TOPICAL REVIEW

Lightning hazards to human societies in a changing climate

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Abstract

Lightning is a natural hazard, lethal and destructive on short time scales and with important climatic effects on longer time-scales (through NOx production and forest fire ignition). It is accompanied by severe weather, hail and flash flooding that often entail significant economic losses. It also poses threats to aviation safety and to renewable energy production by wind-turbines, and is known to adversely affect electric power utilities and transmission lines. Present day global trends in urbanization, land-use and energy production are mapped to climate change through several scenarios, relating future concentrations of greenhouse gases in the atmosphere ('Representative Concentration Pathways' or RCPs; IPCC et al 2013 Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge: Cambridge University Press) p 1535) to the adopted energy policies and international agreements. These scenarios predict a few degrees of atmospheric warming near Earth surface, which offer significantly different climatic regimes in many regions on Earth, and also affect the intensity and frequency of atmospheric natural disasters (e.g. tropical storms). Although it is hard to precisely predict what future lightning distributions will look like, the combination of large metropolitan areas, increased population and a warmer climate almost guarantee an intensification of the human exposure to lightning hazard. We review current trends in population, urbanization and technology usage and assess their vulnerability to future lightning activity in different scenarios.

1. Lightning effects on human society

We briefly survey the direct impacts lightning has on human societies. There are various aspects of related effects accompanying thunderstorms during severe storms, and these include tornados, hail and flash flooding (Price et al 2011), but here we shall focus only on effects directly related to the actual cloud-to-ground stroke of a lightning flash.

1.1. Fatalities and injuries

Lightning is still one of the most lethal natural phenomena, and globally claims the lives of several hundreds of people each year. The national annual number of human fatalities and injuries presents morbid statistical information; it reflects a persistent, often under-reported, societal hazard (Curran et al 2000, Holle et al 2005) the scale of which is not accurately known. Holle (2016) presented a comprehensive comparison of reported lightning fatalities from 23 countries for an average duration of 10 years, and table 1 in that paper details the annual number of deaths for different periods of time in many countries. The national reports offer a clear distinction between developed and developing countries in the numbers and trends of lightning casualties. In the US the numbers of lightning deaths per capita had steadily declined from 6 fatalities per million people in the 20th century to 0.1 at present, while in Malawi it is 84, Swaziland 15.5, Zimbabwe 14–21, India 2; Much lower values are reported in Australia 0.1, Canada and France 0.2, Turkey 0.4 and Brazil 0.8. Such numbers reflect both the frequency of thunderstorms (tropics vs. mid-latitudes) but also the reality of the population distribution, economy and life-style of people, and awareness of lightning danger. One should consider that the national reports reflect only the lower bound of a much broader range of casualties, because in rural, agricultural areas lightning-related deaths often remain within the community and are seldom reported, and official hospital records are not readily available. These factors limit the creation of reliable
time-series and a comprehensive picture of the global number of casualties, which range from hundreds to thousands annually.

An indirect effect of thunderstorms on public health, that is not apparent in the lightning-safety literature, is sometimes caused by downdrafts during the mature and decay stages of cloud evolution. The strong down-wind (downburst or microburst) and precipitation reaches the surface and the resulting outflow can eject large concentration of pollen and dust particles into the air, releasing allergens in the size range <2.5 micrometers. These particles can be inhaled into the respiratory system and cause an acute allergic response. If occurring during the flowering season of specific plants, this may result in ‘Thunderstorm Asthma’ (Wardman et al 2002, Dales et al 2003, D’Amato et al 2016, 2017), that is expressed as severe respiratory problems, especially in sensitive populations (infants, senior citizens). The most extreme case on record occurred in Melbourne, Australia, in November 2016 (Thien et al 2018), when a thunderstorm asthma epidemic followed a gust front induced by thunderstorms and resulted in more than 8000 people being admitted to hospitals for allergy and respiratory problems, with 10 fatalities. Though not directly caused by lightning as electrical phenomenon, the allergic response of the population followed (or was prompted) by a chain-reaction commencing with the dynamics of the thunderstorm.

1.2. Forest fires
Lightning is a major cause for damage to trees and forests, either by directly killing trees on strike or by igniting fires and burning large numbers of trees when conditions are conducive to the spread of wildfires (Latham and Williams 2001). Wildfires affect the carbon cycle through complex feedbacks, due to changes in the carbon sequestering capacity of the forest, the direct emission of volatile organic compounds and carbon dioxide (which in turn affect clouds and precipitation), and due to the large-scale reduction in albedo of the burnt area. The exact relationships between lightning frequency, fire occurrence and the area burnt is hard to establish, because several factors impact the outcome of an ignition event by a cloud-to-ground flash, such as the terrain, tree density, precipitation and fuel availability. Abatzoglou and Williams (2016) studied the inter-annual variability in lightning-induced fires in the western US from 1992–2013, and showed that lightning ignition was responsible to 40% of the total number of wildfires with an area larger than 0.4 ha. Veraverbeke et al (2017) studied lightning ignition and fires in the boreal forests of North America during 1975–2015 in the Northeast Territories and interior Alaska and showed a significant increase in this time interval (their figure 3). They found that lightning was responsible for over 76% of the fires with areas larger than 200 ha in the Northeast Territories, and to 87% of fires larger than 405 ha in interior Alaska. They predict that future warming in these areas will affect the long-term trend, with increasing ignition events and larger burnt areas. On a global scale, Krause et al (2014) modeled future trends in wildfires in different climate scenarios suing the ECHAM6 GCM (using the Price and Rind 1992, lightning parameterization) and found that even in the extreme RCP8.5 scenario, the global burned area increased only by only 3.3% even though lightning frequency was calculated to increase by 21.3%. Jolly et al (2015) analyzed global fire-weather conditions using reanalysis data and various fire-weather indices. They showed that in the 1973–2013 period there was a clear increase in global mean fire season length (18.7%) and a doubling of the burnable area (108.1%). On a regional scale, Abatzoglou and Williams (2016) showed that in the western US, anthropogenic climate change caused more than a 50% increase in fuel aridity 1984–2015. They note that this trend is likely to continue in this region, foretelling the expected increase in burned area (as already evident). Clearly, the complicated global picture is a result of the different regional responses in precipitation amounts, air temperature and soil moisture trends (determining fuel aridity), and lightning flash density (as ignition agent).

1.3. Damages to wind turbines
In a global economy gradually transferring to sustainable carbon-free energy production, the role of renewable energies is becoming increasingly important. A key technology with a remarkable upward trend is wind energy production, with a present cumulative installed capacity in more than 90 countries of 514 GW which is forecast to exceed 5476 GW by mid-century (IRENA (International Renewable Energy Agency) (2018)). Turbine blades rotating at heights of several hundred meters are often struck by lightning, with damages to the rotor, requiring temporary shutdown for part replacement and maintenance (Rachidi et al 2008). The locations of wind farms in wind-prone areas make them act as triggers for direct attachment of lightning to the turbine blade. The surge of electric current often overpasses lightning protection systems installed on wind turbines (Garolera et al 2016) and leads to burns, punctures, tip damage and edge debonding. As a result, energy companies search for mitigation techniques to alleviate downtime and economic losses (Shohag et al 2017). Lightning attachment to tall structures is a well-known engineering problem addressed in antenna and building design, but the movement of the rotor in wind turbines adds a unique aspect. Montanyà et al (2014) used a lightning mapping array (LMA) to study the incidence of lightning strikes to wind turbines in Spain, and found that the rotation of turbine blades initiated electrical discharges at 3 s intervals, over periods ranging from
minutes to hours, when thunderstorm conditions prevailed nearby. The results indicate that rotating wind turbine blades often act to trigger lightning and thus enhance their own vulnerability.

1.4. Aviation and other modes of transportation

The rapid growth of the aviation sector in the early 21st century is attributed to several economic and regulatory issues, which transformed air-travel into a relatively accessible commodity to large sectors of society. A recent report by the International Air Transport Association (IATA) (2017) predicts that by 2036, global aviation will see 7.8 billion passengers, compares with the 4 billion today. In their study of the radiative effects of global aviation due to greenhouse gas emissions and formation of contrails, Lee et al (2009) cite a report by European manufacturer Airbus that foresees a doubling of the existing fleet of 20 500 aircraft in 2007 to nearly 40 500 by mid-century. With the expected future growth of economies in Asia, Africa and Latin America, the volume of air-traffic between these countries and major hubs in Europe, US and Asia will increase significantly. The IATA report projects that China, US, India, Indonesia and Turkey will be the leading fleets by 2036. Transportation from, within and to the Asia-Pacific region is expected to rise by 4.6% annually, with 3.5 billion total passengers. Since these regions overlap with the major lightning-producing ‘chimneys’ (Williams 2005) the amount of aircraft susceptible to lightning damage is bound to increase (figure 2), although it is hard to estimate by what percentage. A thorough analysis of lightning risks to aircraft was presented by Lee and Collins (2017) and offers a methodology for risk assessment and monitoring. They focus mostly on technical drivers, for example the rapid shift to composite materials in airplane design (which makes them more susceptible to damage upon lightning strike). Their analysis does not include external risks such as the increase in global lightning (discussed in section 4). While in-flight damages are known and operationally considered, the ground segment of aviation is also affected by thunderstorms, lightning and the related weather phenomena, such as hail, heavy rain, turbulence and downbursts. Airports, air-traffic control centers, communication towers and navigation beacons are extremely vulnerable to thunderstorms and lightning. Since the world’s largest air travel hubs reside near big cities, the urban effects on thunderstorm occurrence (discussed in section 3.1) and lightning incidence is bound to adversely affect airport operations, with increased flight delays, cancellations and route disruptions. Other modes of transportation are also susceptible to increased lightning hazards. Thornton et al (2017) used lightning data obtained from the world wide lightning detection network (WWLLN) and reported a doubling in lightning occurrence above major shipping lanes, likely due to modification of cloud properties by the particles emitted from the ships, and consequently the risk of vessels being struck by lightning is much amplified. This is expected to increase as the volume of shipped goods in the oceans is showing strong growth (figure 1). Cars are also susceptible to lightning damages, even though the passengers are normally protected due the Faraday Cage effect. Yana-gawa et al (2016) studied 179 incidents of vehicles struck by lightning and showed that most strikes to

Figure 1. Superposition of the Optical Transient Detector (OTD) lightning distribution in fl/km²/year and the IATA air transportation route map. The forecasted increase in air-travel within the Asia-Pacific region is bound to encounter major lightning activity in the Maritime Continent chimney.
cars were to the antenna (15.6%) or roof (10.6%). The vulnerability of electric cars to lightning strikes (Kanata et al 2012) is larger than normal cars because their systems are all electrical and can be affected by induced currents and over-voltages caused even by non-direct lightning strikes. As the numbers of electric cars is expected to rise, this type of risk to public safety is also expected to increase.

2. Societal development trends as drivers of change in lightning risk

2.1. Population and urbanization

Most of the world population now resides in large cities and urban complexes, with some mega-cities exceeding 20 million people. The five major mega-cities are Tokyo (37 million), New-Delhi (29), Shanghai (26) Sau-Paulo and Mexico City (22). This trend is foreseen to increase by the mid-21st century, as socio-logical, political and economic processes create incen-tives for moving into cities, thus dwindling rural areas from their earlier populations. As of 2018, 55% of the worlds’ population resides in cities, a number expected to increase to 68% by 2050. The urban areas of major cities cover just a small percentage of the Earth’s surface, yet they exert a noticeable and non-negligible effect on their surroundings and even further away. Heat, humidity, turbulence and particle fluxes alter the thermodynamical properties of the boundary layer, and modify precipitation and wind regimes above the city and downwind of the built area. The urban heat-island (UHI) is the most evident effect, where the differences in albedo and heat capacity of the built surfaces result in marked differences in the temperature and precipitation regime (see reviews by Arnfield 2003, Shepherd 2005, and the papers by Orville et al (2001), Naccarato et al (2003) and Pinto et al (2004)).

One notable result of the interaction between large urban areas and the atmosphere is the effect on thunderstorms and lightning flash densities. Abundant evidence shows considerable change of lightning frequency above and around (especially downwind of-) major urban areas compared with their rural sur-roundings. In addition to the enhancement of lightning striking damages resulted from the increase of high structures and electrical equipment in the urban areas, the urban effect on lightning has two different components: a thermodynamic one, which relates to instability and differential surface heating, and a microphysical one, which relates to aerosol concentra-tions and their effects on cloud and charging processes.

Figure 2. (Top) Lightning stroke density in #/km²/year obtained from the WWLLN for the period 2006–2015. Note the straight line from Singapore toward China (bottom) The concentrations of PM2.5 particles in kg/km²/year for 2010, at 0.1° resolution. Taken from Thornton et al (2017). Copyright 2017 by the American Geophysical Union.
increase of 40% for the period 1989–1992. She attributed the result to the convergence, Orville et al. (2001) simulated the sea-breeze regime using the MM5 model. The effect of the city on the wind regime was evident compared with the no-city case, and the formation of a simulated thunderstorm was aided by a deeper boundary layer over the city, caused by the higher surface temperatures. The urban convergence zone was displaced downwind of the built area due to the synoptic-scale flow, and so was the location of the convective cell (and by inference, of the lightning).

Naccarato et al. (2003) studied lightning distributions in the Metropolitan Area of São-Paulo (MASP) during three summer seasons (2000–2002). They were able to show a marked increase of flash densities around the built area of São-Paulo, where flash densities were 60%–100% larger compared with the surrounding area (in red colors in figure 1(a)). The results showed a decrease of 7%–8% in the percentage of positive cloud-to-ground (+CG) flashes out of the total. The shape of the area with increased lightning follows closely that of the UHI of São-Paulo, lending support to the thermal explanation. However, the PM10 concentrations showed linear correlations with the number of CGs, supporting the aerosol contribution and showing that the interaction between the various factors involved is complex. In a follow-up study, Farias et al. (2009) showed a significant enhancement in the number of -CGs and a simultaneous decrease in the respective amount of +CG flashes over São-Paulo. They used six years of data from the BrazilDAT lightning detection network and attempted to evaluate the relative importance of the thermodynamic and microphysical factors. Their results suggest that the increased amounts of particles prolonged the life-time of storms and their total lightning amounts, but did not change their flash-rates. Farias et al. (2009) conclude that the aerosol effect is likely to be of smaller magnitude compared with the thermal one, caused by the UHI. The observed changes in the +CG fraction in thunderstorms over urban areas reflect changes in the location of the negative and positive charge centers within the convective clouds and their respective heights above the ground, which are known to affect the Intracloud/Cloud-to-Ground (IC/CG) flash ratio (Price and Rind 1993, Mackerras and Darveniza 1994) and also the CG flash polarity (Brook et al. 1982), but further observations will be needed to ascertain this explanation.

In a similar study, Kar et al. (2009) conducted a long-term study of CG distributions around major cities in South Korea (Busan, Incheon, Daegu, Taehon and Gwangju) using the KMA lightning detection network from 1989–1999. They compared the lightning
flash densities with PM_{10} and SO_{2} concentrations from those cities. The results show that –CG densities are increased by 40%–64% and +CGs by 26%–49% compared to their surroundings (figure 3(b)). The relative fraction of +CG was decreased by 7%–19% above the urban area. There were positive correlations between the concentrations of PM10 (0.795), SO_{2} (0.801) and the amounts of lightning above the cities. In India, where urbanization and the growth of megacities are remarkably strong, Lal and Pawar (2011) studied the effects of urbanization on the lightning flash densities based on eight years of data from the LIS on-board the TRMM satellite, supported by Aerosol Optical Depth data from MODIS on-board the Terra and Aqua satellites. Clear differences were noted between inland cities (Delhi and Bangalore) and coastal ones (Mumbai and Kolkata). In Delhi there was a 5 fold increase in the amount of lightning, with a parallel increase in pre-monsoon rainfall, though a clear trend in AOD (aerosol concentrations) is not evident. Lal and Pawar (2011) attributed this increase in lightning to the heat island effect on Delhi. In the coastal cities of Mumbai and Kolkata there was no clear increase in the amount of lightning, and the trend in AOD is also unclear. The closeness to the ocean may be counteracting the UHI effect in these two cities. Chaudhuri and Middey (2013) studied pre-monsoon lightning trends in Kolkata based on TRMM/LIS measurements combined with pollution measurements and other meteorological data. They found a positive correlation ($R^2 = 0.79$) between levels of particle pollution and lightning flash counts. In a recent study, Pawar et al (2017) studied the role of aerosols on the charge structure of 32 small thunderstorms, by using surface electric-field mills and MODIS AOD data over Pune (India). They found that thunderstorms developing in days with large amounts of aerosols (AOD > 0.57) preferably showed an inverted polarity structure (with positive charge below negative) compared to normal thunderstorms (AOD = 0.42). They were cautious in suggesting that this polarity reversal may be due to increased amounts of ice nuclei, which would operate to modify the charging and precipitation processes. Another explanation may be related to the fact that the average dew-point depression (DPD) in days with inverted polarity thunderstorms was significantly larger compared with normal polarity days (22 °C and 15.1 °C, respectively). Since pre-monsoon thunderstorms develop due to intense local heating, the larger DPD leads to higher cloud-base that can lead to an inverted dipole structure (Williams 2005). Disentangling these two factors requires detailed numerical modeling, supported by radar observations and usage of advanced lightning detection systems (e.g. LMA or ENTLN).

Evidently, city size and the size of built urban area play a major factor in determining the effects on thunderstorm evolution, dynamics and resultant lightning activity. Kingfield et al (2018) used radar and lightning location system data and compared 4 large urban areas in the US (Dallas - Forth Worth; Minneapolis-St. Paul; Oklahoma City and Omaha). He defined ‘urban-favorable’ (UF) conditions, when the synoptic forcing was weak during late summer afternoon/evening storms. Results showed that in such UF days, only the two largest cities (Dallas and Minneapolis) showed a 24%–50% increase in the number of downwind thunderstorms, while the smaller cities showed no such effect. This hints at the existence of a certain ‘threshold urban size’ below which the city will have only marginal effect on the pattern of lightning activity in its vicinity. This need not be necessarily a physical size, but rather an equivalent dimension that incorporates
population, transportation, industry and heat and particle emissions.

3.2. The aerosol effect in urban areas
The role of aerosol in thunderstorm development and lightning properties has received considerable attention and has been investigated using data from ground-based lightning location systems, numerical modeling and remote-sensing satellite observations. Bell et al. (2009) reported a weekly cycle in lightning frequency in the southeastern US, but only a weak signal over major cities. There is a clear midweek increase in storm intensity, indicating that increases in aerosol levels due to transportation and economic activity lead to the invigoration of storms in regions where convective instability and humidity are high (figure 4(a)). A similar weekday-weekend difference was reported for the Atlanta, Georgia metropolitan area by Stallins et al. (2012; figure 4(b)), however they showed that its magnitude depended, among other factors, on the specific geographical division of the sampled area based on central, suburban and rural grids.

The effect of aerosols on lightning is not restricted to locally-produced particles, but can also be a result of long-range transport. Such is the case with smoke from bio-mass burning which is often ingested into developing storm systems and individual cumulonimbus clouds that as a result exhibit unusual lightning activity. This was first reported by Lyons et al. (1998) who noted abnormally high percentages (triple the norm) of +CGs in storms that ingested smoke from bio-mass burning fires in 1998 in Mexico and Guatemala from April to June 1998. Murray et al. (2000) later studied the effect on lightning properties in the US by obtaining a ‘difference value’ after subtracting statistical values of previous years from the observed NLDN data for May 1998. They found that the properties of the lightning were indeed affected; most notably a 2 fold increased fraction of +CG, and a reduction in multiplicity as well as in the median peak current of –CG. Murray et al. (2000) found that the average peak current of +CGs increased by 20 kA, while their average multiplicity remained unchanged.

This type of large-scale modification of clouds by bio-mass burning smoke ingested into clouds was further explored by Wang et al. (2009). The chain of processes is based on the microphysical effect of large amounts of CCNs, delaying warm rain production and invigorating convection by transporting large amounts of super-cooled droplets in higher altitudes, where they freeze and release additional latent heat. This culminates in storm intensification which manifests itself in the production of severe weather including hail and lightning. Observations of Pyro-Cumulonimbus clouds show (Lang et al. 2014, LaRoche and Lang 2017) that in some cases the over-abundance of smoke and ash particles from the fire affect lightning onset due to a delay in graupel formation, which is essential for effective charge separation. This is caused by the competition on the available humidity by particles ingested into the convective cloud (Rosenfeld et al. 2007), a process simulated by Mansell and Ziegler (2013) and Reutter et al. (2014).

Altaratz et al. (2010) studied the effect of smoke from Amazonian fires on lightning frequencies over Brazil and neighboring countries. They showed that aerosol concentrations (based on AOD) scale linearly with lightning flash densities only until a certain level, above which the trend reverses and increased aerosol concentration actually lower lightning amounts. They repeated the analysis on a global scale for data for the entire year 2012, with the aim of entangling aerosol effects from meteorology. Based on MODIS-derived AOD and WWLLN data determined that instability (CAPE) and vertical velocity \( \omega_{400} \) Pa (vertical wind component at the 400 mb pressure level) are the dominant factors determining lightning activity, however aerosol concentrations act as a modulating factor (Altaratz et al. 2017). A similar approach of comparing
MODIS AOD data with lightning location system flash densities was used by Proestakis et al (2016) for the period 2005–2013. They looked for possible connection between dust loading in the Mediterranean (mostly from natural sources such as the Sahara desert, but also from anthropogenic sources) and lightning frequencies as measured by the ZEUS network. Their results show a similar temporal behavior between AOD anomalies and days with increased lightning activity. The mean AOD for days with electrical activity was higher than the mean seasonal AOD for 90% of lightning days. For AOD values up to 0.4 there was a pronounced increase in lightning with aerosol concentrations in summer-time storms. Ren et al (2018) found a weak positive correlation between MODIS-retrieved AOD values 2–4 h before local afternoon lightning activity, however it was less useful in predicting lightning enhancement compared with other meteorological factors. Wang et al (2018) found that lightning flash rates increases with AOD but at AOD = 0.3 starts to decrease, forming the familiar boomerang shape reported by Altaratz et al (2010).

Yuan et al (2011) studied lightning flash densities in the west-Pacific Ocean east of the Philippines during 2005 and related the 150% increase in lightning activity to the 60% increase in volcanic ash particle concentrations. They maintain that the increase in aerosol concentrations invigorates convection by affecting microphysical processes in the cloud above the ocean. The abundance of aerosols reduces cloud-ice particle sizes and delays freezing to colder temperatures, a fact that increases the vertical dimension of the mixed-phase layer. This should increase the effectiveness of charge-separation processes and lead to more lightning (Lang et al 2014). Venekesky 2014 used a simplified global model utilizing annually averaged mid-month CCN concentrations with a simple parameterization in an attempt to correlate these values with satellite-observed global lightning densities. This model lacks the necessary spatial resolution and a robust microphysical scheme to support the existence of a global aerosol-lightning feedback. A recent study by Thornton et al (2017) utilized 12 years of WWLLN data and showed a factor 2 increase in lightning density over major shipping lanes in the South China Sea and the northeastern Indian Ocean compared with clean maritime areas where ships are less frequent. The increase in lightning activity above shipping lanes is explained by the modification of cloud properties caused by aerosols emitted from the vessels’ chimneys. Wang et al (2011) conducted a study on the long-term effects of aerosols on precipitation and lightning flash density over the Guangzhou megacity area. Their results show that heavy precipitation and lightning are negatively correlated with visibility, indicating that higher aerosol concentrations tend to increase both. Simulating a Mesoscale Convective System with the CR-WRF (cloud-resolving version of the WRF) they calculated the lightning potential index (LPI; Yair et al 2010) and showed that under polluted conditions, the precipitation amount and LPI were increased by 16% and 50% respectively. Zhong et al (2015) used Convexion-resolving ensemble simulations with the WRF-Chem model to study urban effects on precipitation in the great Beijing Metropolitan area (GBMA). The effect of aerosols was found to surpass that of the land-surface albedo, and the simulations show a reduction in precipitation over the upstream (northwest) area, and enhanced convection and more precipitation in the downstream (southeast) region of the GBMA. Recent simulations by Zhao et al (2015) also showed that increasing aerosol concentrations led to enhanced charging processes resulting in a modified charge structure of the thunderstorm.

4. Lightning in a warmer climate

In order to gauge the future impacts of lightning on human societies, one must consider how lightning frequency and geographical distribution will be affected by climate change, and superimpose this information on the expected trends in urban development, transportation and energy production. This task seems insurmountable due to the complexity of predicting both economic indices and meteorological ones, which are not easily decoupled from each other. From a thermodynamic standpoint, a warmer troposphere and higher sea-surface temperature will result in increased heat and moisture fluxes and higher CAPE values, driving stronger convection and increasing the potential for cloud development, charge separation and lightning. Agard and Emanuel (2017) used an idealized 1D column model of the boundary layer in order to examine how future continental surface warming will affect maximum CAPE values. They showed that maximum CAPE values scale exponentially with the initial near-surface air temperature (their figure 6), and by imposing a diurnal radiative input cycle they show that it appears later in the day. They conclude that warmer climates will permit increasingly severe convection, but still caution against over-generalization of their model results. Considering the entire troposphere, an expanded troposphere allows clouds to have a larger vertically dimension, a property known to be strongly correlated with higher flash rates (Williams 1983, Price and Rind 1992, Yoshida et al 2009). However, changes in global circulation and the Hadley cell may alter the location and frequency of large-scale storms, affecting their lightning production rates. Another unknown is the effect of future warming on the frequency and intensity of tropical storms (especially over warmer oceans), and on the ENSO cycle. Both phenomena are known to exert strong influence on the amount of lightning on regional and global scales (Goodman et al 2000, Hamid et al 2001), but will not be discussed here.
Observational indications for long-term changes in lightning frequencies are hard to establish due to the lack of reliable, long-duration time-series of lightning flash density data. This stems from the fact that the global coverage from lightning location networks have detection inconsistencies (the network performance improves over time and they observe more lightning) and have range limitations, while satellite-based platforms are few and not continuous enough. Using the standard methodology of counting thunder days, Changnon and Changnon (2001) analyzed data from 86 US stations for the period 1896–1995. Using 20 year averages they were able to identify six types of lightning distributions, forming complex patterns of change in various regions of the country. A recent work by Yamamoto et al (2016) showed that over the last century the temperature of the Sea of Japan increased by 1.2–2.2 °C. The respective increase in the number of thunder days was between 20 and 45 d, most notable during winter and in cities near the coast.

There are contradicting assessments how warmer conditions of future climates will affect convective weather systems and their ensuing electrical activity, and we will briefly review key findings as they relate to thunderstorms and lightning (earlier perspectives were presented by Williams (1992, 2005)). Tools for evaluating lightning density in future climate conditions rely on the representation of lightning in Global Circulation Models (GCM) that undeniably simplify the complex nature of cloud microphysics and charge generation processes. The coarse resolution of global models cannot accurately portray microphysical processes that are conducive to electrical activity such as ice and graupel collisions or ice multiplication, and revert to using parameterizations. Thus, we cannot expect that GCMs will give accurate depiction of future cloud properties, and accept that they attempt to portray general trends and distributions. Price and Rind (1994) used their 1992 parameterization in the GISS-GCM to assess global lightning frequencies in a 2 × CO₂ world, and showed a 30% increase for a world warmer by 4.2 °C (compared with preindustrial values). Their model predicted a 5%–6% increase per 1 °C, with the exact magnitude dependent on the geographical location, season and diurnal cycle. Reeve and Touni (1999) used data from the OTD and evaluated the response of global lightning activity to a global temperature increase. Their results showed that if the wet-bulb temperature over the land areas of Earth will increase by 1 K lightning will be enhanced by 40%. Del-Genio et al (2007) used the GISS-GCM and showed that moist convection is expected to strengthen in a warmer climate, with stronger updrafts in all major lightning producing regions (figure 5). Although the number of storms in the western US with updrafts stronger than 7 m s⁻¹ (threshold for

![Figure 5. Predicted changes in updraft velocities in four major lightning areas, in the present and 2 × CO₂ climate. Due to the nonlinear response of lightning rates to cloud updrafts, the model predicts enhanced lightning activity. Taken from Del-Genio et al (2007) (copyright 2007 by the American Geophysical Union).](image-url)
lightning; Zipser and Lutz 1994) shows a 9% decline, events with strong updrafts (>10 m s⁻¹) become 26% more prevalent, meaning fewer storms overall but with more lightning when they do occur. This can be expected from the scaling relations presented by Boccippio (2002).

Price (2009) surveyed both TRMM data and modeling studies in order to determine whether a drier climate will result in more lightning, with location dependent, inconclusive results. Trapp et al (2007) estimated the increase in number of days with severe thunderstorms environmental conditions in response to a warmer climate, based on CAPE and wind-shear values (factors known to affect storm organization and duration on Mesoscale dimensions). They showed an increase in the occurrence of environments with positive potential for severe convective weather that leads to enhanced occurrence of lightning, hail and tornadoes, with the ensuing risks to human life and property. Similar conclusions were presented by Diffenbaugh et al (2013), Brooks (2013) and Tippett et al (2015). Romps et al (2014) used a product of precipitation rate P and CAPE as a proxy for cloud-to-ground (CG) flash density over the contiguous US, and computed the expected average change with 11 different general circulation models (GCMs in the Coupled Model Inter-comparison Project phase 5; CMIP5; their table 1). Their results show an average 12% ± 5 increase per 1°C warming, based on a comparison of the period 1996–2005 with RCP8.5 scenario for the period 2079–2088. For the Indian sub-continent, Saha et al (2017) correlated lightning distributions with CAPE, Aerosol Optical Depth (AOD), surface precipitation and vegetation cover, and used a similar approach with the CMIP5 RCPs 2.6, 4.5 and 8.5 scenarios and showed consistent mid-century (2036–2045) increases in AOD (1.28%–1.42%), convective precipitation amounts (1.9%–2.01%) and upper troposphere specific humidity at 300 hPa (1.31%–1.4%), which they considered to be strongly indicative of increased lightning activity. These regional estimates do not necessarily match global values. For the same period and RCP8.5 scenario, Clark et al (2017) evaluated the sensitivity of lightning parameterizations in the Community Atmospheric Model (CAM5) and found that results strongly depend on the type used. They matched modeled annual mean flash densities with satellite data and showed that the highest correlations were obtained for cloud-top height and cold-cloud depth (0.83 and 0.8, respectively), which predict a 36%–45% and 12.6% increase in flash densities for that period. A parameterization which relies on the convective mass flux predicted a −6.7% decrease in future lightning densities. These widely different results reflect the limitation of microphysical parameterizations, especially those that use specific cloud quantities as proxies for lightning. In a recent paper Finney et al (2018) used their new upward cloud-ice flux (Finney et al 2014; IFLUX) approach and compared the end-of-century (2100) lightning flash density to the often-used cloud-top height (CTH) approach, for the worst warming scenario depicted by RCP8.5. Both scheme show an increase in lightning over the US of 3.4 (IFLUX) and 14.2% (CTH) per 1 K warming however they note a significant decrease in lightning activity in the tropics ~ −10% when using the IFLUX scheme. This marked difference is explained by the fact that tropical cloud top height is expected to increase by 900 m due to warming in the tropics, and the 5th order dependence of flash rates may over-estimate the lightning density there, when in reality ice content an updraft speed offer a more realistic (and verifiable) representation of cloud electrification in climate models.

5. Summary

The coming decades of the 21st century will experience the convergence of several on-going trends in population growth, natural resource exploitation, energy production and urban expansion, which all dictate the emission rates of greenhouse gases and particles into the atmosphere. The Representative Concentration Pathways (RCPs) are a tool for investigating future climate scenarios, based on the radiative forcing (RF) incurred on the atmosphere by the projected emission rates. These scenarios offer—at least in principle, political will not withstanding—a tool for policy decisions related to sustainable development issues, such as the UN 2030 Sustainable Development Goals (https://un.org/sustainabledevelopment/sustainable-development-goals/).

When attempting to properly estimate the expected changes in lightning flash densities in different climate scenarios, we need to move across scales, from large-scale long-duration simulations in GCMs to models of cloud life-times and processes. The assumptions embedded in the parameterizations of convection, microphysical and electrical processes used in GCMs are becoming more refined, as they are being tuned against data from satellites and lightning detection networks, compounded by meteorological observations. A better understanding of the dynamics and life-cycle of thunderstorms in different geographical and seasonal settings is needed, as well as the myriad feedback mechanisms within the Earth system (such as the lightning-NOx-atmospheric chemistry). In a sense, we are in a time of transition from large-scale averaging within 2.5° × 2.5° global models to finer, more accurate capabilities, downscaling to 4 × 4 km resolutions. Thus, different models show remarkably different, and sometimes contradicting, outcomes for the RCPs and their predicted lightning flash density. New and advanced computational abilities, based on solid understanding of the relationship between environmental conditions and localized convective storms
and clouds, will greatly improve the success of models in predicting lightning response to different initial condition of the future atmosphere. This information, once validated by observations in the coming decade, will be essential for planning cities, airports and wind-energy farms for the sustainable future of humanity.

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