2012
22nd International Lightning Detection Conference
2 – 3 April • Broomfield, Colorado, USA
4th International Lightning Meteorology Conference
4 – 5 April • Broomfield, Colorado, USA

RECENT STUDIES OF LIGHTNING SAFETY AND DEMOGRAPHICS

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ABSTRACT

A wide variety of lightning safety-related studies has been made by the author since 2007. The studies involve analyses of large datasets of lightning casualties and flashes, and are oriented toward results that relate to safety topics. Eight topics have been presented and published at several conferences and venues that may not be readily available, so the results will be summarized in the following numbered sections:

1. Diurnal U.S. cloud-to-ground lightning maps.
2. Monthly U.S. cloud-to-ground lightning maps.
3. Lightning fatalities by U.S. state.
4. Mechanisms of lightning injury.
5. Lightning casualties in and near vehicles.
6. Lightning casualties in and near dwellings and buildings.
7. Lightning casualties in and near water.
8. Global lightning casualties.

1. DIURNAL U.S. CLOUD-TO-GROUND LIGHTNING MAPS

The diurnal distribution of U.S. cloud-to-ground lightning from the NLDN indicates that much of the lightning is in the afternoon. However, some activity starts before noon in the mountainous western states, as well as on the Florida and Gulf Coast coasts. Lightning continues into the late evening and night on the plains and in the Mississippi Valley (Holle 2012).

Holle (2012) describes the diurnal distribution of cloud-to-ground lightning from the National Lightning Detection Network (NLDN). Previous diurnal cycle studies were typically in the form of time series for an entire region, occasionally by flow regime, and sometimes a map was shown for one or two time periods.

This study assigns flash data to two-hour time periods in five-degree longitude segments, and identifies patterns of two-hourly lightning without identifiable boundaries between segments. Distributions are shown and labeled in Local Mean Time (LMT).

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1A. 1000 to noon LMT

The diurnal cycle of new lightning activity during a day with convection is often characterized as starting around 1000 LMT. Starting at this time, the first two hours have an average of 1,328,108 flashes per year from 2006 through 2010 in the area shown in Figure 1. The higher elevation regions of the southwestern states, and on beaches along the Florida and Gulf of Mexico coasts, have flashes before noon that are a threat to outdoor recreation vulnerable to lightning. The locations in the southwestern states and along the Gulf and Florida coasts become locations of much higher lightning frequency later in the day. The frequent lightning in the plains to Mississippi valley is mainly a remnant from the previous night's convection that is described by two-hourly maps in Holle (2012) during other time periods of the day.

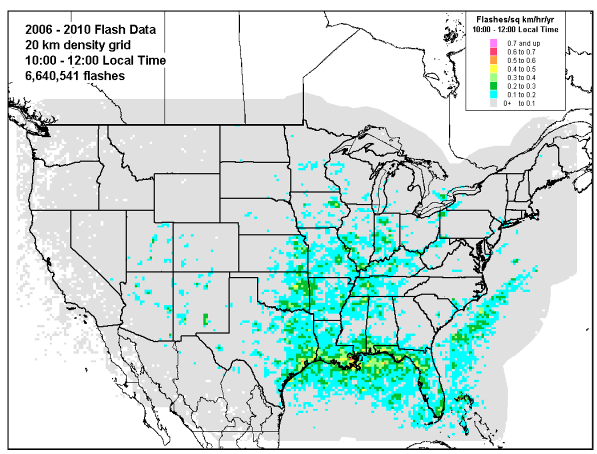

FIGURE 1. Map of cloud-to-ground lightning flashes in flash density per square kilometer from 1000 to noon LMT for the U.S. from 2006 through 2010. Scale is in upper right portion of map.

1B. Noon to 1400 LMT

The map two hours later (Figure 2) shows that the number of flashes is double the total of the previous two hours. Florida and the Gulf Coast have frequent lightning, and areas in the southeastern states have also grown in frequency of flashes. Cloud-to-ground flash activity has greatly increased over the higher elevations of Arizona, Colorado, New Mexico, and Utah, where this period has much of the day's lightning.

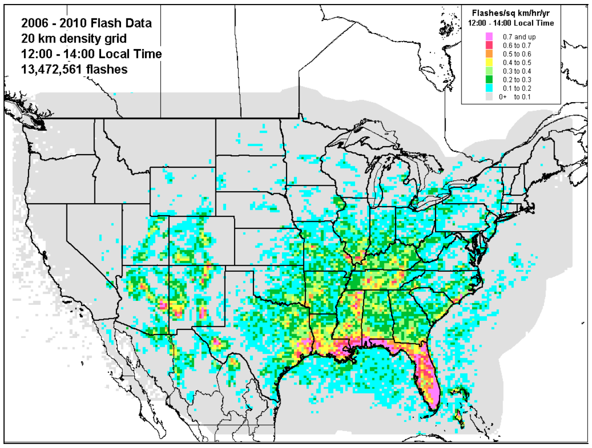

FIGURE 2. Same as Figure 1, except from noon to 1400 LMT.

1C. 1400 to 1600 LMT

At the time of maximum heating between 1400 and 1600 LMT, Figure 3 shows a large increase in lightning frequency. Florida and the Gulf Coast now have very frequent lightning, as well as the Mogollon Rim, Colorado Rockies, and New Mexico mountain ranges. In general, there are no large new areas of lightning activity, but there is a general intensification and expansion where flashes were occurring two hours earlier.

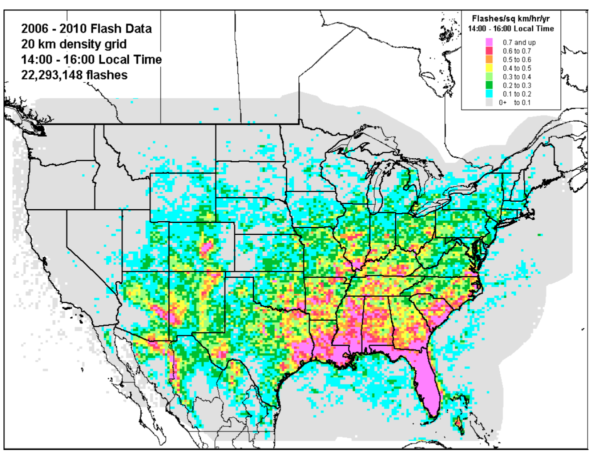

FIGURE 3. Same as Figure 1, except from 1400 to 1600 LMT.

1D. Summary

Diurnal patterns of lightning frequency show that most regions have a concentration of cloud-to-ground lightning during the afternoon (Holle 2012). However, lightning starts before noon over the higher elevations of the southwestern states, and the beaches along the Florida and Gulf of Mexico coasts. Such information is important for planning to avoid the lightning threat, as well as the timing and messages for lightning safety programs.

2. MONTHLY U.S. CLOUD-TO-GROUND LIGHTNING MAPS

The monthly distribution of U.S. cloud-to-ground lightning from the NLDN has a rather sharp concentration in June, July, and August in most parts of the country that should affect lightning safety avoidance recommendations (Holle and Cummins 2010; Holle et al. 2011).

Two conference papers describe monthly distributions of U.S. cloud-to-ground lightning from the NLDN (Holle and Cummins 2010; Holle et al. 2011). Monthly maps had not been shown before, although national and regional climatologies have been developed (see references for an extensive list of prior U.S. cloud-to-ground lightning climatologies).

These monthly maps have implications for lightning safety recommendations. Lightning is concentrated within a few months in most areas of the country, including Florida that has a strong concentration in June, July, and August. In contrast, Arizona and surrounding states have nearly all of their flashes in July and August only.

With these monthly maps, it is possible to define the lightning threat season more clearly for vulnerable activities such as hiking and boating, depending on the area of the country. Since most locations have the lightning threat concentrated in a few months, some outdoor activities can be pursued outside of those months in order to avoid lightning.

2A. Annual

Figure 4 shows measured monthly flash distributions over the contiguous U.S. and adjacent areas. An average of 27 million cloud-to-ground flashes was detected per year by the NLDN over the contiguous U.S. land area, when corrected for detection efficiency. Lightning is most common in summer, since two thirds of cloud-to-ground flashes occur in June, July, and August.

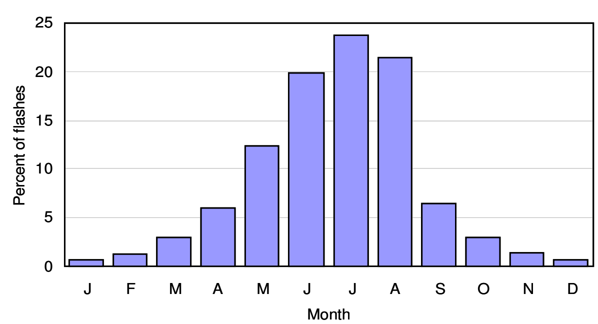

FIGURE 4. Cloud-to-ground flashes per month from 2004 though 2008 for the U.S. and adjacent areas from the NLDN.

2B. Sample monthly flash density maps

In January most 20 by 20 km grid squares in the eastern half of the country had at least some lightning. The February and March lightning areas grew in intensity and area until in April, Figure 5 shows extensive areal coverage and flash density in nearly every region of the U.S.

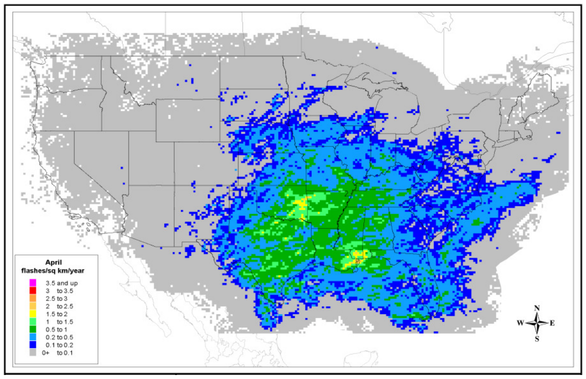

FIGURE 5. Cloud-to-ground lightning flash density per square kilometer in April for the U.S. from 2004 through 2008. Scale is in lower left portion of map.

Lightning continues to intensify and spread until in June, the NLDN (Figure 6) shows the Florida lightning maximum exceeding 3.0 flashes/km^2/year across much of the peninsula due to the influence of the two coastal sea breezes. Additional sea breezes are apparent across the Florida Panhandle to Texas. High lightning frequencies also occur from Kansas and Oklahoma eastward to Illinois and other states.

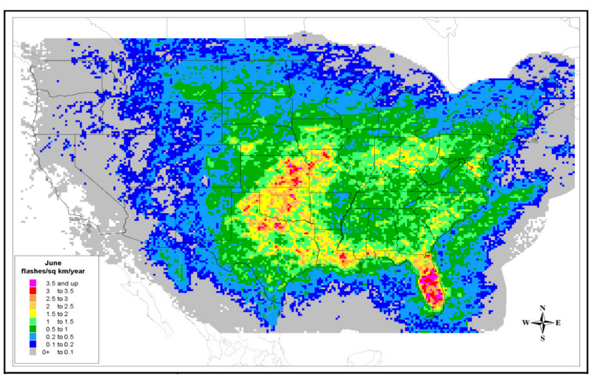

FIGURE 6. Same as Figure 5, except for June.

In July, the NLDN in Figure 7 shows the appearance of two lightning maxima over Arizona compared with June as the Southwest Monsoon begins. Also resulting from monsoonal moisture flow is a large increase in lightning in Colorado and New Mexico compared with June. Over Florida, flash density exceeds 3.5 flashes/km^2/year over many areas of the peninsula.

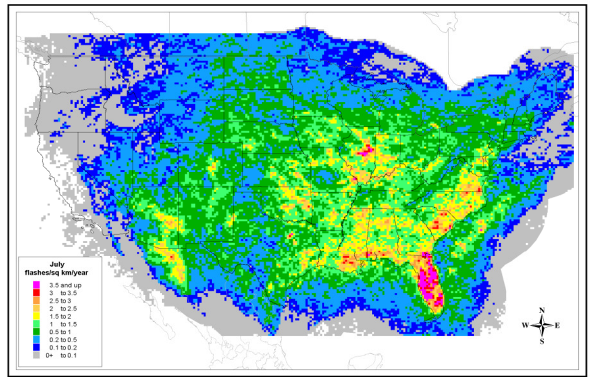

FIGURE 7. Same as Figure 5, except for July.

Vaisala's Global Lightning Dataset GLD360 detects most cloud-to-ground lightning around the world. Monthly GLD360 summer maps in the region surrounding the NLDN are in Holle et al. (2011). In July GLD360 (Figure 8) shows similar U.S. features to the NLDN (Figure 7). GLD360 also shows the extension of the coastal U.S. maximum along the Gulf of Mexico around Mexico, as well as maxima over Cuba, Hispaniola, and northern South America. The maximum over northwest Mexico has extended into Arizona and New Mexico in July (Figures 6 and 7).

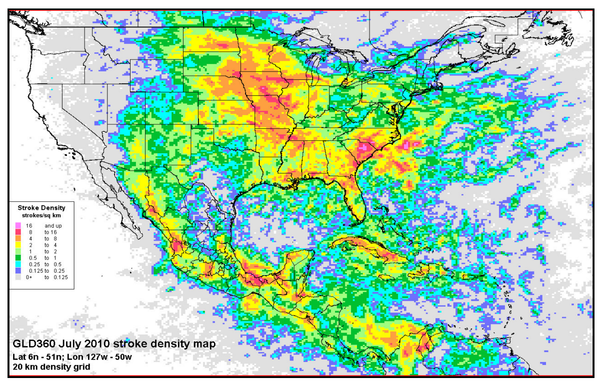

FIGURE 8. Global Lightning Dataset GLD360 strokes in July from 2004 though 2008 for the U.S., Mexico, Central America, Gulf of Mexico, Caribbean, and northern South America. Scale is in lower left portion of map.

In August, the NLDN shows a modest lightning decrease over Arizona, Florida, the southeast coast, and offshore Gulf Stream regions compared with maps in July. In September, there is a marked decrease in flash density values across the entire U.S., then a continued decrease to the end of the year (Holle and Cummins 2010; Holle et al. 2011).

2C. Summary

Monthly maps of lightning frequency and their monthly percentages show that most states and regions have a concentration of cloud-to-ground lightning in a few months (Holle and Cummins 2010; Holle et al. 2011). Such information is important for planning to avoid the lightning threat, as well as the timing and messages for lightning safety programs.

3. LIGHTNING FATALITIES BY U.S. STATE

U.S. states with the most lightning fatalities, when weighted by population, are in the southeast and Northern Rocky Mountain states (Holle 2009c).

Holle (2009c) shows state by state rankings in maps and tables of lightning fatalities, and population-weighted lightning fatalities for the latest 10 years. These datasets are completed annually from *Storm Data* reports. Fatalities have been the focus of these maps and tables since U.S. fatalities are reported better than injuries (Mogil et al. 1977; López et al. 1993; Shearman and Ojala 1999; Richey et al. 2007; Ashley and Gilson 2009). It is estimated that there are 10 injuries per lightning fatality (Cherington et al. 1999).

John Jensenius of the National Weather Service in Gray, Maine updates the lightning fatality list for the current year on a daily basis (Roeder and Jensenius 2012). It is located on the NWS Lightning Awareness Week website www.lightningsafety.noaa.gov.

For 2001 through 2010, Figures 9 and 10 show that states with the most lightning fatalities are in southeast, populous northeast and Midwest states, and Texas and Colorado. However, when weighted by population, the highest ranks are in the southeast and Northern Rocky Mountain states. First attempts to relate these state-by-state differences to numerous other meteorological parameters are explored in Holle (2009a).

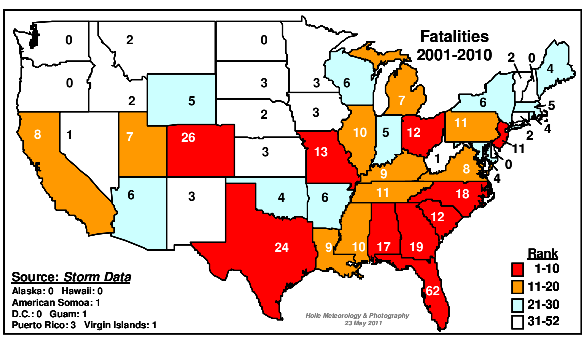

FIGURE 9. Map of the number and rank of U.S. lightning fatalities by state from 2001 to 2010 from Storm Data.

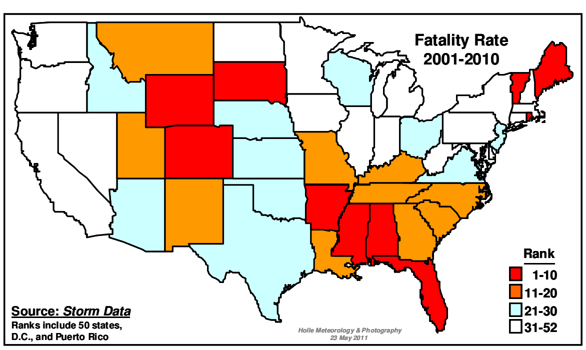

FIGURE 10. Map of the rank of U.S. lightning fatalities weighted by population by state from 2001 to 2010 from Storm Data.

Further historical context has been provided by extending the data back in time. Curran et al. (2000) showed maps and tables of state-by-state fatalities and injuries, both with and without population weighting from 1959 to 1994 (*Storm Data* began in 1959). Figures 11 and 12 show lightning fatalities and population-weighted fatality rates from 1959 to 2010 from *Storm Data*. Shifts in recent years are shown by comparison with Figures 9 and 10 for 2001-2010. It is recommended that the latest decade of record is much more appropriate to show for educational purposes.

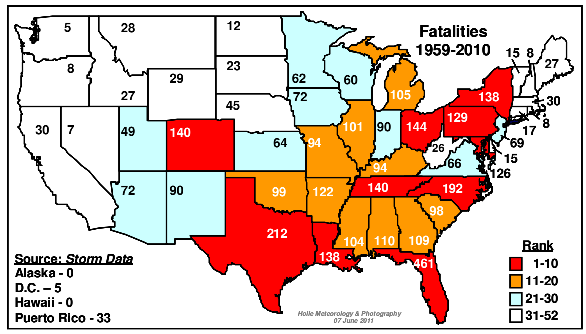

FIGURE 11. Map of the number and rank of U.S. lightning fatalities by state from 1959 to 2010 from Storm Data.

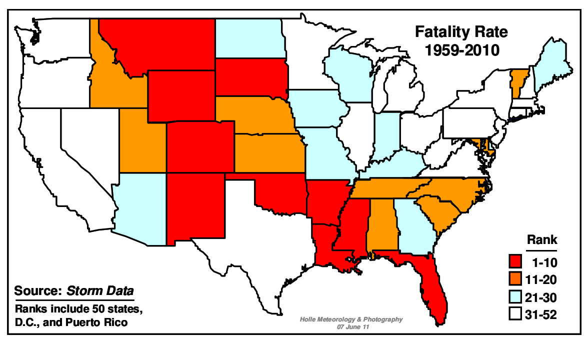

FIGURE 12. Map of the rank of U.S. lightning fatalities weighted by population by state from 1959 to 2010 from Storm Data.

4. MECHANISMS OF LIGHTNING INJURY

Lightning injury is due to five distinct mechanisms, but while the direct strike is the most discussed, it is the least common (~5%) and should not be a significant factor in lightning education (Cooper and Holle 2010).

4A. Introduction

Cooper and Holle (2010) describe mechanisms of lightning injury (Figure 13). The distribution of injuries is based on hundreds of cases over several decades by researchers primarily from more developed countries. Web, newspaper, and other media reports and personal accounts most often recount 'direct strike' as the mechanism of lightning injury, but examination of many cases reveals that direct strike is a very small proportion of the injuries.

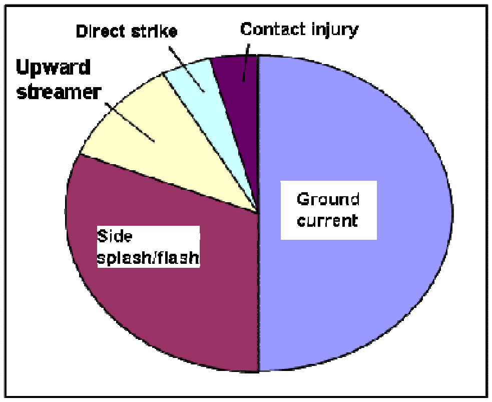

Figure 13. Distribution of lightning injury mechanisms.

Reasons for misreporting include lack of knowledge of other mechanisms by the witness, victim or reporter; errors in observation; assumptions by eyewitnesses untrained in lightning observation; amnesia of victims; and over-dramatization of the event. In addition, misreporting of mechanisms is partially due to the retrospective nature of the reports gathered from witnesses and survivors. In particular, the expectation of a direct strike is so prevalent that it is often considered as the only mechanism despite evidence to the contrary.

4B. Types of strikes

- Direct strike - 3 to 5%

A direct strike occurs when lightning attaches directly to the victim. This is most likely in the open when a person has not taken the time to reach the safety of a large substantial building or fully-enclosed metal-topped vehicle. While it is intuitive that the direct strike might be the most likely to cause fatalities, this has not been shown in any studies or reviews of a large number of lightning casualties.

- Contact injury - 3 to 5%

Contact, or touch potential injury occurs when the person is touching or holding an object to which lightning attaches, such as indoor wired telephones or plumbing that transmits current to the person. A voltage gradient is set up on that object from strike point to ground, and a person in contact with the object is subject to voltage between the contact point and ground; current flows through the person.

- Side flash - 30 to 35%

A more frequent cause of injury is a side flash, also termed splash. Side flashes occur when lightning hits an object such as a tree or building, and travels partly down that object before a portion "jumps" to a nearby victim. Standing under or close to trees and other tall objects is a very common way in which people are splashed. Current divides itself between the two or more paths in inverse proportion to their resistances.

- Ground current - 50 to 55%

Ground current, also known as Earth Potential Rise (EPR), arises because the earth is not a perfect conductor. When lightning current is injected into the earth, it travels through the earth as in any other conductor. Earth has a finite resistance so that voltages are set up in the ground, decreasing in size with distance. The voltage (potential) of the earth is raised, hence EPR.

Ground current effects may be more likely to be temporary, slight, and less likely to produce fatalities. However, multiple victims and injuries are frequent. Kitigawa et al. (2001) notes that not only can EPR occur as above, but also in a manner similar to surface flashes over a body. If terrain is very irregular, the spreading lightning current may reach the surface and a surface arc discharge develops with the flow of the conduction current in the ground. This mechanism makes it dangerous on a mountainside inside a shallow cave or under a small cliff where surface arcing is more likely to occur, despite an expectation of safety.

- Upward leader - 10 to 15%

Injury may occur when a victim serves as the conduit for one of the multiple upward leaders induced by a downward stepped leader and its field. Leaders also occur when there is no attachment between them and the stepped leader. While weak in energy compared to the full lightning strike, they may carry several hundred amperes of current. This mechanism has been mentioned by many engineering and physicist lightning experts, and a medical case report has been published. Upward streamer injury is probably a much underestimated mechanism of injury.

- Blunt injury

Persons may suffer from (non-electrical) blunt injury either by 1) being close to the concussive force of the shock wave produced by a nearby strike, or 2) ground current or other mechanism induces intense muscle contractions which can throw the victim up to tens of yards away. In addition, a person struck by lightning may suffer from explosive and implosive forces created by thunder, resulting in contusions and pressure injuries, including tympanic membrane rupture. Another mechanism of blunt injury is blast injury resulting from vaporization of water on the body from a surface flashover spark.

4C. Summary

The vast majority of lightning injuries and deaths are caused by mechanisms other than direct strike. Any public education efforts should take into account all of these mechanisms.

There have been many reports of multiple injuries. It is likely that these may involve groups who are exposed to a combination of mechanisms, with the majority of the people injured by EPR and upward streamers, sometimes complicated by side flashes if people are standing close together. In summary, information on the exact mechanisms of lightning injury remains poorly documented and understood, nevertheless the direct strike is not a frequent mechanism of lightning injury.

5. LIGHTNING CASUALTIES IN AND NEAR VEHICLES

Fully-enclosed metal-topped vehicles are very safe places from lightning that should be reached when they are nearby, although they are often damaged and the experience is frightening; motorcycles are very unsafe (Holle 2007b, 2008b).

5A. Introduction

Holle (2007b and 2008b) summarize a large number of people impacted by lightning in and near vehicles. Cooper and Holle (2007) showed that motorcycles and similar vehicles are very unsafe from lightning. Lightning safety recommendations identify two reliable safe places (Holle et al. 1999 and others). One is inside a fully-enclosed metal-topped vehicle, and the other is inside a large well-constructed enclosed building (section 6).

The category of "Near vehicles" accounted for 4.1% of deaths and 5.0% of injuries in Holle et al. (2001, 2005). The cases in Table 1 were collected from newspapers, web reports, broadcast media, scientific publications, NOAA's *Storm Data,* and other sources, mainly from the last 20 years.

TABLE 1. *Type and number of vehicle-related events, deaths, and injuries.*

Type of vehicle event	Events	Deaths	Injuries
Inside fully enclosed metal-topped vehicles	76	4	77
Direct contact	36	9	37
On or near non-enclosed vehicles	29	7	67
Parking lots	24	8	30
Other casualties related to vehicles	47	14	77
Total	212	42	288

5B. People inside fully-enclosed metal-topped vehicles struck by lightning

During the 76 events in Table 1 in this category, people inside the vehicles described themselves as *uninjured* in more than half of the events. Since the rest were typically minor impacts, the recommended lightning safety precaution (Holle et al. 1999) to seek safety inside a fully-enclosed metal-topped vehicle appears well supported.

Of the four events in Table 1 involving deaths inside a vehicle, two were ambiguous. The most reliable report was when a driver started a crash as lightning struck near the vehicle, killing two and injuring two more motorists. Otherwise, there are no fatalities in 212 cases to people inside fully-enclosed metal-topped vehicles.

The most common injury involved the arm or elbow. No significant injuries appear to have resulted from direct contact with metal in the vehicle, except for an earplug attached by a power cord to the dashboard. As a result, less emphasis may be made in safety recommendations about avoiding metal contact while inside a vehicle.

With respect to vehicle damage with people inside, the most common impact was for the antenna to be hit, followed by destroyed or damaged electrical systems, flat tires, glass damage, stopped engine, burn marks, and smoke. Relating these results to the rubber tire myth saving people inside vehicles, some direct strikes involve lightning current flowing around the outside metal body that finds its way to an axle and arc to the ground, resulting in blown tires or pavement marks.

Most vehicles were in motion when struck by lightning. The rest were waiting at a stop sign, intersection, parking lot, football game, or for the thunderstorm to end.

5C. People in direct contact with vehicles struck by lightning

The most common category that involved people in contact with the outside of vehicles at the time of a strike is entering/exiting vehicles. This category in section 4B is described as ground current, Earth Potential Rise, or step voltage. This is very dangerous; five of the nine direct-contact deaths were in this posture. Another category had eight events when people were working on vehicles when current from a nearby flash traveled to them while in contact with the ground.

5D. People on or near non-enclosed vehicles

Table 1 has 29 events with casualties on or near non-enclosed vehicles. In these cases, there was no protection provided by any structure surrounding the people. The most common location was standing or working near a crane, followed by under a trailer awning or porch.

5E. Parking lots

Table 1 has 24 events, often fatalities, while in parking lots. These casualties were not inside vehicles, or in direct contact with vehicles. People in these cases were usually in the process of crossing a parking lot to or from a vehicle, or under a tree at the lot.

5F. Other casualties related to vehicles

Other cases in Table 1 include the common event of people waiting outside for a bus or other transportation. All other cases included people outside a vehicle.

5G. Summary

The most common type of vehicle impact was a strike to a fully-enclosed metal-topped vehicle with people inside. People described themselves as *uninjured* in more than half of these events. Few events involved major injuries. It is concluded that being inside a fully-enclosed metal-topped vehicle is a safe place to be from the danger of lightning compared with remaining outside at the same time and place.

6. LIGHTNING CASUALTIES IN DWELLINGS AND BUILDINGS

Large well-constructed buildings are safe from lightning if people inside are not in contact with conducting wiring and plumbing. Unfortunately many buildings in less developed areas of the world are not safe, including dwellings, schools, and other straw-roofed structures (Holle 2009a, 2009b, 2010).

6A. Introduction

Lightning safety recommendations identify two reliable safe places (Holle et al. 1999 and others). One is inside a fully-enclosed metal-topped vehicle (section 5). The other is inside a large substantial building (Holle 2009a, 2009b, 2010). "Indoors" accounted for 4% of lightning deaths and 12% of injuries from 1991-1994 (Holle et al. 2001, 2005). These are much lower than 100 years ago, when 29% of deaths and 61% of injuries were indoors (Holle et al. 2001, 2005).

Large enclosed buildings are those where people often live or work. Beginning in the 20th century in more developed countries, they surround occupants with an effect similar to a Faraday cage such that a direct strike is conducted around people inside the structure. When such buildings are grounded according to code, people inside are usually safe from lightning if not in direct contact with conducting paths. Structures in more developed countries also tend to have metal reinforcing infrastructure to help conduct lightning.

The following cases were randomly collected through the same methods as in section 5. U.S. cases were separated as representative of situations in more developed areas, although similar structures are also located in many other areas of the world.

6B. U.S. dwellings

Table 2 shows 355 events related to U.S. dwellings. These cases accounted for 106 deaths and 295 injuries. The ratio of 3 injuries for each death is low compared with the 10 injuries per death ratio found from a review of available medical records in Colorado by Cherington et al. (1999).

TABLE 2. Type and number of lightning-related events, deaths, and injuries involving U.S. dwellings.

Activity	Events	Deaths-	Injuries
Deaths inside	21	31	4
Injuries inside	169	0	173
During construction	27	15	16
On property	138	60	102
Total	**355**	**106**	**295**

6B.1. Deaths inside U.S. dwellings

Table 2 has 21 U.S. dwelling events with 31 deaths and four injuries. All but three occurred from a home catching fire, and most occurred between 11 pm and 8 am. In these events, 14 of the 31 deaths occurred to people aged 70 or older. Most of the other cases involved children, and two events were with mentally and/or physically challenged people.

6B.2. Injuries inside U.S. dwellings

Table 2 lists people injured while inside U.S. dwellings, many more than fatalities inside dwellings. Most injuries were minor, although they can result in significant long-term impacts (Cooper et al. 2007). There are several major expected groupings:

- **Wiring**: 42 events involved wiring connected to an electrical device inside a U.S. dwelling,
- **Telephone**: 26 involved telephones (Andrews 2007),
- **Plumbing**: 19 involved plumbing.
- Lightning safety recommendations often add to stay away from windows inside a dwelling; however, only 10 injury entries involved a window. Besides wiring, telephones, and plumbing, doorways (20) and garages (19) are larger than windows (10).

6B.3. Construction of U.S. dwellings

A previously unrecognized category in Table 2 involves dwellings under construction. The roof is very unsafe, and a complete Faraday cage effect is not provided inside an unfinished dwelling. The perception may be that the enclosure is safe from lightning, since it shelters from rain. The safety recommendation is to go inside fully-enclosed metal-topped vehicles that are typically located at a construction site, rather than inside an unfinished dwelling (Holle 2007b, 2008b).

6B.4. On property of U.S. dwellings

Lightning safety recommendations emphasize going inside a substantial building. Being on the property near a dwelling is the largest dwelling fatality category - outside a dwelling, since anywhere else outside is very unsafe from lightning. Major categories are:

- **Yard**: 45 events involved people in the yard, not necessarily in the garden.
- **Tree in yard**: 16 events involved a person under or near a tree.
- **Mowing lawn:** 13 events involved a person mowing the lawn; more than half were killed.
- **Garden**: 12 events involved people working in the yard or garden. Six involved a resident or neighbor working in a yard or garden, and another six involved hired yard workers.
- **Playing in yard:** Nine events involved six children who were killed, and 10 children were injured while playing in the yard of a dwelling.
- **Driveway**: Seven events.

6C. Non-U.S. dwellings

Table 3 summarizes lightning casualties related to dwellings that are not in the United States.

TABLE 3. Type and number of lightning-related events, deaths, and injuries involving dwellings not in the U.S.

Type of event	Events	Deaths-	Injuries
Deaths inside	26	106	33
Injuries inside	27	0	30
Huts	25	76	68
On property	13	17	4
Total	**91**	**199**	**135**

6C.1. Deaths inside non-U.S. dwellings

Only six of the 26 events in Table 3 involve people sleeping, and three events mention burns or fires. Compared with the U.S. dwelling events in Table 2, the ratio of fires and late-night events is much lower. No cases from outside the U.S. mention physical or mental disability, or a tendency toward elderly people, as in the U.S.

The number of casualties per event is much higher than in the U.S. cases. More than half of the events involved two or more fatalities; 16 people were killed in one case in a home. The most frequent U.S. case was one person per incident.

The current scenario in non-U.S. dwellings, mainly in developing countries, is similar to that of U.S. events in the late 1800s (Holle et al. 2001, 2005). At that time, people were killed inside U.S. dwellings before there was widespread grounding by coded electrical and plumbing systems, and metal infrastructure components.

6C.2. Huts

A separate category was identified for non-U.S. dwellings described in the local English-language information source as a hut used as a dwelling (Table 2). All hut events involved at least one fatality. Most involved multiple casualties - one case involved 13 deaths and another had 21 injuries. More than half of the hut reports came from South Africa, where the typical dwelling was a rondavel. More than half involved a fire.

6C.3. Casualties on property of non-U.S. dwellings

Table 3 lists 13 incidents on the property of non-U.S dwellings. Many situations are the same as found in Table 2 for the U.S. property cases. All reported incidents include fatalities, and few have injuries, which indicates the tendency for reports of lightning casualties outside the U.S. to consist primarily of fatalities.

6D. U.S. buildings, except dwellings

Table 4 shows events related to U.S. buildings that are not dwellings. The ratio of 13 injuries per death is similar to the 10 injuries per death in Colorado (Cherington et al. 1999).

TABLE 4. Summary of type and number of lightning-related events, deaths, and injuries involving U.S. buildings other than dwellings.

Type of event	Events	Deaths-	Injuries
Inside	24	0	42
On property	25	6	55
Schools	44	9	88
Small structures	34	10	110
Communications	19	0	24
Total	**146**	**25**	**319**

6D.1. Casualties inside U.S. buildings

Table 4 lists 24 events that involved people who were casualties inside U.S. buildings. When the very large number of buildings is considered, and the large amount of time people spend in such structures, it is notable that no fatalities and very few injuries occur. It can be concluded that such buildings are quite safe from lightning while inside.

6D.2. Casualties related to U.S. schools

Most of the U.S. school cases in Table 4 were outside; only a few injuries occurred inside. Many involved transportation, including those around buses and in parking lots. The largest activity category was walking near school buildings. Issues involved in school lightning safety are addressed in Jensenius et al. (2010), and some cases were also included in the vehicle study in Section 5.

6D.3. Casualties related to U.S. small structures

Table 4 includes the category of small structures identified in Holle et al. (2001, 2005) as the source of 3% of U.S. deaths and 2% of U.S. injuries. Nine cases involved people seeking safety under small structures on golf courses (Holle 2005). Other locations being sought for shelter from rain include pavilions, gazebos, and sheds with mostly open sides and minimal grounded wiring and plumbing. Such small structures can be assumed to be unsafe, but can be made safe with specific knowledgeable advance planning (Kithil and Rakov 2001; Tobias 2002).

6D.4. Casualties related to U.S. communications

Table 4 also lists U.S. events with lightning casualties of while using communications, except in dwellings. The largest groups are people using corded telephones. Nearly as large is the group of 911 operators at emergency operations centers.

6E. Non-U.S. buildings, except dwellings

Table 5 shows events related to non-U.S. buildings. While the number of cases in Table 5 outside the U.S. is half that within the U.S. in Table 4, the number of deaths is nearly ten times as large and injuries are twice as frequent.

TABLE 5. Summary of type and number of lightning-related events, deaths, and injuries involving non-U.S. buildings other than dwellings.

Location	Events	Deaths-	Injuries
Inside	11	26	189
On property	10	18	77
Schools	30	79	378
Small structures	28	111	179
Total	**79**	**234**	**823**

6E.1. Casualties inside non-U.S. buildings, except dwellings and schools

Table 5 has 11 events involving people who were casualties of lightning while inside non-U.S. buildings that were not dwellings or schools. The largest was a Philippine prison camp explosion resulting from lightning striking a concrete ammunition bunker that blasted through nearby buildings housing 107 inmates that were injured.

6E.2. Casualties related to non-U.S. schools

Table 5 lists 30 events involving casualties of lightning at non-U.S. schools. There were many more deaths and injuries in fewer cases than at U.S. schools (Table 4). Most incidents had multiple casualties in Africa and Southeast Asia.

6E.3. Casualties related to non-U.S. small structures

Table 5 lists events of lightning casualties within non-U.S. small shelters not used as dwellings. A notable number of cases involved people seeking safety in huts in agricultural fields when heavy rain arrived. Not included here are beach shelter incidents (Holle 2007b). The largest loss of life was 17 deaths at a Honduras soccer game, and 35 were injured when the crowd stood under a shelter, type unspecified, next to the field in heavy rain.

6F. Fatalities per event inside buildings

Curran et al. (2000) found that 91% of U.S. *Storm Data* lightning fatalities involved one person per incident. Another 8% involved two people, and 1% involved more than two. For the present study, Figure 14 indicates that the number of U.S. single events is 77% compared with 23% outside the U.S. The number of U.S. incidents with two fatalities is 17% and 33% for non-U.S. locations. No U.S. case had more than five fatalities inside buildings, while 23% had more than five outside the U.S.

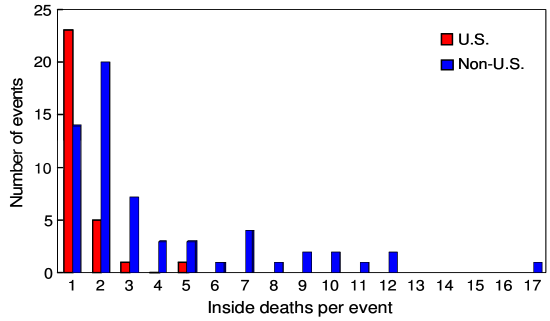

FIGURE 14. Number of fatalities per event inside buildings within and outside the U.S.

6G. Comparisons

Figures 15 and 16 summarize results from incidents involving dwelling and building events. Figure 15 shows seven times as many dwelling deaths per non-U.S event than within the U.S., and 18 times as many building deaths. Figure 16 shows a high relative frequency of reported lightning deaths inside non-U.S. buildings compared with the U.S. There is a similar proportion of deaths on the property of buildings in both places.

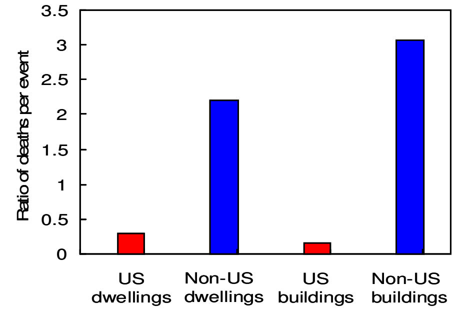

FIGURE 15. Ratio of building-related lightning deaths per event separated by dwellings and other buildings, within and outside the U.S.

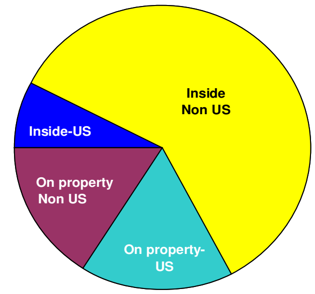

FIGURE 16. Building-related lightning deaths separated by whether people were inside or on property of buildings, within and outside the U.S.

7. LIGHTNING CASUALTIES IN AND NEAR WATER

Anywhere on the water places a person at risk from lightning; the largest casualty categories are fishing, beach, and boat events (Holle 2007b).

7A. Introduction

The category of “Beach/water” accounted for 18.0% of U.S. lightning deaths and 7.2% of injuries (Holle et al. 2005) using the NOAA publication *Storm Data*. There is a wide variety of situations under which people have become lightning victims in the vicinity of water. Table 6 shows events related to water.

The most frequent type of water event is related to fishing, followed by beaches and boats. Table 6 shows a ratio of one lightning death per 1.7 injuries for the water-related dataset. In particular, fishing and boating have nearly the same number of deaths as injuries. This is a very large ratio compared to the 10 injuries per death ratio in Colorado (Cherington et al. 1999). This large ratio appears to indicate that people in water situations are especially exposed to the lightning danger by being taller than the surrounding water.

TABLE 6. Summary of type and number of lightning events, deaths, and injuries related to bodies of water.

Type of water event	Events	Deaths-Injuries	
Fishing	66	55	53
Beach	37	24	85
Boats	23	17	18
Boat ramp	9	3	13
Lake, pond	9	3	9
Small island	7	14	9
Swimming – not in pool	7	12	9
Personal watercraft (jetski)	7	2	5
River	6	5	14
Swimming pool	6	4	5
Lifeguard	6	1	7
Other casualties related to water	19	7	27
Total	202	147	254

7B. Multiple casualty events

There are 14 events with five or more lightning casualties in Table 6. One multiple-injury case apparently involved people swimming in Japan (Kitagawa 2002). Others involved boaters, surfers, and rafters (5 injuries each), as well as Malaysian soldiers crossing a river (6 injuries). More than half of these events were in two situations:

- Five cases occurred on crowded beaches, and they accounted for a total of 2 deaths and 51 injuries.
- The small island category (Holle 2007b) has three events that account for 13 deaths and 5 injuries, a high ratio of deaths to injuries.

7C. Swimming pools

Swimming pools are often considered to be a source of danger from lightning. Table 6 includes six pool events that involve being in the pool, leaving the pool, on the deck, holding onto a metal ladder, and working inside a pool building. The range of situations indicates that anywhere in a pool complex is vulnerable to lightning. Detailed accounts are in Holle (2007b).

7D. Location

Oceans and lakes account for about half of all locations of events, deaths, and injuries. The other half involves rivers, as well as nearly every type of water entity, ranging from the ocean to a stock tank. Note that eight events involved people near some type of water when they sought safety under a tree when a storm was approaching or overhead. Another four events occurred when people sought safety under a building overhang or river bluff close to the water. There were three cases involving lifeguards on observation towers.

7E. Activity

Fishing and boating activities account for a third of all water events and deaths, and somewhat less of the injuries. Walking and standing also occur often around water when lightning occurred. Seeking safety under trees (11 events) accounted for multiple casualties. The activity of swimming (9) and standing (3) directly in the water is a very dangerous category.

7F. Summary

The most common type of lightning impact on a water event relates to fishing, whether from a boat or elsewhere. The next most frequent cases occur on beaches and boats. A dangerous location is being on a small island where there are trees. Locations of lightning casualties most often were on or near an ocean or lake. Other large categories included rivers, and people seeking safety from lightning under trees and buildings next to the water. Activities of lightning casualties were most often related to fishing and boating.

8. GLOBAL LIGHTNING CASUALTIES

A very general extrapolation of six deaths per million people applying to four billion people results in an estimate of 24,000 lightning deaths and 240,000 lightning injuries per year worldwide. Another reasonable estimate results in 8,000 per year, but data are very sparse (Holle 2007a, 2008a).

8A. Background

The annual number of lightning deaths has been compiled in the U.S. since 1900, and in other developed countries. However, there has been little systematic collection of information on lightning deaths in many regions of the world. Holle and López (2003) first made an assessment of the worldwide impact of lightning, and concluded that 24,000 deaths and 240,000 injuries occur per year (Holle and López 2003, 2007a, 2008a).

The underlying basis is that a rate of less than 0.3 deaths per million people applies to more developed countries with substantial housing and a decreasing amount of labor-intensive agricultural labor. Other regions were assumed to have an annual lightning fatality rate of 6 deaths per million per year, and this rate was applied to a large portion of the world's population. Using other reasonable methods, Cardoso et al. (2011) obtained a total of 8,000 global deaths per year.

Only fatalities are considered due to underreporting of injuries (López et al. 1993). Although exact death totals continue to be somewhat inconsistent (Richey et al. 2007), underreporting in other countries is unknown and appears to be large.

All known published lightning fatality data around the world are described in detail by country and decade in Holle (2007a, 2008a). Figures 17 to 19 summarize results by decade and region.

8B. 19th century

Figure 17 combines 19th century fatality rates for eight countries in Europe and Australia. The median decadal value was 3 deaths per million people per year. Most reporting countries are in Europe, which has less lightning than tropical regions. In general, 19th-century populations in these countries lived in rural areas and had agricultural occupations. In addition, homes and workplaces had little to no protection provided by wiring, plumbing, and structural metal components that provide safe places when lightning strikes.

8C. 20th century

Fatality rates are combined for the 20th century in Figures 18 and 19. Data were available in this century for eight countries in Europe and eight more in the rest of the world. Figure 18 summarizes decadal rates during the 20th century in Europe. Most rates are low, especially in the latter half of the century. The median in Europe of 0.3 is a ten-fold reduction since the 19th century (Figure 17).

Figure 19 summarizes decadal rates outside Europe during the 20th century. During the first half of the 20th century in the more developed countries, the typical annual rate was 2 per million. During the last half of the 20th century, the median annual value is 0.4 deaths per million. However, recent rates in Malawi (Mulder et al 2012), South Africa, and Zimbabwe are high, and may be representative of lesser developed regions.

8D. 21st century

Table 7 combines results for the 21st century. National data are provided first, then regional. Europe, North America and other more developed countries have annual rates as low as 0.1. At present, high rates of lightning deaths are found from limited data in Africa and portions of Asia. Lightning frequencies are high in these regions, the population is often rural, oriented toward agriculture, and living or working in structures that are not safe from lightning. The lack of reliable data for these populous regions is a significant gap for this study.

TABLE 7. Annual lightning deaths per million people during the first decade of the 21st century. National rates are followed by regional rates when available.

Country	Decadal fatality rate	Maximum annual rate
Bangladesh	0.9	0.9
Brazil (Sao Paulo)	0.8	0.8
Canada	0.1	0.3
China	0.5	0.7
Guangdong	0.9	0.9
Guizhou	1.2	1.2
Hainan	10.6	10.6
Hong Kong	0.04	0.04
Greece	0.2	0.4
India (Orissa)	2.5	2.5
Lithuania	0.1	0.1
Malawi	84.0	84.0
Malaysia	3.4	3.4
Nepal	2.7	2.7
South Africa	8.8 rural 1.5 urban	8.8 rural 1.5 urban
Sri Lanka	2.4	2.4
Vietnam	1.2	1.2
Bac Lieu	8.8	8.8
United States	0.2	0.2
Yemen (Saada)	71.4	71.4
Zimbabwe	14.2	14.2

8E. Discussion

Table 8 lists assumptions relating to the estimate of 24,000 worldwide annual deaths. The present study attempted to address factor number 2, that of the 6 per million rate per year. Lightning fatality information continues to be missing for heavily-populated areas with frequent lightning.

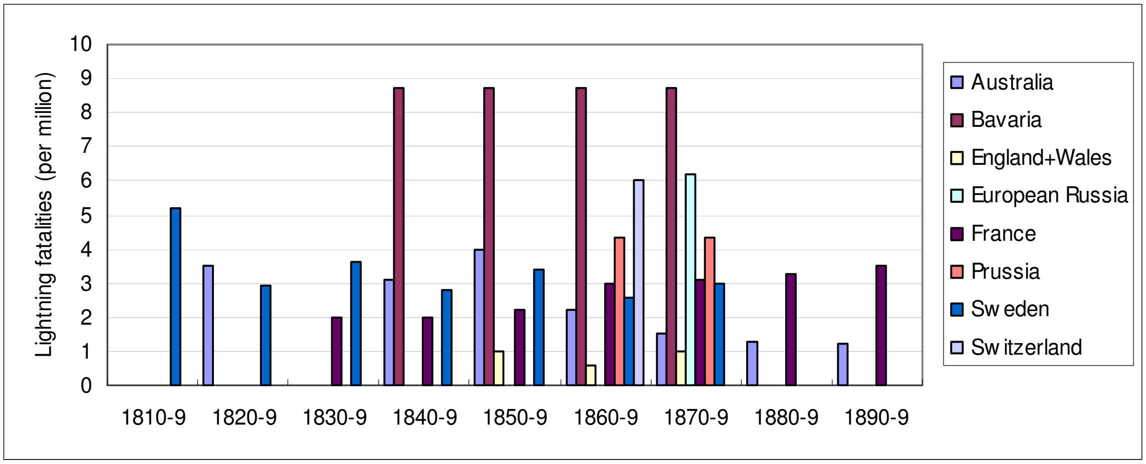

FIGURE 17. Lightning deaths per million people per year for eight countries in Europe and Australia by decade during 19th century.

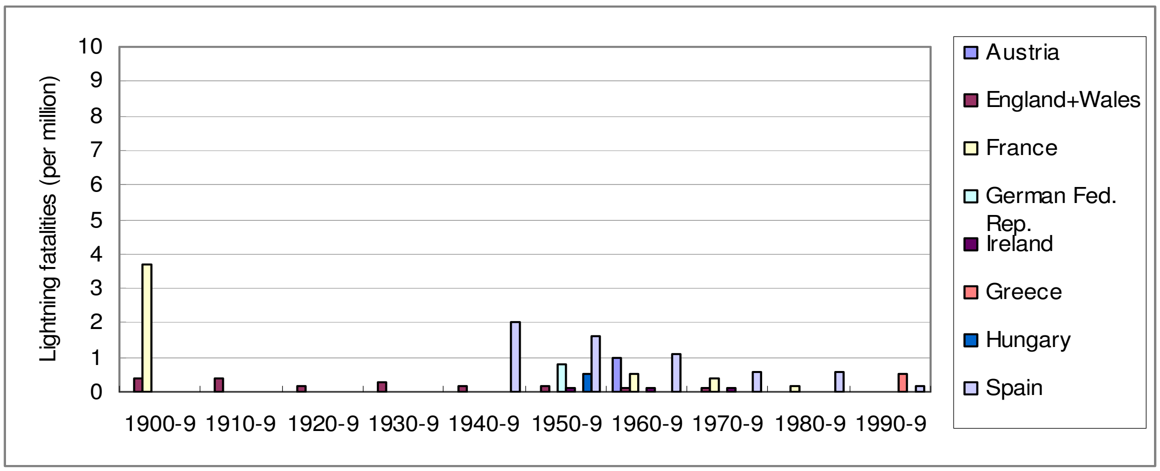

FIGURE 18. Lightning deaths per million people per year for eight countries in Europe by decade during 20th century.

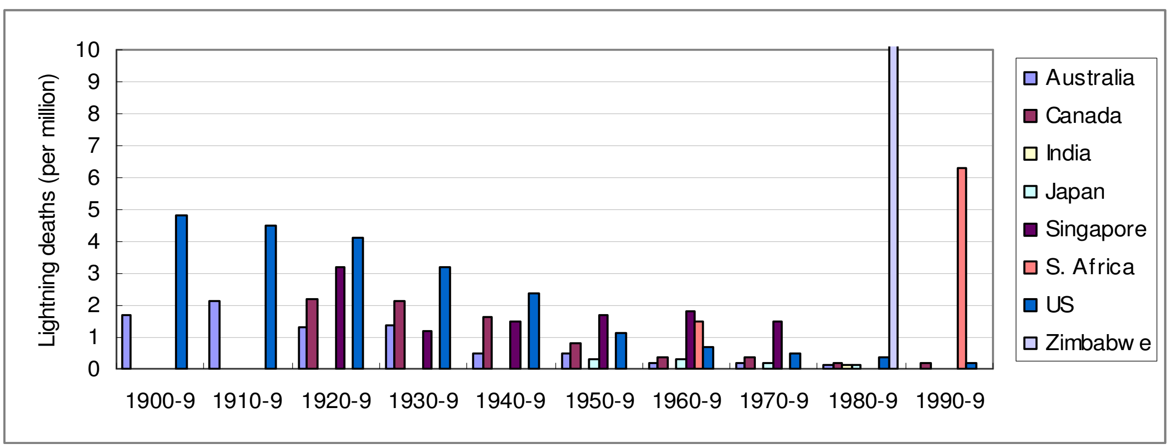

FIGURE 19. Lightning deaths per million people per year for eight countries outside Europe by decade during 20th century. Note that 1990s Zimbabwe value is 17.8.

TABLE 8. Factors that can change the estimate of 24,000 worldwide lightning fatalities per year (Holle and López 2003, Table 3).

Factor	Change	Impact on number of deaths
1. Area of high lightning frequency	Too small Too large	Increase Decrease
2. Fatality rate of 6 deaths per million people	Too low Too high	Increase Decrease
3. Rural-agricultural setting of people in high lightning areas compared to US and western Europe in 1900	More rural Less rural	Increase Decrease
4. Buildings occupied by people in high lightning areas compared to US and western Europe in 1900	Less substantial More substantial	Increase Decrease
5. Fatalities in areas outside Table 1 regions	Add areas	Increase
6. Organized recreational sports compared to US and western Europe in 1900	More	Increase
7. Meteorological forecasts and warnings	Improved	Decrease
8. Awareness of the lightning threat through education, planning and detection	Enhanced	Decrease
9. Medical care and emergency communications	Enhanced	Decrease
10. Other socioeconomic changes	Unknown	Unknown

9. CONCLUSIONS

A multidisciplinary group of lightning safety experts met in 1998 to develop guidelines that had not been adjusted for several decades (Holle et al. 1999). Development of national lightning detection networks and availability of other meteorological datasets had caused major reexamination of existing guidelines. Most of the 1998 guidelines have been supported, others have been evaluated, and some have been adjusted. It is now apparent that there are no reliable places outside to be safe from lightning, and the present paper shows how the lightning safety recommendations can be clarified with recent information.

The first sections of this summary paper identify better the actual lightning threat (sections 1 and 2), and the lightning fatalities by state (section 3). Some recommendations continue to assume that direct strike is the most common type of injury, which is not the case (section 4). Earlier recommendations had not sufficiently emphasized the nearly complete safety of being inside a large substantial building or fully-enclosed metal-topped vehicle, as described in sections 5 and 6. Instead, lightning recommendations should point out the reliable safety in more developed countries of nearby substantial buildings and fully-enclosed metal-topped vehicles. The lack of these safe places in lesser developed countries results in a high casualty rate at the present time that is difficult to estimate (section 8).

Acknowledgments

All of these projects are the result of ongoing interactions and cooperation with a large number of people in the lightning safety community in the U.S. and elsewhere. Lightning Awareness Week involves many individuals and agencies during the course of the year of planning for, and carrying out during this special week in late June.

Particular recognition must be given with respect to the content of the papers described in this report to:

- Dr. Mary Ann Cooper, formerly University of Illinois at Chicago,
- William Roeder, Rockledge, Florida,
- John Jensenius, National Weather Service, Gray, Maine,
- Dr. Raul López, formerly with NOAA research laboratories in Boulder and Norman,
- Donna Franklin, National Weather Service, Silver Spring, Maryland,
- Dr. Chris Andrews, Australia,
- Dr. Ryan Blumenthal, South Africa, and
- Many others who are actively involved in lightning safety issues that should be mentioned here.

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