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**To cite this article:** Shriram Sharma, Bishnu Neupane, Hari B. KC, Maha P. Koirala, Narayan P. Damase, Suman Dhakal, Chandima Gomes, Mary Ann Cooper, Ronald L. Holle, Ramji Jaisi Bhusal, John Cramer & Ryan Said (2022) Lightning threats in Nepal: occurrence and human impacts, *Geomatics, Natural Hazards and Risk*, 13:1, 1-18, DOI: [10.1080/19475705.2021.2009922](https://doi.org/10.1080/19475705.2021.2009922)

**To link to this article:** <https://doi.org/10.1080/19475705.2021.2009922>



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Published online: 13 Dec 2021.



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## Lightning threats in Nepal: occurrence and human impacts

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### ABSTRACT

Nepal has a very large topographical variation; this elevation change has a major influence on lightning occurrence and human casualties. The Himalayan peaks cover the northern part of Nepal with low population density, the middle is covered by hills with intermediate density, and the southern plain with the greatest density. This study will leverage lightning detection by Vaisala's Global Lightning Dataset GLD360 network with a recent detailed compilation of lightning casualties from 2011 through 2020. Over one million lightning strokes per year were detected from 2016 through 2020. Stroke density is least over high elevations to the north, moderate in hilly regions, and very frequent over the south. The thunderstorm season begins in March and ceases by August after the annual monsoon cycle. Of all the natural disasters, lightning has been recorded to be the second highest killer after earthquakes. The Ministry of Home Affairs reports an average of 103 lightning deaths per year. The fatality rate of 3.8 deaths million<sup>-1</sup> year<sup>-1</sup> is highest among the South Asian countries. Fatalities over high mountains are rare, with most casualties over the center of Nepal. Lightning Fatality Risk is not a good indicator of the fatalities that occur in a district.

### ARTICLE HISTORY

Received 23 June 2021

Accepted 18 November 2021

### KEYWORDS

Nepal; lightning injury; lightning casualty; lightning fatality; thunderstorm days; thunderstorm hours; thunderstorm warning hours

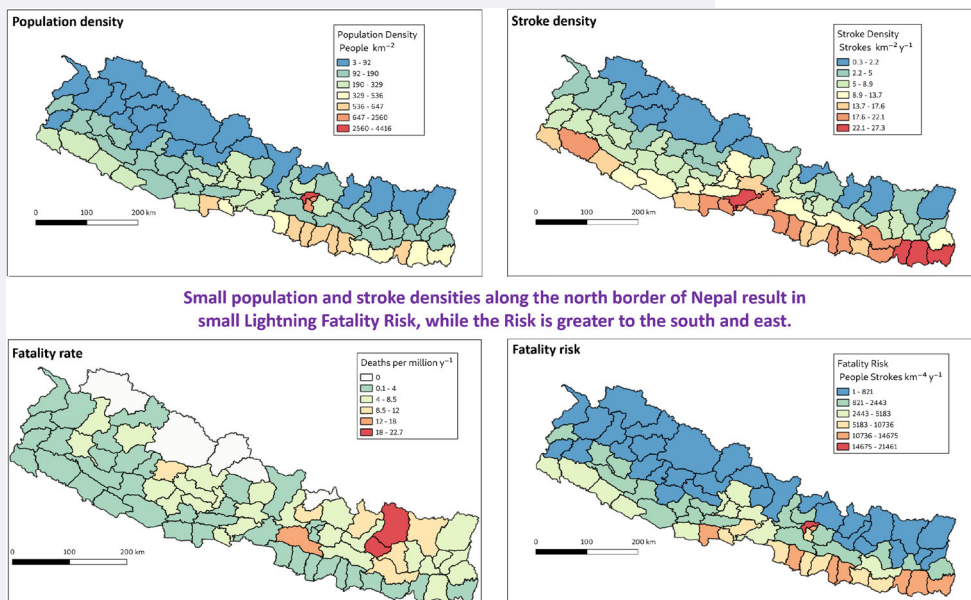
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## GRAPHICAL ABSTRACT



## HIGHLIGHTS

- Lightning occurrence and fatalities are most frequent in districts along the southern border, and least in the northern high-elevation districts
- Lightning occurrence and fatalities are concentrated in the pre-monsoon and monsoon months
- Districts with the largest stroke densities often do not coincide with the districts with the greatest fatality rates per million people

## 1. Introduction

Documented numbers of lightning fatalities and injuries in developing countries are often not available. The paucity of the fatality data could be due to the fact that unlike other disasters such as earthquakes, landslides, tornadoes etc., lightning fatalities are rather sporadic and scattered that leads to the underestimation of fatalities by the governments and other concerned organizations/authorities. As a result, there have been some unreliable estimates by researchers in the recent past and several recent studies have attempted to fill this gap. One estimate of global fatalities is several thousand (Gomes and Kadir 2011, 719–725), another is 6000 fatalities per year (Cardoso et al. 2014, 4), and the third is 24,000 fatalities per year (Holle and López 2003, 103–34). Holle and López (2003, 103–34) also estimated that 240,000 people are injured each year based on lightning stroke density and populations in the tropical and subtropical areas of the world.

Fatality rates are higher in the developing nations of Africa and Southeast Asia and lowest in developed countries such as the U.S., Europe, U.K., Australia, and

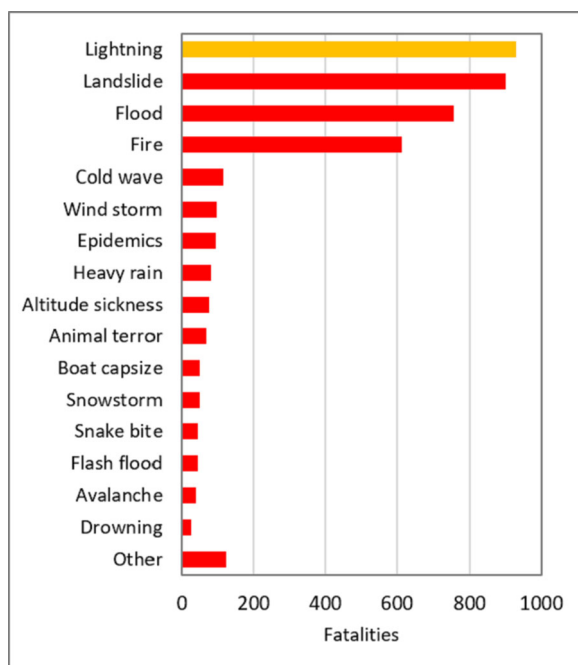
Japan (Holle 2016, 35–42). These differences in fatality rates have been attributed to several factors common in developing countries:

1. Fewer lightning-safe homes, workplaces, schools, and other facilities than in more developed countries.
2. Higher rate of labor-intensive manual agriculture.
3. Lack of awareness or data about the lightning threat, how to avoid injury, and medical treatment.
4. Fewer easily available substantial buildings and fully enclosed metal-topped vehicles.
5. Inadequate emergency medical services and high-quality medical care.
6. Lack of Disaster Risk Reduction programs.

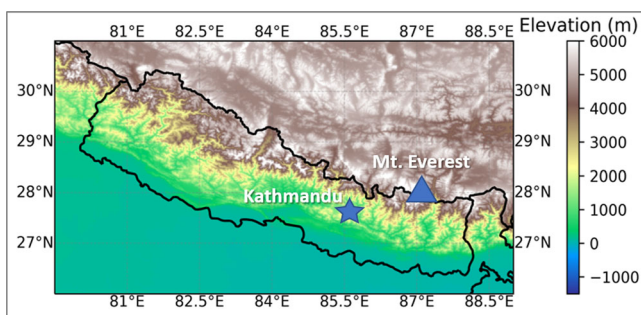
An empirical formula was developed to estimate the annual fatality rate in a region (Gomes and Kadir 2011, 719–725). The equation takes factors into account such as lightning ground flash density, population density, literacy, fraction of urban population, etc. However, when this formula was applied to Mongolia, it was unsuccessful in estimating the fatality rate: the computed fatality of 0.8 deaths per year was lower than the predicted value of 4.3 deaths per year. Doljinsuren and Gomes (2015, 686–701) suggested that other parameters, such as surface topography and degree of vegetation, have significant influence on annual deaths due to lightning. Although lightning is a threat to people and livestock, particularly in the developing world, this natural hazard has largely been ignored in many countries and lightning injury data are unavailable in the literature for most developing countries.

In particular, Nepal has largely underrated the lightning hazard even though it is one of the most frequent and dangerous natural hazards that its people encounter (Figure 1). The atmospheric structure and hydro-meteorological processes along the southern slopes of the Himalayas are not well known or documented, mainly because of the rugged and remote terrain. Also, the mountain range lies within several developing countries that do not have the resources to carry out sophisticated meteorological studies (Barros and Lang 2003, 1408–1427). This challenging terrain may also affect the comprehensive collection of news reports of lightning deaths and injuries.

To date, few published studies of Nepalese lightning occurrence and casualties have taken place. The annual and diurnal cycles of lightning by region of Nepal was identified in Saha et al. (2019, 128–221), using several datasets ending in 2013 to show that April and May are prime months for thunderstorms. In another study, using three months of data from the Global Lightning Dataset GLD360 network during the pre-monsoon season of 2012, Mäkelä et al. (2014, 91–99) examined the thunderstorm pattern over Nepal, as part of a training program for meteorologists. Mäkelä et al. (2014) observed that the south and southeastern border of Nepal receives intense thunderstorms with a peak lightning occurrence in the month of June (43%) followed by May (38.6%) and April (18.4%). Mäkelä et al. (2014) also found that the diurnal distribution of thunderstorm activity peaks at around 1700–1800 local time. Recently, Adhikari (2021) analyzed the frequency, location, and timing of lightning fatalities in Nepal since 1971. It summarized that a large recent



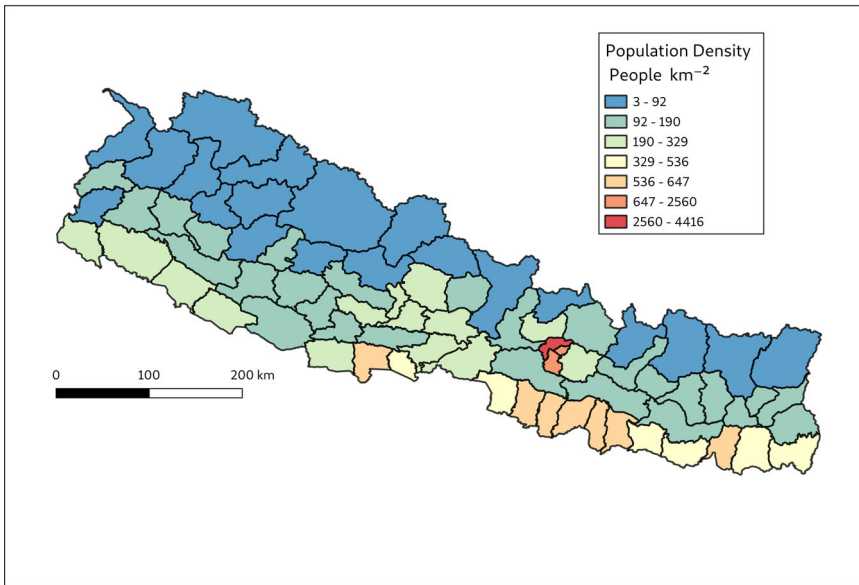
**Figure 1.** Fatalities due to natural hazards in Nepal (except earthquakes) between 14 April 2011 and 15 April 2020. Data source: DRR portal, MoHA, Govt. of Nepal. Source: Ronald Holle



**Figure 2.** Topographic map of Nepal including locations of Kathmandu and Mt. Everest. Source: John Cramer.

increase in the annual fatalities can be attributed to the improvements in communications leading to better reporting of such events; however, no lightning occurrence data were available for the study.

The present study expands Saha et al. (2019, 128:221) and Mäkelä et al. (2014, 91–99) to a longer period of GLD360 data and matches it with the recent years of a somewhat different fatality dataset than used in Adhikari (2021). Although there have been some recent works analyzing the lightning climatology over the Himalayan region, this paper provides a detailed comparison between spatio-temporal distribution of lightning and fatality risk over Nepal. Specifically, the present study associates the distribution of lightning occurrence over Nepal with lightning fatalities with altitude and population density. Establishing such connections is valuable for building a

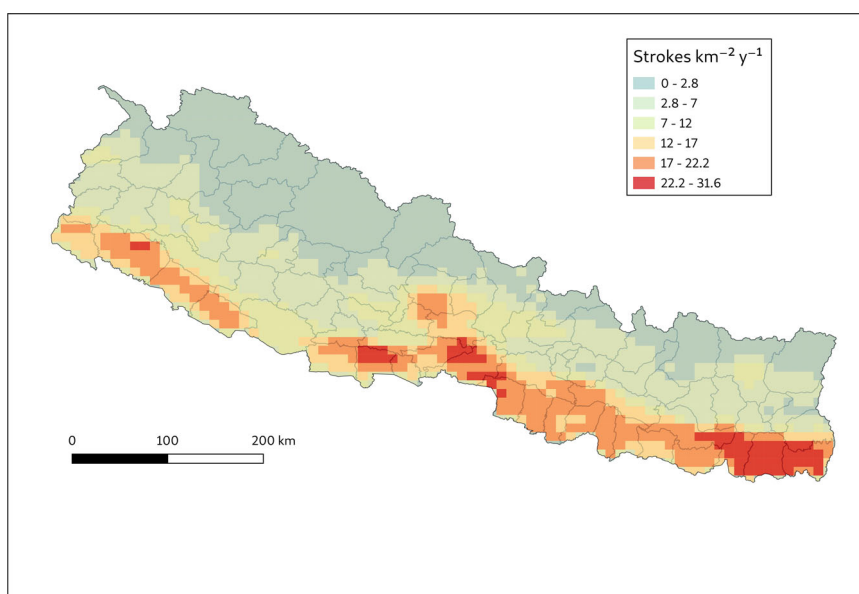


**Figure 3.** Population density of Nepal shaded by district using 2011 census data. The capital city Katmandu, and other two cities (Lalitpur and Bhaktapur) within the Kathmandu valley have the highest population density. Source: John Cramer.

fuller assessment of the lightning risk in the region. The paper proceeds as follows: Sections 2 and 3 detail the remarkable geography of Nepal and provide an overview of the population distribution by district and a description of the datasets used in the present analysis. Section 4 shows lightning stroke distributions in time and space, including hourly distribution and peak warning hour and maps the district-level fatality rates. The paper concludes with a calculation of Lightning Fatality Risk that relates district fatalities with the product of population and stroke densities.

## 2. Topographical and altitudinal variation of Nepal

Nepal has tremendous geographic diversity resulting from a large altitudinal variation within a stretch of 150 km to 250 km north to south within the land area of 147,516 sq. km. The altitudinal variation from as low as 59 m to as high as 8848 m above mean sea level (Figure 2) results in the large climatic variation that ranges from the tropical zone, (southern Gangetic plains) to the arctic zones (northern high mountains). Over 83% of Nepal is hilly or mountainous, including the world's highest peak, Mt. Everest, and eight other peaks over 8000 m. This geographic structure plays a vital role in the observed meteorological effects. Nepal is topographically divided into three regions. The Himalayas and its foothills make up the northern border of the country covering 16% of the total land area. This is the least inhabited region of Nepal with less than 8% of the population (Figure 3). The Mahabharat range and the Churia hills in the middle of the country cover about 65% of the total land area and are home to about 44% of the population. The Terai in the southern part of Nepal, is an extension of the Gangetic plains and covers 17% of the total land area with 48%



**Figure 4.** Average annual lightning stroke density (cloud-to-ground plus in-cloud) over Nepal on a grid of  $10 \times 10$  km from the Global Lightning Dataset GLD360 network from 2016 to 2020. More than one million strokes per year were detected. Source: Ryan Said.

of the population for the highest population density. Most permanent settlements in Nepal are at less than 400 m altitude.

### 3. Datasets

Lightning activity over Nepal has been continuously monitored in recent years by the Global Lightning Dataset GLD360, a global lightning network owned and operated by Vaisala, Inc. (Said 2017, 36–40, Said et al. 2010). The location accuracy of GLD360 during the three years of the map in Figure 2 is about 3 km, and the detection efficiency of cloud-to-ground flashes is over 60% for this region and time period.

Fatality and injury data were obtained from the Disaster Risk Reduction (DRR) portal of Ministry of Home Affairs (MoHA), Nepal. Fortunately, lightning is becoming recognized as one of the major natural hazards in Nepal (Nepal Times, 26 September 2020; ([www.nepalitimes.com/latest/abnormal-rise-in-monsoon-lightning-in-nepal/](http://www.nepalitimes.com/latest/abnormal-rise-in-monsoon-lightning-in-nepal/))). Nevertheless, it can be safely assumed that the data obtained from the DRR portal underestimate the true number as has been observed in many countries, including the United States (López et al. 1993, 2171–2178).

## 4. Lightning occurrence

### 4.1. Annual strokes across Nepal

Lightning occurs across all of Nepal (Figure 4); GLD 360 detected over one million strokes per year over the period of this study. The high mountains, stretching along the northern border with China from east to west, have the least lightning strokes

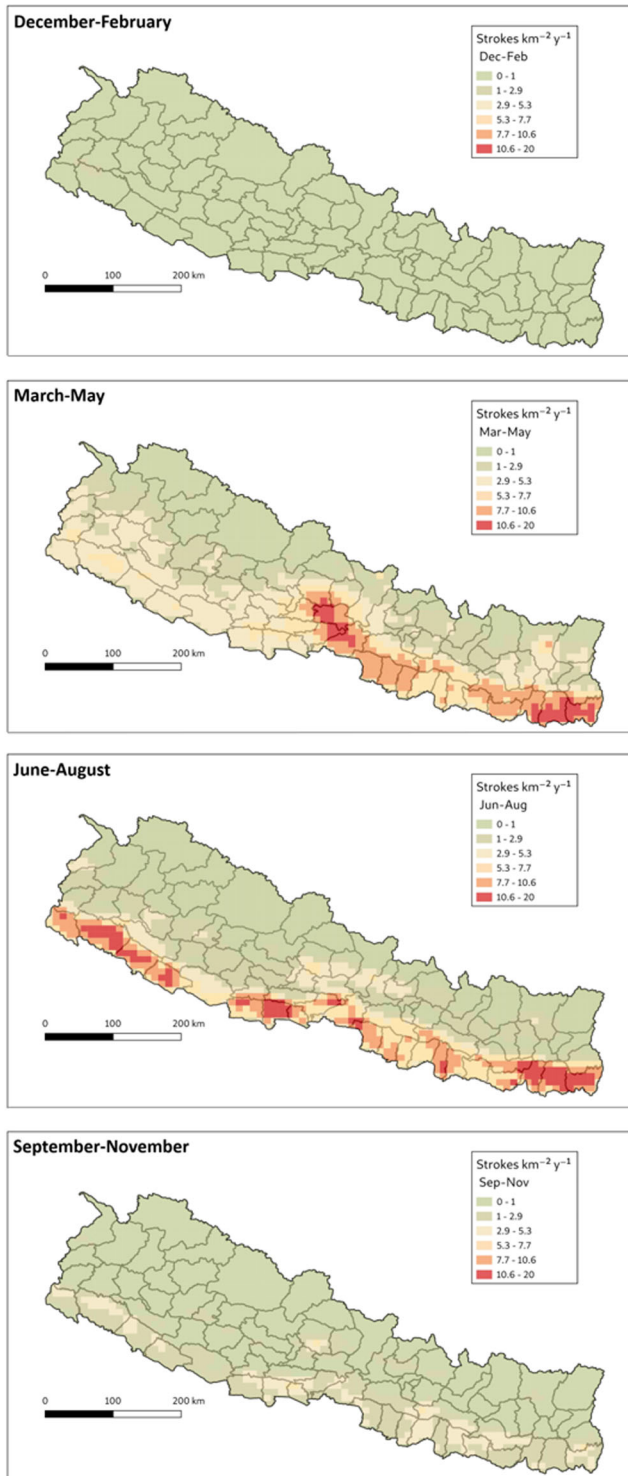
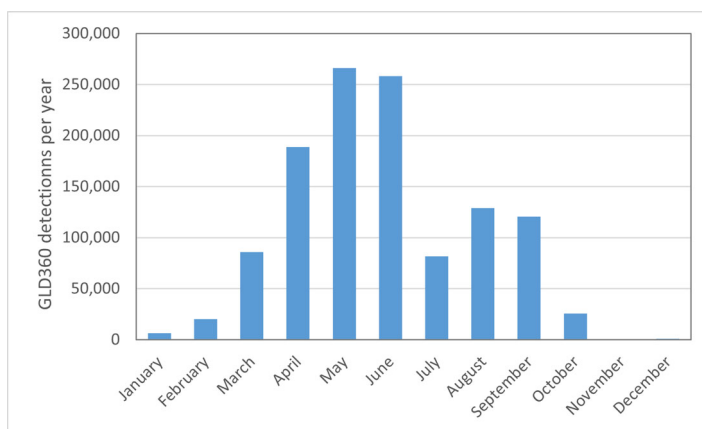


Figure 5. Same as Fig. 4 except by seasons. Source: Ryan Said.





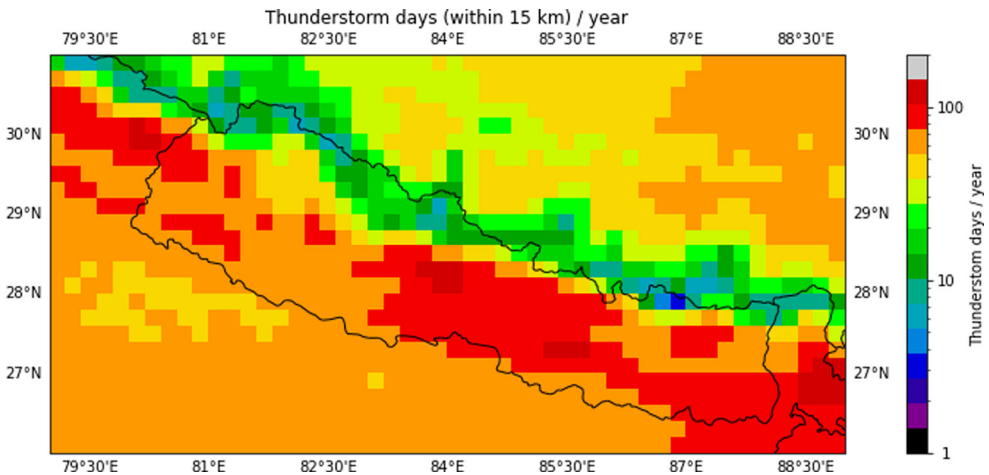
**Figure 6.** Monthly variation of lightning activity over Nepal from 2016 to 2020 as recorded by GLD360. Source: Ronald Holle.

(both cloud-to-ground and in-cloud). An intermediate stroke density of  $3\text{--}7$  strokes  $\text{km}^{-2} \text{y}^{-1}$  in the central region is over the Chure range of hills that extends from the Indus River of Pakistan in the west to the Brahmaputra River of India in the east. These Chure hills, also known as the Siwalik hills, are the southernmost foothills of Himalayas and have an average elevation from 600 m to 1220 m. Largest stroke densities exceeding  $22$  strokes  $\text{km}^{-2} \text{y}^{-1}$  are along the southern Nepal border, especially the southeast part of the country that receives the highest number of strokes.

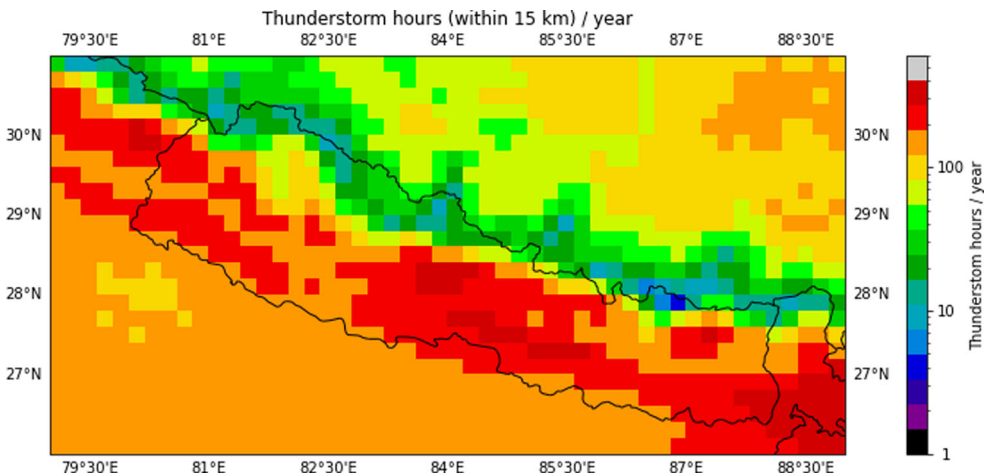
At the highest elevations, almost no thunderstorms occur due to insufficient low-level atmospheric water vapor content. To the south of the high mountains, there is an intermediate stroke density where low-level moisture impinges on the mountain slopes. The lightning maximum toward the southern border at the base of the major elevation change is caused by the terrain facing toward the influx of low-level moisture from the south during the pre-monsoon and monsoon seasons. This maximum has been observed to occur over all of the Indian Subcontinent (Nag et al. 2017, 6). All these lightning climatology features are also evident in Colombia (Navarrete-Aldana et al. 2014, 1349–1362), Venezuela, East Africa, the Andes, and Southeast Asia (Holle and Murphy 2017, 4559–4573).

#### **4.2. Seasonal, monthly, diurnal, and hourly variations of lightning strokes across Nepal**

By season, strokes in Figure 5 show that only 27,542 (23.3% of year) strokes occur per year during the winter months of December-February (top panel); the counts are highly variable from year to year. Lightning increases quickly to an average of 540,752 (45.7%) annual strokes during the pre-monsoon (March to May) in the second panel from the top of Figure 5 and is concentrated toward the southeast portion of the country. During the monsoon season from June through August (third panel from top), strokes are also frequent for an average of 468,705 (39.6%) per year and are most plentiful across all of the southern portion of Nepal. During this season, there is also heavy rainfall resulting in landslides, floods, and inundations. The post-

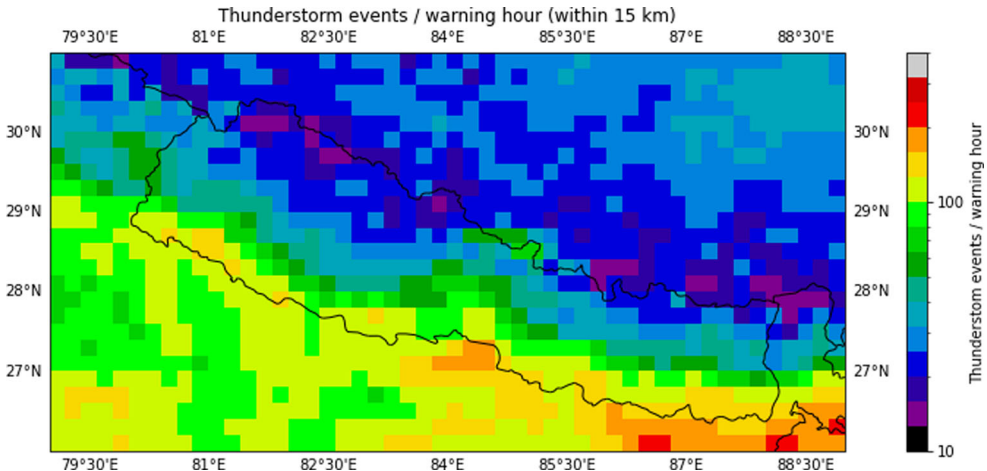


**Figure 7.** Thunderstorm days per year (within 15 km) obtained by GLD360 from 2015 to 2019. Source: Ryan Said.

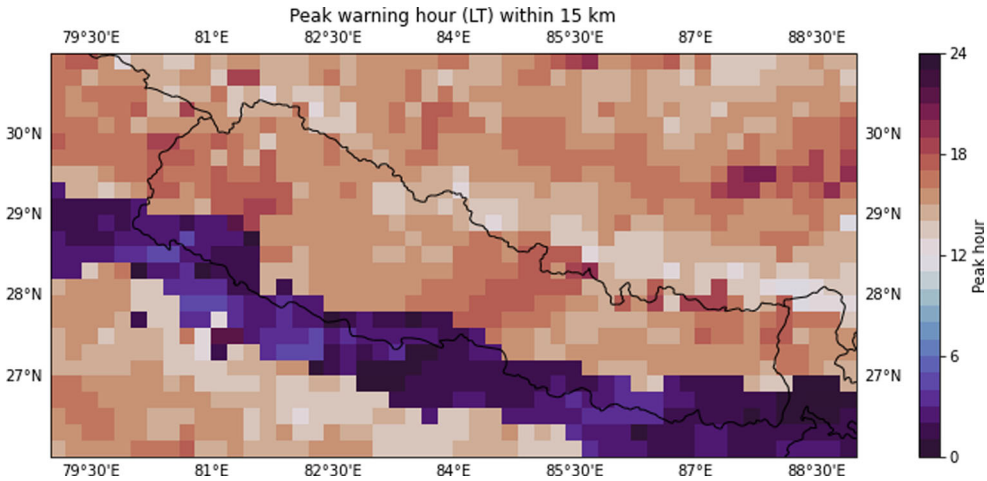


**Figure 8.** Thunderstorm hours per year (within 15 km) obtained by GLD360 from 2015 to 2019. Source: Ryan Said.

monsoon season from September through November (bottom [Figure 5](#)) has only 146,287 (12.4%) strokes annually. Lightning in the post-monsoon season and winter months is much more variable from year to year than during the pre-monsoon and monsoon seasons. Depicted in [Figure 6](#) is the monthly variation of lightning across Nepal. Differing with the results of Mäkelä et al. (2014, 91–99), we found that the lightning peaks during the month of May rather than June. However, the maximum lightning activity takes place during the months of April, May, and June, the peak pre-monsoon months. Shown in [Figure 7](#) is the number of thunderstorm days per year, where at each location, a thunderstorm day is defined as any day with at least two lightning strokes within 15 km. As is seen from [Figure 7](#), the southeastern border and central part of Nepal observe maximum thunderstorm days with over 100 days per year, whereas the northern mountains observe around 10 thunderstorm days per year.



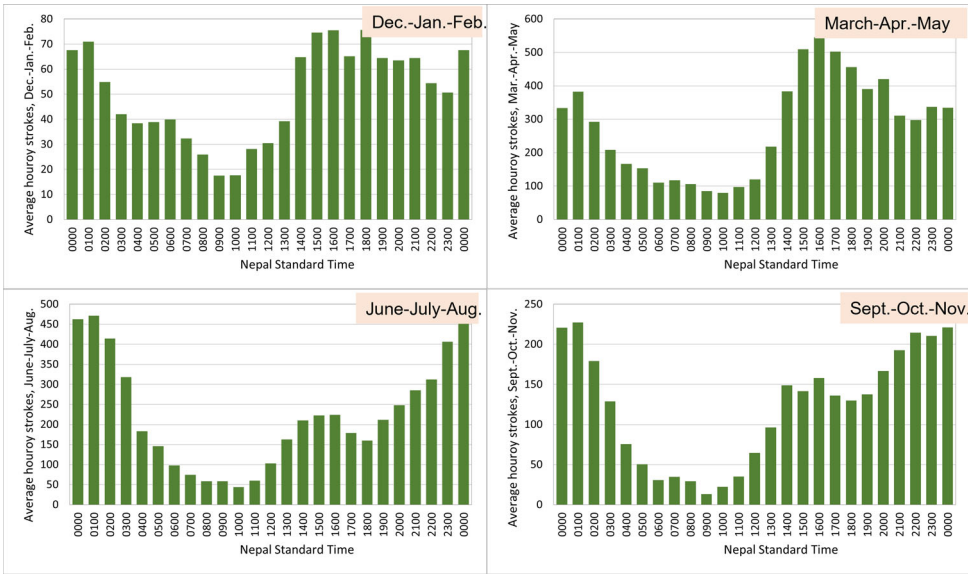
**Figure 9.** Thunderstorm events per warning hours (within 15 km) obtained by GLD360 from 2015 to 2019. Source: Ryan Said.



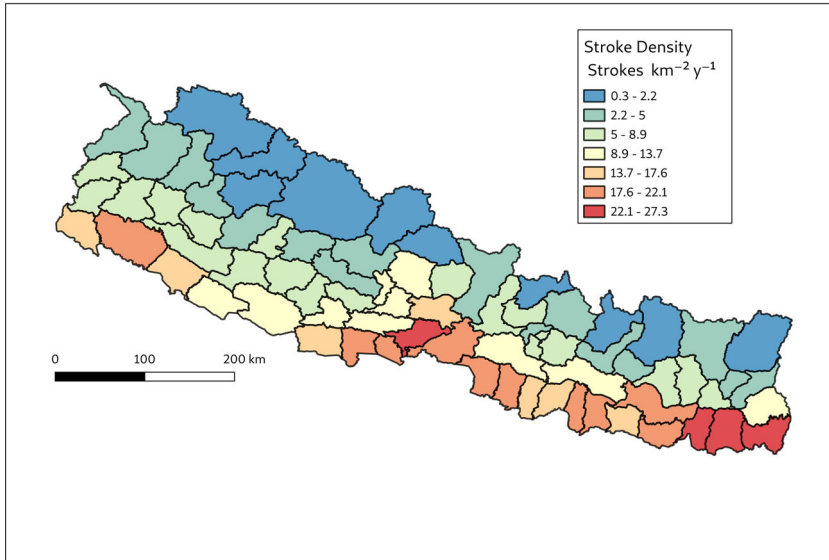
**Figure 10.** Thunderstorm peak warning hour (within 15 km) obtained by GLD360 from 2015 to 2019. Source: Ryan Said.

In addition to the lightning incidence maps, we analyzed the number of hours with at least two lightning detections within 15 km during an hour (DiGangi et al. 2021). Figure 8 shows the number of hours with lightning to exceed 300 in several regions. All of these maxima are in the middle-altitude regions of Nepal, and are located to the northwest of the national border, as well as in central and especially southeast locations.

To estimate the annual lightning threat at any place in both time and space, we assume each location has a warning system that issues an alert for any lightning within 15 km, and a warning hold-time of 10 min after the last lightning event in a thunderstorm within this range. The accumulated warning hours (not shown) are very similar to the thunderstorm hours in Figure 8. Figure 9 combines the accumulated warning hour and lightning density data to show thunderstorm events per warning hour.

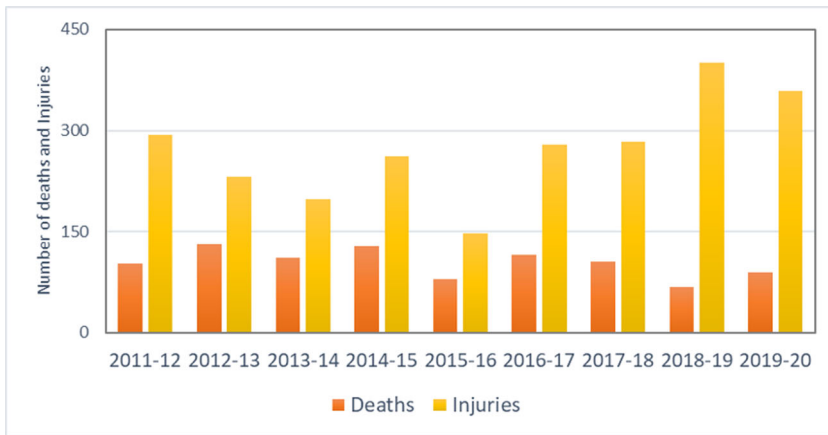


**Figure 11.** Hourly variation of thunderstorm activity over the four major seasons obtained by GLD360 from 2016 to 2020. Top left shows winter season, top right shows pre-monsoon period, bottom left shows monsoon season, and bottom right shows post monsoon season. Source: Ronald Holle.



**Figure 12.** Same as Figure 4 except for the 77 districts of Nepal (density per sq. km of the corresponding district). Source: John Cramer.

The ratio between event density and total warning duration gives a sense of the average event intensity per unit warning time. Higher values mean there is more lightning per active thunderstorm hour. The intensity drops significantly towards the mountains, which is probably why the event density remains the more relevant metric from a safety standpoint compared to accumulated warning durations.



**Figure 13.** Annual lightning fatalities and injuries in Nepal from 14 April 2011 through 15 April 2020. Source: Shriram.

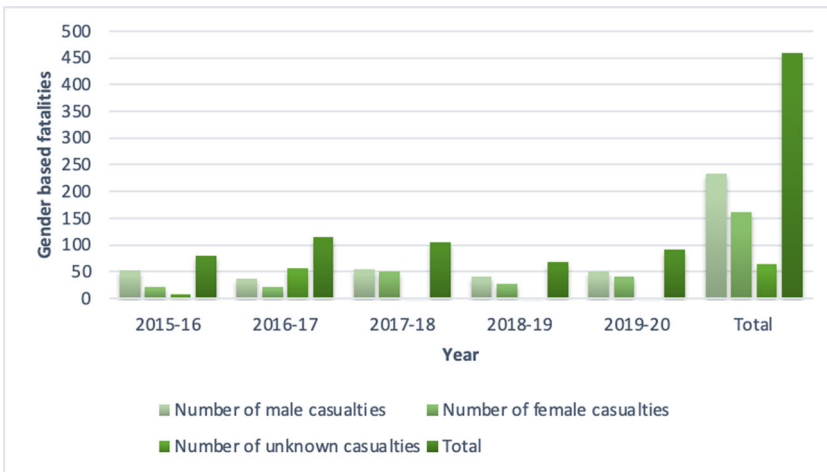
Finally, we have plotted the peak warning hour across Nepal in [Figure 10](#). The peak warning hour is the local time at which the largest number of lightning impact hours were detected. While most of the country sees the typical late afternoon peak, there is a strip of midnight to early morning peak activity from west-northwest to east-southeast along the base of the high mountains. The average hourly variation of thunderstorm activities has further been divided for each season and is depicted in [Figure 11](#). Here, the thunderstorm activity is high from midnight to early morning, whereas it is relatively very low between 0600 and 1200 local time. It should also be noted that the thunderstorms activity peaks at about 1600 during winter and pre-monsoon though the activity continues in the winter and slightly decreases during the pre-monsoon. However, thunderstorm activity peaks during nighttime and around midnight in the monsoon and post-monsoon periods ([Figure 11](#)).

#### 4.3. Strokes by district of Nepal

Another depiction of the annual stroke patterns is by district in [Figure 6](#) rather than the grids in [Figures 4](#) and [5](#). [Figure 12](#) indicates that districts in the northern border districts at high elevations ([Figure 2](#)) have very small stroke densities. In contrast, the most lightning is in the south and especially east. This district stroke density map can be compared with population by district in [Figure 3](#) and other district-level maps to be shown later in this study.

### 5. Lightning fatalities and injuries

In the last nine years, an average of 103 people were killed by lightning each year and 273 people injured ([Figure 13](#)) in Nepal. The total for this period is 930 deaths and 2,454 injuries. Of the 495 deaths with reported gender (53.2% of the total); 50.8% are male and 35.3% are female; 14% were not identified. The fatality data prior to 2015 with gender division was not available from the DRR portal and hence could



**Figure 14.** Gender based lightning fatalities between April 2015 and April 2020. The fatalities data prior to 2015 with gender division was not available from DRR portal. Source: Shriram.

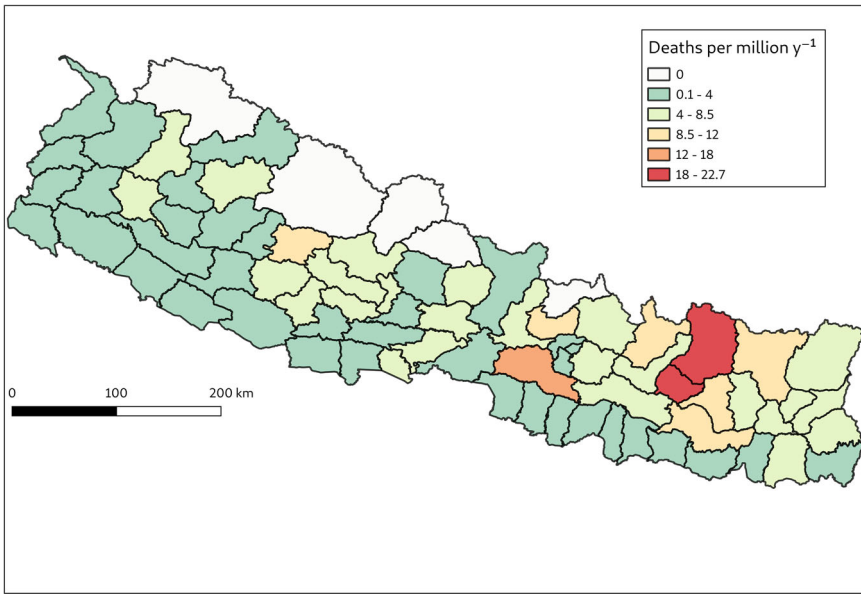


**Figure 15.** Locations of 883 lightning fatality incidents in Nepal from 14 April 2011 through 15 April 2020; some represent more than one death and 47 fatalities could not be located as the information acquired from the DRR portal MoHA were unclear about the location. Source: Ramji Jaisi Bhusal.

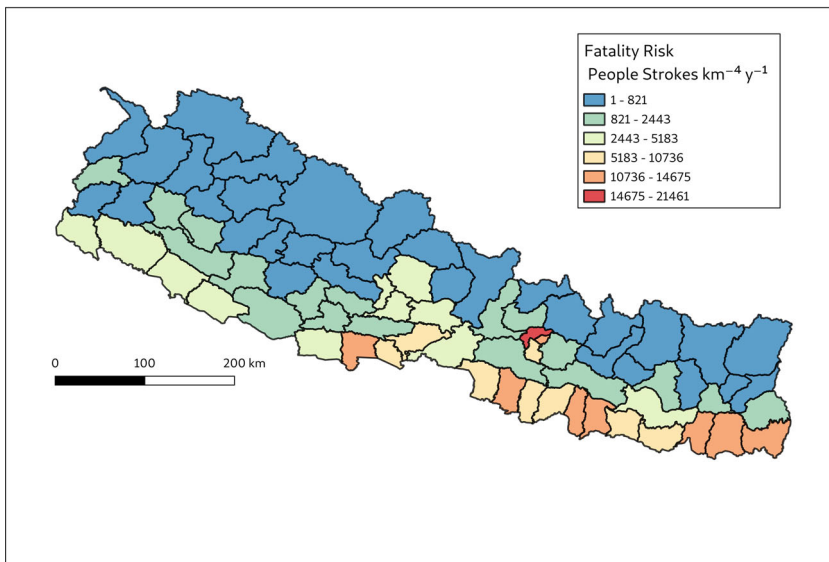
not be included in the analysis. This is an indicative of more males being engaged in the outdoor activities than that of females. The largest number of casualties (131) was recorded in the year 2012/13 and the least number (68) in 2018/19. This results in a fatality rate of 3.8 deaths per million people per year, which is positioned in the intermediate rate of between 0.5 and 5.0 deaths per million frequently observed in the developing nations (Holle 2016, 35–42).

An analysis of the gender division of lightning fatalities from the available data shows that lightning kills more males than women (Figure 14).

Specific locations of incidents involving at least one lightning fatality are shown in Figure 15. It is readily apparent that no lightning deaths were reported during these nine years in some northwestern districts, while the events were more common along the southern and especially eastern districts.

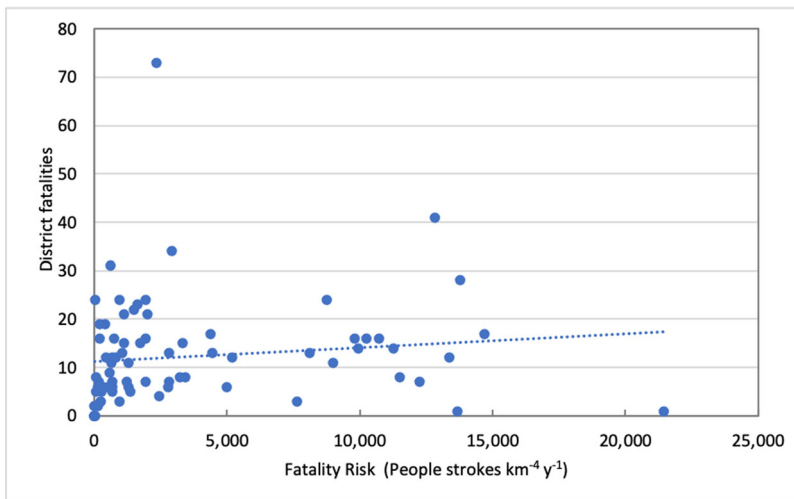


**Figure 16.** Annual fatality rate per million people by district of Nepal from 14 April 2011 through 15 April 2020. Source: John Cramer.



**Figure 17.** Lightning Fatality Risk by district of Nepal from 14 April 2011 through 15 April 2020. Units are people strokes  $\text{km}^{-4} \text{y}^{-1}$ . Source: John Cramer.

By district, [Figure 16](#) shows the spatial distribution of lightning fatality rates in the same district format as previous figures. Out of the 930 fatalities, 65 fatalities are reported from the mountainous districts (6.65 fatalities per million per year); none are from the high mountains above 6000 m. A total of 566 are reported from the hilly region and 303 fatalities from the Terai plains region. In summary, most of the fatalities are reported from the lesser Himalayas and Siwalik hills region (10.70 fatalities



**Figure 18.** Lightning Fatality Risk versus reported fatalities by district of Nepal from 14 April 2011 through 15 April 2020. Blue dashed line is correlation between district fatalities and Lightning Fatality Risk. Source: Ronald Holle.

per million per year). The fatality rate for the hilly (lesser Himalayas and Siwalik) region is 8.68 (an average of Himalayan districts and hilly districts) deaths per million people per year while the fatality rate is 2.23 deaths per million people per year for the plains (Terai) region – less than half that of the hilly region. The two districts with the highest rates in [Figure 16](#) are Okhaldhunga (southern, smaller) and Solukhumbu (northern, larger).

## 6. Lightning fatality risk

It is now possible to combine these datasets to explore the lightning risk to people in Nepal by district. It was found in Roeder et al. (2015, 1681–1692), that a parameter termed Lightning Fatality Risk showed skill in identifying regions with the most reported deaths in the U.S. For Nepal, Lightning Fatality Risk is plotted by district in [Figure 17](#). It is the product of population density from [Figure 3](#) in people  $\text{km}^{-2}$  and stroke density from [Figure 4](#) in strokes  $\text{km}^{-2} \text{y}^{-1}$ . Lightning Fatality Risk has the unusual unit of people strokes  $\text{km}^{-4} \text{y}^{-1}$ . In [Figure 17](#), all districts at the northern higher elevations have very low Lightning Fatality Risk values due to both low population and stroke densities. The largest Lightning Fatality Risk in the east-central district shown in red shading includes the populous capital city of Kathmandu ([Figure 2](#)). Other districts with large Lightning Fatality Risk values are along the southern border, especially to the east.

How often Lightning Fatality Risk can anticipate actual fatalities is explored in [Figure 18](#). It has not turned out well in this attempt, as the correlation coefficient is only 0.12098. This is shown graphically by the blue dashed line in [Figure 18](#) where the relationship between deaths and Lightning Fatality Risk is minimal. The largest number of deaths is 52 in the Makawanpur district located directly south of Kathmandu and shaded red in [Figure 17](#); however, the stroke density here is quite



low (Figure 4) so Lightning Fatality Risk is weak. In contrast, the largest Fatality Risk of 21,461 people strokes  $\text{km}^{-4} \text{y}^{-1}$  is in the Kathmandu district where only one death was reported. Many of the districts in Figure 18 have both small numbers of lightning deaths and Lightning Fatality Risk. There is a cluster of intermediate values of less than 30 deaths and a Lightning Fatality Risk between 7500 and 15,000  $\text{km}^{-4} \text{y}^{-1}$  that shows no particular trend.

## 7. Discussion

This is the first published result calculating Lightning Fatality Risk on a scale such as a district level for a nation. A much smaller (8 by 10 km grid) was used by Roeder et al. (2015, 4559–4573), for U.S. population than the districts shown here for Nepal; many districts have areas in the range of 1000  $\text{km}^2$ , so they are much larger than employed in the U.S. study. It had been expected that the results would be better since the Nepalese districts are not especially large. It is possible that introducing factors such as farming percentage and quality of housing may improve this relationship. Since those data are not currently available for Nepal on a district level, that supposition could not be considered further at this time. Nevertheless, the newly explored investigation on peak warning hour in Figure 10 explains to some extent why the Lightning Fatality Risk is weak. Since the peak warning hour falls between midnight to early morning, when there is no outdoor activity, the fatality risk certainly decreases. The nighttime peak warning hour can be explained as storms from the west of Nepal move rapidly to the east-southeast, along the foothills of Himalayas, during the night-time hours. Unfortunately, these storms arrive in Bangladesh around sunrise and last until noon, which coincides with the time of major farming activities during the pre-monsoon (Holle et al. 2019).

There appear to be other reasons that contribute to the human lightning fatalities across Nepal that include:

- I. Most people in the hilly regions live in houses with roofs thatched with hay and similar material. Such houses provide no protection against lightning (Gomes et al. 2012, 11; Cooper and Holle 2018, 233).
- II. The people living in the hills tend to make their livelihood from labor-intensive agriculture and other outdoor activities that are fully exposed to thunderstorms.
- III. There is an acute lack of awareness raising programs and training chiefly due to the fact that they are very sporadic and scattered with no mass casualties and are therefore not widely reported.
- IV. Unavailability of early warning system or forecasting systems.

Taking the percentage of farming participation into account along with stroke destiny was somewhat beneficial in explaining district-level fatality rates in Bangladesh (Holle et al. 2019, 15). Combining the factors of housing and activity in Nepal, people in this middle hilly district have no or few safe areas to seek refuge and are exposed to lightning without the opportunity to move to a safe alternative. Although there are some urban and suburban areas in the hilly region, there are few houses constructed with metal components such as steel rebar that provide protective shelters.

## 8. Conclusions

Most of Nepal is clad with high hills and mountains. The mountainous region has both a sparse population and minimal lightning occurrence, resulting in fewer fatalities, as would be expected. The fatality rate of the middle hilly region is twice that of the southern plains region, despite the plains region having both a considerably higher population density and lightning stroke density. This can be expected as the lightning peak warning hour passes over the southern plains during nighttime hours. However, on a district scale, the relationship between the number of lightning deaths with the density of people living where there is a large stroke density is minimal.

Clearly, there is an acute need for the development of effective, inexpensive lightning protection systems to be installed for each house, particularly in the hilly region (Gomes et al. 2012, 11; Cooper and Holle 2018, 233). Additionally, extensive lightning awareness-raising and safety programs should be conducted throughout the hilly regions. The present study helps define these regions to emphasize.

The outcome of this study, under the topic of lightning occurrence can be very helpful in the mitigation of human fatalities in Nepal and can be an example for other researchers in various countries across the globe. The new exploration into the perspective of occurrence of thunderstorm activity provides us with the following information:

- I. Lightning activity across Nepal peaks during the pre-monsoon (April-June) and maximum lightning occurs during May.
- II. The middle and southeast part of country observe maximum thunderstorm days of over 100 per year within 15 km.
- III. Peak warning month for the hilly region is May, whereas that for the southern plains (Terai) is June.
- IV. The southern plains and middle hills observe maximum thunderstorm hours that may reach to about 300 hours per year within a 15-km range.
- V. The peak warning hour for the southern part (plain region) falls from midnight to early morning, whereas that for the hilly region begins at around 1500 and ceases by around 2000.
- VI. One of the most important outcomes that has been explored is that the lightning activity is weakest during the morning hours (0500–1200) throughout the year. This information can be very instrumental for scheduling the outdoor agricultural activities avoiding the thunderstorm hours.

## Acknowledgments

This research work was partly supported by Worldwide Wildlife Fund (WWF)'s Hariyoban Programme and partly supported by International Science Program (ISP) of Uppsala University, Sweden under Nep01.

## Disclosure statement

No potential conflict of interest was reported by the authors.

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## Data availability statement

The lightning fatality data used in this manuscript were obtained from the Disaster Risk Reduction portal of Ministry of Home Affairs, Government of Nepal and is publicly accessible from <http://drrportal.gov.np/>. Lightning occurrence data used in the research were obtained from Vaisala Inc. and can be made available upon request to Vaisala.

## References

- Adhikari BR. 2021. Lightning fatalities and injuries in Nepal. *Weather Climate Soc.* 13(3): 449–458. doi:10.1175/WCAS-D-20-0106.1.
- Barros AP, Lang TJ. 2003. Monitoring the monsoon in the Himalayas: observations in central Nepal. *Mon Wea Rev.* 131(7):1408–1427.
- DiGangi EA, Stock M, Lapierre J. 2021. Thunder hours: How old methods offer new insights into thunderstorm climatology. *Bull Amr Meteor Soc.* 102. <https://journals.ametsoc.org/view/journals/bams/aop/BAMS-D-20-0198.1/BAMS-D-20-0198.1.xml>.
- Cardoso I, Pinto O, Jr., Pinto IRCA, Holle R. 2014. Lightning casualty demographics in Brazil and their implications for safety rules. *Atmos Res.* 135–136:374–379.
- Gomes C, Kadir MZA. a. 2011. A theoretical approach to estimate the annual lightning hazards on human beings. *Atmos. Res.* 101(3):719–725.
- Gomes C, Ab Kadir MZA, Cooper MA. 2012. Lightning safety scheme for sheltering structures in low-income societies and problematic environments. Preprints, Intl. Conf. Lightning Protection, Vienna, Austria, 11.
- Cooper MA, Holle RL. 2018. Reducing lightning injuries worldwide. New York: Springer Natural Hazards, p. 233. [10.1007/978-3-319-77563-0](https://doi.org/10.1007/978-3-319-77563-0).
- Doljinsuren M, Gomes C. 2015. Lightning incidents in Mongolia. *Geomatics Nat Hazards Risk.* 6(8):686–701.
- Holle RL. 2016. A summary of recent national-scale lightning fatality studies. *Weather, Climate and Society.* 8(1):35–42.
- Holle RL, López RE. 2003. A comparison of current lightning death rates in the U.S. with other locations and times, Preprints. Intl. Conf. Lightning and Static Electricity, Blackpool, U.K., Royal Aeronautical Soc., P103–34 KMS, p. 7.
- Holle RL, Murphy MJ. 2017. Lightning over three tropical lakes and the Strait of Malacca: Exploratory analyses. *Mon Wea Rev.* 145(11):4559–4573.
- Holle RL, Dewan A, Said R, Brooks WA, Hossain MF, Rafiuddin M. 2019. Fatalities related to lightning occurrence and agriculture in Bangladesh. *Int J Disaster Risk Reduct.* 4:15.
- López RE, Holle RL, Heitkamp T, Boyson M, Cherington M, Langford K. 1993. The underreporting of lightning injuries and deaths in Colorado. *Bull Amer Meteor Soc.* 74(11): 2171–2178.
- Mäkelä A, Shrestha R, Karki R. 2014. Thunderstorm characteristics in Nepal during the pre-monsoon season 2012. *Atmos. Res.* 137:91–99.
- Nag A, Holle RL, Murphy MJ. 2017. Cloud-to-ground lightning over the Indian subcontinent. Preprints, 8th Conf. on the Meteorological Applications of Lightning Data, Seattle, Washington, Amer. Meteor. Soc., p. 6.
- Navarrete-Aldana N, Cooper MA, Holle RL. 2014. Lightning fatalities in Colombia from 2000 to 2009. *Nat Hazards.* 74(3):1349–1362.
- Roeder WP, Cummins BH, Cummins KL, Holle RL, Ashley WS. 2015. Lightning fatality risk map of the contiguous United States. *Nat Hazards.* 79(3):1681–1692.
- Saha K, Damase NP, Banik T, Paul B, Sharma S, De BK, Guha A. 2019. Satellite-based observation of lightning climatology over Nepal. *J Earth Syst Sci.* 128:221.
- Said R. 2017. Towards a global lightning detection system. *Weather.* 72(2):36–40.
- Said RK, Inan U, Cummins KL. 2010. Long-range lightning geolocation using a VLF radio atmospheric waveform bank. *J Geophys Res.* 115(D23):D23108. .