Lightning and Climate Change*

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***Abstract*— This study is concerned with the responsiveness of regional and global lightning activity to surface air temperature and to aerosol on many different time scales, including the diurnal, semiannual, annual, ENSO, decadal and multi-decadal. The main goal is the projection of lightning activity in a changing climate that will involve changes in both thermodynamics and aerosol concentration.**

***Keywords*— lightning; thunderstorm; convection; climate; climate change; aerosol; cloud condensation nuclei; hiatus; El Nino**

I. Introduction

Lightning is a natural phenomenon originating in the large voltage differences encountered in thunderstorms (up to one billion volts) and exhibiting currents as large as hundreds of kiloamperes. The lightning threat to worldwide energy infrastructure is widely recognized [1]. Lightning dominates the damage to electrical/electronic equipment in homes, commercial installations and industrial facilities. The total cost is dependent on both the total exposure and the worldwide lightning activity. Both these contributions to cost are increasing with time as a result of a growing infrastructure worldwide.

Much attention is given today to extreme events in a warmer climate (e.g., [2]). This attention serves to place lightning at center stage, to the extent that lightning is a manifestation of the extreme form of moist convection—largest clouds, strongest updrafts, most hazardous precipitation. One can expect volatile behavior in the tail of any distribution, and for this reason alone, the recent selection of lightning as a climate variable [3] is most appropriate.

This chapter is concerned with an assessment of how global lightning may respond to global climate change. This turns out to be a difficult problem. Some understanding of this difficulty is derived from the limits of our current ability to understand the general behavior and global distribution of lightning in the present climate. One particular challenge is that both temperature and aerosol play important roles in lightning activity in the present climate. Accordingly, this aspect shall be the point of departure in this chapter.

A global climatology for lightning measured from optical sensors on satellites in space is shown in Figure 1a. This integration is based on nearly two decades of observation. The most conspicuous feature of the global distribution is the strong preference of lightning for land, with a 10 to 20-fold contrast between land and ocean. The leading factor in this contrast is the number of thunderstorms, with a secondary contribution from a greater flash rate per storm in the continental case [4]. Since the majority of the world's population density and infrastructure is also over land, this land dominance aggravates the lightning threat. On the other hand, since the lightning is also strongly centered on equatorial regions (for reasons that are soon to be discussed) where population and infrastructure are reduced in comparison to higher latitudes in the norther hemisphere, the overall threat is ameliorated to some extent on a global basis.

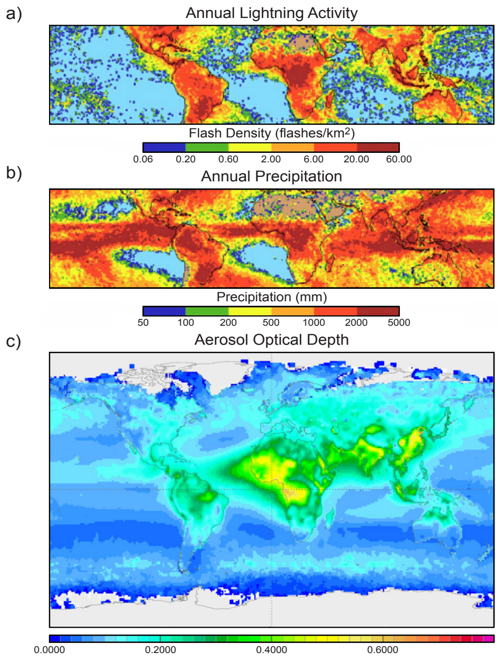


Fig. 1. Global climatologies of (a) lightning flash density (Lightning Imaging Sensor), (b) rainfall (NASA TRMM), and (c) aerosol concentration (as measured with satellite aerosol optical depth (Kinne, 2009).

Three major continental zones straddling the equator—the Americas, Africa and the Maritime Continent (southeast Asia, Indonesia and northern Australia)--- dominate the global lightning activity. The same three zones are also the major players in the Earth's global electrical circuit [5, 6]. From a climate perspective, the three major continental zones have previously been ranked in their continentality [7], with Africa leading, followed by America and with the Maritime Continent closest to oceanic behavior. Both the total lightning activity and the aerosol burden in these three regions follow the same order, whereas rainfall amounts follow the reverse order.

The energy involved with global lightning activity is derived from the much larger latent heat released when water vapor condenses. Rainfall is also a product of the condensation process. The global distribution of rainfall (Figure 1b), more readily measured than condensation, provides some global measure of the distribution of latent heat release. In marked contrast with the lightning distribution, rainfall and latent heat release is as prevalent over the ocean than over the land, but as will be shown by the evidence in this chapter, the vertical profile of latent heat release is markedly different between land and ocean. Both thermodynamic and aerosol effects are at play in this difference, by virtue of their impact on thunderstorm updrafts, and both are important in considerations of how lightning will respond to climate change.

The traditional explanation [8.9] for the contrast in lightning activity between land and ocean, aptly illustrated in Figure 1a, is based on thermodynamics: land is hotter and more unstable to vertical motion. In recent years, a growing body of evidence [10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20] has shown that the atmospheric aerosol, an; d in particular the cloud condensation nuclei that provide the embryos for cloud droplets, is also playing a key role in this contrast. The global aerosol population shown in Figure 1c also shows a prominent land-ocean contrast, with more polluted conditions over the land. Since climate change will invariably involve change in both thermodynamics and aerosol, the physical basis for both controls needs to be explored. The treatment of the thermodynamic part appears in Section 4 and for the aerosol part in Section 5. Ahead of these discussions, some attention is warranted on the workings of the thunderstorm in the next section.

II. Basics of Thunderstorm Electrification and Lightning

The deepest and most vigorous convective clouds in the atmosphere are thunderstorms, and extend deeply into the cold portion (defined here at $T < 0$ °C) of the atmosphere (Figure 2). Considerable evidence has accrued [21, 22] that the mechanism for charging a thunderstorm and for the production of lightning flashes is based on the collisions of two kinds of particles: small ice crystals and larger graupel particles. Both ice particles are the product of mixed phase conditions involving water substance in all three thermodynamic phases: vapor, liquid and solid (ice). The liquid phase at 'cold' temperature ($T< 0$ °C) is referred to as supercooled water. The ice crystals form by diffusion of water vapor in the so-called Bergeron process based on the asymmetry in equilibrium vapor pressure between liquid and ice. The mass of ice crystals increases at the expense of the supercooled cloud water. The graupel particles grow by the accretion of supercooled cloud droplets, which freeze in contact with the graupel surface. The collisions between graupel particles and ice crystals result in the transfer of negative charge to graupel and positive charge to the crystals, by a mechanism at the molecular scale that has long eluded scientists. [22,23]. The descent of negative graupel with respect to positive ice crystals under gravity sets up the macroscopic positive dipole of the thunderstorm (Fig. 2). This hydrometeor-based mechanism of differential charge separation (based on different fallspeeds of ice crystals and graupel) is immune to the effects of turbulence, which often shows a strong presence in thunderstorms.

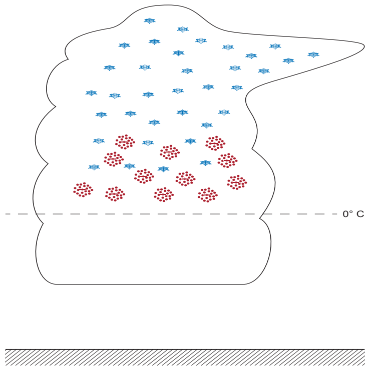


Fig. 2. The mechanism of the thunderstorm: storm cloud with colliding ice particles and positive electric dipole. The smaller (blue) hydrometeors are ice crystals and the larger (red) hydrometeors are graupel particles.

III. Thermodynamic Control on Lightning Activity

A number of basic thermodynamic parameters as well as relationships from physical meteorology deserve discussion when one considers possible changes in lightning in a changing climate. These items are here addressed in turn.

A. Water Vapor and the Clausius-Clapeyron relationship

The working substance of a thunderstorm is water vapor. Energy is released when water vapor rises and condenses to form cloud. The latent heat of condensation L_v is 2.5×10^6 joules per kilogram of water, sufficient energy to raise the condensate 250 km against gravity if this transformation took place with perfect efficiency.

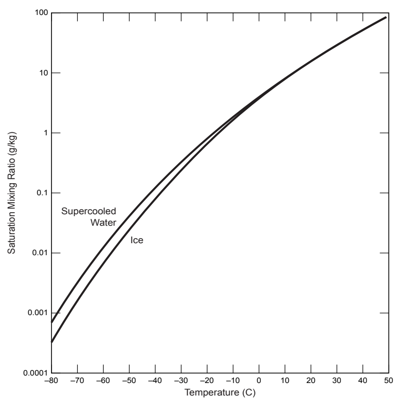


Fig. 3. Equilibrium water vapor mixing ratio (g/kg) versus temperature: the Clausius-Clapeyron relation

The water vapor concentration in the atmosphere in a condition of thermodynamic equilibrium is controlled by temperature in an exponential dependence known as the Clausius-Clapeyron relation. In differential form:

$$de^*(T)/dT = L_v e^*/R_v T^2 \tag{1}$$

where T is absolute temperature (K), $e^*(T)$ is the saturation vapor pressure of water vapor, and R_v is the gas constant for water vapor (461 joule/kg/K). The integral form of this relationship (see for example, [25] Emanuel, 1994) in terms of the water vapor mixing ratio is shown graphically in Figure 3. As a rough rule of thumb, the equilibrium water vapor concentration $e^*(T)$ doubles for every 10 °C of temperature increase. This result has much to say about the sparsity of thunderstorms in polar regions and their predominance in tropical latitudes. A change in temperature of 30 °C amounts to nearly an order of magnitude difference in available water vapor. A quantitative consideration of the global lightning climatology shows that two of every three lightning flashes lie within +/-23 deg of the equator [24].

The slope de^*/dT in the Clausius-Clapeyron relationship in (1) is a valuable benchmark for judging results on the response of lightning to temperature on various time scales (Section 4). This slope depends on temperature, but at the mean Earth surface temperature (~14 °C), the slope is 7% per 1 °C.

Cumulonimbus clouds are the primary agents for transporting water vapor from the planetary boundary layer in the lower troposphere to the upper troposphere. Consistent with this general picture, reference [26] has shown variations in upper tropospheric water vapor correlated with lightning variations over the African continent.

B. Convective Available Potential Energy and its temperature dependence

The maintenance of thunderstorm mixed phase conditions and the associated 'factory' for ice and electric charge requires an energy source for the updraft. That energy source is Convective Available Potential Energy (CAPE), and is illustrated in Figure 4. CAPE is represented as the area on a thermodynamic diagram involving height (or pressure) and temperature. This area is bounded on the left by the temperature sounding in the storm environment and on the right by a "wet bulb adiabat" which is a theoretical prediction for the temperature of the air in an updraft parcel which is buoyant with respect to the storm's environment. At any given altitude, the different between the wet bulb adiabat and the environment is a measure of the buoyancy force acting on the updraft parcel of air. The buoyant force per unit mass at an altitude is given simply as $g\ (\Delta T/T)$ where ΔT is the temperature contrast between the updraft and the environment and where g is the acceleration of gravity (9.8 m/s^2). Since the wet bulb adiabat is determined by purely thermodynamic quantities temperature and dew point temperature of the surface air ingested by the storm to form the updraft, it would seem that CAPE is also a purely thermodynamic quantity. A complication arises here, however, making CAPE dependent on both thermodynamic and aerosol characteristics, and adds to the challenge of disentangling thermodynamic from aerosol influences on lightning activity. The updraft parcel buoyancy depends not only on temperature but also on the mass of condensate within the parcel. For example, if the temperature contrast is 1°C, a typical value, the local cloud buoyancy force per unit mass is roughly 1/300 g = 0.03% of g. Since the density of surface air is 1.2 kg/m^3, a mass of condensate as small as 4 g/m^3 would completely negate the thermal buoyancy and strongly impact the dynamics of air parcels at that level. This point will be elaborated on below.

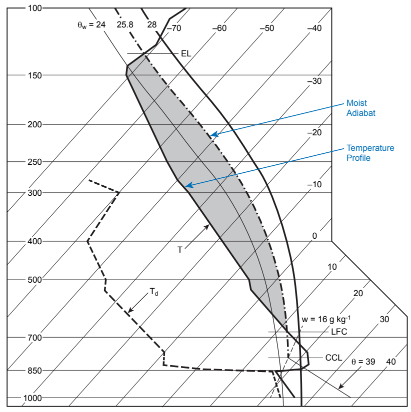


Fig. 4. Temperature sounding, wet bulb adiabatic approximation for the updraft temperature, and the area representing Convective Available Potential Energy (CAPE)

Accurate estimates of condensate mass are lacking in real thunderstorms, and theoretical CAPE calculations typically resort to two extreme assumptions, neither of which is entirely satisfied. In the most common pseudo-adiabatic (or "irreversible") approach, all the condensate is removed as the updraft parcel ascends (e.g., [11]. In this situation, only the temperature contrast (and a smaller contribution from the water vapor component) affects the parcel buoyancy. The implication is that the transformation from cloud water to precipitation is very efficient. In the context of cloud condensation nuclei CCN, this would be a situation with small concentration, typical of clean oceanic conditions. The observation of initial radar echoes in maritime convection at altitudes of only a few km (and in the 'warm' portion of the troposphere) [27] is evidence for an efficient precipitation process in clean conditions

The other extreme assumption in the evaluation of CAPE is that all condensate is retained as the updraft parcel ascends. The process is reversible and the wet bulb adiabat has a different mathematical form [28]. The implication is that the transformation from cloud water to precipitation has zero efficiency, because the cloud droplets remain too small to coalesce. This situation is typical of rich CCN concentrations, as in polluted continental conditions. In early investigations of tropical oceanic convection [29, 30] the reversible process was favored in computing CAPE, but it is now recognized that for maritime convection drawing from clean boundary layer air, the pseudoadiabatic irreversible process was a more appropriate choice. Given the negative buoyancy contribution of condensate loading, reversible CAPE is expected to be systematically less than irreversible CAPE. This expectation is consistent with numerous published results [25, 31]. In early considerations of the reversible and irreversible processes [32], it was concluded that the "differences between the products of condensation as falling out or being retained, are so small as to be negligible in practice", but today this difference is acknowledged as being all important in deep moist convection.

Reference [31] also showed that CAPE in the current climate was well predicted by the wet bulb potential temperature of surface air, though different relationships were apparent for land and ocean. Global maps of wet bulb potential temperature show that maximum CAPE over land is greater than over ocean. Reference [33] claimed that CAPE over land was similar to values over ocean, but they did not consider the diurnal variation of CAPE over land. A global climatology of CAPE has been prepared [34]. These results also show that CAPE is larger over continents than over oceans, though no consideration was given to aerosol-related effects in condensate loading. The land-ocean CAPE contrast is qualitatively consistent with the land-ocean lightning contrast, but on closer examination ([9],[33],[35]), the contrast is not sufficient to account for the order-of-magnitude contrast in lightning. This aspect will be revisited below in the context of cloud base height.

Given the primary role for CAPE in the charge separation and lightning activity of thunderstorms, the variation of CAPE with temperature on the long time scale of global warming is of considerable interest. This problem is non-trivial because the entire temperature profile is involved, as well as the condensate-related ambiguities of the wet bulb adiabat. In early work [36] CAPE was postulated to be a climate invariant. However, many GCM results show CAPE to increase with global warming [37],[38], and reference [39] found increases in cumulonimbus velocity in climate models in a warmer world. Furthermore, still more recent theoretical work [40],[41] support a scaling of CAPE with the Clausius-Clapeyron exponential temperature dependence. On this basis alone, one expects to have more lightning in a warmer climate. However, recent model results [42] show the opposite result for the tropics. This contrast in predictions is not well understood at present, though the model finding is for less ice flux in a warmer tropics.

C. Cloud Base Height and its Influence on Cloud Microphysics

The contrast in physical characteristics between land and ocean surfaces exerts an important influence on the behavior of thermodynamic parameters of surface air. The contrast in heat capacity and mobility between land and ocean affect the surface air temperature, with ocean water and overlying air resisting temperature increase in response to solar heating, in comparison with dry land surfaces. The diurnal variation of ocean surface temperature is typically a fraction of 1 ^{o}C. In contrast, the diurnal variation of land surface temperature invariably exceeds 1 ^{o}C but the surface temperatures over deserts can vary by tens of ^{o}C. The contrast in available surface water between land and ocean affects the dew point temperature and relative humidity of surface air. Land surfaces are generally both hotter (larger T) and drier (smaller T_d) than oceans, and as a consequence of both of these contributions, the dew point depression of surface air (T-Td), a purely thermodynamic quantity, is invariably larger over land than ocean. (Global maps of daytime dew point depression (and equivalently cloud base height) would show marked land-ocean contrasts as in Figure 1a and c.)

The convenience of cloud physics is that the Lifted Condensation Level (LCL) and cloud base height (CBH) are both proportional to $T-T_d$. If $T = T_d$, the air is saturated (RH=100%) and the cloud extends downward to the surface. Over oceans, typical cloud base heights are 500 m (corresponding to typical relative humidity of 80%), but over land can vary from 1000 to 5000 m (with relative humidity in the range of 20-70%).

The contrast in cloud base height between continental and maritime environments is illustrated in Figure 5a, for afternoon clouds at the first-radar-echo stage. The oceanic cloud achieves the first echo while still a warm cloud. In contrast, the continental cloud with systematically higher cloud base height is usually extended in to the cold region of the atmosphere at first-echo stage. The heights of the 0 ^{o}C isotherm are similar for land and ocean, near 4500 m MSL, but the cloud base heights differ markedly for thermodynamic reasons. Figure 5b shows deeper clouds for both land and ocean that include the mixed phase region bounded by the 0 ^{o}C and -40 ^{o}C isotherms where active charge separation can occur under appropriate conditions of cloud vertical development. The cloud base heights remain the same, and often coincide with the top of the planetary boundary layer. The cloud widths are different based on observations showing that continental clouds are broader than maritime ones [9],[43], [44].

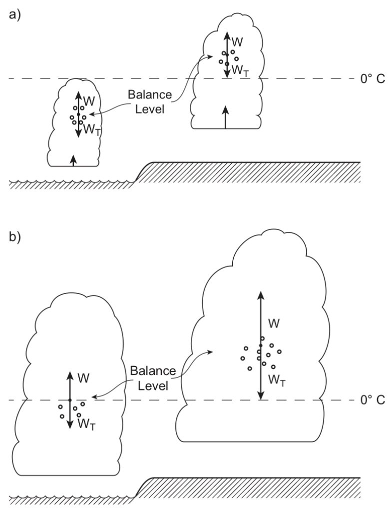


Fig. 5. Comparison of typical maritime (left) and continental (right) convection at (a) the time of radar first echo and (b) at the cumulonimbus stage. The balance level heights in all cases are also indicated.

The updrafts in clouds are fundamentally important in regulating cloud microphysics and electrification. Scaling analysis indicates a sensitive fourth power relationship of lightning flash rate on updraft speed [45]. Accordingly, modest changes in CAPE can have substantial effects on lightning flash rate. Figure 5 also includes vertical arrows to contrast the updraft speeds in different regions (including cloud base height in Figure 5a) of both shallow and deep convection.

Regarding the sub-cloud region, reference [46] shows larger ascent speeds (by 50 to 100%) in the continental boundary layer than the oceanic one, and larger speeds at cloud base height, consistent with predictions based on thermodynamics and the contrast in surface properties in [9]. Puzzlingly, model results on deep clouds with greater cloud base height do not show evidence for larger updraft speeds [47].

Earlier studies [43], [44] have shown systematically larger updraft speeds in deep moist continental convection over land than over ocean. The contrast in ascent speeds is unmistakably linked with a contrast in the ice phase microphysics and lightning activity between land and ocean, but the explanation for the contrast in ascent speeds remains a controversial issue [9], [35], [47]. When thunderstorms over land alone are examined, lightning flash rate and cloud base height are positively correlated in global comparisons with the Lightning Imaging Sensor in space and with surface thermodynamic observations of dew point depression [48]. These measurements need to be controlled for CAPE and aerosol variations to narrow down on the physical causality.

The formation of precipitation within the updraft of convective clouds is important because the precipitation can load the updraft, and ultimately reduce the updraft speed. This issue was raised initially in the context of Convective Available Potential Energy, but here one can be more quantitative by estimating the precipitation content that will offset the effect of thermal buoyancy. Simple considerations of Archimedean buoyancy show that the force per unit mass associated with a temperature perturbation ΔT is simply $\Delta T/T$ g, where T is the ambient temperature. The negative buoyancy contribution (again force per unit total mass) from additional mass loading m in a parcel with mass of air M is simply m/(m+M) g. For a parcel at the 0 ^{o}C isotherm with nominal air density 0.6 kg/m^3, the condensate loading needed to offset a thermal buoyancy of 1 ^{o}C is 2.0 g/m^3.

Extensive documentation on the detection of first radar echo and the formation of precipitation in deep convection has come from radar studies (good summary in Ludlam (1980), with additional examples in [49]. The D^6 dependence of the radar cross section of precipitation particles gives radar considerable sensitivity in detecting the formation of precipitation, given the runaway nature of coalescence of cloud droplets in the diameter range 25 μm [50] where the rate of droplet coalescence varies steeply with droplet size as D^5. The radar studies have shown that cloud depths (cloud top height minus cloud base height) in the 4000-5000m range over continents and as small as 2000 m over oceans [27], [49] are needed for first echo development. These radar-based estimates are broadly consistent with aircraft in situ measurements of cloud depths needed to achieve critical cloud droplet size [50] . The relevance of these results in the context of Figure 5 is that the warm cloud depth in the maritime case (4000 m), a thermodynamic effect, is large in comparison with that needed for the formation of precipitation. In the continental case this condition is not fulfilled. These comparisons are consistent with observations of radar first echoes that appear consistently in the 'warm' part of the cloud over oceans, but more typically in the 'cold' part of the cloud over land [27],[49],[51]. In a more global context, the results are also consistent with observations that warm precipitating clouds are prevalent over oceans, and scarce over land [9],[52]. Still the conundrum remains between a thermodynamic effect and an aerosol effect (Section 5 below.) The lower cloud base heights over ocean overlie cleaner air with more dilute CCN concentrations [53]. Accordingly, following the discussion in Section 5, the cloud droplets above cloud base height will be larger and more prone to form precipitation and radar first echoes at lower heights. Reference [53] gives emphasis to the aerosol effect, and neglect the thermodynamic effect.

The formation of precipitation in moist convection is important because it can then descend with respect to the air parcel in which it forms, and thereby load the updraft column beneath. (In barotropic conditions typical of tropical convection, the updraft is vertical.) This is sometimes called 'super-adiabatic' loading because the precipitation condensate is added to the adiabatic condensate at lower levels. (In baroclinic conditions (Section 3.7 below.) more typical of convection at higher latitudes, the updraft can be tilted and then the updraft can unload its precipitation, as is assumed in the irreversible calculation of CAPE.) Based on observations with a precipitation radar in space, warm rain clouds over oceans (where the warm cloud depths are greatest) are capable of achieving precipitation concentrations up to 2-3 g/m^3 [52]. These mass loadings are commensurate with cloud buoyancy at the 1 ^{o}C level as was shown earlier. These superadiabatic loadings represent reductions in the condensate that is delivered to the mixed phase region by the updraft, and where the conversion of supercooled water to ice can invigorate the updraft by the latent heat of freezing. This process can strongly influence the nature of the vertical profiles of latent heat release and larger ice-phase hydrometeors, and help explain the marked land-ocean contrasts in differences in lightning (Fig. 1a) and rainfall (Fig. 1b). In short, the warm rain cells over ocean may be substantially prevented from becoming thunderstorms by virtue of the raindrop loading they achieve. Further evidence for this suggestion is found in the next section.

D. Balance level considerations in deep convection

The unloading of the updraft laden with warm rain, and the delivery of condensate to the mixed phase region are both sensitive to the updraft profile and to the location of the balance level [54], [55] as illustrated in Figure 5. Vertically pointing Doppler radar observations of moist convection show a zero-crossing of mean Doppler velocity, with upward motions above and downward motions below. In the maritime case this balance level is located initially in the warm rain region, whereas in the continental case [55] (Lhermitte and Williams, 1985), its location is often in the mixed phase above. The precipitation particle fallspeed is balanced by the updraft w at the zero-crossing. Since the fallspeed of raindrops varies as D$^{1/2}$ at the balance level, the particle mass (~D^3) varies as W^6, and the reflectivity contribution varies as D^6 or as W^{12}. Following these sensitive dependences, a reduction in W by 40% ($\sqrt{2}$) by adiabatic loading in the maritime case relative to the continental case can cause an eight-fold reduction in mass and a 64-fold (18 dB) reduction in radar reflectivity. Eventually the supercooled raindrops will freeze and then one needs to consider the gravitational power contribution from the ice particles [56] will scale as D$^{7/2}$, leading to an 11-fold difference in gravitational power between the land and ocean case.

Indirect evidence for the severe loading of an updraft by raindrops comes from experience in vertical mine shafts in South Africa [57], [58], [59]. Air that is nearly saturated with water at 30 ^{o}C at the bottom of a mineshaft (with vertical extent ~1500 m) is forced vertically by a powerful ventilator system. At a vertical air speed near 10 m/s, matched with the fallspeeds of the largest raindrops, the load on the ventilator system frequently exceeded its capacity and failed, allowing the suspended water to fall to the bottom of the shaft in a deluge. In a vertical shaft, no opportunity was afforded for unloading of the updraft, as in the irreversible thermodynamic process discussed in the previous section. In moist convection over the ocean for which the radar first echo appears below the 0 ^{o}C isotherm [27], [49] (Ludlam, 1980; Williams et al., 1999), this mineshaft experiment is likely applicable, and is reminiscent of suggestions by [60] that the updraft speeds in oceanic cumulonimbus clouds [44] would be limited to the fall speeds of the raindrops within them. The mineshaft experiment is also a reminder that vertical updrafts cannot unload their condensates.

In continental convection in which the radar first echo is found typically above the 0 ^{0}C isotherm [27], [49], the balance level updraft loading by raindrops near 10 m/s is avoided, and larger ascent rates are possible. Now in the mixed phase region, the main hydrometeors are graupel and so the new balance level there, manifest in triple Doppler radar measurements [55] can be substantially higher. In severe storms, still larger ascent rates are possible, with a balance level accommodating the growth of hailstones that may reach softball size in updrafts approaching 100 m/s. In these situations, a BWER (Bounded Weak Echo Region) in radar observations is indicative of the balance level above, and may be 2-3 times higher than the balance level in warm rain cells. But in this strongly baroclinic situation (see Section 3.6 below) the updraft is strongly tilted and the hailstones can fall out of the updraft. In a special class of supercells (called LP for "Low Precipitation" but storms invariably productive of hail) with high cloud base heights (occasionally with sub-zero ^{o}C cloud base temperatures), no condensate is lost in a warm rain process and the adiabatic cloud water is available for the growth of the hail.

IV. Global Lightning Response to Temperature on Different Time Scales

The global temperature is known to vary on a number of natural time scales: the diurnal, the semiannual, the annual, on the El Nino/La Nina time scale and on the 11-year time scale of the solar cycle. In understanding global lightning's response to climate change on the long time scale, it is valuable to look for inconsistent patterns of response on other time scales whose physical origin is better understood. It is also possible that systematic changes in aerosol may accompany these natural variations in temperature. Here again we encounter the problem of disentangling aerosol and thermodynamic effects.

A. Diurnal Variation

On a planet covered with ocean, the variation of global temperature over the 24-hour period of the Earth's rotation in sunlight is expected to be nil. But based on the contrasting properties of land and ocean discussed earlier (Section 3.5), with preferential heating of land relative to ocean in response to incoming shortwave radiation from the Sun, a consistent diurnal variation of global temperature in UT time is established. The local diurnal variation of surface air temperature typically shows a maximum value shortly after local noon, whereas the lightning activity peaks later in the afternoon, near 4 pm [5], [6],[61],[62]. The globally integrated effect is a consistent global variation of temperature in universal time [63] that would appear to be the physical basis for the Carnegie curve of atmospheric electricity [5], [6],[64],[65],[66]. The regions that are sequentially heated by the Sun are the three 'chimneys' of global lightning activity—the Maritime Continent, Africa and the Americas, prominently manifest in the climatology of global lightning activity, as shown in Figure 6. In the global surface skin temperature (Price, 1993) found a peak-to-peak diurnal variation of 3.0 ^{o}C for the globe. For a variation in global lightning activity of 60% [62],[67],[68], this amounts to a sensitivity of 20% per ^{o}C [7],[38],[69].

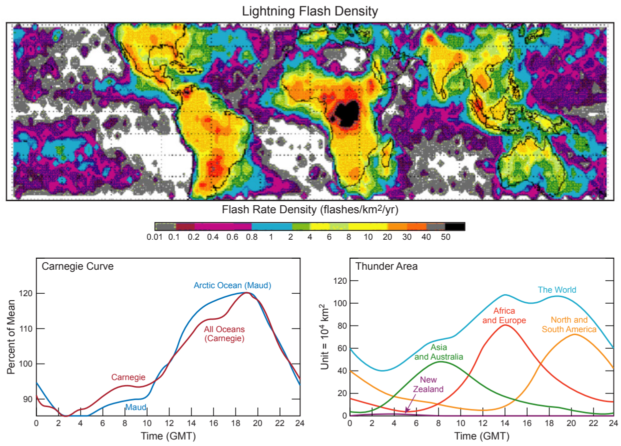


Fig. 6. The Carnegie curve of atmospheric electricity over 24 hour of Universal Time, the global diurnal analysis of thunder area (Brooks, 1920), and a global map showing three continental lightning "chimneys"

By using surface temperature at airports with hourly variation during a period of active measurement of ionospheric potential (V_i) of the DC global electrical circuit, references [70],[71] established positive correlations between V_i and tropical continental air temperature on the UT diurnal time scale, with a sensitivity of 7% per ^{o}C.

The variation of aerosol and CCN concentration on the diurnal time scale has been investigated (e.g., [72]) but observations are insufficient to compile a climatology of UT variation. A climatological variation in storm flash rate in local time [61] shows a maximum between the time of maximum temperature and the time of maximum number of storms. This finding is inconclusive toward distinguishing thermodynamic and aerosol contributions to lightning activity.

B. Semiannual Variation

A consistent repetition of weather twice per year is a foreign concept to mid-latitude observers, but is a very consistent feature of the near-equatorial region over land [73]. The sensible semiannual variation then in a number of meteorological quantities is a direct result of the Sun's traversal of the equator twice per year at equinoxes [74]. The variation in solar insolation for the global tropics (+/- 23^{o} latitude) is ~7% (max-min/mean). The corresponding peak-to-peak amplitude variation in global tropical surface air temperature is about 1 ^{o}C.

Clear evidence for a semiannual variation in global lightning with the same phase as the temperature variation has been provided by optical observations of lightning from space [75]. This signal is most conspicuous when analysis is concentrated in the near-equatorial zone. Here the sensitivity of lightning to temperature is 20-30% per 1 ^{o}C. Rainfall observations are also consistent with double rainy seasons in northern South America and in near-equatorial Africa. The discharge record from the extensive Congo River basin, straddling the equator in central Africa, also shows a distinct semiannual variation.

Several independent observations of the global electrical circuit (both DC and AC) show evidence for semiannual signals [65],[66],[74],[76],[77],[78] that are plausibly linked with the semiannual variation of temperature

The aerosol contribution to the semiannual variation in global lightning activity has not been studied. We are presently unaware of long-term investigations of CCN concentration in the near-equatorial zone over continents that would shed further light here.

C. Annual Variation

The global distribution of land/ocean area is decidedly asymmetrical in the extra-tropics [74], with a five-fold greater land/ocean area ratio in the northern than southern hemispheres. The smaller heat capacity of land relative to ocean assures that the temperature of the surface air is greater in northern hemisphere summer than in northern hemisphere winter. This asymmetry is in large part responsible for the annual variation in mean global temperature, showing a maximum in August and with peak-to-peak amplitude variation of about 4 ^{o}C.

Many observations of global lightning have shown a seasonal variation in phase with this variation in surface air temperature, both in optical observations of lightning from space [62],[67],[75] from surface-based observations of the intensity of the Earth's Schumann resonances (e.g., [79], [80]). The variation of global flash rate is nearly a factor of two, and the computed sensitivity of flash rate to temperature is 11 % per ^{o}C. It has also been established that the major contribution to global flash rate on the annual cycle is number of thunderstorms rather than mean flash rate per storm. If temperature is the controlling thermodynamic variable, this would imply that higher temperature is favorable for more frequent release of conditional instability rather than in increasing of CAPE. It is remarkable to have a globally integrated quantity that nearly doubles on the annual time scale. This finding is testament to the volatile nature of lightning in its apparent response to temperature.

Similar to the discussion on the semiannual time scale (Section 4.2), the contribution of aerosol to lightning activity on the annual time scale has not been evaluated, for lack of comprehensive observations of the global aerosol climatology. It stands to reason that substantially larger CCN concentration will be available for storm ingestion in norther hemisphere summer than winter, for the same reasons pertaining to land/ocean asymmetry, and the dramatic contrast in aerosol optical depth and CCN between land and ocean (Figure 1c). New methods now under development for the observation of CCN at cloud base height from satellite (Rosenfeld et al., 2016) will be particularly valuable in this context.

Ambiguity about the annual phase of the DC global electrical circuit began when Lord Kelvin observed [81] in the United Kingdom that the Earth's electric field was greatest in winter, contrary to the general picture based on global lightning activity and temperature. Reference [5] identified this apparent contradiction but did not resolve it. Reference [82] pointed out the local effect of wintertime aerosol (in both hemispheres) in decreasing the electrical conductivity of the atmosphere and thereby increasing the electric field. A more reliable ground-based measurement of the DC global circuit is the air-earth current which represent the product of the electric field and conductivity. For example, long-term measurements of the air-Earth current in Athens [83] have been shown to peak in August. Seasonal averages of the ionospheric potential [71], the preferred measure of the DC global circuit, also show a maximum in Northern Hemisphere summer.

D. ENSO

Early interest in a strong relationship between the phase of the El Nino-Southern Oscillation and lightning developed out of analysis of a single magnetic coil recording of the first resonance mode of Schumann resonances [24] for a single ENSO event (in 1973-74). A remarkably sensitive response of lightning to temperature was inferred from this analysis. Though the sign of this response has been corroborated in more recent work (e.g., [84] Satori et al., 2009), the magnitude of the response in the data obtained by C. Polk is unprecedented, and may not be valid. Based on the global temperature analysis of [85] and the classical analysis of rainfall variations [86] showing less rainfall over land in the warm phase, the general picture that developed was one in which all tropical land regions warmed in the El Nino warm phase, with the major upwelling in the central/eastern Pacific region causing large scale subsidence over tropical continental regions. This picture is in keeping with reductions in total river discharge in large drainage basins (Amazon and Congo), serving as continental-scale rain gauges, straddling the equatorial region [87] in the warm phase. This investigation was later extended to the Nile and the Ganges [88] River basins, with similar ENSO phasing. This picture on regional rainfall variability is also consistent with the majority of multiple ENSO events pictorialized in [89].

The regional behavior of lightning over the ENSO cycle shows somewhat less consistency overall, but a definite tendency in behavior is evident. This is most apparent in the Maritime Continent (including southeast Asia, Indonesia and tropical Australia), where the ENSO studies are most numerous and where lightning is more prevalent in the warm El Nino phase [90],[91],[92][93].[94],[95],[96]. Generally speaking, in this part of the world, the warm ENSO phase is also the drier (lower relative humidity and higher cloud base height) phase, and the more polluted phase. As noted above, the wet cool phase (La Nina) is more abundant in rainfall. So here again we have again the disentanglement issue of thermodynamics and aerosol. The opposite tendencies for rainfall and lightning on the ENSO time scale is at first peculiar, but highly variable lightning/rainfall relationships, temporarily and regionally, are now widely recognized [97],[98] and are linked with differences in the vertical development of the precipitation in the cold part of the cloud. This situation of opposite ENSO phase relationships for rainfall and lightning has also led to speculation that the two global electrical circuits (DC and AC) may have opposite tendencies over ENSO cycles [99],[100], though coordinated synchronous measurements are lacking to check on this prediction. In this context, it is seems likely that the contribution of electrified shower clouds [101],[102],[103],[104] will be more potent over land during the cold La Nina phase, when continental rainfall is greater [89].

In South America, both [84] and [105] using lightning observations from space found greater amounts of lightning in northeast Brazil during the cold La Nina phase. In contrast, reference [106] using thunder day observations over many ENSO cycles found a conspicuous tendency for greater numbers in the warm El Nino phase. An extreme El Nino event in 1926 has been documented by [107] and by [108] in the Amazon basin, with exceptional hot and dry characteristics but no information on lightning activity is available. References [84] and [105] agree in finding more lightning in the warm phase in southern Brazil and eastern Argentina, where the discharge of the Parana River is also maximum [87]. This region appears to be the southern component of the north-south rainfall dipole anomaly identified by [109]. This distinctly extra-tropical tendency for greater lightning in the warm phase was found earlier in the opposite hemisphere by [110] in the Gulf of Mexico region of the United States, in a similar range of latitude.

Among three tropical lightning ‘chimneys’ [7] Africa appears to show the weakest lightning variation on the ENSO time scale. Reference [105] found some enhancement in the La Nina phase, whereas [84] reported a modest lightning increase in the warm phase. Given Africa’s status as the most distant lightning chimney from the Pacific Ocean source of convective upwelling, it seems likely that global scale subsidence would have the least effect on Africa, while leaving conspicuous effects on adjacent chimneys Maritime Continent and America. Reference [111] has considered the effect of season on the lightning response to temperature on the ENSO time scale and this may impact the generality of a simple positive response in the warm phase. This seasonal aspect has also been discussed by [99].

Extreme El Nino events, such as the drought of the century in South America, can lead to so much warming and drying as to prevent both moist convection and lightning. Evidence for this situation may be found in the 1926 drought on the Amazon basin [7],[107],[112].

Despite the great sparsity of oceanic lightning (recall Figure 1a), easily discernible regional variations are discernible on the ENSO time scale. The general tendency for oceans is opposite to that for land: greater lightning over ocean in the cold La Nina phase [84],[113],[114]. This has been interpreted on a basis consistent with that for the warm phase: greater regional subsidence signifies less overall cloudiness, and hence greater surface heating and greater instability to drive moist convection.

On a worldwide basis, reference [84] documented greater lightning in the ENSO warm phase than the cold phase. Reference [115] has found evidence for inferred increases in the global electrical circuit in the warm phase.

The transition from the cold to the warm phase of El Nino has been studied recently [116] for the two Super El Nino [117] events, 1997-1998 and 2014-2015, and their further evolution to local maxima in global temperature (in February 1998 and February 2015, respectively). The discussion on the most recent Super El Nino that followed the hiatus in global warming for land surface temperature is discussed further in Section 4.6 on the multi-decadal time scale.

E. Decadal time scale

Modest changes (~0.1%) in the integrated energy output of the Sun have long been recognized over the 11-year solar cycle, and the corresponding changes in global temperature have been investigated. The peak-to-peak variation of temperature from this analysis is about 0.1 ^{o}C [118],[119],[120]. Attempts to see these changes in global records of thunder day data have been mostly unsuccessful [121],[122]. No solar cycle signal has been found in the LIS/OTD satellite record of global lightning. It should be noted however that solar cycle variations have been detected in the analysis of thunder day records at selected stations in Brazil [123] on the basis of wavelet analysis. Solar cycle variations in the intensity of Schumann resonances at high latitude are not plausibly explained by temperature-related variations in lightning activity [124].

Reference [125] studied variations in lightning incidence over the continental United States (CONUS) in the decadal period 2003-2012. The trend in cloud-to-ground lightning was negative over this period, with a 12% decrease from the interval 2003-2007 compared to the interval 2008-2012. The trend in wet bulb temperature over the CONUS was also negative for the same period, but the dry bulb temperature showed an increase. The total lightning activity measured by the Lightning Imaging Sensor in space showed no significant trend over the same period. In retrospect, the decadal period examined in this study lay within the period now frequently referred to as the hiatus in global warming (1998-2013). It is also interesting to speculate about a possible decadal increase in cloud base height, as the average dry bulb temperature increased and a moisture variable decreased, together entailing an increase in the dew point depression which is proportional to the cloud base height. Reference [126] Boccippio et al. (2001) had found a large enhancement in the IC/CG ratio in a region of the CONUS (extending from eastern Colorado northward through the Dakotas) with elevated cloud base height [7].

F. Multi-Decadal Time Scale

For studies on lightning variability on time scales longer than the typical lifetimes of lightning detection networks, researchers have resorted to the use of thunder day data (and model calculations: [127]. Thunder day observations have been underway at meteorological stations and airports worldwide for more than a century. One interesting recent application here has focused on an upward lightning trend in the Sea of Japan [128]. A rough doubling in thunder day counts since 1930 has been linked with observed increases in sea surface temperature of 1.2-2.2 C.

The tendency for the current global warming to predominate at high northern latitudes is widely recognized [85],[129]. At Fairbanks, Alaska (latitude 64.8^{o} N) both the temperature and the thunder day counts have been increasing conspicuously [38],[130]. Figure 7 includes plots of both quantities with least squares fits for trend. The number of thunder days has more than doubled in 50 years. Anecdotal reports indicate that Canadian meteorological stations at the highest latitudes have noted thunder days for the first time on record. As recently as August 12, 2019, a forecaster with the US National Weather Service in Fairbanks identified a thunderstorm within 300 km of the North Pole.

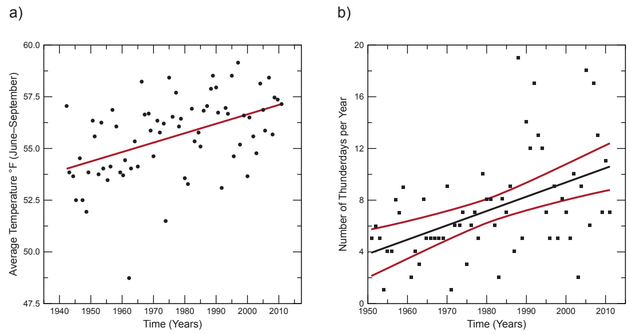
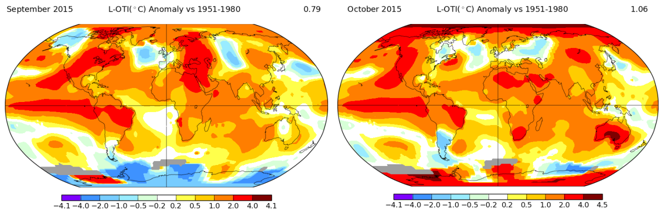


Fig. 7. Upward trends in (a) temperature and (b) thunder days for Fairbanks, Alaska. Linear least squares fits are also included to illustrate these trends.

The long-term record of mean global temperature [85],[117],[129] based on averaging of surface thermometers, shows an increase of the order of 1 ^{o}C on the hundred-year time scale, but is interrupted by shorter intervals when the temperature is flat or declining with time. The two most notable intervals are the so-called "Big Hiatus" from 1940 to 1975, and the more recent (and more controversial) hiatus in global warming from 1998 to 2013. Both these intervals have been addressed recently by [131]. Appeal was made to previously published thunder day observations to address the Big Hiatus, and separate analyses for both North America and Siberia show flat or declining counts of thunder days. A ~15% decline in mean annual thunder days is evident from 1940 to 1970.

For the more recent hiatus in global warming [131], satellite optical observations are available for nearly the entire interval from the Lightning Imaging Sensor. Several global temperature data sets were examined and it was shown that both the temperature trend and the trend in global lightning flash rate were statistically flat during the hiatus period. The hiatus period ended with a pronounced El Nino event in 2015 (discussed earlier in Section 4.4 on the ENSO time scale), and a strong resumption in the rise in global temperature that had been underway between the time of the Big Hiatus and the recent hiatus. Unfortunately, the Lightning Imaging Sensor is no longer operational in space to check the lightning behavior in this later period. Overall, the available satellite lightning observations are not inconsistent with the hypothesis that global lightning is responsive to global temperature.



a) b)

Fig. 8. Global maps of anomalies in surface air temperature for the months of (a) September 2015 and (b) October 2015, based on information from NASA GISS. The largest increase in global mean temperature in more than a century occurred between these two months.

This evidence for a strong resurgence in global warming [117] following the recent hiatus (1998-2013) has motivated a look at the regional changes in temperature. According to the global temperature record of NASA GISS, the largest month-to-month increase in mean global surface air temperature occurred from September to October, 2015. Temperature anomaly maps for September and October 2015 are shown in Figure 8a and 8b, respectively (https://data.giss.nasa.gov/gistemp/maps/index_v3.html). These maps indicate negligible changes in surface air temperature in the three main continental chimney regions that dominate the global lightning activity. The most conspicuous regional temperature increases are found in both polar regions, in Alaska and in Australia. Strong diminishments in temperature are observed in eastern North America and in western Asia. Some effort has been devoted to look for evidence for expected changes in lightning/thunder day data in the regions with the strongest regional changes. Reference [132], for example, has documented monotonic increases in thunder day counts at two stations in Alaska from the end of the hiatus in global warming (2012) to the local maximum in global temperature in 2016. Reference [133] has shown evidence that the 2015 fire season in Alaska (with contributions from both elevated temperature and more abundant lightning strikes) was the second worst in Alaska history. Additional evidence on regional behavior will be reported at the time of the Conference.

V. Aerosol Influence on Moist Convection and Lightning Activity

A. Basic concepts

When condensation of water vapor occurs during the ascent of air parcels in the real atmosphere, every cloud droplet that forms is dependent on some nucleus to initiate its formation. The process is known as heterogeneous nucleation. The subset of the atmospheric aerosol population that serves this role is called cloud condensation nuclei (CCN) [134]. Were it not for the ubiquitous presence of CCN throughout the atmosphere, large departures in water vapor concentrations from the equilibrium predictions of the Clausius-Clapeyron relation (Section 3.4) would develop in a thunderstorm updraft, and these departures are not generally observed. (But see recent findings in Fan et al., 2018.) As an air parcel ascends in a thunderstorm updraft, the adiabatic cloud water content that appears (enforced by Clausius-Clapeyron) is shared roughly equally among all the available nucleation sites. This means that the cloud droplet concentration is matched with the CCN population at cloud base height, and when the CCN population is large (polluted conditions) the cloud droplets are smaller than they are in clean conditions. Since the tendency of cloud droplets to coalesce and form precipitation particles is strongly dependent on their size, the CCN concentration can be influential on the development of convection[10],[11],[12] [135]. The contrast in conditions for convection growing over clean and polluted boundary layers is illustrated in Figure 9. Three broad ranges of CCN population can be considered: (1) clean conditions with CCN concentrations typical of maritime air (10-100 per cc), (2) more polluted conditions (a few hundred to 1000 per cc) typical for continents, and (3) ultra-polluted conditions with concentration exceeding several 1000 per cc.

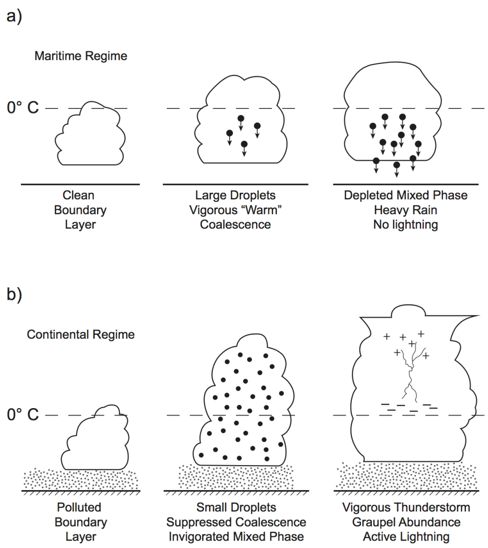


Fig. 9. Illustration of the aerosol effect on convection and lightning in clean and polluted situations

These regimes have been treated in cloud models [135]. Condition (1) may favor the rapid formation of precipitation and the production of rain, which may ultimately contribute to the superadiabatic loading of the air parcel (Section 3.5). Condition (2) may enable the retention of condensate in the updraft (consistent with the assumptions of reversible ascent (reference [11] and Section 3.5)) until the mixed phase region is attained. The most pollution condition (3) may lead to cloud droplets so small that the formation of graupel particles in the mixed phase region is prevented, thereby enabling the cloud water to rise as high as the -40 ^{o}C isotherm, where homogenous nucleation of the cloud water may occur.

B. Observational Support

A major shortcoming in the evaluation of aerosol effects on convective vigor and lightning activity, and making detailed comparisons with competing thermodynamic contributions, has been the general absence of information on the CCN concentrations involved in specific situations. The innovative development of satellite methods, both for observing the cloud droplet sizes from space [136] and for obtaining the CCN concentration at cloud base height, is having a dramatic impact at the time of this writing on the understanding of the influence of aerosol on cloud microphysics and lightning.

Reference [137] documented an approximate doubling of cloud-to-ground lightning flash density in the vicinity of oil refineries in the vicinity of Houston, Texas that was attributed to an aerosol effect. A more elaborate investigation of both thermodynamic and aerosol effects in the same general area [19] shows evidence that the lightning enhancement there is more likely due to an effect of cloud condensation nuclei than to a heat island effect.

Even in the absence of this direct measurement of CCN, several studies have appeared that make use of global proxies for aerosol, to compare with lightning activity obtained with other platforms. References[15], [138], have used aerosol estimates from GEOS-chem (www.geos-chem.org) to compare with NASA TRMM Lightning Imaging Sensor observations to show that aerosol contributions to lightning activity are comparable with thermodynamic ones. Reference [139] has examined the influence of aerosol (estimated with satellite measurements of aerosol optical depth) and CAPE on lightning recorded with the World Wide Lightning Location Network (WWLLN) on a regional basis. They found that statistically significant increases in lightning activity were associated with more polluted conditions.

Published examples of perturbations in lightning activity when aerosol is introduced in maritime convection have produced the most convincing evidence for aerosol control. In the first case ([140]) volcanic aerosol documented by satellite was ingested by oceanic cumulonimbus clouds whose exceptional lightning activity was documented by and specific controls were placed on thermodynamic influence. In a more recent study by [17], a rough doubling of lightning activity along sharply defined oceanic shipping lanes in Southeast Asia has been documented with the WWLLN. In this case, it can be shown that the warming of the sea by engine cooling exhaust water by the sea-going vessels is of negligible consequence, and diesel exhaust is rich in fine aerosol [141]. The introduction of rich aerosol concentrations in the pristine environment of the ocean represents a dramatic change in cloud microphysical conditions, with maximum likelihood of manifestation on lightning when none is present in the pristine state. The collection of different kinds of lightning studies by [17],[139],[140],[142], all over oceans, may reflect this more sensitive response of lightning to aerosol in that regime.

One may contrast the aerosol sensitivity in the maritime regime with the situation with high cloud base height (and shallow warm cloud depth) over land [7],[143],[144]. Reference [143] concluded that in this regime, there was little change in cloud microphysical behavior in response to aerosol variations. One reason for this is that the cloud droplet sizes in the mixed phase region are already small by virtue of the proximity to cloud base [50] and the absence of a deep warm rain process to mediate with aerosol. Without the depletion by warm rain, the cloud water contents in the mixed phase region are expected to be large in such continental storms, promoting the growth of hail and also conditions conducive to thunderstorms with inverted electrical polarity [7],[144],[145],[146]. Reference [147] had earlier found that storms ingesting smoke from fire were exhibiting greater numbers of positive ground flashes.

Additional evidence that aerosol has a pervasive influence not only on lightning but other aspects of meteorology are studies that show reduced activity on weekends, when the anthropogenic contribution to aerosol in industrialized regions has been shown to be reduced. Weekend effects on rainfall [148]; on lightning [149], on hail [150], and even tornadoes [150] have been documented in recent years, with statistically verified results.

VI. METEOROLOGICAL CONTROL ON LIGHTNING TYPE

The greater danger to both mankind and infrastructure posed by cloud-to-ground (CG) lightning in comparison with intracloud (IC) lightning motivates some discussion on the meteorological conditions favoring the former over the latter. A related issue pertains to how a changing climate may influence the relative numbers of cloud-to-ground and intracloud lightning.

The abundant evidence that CG lightning does not occur until late in the lightning life cycle of thunderstorms [51] is strongly suggestive that clouds with substantial width of the main negative charge region are needed to provide a discharge from cloud to ground, and that multi-stroke CG flashes are more likely, the greater that width [151]. Narrow storms with extraordinary vertical development tend to be dominated by IC lightning in the author's personal experience. But the meteorological controls on thunderstorm width are still not well tied down.

Conspicuous variations in the IC/CG ratio over the continental United States have been shown by [126]. When the map of this ratio is compared with the climatology of summertime cloud base height, it is apparent that the largest IC/CG ratios are found in a region (eastern Colorado and extending northward into the Dakotas) with elevated cloud base height, and also a region where the climatology of CG lightning shows a diminished incidence of CG flash density (e.g., [125]. It has also been suggested [152] that cloud base height may be influencing the latitudinal variation of the IC/CG lightning ratio. Given the evidence that the surface relative humidity is quasi-invariant with climate change [153],[154],[155],[156],[157],[158], it may also be true that the relative incidence of CG lightning may not change appreciably in a warmer climate. This general area of research is in need of further attention.

VII. THE GLOBAL CIRCUITS AS MONITORS FOR DESTRUCTIVE LIGHTNING AND CLIMATE CHANGE

The conductive Earth and the conductive ionosphere sandwich the more electrically insulating atmosphere to form two global electrical circuits. In the classical DC global circuit, a quasi-steady DC voltage of ~250 kV known as the "ionospheric potential" [71],[159],[160],[161] is maintained between the Earth and ionosphere by electrical source currents from thunderstorms and electrified shower clouds [101],[130],[162],[163] that together provide about 1000 amperes. For the AC global circuit, otherwise known as Schumann resonances [80],[130],[164],[165],[166],[167],[168],[169], the insulating space between two spherical conductors serves as a giant waveguide that supports resonant electromagnetic waves maintained continuously by the vertical charge transfers enacted by global lightning activity. The naturally occurring waveguide signals are manifest in two ways: as the 'background' Schumann resonances consisting of the overlapping waveforms of ordinary lightning produced at rates of order 100 per second globally, and as the transient resonances (or 'Q-bursts) produced by exceptional mesoscale lightning with global rates of only a few per minute, but which singlehandedly ring the global waveguide to amplitude levels that dominate all the other lightning contributions combined. Simple illustrations of the two global circuits are shown in Figure 10. The simultaneous behavior of the two global circuits has been considered recently by [170].

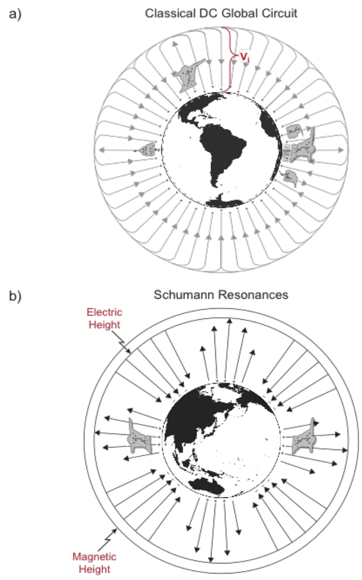


Fig. 10. Illustration of the two global electrical circuits: (a) the classical DC global circuit, and (b) the AC global circuit, otherwise known as Schumann resonances.

The two global circuits provide natural frameworks for global monitoring. In the case of the DC global circuit [71],[159],[160],[161], the ionospheric potential is a measure of all the electrified weather underway at any time, including thunderstorms and electrified shower clouds that provide current the ionosphere without producing lightning. For the AC circuit, the background resonances can be monitored at multiple stations (of the order of ten stations) to produce chimney-resolved measures of lightning activity in units of coul^{2}km^2/sec [169],[171]. The AC global circuit can also be used to locate and monitor the special population of mesoscale lightning flashes worldwide that are most damaging to mankind and infrastructure, by virtue of their exceptional charge transfers and their long continuing currents [172],[173],[174],[175],[176],[177],[178],[179]. Conventional lightning detection networks operating in the LF and VLF range do not have sufficient low frequency bandwidth to identify particularly hazardous ground flashes with long continuing current and large charge moment change.

Early attempts to evaluate the DC and AC global circuits as diagnostics for global temperature were made by [24] for the AC global circuit and by [70],[71][180] for the DC global circuit. A substantial challenge remaining is to provide for the continuous monitoring of both global circuits over the long time scales that are relevant to climate change. When this problem is overcome, comprehensive diagnostics of global weather will be available in the electromagnetic field.

VIII. Expectations for the Future

The foregoing discussion has given emphasis to the response of lightning to climate variables on a number of time scales as well as the growing body of evidence supporting an important role for aerosol in cloud electrification and lightning. On the basis of this body of evidence, one may speculate about changes in lightning and its effect on mankind and infrastructure into the future. As global warming proceeds, uncertainties remain about what quantities are invariant and what quantities are changing. Inferences about changing quantities are often based on their behavior in the current climate, but still uncertainties remain.

If total water vapor in the Earth's atmosphere follows the Clausius-Clapeyron relationship, one expects greater total water and more condensate in a warmer world, and given the need for condensates for lightning, greater lightning is expected. Global climate models [154],[155],[181] do show increased precipitation in a warmer world, though this change is regionally dependent. It must also be recognized that the nature of the precipitation increase is important and that an increase in warm rain alone is unlikely to be accompanied by an increase in lightning.

Given the evidence for CAPE in lightning in the present climate, more lightning is expected in a warmer climate if CAPE increases. Early speculation showed CAPE to be a climate invariant [36]. Reference [182] has predicted increases over the CONUS in a warmer climate on the basis of both increases in CAPE and increases in precipitation. More recent global climate models show larger CAPE in warmer climates [38]. Theoretical calculations in equilibrium atmospheres [183] show CAPE scaling with the Clausius-Clapeyron relationship. Estimations of CAPE changes in the western United States based on the advection of dry desert area over the moist boundary layer with origin in the Gulf of Mexico also lead to predictions that CAPE should scale with Clausius-Clapeyron [41]. For all of these reasons, one expects greater lightning in a warmer world.

A frequent assumption in the climate community is that surface relative humidity is a climate invariant [156],[158]. This assumption is based in part on the empirical evidence in the present climate for a quasi-fixed relative humidity near 80% over large areas of the tropical oceans, with an associated cloud base height for moist convection near 500 m. If the ocean surface temperature were to increase globally, the mean dew point temperature would also increase so as to keep the dew point depression ($T-T_d$) and the associated cloud base height (above local terrain) both constant. But the height of the 0^oC isotherm would increase following a presumed lifting along a dry adiabat. Accordingly, the warm cloud depth (distance between the 0^oC isotherm and the cloud base height) would increase. Based on findings in the current climate that the lightning flash rate is decreasing with increased warm cloud depth, in this scenario one might expect less lightning in the warmer world. However, the CAPE change in this scenario also deserves consideration. The expected increases in both T and T_d both contribute to increases in the wet bulb potential temperature of the boundary layer, a result that certainly favors greater CAPE in the current climate. But the ultimate CAPE change depends also on the change in the overall temperature profile in a warmer climate, and this is indeterminate in the context of the foregoing assumptions.

One recent study [42] predicts less tropical lightning in a warmer world. The prediction is model-based and with the finding that less ice phase is reaching the upper portion of the troposphere where active charge separation is known to occur. More information about this model, and in the context of expected changes in warm cloud depth, is needed to understand this result. Other recent observations on extremes in tropical rainfall in a warmer climate, showing enhancements exceeding the simple predictions based on Clausius Clapeyron [184] would seem to contradict the model predictions of [42]. Further discussion on this issue and predictions for the behavior of lightning in a warmer climate can be found in [185].

Given the recent evidence for an important role for cloud condensation nuclei in increasing lightning activity in the present climate [20], one can surely speculate about changes in lightning in a more polluted world on the basis of this effect. China for example continues to undergo major industrialization and with a major reliance on coal [186] and so one can expect an increasing aerosol production from that region alone. From what is known at present, the lightning enhancements are expected over a finite range of CCN concentrations, from typical oceanic concentrations of a few per cc to up to about 1000 per cc [19], [20]. Above that level (typical of continental conditions described in Section 5), the lightning activity is expected to flatten and then decrease, for reasons that are evident in model calculations [135]. An assessment of where the world stands relative to this important threshold will be much aided by a new satellite method for estimation of CCN concentration at cloud base height [16].

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