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Chapter 1

Lightning Occurrence and Social Vulnerability

Ronald L. Holle and Mary Ann Cooper

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Abstract

The occurrence of lightning in time and space around the world is well known. Lightning fatalities and injuries are well delineated in the United States; however, there is much less information about lightning impacts on people in the developing world. It is estimated that between 6000 and 24,000 people are killed globally per year, and 10 times as many are injured. The fatality rate per capita has become very low in the developed countries during the past century due to the availability of lightning-safe structures and vehicles, less labor-intensive agriculture, and other factors, but this reduction has not occurred where people continue to work and live in lightning-unsafe situations. Lightning safety advice often mistakenly expects that the direct strike is most common, but ground current, direct contact, side flash, and upward streamers are much more frequent mechanisms. In developed countries, the injury:death ratio is approximately 10:1, meaning that 90% survive but may have permanent disabling injuries. The proximate cause of death is cardiac arrest and anoxic brain injury at the time of the lightning strike, and, at this time, the damage from a lightning strike cannot be reversed or decreased in survivors. Lightning vulnerability in many developing countries continues to be a major issue due to widespread exposure during labor-intensive agriculture during the day when thunderstorms are the most frequent and while occupying lightning-unsafe dwellings at night.

Keywords: lightning, lightning strikes, lightning fatalities, lightning safety, lightning occurrence

1. Introduction

More lightning occurs in clouds than that strikes the ground; and as the cloud moves above the earth, opposite charges are induced on the surface of the earth and on objects on the ground under the cloud. Upward streamers, not usually visible from these objects, will reach up and attempt to connect with the downward-moving lightning channel. A cloud-to-ground flash has one or more return strokes. When you see lightning flickering, those are return strokes within the same flash. There are about four strokes per flash, when averaged over a large sample size. The first stroke comes faintly to ground and contacts the surface of the earth. The stroke may attach to a tree, open land, the ocean, or other objects. Then the light fills the channel going upward. The next stroke in the flash will likely come down from the cloud to the ground in the same channel as the first stroke, and so on. Occasionally, one of the subsequent strokes will stray from the pre-existing channel and come to ground one or two kilometers away.

One of the important features of this well-known mechanism of lightning strikes is the search radius. The cloud-to-ground channel makes its way downward in step leaders of about 50-m lengths (**Figure 1**). At the lower tip of each step, the channel searches for a feature that makes a convenient connection to ground. Higher up in the cloud, there is nothing to strike, so the step leader keeps coming toward the ground as each step attempts to reach out and connect to the ground. Branching occurs that is generally downward. Only when the lowest tip of the channel is 30–50 m from the surface of the earth does it 'decide' what to strike. This last step leader, not usually visible from a distance, is nearly vertical and connects one of the upward streamers emanating from objects such as trees, poles, and sometimes open water. The most likely connections will be made to objects that are tall, isolated, and pointed. But if that object is more than 30–50 m away from the lowest tip of the downward leader, the lightning channel may come all the way to ground, close to a tall building or tower.

Figure 1. Cloud-to-ground lightning photographed from Oro Valley, Arizona, USA (©R. Holle).

2. Lightning occurrence

The location, time of year and day, and number of lightning occurrences throughout the world are known quite well. **Figure 2** shows the latest 10-year map of the United States cloud-to-ground flash density per square kilometer. With respect to time of day, about two-thirds of lightning occurs during the afternoon from noon to 1800 local time. Cloud-to-ground lightning is the most frequent along the coasts of Florida and the Gulf of Mexico, and generally decreases to the north and west as the number of days with substantial low-level moisture decreases in frequency. Large variations in lightning frequency also occur in the western states where large elevation changes affect thunderstorm formation.

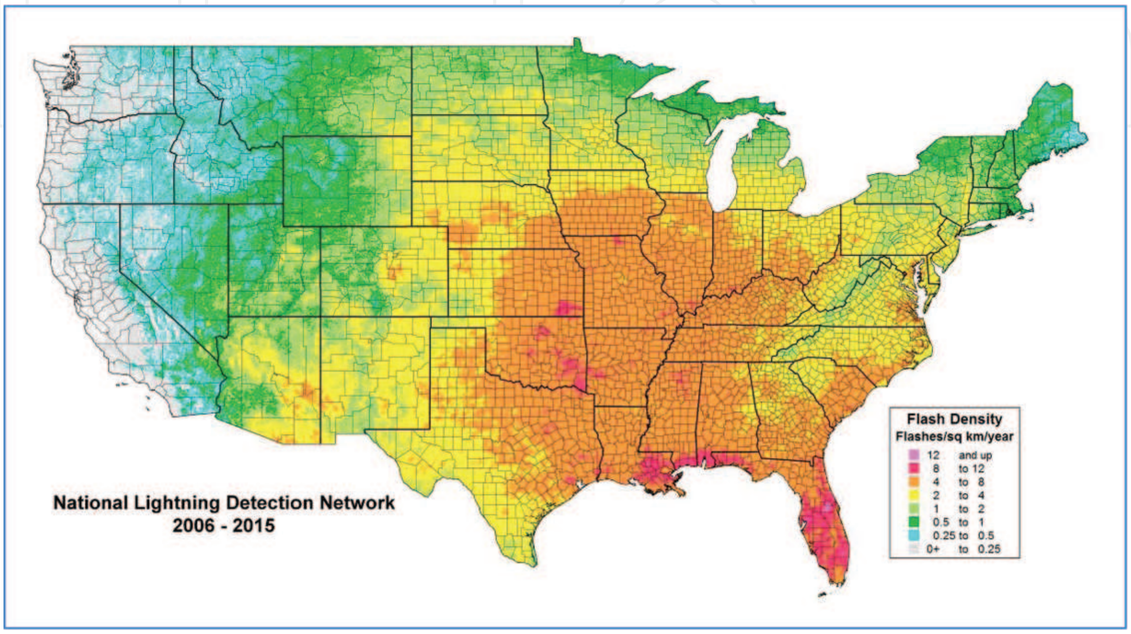

Figure 2. Cloud-to-ground flash density per square kilometer per year over the contiguous United States from the National Lightning Detection Network from 2006 through 2015 (Courtesy Vaisala, Inc.).

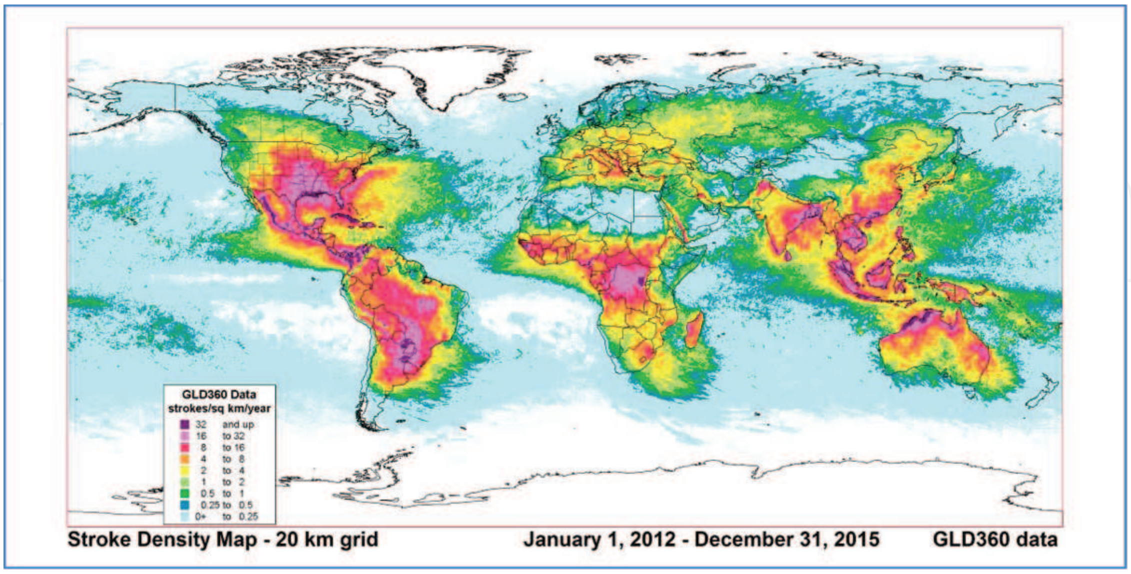

Figure 3. Lightning stroke density per square kilometer per year over the world from the Global Lightning Dataset GLD360 from 2012 through 2015 (Courtesy Vaisala, Inc.).

Figure 3 shows the global occurrence of lightning strokes. The highest densities are over tropical and subtropical coastlines, near large elevation changes, and east coasts at middle latitudes. The lowest lightning frequency is over oceans, the polar regions, and west coasts at middle latitudes. The dominance of land lightning is due to daytime heating that can produce updrafts rising to altitudes where temperatures are colder than freezing, the altitudes where lightning initiates. Since much of outdoor human activity occurs during daytime, the juxtaposition of lightning with people can be expected to result in fatalities and injuries.

Nearly everywhere in the world has a season with more lightning than others. In the middle latitudes about two-thirds of lightning occurs during meteorological summer (June, July, and August in the Northern Hemisphere and December, January, and February in the Southern Hemisphere). In the Tropics, the passage of the equatorial trough or the summer monsoon strongly affects the frequency of lightning. The equatorial trough (also known as the Intertropical Convergence Zone, or ITCZ) is a somewhat continuous east-west area of rain and thunderstorms that stays within about 20 degrees latitude of the equator, shifting northward (southward) during the Northern (Southern) Hemisphere summer. For locations near the equator, the equatorial trough crosses locations twice a year which can result in two rainy seasons whereas more subtropical locations have only a single rainy season. The Asian Monsoon can be considered to be a variation of the equatorial trough that is strongly affected by the large land mass of Asia and the Himalayas. The equatorial trough generally moves northward in the Northern Hemisphere summer and brings tropical moisture from the south, often resulting in higher thunderstorm and lightning frequencies, and then reverses to send dry air flowing from the north during the Northern Hemisphere winter when lightning occurrence is much less likely.

3. Lightning fatalities and injuries

3.1. United States fatalities and injuries

According to the U.S. National Weather Service (NWS), lightning fatalities have averaged 32 per year over the past decade. **Figure 4** shows the latest decade of available fatality data with the top panel showing the number of fatalities by state while the lower panel indicates the fatality rate per million people. The fatality rate turns out to be rather different from the actual number of fatalities, and indicates how the number of lightning flashes and the number of fatalities are related, but not as directly as may be expected. States with the highest fatality rates in the western United States appear to indicate a region with drier air and lower rainfall rates that give the perception that lightning is not as much of a threat as when it is raining heavily in other locations in the United States.

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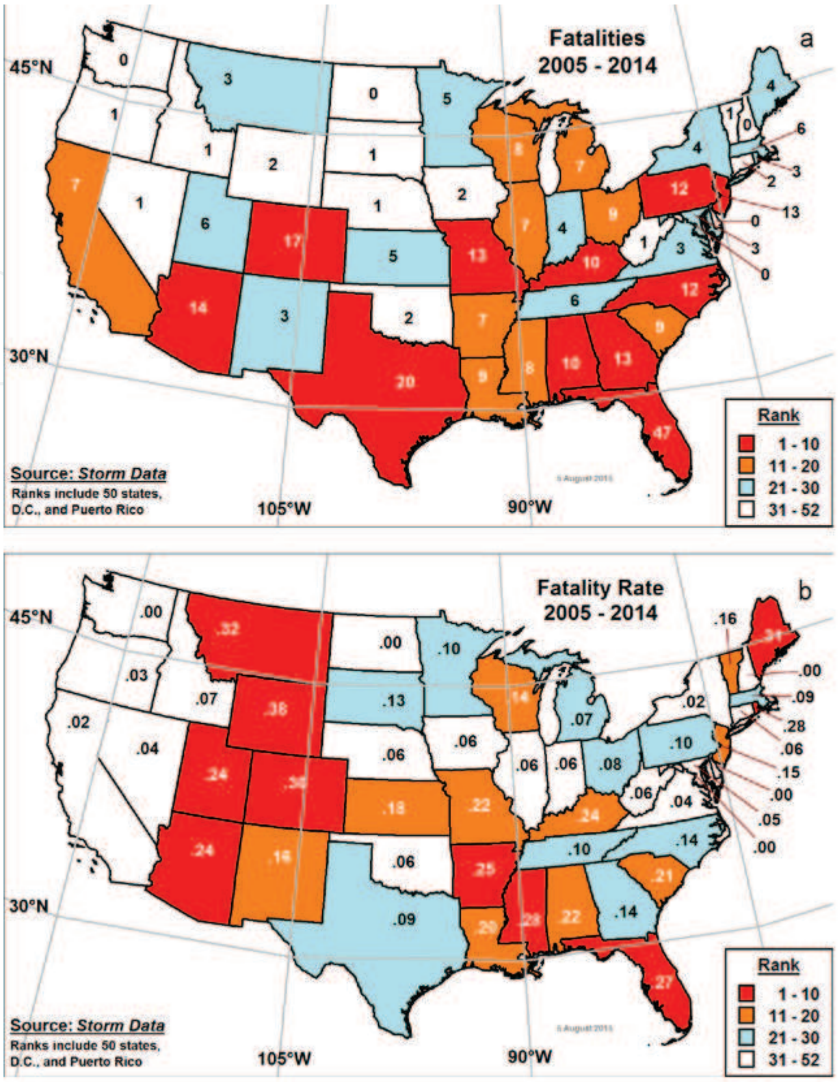

Figure 4. Ranks of lightning fatalities per state (a) and fatality rate per million people (b) from 2005 through 2014 based on the United States National Weather Service website [2].

The necessary ingredients of lightning frequency and population density in the United States have been combined in a recent study that is able to replicate the primary locations of observed lightning fatalities [1]. This approach shows the concentration of fatalities in urban areas that have moderate to high lightning frequencies. Such a study has not yet been attempted in other countries where the lightning risk is very different due to such factors as the availability of lightning-safe buildings and vehicles, agricultural participation, and related societal differences.

Underreporting of lightning casualties has been a problem in past years in the United States, but much less in the past couple of decades. A primary reason for underreporting is that about 90% of all lightning fatalities and injuries are to one person at a time, which leads to the tendency for such events to be reported less often in the media than multiple-casualty events. With the inception of the Lightning Safety Awareness Team, a multidisciplinary group sponsored by the National Weather Service, it is probable that every fatality is documented [2], but an estimate is that only about 70% of the injuries reach the reporting system that is maintained by all NWS offices across the country. An additional issue is that underreporting may seem to be occurring when there is actually a definition issue. The National Weather Service in its *Storm Data* publication does not include secondary casualties due to lightning. For example, a house caught on fire at night due to lightning that results in a fatality or injury is not counted as a lightning impact, since the primary cause is coded as fire not lightning. A useful method for estimating injury underreporting is the ratio of injuries to deaths. An intensive study over three full years across the state of Colorado showed that about ten injuries occur per fatality [3]. When the ratio is less than ten, an indication exists that not enough injuries have been reported and documented. The 10:1 injury:death ratio is assumed to apply to the United States and more developed countries with their similar socio-economic infrastructures, providing widespread availability of lightning-safe buildings and vehicles.

The lightning fatality rate per million people in the United States has dropped by more than two orders of magnitude since 1900 (**Figure 5**). Similar trends have been observed in many more developed countries of the world with published lightning fatality rates during the same period [4]. Also shown is the rural percentage of the population, which decreased from 60% in 1900 to fewer than 20% at present. The United States population not only transitioned out of a mainly labor-intensive agricultural society a century ago, but also moved into more substantial home and workplace buildings with grounded wiring and plumbing, together with the ready availability of fully enclosed metal-topped vehicles, better medical care, and greatly improved meteorological information about thunderstorms. All of these factors are present in more developed countries that have lower lightning death rates.

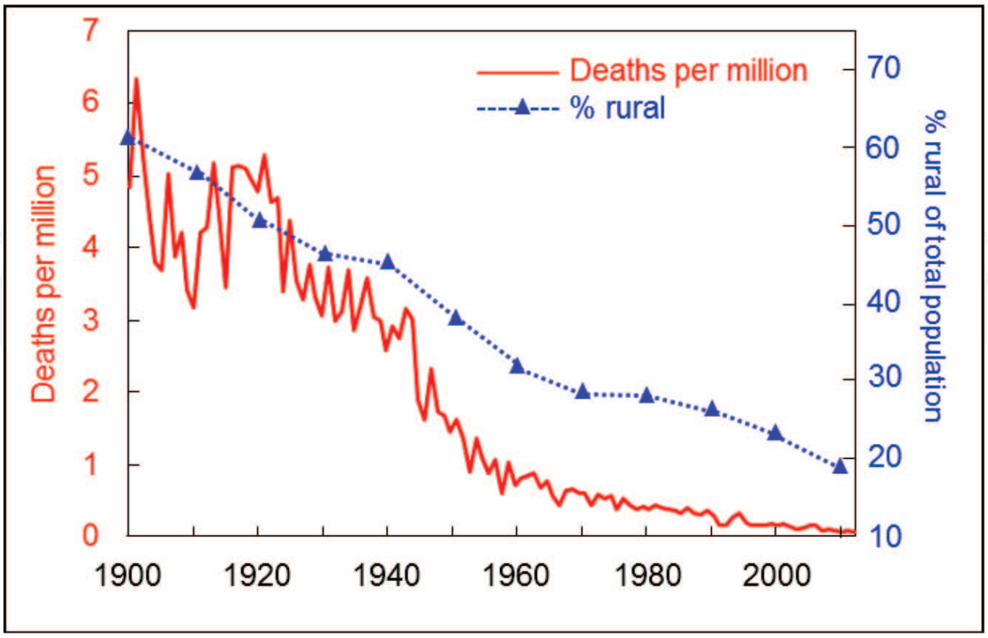

Figure 5. Solid red line: United States lightning deaths per million people from 1900 to 2013. Dashed blue line: percent rural population.

Figure 6 graphs United States lightning fatality types one hundred years apart, comparing the 1890s (top) with the 2005–2014 period (bottom). During the late nineteenth century, being indoors was the most common situation for lightning fatalities, while agriculture and outdoors were also a large component of the events. During the decade starting in 2005, indoor fatalities have become quite rare, agriculture events have greatly reduced from a century ago as farming became mechanized, and lightning-safe buildings and vehicles became common. Recreation and sports situations are relatively more frequent now than earlier. However, the overstated scenario of golf fatalities has been exceeded substantially in recent years by hiking, climbing, boating, and other water-related activities [2].

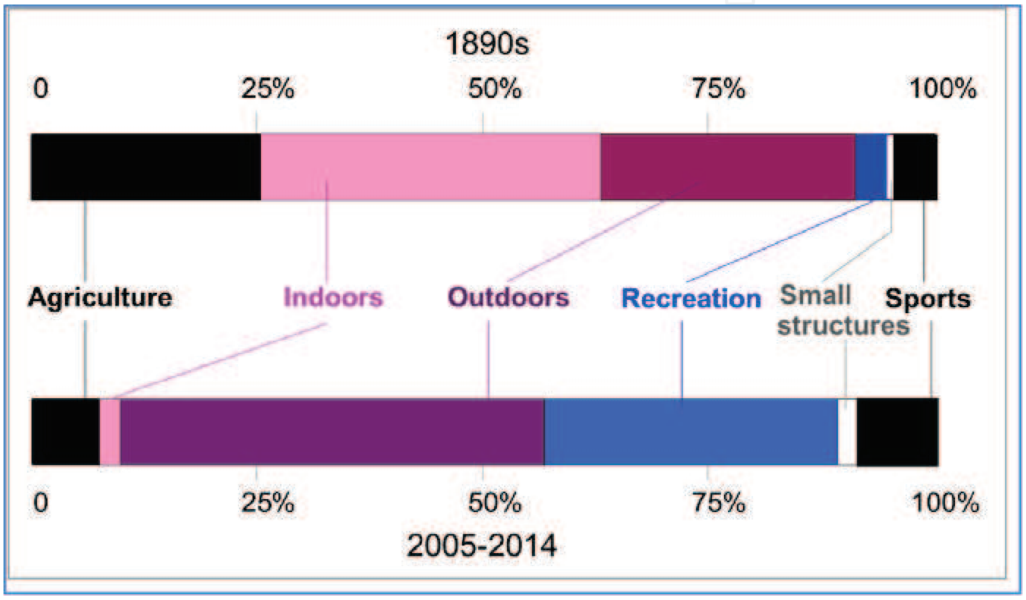

Figure 6. Comparison of the percentage of types of the United States lightning fatalities in the 1890s versus 2005 through 2014 [20].

3.2. Global fatalities and injuries

Worldwide, **Figure 7** shows information on lightning fatality rates that has been collected in a number of countries during the last quarter century; nevertheless, significant gaps exist in our knowledge of the absolute numbers [4]. Studies have estimated the number of deaths per year attributed to lightning globally anywhere from a few thousand to 24,000 [5–7]; however, much uncertainty exists due to the limited sample size (**Figure 7**). One country of particular interest is Malawi with a very high rate of 84 lightning deaths per million people per year that far exceeds the rate in any other country [4]. The 1008 annual fatalities for this small but populous country may represent a very complete data collection method that is what adjacent countries in the region should report, so very large numbers of lightning fatalities may be actually occurring but we do not know them. If the "10:1 (injury:death) rule" is appropriate for developing countries, then lightning is causing a large number of deaths and injuries worldwide, regardless of our inability to state the actual numbers.

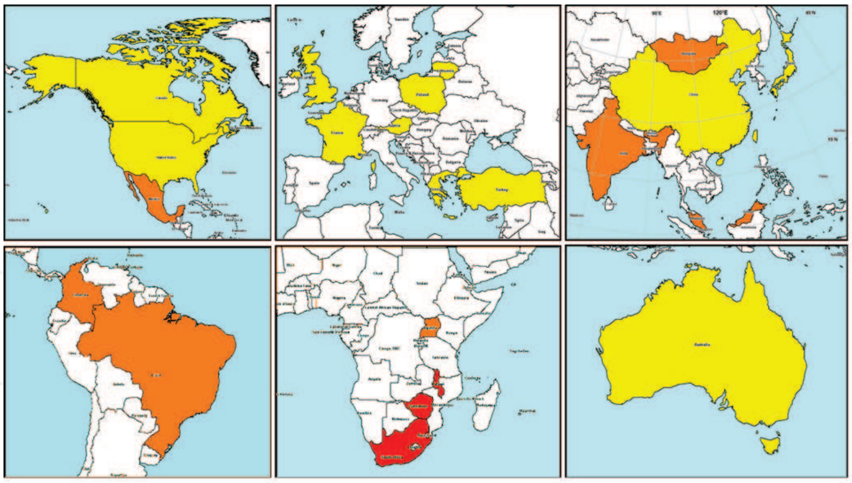

Figure 7. Lightning fatality rate per million people per year by continent. Red shading indicates rate >5.0 fatalities per million per year, orange is 0.6 to 5.0, and yellow is 0.5 or less. White indicates no national summaries have been published for datasets ending in 1979 or later (Updated with permission from Holle [4]).

Figure 8. Many forms of labor-intensive work are far from lightning safety such as (a) fishermen in open boats on Lake Victoria, the second largest lake in the world, and (b) fields in Nepal (courtesy ACLENet and M.A. Cooper).

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In contrast with the United States, many populous less-developed countries have as much as 90% of the population living and working in lightning-unsafe locations and situations. During the day, many people are involved in labor-intensive agriculture, fishing in open boats, walking to market, or inside schools without recourse to safety in an appropriate building or vehicle [8] (**Figures 8** and **9**). At night, people live in lightning-unsafe dwellings without adequate wiring, plumbing, or metal structural components that can carry lightning into the ground without affecting individuals inside [9] (**Figure 10**).

Figure 9. Most forms of transportation or going to market in developing countries are not lightning safe such as (a) taxi in India, (b) ox cart in India, and (c) bota-bota taxi in Nepal (©M.A. Cooper).

Figure 10. An estimated 90% of sub-Saharan buildings and housing are not lightning-safe, such as (a) farming settlement with thatch and sheet metal roofs on mud brick walls in Zambia, (b,c) combination shops and homes in India (©M.A. Cooper).

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In the developing world, the injury:death ratio is expected to be lower since fewer lightning-safe locations are available, resulting in a higher proportion of deaths. In addition, more people die per lightning event in the developing world than in the United States, particularly in agriculture and school events. For developing countries, counting both "primary" and "secondary" causes may be preferable until fatality rates decrease and the availability of safe locations increases.

In more developed countries, the dominant profile of lightning casualties is the young male. Risk-taking in recreation, workplaces, and organized sports tends to be dominated by this group of males between about 15 and 30 years old. However, in lesser developed countries, the distribution is substantially more equal between female and male, and the ages are much more disperse, both because of more widespread exposure. A recent study of labor-intensive agriculture in mainly India and Bangladesh shows that 47% of the fatalities and injuries were females as they work during the daytime when thunderstorms are most frequent [8]. The lack of lightning-safe dwellings, schools, and workplaces means that all ages and both genders are equally vulnerable at all times.

3.3. Damage to property and indirect impacts

In developed countries, precautions against the effects of lightning to property, electronics, and utility lines are usually routine and subject to building codes using well-accepted practices for public buildings such as churches, hospitals, and schools. In developing countries, the effects of lightning damage to property can have not only direct effects on the structure but also indirect economic effects. The impacts include food spoilage from lack of refrigeration after electrical failure, electrical parts and repairs are unaffordable or not available for days, hospitals are without power, and databases and expensive, irreplaceable electronics are damaged. These adverse effects can occur in countries that are already struggling with other pressing issues such as drought, HIV, underemployment, or civil strife. Individual families can suffer not only when one or more of their members is injured or killed by lightning but also when their livestock, often the major measure of wealth, are killed en masse by lightning (**Figure 11**).

Figure 11. Cattle killed by a cloud-to-ground lightning strike in South Africa (©I. Jandrell).

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4. Lightning injury mechanisms and safety

A widespread misconception exists that the direct strike is the most common lightning injury mechanism. A direct result of this misconception is the mistaken development of the most lightning safety avoidance rules that address the stroke coming straight down and striking a person in the head. This is the least common mechanism. Instead, there are five primary mechanisms of lightning injuries (**Figure 12**).

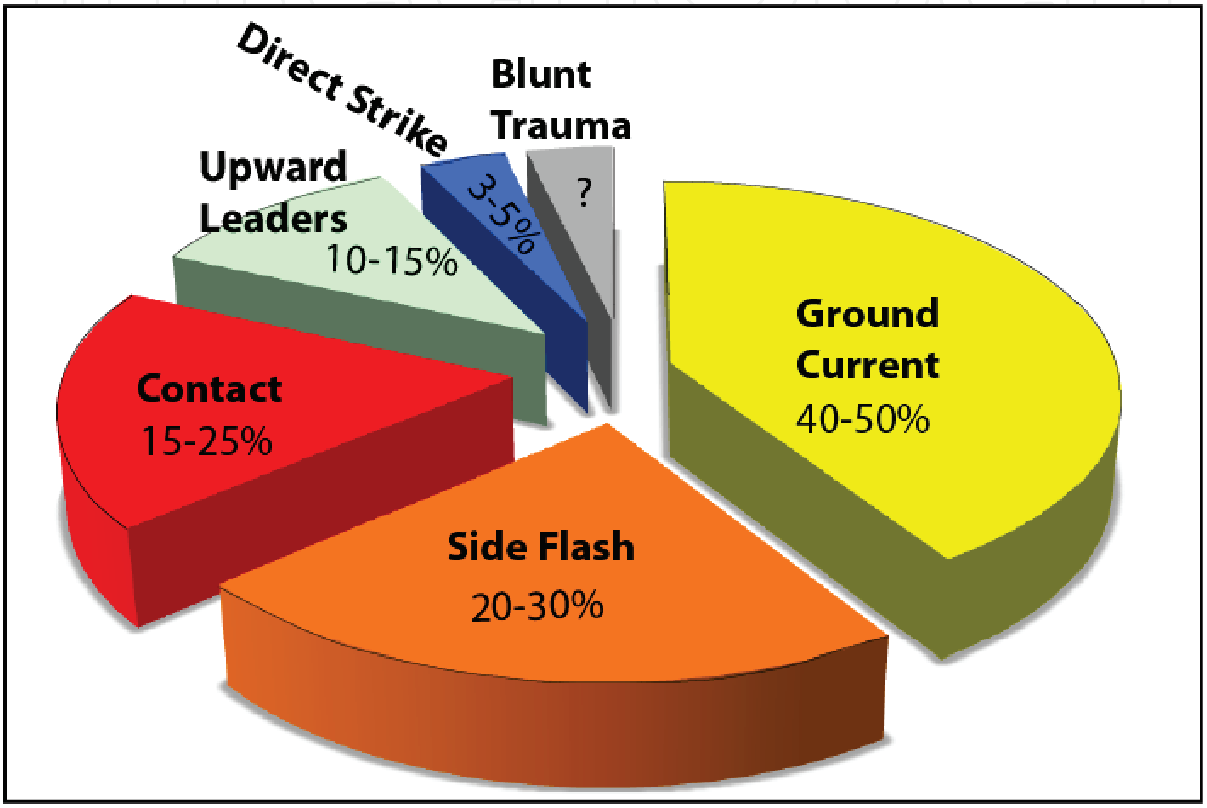

Figure 12. Mechanisms of lightning injury and death.

The five mechanisms lead to a very different conclusion regarding lightning avoidance than the direct strike—everywhere outside is unsafe from lightning. Lowering oneself in height is not sufficient. In the order of highest frequency:

- Ground current: The most common mechanism appears to be ground current, where lightning strikes the surface of the earth and spreads to nearby people and can affect a large number of people.
- Side flash: This occurs when trees, poles, towers, and many other objects that are not necessarily tall are struck and a portion of the lightning's effects jumps to a nearby person.
- Contact: Being in contact with conducting paths such as plumbing or wiring either outdoors or inside structures can be dangerous when they are struck at a distance by a cloud-to-ground lightning flash.

- Upward leader: Occurs when an upward leader is induced from a person and rises to meet the downward-traveling stepped leader from cloud to the ground. The upward streamer is strong enough to cause injury even when the lightning channel is not completed through the person.
- Direct strike: The least common mechanism.
- Blunt trauma: Occurs with or separately from all of these mechanisms as a person is thrown or when too near where the lightning strikes [10].

Lightning safety myths abound. One cannot anticipate with certainty where lightning will strike the ground or what it will strike. At best, lightning can only be described statistically as more likely to hit certain types of objects: tall, isolated, and/or pointed. Safety messages that stress avoiding standing in a certain way, not holding specific objects, being a certain distance from tall objects, and variations on these concepts are not reliable. Safety messages that emphasize what is on the feet are irrelevant; after lightning rips apart several kilometers of air on its journey from cloud to ground, a thin rubber shoe is overwhelmed and immaterial. Part of the perpetuation of many false myths is due to the fact that around 90% of lightning casualties survive. What may seem to be a factor in an individual case, and go on to assume mythological quality, usually does not generalize to a population.

It is estimated that around 10% of lightning casualties are related to trees [11]. Perhaps, a third of all cloud-to-ground lightning flashes around the globe attach to trees. Once lightning strikes a tree, the current comes down the trunk and spreads horizontally (ground current). It also produces side flashes to people or animals who are close by, such as those seeking to stay dry under the canopy (**Figure 11**) and are also close to the trunk. Some people may suffer contact injury if they are touching the tree at the moment lightning strikes it. Finally, blunt and penetrating trauma can occur when bark and tree limbs explode outward at a high speed up to tens of meters away.

Only two reliable safe locations exist from lightning. One reliably safe location is inside a substantial well-constructed building with wiring, plumbing, and perhaps metal structural members. Such buildings where people work or live are able to provide a path for a lightning strike into the ground without causing harm. The other reliably safe location is inside a fully enclosed metal-topped vehicle. The effects of such buildings and vehicles are similar to that of a Faraday cage where the current flows outside of people within the structure or vehicle. Direct strikes to such buildings and vehicles can be frightening and sometimes have disconcerting impacts. However, such property damage is massively preferred to people being outside of such locations.

Unsafe structures include anywhere with the word shelter attached—beach, sun, shade, rain, or bus shelter. While they can be made safe, most people cannot tell if that is the case (**Figure 13**). One should always assume they are not lightning-safe because they will likely not surround a person inside with a certain path for lightning to follow. Similarly, any other structure is unsafe when made of mud, brick, or thatch without specifically designed metal-conducting paths for the current to follow.

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Figure 13. Lightning-unsafe small structure. Note sign recommending a safe place elsewhere rather than staying at this location (©R. Holle).

Unsafe vehicles include motorcycles, convertibles, golf carts, tuk-tuks, bota-botas, four-wheelers, and similar vehicles. A summary of motorcycle lightning events, often resulting in deaths, is in [12]. A common misconception refers to rubber tires being of relevance. When lightning strikes a fully enclosed metal-topped vehicle, the current flows through the metal structure around the people inside, then exits through the ground. The tires are the shortest path to ground, so they may explode or flatten. Tires are damaged as an effect of the lightning strike, but they did not protect people inside, instead safety is provided by the metal structure surrounding the person inside.

5. Lightning injury

5.1. Effects of lightning on people

A myriad of injuries from lightning have been reported including damage to the ears, eyes, skin, heart, and brain [13]. The proximate cause of death is cardiac arrest and anoxic brain injury at the time of the strike, even if resuscitation delays the legal pronouncement for a few days.

Most people assume that lightning causes a significant burn injury but, in developed countries, burns tend to be superficial and insignificant and lightning causes more neurological injury and blunt trauma. At the time of the strike, injured persons often suffer keraunoparalysis, a paralytic state lasting minutes to hours with loss of sensation affecting the lower limbs more than the upper limbs. In developed countries, keraunoparalysis usually resolves without treatment, although some may have permanent weakness. In developing countries, where mud brick, thatched roofs, and other insubstantial buildings are the norm, keraunoparalysis may prevent even the most robust person from escaping as burning thatch falls on them, resulting in reports by journalists of "charred bodies" [14].

Lightning-injured persons may suffer temporary or permanent neurological problems including chronic pain syndromes and cognitive damage similar to those reported in post-concussive syndrome with inability to multitask, attention-deficit, memory problems, learning difficulty, irritability, and inability to return to their previous level of employment [15, 16]. Disability may significantly affect a family's socioeconomic status if the survivor is unable to return to work or needs chronic care. A further setback to the victim's family, particularly in developing countries such as in Africa, is a common belief that a family affected by lightning injury has been "cursed". This may force the family to leave their community, home, and employment to start over in a new community where their tragedy is unknown [17].

5.2. Treatment of lightning injury

While the effects of lightning injury can be treated, currently there is no way to reverse or decrease the damage that is set in motion when the strike occurs. Lightning Strike and Electric Shock Survivors International (LSESSI) is a support group that has helped hundreds of survivors and their families [16]. Treatment is standard for pain syndromes, anoxic brain injury, and cognitive disability. Unfortunately, this type of care is expensive and seldom available in developing countries.

As in most injuries and illnesses, prevention is far better than caring for those injured by lightning and, in developed countries, lightning injury prevention is simple and cost-effective [18]. However, decreasing lightning injuries in developing countries is a much more complex task than in countries where lightning-safe structures and vehicles are common and close by. In cases where lightning affected pupils and staff at unsubstantial schools in developing nations, a review of over 100 events in the past decade found 200 deaths and 700 injuries. These events occurred most often in primary and high schools with many situations involving dozens of children per event. Partially in response to such events, the African Centre for Lightning and Electromagnetics Network (www.ACLENet.org) was established in 2013. The confluence of lightning frequency, personal vulnerability at work, school, and home in less developed countries in Africa, as well as in Southeast Asia [19], makes this a timely endeavor.

6. Conclusions

The location, time, and frequency of cloud-to-ground lightning around the globe have become quite well known. About two-thirds of cloud-to-ground lightning occurs between noon and 1800 local time, and about two-thirds occur in summer in the middle latitudes. Lightning is

http://dx.doi.org/10.5772/63001

more frequent along coastlines and near large topographic features in the Tropics and subtropics. However, due to socio-economic factors, the number of fatalities and injuries is not as closely related to lightning frequency as might be expected. In the United States and other developed countries, the fatality rate per capita is more than two orders of magnitude lower than a century ago. This rate decrease is attributable to a shift from rural to urban settings where fewer people are involved in labor-intensive agriculture. Many lightning injuries and deaths in the developed world are from leisure activities, often related to various types of activities in the vicinity of water bodies [2]. At least as important has been improvements to the quality of buildings that are usually safe from lightning due to grounding according to codes that provide safety to people inside. In addition, the widespread availability of fully enclosed metal-topped vehicles provides mobile lightning-safe locations almost everywhere. Additional factors include better medical treatment and improved understanding of thunderstorms and their associated lightning threat.

In contrast, many developing countries continue to have very high per-capita fatality and injury rates. A large portion of their population is involved in labor-intensive agriculture during the daytime when thunderstorms are more common. No lightning-safe locations are typically available to these people, often nearly equally male and female, while working in the fields. In addition, dwellings occupied outside of working hours often are not lightning-safe due to their construction of mud brick and thatch or sheet metal roofing. As a result, an estimate is that as many as 24,000 deaths and 240,000 injuries occur from lightning globally every year [7], almost entirely in the less-developed countries of the world. These figures remain elusive, due to sporadic data gathering in the most lightning-vulnerable locations where data collection will be slow to improve in the near future such as equatorial countries of Africa and Asia. Injury prevention is far better than taking care of people after they are injured; both scenarios are relatively easier in developed countries. Unfortunately, the infrastructure and housing in developing countries precludes easy answers like "When Thunder Roars, Go Indoors", and lightning remains a substantial threat to entire villages, schools, and populations.

Author details

Ronald L. Holle[1*] and Mary Ann Cooper[2]

*Address all correspondence to: rholle@earthlink.net

1 Holle Meteorology & Photography, Oro Valley, Arizona, USA

2 Department of Emergency Medicine, University of Illinois at Chicago, Chicago, Illinois, USA

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