Figure S1: The annual spatial distribution of stroke numbers detected by the WWLLN and the Chinese CGLLS during 2016–2019.

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Data Availability Statement: The ERA5 is available online at <https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5>, accessed on 20 December 2023 [91]. The MEERA-2 is available online at https://disc.gsfc.nasa.gov/datasets/M2T1NXSLV_5.12.4/summary, accessed on 20 December 2023 [92].

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