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Lightning and middle atmospheric discharges in the atmosphere

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ABSTRACT

Recent development in lightning discharges including transient luminous events (TLEs) and global electric circuit are discussed. Role of solar activity, convective available potential energy, surface temperature and difference of land–ocean surfaces on convection process are discussed. Different processes of discharge initiation are discussed. Events like sprites and halos are caused by the upward quasi-electrostatic fields associated with intense cloud-to-ground discharges while jets (blue starter, blue jet, gigantic jet) are caused by charge imbalance in thunderstorm during lightning discharges but they are not associated with a particular discharge flash. Elves are generated by the electromagnetic pulse radiated during lightning discharges. The present understanding of global electric circuit is also reviewed. Relation between lightning activity/global electric circuit and climate is discussed.

Contents

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1. Introduction

The discharges in thunderstorms could be cloud-to-ground (CG), inter cloud, intra-cloud and from cloud top upwards and the activity is related to the stage of convective cloud development (Vonnegut et al., 1963), cloud top height (Price and Rind, 1992), the updraft intensity (Williams, 1992), convective available potential energy (CAPE) (Williams et al., 1992; Siingh et al., 2013a, 2014, 2015), rainfall rate (Tapia et al., 1998; Soula et al., 2009; Singh et al., 2015; Siingh et al., 2014, 2015) and surface air temperature (Price, 1993; Singh et al., 2015; Siingh et al., 2013a, 2014, 2015). The spatial and temporal distributions of lightning flashes around the globe have been studied using ground and satellite based measurements (Christian et al., 2003; Bailey et al., 2007; Mach et al., 2011; Cecil et al., 2014). Based on early observations, Brooks (1925) proposed global mean flash rate ~100 flashes s^{-1}, whereas from a combination of observations and model studies, Mackerras et al. (1998) proposed 65 flashes s^{-1}. Recently Cecil et al. (2014) analyzed Lightning Imaging Sensors (LIS) and Optical Transient Detector (OTD) data from Tropical Rainfall Measuring Mission (TRMM) satellite and reported global mean flash rate as 46 flashes s^{-1}. The diurnal variation showed the average peak flash rate maximum between 1600 UT and 1800 UT and the minimum between 0200 UT and 0400 UT. The global monthly average flash rate was the maximum in August (60 flashes s^{-1}) and the minimum in February (35 flashes s^{-1}).

The latitudinal distribution of lightning flashes showed the largest occurrence in the tropical region during summer months (Christian et al., 2003, Cecil et al., 2014; Blakeslee et al., 2014) and is highly dependent on surface temperature (Williams et al., 2005; Markson, 2007; Siingh et al., 2013a, 2014, 2015). Global measurements of surface temperature suggested warming of tropical land regions during the El Niño phase and the cooling during the La Niña phase (Williams, 1992; Wang et al., 2012); as a result global lightning was found to be enhanced in the warm El Niño phase and slightly suppressed in the cold La Niña phase (Satori and Zieger, 1999; Yoshida et al., 2007; Harrison et al., 2011; Kulkarni and Siingh, 2014).

Lightning discharges are major source of maintenance of global electrical circuit (GEC) as is evident from the comparison of the diurnal variation of global lightning flash rate distribution and measured electric fields from the Carnegie and Maud research ships (Whipple, 1929; Blakeslee et al., 1999; Bailey et al., 2007; Harrison, 2013; Siingh et al., 2013b). The diurnal variation of percentage of mean global flash rate agrees with that of fair-weather electric field (Carnegie curve) and thunderstorm days in phase but not in amplitude (Fig. 1), with a maxima in the afternoon time sector and a minima around the morning hours (Mach et al., 2011). They also reported 10–20% mean-to-peak variations in Carnegie curve and about 35–40% in the thunderstorm days and lightning flash rates.

Discharges between the cloud top and the middle atmosphere (stratosphere and mesosphere) are referred to as transient luminous events (TLEs), which are short lived discharges either caused by the transient electrostatic fields associated with the charge imbalance in thunderstorm during cloud-to-ground and inter/intra cloud discharges or by the electromagnetic fields associated with the return stroke current during lightning process. The morphological features of some form of TLEs above mesoscale convective cloud system along with altitude profile of day/night time electron density and temperature are shown in Fig. 2. Blue starters (not shown in the figure), blue jets, gigantic jets are upward electrical discharges from top of thunderstorms with their tops reaching different altitudes: 20–30 km for blue starters, 40–50 km for blue jets, and 70–90 km for gigantic jets (Wescott et al., 1995, 1996; Pasko, 2003, 2008; Lyons et al., 2003a; Krehbiel et al., 2008; Siingh et al., 2012; Liu et al., 2015). Blue starters and jets are cone of light shooting upward from thunderstorm and their intensity decreases near their tops (Wescott et al., 1995; Edens, 2011; Chou et al., 2011; Liu et al., 2015). Gigantic jets having a tree-like structure display complex dynamics (Su et al., 2003; Hsu et al., 2005; Chou et al., 2010; Soula et al., 2011; Liu et al., 2015). The top of gigantic jet may reach the Earth's lower ionosphere and can transfer charge between thunderstorm and ionosphere (Pasko, 2008). The amount of charge transfer will depend on the intensity and duration of gigantic jet. In typical cases it can be as high as (100–200 °C) the charge transfer between thunderstorm and ground during intense lightning discharges (Cummer et al., 2009).

Sprites are large luminous electrical discharges in the upper atmosphere caused by intense cloud-to-ground discharges and their dynamics is governed by streamer discharges (Sentman et al., 1995; Lyons et al., 2003b; Pasko, 2007; Siingh et al., 2012; Pasko et al., 2013; Liu, 2014). They are typically initiated at 70–85 km altitude with downward propagating streamers, which may terminate at about 40–50 km altitude (Stenbaek-Nielsen et al., 2007, 2010, 2013). Later upward propagating streamer may appear, which can reach up to about 90 km altitude (Stenbaek-Nielsen et al., 2007, 2010, 2013).

Inan et al. (1999) theoretically showed that electromagnetic field pulses radiated by cloud-to-ground discharges can heat electrons in the lower ionosphere (about 90–95 km altitude) to sufficiently high energy which can excite and ionize neutral molecules leading to brief flash of light, which is now called as elves (an achronym for emission of light and VLF perturbations due to EMP sources) (Fukunishi et al., 1996). Elves are short duration (<1 ms) outward fast expending ring of optical emissions in the lower ionosphere. When viewed upward (from the top of thunderstorm) elves may appear as a doughnut shape ring with

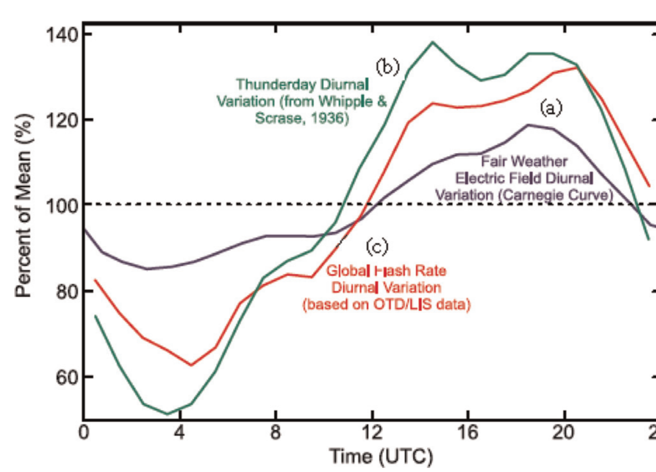

Fig. 1. Diurnal variation of the fair-weather field; (a) Carnegie curve, (b) diurnal variation of flash rates (Whipple and Scrase, 1936), (c) derived from Lightning Imaging Sensor (LIS) and Optical Transient Detector (OTD) data (after: Mach et al., 2011).

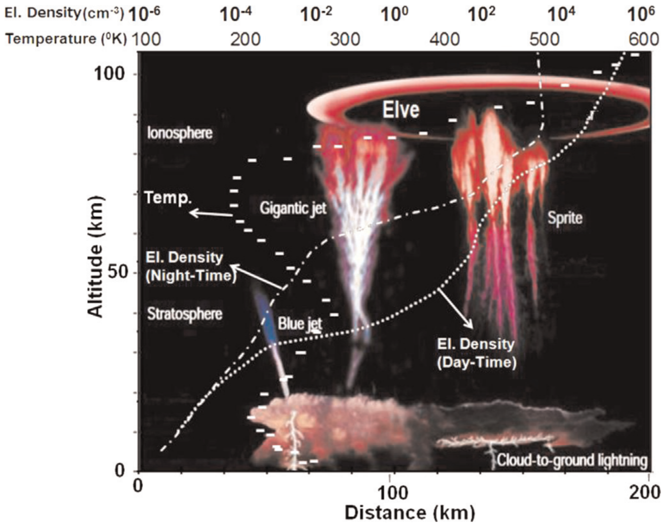

Fig. 2. Transient luminous events (sprites, blue jets, gigantic jets and elves) above the mesoscale convective system along with altitude are shown. The variation of day- and night-time electron density (El. density) and temperature are also shown (modified figure after: Lyons et al., 2000; Pasko, 2003).

minimum intensity at the center of the ring. The minimum intensity is due to the minimum intensity of radiated EMP above the source lightning current.

The halos (not shown in the figure) are different from sprite on account of its inferior brightness (0.3 MR versus 1.5 MR, where MR represents a typical value of few tens of mega Rayleigh) and shorter duration (1–2 ms versus 10–100 ms) (Newsome and Inan, 2010; Wescott et al., 2001; McHarg et al., 2002; Moudry et al., 2003; Kuo et al., 2008). Observations with improved temporal and intensity resolutions from the Imagers of Sprites and Upper Atmospheric Lightnings (ISUAL) payload on FORMOSAT-2 satellite provide evidence that flashes with negative polarity dominate the global halos population (Williams et al., 2012). Further, from the analysis of ISUAL data, Chen et al. (2008) showed that global average rates of elves and sprites are in the ratio of roughly 9:1; and that elves and halos occur over sea surface and costal area at almost twice their over land rates. The survey from ISUAL experiment aboard the FORMOSAT-2 satellite revealed that the global occurrence rates of elves, sprites, halos and gigantic jets are 3.23, 0.5, 0.939 and 0.01 events per minutes respectively (Chen et al., 2008).

Lightning discharges are considered to be the largest natural source of NO_x production. The best estimate of the annual global LNO_x and its uncertainty range based on global model studies related observations is ($\sim 5 \pm 3$ Tg a^{-1}) (Christian et al., 2003; Galloway et al., 2004; Schumann and Huntrieser, 2007; Pickering et al., 2009; Huntrieser et al., 2012), which may critically affect the abundance of ozone (O_3) and hydroxyl radical (OH) in the troposphere (Rohrer and Berresheim, 2006) and hence the atmospheric radiative forcing (Toumi et al., 1996; Hansen et al., 2005). Toumi et al. (1996) estimated that a 100% increase in lightning activity enhances the global mean radiative forcing via tropospheric O_3 by $\sim$0.3 W m^{-2}. Hopkins (2003) reported that the global average radiative forcing due to O_3 formed by lightning induced NO_x could be $\sim$0.1 W m^{-2}. Based on simulation, Grewe et al. (2009) reported a mean value of 0.54 W m^{-2} for the lightning induced ozone. These estimates did not consider the fact that an enhancement in lightning activity attributed to surface warming or global warming will also be associated with enhanced tropospheric water vapor, which may partially damp O_3 and other emissions (Brasseur et al., 2006). Changes in radiative forcing directly affect atmospheric circulation and climate parameters.

In the present paper salient features of lightning discharges in the troposphere, stratosphere and mesosphere, global electric circuit and their impact on climate are briefly discussed. Section 2 discusses dependence of lightning activity on solar activity, convective available potential energy, land and ocean surfaces, and El-Niño activity. Role of cosmic rays in the initiation of lightning discharges is also discussed. Discharges in the stratosphere and mesosphere include blue starters, blue jets, gigantic jets sprites, holes, and elves. Their features and generation mechanism are briefly discussed in Section 3. Global electric circuit and its relevance in the atmospheric discharges are discussed in Section 4. Section 5 discusses relevance of atmospheric discharges in climate studies. Some problems for future studies are indicated in Section 6. A brief summary is given in Section 7.

2. Lightning discharges

Lightning discharges are manifestation of processes that generate, separate and lastly neutralize electrical charges in nature through thunderstorms. Charge generation process includes both inductive and non-inductive mechanisms (Yair, 2008; Saunders, 2008). The electrification process in thunderstorm depends on the existence of super cooled water, ice crystals, snow, hail and soft hail, which may lies between the 0 °C isotherm and −40 °C isotherm (Williams et al., 1991; Saunders, 2008), because ice may start melting above 0 °C and all hydrometeors solidifies below −40 °C. This region can extend from about 2 to 10 km altitude. Their presence in the mixed phase region is also governed by the large scale circulation pattern of the atmosphere (Zipser and Lutz, 1994). The charge separation process very sensitively depends on temperature and usually may occur between the above altitude levels through the slow hydrodynamic processes (Saunders, 2008). The updraft in thunderstorms drag small and light positively charged ice fragments upwards, whereas, the heavy negatively charged hailstones due to gravitational force predominantly fall downwards, which may result into charge separation. The stronger updraft also enhances the collision between different particles, which may result in increased charge transfer between particles, leading to rapid electrification. Charge distribution in thunderstorm is very complex and may involve multi-layers of charges (Lyons et al., 2006; Krehbiel et al., 2008, Stolzenburg and Marshall, 2009; Pasko, 2010; Siingh et al., 2011, 2012).

The pile up charges of certain sign amounts to several tens of coulombs resulting in strong quasi-electrostatic fields inside and around thunderstorm, which may lead to discharge in atmospheric gas. Measurements of electric fields in thunderstorms and Monte-Carlo calculations showed that the field strength never reaches the value required for conventional breakdown of air, which is $\sim$32 kV cm^{-1} at atmospheric pressure (Marshall et al., 2005; Dwyer et al., 2006; Stolzenburg et al., 2007; Stolzenburg and Marshall, 2009). Therefore, it is proposed that the thermal electron avalanches (of mean thermal energy $\sim$several eV) produced by intense electric field of thunderstorm may aid discharge phenomena.

Another mechanism operating at a lower breakdown field ($\sim$2.10 kV cm^{-1}) called runaway mechanism based on the relativistic electron avalanches is also proposed (Gurevich and Zybin, 2001, 2005; Gurevich et al., 2009). A runaway electron produces large amount of secondary low-energy electrons due to the neutral molecule ionization, which are accelerated to high energy in the presence of cloud electric fields. Theses energetic electrons in turn act as runaway electrons. As a result one may expect an exponentially increasing avalanche of runaway electrons (Colman et al., 2010), leading to the electrical breakdown of air.

The lightning flashes develop through the process of step leader, which is a thin conducting channel created by the intense electric field caused by the charges present in the leader head. The processes which sustain the conducting leader channel are associative ionization, direct and stepwise acceleration and detachment reaction in the elevated gas temperature. Observations both in the laboratory and lightning discharges suggest a quasi-continuous development of positive leaders and an impulsive and stepwise development of negative leaders (Bazelyan and Raizer, 2000; Gallimberti et al., 2002).

2.1. Convection in the atmosphere

Atmospheric convection is upward/downward movement of air driven by buoyancy i.e. gravity forces caused by horizontal density differences. The net buoyancy force acting on the air parcel determines updraft velocity and hence nature and altitude location of thunderstorms. Thunderstorms with updraft velocity < 10 m/s usually have low lightning activity while electrically active storms producing good amount of lightning flashes have updraft velocity up to 50 m/s (Williams, 2001, 2005; Deierling and Petersen, 2008).

The vertical profiles of temperature and moisture in the atmosphere critically control development of convection. The vertical wind profile influences structure, evolution and movement of convective storm. Convergent flow of warm and moist air in the boundary layer and divergent flows in the upper troposphere, as well as large scale advection of cold air in the upper troposphere above warm and moist air in the lower troposphere by vertical shear makes the system convectively unstable. The potential energy inherent in the temperature and moisture stratification (the so called CAPE) feeds/sustains convection process.

2.1.1. Convection, CAPE and lightning

Thunderstorms derive their kinetic energy from CAPE, which is the upward integration of buoyancy force and depends on vertical profile of temperature difference between a warmer rising air parcel within an updraft and a relatively cooler air far outside the updraft (Williams, 1995). Low buoyancy force leads to low altitude clouds and convection is referred to as shallow convection. Deep convection may result into towering clouds up to the tropopause leading to the possibility of enhanced lightning activity. However, CAPE is not the sole parameter to control lightning activity (Williams et al., 2002) as is evident from the fact that for the same value of CAPE over land surface and warm ocean water, maritime lightning activity is much reduced (Lucas et al., 1994; Kandalgaonkar et al., 2005; Tinmaker et al., 2010; Kumar and Kamra, 2012; Siingh et al., 2015). One of the reasons may be difference in conversion efficiency of CAPE to updraft kinetic energy. The large contrast of lightning distribution between the continent and ocean can be explained in terms of Bowen ratio (ratio of sensible heat to latent heat flux), which is high for continental storms (Williams and Stanfill, 2002). Qie et al. (2003) analyzed lightning imaging sensor data over Tibetan plateau and reported that the Bowen ratio plays some role in lightning variation over seasons and plateau regions. They also showed in agreement with Williams et al. (1992) that lightning activity and monthly averaged CAPE are nonlinearly related. Flash per CAPE varied in different parts of plateau between 6 and 18 (Qie et al., 2003). In most parts of plateau, the flash per CAPE is 2–3 times higher than that in Florida and Congo (Williams et al., 1992), although CAPE is relatively much smaller over the plateau (Qie et al., 2003). Toumi and Qie (2004) proposed that the product of the Bowen ratio and CAPE could be a better measure of actual lightning on the plateau than the CAPE or rainfall themselves. The involved sensible and latent heat fluxes play different roles. The latent heat flux is critical for rainfall amounts, but does not control deep convection. The sensible heat flux seems to modify the efficiency of lightning production for a given CAPE (Qie et al., 2003; Toumi and Qie, 2004).

Recently, Siingh et al. (2013a) reported similar relation between lightning flash and convective rain over the South/Southeast Asia with correlation coefficient 0.68 and 0.81 respectively; attributed it to the similar meteorological factors having identical effects on lightning and precipitation and suggested that the convective processes in the above two regions were similar. Liou and Kar (2010) found that the values of rain yield per lightning flash over Taiwan are different for inland and coastal stations and also rain yields per flash are different for different seasons and attributed these differences to the cloud base height and CAPE. Larger cloud base height may lead to broader cloud with reduced entrainment so that more of the CAPE is effectively converted into vertical updraft and ice particle growth. Cloud base height is directly proportional to the dew point depression of the surface and hence to the sensible heat flux. Recently, Siingh et al. (2014) found correlation coefficient between lightning flash and CAPE in different regions of India between 0.23 and 0.81, whereas the same between convective rain and CAPE lied between 0.68 and 0.86. However, lightning flashes were well correlated with the surface temperature in all the considered Indian regions, whereas, the same is not true with the convective rain. These studies show that CAPE and surface temperature partly control the convective process and partly other factors such as sensible heat flux, total surface heat flux, orographic condition of the region, thermodynamic state of boundary layer, etc.

2.1.2. Convection over land and ocean Surfaces and lightning

The diurnal variation of lightning flash rate distribution over major continents and ocean surfaces are shown in Fig. 3 (Bailey et al., 2007; Mach et al., 2011). The peak flash rate occurred at different hours of the day for different continents with the African continent having the largest peak flash rate at around 1500 UT (Fig. 3a), but the diurnal peak in lightning activity occurred later because of the combined contributions from Africa, South America and North America (Fig. 3b). The diurnal variation with local time for all the continents individually showed peak around 1600 h local time (Bailey et al., 2007). The land-based storms have a much larger mean flash rate (40 s^{-1}) and also larger variation between peak and trough than ocean lightning storms (mean 5 s^{-1}), which almost shows a constant value (Mach et al., 2009, 2010).

The global distribution of negative (Fig. 4a) and positive (b) CG discharges in the summer season (June–August, 2004) show that the $-$CG discharges occur mainly in the middle America, Africa, India and Southeast Asia both over the land and oceanic regions (Sato et al., 2008). The occurrence of $-$CG discharge over the oceanic region seems to be more dominant compared with that over the land region. For example, in the Middle America most of the $-$CG discharges occur over the North Pacific Ocean. The same feature can be seen in the northern and southern parts of the Indian Ocean. On the other hand the global distribution of $+$CG flashes in the same period (Fig. 4b) mostly occur over the land region, especially in the North America, equatorial and northwest parts of Africa, India and Southeast Asia.

The difference in lightning activity over land surface and ocean surface arises due to their differential response to the solar radiations. The sensible heat flux over land surface is stronger than over ocean surface, provide stronger updrafts required for more lightning (Williams et al., 2002, 2004). Further, larger concentrations of cloud condensation nuclei over land surface may cause more numerous and smaller cloud droplets, which suppress coalescence process and provide more super cooled droplets in the mixed-phase region, where they participate in the charge generation processes (Williams and Stanfill, 2002). These mechanisms have been tested over islands of different areas (Williams et al., 2004; Kumar and Kamra, 2010).

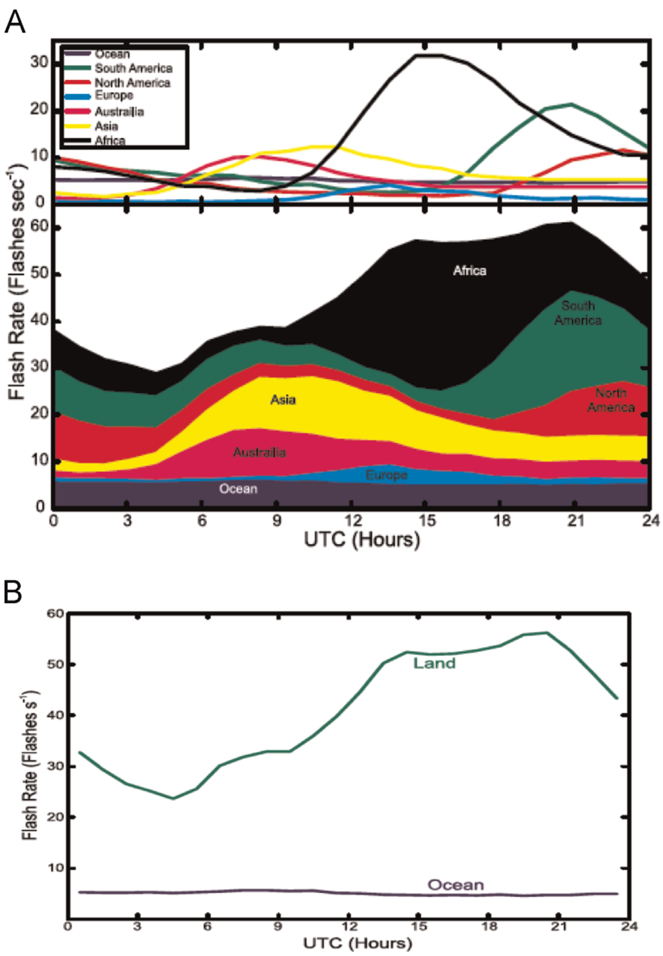

Fig. 3. (a) Diurnal variations of the lightning flash rates for the major continental masses and ocean (Bailey et al., 2007; Mach et al., 2011) are shown in the top panel. Contribution of each region to the total global diurnal flash rate distribution is shown in the bottom panel. (b) Land and ocean contributions to the LIS-OTD flash rate diurnal variation are shown. The land peak is around 2000–2100 UT, while the distribution over the ocean is almost constant (after: Mach et al., 2011).

Lightning discharges mostly occur in convective clouds which have different features over land and oceans due to surface properties. The maritime clouds have less super cooled water compared with the continental clouds (Black and Hallett, 1986). The updraft velocity is limited below the terminal fall velocity of the rain drops, whereas, no such limit is observed in the continental clouds (Zipser and Lutz, 1994). Contrary to this, Williams et al. (2002) reported that over the Amazon basin (inhomogeneous terrain) convective system resembles the real oceanic-like tropical system. This suggests that surface properties are not the only cause of difference in convective processes over continents and oceans.

Kumar and Kamra (2012) considered three sea regions (Arabian Sea (AS), Bay of Bengal (BB) and Chinese Sea (CS)) and two land regions (the Peninsular India (PI) and Indo-China Peninsula (ICP)) and showed that the flash rates over peninsular region (PI and ICP) are 2.6–33 times of those over sea regions (AS, BB, CS). The flashes occurring over oceans are more energetic than those occurring over peninsulas. Among the considered sea regions, flashes were found to be most frequent but least energetic in the BB and least frequent but most energetic in the AS region, which may be due to the warmer sea surface temperature with their average value remaining above convective threshold in the BB. In another study frequent lightning over Gulf Stream in the Atlantic Ocean and the South Pacific Ocean near Australia also were attributed to the warm water and overlying cold air (Biswas and Hobbs, 1990; Rutledge et al., 1992; Zipser, 1994).

2.1.3. Convection, solar activity and lightning

Earlier studies attempting to establish some relation between solar activity and thunderstorm activity showed both a positive and negative correlations at different stations in Britain, Germany and other places (Fritz, 1878; Brooks, 1934; Myrbach, 1935; Aniol, 1952; Sen, 1963; Kleymenova, 1967). Stringfellow (1974) reported a positive correlation ($R \sim 0.8$) for 1930–1973 in Britain, where earlier negative correlation was reported by Brooks (1934). Schlegel et al. (2001) analyzed data for the period 1992–2000 over middle Europe and reported a significant positive correlation between lightning frequency and A_p index a negative correlation with cosmic rays fluxes. Girish and Eapen (2008) reported an inverse relation between sunspot cycle and thunderstorm/lightning occurrence rate at Trivandrum (India) between 1853 and 2005. Recently, Siingh et al. (2013a) studied the effect of sunspot numbers, A_p index, cosmic rays and $F_{10.7}$ flux (solar radiation flux at 10.7 cm wavelength) on the lightning activity in the South Asia (8–34°N, 60–95°E) and Southeast Asia (8–34°N, 95–120°E) based on the data from 1998–2010 and reported no significant correlation with sunspot numbers/A_p index, a negative correlation with $F_{10.7}$ cm fluxes and cosmic fluxes. Neto et al. (2013) analyzed monthly thunder day data from seven cities in Brazil from 1951 to 2009 using wavelet analysis and reported the 11 year periodicity in six cities with a predominant anti-phase behavior with sunspot numbers. These results suggest that convective/thunderstorm activity in relation to solar activity varies with the location of observing station on the Earth and it may change its sign over time scale of a few decades.

The global flash rate varies from $\sim 35\ s^{-1}$ in February (austral summer) to $\sim 60\ s^{-1}$ in August (boreal summer) (Cecil et al., 2014). The mean global flash rate is $\sim 46\ s^{-1}$. The peak monthly average flash rate (at $2.5 \times 2.5°$ grid) is 18 km^{-2} $month^{-1}$ from early April to early May in the Brahmaputra valley of eastern India (Cecil et al., 2014). The annual global lightning activity peaks in summer hemisphere in agreement with the seasonal migration of the Inter Tropical Convergence Zone (ITCZ) and the atmospheric circulation patterns (Price, 2006, 2009a; Cecil et al., 2012). Thunderstorms develop in subsidence and low level moisture conditions and hence these are expected to develop in regions not far from ITCZ. During the spring and fall, the distribution of lightning is not symmetric about the equator, simply because of the asymmetry in land–ocean distribution between the two hemispheres.

2.1.4. Lightning and EL-Niño activity

The thunderstorm activity distribution is highly dependent on surface air temperature and hence it is expected to be quite different during the warm El Niño phase as compared to the cool La Niña phase (Williams, 1992; Hamid et al., 2001; Sátori et al., 2009a). Global thunderstorm/lightning activity with El Niño Southern Oscillation (ENSO) perspective reported more lightning activity in the warm EL Niño phase as compared to the cool La Niña phase (Satori and Zieger, 1998, 1999; Price et al., 1998; Chronis et al., 2008; Goodman et al., 2000; Hamid et al., 2001; Sátori et al., 2009a; Kulkarni and Siingh, 2014). Sátori et al. (2009a) reported moderate relative increase of lightning activity in the longitudinal range of Africa and Europe, more pronounced in the coastal regions of North West Africa and the Eastern Mediterranean than the equatorial Africa. The largest lightning response was observed in Southeast Asia. The ratio of zonal lightning distributions in the warm and cold ENSO periods for three longitudinal ranges containing three tropical chimney regions (South America, Africa and Maritime continent) are shown in Fig. 5 (Sátori et al., 2009a). On the right side global air circulation pattern is shown.

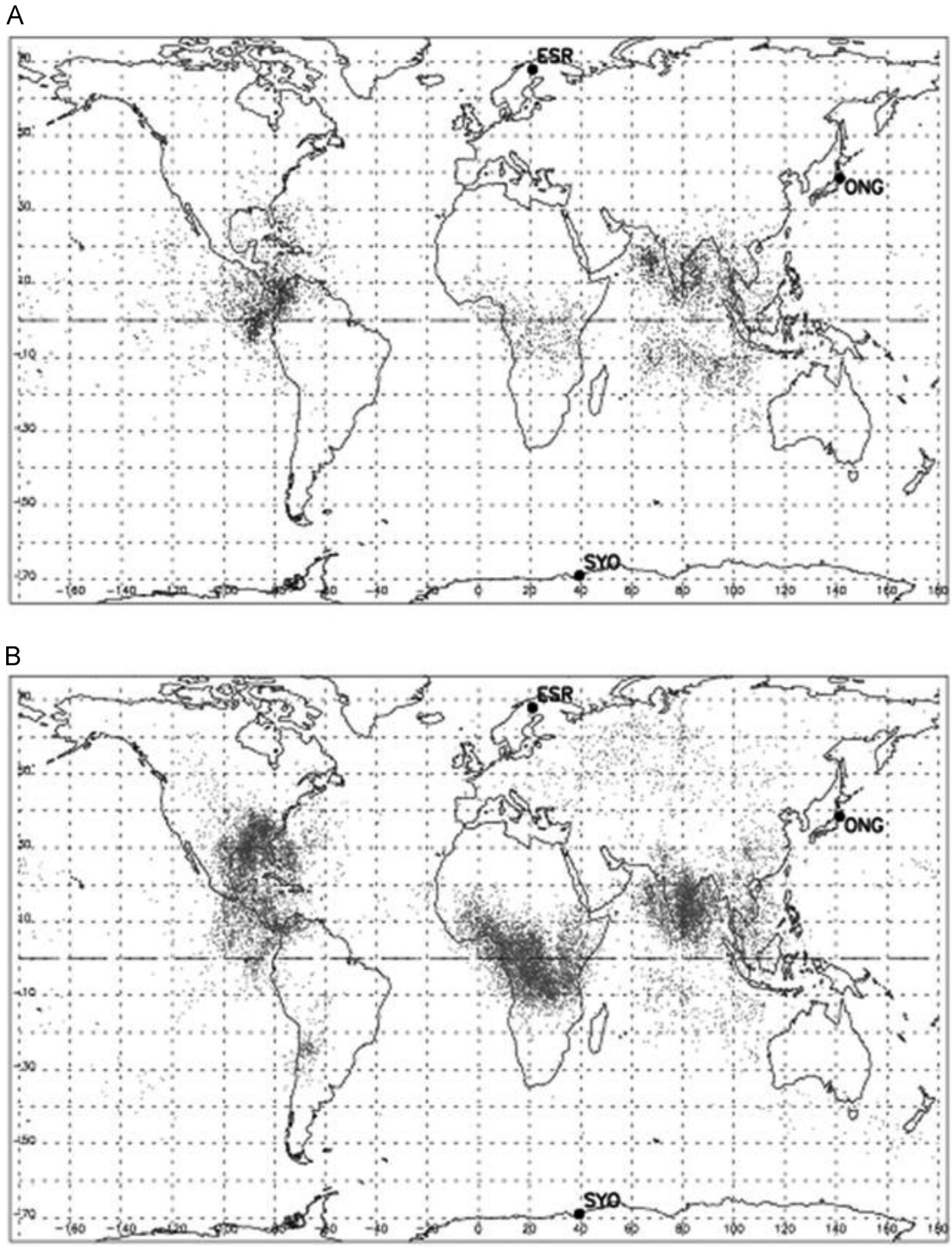

Fig. 4. Global distribution of intense CG discharges during the summer season; (a) −CG discharges; (b) +CG discharges (after: Sato et al., 2008).

The greatest ENSO contrast occurs in the regions of synoptic scale subsidence and increased large scale subsidence favored more lightning. At the interface of the Hadley cell and Ferrel cell descending warms dry air creates temperature inversion, which may act a kind of isolating lid on the planetary boundary layer that helps in the buildup of wet bulb potential temperature and moist static energy in response to the short wave radiation (Williams and Renno, 1993; Sátori et al., 2009a). This leads to CAPE enhancement and hence initiation and strengthening of convection and thereby increased lightning activity.

2.2. Cosmic rays and lightning discharge

Cosmic rays (high energy charged particles) in the presence of relatively smaller electric fields ($\sim$2.16 kV cm^{-1}) can initiate discharge process (Gurevich and Zybin, 2001, 2005). The high energy charged particles moving through cloud generate a considerable number of electron–ion pairs producing an ionized plasma

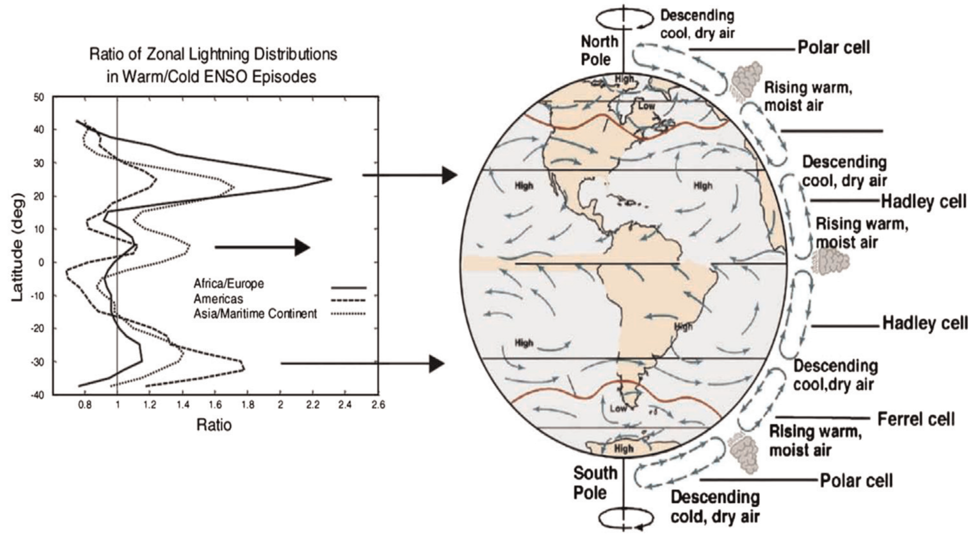

Fig. 5. Ratios of zonal lightning distributions of three tropical chimney regions: South America, Africa and the Maritime continent, in the three longitudinal ranges. The regions with the greatest relative changes are in regions of synoptic scale subsidence in the thermally-direct Hadley cells shown here, but also regions where sufficient moisture is available for moist convection (Sátori et al., 2009a).

domain, polarization of which in the presence of thundercloud electric field leads to a local enhancement of electric field at the edges of the domain and initiate discharge (Gurevich et al., 1997), similar to self-sustained laboratory discharges at atmospheric pressure initiated by sub-nanosecond pulses of runaway electrons (Babich, 2005; Babich and Loiko, 2009). However, based on simulation results, Babich et al. (2012) reported that "it is very unlikely that the lightning discharge can be triggered by joint action of cosmic ray showers and relativistic runaway electron avalanches (RREAs) even in the presence of precipitation particles". On the contrary, the RREAs seeded by low energy cosmic rays, produce a plasma domain, at the edges of which, the electric field of the cloud is enhanced above the breakdown field. In this mechanism steady supply of seed electrons from the more common lower energy cosmic ray is required, instead of cosmic ray showers as proposed by Gurevich et al. (1999). In support of their hypothesis Gurevich et al. (2009) reported 4 events of lightning discharges while an extensive air shower (EAS) passed through a thunderstorm. However, it is not yet possible to identify the percentage of lightning flash triggered by this process.

Cosmic rays produce ion clusters in the lower atmosphere which modify the vertical current and cause accumulation of space charges on the upper and lower edges of cloud (Tinsley, 2000; Siingh, 2008; Nicoll and Harrison, 2010; Siingh and Singh, 2010; Singh et al., 2011; Nicoll, 2012). Space charges could influence microphysical processes such as droplet–droplet collision (Khain et al., 2004), droplet–particle collision (Tripathi and Harrison, 2002), droplet formation (Harrison and Ambaum, 2008), etc. In turn these may influence cloud lifetime, cloud radiative properties, precipitation and lightning activity. Thunderstorm electric field is also found to influence the intensity of cosmic ray muons. Lidvansky and Khaerdinov (2009) reported a strong decrease of the intensity of cosmic ray muons during a thunderstorm on September 24, 2007 in Baksan Valley (North Caucasus). Jun-Fang et al. (2012) on the basis of synchronous data of neutron monitor and atmospheric electric field during 62 thunderstorm activities from 2008 to 2010, reported changes in neutron counting rates during 27 cases with significance $S>5\sigma$ (σ is standard deviation). During measurement it was observed that the measuring set showed changes in its reading only when thunderstorms were at slant angle and not vertically above the instrument. Although, the measuring set up had to be in control of positive charge layer of thunderstorm. When thunderclouds were vertically overhead, the low energy cosmic ray particles may not have been accelerated to energy level above threshold value of the measuring system.

The avalanche multiplication in the runaway mechanism leads to relativistic electrons, which may cause X-ray and gamma ray flashes through Bremsstrahlung process (Gurevich et al., 1992). Such flashes termed terrestrial gamma ray flashes (TGFs) were observed by the Burst and Transient Source Experiment (BATSE) on the Compton Gamma Ray Observatory (CGRO) in the early 1990s (Fishman et al., 1994). These gamma ray events are observed to be associated with optical discharge phenomena in the atmosphere (Smith et al., 2005; Dwyer and Smith, 2005). Analyzing Solar Neutron and Gamma Ray (SONG) data aboard the Russian Complex Orbital Near-Earth Observations of the Activity of the Sun (CORONAS-F) low-altitude satellite, Bucik et al. (2006) revealed many X-ray emissions and suggested their association with the underlying lightning activity. Gamma ray, in a TGF propagating away from a source may produce secondary electrons, mostly via Compton scattering and pair production (Dwyer et al., 2008). As electron TGFs has small diameter and long duration, they are infrequently observed (Dwyer et al., 2008; Carlson et al., 2009; Barnes et al., 2015). The spectral analysis of bright TGFs showed presence of strong 511 keV positron annihilation lines (Briggs et al., 2011). This shows that electron TGFs contains positron components, indicating the occurrence of pair production in conjunction with terrestrial lightning. Chilingarian et al. (2012) analyzed the observation of the simultaneous enhancements of gamma ray and neutron fluxes during thunderstorm ground enhancements (TGEs) and reported that in addition to neutron production by gamma ray, the mesoatom nuclei decay could also be a possible source of additional neutrons. Chilingarian et al. (2013) further showed that the power law indices of the energy spectra of the small TGEs are close to the background cosmic gamma ray spectrum, while that of larger TGEs the energy spectra is much steeper typical of the avalanche process. This clearly supports the role of cosmic ray in thunderstorm discharge activity.

2.3. Schumann resonances

Transient currents associated with lightning discharges generate electric and magnetic fields, excite the Earths-ionosphere cavity which oscillates at 8, 14, 20, 26,…, Hz. These ELF signals are commonly known as Schumann resonance (SR) signals and their frequencies are a direct result of the Earth's dimensions and of the properties of the imperfectly conducting ionosphere. Large amplitude SR is known as Q-bursts.

The received SR signals are usually grouped under three categories. In the first category large amplitude ELF transients having ultra-energetic Q bursts associated with TLEs are considered, which can be detected and processed with wave impedance techniques from a single site (Huang et al., 1999; Hobara et al., 2006; Williams et al., 2010). The wave impedance (E/H) is the unique function of the source–receiver distance and it is independent of the form of the source current (Jones and Kemp, 1971). By comparing the recorded wave impedance with the theoretical wave forms, the source receiver distance is estimated with an error of few hundred kilometers (Boccippio et al., 1998; Huang et al., 1999). In the second category, ELF transients of large amplitude generated by intense lightning discharges with clearly identified Q burst above the background level. In this case wave impedance technique cannot be used because wave amplitude is below the required level (Yamashita et al., 2011), but Finite Difference Time Domain (Taflove, 1995; Simpson and Taflove, 2004, 2007; Hu and Cummer, 2006) and other techniques are useful (Mushtak and Williams, 2002; Kirillov, 2002, 2005; Price and Melnikov, 2004; Haupt and Haupt, 2004; Greifinger et al., 2007; Ando and Hayakawa, 2007). The continuous back ground noise-like signals produced by many superposed and time overlapping signals from ordinary convective scale lightning discharges form the third category (Nickolaenko et al., 2010; Rycroft and Odzimek, 2010).

The long term SR data collected at different stations clearly show diurnal, seasonal and inter-annual variation of SR parameters (Satori et al., 1996, 2003, 2009b, 2013; Price and Melnikov, 2004; Sekiguchi et al., 2008), which have been used to remotely sense the global lightning activity, global climate variation and variability of the lower ionosphere (Williams, 1992; Yang et al., 2009; Satori et al., 2013; Williams and Mareev, 2014). Global distribution of lightning activity is obtained using global inversion technique for the Schumann resonance data collected at either a single station/multiple stations (Williams, 1992; Satori et al., 1996; 2009b, 2013; Hobara et al., 2006; Williams et al., 2010; Shvets et al., 2010; Shvets and Hayakawa, 2011; Yamashita et al., 2011; Mushtak and Williams, 2011; Williams and Mareev, 2014). The diurnal variation of the cumulative intensity of the first three Schumann resonant signals observed at Nagycenk, Hungary for the Years 1994–1998 clearly showed peaks at 0700–0900 UT, 1400–1600 UT and 1900–2100 UT (Satori et al., 2009b, 2013) corresponding to intense tropical thunderstorm activity over South East Asia, Africa and South America. These results are very similar to the diurnal variations obtained from optical measurements from space (Christian et al., 2003).

The diurnal variation of the mean SR intensity of the first, second and third modes have been used to study the shift in the global position of the lightning activity in the warm El Niño years and cool La Niña years (Satori and Zieger, 1998, 1999; Sátori et al., 2009a, 2009b). Using the annual diurnal variation of SR intensities observed at Rhode Island, USA, and Nagycenk, Hungary along with observations of lightning from space, Williams and Satori (2004) reported that lightning activity in the African zone dominates over that in the South America and that electrified rain/shower clouds are more numerous in the South America than in the Africa, an important result in the context of global electric circuit studies.

The SR frequencies vary with time of the day, season and year and with the solar cycle. Satori et al. (2005, 2009b) showed that the frequencies of the first three SR modes vary through each year exhibiting a maximum near solar maximum and a minimum near solar minimum. This is explained in terms of large changes in the solar X-ray flux, which dominate the variation in the conductivity profile within the 90–100 km altitude affecting ELF characteristics. The electron density is higher at the solar minimum and minimum at the solar maximum. Satori and Zieger (1999) reported changes in the third mode behavior during late 1995 and early 1997 and attributed it to the northward shift of the African thunderstorm center when an elongated warm El-Niño period suddenly turned in to a cold La Niña phase. These results support the idea that Schumann resonances can be used to study the changes in the spatial distribution of lightning flashes, seasonal variation of global lightning activity (Yang et al., 2009) as well as the variability of the lower ionosphere (Williams,1992).

3. Transient luminous events

MacKenzie and Toynbee (1886) reported for the first time visual observation of brief flash of light above thunderstorm. Almost after a gap of 35 years, Wilson (1921) predicted the possibility of electrical discharge in the mesosphere above an intense thunderstorm. Almost 70 years after the prediction of CTR Wilson, Vaughan and Vonnegut (1989) analyzed video recordings made by the space shuttle payload camera and showed many TLEs. The first ground based observation is reported by Franz et al. (1990). Inspired by these early findings, two independent groups lead by Waltor Lyons of Mission Research Corporation (Lyons, 1994) and Davis Sentman of the University of Alaska, Fairbanks (Sentman and Wescott, 1993) initiated field programs to study the new phenomenon. The interest in TLEs have subsequently spurred worldwide and several hundred research papers and many review papers including books have been published (recent review papers—Pasko, 2008, 2010; Neubert et al., 2008; Sentman et al., 2008; Lyons et al., 2009; Raizer et al., 2010; Inan et al., 2010; Siingh et al., 2010, 2012; Pasko et al., 2012; Surkov and Hayakawa, 2012; Sato et al., 2015; Liu et al., 2015; etc.). Some features of TLEs are listed in Table 1.

Starters, blue jets and gigantic jets are not coincident with a particular CG strokes (Cummer et al., 2009; Edens, 2011; Suzuki et al., 2012). However, preceding CG may create electrical condition that promotes their formation (Krehbiel et al., 2008; Edens, 2011). Even IC discharges can also create favorable condition for their generation (Krehbiel et al., 2008; Riousset et al., 2010; Lu et al., 2011). In some cases, the upward discharges were observed to begin as part of normal IC flashes (Lu et al., 2011; Liu et al., 2015). Sprites, halos and elves are caused by intense CGs. Sprites and halos are the results of the excitation and ionization of air molecules due to collisions with electrons accelerated by quasi-electrostatic field in the upper atmosphere established by CGs and their possible continuing current (Pasko et al., 1997; Li et al., 2008). Elves are caused by electromagnetic pulse radiated from the return stroke current of CGs (Newsome and Inan, 2010).

The magnitude and duration of electric field at the relevant altitude in the atmosphere seems to determine dynamics of transient luminous events. The accelerated electrons gain energy from the electric field and loose energy to air molecules via collisions, which is determined by air density. The duration of electric field, controlled by atmospheric conductivity, characterize the life time of the discharge events at those altitudes. Considering electric field duration to be the Maxwellian relaxation time, Pasko et al. (1997) reported it to be <1 ms above 80 km altitude, 1–10 ms at 70 km, and ~ 1 s at 30 km. Thus, life time of transient luminous events at those altitudes are: <1 ms for elves, ~ 2 ms for halos, 1–10 ms for sprites, and 100 ms for jets and gigantic jets. As the ionospheric conductivity between 60 and 90 km altitudes varies significantly from day-to-night and from low latitude to high latitudes, the life time of events observed in those altitude

Table 1
Characteristic features of TLEs.

	Name	Height region	Properties	References
1	Sprites	40–90 km	The upper portion is red with faint blue tendrils extending downwards to 40 km altitude. Intensity may reach 1.5 MR; 1–500 GR has also been reported. Life time could be ~10–100 ms. Based on the structures, sprites are classified as column, Carrot, Jelly fish and Angel types. Mostly, they are associated with + CG lightning flashes.	Sentman et al. (1995), Lyons et al. (2003b), Pasko (2007), Stenbaek-Nielsen et al. (2007), Inan et al. (2010), Siingh et al. (2008, 2010, 2012).
2	Halos	75–85 km	Transverse dimension ~40–70 km, horizontal cross section as large as 700 km^2. Featureless diffuse descending glows of ~1–2 ms duration. They may occur as an isolated events or may be preceded by elves and/or followed by sprites.	Stenbaek-Nielsen et al. (2000), Frey et al. (2007).
3	Blue Jets	Cloud top to ~40–50 km	Slow moving fountains of blue light emerging from the cloud top, vertical velocity $\sim 112 \pm 24$ km s^{-1} and life time 200–300 ms. Upward development in conical shape with conical angle $14.7 \pm 7.5°$. Associated mostly with high negative CG discharge rate. They have same polarity as the upper storm charge. Screening charges are required to initiate blue jets.	Wescott et al. (1998), Lyons et al. (2003a), Krehbiel et al. (2008), Siingh et al. (2012)
4	Blue starters	Cloud top to ~20–30 km	Closely related to blue jets except that the terminal altitude is limited to 25 km or less. Velocities varied over the life time and lied between 27 and 53 km s^{-1}. In this case also screening charges are required to initiate them.	Wescott et al. (1996, 2001), Lyons et al. (2003a), Edens (2011)
5	Gignatic jets	Cloud top to the lower edge of ionosphere (~70–90 km)	Gigantic jets have an impulsive and structured appearance. They are cloud-to-ionosphere discharges of both polarities and induced large amount of charge transfer. Discharge polarity depends on the charge imbalance in the cloud. They can last up to ~1 s.	Su et al. (2003), Hsu et al. (2005), Chou et al. (2010), Soula et al. (2011)
6	Palm tree	Cloud to ~60–70 km altitude	A single stem initiated from cloud moves upward and spread into a wider crown near 60–70 km altitude exhibiting red color. It follows with the occurrence of large groups of sprites. Palm trees are short duration phenomena.	Heavner (2000), Moudry (2003), Marshall and Inan (2007)
7	Elves	Bottom edge of the ionosphere (80–95 km altitudes)	Donut shape (concentric rings) elves of short duration (<1 ms) are of 200–500 km size with dark central region and exhibit fast lateral expansion with much brighter red emissions than blue. Pancake (flat disc) shape elves with a central luminous part are also observed. Observed multiple elves events are attributed to multiple peaks of return current.	Krider (1994), Kuo et al. (2007), Newsome and Inan (2010), Chang et al. (2010), Mende et al. (2004), Lu (2006)

ranges will also vary.

3.1. Blue starters and blue Jets

Blue starters are slow moving fountains of blue light emanating from the cloud top and reaching up to ~21 km altitude (Lyons et al., 2003a; Pasko, 2008). Edens (2011) reported a blue starter emanating from the cloud top at ~15.2 km and terminating at 17 km altitude. Lyons et al. (2003a) reported 17 short upward discharges from convective dome of a super cell storm and termed them as gnomes and pixies, rather than blue starter. The velocity of blue starter varies over its life span, from ~27 km s^{-1} to ~180 km s^{-1} (Pasko, 2008).

Blue jets are extended version of blue starter and may continue up to ~50 km altitude (Pasko, 2008). They develop upward in conical shape at a speed of ~100–140 km s^{-1}, having a life time of ~200–300 ms. Observations suggest that blue jets show association with high negative cloud-to-ground flash rates (not with any individual flash) and large hail (Wescott et al., 1998).

Pasko and George (2002) based on the three-dimensional modeling studies reported blue starters to be the critical phase of blue jet and both the phenomenon could be considered as a positive streamer corona developing from a conventional lightning leader. Further, the presence of screening charges on the cloud top is an essential requirement for the initiation of blue starters/blue jets (Krehbiel et al., 2008; Riousset et al., 2010). There is no critical limit on the amount of charges in the cloud for the initiation of blue jet/starter. Even a moderate cloud charge of 50 C with radius of ~3 km could sustain blue jet development (Raizer et al., 2006, 2007, 2010). Krehbiel et al. (2008) also suggested that in a decaying storm, the upper positive charge region (just below the screening negative charge layer) may be of limited magnitude and in such a situation jet could propagate to only small distance above cloud top and result into a starter.

A simple scenario of a blue jet development into a gigantic jet along with spatial charge distribution in the thunderstorm cloud is given in Fig. (6) (Surkov and Hayakawa, 2012). j_g is the gravity driven updraft current inside thundercloud, which is zero outside. It causes charge separation in the cloud and hence may be considered as a source for the upward/downward-directed lightning discharges, which may remain operative as long as j_g supplies positive charges and maintains sufficient positive charges at the top of the cloud. j_f is the weak fair-weather current flowing from the mesosphere to the ground. j_j is the conduction current density in the leader. In the absence of streamer zone blue jets are observed whereas, the full grown system represents gigantic jets.

Riousset et al. (2010) considering time dependent conduction current and screening charges, simulated the dynamics of the screening charges near the cloud boundaries and found that prior occurrence of IC discharges prevent the development of blue jet until a CG discharge enhances the positive charges in the cloud by bringing negative charges to the ground. The screening charges gradually developing at cloud top lead to breakdown initiation near the upper boundary of cloud resulting into upward moving blue jet.

3.2. Gigantic jets

Gigantic jets (GJs) are discharges originating from the cloud top and terminating at the lower boundary (70–90 km altitude) of the ionosphere. The evolution of gigantic jets can be discussed as the leading jet, the fully developed jet and the trailing jet (Su et al., 2003). Ground observations carried out in the USA (Pasko et al., 2002; van der Velde et al., 2007; Cummer et al., 2009; Lu et al., 2011), Europe (van der Velde et al., 2010), Indian Ocean (Soula et al., 2011), Asia (Su et al., 2003; Chou et al., 2011; Huang et al.,

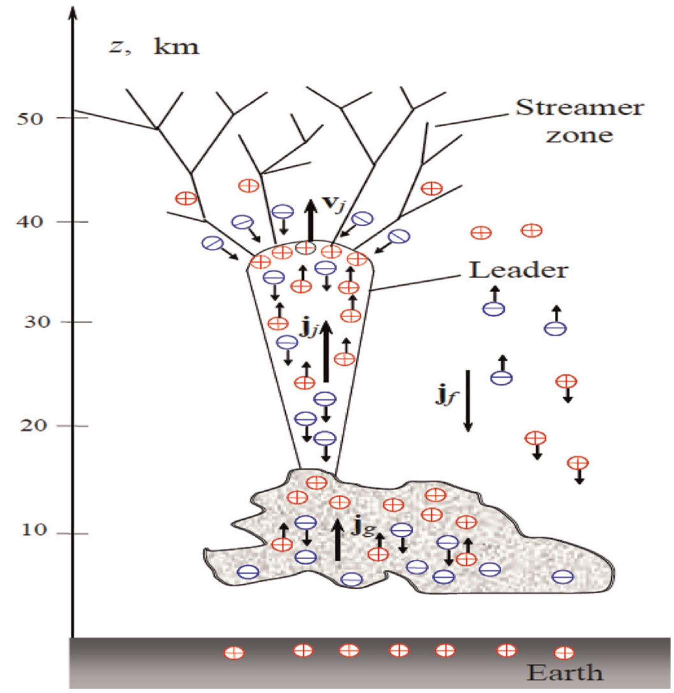

Fig. 6. A simple scenario of blue jet development into a gigantic along with spatial charge distribution in the thunderstorm (after: Surkov and Hayakawa, 2012). Where v_j is the vector of blue jet velocity, j_g is gravity driven updrafts current density inside thunder cloud, j_j and j_f are the conduction current density and fair weather mean current density, respectively.

2012) and surveys from space (Chen et al., 2008; Kuo et al., 2009; Chou et al., 2010; Lee et al., 2012) showed gigantic jets to be a global phenomenon and they transferred positive as well as negative charges from cloud to the ionosphere.

Gigantic jets may involve charge moment changes as low as 1000–2000 Ckm (Su et al., 2003) and as high as ~12,000 Ckm (Cummer et al., 2009; Van der Velde et al., 2010) and may originate either from a tall cloud top (Pasko et al., 2002; Su et al., 2003; Hsu et al., 2005; van der Velde et al., 2007; Kuo et al., 2008, 2009; Chou et al., 2010; Soula et al., 2011) or a winter thunderstorm of only ~6.5 km tall (van der Velde et al., 2010). Similar to starters and jets, the occurrence of GJs mainly depends on the electrical properties of thunderstorms and related dynamics during lightning discharges.

Krehbiel et al. (2008) indicated that GJs may begin as a normal IC discharges between dominant mid-level charges and screening-depleted upper level charges and continue to propagate upward out of the cloud top. Fig. 7 summarizes IC, −CG, low altitude IC, blue jets and GJs discharges (after; Krehbiel et al., 2008). Relevant charge amount and their approximate altitude locations are also given. IC discharge starting from the central negative (positive) charge layer penetrates the upper weaker-positive (negative) charge layer, emanates from the cloud top and propagates upward as a negative (positive) GJ (Fig. 7). Using observational results, Lu et al. (2011) suggested that this charge imbalance might be amplified by the IC lightning progression prior to GJ initiation. They reported two examples of −GJs which began as an ordinary IC discharges (not associated with any discharge channels to ground) and continued up to the ionosphere.

Analyzing GJ events recorded by the ISUAL payload, Kuo et al. (2009) reported that after the GJ reaches the lower ionosphere, the ionized gas in the channel could short-out the upper discharge channel and cause the local ionosphere boundary to drop down to ~50 km altitude (Marshall and Inan, 2007; Lee et al., 2012). As a result a current continuously may flow between the cloud top and

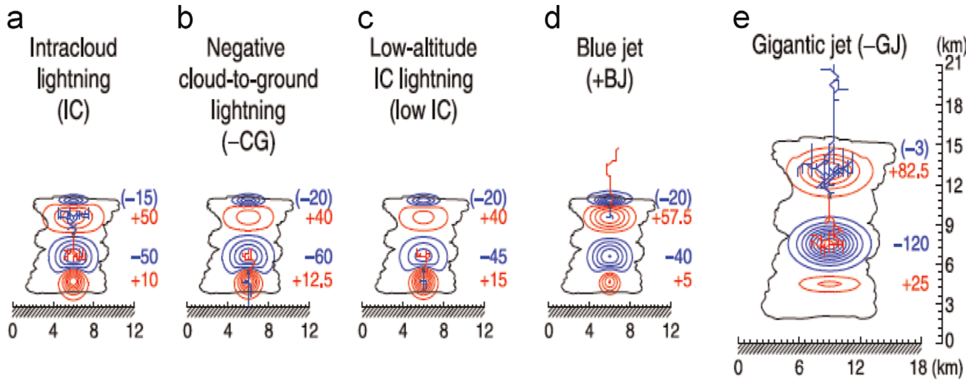

Fig. 7. Simulated discharges illustrating the different known and postulated lightning types in a normally electrified storm (Krehbiel et al., 2008). Relevant charge amount and their approximate altitude locations are given.

the lower ionosphere. When the boundary recovers its original altitude, the contact point moves up and the continuing current appears as an upward surging/trailing jet. The surge current moments (CM) at the GJ ionosphere contact are derived from the ULF measurements, which has the largest value (60–160 kA km) for the tree-like GJs, medium values (18–36 kA km) for tree-carrot like GJs and relatively smaller values for carrot-like GJs. The spatial structures of GJs may be the result of interplay of time scale of different phenomena such as the dissociative attachment, ambient dielectric relaxation, development of individual avalanche into a streamer (Pasko et al., 1998; Pasko and Stenbaek-Nielsen 2002; Pasko, 2010).

3.3. Sprites

Sprites may occur as a single straight luminous column, in cluster of two or more repeated elements with a mixture of complex shapes, sizes and intensities. Single vertical column is termed C sprites and a large collection of C sprites with downward branching tendrils resembling to fireworks are Jellyfish (Fig. 8). Carrots are the sprites with tendrils and upward branching towards the ionosphere. Large sprites with diffused tops and lower tendrils extending down to altitudes of 30–40 km are named angels/A-bombs (Fig. 9). The vertical extent of giant sprites may exceed 60 km. The upper portion of sprite is red with wispy and faint blue tendrils extending downward. The red color is attributed to the first positive band system of N_2 ($1PN_2$) and the blue color to the first negative N_2^+ ($1NN_2^+$) and the second positive N_2 ($2PN_2$) band systems primarily during early time of sprite developments. Summary of emission band systems, transition involved, excitation energy threshold, life time and quenching altitude are given in Table 2 (after: Liu et al., 2006; Pasko, 2007). Details of energy transfer mechanisms and involved reactions are discussed in (Kanmae et al., 2007; Sentman et al., 2008; Sentman and Stenbaek-Nielsen, 2009; Pasko, 2010; Luque and Gordillo-Vazquez, 2011, 2012; Luque and Ebert, 2012).

To understand discharges in the upper atmosphere, Wilson (1925) proposed that cloud-to-ground lightning's rearrangement of charge can be represented as a vertical dipole with a charge moment equal to the product of the charge transferred and its height above ground. The field of such a dipole at certain altitude may exceed the dielectric breakdown field and discharge may initiate at that altitude. This may occur because a breakdown dielectric field follows the density of air, which decreases exponentially with altitude, whereas, the vertical dipole field decreases as inverse cube of altitude. Observations suggest that instead of charge moment, the initiation of sprite depends on the rate of charge removal from the cloud during discharges (intra-cloud and cloud-to-ground) (Liu and Pasko, 2004; Cummer and Lyons, 2005; Hiraki and Fukunishi, 2006). Discharges involving small charge moments (~hundreds of coulomb kilometer) with sufficiently short (~10^{-4} s) discharge time may initiate sprite, whereas, discharges with large charge moments (ten thousand Coulomb km) with relatively longer discharge time (~10^{-2} s) may not initiate sprite (Hiraki and Fukunishi, 2006). Short duration discharges with very high peak current may lead to a relatively faint and diffused sprite at lower altitudes (Gerken and Inan, 2002, 2004).

Based on simulation, Li et al. (2012) reported that a more

Fig. 8. Example of Jellyfish sprites (after http://www.heliotown.com/Sprite_June_16_2013_044531UT.html) capture on June 16, 2013 at 04:45:31 UT over West Kansas.

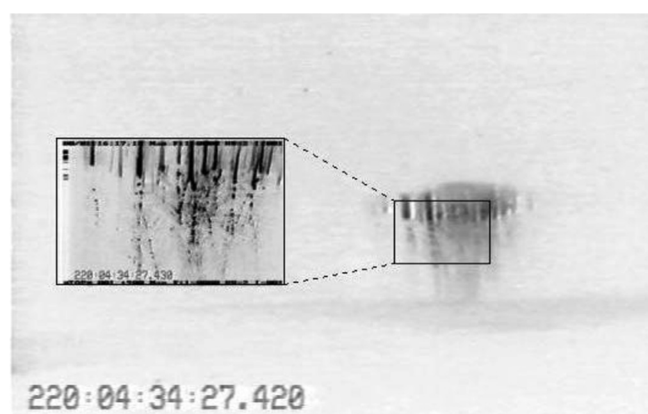

Fig. 9. Example of wide-angle view (right) and telephoto view (left) of a sprite event recorded at 04:34:27UT on 8 August 1999 over Kitt Peak, Arizona (after Su et al., 2002).

impulsive current source with the same amount of charge transferred produced a higher electric field of shorter duration at halos and sprite altitudes. This suggests that the time scale of lightning source current plays significant role in the sprite initiation and morphology. Simulation studies also show that velocity, radius and brightness of sprite streamers exponentially increases in time (Liu and Pasko, 2004; Liu et al., 2009a, 2009b; Liu, 2010; Celestin and Pasko, 2011; Kosar et al., 2012), which is consistent with the observations by high speed camera (Stenbaek-Nielsen et al., 2007; McHarg et al., 2007; Liu et al., 2009b).

Observations suggest that sprites are mostly associated with positive CG discharges, rarely with negative CG discharges (Taylor et al., 2008; Li et al., 2012; Lang et al., 2013; Singh et al., 2013). Relatively low −CG flash rates are observed during the time of initiation by −CG discharges (Soula et al., 2009; Lang et al., 2013). Low flash rates may allow the built up of large amount of negative charge leading to a large peak current and impulse charge moment change. Negative sprite-class lightning mainly occurred in or near intense, deep convection (Soula et al., 2009; Lang et al., 2013; Singh et al., 2013). One example along with charge moment, current moment and simulated electric field is shown in Fig. 10 (Li et al., 2012). All negative sprites show remarkably similar features including relatively simple streamer structure, streamer termination altitudes greater than 55 km and accompany bright halos. Comparative features of negative and positive sprites are given in Table 3 (Li et al., 2012).

Rare observations of sprites associated with −CG discharges seem to contradict the proposed Wilson's hypothesis of initiations of sprites based on electric field calculations, however, the observation of halos by ISUAL payload and ground based PIPER system show abundance of halos associated with −CG discharges (Frey et al., 2007; Williams et al., 2012). Using ground based

Table 2
Summary of emissions from sprites (after: Liu et al., 2006; Pasko, 2007).

Emission band system	Transition	Excitation energy threshold (eV)	Lifetime at 70 km alt.	Quenching altitude (km)
1PN2	$N^2(B^3\Pi_g)\rightarrow N^2(A^3\Sigma_{+u})$	~7.35	5.4 µs	~537
$2PN_2$	$N_2(C\ ^3\Pi_u)\rightarrow N_2(B\ ^3\Pi_g)$	~11	50 ns	~30
LBH N_2	$N_2(a^1\Pi_g)\rightarrow N_2(X^1\Sigma_g^+)$	~8.55	14 µs	~77
$1NN_2^+$	$N_2^+\ (B\ ^2\Sigma_u^+)\rightarrow N^{+2}\ (X^2\Sigma_g^+)$	~18.8	69 ns	~48

Table 3
Comparison of negative sprites with positive sprites in their morphology, lightning source current, and lightning-driven electric fields (after Li et al., 2012).

Feature negative positive		
Delay	A few ms highly variable	
Morphology		
Halo	Always	Not always
Altitude range (km)	55–90	40–90
Structure	Always same	Highly variable
Lightning source		
Pulse duration	0.5 ms	1–2 ms
CMC (C km)	> 450	> 300
Lightning-driven electric fields		
Strength	Very high	High
Persistence	Short	Longer
Streamer termination (Ek)	0.2–0.3	0.05–0.1

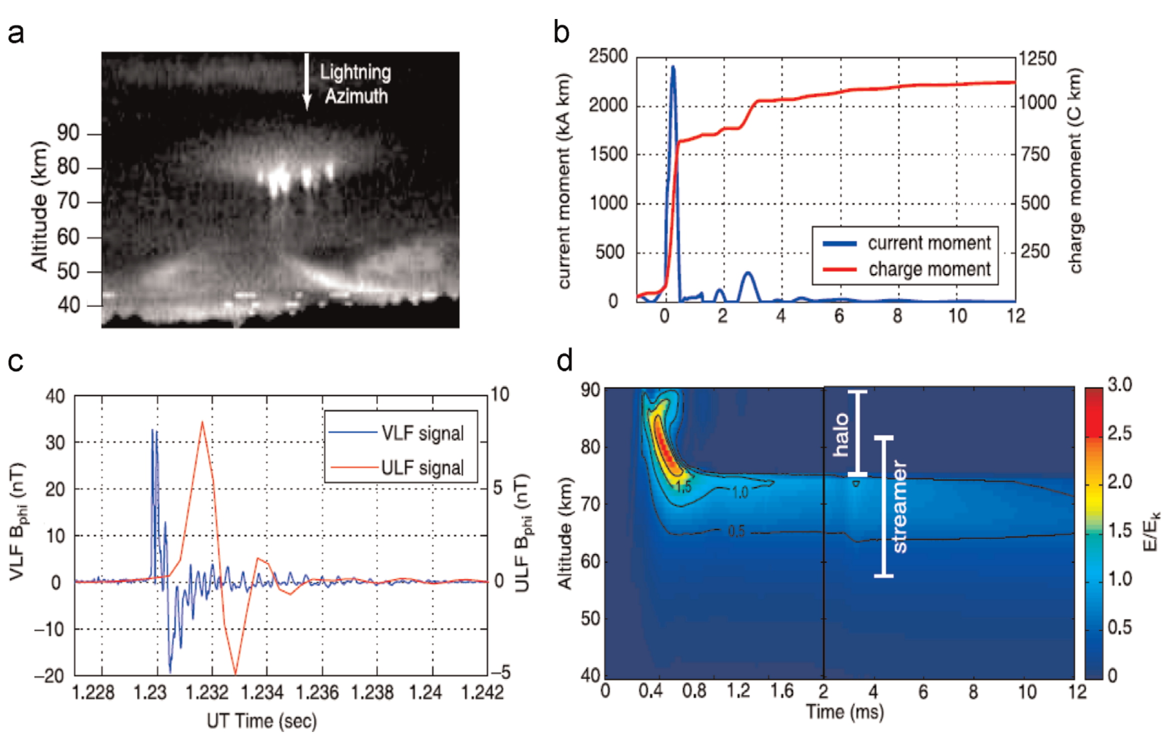

Fig. 10. Sprites detected from negative CG lightning discharges on 25 October, 2009 at 06:52:01 UT (Li et al., 2012). (a) Sprite image from WATEC 902H low light camera (the vertical line represents azimuth location of the lightning discharge). (b) Azimuthal magnetic field measured from Duke ELF/VLF sensor (100 Hz to 25 kHz) and Duke ULF/ELF sensor (0.1 Hz to 500 Hz). (c) Extracted full bandwidth lightning source current waveform and charge moment change of sprite. (d) Normalized lightning-driven electric field from FDTD simulation. Electric fields in the first 2 ms are zoomed to show the fast changing fields at high altitudes. The vertical bars represent the altitude range of the halos and the sprite (after Li et al., 2012).

photometric array system, Newsome and Inan (2010) found that halos generated by both +CG and −CG flashes for a given lightning current occur with almost the same frequency in accordance with the Wilson's theory. Hence, the rare association of sprites with −CG flashes may be attributed to the temporal and spatial development of sprite-structure after initiation. Observations show structured sprite below 75 km altitude and diffused above 85 km, which is explained comparing the relaxation time of electric field and the time scale of streamer formation (McHarg et al., 2007; Qin et al., 2011). Streamers are narrow filamentary plasma waves driven by non-linear space charge waves (Raizer, 1991). At lower altitudes due to lower electron density (hence lower conductivity) relaxation time of electric field is longer compared to the streamer formation time and as a result electron avalanches can develop without overlapping and form filamentary structure. At higher altitudes situation is reversed and diffused halos are formed.

Simulation of sprites and halos showed that both +CG and −CG discharges are equally capable of triggering streamers (Asano et al., 2008, 2009), but evolution of streamer strongly depends on the local electric field and ambient electron density profile (Qin et al., 2011). The size of the streamer zone (distance required for development) is inversely proportional to the required minimum (critical) electric field (E_{cr}) for the propagation of streamer and not for the initiation of streamer. Streamers can be launched by individual electron avalanches in electric fields exceeding the threshold field (Pasko, 2008). For the positive streamer $E_{cr}^{+}=4.4$ kV cm^{-1} (Allen and Ghaffar, 1995) and that for the negative streamer $E_{cr}^{-}=7.5$–12.5 kV cm^{-1} (Babaeva and Naidis, 1997; Bazelyan and Raizer, 2000). As a result the streamer initiation region (SIR) for the negative streamer is much smaller than that for the positive streamer. Because of smaller SIR associated with −CG discharges, streamer formation/development is hindered and hence sprite structure is rarely observed in association with −CG discharges, but halos are observed.

Recent observations with improved temporal and intensity resolutions (Newsome and Inan, 2010; Williams et al., 2012) and modeling studies (Asano et al., 2008, 2009) indicated that both +CG and −CG discharges are equally capable of triggering discharges in the mesosphere (sprites and halos). However, streamer evolution/development strongly depends on electric field and local electron density profile (Qin et al., 2011, 2012a, 2012b). In the case of +CG discharges, the source current is less impulsive, lasts for longer time and creates a region with $E>E_k$ even in the presence of low electron density which persists for tens of milliseconds. Such a situation is more suitable for streamer (sprite structure) development. These properties are not usually present with −CG discharges (Li et al., 2008; Li and Cummer, 2012) and hence streamer development is restricted but halos are formed. This explains the observation of sprites associated with +CG discharges and rarely associated with −CG discharges. Formation and development of streamer involve highly nonlinear processes (Kosar et al., 2012) and hence further observation and modeling studies are required.

3.4. Halos

Halos, sometimes also referred as sprite halos are short lived diffused luminous events having lateral extent 40–70 km (Pasko, 2010) and usually are observed in the altitude range 75–85 km. They are produced by both +CG and −CG discharges (Frey et al., 2007; Williams et al., 2012). Halos are much dimmer than sprites (Kuo et al., 2008; Takahashi et al., 2010). The brightness and duration of halos depend on peak current and polarity of discharges (Fig. 11) (Williams et al., 2012). Halos associated with +CG flashes are brighter and last for longer duration. Negative CG

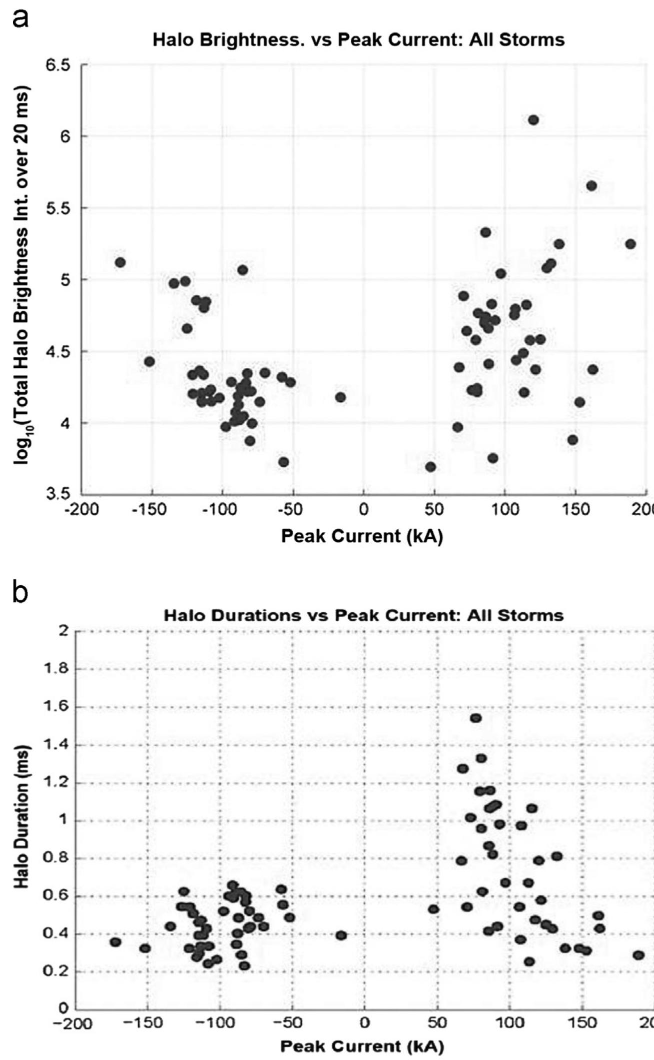

Fig. 11. Variation of (a) halos brightness and (b) variation of halos duration (derived from PIPER observations) with peak current of the parent lightning (derived from the National Lightning Detection Network measurements) (after Williams et al., 2012).

discharges usually are multiple stroke type, but halos are produced by the first return stroke having the largest peak current. Both over land and sea, negative halos are more prevalent than positive halos (Frey et al., 2007; Adachi et al., 2008).

3.5. Elves

Elves are short duration (<1 ms) luminous events of 200–500 km size expanding outwards and observed at the bottom edge (80–95 km altitude) of the ionosphere either in the form of donut shape with dark central region (Fukunishi et al., 1996; Krider, 1994; Kuo et al., 2007; Siingh et al., 2012) or pancake shape (flat disc shape) with a luminous central part (Mende et al., 2004; Lu, 2006). The donut shape elves are explained considering the radiation pattern of CG lightning discharges as a vertical dipole, whereas, the pancake shape with centric luminous could be explained by considering intra-cloud discharges as horizontal (tilted) dipole (Rowland, 1998). Lu (2006) proposed the contribution of induction field in addition to radiation field to explain the observed central region of the pancake shape elves.

Newsome and Inan (2010) reported that about 78% of elves and 55% of halos were associated with −CG discharges, which is in accordance with the fact that lightning with peak current greater than 80 kA over ocean is ten times more than over land. In fact most CGs having peak current less than 50 kA are negative, while most CGs with peak current greater than 100 kA are positive (Rakov and Uman, 2003; Singh et al., 2013). However, majority of CGs producing elves are negative with peak current less than 100 kA (Newsome and Inan, 2010).

Three-dimensional models of the electromagnetic pulse (EMP) interaction with the ionosphere without the effect of the Earth's magnetic field (Cho and Rycroft, 2001) and including the effect of magnetic field (Marshall et al., 2010) are developed to explain frequently observed donut-shaped elves. The Earth's magnetic field exhibits asymmetric structure. Horizontal lightning channels produce a much stronger optical output for the same channel current (Marshall et al., 2010). A sequence of many IC discharges (as in the case of spider lightning) may create a sequence of "flashing elves" as well as cumulative density perturbations of many tens to hundreds of percent in the overlying ionosphere (Marshall et al., 2008). Newsome and Inan (2010) reported 40 events in which pair of elves (elves doublets) occurred in succession. The duration between elves-element is $\sim 120\ \mu s$. The doublet events are ~5% of the total elves count. They further pointed out that sferics associated with doublet events are relatively more intense and exhibit multiple strong initial peaks which suggests the cause of the second event of the doublet may be the return stroke waveform.

Transient luminous events such as sprites, halos and elves may be affected by local perturbations in the mesosphere and lower thermosphere (Neubert et al., 2008; Siingh et al., 2012), caused by solar tidal waves and gravity waves. Solar tides are thermally forced atmospheric oscillations propagating upward with its amplitude growing exponentially with altitude in response to the decrease of the atmospheric density (Chapman and Lindzen, 1970; Sentman et al., 2003; Sao Sabbas et al., 2009; Ghodpage et al., 2012). Gravity waves generated in the troposphere by strong orographic forcing (Jiang et al., 2004; Ghodpage et al., 2012, 2015), deep convection (Fritts and Alexander, 2003), frontal acceleration and geostrophic adjustments (Ford et al., 2000) etc may propagate upward up to the lower thermosphere. At tropical latitudes deep convection associated with severe thunderstorms is found to be a source of broad spectrum gravity waves observed at mesospheric heights (Taylor et al., 2009; Sao Sabbas et al., 2009; Vadas et al., 2009). Breaking gravity waves in the mesosphere and lower thermosphere modulate neutral density there; reduced density values will facilitate the electrical breakdown process (Sao Sabbas et al., 2009; Fadnavis et al., 2009). Striated or mottled elves (Yair et al., 2009; van der Velde et al., 2011; Haldoupis et al., 2012) could be the result of gravity wave induced striation/modulation of neutral density. Yue and Lyons (2015) reported elves observed in the presence of a strong gravity wave, which lead striations in the elves luminosity. Marshall et al. (2015) have matched the elves striations directly with gravity wave striations present at the time of the elves. The gravity wave was generated in a different storm system than that of the elves-producing lightning discharge (Marshall et al., 2015). There are very few simultaneous observations of gravity waves and transient luminous events. Therefore, it is not precisely known the impact of gravity waves on different events. The reverse phenomena i.e. the role of transient luminous events on the spectra and amplitude of gravity wave are also not yet studied.

4. Global electric circuits

The global electric circuit is formed between the Earth's surface and the lower ionosphere, both of which are good electric conductor with respect to the atmosphere between them. The electrical sources in the lower atmosphere are thunderstorms, shower clouds, point discharge currents, ionization by radon isotopes and galactic cosmic rays (Siingh and Singh, 2010; Siingh et al., 2013c; Kamra et al., 2015). The circuit closes through fair-weather current remote from the source/generator. Other GEC topics are discussed in (Rycroft et al., 2000, 2007, 2008, 2012; Singh et al., 2004; Siingh et al., 2005, 2007, 2008, 2011, 2013b; Markson, 2007; Harrison et al., 2008; Tinsley, 2008; Williams, 2009; Rycroft and Harrison, 2012).

The phenomenon and processes involved have huge temporal and spatial scales ranging between 10^{-6} s and 10^{9} s and 10^{-9} m and 10^{9} m respectively (Rycroft and Harrison, 2012). As an example, lightning discharges operate at microsecond time scales (Rakov and Uman, 2003) and solar cycle variation/long term variations involve 10^{9} s. The point discharge currents form sharp ended grass and the spiky needles of coniferous trees having scales of millimeter size, whereas, pointed hills/ridges may have hundreds of kms. Ion-aerosol interaction operates at a scale of 10^{-9} m (Aplin et al., 2008; Rycroft et al., 2008). Considering the global electric circuit to be equivalent to a spherical capacitor with time constant of ~200 s, Details about AC generators (time scale < 200 s) and DC generators (time scale > 200 s) present in the atmosphere are summarized in Fig. (12) (after Rycroft and Harrison, 2012). The main generators: thunderstorms and electrified rain/shower clouds contribute to the upward current which are estimated to be 60% and 40% respectively (Wilson, 1925; Rycroft et al., 2007), 80% and 20% respectively (Odzimek et al., 2010) and 90% and 10% respectively (Mach et al., 2011). Shower clouds generally transport negative charges to the ground on raindrops (Liu et al., 2010). Mareev et al. (2008) using numerical simulation found that 55–75% of the charges are neutralized during the lightning discharges and remaining are transferred to the ground during a typical cloud-to-ground (CG) flashes. In the case of intra-cloud (IC) flashes, the amount of charge transferred to the ionosphere is ~5–15%. Maggio et al. (2009) estimated charge transfer due to lightning transients to be ~35% to the ground during CG flashes and during IC flashes upward charge transfer was ~12%. There are approximately 75% IC flashes and 25% CG flashes (Rakov and Uman, 2003). This is a tentative value; exact flash number ratio is not well known (Schumann and Huntrieser, 2007). Mallios and Pasko (2012) have reported that there is charge flow to the ionosphere during all phases of thunderstorm evolution and charge flow to the ground is only during CG discharges and cloud dissipation phases.

The electrodynamic properties of thunderstorms developed over land and ocean surfaces are quite different which is evident from the measurements of Mach et al. (2010). Based on a large number of measurements of electric fields/currents by aircraft (~850 flights over electrified clouds), they found upward positive current in 93% cases and negative polarity currents in 7% cases. The negative current may be from inverted polarity thunderstorms (Rust and MacGorman, 2002; Tessendorf et al., 2007). The upward positive current from storms with lightning over ocean is larger (~1.0 A) as compared to land (~0.43 A) while the negative current is larger (~ −0.30 A) over land than over ocean (~ −0.19 A) (Mach et al., 2010). In a small number of storms both over land and ocean, no measurable current was reported.

The contribution to GEC from electrified showers is both positive and negative +0.19 A and −0.17 A respectively over ocean and +0.09 A and −0.12 A respectively over land surfaces (Mach et al., 2010). The positive values are currents from electrified showers to the ground and current from ground to the electrified shower is negative. These values are in accordance with the results of Rycroft et al. (2007) and Liu et al. (2010). Considering the distribution of thunderstorms and shower clouds, Mach et al. (2011) estimated contribution to the GEC from thunderstorms over land

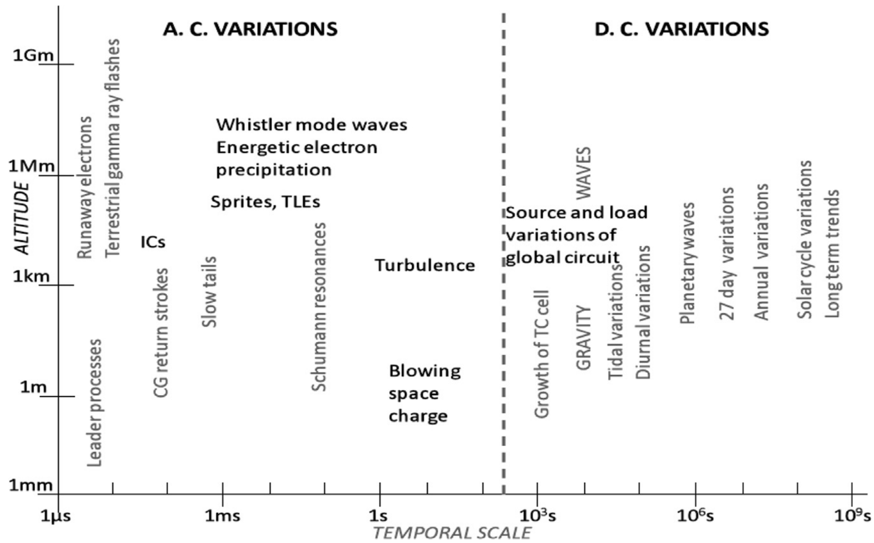

Fig. 12. Diagram showing the boundary between A.C. (time scale < 200 s) and D.C. (> 200 s) variations (after Rycroft and Harrison, 2012). Also Diagram showing the enormous physical processes *horizontal words* and *vertical words* ranges of different time and temporal scales respectively, occurring at different altitudes (for detail please refer Rycroft and Harrison, 2012).

and ocean to be 1.1 kA and 0.7 kA respectively, and that from rain/shower clouds 0.04 kA and 0.22 kA respectively. This turn out to be approximately 55% from land surface and 45% from ocean surface. Recently, Blakeslee et al. (2014) studied seasonal variations in the lightning diurnal cycle and estimated contribution to the global current from land thunderstorms ~52%, ocean thunderstorm ~31%, land ESCs (electrified shower clouds) ~2% and ocean ESCs ~15%. These results suggest that land and ocean storms are quite different in their electric current output per flash. The cause of this difference needs to be investigated.

The discharges in the middle atmosphere commonly called as TLEs may act as electric generators for the global electric circuit situated in the stratosphere and mesosphere, and also affect the vertical conductivity above thunderstorms (Rycroft and Odzimek, 2009, 2010). A single sprite may lower the ionosphere potential by ~1 V (Rycroft and Odzimek, 2009, 2010) and could have space charges of the order of mC (Li and Cummer, 2011). However, ELF radiation produced by current flowing in the sprite is comparable to that radiated by the causative lightning discharges (Pasko et al., 1998; Li and Cummer, 2011; Rycroft and Odzimek, 2010). Thus, the contribution of sprite as DC generator is small but as an AC generator it is substantial. van der Velde et al. (2010) reported that a gigantic jet transferred ~136 C negative charge in short duration (~120 ms) from the ionosphere to the cloud. The leader process in blue starter and blue jets terminate before reaching the lower edge of the ionosphere and thus affect the vertical conductivity above the thunderstorm. However, gigantic jets transfer charges to the ionosphere and affect ionosphere potential.

The current flow in GEC may also be affected by cosmic rays which produce ionization in the lower atmosphere and modify conductivity and potential (Siingh and Singh, 2010). Based on observations during 1966–1972, Harrison and Usoskin (2010) demonstrated a positive relation between the ionosphere potential and neutron count rate at Climax, Colorado. The ionosphere potential was ~17% less at solar maximum than at solar minimum. Rycroft et al. (2008) estimated ~6% less conductivity near solar maximum due to cosmic ray ion production. This may result into ~23% less fair-weather current at solar minimum than at solar maximum. Changes of the cloud cover at Vostok, Antarctica is found to be associated with extreme increase of the vertical electric field (Kniveton et al., 2008). Harrison and Ambaum (2010) reported a median 10% decrease in cloud amount at Lerwick observatory, Shetland Islands, Scotland associated with 10% decrease in Climax neutron rate. Thus, modulation of current density, vertical electric field and potential by solar activity and associated cosmic ray changes may provide a potential mechanism to understand the linkage between cosmic ray and cloud properties.

The flow of vertical current through a cloud layer generates space charges at the cloud edges over a wide (~65 km) region (Nicoll and Harrison, 2009a, 2009b). In another measurement through stratocumulus cloud layer, Nicoll and Harrison (2010) reported the presence of a layer of space charge at the cloud base. Measurements in the space charge region showed charges in cloud droplet concentration, which means change in conductivity. The magnitude and sign of the charge near the cloud boundaries were consistent with the calculation of droplets charging by the flow of vertical current through clouds using Gauss's law (Zhou and Tinsley, 2007).

Electrical properties of GEC are also affected by the presence of aerosols of natural and anthropogenic origin (Markson, 2007). The presence of space charges in volcanic ash layers even after a month from eruption (Harrision et al., 2010), Saharan dust several kilometers above the surface (Nicoll et al., 2011), and dust devils (Renno et al., 2004; Farrell et al., 2004) show that the altitude distribution of aerosol particles significantly affects electrical parameters of the atmosphere. Zhou and Tinsley (2010) reported that aerosols can increase the global columnar resistance by up to 60–90% and the largest effect comes from the continental boundary layers. The effect of clouds on the global columnar resistance is about 10% (Zhou and Tinsley, 2010) which is also indirectly corroborated with the measurements of vertical current and co-located cloud cover with thin and thick overcast conditions (Nicoll and Harrison, 2009a). Even the presence of turbulence in the troposphere affects droplet charging by the vertical current (Tinsley, 2008).

5. Atmospheric discharges and climate

The general circulation of the atmosphere driven by the Hadley circulation between the equator and mid-latitudes determines the location of sub-tropical and polar jets and strongly influence climate (Price, 2006). The Hadley circulation in combination with jets influences the location and quality of thunderstorms. The orography and distribution of land mass influences the convective process and hence impact the distribution of thunderstorms and

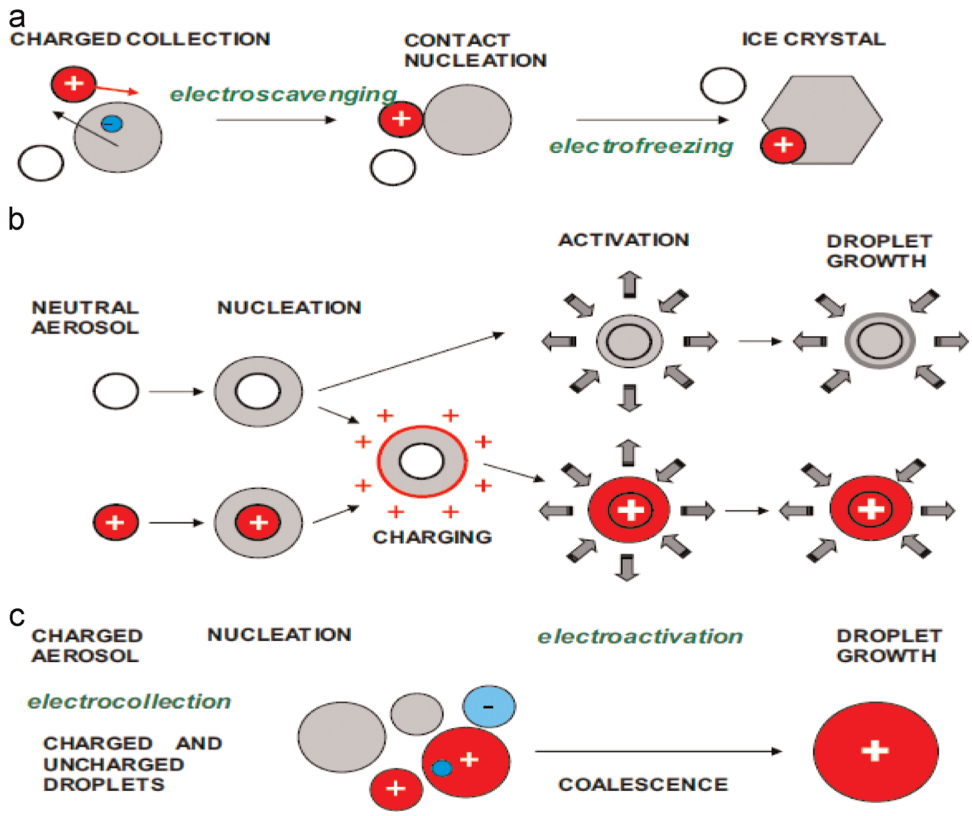

Fig. 13. Schematic diagram of various cloud microphysical processes which may be affected by electrical charge, (a) electro-scavenging, (b) electro-activation, and (c) electro-collection (after Rycroft et al., 2012).

lightning (Christian et al., 2003; Kumar and Kamra, 2010; Siingh et al., 2013a, 2014, 2015). Convective process and Lightning activity depends on surface temperature (Williams, 1992, 2009; Nath et al., 2009; Siingh et al., 2013a, 2014, 2015), upper tropospheric water vapor (Price, 2000; Price and Asfur, 2006), cloud cover (Sato and Fukunishi, 2005; Siingh et al., 2013a, 2014), ice crystal size distribution (Sherwood et al., 2006), ice water content in thunderstorms (Petersen et al., 2005), CAPE (Williams, 2005; Siingh et al., 2014) and aerosol concentration (Siingh et al., 2013a, 2014, 2015). Therefore, lightning activity may be considered as a sensitive indicator of these parameters which also affect the state of the atmosphere and hence climate.

5.1. Atmospheric circulation, lightning and climate

The global distribution of atmospheric discharges (CG, IC, TLEs) driven by solar heating and also influenced by land/ocean distribution on the planet follow the general circulation patterns of the atmosphere (Williams, 2005). Atmospheric discharges are the main contributor to the global electric circuit. The electric field and vertical current near cloud may influence the change in shape, terminal velocities, collision, coalescence and disruption characteristics of the drops (Coqillat et al., 2003; Bhalwankar and Kamra, 2008, 2013) which may affect precipitation and also surface temperature. It is known that Africa, South America and Southeast Asia regions rank from the most lightning active and least rainfall region to least lightning active and most rainfall region (Williams and Stanfill, 2002; Christian et al., 2003; Siingh et al., 2011). These regions also dominate the Walker circulation which clearly support to the fact that the global circulation is energized by the convective process in the atmosphere.

The increasing greenhouse gases in the atmosphere may lead to a warming at local/global level. The more (less) warming at the surface than the upper troposphere may lead to a more (less) unstable atmosphere (Price, 2013) and as a result one would expect more (less) convection and thunderstorms. There would not be any change if the surface and upper troposphere warm at the same rate, because there will not be any change in the stability of the atmosphere. In a warmer climate CAPE increases (Del Genio et al., 2007) resulting in increased lightning activity (Williams et al., 1992; Siingh et al., 2013a, 2014, 2015). An increase of 10–15% lightning for every 1 K global warming **is** found in multi-decadal modeling studies with a range of 0–60%/K (Price and Rind, 1994; Grenfell et al., 2003; Schumann and Huntrieser, 2007; Grewe et al., 2009; Price 2009b). At tropical stations lightning activity may increase by ~25% for an increase of surface temperature by 1 K above 296 K (Williams and Renno, 1993). Del Genio et al. (2007) based on climate simulation indicated a decrease in the number, but increase in the strength of lightning producing storms. The implications of all these studies on future changes in lightning/precipitation are unclear. This is because in simulation studies different controlling agencies are parameterized with mathematically relations, which are not precisely known. Different parameterizations yield different projection of lightning frequencies.

Convection transports water vapor in the atmosphere which acts as a strong greenhouse gas, leads to warming of the atmosphere and enhances precipitation (Price and Asfur, 2006; Siingh et al., 2011). Climate models predict 10–20% enhancement in water vapor for every 1 K increase of temperature in that layer, although the Clausius–Clapeyron equation predicts ~6% enhancement for 1 K change (Rind, 1998; Price, 2000; Dotzek and Price, 2009). Contrary to this during the severe drought period of 1997–1998 (decreased water vapor) the lightning activity in Indonesia increased by 60% (Hamid et al., 2001; Yoshida et al., 2007), which was explained considering that in the El-Niño dry period fewer thunderstorms develop, but they are much more explosive producing much more lightning activity (Grewe et al., 2009; Price, 2009b). The dependence of lightning activity on the content of vapor and its relation with the content of other phases of water such as ice, super cooled water in the cloud is not quantified. These phases of water vary during ENSO events and hence impact on lightning distribution.

5.2. GEC and climate

The microphysical processes linking space charges at the cloud edges with cloud properties are illustrated in Fig. 13 (after Rycroft et al., 2012). In electro-scavenging collision efficiency of charged particles and liquid droplets are enhanced (Tinsley et al., 2001; Tripathi et al., 2006) and formation of ice crystal is facilitated. The other impact of cloud charges is formation of additional droplet or an enhancement of droplet size by droplet–droplet coalescence (electro-activation) (Harrison and Ambaum, 2008). Droplet–droplet collision efficiency also enhances by charging (Khain et al., 2004) leading to droplet growth by charged coalescence. These processes may occur simultaneously in a real cloud and therefore, much more research activity is required by considering different droplet size distribution, concentration and variation in the vertical current both under fair-weather and disturbed conditions. In the absence of detail studies, material discussed in this diagram to a large extent seems to be speculative.

Harrison and Ambaum (2008) reported reduction (by $0.3\ \mathrm{W\,m^{-2}}$) in long wave radiation underneath a stratocumulus layer during a solar flare event and suggested it to be due to change in the height of cloud base caused by variation in cloud droplet charge as a result of variation in the vertical current. The vertical current may causes change cloud-cover/cloud-properties (Harrison and Ambaum, 2010), as is evident from the observation of $\sim$10% more broken cloud cover within one day of a Forbush decrease event (Harrison et al., 2008). The time delay of few hours is attributed to the fact that a vertical current effect on cloud microphysical process is expected to take few hours (Zhou and Tinsley, 2007). This shows how GEC can change climate condition by controlling cloud properties.

5.3. Atmospheric discharges and NO_x/ozone perturbation

Atmospheric discharges produce NO_x, which acts as a moderator of ozone distribution in the atmosphere (Schumann and Huntrieser, 2007). NO_x has short life time of days in the upper troposphere and hence it does not have effective impact on radiation balance of the atmosphere. Ozone having longer life time of weeks in the troposphere acts as a greenhouse gas (Price, 2013). In conformity with the lightning activity, the major contribution comes from the northern hemisphere. On the global basis, the share of lightning produced NO_x is $\sim$10%, which rises to $\sim$23% in the 35°S–35°N region (Bond et al., 2002; Neubert et al., 2008). Measurements show greatly enhanced concentration of NO_x in thunderstorm anvils and enhanced ozone concentration downwind (Huntrieser et al., 2007, 2012). Enhanced concentration of ozone is not the results of NO_x driven oxidation of CO and methane by photochemistry (which would be far too slow for this purpose) but mostly driven by transport out of the boundary layer or intrusion of ozone-rich stratospheric air.

In addition to usual lightning discharges, the discharges between cloud tops and the ionosphere also contribute to the production of NO_x (Enell et al., 2008; Sentman et al., 2008; Gordillo-Vázquez, 2008; Neubert et al., 2008; Siingh et al., 2011). In the absence of direct measurements of TLEs induced NO_x, Peterson et al. (2009) estimated TLE-NO_x production of blue jet and red sprite to be 1.7×10^{22}–7.4×10^{26} molecules and 6.8×10^{23}–6.3×10^{27} molecules per event, respectively. These result into global TLE-NO_x to be $\sim7\times10^{23}$–2×10^{28} molecules per second. These estimates are still under debate (Nijdam et al., 2010; Peterson et al., 2010) and values given are rough estimates with large uncertainties.

6. Some unsolved problems

Measurements of different features of laboratory discharges were used to understand lightning processes in the troposphere. However, there are some detail features which are not well understood. Discharges in the middle atmosphere have large spatial scales, occur short duration and are less intense. Jets, sprites, halos and elves involve different physical processes, and many of their features including those of ordinary lightning discharges are not well understood. For example:

i. Convective process leading to lightning discharges and precipitation depends on surface temperature, CAPE, orography of place and its location, moisture content, features of boundary layer and wind profile, etc. Details of contribution from each component individually and their dependence on other components are not well understood. More simulation studies and relevant measurements are needed.
ii. Observations suggest that the spatial/temporal distribution of lightning discharges is influenced by the Walker and Hadley circulations and El Niño/La Niña conditions of the atmosphere. However, quantitative studies are lacking. The impact of these phenomena on lightning flash distribution could be studied using recent satellite and ground based data.
iii. Based on experimental/theoretical studies, it has been proposed that cosmic rays influence cloud life time, cloud radiative properties, precipitation and lightning activity. Quantitative studies are not available. Even it is not possible to identify the features and percentage of lightning triggered by cosmic rays. Cosmic rays around cloud generate electron–ion pairs, which may affect charge structure of thunderstorm. It remains an open question—how charge distribution is affected? Further studies are required specially using simulation and measurements—under different conditions of cosmic rays.
iv. There are wide variations in the estimated contribution of different charging sources which are based on isolated and short term measurements, although many of them are dynamically coupled. Long term simultaneous measurements of space charges, vertical current, conductivity and electric fields at different latitudes, longitudes and altitudes under quiet and disturbed solar conditions are required. Environment of measurement should be selected in such a way that the role of aerosols could be deciphered. This also requires much effort to put on the related simulation studies.
v. Clouds being non-linear system (Tsonis, 2013) are very sensitive to the initial conditions and to changes in parameters. The basic physics of cloud formation and involved thermodynamics is understood but detailed cloud microphysics and complex connection between climate and ecosystems are not fully understood which are important and essential for a non-linear system.
vi. Development of streamers under laboratory conditions is known but under terrestrial condition at large spatial scale the same requires further studies. Observations suggest that minimum electric field required for development and propagation of negative streamer is 2–3 times more than that for positive streamer. This point also needs detail study.
vii. Blue starters, blue jets and gigantic jets are explained using the concept of charge imbalance in clouds. Details of spatial/temporal charge imbalance and redistribution of charges CG

and IC discharges and their impact on the characteristics of the jet are not clearly understood.

viii. Signature of multiple elves is reported based on multiple peaks in the return stroke process of lightning flashes. However, it is not known how lightning flashes exhibiting multiple return strokes are related to thunderstorm properties. Such thunderstorms may have a strong feedback on climate variables. This is also an open area for further studies.

7. Summary

This paper summarizes results from the literature to the best of the author's understanding. Not all of the results are firmly supported and hence may change with further research.

The solar activity affects meteorological variables at large distances through the east–west (Hadley) and north–south (Walker) tropical circulations. These circulations play active role in the distribution of lightning and precipitation. The effect of CAPE on lightning activity is not uniform over land and ocean surface for the same solar heating. This arises due to different roles of sensible heat flux and latent heat flux, which differ over land and ocean surfaces. The sensible heat flux controls the efficiency of lightning production for a given CAPE, whereas, the latent heat flux is critical for the rainfall amount. It seems to be non-linear relation between lightning flash distribution and surface temperature, CAPE, total surface heat flux, sensible heat flux, orography of the region and thermodynamic state of the boundary layer.

Observations of enhanced lightning activity during the passage of an extensive air shower passing through a thunderstorm are attributed to the initiation of lightning activity by energetic cosmic rays. There are some evidences in favor of proposed mechanism, however, much more work is needed both on observation and theory.

The lightning discharges in the troposphere and TLEs control properties of Schumann resonances and hence changes in their properties have been used to study the changes in the spatial distribution and seasonal variations of global lightning activity.

The conventional breakdown mechanism based on leaders and streamers could not explain all the observed features of sprites, halos and jets. Filamentary structures of sprites are streamers, whose initiation and development are found to be more probable and feasible in association with +CG discharges than that associated with −CG discharges for a given charge moment change. This explains more frequent observation of sprites associated with +CG discharges than −CG discharges.

Different models have been proposed to explain upward moving blue starter, blue jet and gigantic jet. The upward discharges between the upper charge layer and the screening charges escaping from the cloud tend to develop into starter and jets. On the other hand discharges between the two charge layers and escaping upward may develop into gigantic jets through the process of leaders as in the case of ordinary lightning. The role of cloud temperature and cloud electrodynamics on the excitation mechanism of large scale jets and their properties are not well understood at present. Some observations suggest association of GJs with the dropping down of the local ionosphere boundary, which have been explained considering short-circuit due to ionized channel between cloud top and the lower boundary of ionosphere. More observations and detail analysis are required to understand dynamics of charge transfer and electrical structure of thunderstorm.

The electromagnetic pulses generated by CG discharge-current heat and ionize the ambient medium at the mesospheric height and help in the generation of elves. Some features related to temporal development, observed color and intensity distributions are broadly understood. However, many details such as relation between current pulse and spatial–temporal variations of elves are yet to be established.

Different generators and their contribution to GEC are briefly discussed. Electric field in the cloud may change the droplet size distribution, as a consequence of which precipitation and cloud lifetime may change depending upon local temperature, aerosol environment, strength of vertical current and cloud dynamics.

In addition to controlling the substance of GEC, lightning discharges also produce NO_x, a moderator of ozone distribution in the atmosphere, which acts a greenhouse gas. The share of NO_x produced by lightning relative to the total atmospheric sources in the 35°S–35°N region is ~23%, which reduces to ~10% on the global basis. The contribution of TLEs seems to be relatively small because of much reduced generation rates as compared to lightning. Besides the absolute share it is also important where in the atmosphere the sources occur (Grewe et al., 2009; Schumann and Huntrieser, 2007). LNO_x sources cause a far larger contribution to ozone production than surface sources simply because they are emitted into the upper troposphere where NO_x life time is larger than near the surface.

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