RECENT LIGHTNING FATALITIES IN YUNNAN PROVINCE, SOUTHWEST CHINA

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Abstract. The Yunnan Meteorological Administration of Statistics has provided data for the first analysis and presentation of fatalities related to lightning in Yunnan, Southwest China. According to records from 2006 to 2020, 361 people were killed in Yunnan due to lightning strikes. The fatality rate in Yunnan is approximately 0.51 per million population annually. The prefecture of Honghe recorded the highest percentage of fatalities from lightning (13%). Lightning fatalities are more prevalent in southern and eastern Yunnan based on the spatial variation. Most of the fatalities occurred in April–September (96.4% of all fatalities) with a peak in August (28.3%). Deaths caused by lightning were more common in the afternoon (14:00-18:00 local time (LT)). Rural areas were the most common locations for fatalities (97%). Males accounted for approximately 59.2% of the victims with known gender. Males between 30 and 39 years old were the most vulnerable group. The primary activity carried out during lightning fatalities is farming, followed by being under trees, in open fields, and herding. It is essential to improve the awereness of farmers about lightning protection and defence possibilities in Yunnan.
Keywords: *developing country, lightning death, cloud-to-ground (CG) lightning, rural, natural disaster*

Introduction

The term lightning disaster is used to describe events caused by lightning strikes or electromagnetic pulse intrusion and impact, which have the potential to cause casualties, ignite wildfires (Holzworth et al., 2021), and significantly damage infrastructure, including power lines (Souto et al., 2023). Lightning was responsible for 2% of all natural disasters worldwide from 1970 to 2019 (WMO, 2021). According to some studies (Cardoso et al., 2011; Holle, 2016), there are estimates that global fatalities are between 6000 and 24000 annually. Therefore, studying lightning fatalities on a global or regional scale is crucial for improving lightning protection and safety education.

There have been numerous studies describing lightning fatalities published in North America (Ashley and Gilson, 2009; Raga et al., 2014; Mills, 2020), South America (Cardoso et al., 2014; Navarrete-Aldana et al., 2014), Europe (Dlamini, 2009; Elsom et al., 2014; Antonescu and Cărbunaru, 2018; Ströhle et al., 2018), Asia (Yadava et al., 2020; Adhikari, 2021; Mishra et al., 2023) and Africa (Borgerhoff Mulder et al., 2012; Hunt et al., 2020). These studies have shown that there are distinct trends in lightning fatalities between developed and developing countries as a result of differences in lightning protection facilities, awareness of lightning protection, and socioeconomic differences. The number of fatalities caused by lightning in developed countries has decreased

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significantly over the last century. For example, The United Kingdom has witnessed a significant decrease in the number of lightning fatalities per million people, from 1.09 in the 1850s to 0.02 in the 2010s (Elsom, 2018). Similarly, changes were observed in the United States (López and Holle, 1998) and Switzerland (Badoux et al., 2016). However, Lightning disaster deaths are on the increase in developing countries as a result of large agricultural and rural populations and the lack of effective lightning protection measures (Dewan et al., 2017).

China has conducted research on the consequences of lightning disasters, such as death and property loss. The investigation on losses caused by lightning disasters in China between 1997 and 2006 showed that the death rate in China was 0.53 per million annually (Ma et al., 2008), which is higher than that of developed countries (Holle, 2016). Zhang et al. (2011) discovered that there was an increase in the number of incidents and damages caused by lightning in China between 1997 and 2007, but then it started to decrease in 2008. The lightning fatality rate in China has fallen to 0.12 per million population per year in 2018, based on a country-scale analysis (Yin et al., 2021). The above-mentioned studies have examined the lightning death rate in China at a national level, but there has been little research on the correlation between lightning death, occurrence of lightning, and population characteristics.

Yunnan, situated in the southwest of China, is a province that is at high risk of being seriously affected by natural disasters because of its complex geographical environment and climate diversity. Its geographical location, diverse terrain and climatic characterize Yunnan as one of the most thundery and hail-stormy provinces in China. Zhang et al. (2011) demonstrated that Yunnan had the most lightning injuries and the third lightning fatality in China during 1997-2009.The climate, population distribution, and economic development across provinces and cities in China vary significantly, which are different from previous studies, based on the examination of the spatial, temporal, and demographic differences in lightning deaths in southwest China from 2006 to 2020, a detailed analysis has been conducted on the main causes of lightning deaths, which can be used as scientific references for decision-making and policy makers to devise strategies and methods to safeguard against lightning.

Materials and methods

The lightning disaster data of Yunnan Province collected by Yunnan Meteorological Bureau from 2006 to 2020 are used in this paper. The Yunnan Meteorological Bureau is responsible for collecting meteorological disaster data in the province, which mainly includes 13 kinds of meteorological disasters, including rainstorms, floods, gales, hail, lightning, drought, snow disaster, frost and low temperature cold damage. Among them, each lightning disaster event records the occurrence and background of the lightning disaster, the damaged property, the injured personnel, etc., such as the time and place of the lightning disaster, the damaged department, the industry, the type of the damaged property, the number of the injured and injured personnel, gender, occupation, and the location of the lightning strike. In total, the database contains 361 fatality reports from all cities in Yunnan province of China from 2006 to 2020. The population data of Yunnan Province are from the Yunnan Statistical Yearbook from 2006 to 2020 compiled by the Yunnan Provincial Bureau of Statistics.

Yunnan province established the provincial lightning detection network in 2006 to study lightning climatology and predict severe weather. The cloud-to-ground (CG)

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lightning data collected by the Yunnan Lightning Detection Network (YNLDN) is the basis for this paper. Information about CG flash occurrences, locations, peak currents, and polarities can be found in each record (Xie et al., 2013, 2015).

The study area is divided into grids with 10-km cells to create density maps. Density values for each block were calculated using ArcGIS software by determining the number of CG lightning strokes within the block and dividing it by its area. The density value (strokes km^{-2}) is assigned to each block.

Lightning climatology of Yunnan

Yunnan Province in southwest China is the boundary between the Tibetan Plateau, the Bay of Bengal, and the South China Sea (*Fig. 1a*). Yunnan Province provides support to approximately 47.2 million people, and it covers a total area of 394,100 km^2. The eastern part of the province is where the majority of the population resides. The province is noted for its mountainous and complex terrain, which has a significant elevation change from northwest to southeast. The summer monsoon area of Yunnan is significantly affected by both the heat and water vapor from the South China Sea and the Bay of Bengal. The environment in Yunnan is characterized by monsoons, which last for from May to October and for November to April.

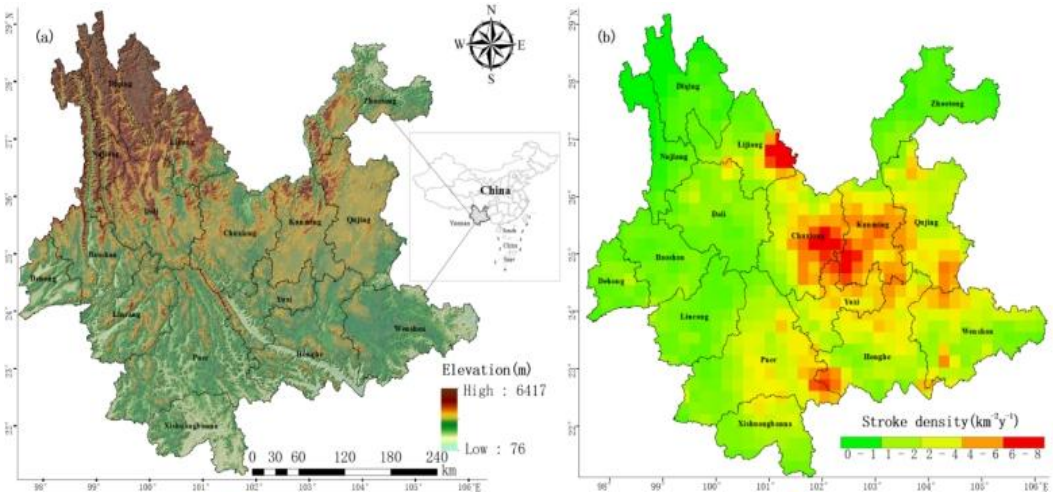

Figure 1. *Terrain (a) and density of cloud-to-ground (CG) lightning strokes (b) in Yunnan*

From 2006 to 2020, YNLDN detected the map of mean stroke density, which is illustrated in *Fig. 1b*. The map shows that there are a variety of lightning incidents, with more instances in the eastern and central regions and less in the western and northeast regions of the province. The values in Western Yunnan province are less than 0.5 strokes $km^{-2}yr^{-1}$, while those in Eastern and Central Yunnan provinces are over 2 strokes $km^{-2}yr^{-1}$. The highest density of lightning strikes in the dry and hot valley of the Jinsha River was over 7 strokes per km per year. There is another maximum of 5 strokes $km^{-2}yr^{-1}$ in the central Yunnan province of Kunming when it comes to lightning activity. The minimum could be explained by the absence of humidity in the northwestern and northeastern regions of Yunnan province. Southern Yunnan province experiences a density of less than 3 CG strokes $km^{-2}yr^{-1}$.

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Results

Spatial pattern of lightning fatalities

The average population per city from 2006 to 2020 is used to depict the population density in *Fig. 2a*. Eight prefecture-level cities and eight autonomous prefectures make up Yunnan, which is made up of sixteen divisions. Over 100 inhabitants per km^2 is the population density of the majority of the cities. Kunming (the provincial capital in the center) has a population density of 309 inhabitants per km^2, while Diqing (with 17 inhabitants per km^2) has the lowest population density (*Fig. 2a*), the eastern portion of the province is home to the majority of the population. In regions of Yunnan, where lightning fatalities were more reported, the southern, central, and eastern regions had a higher rate (*Fig. 2b*). The article's analysis found 36.6% of lightning fatalities, and Honghe, Zhaotong, and Qujing were the top five (*Fig. 2b* and *Table 1*).

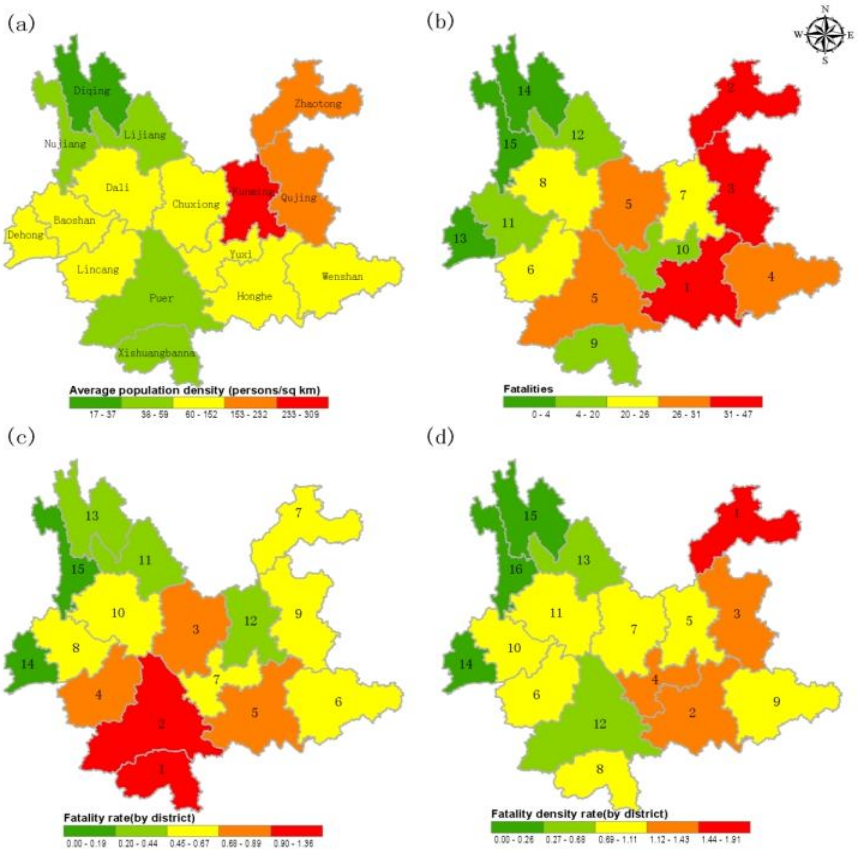

Figure 2. *(a) The population density in Yunnan is determined by the average population between 2006 and 2020, along with the names of every city. (b) Each city's rank is determined by the number of fatalities caused by lightning. (c) Each city's fatality rate per million represents their ranking based on fatality rate per million inhabitants per year. (d) The ranking of the county is determined by the number of fatalities per km^2 in each city using normalized fatalities by area*

Table 1 shows the data on the reports related to lightning from every city in Yunnan between 2006 and 2020. In Yunnan province, there has been a total of 361 fatalities caused by lightning. In Yunnan, there were 24.1 fatalities per year from 2006 to 2020,

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while there were 38 in 1997–2009 (Zhang et al., 2011). Lightning deaths have decreased gradually. In the top 5 cities, Honghe, Zhaotong, Qujing, Chuxiong, and Puer are all located in the southwest and have greater population densities than other cities. Xishuangbanna had the most fatalities caused by lightning, with a ranking of 8th (*Table 1*).

Table 1. *Acrage (km^2), inhabitants (million, average for the period of 2006 to 2020), Counts of fatalities caused by lightning, fatality rates (fatalities per million people per year), and normalized fatalities (fatalities per million people per year per square km × 1000) by district in Yunnan*

District	Area (km^2)	Population (mil.)	Fatalities		Fatality rate		Normalized fatalities	
			Number	Rank	Rate	Rank	Density	Rank
Kunming	21580.77	650.50	24	7	0.28	12	1.11	5
Yuxi	15285.43	232.48	19	9	0.63	8	1.24	4
Zhaotong	23021.74	534.95	44	2	0.63	7	1.91	1
Puer	45360.28	258.95	30	5	0.89	2	0.66	12
Lincang	24455.85	245.52	26	6	0.81	4	1.06	6
Chuxiong	29270.95	271.33	30	5	0.85	3	1.02	7
Qujing	29850.28	593.20	41	3	0.53	10	1.37	3
Honghe	32925.37	455.18	47	1	0.79	5	1.43	2
Lijiang	21234.78	125.64	4	11	0.24	13	0.19	14
Dehong	11527.24	123.78	3	12	0.19	15	0.26	13
Xishuangbanna	19705.34	113.13	20	8	1.36	1	1.01	8
Nujiang	14723.76	53.84	0	14	0.00	16	0.00	16
Baoshan	19633.47	253.48	18	10	0.55	9	0.92	10
Diqing	23860.76	39.76	1	13	0.19	14	0.04	15
Dali	29451.94	351.73	20	8	0.44	11	0.68	11
Wenshan	32236.84	353.83	31	4	0.67	6	0.96	9
Yunnan	394124.8	4657.30	358		0.59		0.91	

Every city is shown in *Fig. 2c* with its fatality rates per million people per year. The cities had a mortality rate of 0.51 per million people per year during the study period. Xishuangbanna, Puer, Chuxiong, and Nujiang, Dehong, and Diqing have the lowest fatality rates (0.19) among all cities, with the highest being observed in southern Yunnan with the rate at 0.34. The top cities ranked by fatality rate are shifting towards cities with a lower population (*Fig. 2b* and *Fig. 2c*). Xishuangbanna is ranked 14th of 16 cities in *Table 1* while having the highest fatality rate and the lowest population density in Yunnan. The United States (Curran et al., 2000) and China (Zhang et al., 2011) carried out similar studies that were similar to these results. The distribution of fatalities is slightly different after normalization by the city's area (*Fig. 2b* and *Fig. 2d*). However, it is important to note that southern and central eastern Yunnan is more susceptible to CG lightning than other regions of Yunnan.

Temporal pattern of lightning fatalities

Fig. 3 presents the annual variations in fatalities caused by lightning and CG lightning strokes in Yunnan between 2006 and 2020. Lightning has caused a decrease in fatalities since 2006, with 84 in 2006 and zero in 2019. Lightning fatalities amounted to an average of 60.5 per year between 2006 and 2009, but by 2020, it has gone down to 10.8 per year on average. Lightning fatalities decreased significantly from 2012 to 2020.

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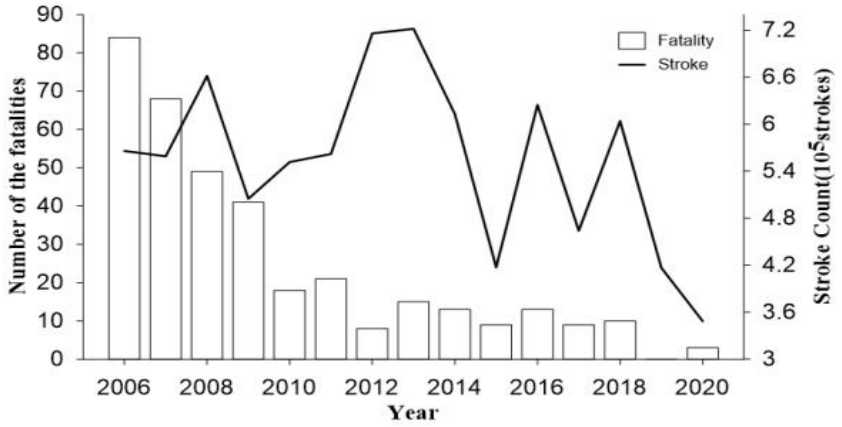

Figure 3. *Lightning-related fatalities and CG lightning strokes in Yunnan fluctuated annually from 2006 to 2020*

May-September is when there is the most lightning fatality activity (90% of all fatalities occurred in 361 cases, *Fig. 4a*). Lightning emergencies are less likely to happen during the dry season between October and March of the following year. Compared with March and April, lightning disasters in May and June have a significant increase over eastern and southern Yunnan, with a high value in June to August and a peak value in August are reported over most part of Yunnan. The sum of June to August in summer accounts for more than 67% of the whole year, and a significant decrease in September, mainly over the south (*Fig. 5*).

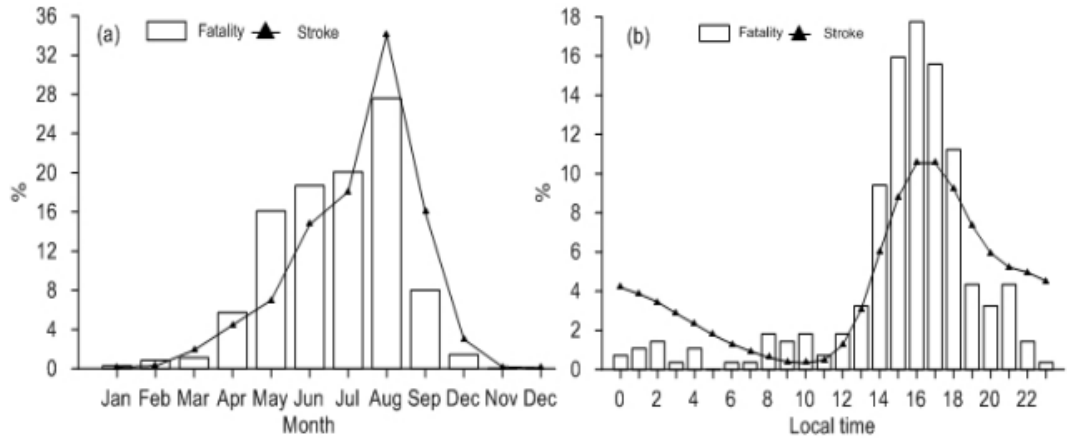

Figure 4. *The number of fatalities and CG lightning strokes in Yunnan fluctuates monthly (a) and diurnal (b)*

Lightning casualty reports are most commonly received during the afternoon and early evening, with a significant amount occurring between 14:00 and 18:00 local time(LT), which coincides with the peak CG lighting strokes activity in Yunnan (*Fig. 4b*). Between 14:00 and 18:00 LT is the time when 70% of all casualties occur. The increase is rapid and reaches a peak at 16:00 LT, then slows down slightly after the peak. The comparison of the results with those in the US (Curran et al., 2000), Swaziland at 14:00-18:00 (Dlamini, 2009), Bangladesh (Al-Amin Hoque et al., 2019) and Turkey (Kucieńska et al.,

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2010) is comparable. There is a considerable negative correlation between fatalities and lightning strokes from 22:00 to 11:00 LT of the following day. Despite the higher number of strokes (29.3%) occurring at the same time, only 7% of the casualties were reported at night (22:00-06:00 LT). In contrast, 6.2% of the fatalities are equivalent to 2.8% of the strokes during 07:00-11:00 LT. The significant difference demonstrates that lightning strikes are closely linked to recreational and occupational activities, as individuals are usually indoors at night and rarely outside, making them unlikely to experience lightning strikes. The risk of lightning strikes has increased as people have become more active outdoors since the beginning of the morning. This suggests that safety precautions must be taken when engaging in risky activities during certain times of day.

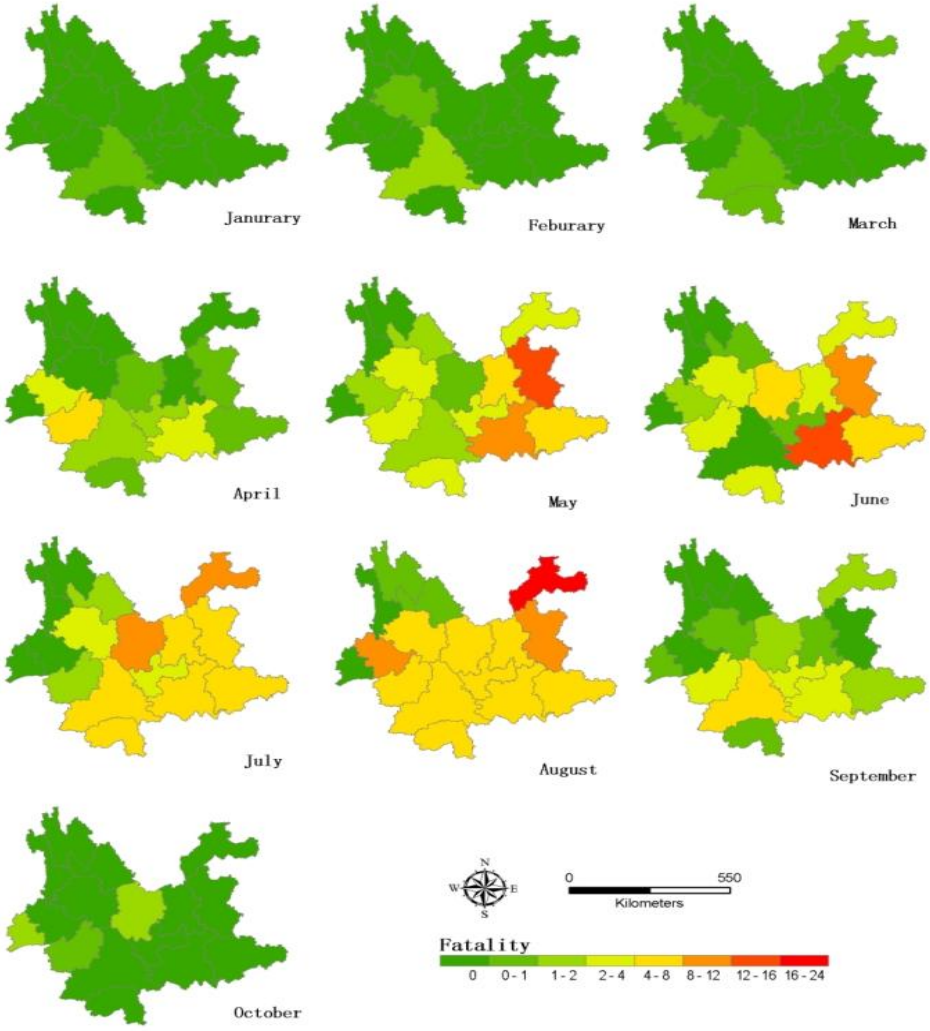

Figure 5. *Between 2006 and 2020, each city reported the number of fatalities due to lightning*

Demographics of lightning fatalities

Rural versus urban

Rural areas accounted for 94.5% of fatalities, while urban areas accounted for only 2.5%, resulting in 338 fatality records with this information. Rural regions are responsible for 97% of all lightning fatalities, without taking into account unknown factors (2%).

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Yunnan has a significantly higher proportion of the rural population affected by lightning disasters than other areas according to other research results. Zhang et al. (2011) emphasized that 51% of all lightning deaths in China were caused by farmers killed in lightning disasters. Rural areas account for most of the deaths in other countries, with 78% in Romania (Antonescu and Cărbunaru, 2018) and 86% in Turkey (Tilev-Tanriover et al., 2015). Yunnan's high forest cover and mountainous terrain are the main reasons for this traditional agricultural province. The rural population is more likely to be engaged in labor-intensive agriculture (field planting, grazing cattle, and sheep) during lightning, making it difficult for individuals to find adequate, safe shelter.

Casualty environment

The location and activity of individuals during thunderstorms play a significant role in the deaths caused by lightning. The study categorizes lightning casualties into nine categories: farming, outdoor fields, around buildings, inside houses, mountains, herds, telephones and radios, and transportation related (*Fig. 6*). 38.5% of those who were struck while working on farms were mostly in the farming category. 17.5% of casualties fall under the second largest category, which happens to be under a tree. “Open Fields” make up 14.3% of the casualties and are the third largest category. The majority of lightning deaths occur outdoors in open areas in Yunnan province (*Fig. 6*), which is the same as the one in Bangladesh (Dewan et al., 2017).

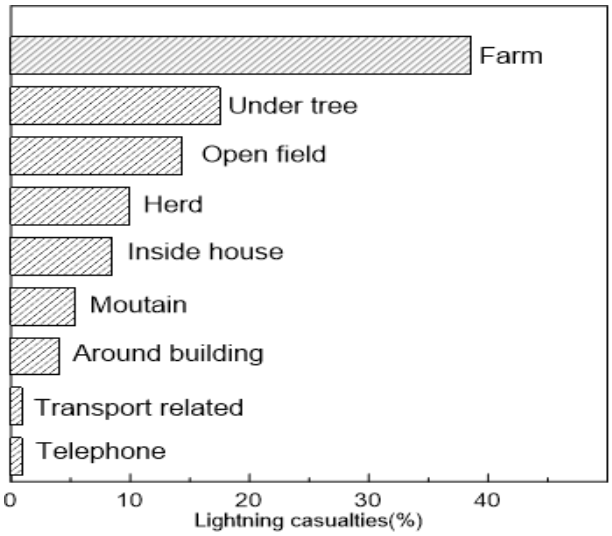

Figure 6. *The distribution of lightning casualties at different frequencies*

Gender and age variations

The gender of 240 (67%) out of the 361 individuals killed in our database was known. The proportion of fatalities that were male is 59.2%, females is 32.1%, and children is 8.7% (*Fig. 7*). In China, children are defined as those under the age of 18. This result is less than previous studies. The number of male fatalities in India increased by 89% according to Singh and singh (2015), and men were the main victims of lightning in Bangladesh, accounting for 78.8% of all fatalities from 2013 to 2017 (Holle et al., 2019). The number of lightning fatalities in Canada was 84% for men (Mills et al., 2008), which was the same percentage as that found in the U.S. by Ashley and Gilson (2009). Tilev-

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Tanriover et al. (2015) reported that male fatalities were lower in Turkey, where 67% of all fatalities were reported. Young males' higher risk-taking, specifically in rural Yunnan, where they have more outdoor work commitments, is believed to be the reason for more male deaths (Singh and Singh, 2015; Tilev-Tanriover et al., 2015).

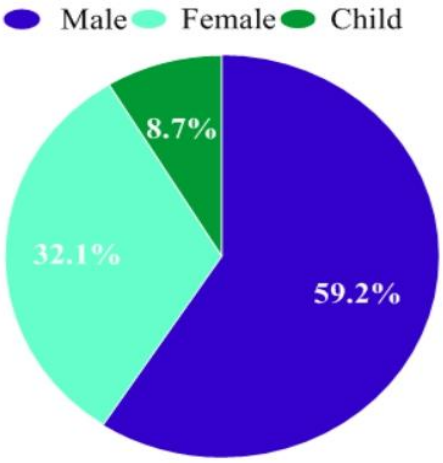

Figure 7. *Gender variation in fatalities caused by lightning*

177 fatalities have been identified by both age and gender (*Fig. 8*). The number of males in these is 62.1% (110 individuals) and 37.9% (67 individuals) are females. According to the age pattern, 30–59-year-old males were responsible for 62.9% (66) of all fatalities, while females in this age group were responsible for 62.5% (40). Both males and females experience a secondary peak that is contiguous when they are between 10 and 29 years old. It's important to note that men are more likely to experience fatalities than women across all age groups. Almost half (62.7%) of the total fatalities occur between the ages of 30–59. Yunnan was 38 years old at the median age. The outcomes are different from those obtained by Dlamini (2009), who reported that the majority (52.5%) of victims were aged 10–19 and that the median age of death in Swaziland was 28.5 years. The reason for this is that a majority of Yunnan's population under 30 has moved to urban areas for work or school, while the majority of those remaining in rural areas are older than 30.

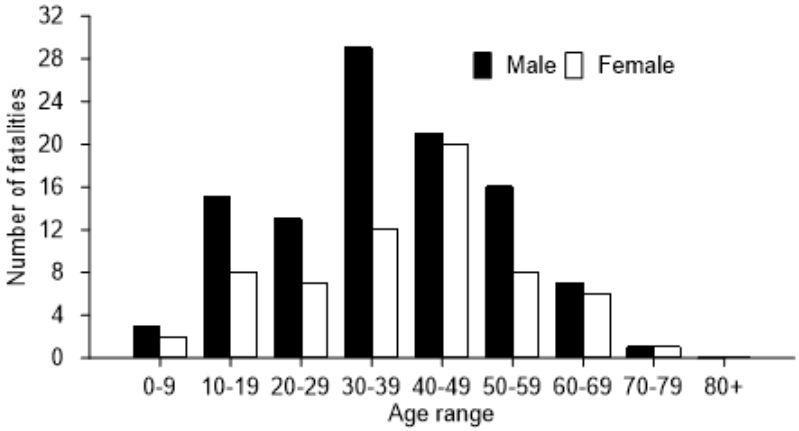

Figure 8. *The age distribution of lightning fatalities in Yunnan is based on gender*

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The number of fatalities per incident

Table 2 indicates that 76% of the lightning incidents result in a single death, while 16.21% involve two deaths. There are incidents where there are more than two victims per incident in the remaining 27% of them (*Table 2*). Four victims were reported in connection with a lightning event. The number of single fatalities in England lightning events (Elsom and Webb, 2014) and the United States (Curran et al., 2000) was 98%, while the number of deaths in developing countries, such as Bangladesh (Dewan et al., 2017), was relatively low.

Table 2. *The number of fatalities that occur during lightning events*

Number of fatalities	Events	Percentage (%)
1	203	76.0
2	44	16.5
3	13	4.9
4	7	2.6
Total	267	100

Discussion

Population density and maximum lightning density in Yunnan do not correlate with the geographical distribution of fatalities. The area's central Yunnan province does not have the highest fatality rates, unlike Kunming City, which has high stroke rates and the largest population density. The reason could be that Kunming's rural population is at a low level of 32%, which is the lowest in the province (*Fig. 9*). Additionally, there are complete lightning protection facilities in place. The population density and stroke density in the area around Qujing are similar to those in Kunming, but the rural population's high proportion results in an increase of 59%. Therefore, lightning disasters have a higher fatality rate than Kunming. The results obtained in the United States (Roeder et al., 2015) are somewhat dissimilar to these ones. Roeder et al. (2015) demonstrated that rural areas with lower population density experienced a decrease in fatality risk for regions with high CG lightning flash rate.

Interannual variation does not show a significant correlation between the number of lightning deaths and the number of lightning strikes. The number of deaths from lightning disasters decreased steadily despite 2013 being the most active year for lightning. The reason for the sharp decrease in 2010 was primarily because of the continuing decline in the rural population and the availability of more substantial buildings for safe shelter. The increase in lightning warnings since 2010 has made people aware of the danger of lightning (*Fig. 10*).

It's important to ponder why the number of normalized deaths from lightning has decreased exponentially. The fatality rate from lightning was 1.8 fatalities per million people in 2006, but it has since decreased to zero. The trend (*Fig. 10*) shows that the rural Yunnan population is currently below 53%, following the trend of 70% in 2006. Even though Yunnan's population has grown by more than 7%, the actual number of fatalities has decreased greatly. As urbanization occurs in developed countries, the lightning fatality rate decreases (Holle, 2016). A strong correlation was demonstrated between the decreasing percentage of rural population and the decrease in lightning fatality rates (López and Holle, 1998). Between 1900 and the end of the century, the number of rural

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residents in the USA decreased from 60% to 25%. Thanks to this modification, the fatality rate has gone down from more than 5 deaths per million in certain years of the early 20th century to less than 0.5 deaths per million in recent years.

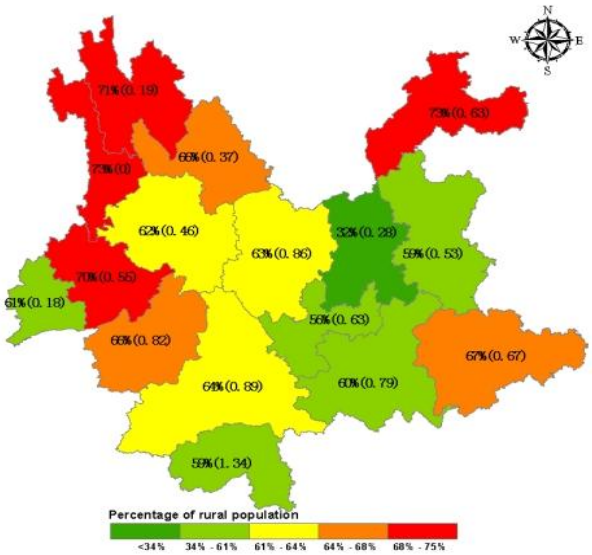

Figure 9. *Spatial distribution of Percentage of rural population. The average value from 2006 to 2020 was calculated*

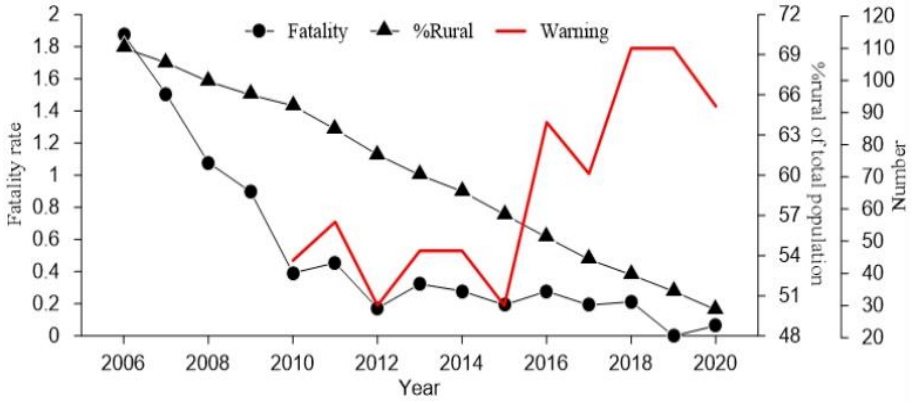

Figure 10. *The number of published lightning warnings, fatalities related to lightning, and percentage of rural population in Yunnan changes annually*

The monthly pattern of death from lightning is in accordance with the climatology of lightning strikes in Yunnan (*Fig. 4a*). From May through September, there was a record of 92% of CG lightning flashes, with a broad maximum of 70% of all CG lightning flashes in July and August (Xie et al., 2013). The warm season (May–September) is the most common season for lightning fatalities, according to many studies (Antonescu and Cărbunaru, 2018; Mishra et al., 2023). The spike in lightning deaths in late spring and summer is a result of the increase in outdoor labor activities during the month than in other times of the year. Farming and shepherding are the primary outdoor activities.

The proportion of the rural population has a positive correlation with the number of fatalities (*Fig. 10*). With the development of urbanization, the living environment and

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lightning protection facilities have greatly improved compared to rural areas, which is the first reason. Second, with the decrease in rural population, the number of people working in farmlands and open land has decreased. Cities or factories with lightning protection facilities provide a relatively safe working environment. Third, Lightning protection awareness is being improved due to the popularity and publicity of lightning protection and other related knowledge.

Conclusion

Lightning occurs frequently in Yunnan, but fatalities can occur due to coincidental circumstances. The way people behave and where they are during the thunderstorm are still mainly responsible for determining their fate. The assumption is that fatalities are largely due to the choices made by individuals and can be prevented. The findings of the study show the following.

The lightning disaster in Yunnan Province caused serious casualties from 2006 to 2020, resulting in 361 deaths. Over time, Yunnan has seen significant annual variations and a decreasing trend in lightning fatalities. According to the normal population, The rate of lightning fatalities per million people per year is 0.51, which is greater than that in many other provinces of China (Yin et al., 2021).

(2) Between 17:00 and 18:00 LT, which coincides with the peak CG lighting stroke activity in Yunnan, is when most fatalities due to lightning occur. The percentage of fatalities caused by lightning is highest between May and September, which suggests that major activities should be postponed during thunderstorms in these months. It is crucial for individuals to comprehend that they must alter their entertainment and work schedules.

(3) Lightning fatalities are different from lightning strokes or population distribution. However, they are much wider and are dependent on factors such as playful and job-related activity, the timing and season of the year in which lightning occurs, as well as other variables.

(4) Being struck by lightning was the most probable way to be involved in outdoor activities like farming and shepherding. Lightning strikes have killed more males than females in Yunnan, indicating that the agricultural economy and males' involvement in labor-intensive practices have contributed to the increase in fatalities. In rural areas, 97% of the incidents were recorded. The presence of the victims under trees indicates the necessity for awareness campaigns, which causes the death by side splash. Lightning strikes often occur in the farming environment, and buildings in rural houses and other buildings do not have a universal installation of lightning protection devices. It can be seen that farmers are the main victims of lightning disasters. Therefore, it is extremely urgent to solve the safety protection of lightning in rural areas and farmers.

(5) For regions in developing countries similar to Yunnan province, strengthening rural lightning protection construction mainly from two aspects. First, raise farmers' awareness of lightning protection. At present, farmers do not pay enough attention to lightning protection, the occurrence of lightning weather process is not enough to understand, protection awareness and coping knowledge are insufficient, therefore, it is urgent to strengthen science popularization to improve farmers' awareness of lightning protection and defense ability. Second, strengthen the construction of rural lightning protection facilities. Especially in southern Yunnan, which is a lightning prone area, more attention should be paid to strengthening rural lightning protection infrastructure construction.

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