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Factors contributing to a long-term decrease in national lightning fatality rates: case study of the United Kingdom with wider implications.

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Abstract

Decadal average lightning fatality rates in the United Kingdom have decreased markedly from 1.09 deaths per million population per year ($M^{-1}yr^{-1}$) in the 1850s to 0.02 $M^{-1}yr^{-1}$ by the 2010s. Factors contributing to the decrease are explored. They include a large reduction in the national workforce engaged in manually-intensive agriculture. Consequently, agricultural workforce deaths fell from 38% of all lightning deaths around 1850 to 9% by 2000. The percentage of the national population living in urban areas, where many jobs were indoors, increased. As buildings were modernised with electric and plumbing circuits they offered greater protection from lightning. Consequently, deaths indoors fell from 39% in 1850 to 11% in 1950, and with none in the past 50 years. Other factors contributing to lower fatality rates in recent decades included improved thunderstorm forecasts, lightning location detection systems, stricter safety regulations for outdoor workers, advances in the medical treatment of lightning casualties, better communication and road networks to request and receive medical help promptly, and greater public awareness of the lightning threat. Factors slowing down the fatality rate decrease include population growth and, in recent decades, the increased participation in outdoor leisure and sports pursuits in exposed locations. Fatality rates in other countries are explored. It is suggested that by recognising the influence each factor has on lightning fatality rates, countries currently experiencing high lightning fatality rates may be able to accelerate and enhance the beneficial impacts of some factors, albeit after adjustments to reflect their national social, economic and cultural characteristics.

Keywords

Lightning risk; Annual lightning fatality rates, Weather hazard

1. Introduction

The annual number of fatalities attributed to lightning and the fatality rate per million people per year in the United Kingdom (UK) have decreased markedly since the mid-nineteenth century. Reasons for this decrease are explored and the relative influence of each factor is assessed, where possible, and discussed. Factors examined include changes in occupations, population, urbanisation, building utility services, accuracy and communication of warnings of lightning, public awareness of lightning risk, medical treatment of casualties, participation in outdoor leisure and sports activities, and long-term frequency of thunderstorms and lightning flash rates.

The UK lies in the mid-latitudes with a temperate oceanic climate with thunderstorms developing up to 15-20 days per year on average, with maximum activity occurring in southeast England. Consequently, the UK experiences a relatively low frequency of thunderstorms and lightning flash rate compared to continental areas in the subtropics and tropics. The maximum UK lightning stroke rate of 1.0 km^2yr^{-1} compares with 16 km^2yr^{-1} or more in many countries in those locations (Vaisala, 2018). Although the UK lightning risk is much lower than in many countries, exploring the reasons for the marked decrease in its lightning fatality rate since the mid-nineteenth century provides an important insight into the factors that have contributed, or are likely to contribute in the future, to a reduction in fatality rates in other countries. Countries that have experienced a long-term decrease in lightning fatality rates are reviewed briefly to confirm the importance of the key common factors found in this UK study. The implications of this study for developing countries currently experiencing high annual lightning fatality rates are discussed.

2. Material and methods

2.1 Annual totals of UK lightning fatalities

The UK comprises the countries of England, Wales, Northern Ireland and Scotland. The annual number of lightning deaths have been recorded on death certificates in England and Wales (combined) since 1852, Northern Ireland since 1964 and Scotland since 1951. Annual summaries are provided in the Registrar-General's Annual Reports, first published in 1839. The early reports did not distinguish lightning-caused deaths separately but included them in broader categories, such as 'violent and accidental deaths' or 'exposure to forces of nature'. The International Classification of Diseases (ICD), Tenth Revision, 1990, currently specifies the code X33 for 'victim of lightning' but the codes for previous ICD revisions (e.g. E935 and E907) are compatible. The code excludes deaths caused indirectly by lightning such as due to fire.

2.2 Types of activities and locations associated with lightning deaths

Deaths due to lightning recorded in the Registrar-General's Annual Reports provide limited information about lightning fatalities such as the annual total number and a breakdown by gender and age range. Some nineteenth century reports also listed the district where death occurred, the date of fatality and the occupation of the deceased although the latter may not always be relevant as the lightning strike may not have taken place where a person worked. The details needed to better understand the circumstances accounting for someone being struck and killed by lightning are the type of location where they were struck and the activity being undertaken at the time. In particular, one needs to know whether they were at work and the nature of the work, or they were engaged in everyday routine activities in or outside the home, or were participating in leisure or sports activities. More specific details of the location and surroundings where a person was struck are needed: indoors or outdoors, in a park or on a mountain, sheltering beneath a tree or touching a metal fence, etc. There are 99 sub-category codes for the X33 code ('victim of lightning') which provide a more detailed breakdown of each fatality such as X33.72: 'victim of lightning, farm, while working for income'. However, these subcategories do not provide vital information such as whether the victim was sheltering under a tree, indoors holding a corded (landline) telephone or near a window, inside a motor vehicle, riding a horse or bicycle, etc. Nor do they indicate the type of sports or leisure activity being undertaken such as whether on a golf course, walking on a mountain or swimming in a lake, pool, river or sea. Also, the subcategories are not available for the whole period of study and for all UK countries. Consequently, to understand the reasons why the number of deaths has decreased since the mid-eighteenth century, alternative sources of information were identified.

In order to obtain more details about each lightning fatality incident, searches for lightning fatalities (and serious injury incidents to follow up, in case they died during the days or weeks after being struck) were undertaken using on-line national, regional and local newspaper resources from the nineteenth century to the present. Half-century interval samples of reports of fatalities were researched and analysed in detail. These centred on 1850 (1840-1859 reports), 1900 (1890-1909), 1950 (1940-1959) and 2000 (1990-2009). The 20-year data sets generated the details of the circumstances which resulted in 394, 340, 154 and 39 lightning fatalities respectively (Table 1). Clearly there has been a marked reduction in the number of lightning fatalities over this period. Since the half-century sample centred on 2000 produced fewer lightning deaths than the other samples, the recent years of 2010-2017 were included to increase the sample total to 47 deaths. For the years and UK home countries listing official annual fatality totals in the Registrar-General's Annual Reports, the four half-century samples uncovered the circumstances in 84, 99, 82 and 92% of the official lightning deaths recorded respectively.

The newspaper reports about each fatality incident varied greatly, some offering limited information while others, especially those summarising coronary inquests, were very detailed. The newspaper reports were supplemented with medical and meteorological journal articles discussing specific UK lightning fatality incidents. Investigative reports of incidents by members of the Thunderstorm Census Organisation (TCO) founded in 1924, the Climatological Observers Link (COL) which began in 1970, and the Tornado and Storm Research Organisation (TORRO) operating since 1974 (Elsom, 2001; Elsom and Webb, 2016) were also included.

The methodology employed in this study was tested initially by Elsom (2015) which was the first systematic approach to attempt to quantify the factors contributing to changing UK annual lightning fatality rates since the mid-nineteenth century. Other studies investigating factors influencing long-term national lightning fatality rates include Ashley and Gilson (2009), who studied annual fatality rates for the USA and individual states from 1959 to 2006, Lopez and Holle (1998a), who examined twentieth century USA fatality rates from 1900 to 1991, and Holle et al. (2005), who analysed and compared two five-year periods, 1891-1894 versus 1991-1994, for the USA. The latter study gained important insights into the factors responsible for the changes in lightning fatality rates between the late-nineteenth and late-twentieth centuries.

3. Results

Figure 1 highlights the annual variability and long-term trend of UK lightning fatalities since the mid-nineteenth century. It highlights that some years in the second half of the nineteenth century exceeded 40 deaths but that no years since 1940 have exceeded 20 deaths and that since the 1990s no year has exceeded 10 deaths. Moreover, since 2000 there were some years with no recorded lightning deaths.

Figure 1: Annual number of UK lightning fatalities 1852-2017. *Note: The annual number of fatalities refer those listed by the Registrar-General's Annual Reports for England and Wales (combined) since 1852, Northern Ireland since 1964 and Scotland since 1951. Most lightning deaths in the UK occur in England and Wales where thunderstorms are more frequent. For example, for the period 1964-2017, when records for all constituent countries are available, England and Wales accounted for 91% of all UK deaths. Consequently, Figure 1 approximates the trend in total UK fatalities. A 10-year moving average trendline has been inserted in red.*

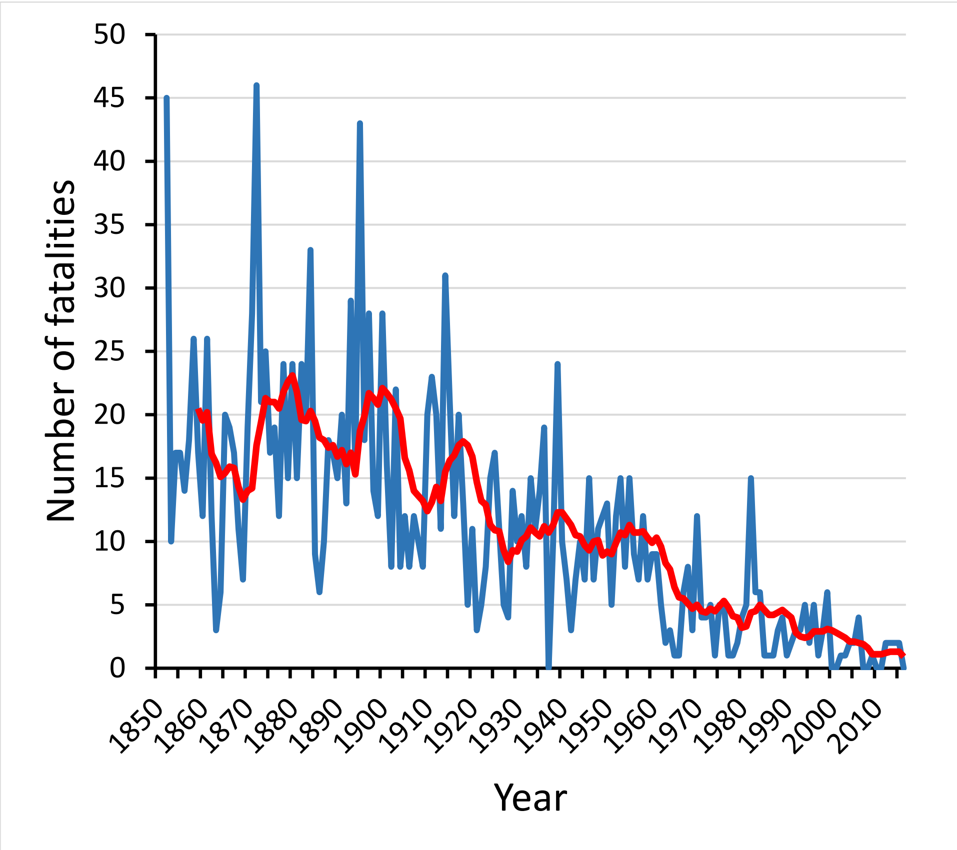

Figure 2 presents the annual and decadal trends of deaths per million people per year ($M^{-1}yr^{-1}$) to enable comparisons with other countries. The normalised figures were constructed using a similar methodology to Lopez and Holle (1998a). To examine lightning fatality rates from 1900 to 1991 for the contiguous USA they employed the number of lightning deaths and population for each reporting state, adding in the data for each state as it became available, to calculate the annual number of deaths per million people per year ($M^{-1}yr^{-1}$). In 1900, ten states reported official lighting deaths and it was not until 1935 when the 49 contiguous states and the District of Columbia provided reports. For the UK analysis, the number of lightning deaths and annual population for England and Wales were employed from 1852, then data for Scotland were included from 1951 and, finally, Northern Ireland data from 1964.

Figure 2: Decadal averages of the number of UK lightning fatalities per million people per year. *Note. Refer to note in Figure 1 for data sources.*

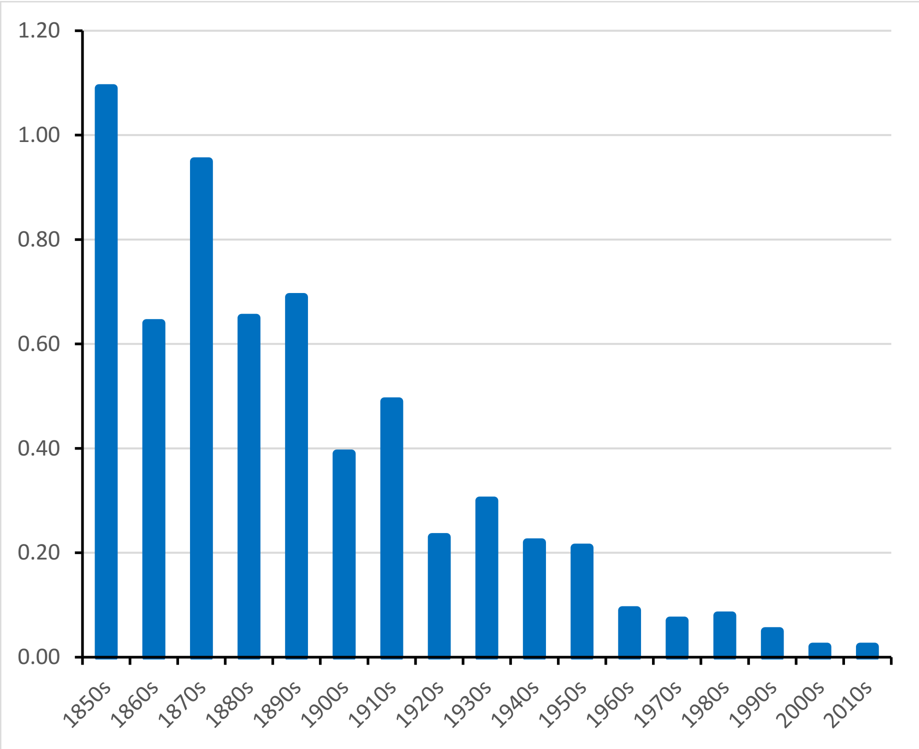

Figure 2 highlights that the decadal average rate of lightning deaths per million population per year in the UK has decreased markedly – a hundredfold - since the nineteenth century, from 1.09 deaths $M^{-1}yr^{-1}$ in the 1850s to 0.02 deaths $M^{-1}yr^{-1}$ by the 2010s (2010-2017). The UK's population has tripled from 22 million in the 1850s to around 66 million currently. This implies more people are at risk of being struck by lightning but it is clear from Figures 2 and 3 that other factors have negated population increase. The highest annual fatality rates occurred in the nineteenth century including 1852 (2.5 $M^{-1}yr^{-1}$ – 45 deaths in England and Wales with a population of 18.2 million), 1872 (2.0) and 1895 (1.4). In addition, the number of annual lightning fatalities for 1838 and 1839 for England and Wales were listed retrospectively in the Third Registrar-General's Report of 1841. The 25 and 18 people killed by lightning in 1838 (population 15.3 million) and 1839 (population 15.5 million) respectively translate into a lightning fatality rate of 1.6 and 1.2 deaths $M^{-1}yr^{-1}$ respectively. Although significant annual variations in the fatality rates occurred during the first half of the twentieth century, no individual year exceeded 1.0 $M^{-1}yr^{-1}$ and since 1950 no year exceeded 0.3 $M^{-1}yr^{-1}$. Since 2000, the fatality rates in individual years of have remained between zero and 0.05 $M^{-1}yr^{-1}$ – the latter is equivalent to one lightning death for every 20 million people in the UK.

4. Discussion

4.1 Changing occupations and the marked reduction in agricultural workforce

The activity being undertaken by the deceased at the time they were struck by lightning is placed in three broad groups of activities for those fatalities in which sufficient details were available (Table 1). The categories are: (1) at work (indoors or outdoors); (2) involved in the daily routine (indoors or outdoors), including travelling to and from home to work or school; and (3) participating in leisure and sports activities. The activity being undertaken when killed refers to the activity which placed the person at risk and resulted in their death. The type of work was identified and this highlighted that agricultural work produced the highest number of deaths in the work category in all half-century sample periods. Outdoor activities including working on the construction of buildings, fishing and serving in the armed forces accounted for much smaller numbers as found by Elsom (2015). Table 1 shows that lightning deaths amongst the agricultural workforce fell from 38% and 37% of all lightning deaths around 1850 and 1900 respectively to 23% by 1950 and only 9% around 2000. As a result, all work-related lightning deaths decreased markedly too. The long-term changes in percentages in the other broad activity categories in table 1 are discussed in later sections.

Table 1: Activity being undertaken when death occurred due to lightning (percentage).

Activity	**1850** (1840-1859)	**1900** (1890-1909)	**1950** (1940-1959)	**2000** (1990-2017)
At work	52	55	34	17
Agriculture only	*38*	*37*	*23*	*9*
Involved in the daily routine and travelling (including to and from work)	46	34	28	9
Undertaking outdoor leisure, and sports activities	2	11	38	74
Sample size (number of fatalities)	394	340	154	47
England and Wales	331	315	146	40
Northern Ireland	18	2	1	1
Scotland	45	23	7	6
Percentage of male fatalities	79	89	84	83

Table 1 highlights that farmers and farm labourers were often the victims of lightning during the nineteenth century through to the early twentieth century. Nearly all the casualties were men, reflecting the dominantly male-employed workforce undertaking work that was strenuous with limited or no mechanical assistance. They worked outdoors for long hours, from dawn to dusk, often in wide open fields or on grazing land (commons) and there was an expectation to continue working during bad weather, including thunderstorms. Even if they stopped work during a thunderstorm there were few safe shelters nearby. Some were killed when they sought unsafe shelters such as in an electrically ungrounded hut or barn or beneath a tree, hay stack, hedge or cart.

Figures for the percentage of people employed in agriculture became available from the 1851 census onwards (includes forestry and fishing in the same industrial census grouping) but only then for England and Wales. In that year it was 21.9% but estimates suggest this already represented a halving of the national workforce employed in agriculture since 1750 when the estimated figure was around 45% (Allen, 2000). This decline was a consequence of the British Industrial revolution beginning in the late eighteenth century. After 1851, census data reveals that the national agricultural workforce fell to 8.9% in 1901, 4.8% in 1951, 1.5% in 2001 and. 0.9% in 2011 (Office of National Statistics, 2013). Data are not available for Scotland and Northern Ireland throughout this census period so the percentages would be higher. However, England and Wales are the home nations which comprise the majority of the UK population and also give rise to most lightning fatalities in the UK, so Figure 3 is a good representation of the overall UK situation. It plots decadal average number of lightning fatalities per 20 $M^{-1}yr^{-1}$ in England and Wales against the percentage of working people employed in agriculture (and fishing) in England and Wales since the 1850s. Although the long-term downward trend in fatality rates generally follows the reduction in the agricultural workforce, there are other interrelated factors which contribute to the decrease too. These include the decrease in percentage of the national population living in rural areas and an increase in urban areas (urbanisation) where vast numbers of new buildings were being built which offered a safer environment in which to live and work when lightning threatened. These factors are discussed in the next section.

Figure 3: Decadal average number of lightning fatalities per 20 million people per year in England and Wales versus the percentage of working people employed in agriculture and fishing in England and Wales. *Note: No census data available for 1941. The industrial classification in 1971 was inconsistent with other censuses.*

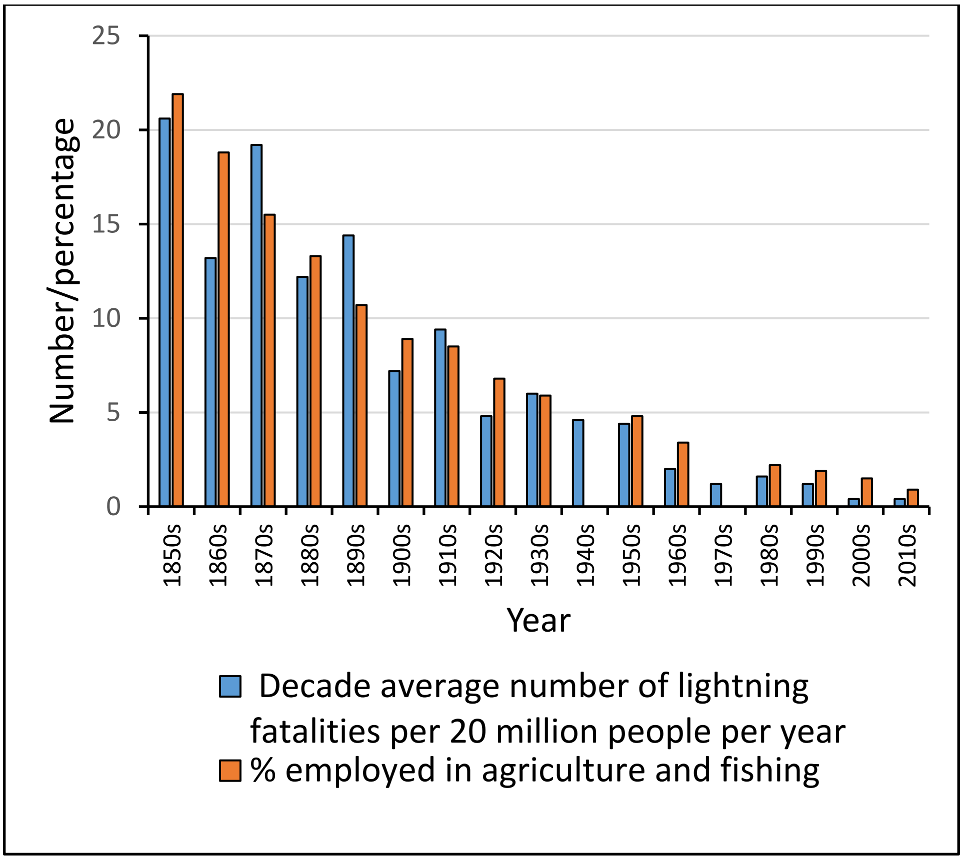

Figure 3 highlights that agricultural employment decreased markedly in the UK from the latter half of the nineteenth century onwards and there were various reasons for this. Cheaper imported foods, made possible by faster steam-powered ships and the development of reliable refrigeration in the 1870s, contributed to a decline in UK agricultural activity. The development and increased use of fertilisers, herbicides and pesticides, mechanisation and more productive practices increased agricultural yields greatly. Consequently, fewer workers were needed in agriculture such that in 1900 one agricultural worker fed around 25 people in Britain but by 2010 one agricultural worker fed 200 people (Office of National Statistics, 2013).

Although the decrease in the agricultural workforce meant fewer people were placed at risk of being killed by lightning, other factors have contributed to the lessening of the risk. These include successive government legislation to limit the number of working days and hours of workers and to strengthen the health and safety regulations relating to them. The availability of safe refuges during thunderstorms increased as more substantial barns were built which were electrically-grounded. The use of tractors and other motorised farm vehicles not only reduced the need to employ as many workers but they provided protection from lightning compared with having to plough using animals. This was because the Agriculture (Tractor Cabs) Regulations of 1967 required them to be fitted with enclosed cabins incorporating a roll-over protective steel structure. The ready availability in recent decades of more accurate and bespoke weather forecasts, such as 7-day farming weather forecasts, has allowed farmers to better schedule their work activities to minimise the exposure of themselves and their workforce to thunderstorms.

4.2 Urbanisation, the modernisation of buildings and lightning protection systems

Homes, schools, factories and offices, if struck by lightning, are much safer for occupants today than they were a century or more ago. Extensive electricity, water and sewage (utility services) circuits were often lacking in buildings then, so when lightning struck the chimney of a house or cottage (coal, wood or peat open fireplaces vented by a chimney were the norm for domestic heating and cooking) it would be conducted down inside the chimney and emerge into a room to injure or even kill an occupant. Families often gathered round the open fireplace in the kitchen, often the only source of heating in the home, and this was the location for many indoor lightning deaths in the nineteenth century. Alternatively, if lightning struck the roof, which was often thatched in rural areas, it would simply pass through the roof and ceilings into the rooms below to strike the occupants. It may set the roof and wooden floors alight and the occupants, if struck by the lightning's electric current and causing temporary paralysis but not death, may not be able physically to escape the burning and collapsing building.

Rapid urbanisation in the UK, especially during the period known as the Industrial Revolution (1760 to 1840), meant that the new factories required large numbers of workers who would need housing. With few building regulations, houses were built as cheaply as possible. Such houses initially had no utility services but throughout the latter part of the nineteenth century the occupants and local councils would add them progressively. During the twentieth century, new buildings in urban areas increasingly included electrical wiring (especially from the 1920s onwards) and water supply and drainage using metal pipes. The installation of electrical and plumbing circuits was also a critical development in relation to lightning protection as they provided a conducting route to earth for lightning's electrical current and so increased the safety of the occupants. The lightning current often makes contact with electrical wiring and/or metal water pipe circuits soon after penetrating a roof or striking a chimney. It is then diverted along the wiring or pipe through the building walls to earth in the ground, and so is kept away from the occupants. Intense heating of the wiring may cause scorch marks on interior walls and explosive damage to electrical sockets. Although a person in contact with, or very close to, the wiring or plumbing circuits may experience a touch voltage or side flash, they should not experience the full electrical current which may otherwise have fatal consequences.

From the mid-1950s onwards, telephone lines and television aerials attached to roofs would often provide a strike point for lightning. Although televisions, telephones, modems and connected computers may be damaged and sometimes catch fire, the lightning would eventually earth to ground and not affect the occupants unless they were, say, using a corded (landline) telephone or wired computer at the time. Increasingly, surge-protection devices have been fitted to electrical and electronic equipment to minimise the electrical current generated by a lightning strike which may otherwise injure or kill the user. Since the 1990s, corded telephones have been replaced increasingly by cordless telephones and smart and mobile (cell) phones. Similarly, personnel computers, ipads and notebooks have become cordless. As these devices are not connected to electric circuits they are relatively safe when lightning strikes a building. Further, many buildings are required by legislation (building codes), especially public and high-rise buildings, to install approved lightning protection systems for which the standards are regularly reviewed and updated.

Analysis of indoor versus outdoor lightning fatalities at half-century intervals confirms the role played by building modernisation in reducing lightning deaths (Table 2). Whereas 39% of all lightning deaths took place indoors in the mid-nineteenth century this figure had fallen to 24% by 1900 to 11% by 1950. Today, and since the 1960s, no person has been killed indoors in the UK (Elsom and Webb, 2014).

Table 2. Percentage of lightning deaths indoors and outdoors at half-century intervals. *Notes: (1) Indoor deaths includes people standing at an external door or window of a building; (2) Small structures refer to huts, sheds, outbuildings and shelters which lack utility service circuits and electrical earthing; (3) Sample size differs slightly from Table 1 as details available for apportioning deaths to each category vary.*

Location	1850 (1840-1859)	1900 (1890-1909)	1950 (1940-1949)	2000 (1990-2015)
Indoors	39	24	11	0
Percentage of indoor deaths in a small structure	*12*	*23*	*71*	*0*
Outdoors	61	76	89	100
Percentage of outdoor deaths sheltering under a tree	*28*	*30*	*28*	*21*
Sample size (number of fatalities)	392	341	150	47

Although the current indoor risk of being killed by lightning in electrically well-grounded, substantial buildings has become small, it is not zero. Touching an electrical appliance or wiring when lightning strikes a building could, on rare occasions, cause serious injury or even death. Also, lightning may strike a person directly if they are standing at an open external door or window. Further, table 2 shows that some indoor deaths occurred in ungrounded small structures such as huts, sheds, outbuildings, hides and shelters (at bus stops, in parks and on golf courses). These structures continue to be potentially dangerous places in which to shelter during thunderstorms as they lack the ‘protective’ utility service circuits of modern homes, shops and workplaces which may lead the lightning’s electrical current safely to the ground.

Urbanisation, especially from the mid-nineteenth onwards, increased the number of modern and modernised buildings and this has meant that urban residents were less likely to be killed by lightning when indoors. Modernisation of rural homes followed but lagged many decades behind the progress being made in urban areas. In the 1851 census of England and Wales, 50% of people lived in rural areas and 50% in urban areas, but by 1901 this had fallen to 23% in rural areas and risen to 77% in urban areas. The population shift from rural to urban areas not only contributed to more people living and working in electrically-grounded lightning-safe buildings but it reflected a large reduction in the number of people working outdoors in labour-intensive agriculture and, to a lesser extent, construction where they were exposed to the risk of being struck by lightning.

The reduction in the agricultural workforce during the nineteenth century resulted in large numbers of people migrating from rural areas to seek work in the growing manufacturing (chemical, engineering, textile), construction, energy and service sectors in urban areas. Many of the labourers who built the national railway network in the nineteenth century were previously farm labourers but they chose not to return to their rural lifestyles after completing their work and moved to the cities instead. Employment in the rural craft industry had offered an alternative to working in agriculture but it declined after the 1850s as it was progressively absorbed into larger urban-based production units. Higher wages and a perception of improved prospects in the cities encouraged people to favour urban living. Not all these population shifts were due to rural people migrating to urban centres but rather because cities needed space to build new homes and so they encroached on to adjacent rural areas: outlying villages became part of the urban suburbs and provided a focal point around which to build extensive new estates of modern affordable homes.

Political reorganisation of the UK's administrative areas, along with changing definitions of urban and rural living, created inconsistency over the long term such that it is not possible to plot decadal lightning fatality rates against percentage of rural population from the 1850s to the present day in the UK as Lopez and Holle (1998a, 1998b) did for the USA. However, it is evident from limited data available that the decreasing decadal lightning fatality rates for the period from the 1850s to the 1920s, a period of greater consistency in rural/urban definitions in the UK, was related to both the increase in the proportion of people living and working in urban areas in lightning-safe buildings and the decrease in the percentage of working people employed in labour-intensive agriculture. These influences on reducing the lightning fatality rate have continued since the 1920s. Urban areas continued to grow even when employment in the manufacturing industries decreased as the rapid growth of the service sector ensured that urban areas rather than rural areas offered the most employment opportunities. Urban populations increased through immigration too (discussed in section 4.4). By the 2011 census in England and Wales, 81% of working people were employed in the service sector, 18% in manufacturing construction and energy industries and only 1% in agriculture and fishing (Office of National Statistics, 2013).

Generally, it is evident that throughout the past century and a half, modernisation of the national building stock has resulted in the occupants being at a lower risk of being killed indoors by lightning. Today this applies whether people live or work inside them in urban or rural areas. Even when outdoors, travelling to and from work, people are much safer than they once were from lightning as they travel in the relative safety of enclosed motor vehicles (buses, trams, trains, metro). Residents who are outdoors in those parts of an urban area where there are tall buildings and structures and street lightning columns may benefit from these higher objects providing an attachment point for cloud-to-ground lightning rather them themselves.

4.3 Increased time spent on outdoor leisure activities and sports

In the nineteenth century people spent long hours at work and there was very limited time for leisure pursuits. Although most people had Sundays off work, along with a few religious holidays, it was not until the Bank Holidays Act 1871 that statutory public holidays were introduced. In 1971, the act was amended to increase the number of such days and they currently total from eight to ten days within the constituent UK countries. The Holidays with Pay Act 1938 implemented the right to one week's paid holiday per year and in 1998 the UK implemented the European Union Working Time Regulations granting workers 28 days of paid annual leave (public holidays are often considered by employees to be part of annual leave). For many people working in urban areas, these public holidays provided an opportunity to spend time outdoors in the open countryside, in parks and on beaches enjoying leisure and recreation activities. The 'working week' is Monday to Friday for many workers which meant the weekend (Saturday and Sunday) became a time to undertake leisure, recreation and sports activities.

The increased availability of time to spend on outdoor leisure, recreation and sports activities for an increasing proportion of the population since the nineteenth century is reflected in the percentage that these activities contribute to lightning deaths (Table 1). Around 1850, only 2% of lightning deaths occurred while people were undertaking leisure, recreation and sport activities. By 1900 this figure had increased to 11% but it was from the mid-twentieth century onwards that saw the greatest percentage increase in lightning deaths in this category of activity with 38% around 1950, albeit the absolute number of annual lightning deaths is relatively low (Table 1). By 2000, three-quarters of all lightning deaths (74%) occurred among people undertaking leisure and sports activities. Similar high percentages for recent years has been reported for studies in Canada (Mills et al., 2006, 2008) and the USA (Jensenius, 2016).

Those engaged in walking for leisure in exposed locations, sometimes remote locations such as hills, mountains and moors, are a long way from a safe refuge (enclosed motor vehicle or substantial, electrically-earthed building) if lightning threatens. Moreover, if someone is struck by lightning in such remote locations, it takes a long time for emergency medical help to reach them (Elsom et al., 2016). Playing golf, participating in or watching sports (cricket, football, hockey, rugby), fishing and swimming take place in wide open spaces and so are also dangerous places to be if lightning strikes. The greater time spent by people in outdoor leisure and sport activities in the UK, especially since the 1960s, is a factor that has slowed the rate of decrease of the annual lightning fatality rate per million people in the UK (Figure 2). However, since the 1990s, those participating in or organising leisure and sports activities have increasingly recognised the risk that thunderstorms pose during these activities and have taken actions to lessen that risk. For example, the rules were changed in golf in 1992 by the Royal and Ancient (R&A), the governing body for golfers in the UK and 140 countries other countries, to allow players to discontinue play without any penalty if they believe there is a danger from lightning. The same rule, part of Rule 6-8, is applied by the United States Golf Association in the USA and Mexico where it is the governing body. Another section of this rule requires committees administering a competition to do everything possible to protect players from bad weather and in particular, lightning. Guidance for competition organising committees as to when to discontinue and then restart play is available from national and local weather forecast services and lightning detection devices. Play is usually discontinued by the sounding of a klaxon (siren) and players, officials and spectators are expected to seek a safe shelter, notably the Clubhouse. Unfortunately, not all golfers seek the safety of the Clubhouse and, instead, seek shelter under a tree which, if struck, conducts the electric current down the trunk before side flashing (splashing) to a person sheltering beneath. Some on-course shelters, which are not electrically earthed, are intended simply as shelters from the rain or for shade so are not safe refuges if lightning threatens.

Organisers of outdoor team sports are increasingly aware that they should delay the start of a match if lightning threatens or they should suspend it and lead the players to the safety of a substantial building (e.g. changing rooms). Spectators should be safe in covered spectator stands, providing they are adequately protected by lightning conductors. Those providing seating or standing for 500 people or more have been required to have a safety certificate in accordance with the provisions of the Fire Safety and Safety of Places of Sport Act 1987. If such stands are not present at, say, local sports fields, then spectators should seek the safety of nearby electrically-earthed buildings or the vehicles (cars, buses) in which many travelled to the event. The organisers of a local and national sport events are expected to advise when and where spectators should seek shelter to avoid a lightning tragedy such as happened at the Royal Ascot racecourse in Berkshire in July 1955 (Elsom and Webb, 2015). Outdoor swimming pools are another potentially dangerous place to be if lightning threatens, as are indoor pools if the building is not properly earthed, so evacuation plans are adopted when a lightning risk is forecast.

4.4 Greater public awareness of the lightning risk

Being aware of the threat of lightning and knowing when and where to seek safety reduces the risk of being struck. UK newspapers and magazines have frequently published articles highlighting the dangers of lightning especially when reporting a lightning death or injuries to a large group of people. The amount of advice about the lightning risk awareness and safety advice increased greatly due to the growth of public radio stations from the 1920s onwards and television sets from the 1950s. Unfortunately, some of the advice perpetuated inappropriate ‘lightning myths’. For example, it was often stated that a person “struck” by lightning would be killed whereas, in reality, 90% of people survive. This myth caused people and the media to rationalise their survival by claiming mistakenly, for example, that they were saved because they were, say, wearing rubber-soled footwear. However, from the late 1990s onward, public awareness of accurate lightning safety advice began to grow as charities (e.g. Royal Society for Prevention of Accidents) and other organisations (e.g. Met Office; TORRO) published lightning safety guidance and encouraged outdoor leisure and sports organisations to adopt lightning safety policies and to issue guidelines to their members. UK safety guidance benefitted greatly from the efforts of the increased attention given to lightning safety in the USA. In 1998, a multidisciplinary group of lightning researchers and experts formulated an agreed set of lightning safety guidelines. These were widely publicised (e.g. Holle et al., 1999) and resulted in a national lightning awareness campaign in the US which included the holding of the first annual Lightning Safety Week in June 2001 (Cooper and Holle, 2012). From the early 2000s onwards, the ease of accessing and sharing lightning safety advice globally via the world wide web greatly increased the numbers of organisations and individuals in the UK who gained a better, informed awareness of the lightning risk and what effective actions to take. Many people are now familiar with the widely publicised 30/30 flash-to-bang rule: if the flash (lightning) to bang (thunder) is 30 seconds in length or less you should be in a safe shelter. Then you should stay inside this shelter until 30 minutes past the last clap of thunder. This ensures that any long distance lightning strikes originating from the forward edge of a thunderstorm (lightning can travel up to 10 km) or those from the trailing rear of the thunderstorm respectively do not take anyone by surprise.

Awareness of the dangers of lightning amongst the UK population has increased significantly since the 1960s because of the growth in international travel to, and immigration from, countries where thunderstorms are more frequent and where the dangers of lightning are more apparent. Accessible air travel and cheap fares in the 1960s resulted in the start of an accelerating increase in overseas travel and tourism. Visits abroad by UK residents grew from 3.3 million in 1961 to 55.6 million in 2010, a 17-fold increase (Barnes and Smith, 2011). Experiencing a lightning injury or near miss or simply being told about someone being struck by lightning strike while on holiday in a tropical country with frequent thunderstorms would have given them a greater respect for the dangers of lightning which they shared with families and friends on their return to the UK. Immigrants from countries where the risk of being struck by lightning is better known have also contributed to raising awareness of the lightning risk amongst the wider UK population. Large influxes of people arrived in the 1960s and 1970s from British Commonwealth and other countries including Bangladesh, India, Jamaica, Pakistan and Uganda. The percentage of foreign-born people in the UK has continued to increase from 7 per cent in 1993 to 13 per cent in 2014 (Rienzo and Vargas-Silva, 2016). The main influx in immigration since 2004 has been from Poland and other eastern European states, following the enlargement of the European Union in 2004, and these are countries where intense summer thunderstorms are prevalent.

Although many people know what actions to take when lightning threatens, some fail to do so. For example, although most people have been aware for the past century or more of the dangers of sheltering under a tree during a thunderstorm, it has not prevented such deaths from continuing to happen even today. Analysis of half-century samples undertaken in this study indicate that the percentage of outdoor deaths to people sheltering beneath a tree were: 1850 (28%), 1900 (30%), 1950 (28%) and 2000 (21%) (Table 2). In other words, even though there has been widespread awareness for more than a century and a half of the dangers of sheltering beneath trees during a thunderstorm, too many people continue to do so. All too often, lightning incident reports indicate that the adults and/or children killed and injured while sheltering under a tree were aware of the danger but either ignored it or left it too late to seek safety in a well-grounded, substantial building or metal-topped, fully enclosed motor vehicle. Clearly, there continues to be a need to ensure greater public awareness of the importance of taking prompt and appropriate action when lightning threatens.

4.5 Availability and improvements in forecasting thunderstorms

Weather forecasts help people avoid putting themselves at risk of being struck by lightning. However, the public, organisers of outdoor events and employers have to be able to access the forecasts readily and have confidence in the forecast accuracy before they are willing to take action. Although daily weather forecasts were first published in *The Times* newspaper in 1861, issued on the radio in 1923, and broadcast live on television in 1954, their accuracy was limited. They helped people to be aware that thunderstorms were possible the next day but, even when the forecast was correct, the hourly timing of the likely occurrence of the thunderstorms in a specific region of the UK was very limited. Not until the early 1960s did the accuracy and availability of weather forecasts begin to increase sufficiently to influence significant numbers of people to reschedule an outdoor activity planned for the next day. Even then, the accuracy of forecasts for several days ahead was not good enough for the many people who needed to make weather-related decisions over that time scale.

The accuracy of weather forecasts by the UK Met Office increased significantly from the 1980s onwards because of rapid advances in computer technology which enabled the running of sophisticated numerical forecast models. Advanced computers were able to process the vast amounts of meteorological data from satellites, radar, ocean buoys, aircraft and automatic weather stations needed by the models and they could run the models more quickly. The growing capacity of supercomputers to run increasingly complex and higher resolution numerical forecast models is exemplified by the Met Office and its successive supercomputers: they could process 50,000 calculations per second in 1965, 200 million calculations per second in 1982, a trillion calculations per second in 1997 and 16,000 trillion calculations per second currently (Met Office, 2016). This has enabled forecasts for five days ahead to improve from 66% accuracy in the early 1980s, through 80% by 2000, to 90% by 2015 (Bauer et al., 2015).

There is always some uncertainty in weather forecasting so it is important to communicate this to the public when they are planning outdoor activities a few days ahead. Since the 1990s, the Met Office has been working towards expressing forecasts in probability terms. This is achieved by using ensemble forecasting which refers to the running of, say, 50 numerical forecast models simultaneously with each being given slightly different starting assumptions. The result can be expressed as, say, a low, medium or high risk of thunderstorms occurring in a region during a three-hour time. The increasing processing capacity of computers has also enabled the use of very high resolution numerical models which are more appropriate for the forecasting the development and movement of relatively small-scale severe weather systems including thunderstorms. Some thunderstorms may be only 5-10 kilometres and last only for an hour although many are much larger and last for many hours. The introduction of the Met Office Arrival Time Difference (ATD) lightning detection system in 1987 and its update, the updated Arrival Time Difference Network (ATDnet) system in 2008, were important contributions to thunderstorm observing and forecasting (Elsom et al., 2018). ATDnet's location accuracy for lightning strikes of 1-3 km or better over the UK, has enabled the detection and tracking of thunderstorms. A current display map of lightning fixes has been available to the public using computers and laptops for the past 20 years (net.weather.tv, 2018). In recent years, smartphone apps are readily available to display the location of lightning without charge using several different lightning location systems. The WeatherBug app, called Spark, tells you where the nearest lightning strike is to you and, if within 15 km, will advise 'Seek shelter now'. It utilises data from the Total Lightning Network operated by Earth Networks (Weatherbug, 2018). Another smartphone app available is Blitzortung, a real-time community collaborative detection network whose strike location accuracy and detection efficiency is good for England and Wales but less so for Northern Ireland and Scotland (lightning.maps.org, 2018). Ready access to such information helps users to be aware of a possible lightning risk in their vicinity but the technology is not infallible so, for safety, all aspects of lightning safety guidance should be borne in mind.

Improvements in weather forecasts since the 1980s, as well as the ease with which forecasts can be received and understood by the public using many different forms of communication since the 1990s, have resulted in thunderstorm forecasts saving lives as individuals and organisations have confidently rescheduled, delayed or curtailed planned outdoor activities. Unfortunately, the forecasts, together with a raised awareness of the lightning risk, have not always resulted in everyone taking effective action to reduce their risk of being struck by lightning. There still remains a reluctance amongst some individuals to reschedule or delay the start of an activity if thunderstorms are forecast. Similarly, some people are slow to curtail an activity and seek safety when a thunderstorm develops. Increasing recognition amongst these individuals of the dangers posed by lightning still remains a challenge.

4.6 Improved medical treatment

The only cause of immediate death from a lightning strike is cardiopulmonary arrest but prompt treatment by bystanders and paramedics in recent decades has resulted in successful resuscitations, especially amongst young and previously healthy individuals (Christophides et al., 2017; Cooper and Johnson, 2005; Cooper et al., 2007; Nelson et al., 2007). Unfortunately this was not the situation in the nineteenth and first half of the twentieth centuries in the UK. Treatment of lightning casualties by bystanders was ineffective and even doctors called to the scene - often taking half an hour or more to arrive - were unable to resuscitate the casualty. Moreover, some seriously injured casualties, who had not suffered an arrest, died later through a deterioration in their condition.

The lack of effective treatment of lightning casualties by bystanders who had witnessed the strike and by doctors called to help was evident in many incidents a century or more ago in the UK. Bystander attempts to resuscitate those struck by lightning, but without success, included placing the casualty ‘into a warm bath’ (Hereford, Herefordshire, 9 August 1843); ‘rubbing his face with vinegar and water’ [without success] (Exeter, Devon, incident on 19 August 1852) and, while waiting for one and a half hours for the doctor to arrive, ‘every endeavour was tried to revive her: rubbing, artificial restoration, gave bandy, eau-de-cologne, and dashed water over her’ (Dover, Kent, 27 July 1904). It is evident from many incident reports in the nineteenth and early twentieth centuries that few bystanders knew what basic life support to administer. Even the doctors called to help had limited medical knowledge and equipment with which to treat a lightning casualty effectively as, for example, a doctor ‘thought the woman was not dead, and attempted to bleed her, but could get but very little blood from her [and she died or was dead already] (Maidstone, Kent,28 September 1852). In too many incidents, no treatment was applied by bystanders or doctors because the casualty was believed to be dead. Only in more recent decades has it been shown that wide (dilated) and unreactive pupils should not be interpreted as an indicator of brain death (Pfortmueller et al., 2012).

Greater awareness amongst the UK public that they could offer immediate first aid (basic life support) to those who had suffered a cardiopulmonary arrest due to a lightning strike took place in the late 1960s when mouth-to-mouth resuscitation (‘kiss of life’) was promoted more widely as an effective method of artificial respiration. During this decade, first aid organisations were also describing in their first aid manuals how to administer external chest compressions as a resuscitation method which the lay public could attempt until professional medical assistance arrived. However, it was not until the 1990s in the UK that defibrillators become essential equipment for ambulances, paramedics and first responders to carry, and not until this century did public access Automated External Defibrillators (AEDs) become widely available. There are now more than 10,000 public access defibrillators across the UK. In the past two decades, paramedics sent to help those suffering cardiopulmonary arrest due to lightning can administer advanced cardiac life support (ACLS) which includes the administration of drugs and other interventions to assist in preserving life.

Medical treatment of lightning casualties continues to improve. If someone suffers a lightning-induced cardiac arrest, it is vital that cardiopulmonary resuscitation (CPR) is initiated promptly and continued until paramedics arrive with a defibrillator and to administer ACLS. Improved guidance to bystanders has been developed in the past decade which is helping bystanders to save more lives. For example, not everyone is willing to undertake the mouth-to-mouth ventilation component of standard CPR on a stranger, partly out of fear of contracting diseases. Moreover, if bystanders perform mouth-to-mouth ventilation, it may take too much time away from chest compressions, which have to be continuous to improve survival chances. While mouth-to-mouth ventilation may “rescue’” an individual with respiratory arrest (e.g. drowning and drug overdose), this approach actually decreases the likelihood of a “rescue” in those with a primary cardiac arrest (Ewy, 2007). While a bystander halts compressions to give two breaths, blood flow also stops, and this cessation of blood flow leads to a quick drop in the blood pressure that had been built up during the previous set of compressions (Bon, 2015). Consequently for non-medical and untrained bystanders in out-of-hospital cardiac arrest incidents such as lightning incidents, compression-only CPR is now recommended (American Heart Association, 2015).

Every minute saved in time from arrest to defibrillation increases the likelihood of survival to hospital discharge by 10% (Cagle et al., 2007). Few bystanders at lightning incidents in remote areas carried mobile phones or smartphones before the mid-1990s in the UK so they would have had to run for help to the nearest location to make an emergency telephone call. Most adults and nearly all teenagers now carry them so are able to call promptly for medical assistance [and it should be mentioned that such devices do not attract lightning]. Overall, the average response time for emergency medical help to reach a casualty has improved since the 1990s. This has been encouraged by the introduction in 2001 of a National Health Service target that expects ambulance services in England to achieve 75% of responses from call to a crew arriving on the scene within 8 minutes for life-threatening cases (category A or Red). Scotland has the same target, Northern Ireland 72.5% and Wales 65%. However, in the past ten years these targets have not always been met and there is much regional variation so there is potential for improvement to ensure more lightning casualties survive in the future. Emergency helicopter air ambulances, with their increasing number and coverage since the 1980s, are contributing to a speedier response to incidents in the more remote areas.

Generally, the number of instances of successful resuscitations *in situ* of lightning casualties in the UK has increased since the 1960s. The largest known number of people resuscitated in a single lightning incident in the UK took place when a group of 17 adults and children were struck by lightning in September 1995 at Aylesford, Kent, while sheltering beneath a tree after an under-10-year-olds soccer match was abandoned. Four suffered cardiopulmonary arrest but were successfully resuscitated (Fahmy et al, 1999).In the past 30 years (1987-2016), there have been 58 people killed by lightning but 20 others are known to have been resuscitated (Elsom and Webb, 2017). In other words, during the past 30 years, the average number of deaths each year in the UK has averaged two (or statistically 1.9 deaths) but, if the successful resuscitation attempts had failed, this number would have been three (or statistically 2.6 deaths). The number of successes may have been even greater but some casualties who were resuscitated and reached hospital alive, died later in intensive care. In total, in the past 30 years, nine lightning-struck patients are known to have died in hospital several hours, days or, for one 12-year-old boy, three weeks after lightning had induced a cardiopulmonary arrest. Even so, it is evident that bystander-initiated CPR and paramedic-administered ACLS have helped to reduce the annual number of lightning fatalities in the UK since the 1960s.

4.7 Variation in thunderstorm frequency

Thunderstorm frequency and cloud-to-ground lightning flash rates vary from year-to-year in the UK but there is no evidence to suggest a long-term trend that may have contributed to a decrease in lightning fatalities since the mid-nineteenth century. Annual variability in the temporal and spatial distribution of UK thunderstorms may contribute to more or fewer fatalities in one year compared to another. For example, a year in which there is a higher-than-average frequency of thunderstorms occurring during the day may expose more people to lightning than when they occur at night when most people are relative safe in their homes. A higher-than-average frequency of thunderstorms during weekends in a year may expose more people to a lightning risk as they typically spend more of their time outdoors than during the working week.

Annual lightning counts for the UK are available only since the late 1980s and although some years have experienced higher rates than others, no trend is evident since then (Elsom, 2015). Webb (2016) analysed the mean annual frequencies of 'days of thunder heard' for seven UK locations from 1890 to 2009. He found that although there have been decades when the frequency of thunderstorms have been below or above the long-term average, there was no downward trend which could have contributed to the long-term decrease in the number of lightning fatalities in the UK.

4.8 Summary of UK factors influencing annual lightning fatality rates

Table 3 summarises the factors contributing to the remarkable one hundred-fold decrease in the annual lightning fatality rates per million people (and associated large decrease in the annual number of fatalities) experienced by the UK since the 1850s as well as some factors which have slowed down the rate of improvement.

Table 3. Factors contributing to the long-term trend in lightning fatality rates per million people per year (and annual number of lightning fatalities) in the UK.

Factors contributing to a decrease
Reduction in the workforce in labour-intensive agriculture.
Decrease in number of all types of outdoor manual workers (agriculture, forestry, construction) and an increase in the number of indoor workers (manufacturing, commercial and service sectors).
Improved health and safety legislation requiring employers to ensure the safety of their employees, especially those working outdoors and in occupations at greater risk from lightning e.g. increased number of lightning-safe shelters (barns) near to farm workers, increased use of farm vehicles fitted with enclosed cabins.
Growth in the percentage of people living in urban areas rather than in dispersed rural villages areas accelerates the rate of modernisation of the national building stock (electricity wiring and metal plumbing pipe circuits provide a relatively safe route to earth for a lightning strike that avoids occupants); urban residents spend most of their time living and working indoors; increase in the number of high-rise buildings offering a preferential lightning attachment point than to people on the streets below.

Stricter Legislation (building codes) requiring public-use buildings to be fitted with approved lightning protection systems, and enforcement of these codes.

Technology advances e.g. better communication to call for medical assistance; surge protectors fitted to electrical appliances; cordless telephones and smartphones replacing corded telephones; portable defibrillators

Modernisation of transport provides safer ways of commuting to and from work and travelling long distances i.e. enclosed metal-topped motor vehicles, trains, trams and aeroplanes replacing walking, riding a horse and riding in open-top horse-drawn carts and carriages.

Greater awareness of the lightning risk amongst people, and the dispelling of lightning myths, through more effective lightning safety campaigns and the implementation of lightning safety policies by schools, sports clubs and other organisations.

Increased availability, accuracy and public understanding of regional and local thunderstorm forecasts enabling rescheduling, delaying or curtailing of planned outdoor activities.

Improved medical treatment e.g. bystanders knowing how to give CPR and employ public-use defibrillators; paramedics and ambulances reaching casualties more quickly to administer defibrillation and other advanced cardiac life support; faster transport of patients to hospital; improved hospital treatments.

Factors contributing to an increase or slowing down a decrease

Population growth (increases the number of people at potential risk).

Increased leisure time enabling more people to participate in outdoor leisure pursuits and sports activities, including those undertaken in remote hilly locations and wide open spaces

Continued erroneous traditional beliefs (myths) about lightning which may put people at greater risk of being struck

Neutral factor

Annual variations in thunderstorm frequency and cloud-to-ground lightning flash rates may be responsible for annual fluctuations in lightning fatalities but there is no evidence of a long-term trend contributing to a decrease or increase in fatalities.

The UK lies at a latitude in a maritime region which experiences a relatively low lightning flash rate compared to continental areas in the subtropics and tropics so the lightning risk is currently, and has been in the past, relatively low compared to countries in those locations. Nevertheless, this UK case study provides detailed insights into the factors which are also likely to have contributed to other countries experiencing a long-term decrease in lightning fatality rates. Even more importantly, the study highlights the factors that have the potential to do so in the future in countries currently experiencing high lightning fatality rates providing these can outweigh the effects of national population growth which increases the number of people exposed to the lightning risk.

4.9 Other national studies of long-term lightning fatality rates

This section reviews other studies of trends of 50 years or more in national fatality rates to help confirm the importance of the factors listed in Table 3 which contribute to a decrease in lightning fatality rates.

Overall, the USA experiences much higher lightning flash densities than the UK but it has shown a marked decrease in lightning fatalities since the late nineteenth century. Lopez and Holle (1998a) examined the number of lightning deaths recorded on death certificates from 1900 to 1991 for the contiguous United States. They found that in the 1920s to 1940s, although the population was less than half what it is today, lightning killed on average 400 or more people each year. In 1937 alone, 460 people died. By the 1980s, this had decreased to 90 lightning fatalities, on average, each year. The reduction has continued such that in the past ten years (2006-2015), the average annual number of deaths has been 32 (Jensenius, 2016).

Normalising the fatality data by population, Lopez and Holle (1998a) found that lightning fatality rates fell from around 6 $M^{-1}yr^{-1}$ around 1900 to 0.4 $M^{-1}yr^{-1}$ by the 1980s. They found the exponential downward trend in fatality rates matched the downward trend in the national percentage of rural population which had decreased from a maximum of 60% in 1900 to about 25% by 1990 (to 19% by the 2010 census). Although the rural population has remained between 45 to 60 million since 1900, the urban population has increased markedly from 30 million in 1900 to around 250 million by the 2010 census (United States Census Bureau, 2016). The increase in national population living in urban areas is due to various factors including the migration of people from rural towards urban areas, the progressive encroachment of urban centres into what were former nearby rural areas which were then re-designated as urban areas, and an influx of immigrants to urban centres where they perceived there to be more employment opportunities. While these rural/urban changes contributed to decreasing lightning fatality rates, other factors helped too, including improvements in the electrical grounding of buildings, medical treatment and emergency communications, education (increasing awareness of the lightning threat) and meteorological forecasts and warnings (Holle et al., 2005; Lopez and Holle, 1998a). Another contributing factor added in later analyses by Holle (2008) was the increased access to the protection provided by fully enclosed metal-topped vehicles. Explaining that the rural/urban percentage shift was coincident with the move away from labour-intensive agriculture was also subsequently given greater emphasis (Holle, 2008). Holle and Cooper (2016) summarised: ‘The United States population not only transitioned out of a mainly labour-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 these factors have contributed to the USA fatality rate decreasing to the current rate of 0.1 fatalities $M^{-1}yr^{-1}$ (Holle, 2015).

More details of the factors responsible for the long-term changes in the number of lightning fatalities in the USA were explored by Holle et al. (2005). They compared lightning fatalities (included direct as well as indirect deaths such as fires) in the 1890s with the 1990s in the USA and concluded that in the 1890s, a lightning fatality "most often was in an indoors, outdoors, or agriculture activity/location in a rural setting" while in the 1990s, "a victim was most often involved in an outdoors incident in an urban setting or a recreation incident in a rural setting" (Holle et al., 2005). This study also explained the reasons for fewer lightning casualties inside dwellings: "Houses are now better grounded than a century ago because of the installation of power, plumbing, and telephones over this time period. A lightning strike to a dwelling in the 1890s often resulted in a fire or killed people during routine household activities. In recent years, however, such a strike usually caused a casualty only when a person was in direct contact with power, telephone, or plumbing that brings the lightning's current into a building" (Holle et al., 2005). Indoor incidents in the USA were responsible for 29% of lightning deaths and 60% of injuries in the 1890s but only 4% of deaths and 12% of the injuries in the 1990s (Holle, 2012).

Canada, like the USA, has shown a marked decrease in lightning deaths in the past century. Mills et al., (2006, 2008) examined lightning deaths for the period 1921-2003 and found the highest five-year average fatality rates reached a maximum of 2.4 $M^{-1}yr^{-1}$ in the 1930s (1931-1935) before decreasing to 0.1 $M^{-1}yr^{-1}$ by the 2000s (1999-2003). This translates into a decrease in the average annual number of lightning fatalities from 26 deaths in 1931-1935 to 3 deaths in 1999-2003. This decrease was largely the result of the modernisation of traditional agriculture and reduction in the number of agricultural workers together with an increasing proportion of the national population living and working in the thriving cities.

Most European countries have experienced a marked decrease in lightning fatality rates to a similar or lesser degree as the UK. Spain since the 1940s have shown a significant fall after the mid-1960s and Lopez and Holle (1998b) explain that this was due the large reduction in people working in agriculture, partly due to rapid mechanisation of farm work. In turn, this led to large numbers of people moving from rural areas to seek employment in the industrial and service sectors in the cities and tourist centres. Unlike being exposed to the lightning threat while farming in rural areas, many people now live and work indoors in the towns and cities in lightning-safe buildings. Holle (2008) reports on two data sets for France, one for the period 1835-1900 and the other from 1968 to 1995 which suggest the average lightning fatality rates increased from 2.0 $M^{-1}yr^{-1}$ in the 1830s to 3.5 $M^{-1}yr^{-1}$ by the 1890s and then decreased markedly to 0.2 $M^{-1}yr^{-1}$ by the 1990s. Badoux et al. (2016) compiled a database of natural hazard fatalities for a 70-year period (1946-2015) in Switzerland. They showed that lightning accounted for 16 per cent of all known natural hazard fatalities, second only in importance to snow avalanches as a cause of death. Lightning deaths decreased over time from a fatality rate of 0.70 $M^{-1}yr^{-1}$ in the first half of the study period (1946-1980) to 0.14 $M^{-1}yr^{-1}$ more recently (1981-

2015). Such low fatality rates in Switzerland, like the UK, translates into some recent years experiencing no lightning deaths at all. In some Eastern European countries, current fatality rates are 0.3 to 0.4 $M^{-1}yr^{-1}$ (e.g. Poland, Turkey) which is higher than most Western European countries. Exceptionally, Romania has a rate of 1.9 $M^{-1}yr^{-1}$ (Table 4). Generally, higher fatality rates in some Eastern European countries reflects their slower progress towards modernising agriculture, economic development and increasing the percentage of national population living in urban areas (with subsequent modernisation of the national building stock).

Countries outside Europe and North America that have experienced a long-term decrease in lightning fatality rates include Australia. It has shown a decrease in the lightning fatality rate from an average of 0.021 $M^{-1}yr^{-1}$ during the period 1910-1919 to 0.001 $M^{-1}yr^{-1}$ by 1980-1989 (Holle, 2008). Japan experienced a rapid changes in the mid-twentieth century and its transformation from a traditional to a modern economy resulted in its lightning fatality rate falling from 0.3 $M^{-1}yr^{-1}$ in the 1950s to less than 0.1 $M^{-1}yr^{-1}$ in the 1990s (Holle, 2008). Singapore is another example of a long-term decrease in fatality rates: from 3.2 $M^{-1}yr^{-1}$ in the 1920s to 1.5 $M^{-1}yr^{-1}$ in the 1970s to 0.35 $M^{-1}yr^{-1}$ by the 2000s (Quek, 2009).

These national studies support the assertion that a substantial long-term reduction in the percentage of the population working in labour-intensive traditional agriculture results in decreasing lightning fatality rates. Also, because many rural lightning fatalities occur when people are living, working or simply sheltering inside a traditional, often non-substantial, building (roofed by thatch, straw, bamboo or corrugated iron materials and lacking electricity wiring and water plumbing pipework circuits), it is evident that progress towards modernising the national building stock reduces lightning fatality rates. Modernisation of the national building stock is accelerated when an increased percentage of the national population live in the economically thriving and expanding urban industrial areas. Unemployment amongst agricultural workers also encourages people to move to towns and cities to seek employment. There is also the perception amongst many rural people and immigrants that urban living may be more attractive and offer more opportunities than living in a rural hamlet or village. Consequently, over the long-term and with the faster economic growth in urban areas, the result is an increasing proportion of the national population living, working and sheltering in modernised buildings where they benefit from better protection from lightning strikes. Moreover urban dwellers commute to and from work, school and shops with the protection that dense, modern transport networks (buses, cars, metro, railways, trams) provide. Where national lightning fatality rates have decreased over the long-term, all the factors listed in Table 3 may be shown to have contributed influence in varying degrees but the reduction in the labour-intensive agricultural workforce, the rural-to-urban percentage shift in population, the modernisation of the national building stock and dense transport networks are confirmed as the key factors.

4.10 Current lightning fatality rates

The relatively low current lightning fatality rates in industrialised countries contrasts with many developing countries where lightning fatality rates are relatively high.

Table 4 provides examples of recent analyses of national lightning fatality rates. These include national rates listed by Doljinsuren and Gomez (2015), Holle (2008, 2015, 2016a) and Singh and Singh (2015) as well as some additions. Table 4 highlights that there are many with fatality rates exceeding 1 $M^{-1}yr^{-1}$ (one in a million deaths per year): in Africa (Burundi, Malawi, South Africa, Swaziland, Uganda), Asia (India, Malaysia, Mongolia, Nepal, Sri Lanka, Vietnam), North America (Mexico) and South America (Colombia). In countries with populations of many hundreds of millions, even a relatively moderate fatality rate of say, 0.5 $M^{-1}yr^{-1}$ represents hundreds or several hundreds of unnecessary deaths each year. Moreover, even if the fatality rate continues unchanged, population growth will result in an increase in the actual number of deaths.

Table 4: Recent examples (post-2000 references) of national assessments of average lightning fatality rates per million people per year and current national indicators. *Notes: Fatality rates are listed to one decimal place. A minimum of 0.1 $M^{-1}yr^{-1}$ is stated where rates stated in the source reference are much less (e.g. UK rate is 0.03 $M^{-1}yr^{-1}$). Australia and Japan are included in this table as they already achieved a rate of 0.1 $M^{-1}yr^{-1}$ before 2000 and it is assumed this rate continued post-2000 rate.*

Country	Average rate ($M^{-1}yr^{-1}$)	National labour force in agriculture (%)	Urban population (%)	GNI per capita (kUS$)	Study period	Lightning data source
Australia	0.1	3	90	45	Post-2000	Holle, 2008
Austria	0.1	4	66	51	2001-2010	Kompacher et al. (2012)
Bangladesh	0.9	39	35	4	1990-2016	Dewan et al. (2017)
Brazil	0.8	10	86	15	2000-2009	Cardoso et al. (2014)
Burundi	2.5	91	12	1	2012-2013	Nibigira and Gomes (2014)
Cambodia	7.8	27	21	4	2007-2011	Wilson (2013)
Canada	0.1	2	82	44	1999-2003	Mills et al. (2006, 2008)
China	0.3	18	57	16	1997-2009	Zhang et al. (2011)
Colombia	1.8	16	77	14	2000-2009	Navarrete-Aldana et al. (2014)
Greece	0.1	12	78	27	2000-2010	Peppas et al. (2012); Matsangouras et al., (2016)
India	0.3	43	33	7	1979-2011	Singh and Singh (2015)
	2.3				1967-2014	Selvi and Rajapandian (2016)

Japan	0.1	3	94	44	post-2000	Holle (2008)
Lithuania	0.1	8	67	29	1994-2003	Galvanaite (2004)
Malawi	11.0	85	16	1	2007-2010	Mulder et al. (2012)
Malaysia	0.8	11	75	27	2008-2011	Ab Kadir et al. (2012)
Mexico	2.7	13	80	17	1979-2011	Raga et al. (2014)
Mongolia	1.5	30	73	11	2004-2013	Doljinsuren and Gomez (2015)
Nepal	2.7	72	19	3	2004	Holle (2008)
Poland	0.3	11	61	26	2001-2006	Loboda (2008)
Romania	1.9	23	55	22	1999-2015	Antonescu and Carbunaru (2018)
Singapore	0.4	0	100	85	2000-2003	Quek (2009)
South Africa	1.5	6	65	13	1997-2000	Blumenthal (2005)
Sri Lanka	2.6	27	18	12	2003	Gomes et al. (2006)
Swaziland	15.5	69	21	8	2000-2007	Dlamini (2009)
Switzerland	0.1	4	74	65	1981-2015	Badoux et al. (2016)
Turkey	0.4	19	74	25	2012-2014	Tilev-Tanriover et al. (2015)
Uganda	0.9	69	16	2	2007-2011	Ahurra and Gomes (2012)
United Kingdom	0.1	1	83	42	1987-2016	Elsom and Webb (2017)
United States	0.1	2	82	59	2006-2015	Jensenius (20xx)
Vietnam	8.8	41	34	6	1997-2000	Holle (2008)

Table 4 also lists three current national indicators as measured by the World Bank (2018): percentage of labour force in agriculture in 2017, percentage of urban population in 2014, and the Gross National Index per capita (average income of a country's citizens) in 2016. Given the variation in the study period of the individual national post-2000 lightning fatality rates and the quality of the data, it is not possible to quantify any relationship between fatality rates and these national indicators. However, some common characteristics of countries currently experiencing either relatively low rates (0.5 $M^{-1}yr^{-1}$ or less) or relatively high rates (1.0 $M^{-1}yr^{-1}$ or more) can be identified. Table 5 summarises the results. India is excluded because its two lightning fatality studies have divergent results.

Table 5. General national characteristics of countries with relatively low lightning fatality rates (0.5 $M^{-1}yr^{-1}$ or less) and relatively high rates (1.0 $M^{-1}yr^{-1}$ or more) post-2000. *Note: The analysis employs the median and range of values given the*

relatively small sample size (13 countries with low fatality rates and 12 with high fatality rates, the latter sample resulting in two median figures listed).

Fatality rate	Labour force in agriculture (%) in 2017		Urban population (%) in 2016		GNI per capita (thousand US$) in 2016	
	Median	Range	Median	Range	Median	Range
Low	4	0-19	78	61-100	44	16-85
High	27-30	6-91	21-34	12-80	8-11	1-22

Table 5 highlights that when a relatively high percentage of the national labour force in employed in agriculture, the national lightning fatality rates are relatively high too. Many agricultural-related fatality incidents involve multiple deaths which contribute to the relatively fatality high rates (Holle, 2016b). Table 5 also reveals that high lightning fatality rates are associated with a relatively small percentage of the national population living in urban areas. Countries with high fatalities are also characterised by a low Gross National Income (GNI) per capita (range of 1 to 22 thousand US$) compared with countries with low fatality rates (16 to 85 thousand US$). This indicator highlights the limited income available to developing countries to invest in transforming agriculture to become less-labour intensive and, not surprisingly, the lower the GNI per capita then the higher the percentage of labour force in agriculture. Moreover, a relatively low GNI per capita indicates the limited income available to modernise the national building stock (which would enhance the safety of the occupants when lightning strikes), install detection location systems to improve warnings, improve medical facilities for prompt and successful treatment of those struck by lightning, etc.

4.11 Implications for countries currently with high lightning fatality rates

As explained previously, although there are many factors that contribute to a country experiencing a high lightning fatality rate, the two most influential are the high proportion of the national workforce employed in rural areas in labour-intensive traditional (subsistence) agriculture and a large proportion of the national building stock which fails to provide a safe shelter from lightning. The latter describes buildings without adequate electrical grounding in which people live or work or, for those people working outdoors, the availability of such buildings nearby where workers may seek safe shelter from a thunderstorm. Consequently, the lightning fatality rates remain high in many developing countries (table 4) and these countries contribute many of the fatalities that add up to an estimated total of 6,000 to 24,000 people killed by lightning worldwide each year (Cardoso et al., 2011; Holle, 2016a; Holle and Lopez (2003). The number of people injured directly by lightning and requiring medical treatment may be ten times the total number killed (Holle, 2015). Further, the total worldwide numbers of lightning-caused injuries and fatalities are much higher if the indirect effects of lightning on people (e.g. initiating fires in occupied homes, schools and work places) were to be included.

The factors contributing to a decrease in lightning fatality rates are relatively slow to change, often taking many decades to have a significant impact. This means the challenge for countries with high lightning fatality rates is to find ways of accelerating the changes in these factors which will bring about a significant reduction in lightning fatality rates (Table 3). However, the transformation of traditional labour-intensive agriculture to a modern mechanised industry and a shift of previously-employed agricultural labourers to employment in construction, energy, industrial, manufacturing and service industries in urban areas, where many buildings offer safety from lightning, will take considerable investment which is not available given the relatively limited national income of many developing countries. Moreover, some urban residents have little or no choice but to live initially in informal settlements (shanty towns) located at the periphery of cities. They are characterised by poor quality improvised dwellings, often made of corrugated-tin and plywood, and lack electricity, water and sewerage systems and so offer no better protection from lightning for their occupants than the rural dwellings they left. Increasing employment opportunities for such residents will eventually enable better quality homes to be built or acquired but this may take many years and slow down the effects of other factors in decreasing lightning fatality rates.

Modernising agriculture and the national building stock may be a slow process in many countries currently experiencing high lightning fatality rates. However, some practical steps may be taken to reduce fatality rates amongst agricultural workers and in rural villages. For example, abandoned cargo shipping containers and defunct metal-topped motor vehicles could be placed near agricultural workers to provide a nearby lightning-safe refuge (Mary and Gomes, 2015; Gomes et al., 2012). In villages, directing limited financial resources to make selective buildings safe from a lightning strike would save many lives. Rural schools, buildings used for religious gatherings and community buildings have been the location for many incidents of multiple indoor lightning deaths and injuries. Following the tragic lightning incident at a Rwanda school in 2011 which resulted in the deaths of 18 pupils, the African Centres for Lightning and Electromagnetics Network (ACLENet) was established in 2014 with international support (Cooper et al., 2016). It is committed to installing lightning protection in schools, starting in Uganda, as well as public education and improving the availability of accurate and timely lightning data, weather forecasts and warnings (Cooper et al., 2018)

Factors other than changes in modernisation of agriculture and building stock that are listed in table 3 as influencing lightning fatality rates, albeit often with lesser impacts, could also help in reducing lightning deaths in countries currently experiencing high fatality rates. Whereas in the UK, USA and other countries which have achieved low lightning fatality rates already, these secondary factors (including increased availability of accurate thunderstorm forecasts and warnings, improved medical knowledge as how to treat lightning casualties in and outside of hospitals, and effective lightning safety campaigns) took many decades to become effective, they could today be implemented over a shorter time scale in countries currently experiencing high lightning fatality rates. This is because they can learn from the successes and mistakes made by countries that now experience a low lightning fatality rate. They can benefit also from the scientific and technological developments and improvements which have taken several decades to implement in, say, the UK and USA, but could now be introduced in a shorter time scale and probably at a lower cost. Implementation will need adjustment to reflect the social, economic and cultural characteristics in each country, as well as the support of the international community (finances and expertise), but it is vital to shorten the time span over which many of these factors can become effective in order to help to reduce lightning fatality rates and save lives in countries throughout the world.

5. Conclusion

The factors responsible for the substantial decrease in the lightning fatality rate per million per year and the annual number of lightning deaths in the UK since the 1850s have been explored. It is shown that these factors are common to other countries where a significant long-term decrease in the annual lightning fatality rate has occurred. A key factor leading to a lower fatality rate is a sizeable reduction in proportion of the national workforce employed in agriculture. This occurs when labour-intensive agriculture transforms to become a modern, mechanised industry. The consequent reduction in the agriculture workforce in rural areas and the growth in the numbers of people employed in the thriving urban-based manufacturing (chemical, engineering, textiles), construction, energy and service (including tourism) industries increases the percentage of national population living in urban areas. Urbanisation encourages the construction of many more substantial electrically-earthed buildings. Modernisation of the building stock is the second key factor as this results in buildings offering greater safety from lightning for the occupants compared to most traditional rural buildings. In the UK in the mid-eighteenth century and around the start of the twentieth century, half of all lightning fatalities occurred amongst the agricultural workforce but today it is less than 10%. Also, indoor fatalities accounted for 39% in 1850 and 24% in 1900 but there have been no indoor fatalities since the 1960s.

Other factors contributing to a reduction in lightning fatality rates in the UK and other countries, especially in the past few decades, are also identified in this study. These include improved forecast models for thunderstorms and more accurate and timely warnings of lightning, installation of lightning location detection systems, advances in the medical treatment of lightning casualties within and outside of hospitals, better communication and road networks to request and dispatch medical help quickly, and greater public awareness of the lightning threat and knowledge of what actions to take to minimise exposure to the lightning risk.

By understanding the potential contribution each factor has contributed to reducing national lightning fatality rates as identified in this study, the challenge to each country currently experiencing high lightning fatality rates is to find ways of accelerating and enhancing the beneficial impact of these factors, albeit after taking into account their social, economic and cultural characteristics. Actions to shorten the time scale of influence of these factors will require a concerted and shared effort involving other nations and world bodies in providing financial aid, knowledge and expertise. It is vital that lightning is recognised as a serious threat to all people's lives and that we should commit to reducing global lightning fatalities.

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