Lighting/Optical Discharges and Climate: A Brief Review

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Abstract

Lightning is a massive electrostatic discharge between the electrically charged regions within clouds or between a cloud and the Earth's surface. Present paper reviewed various features including generation mechanism of lightning discharges and many transient luminous events (TLEs). Optical discharges like sprites and halos are been caused by the upward developing quasi-electrostatic fields associated with intense cloud-to-ground discharges whereas jets (blue starters, blue jets, gigantic jets, palm tree) are caused by the charge imbalance in the thunderstorms during the intra-cloud and cloud-to-ground discharges and evolve through the process of leaders and streamers. Elves are been generated by the electromagnetic pulse radiated from the return stroke current of lightning discharges. The impact of atmospheric circulation, global electric circuits (GECs), NO_x/O₃ perturbations (in the troposphere and stratosphere) and aerosols on lightning discharges are discussed and their role on climate change are briefly described.

Keywords: Lightning/thunderstorm, Transient Luminous Events (TLEs), Global Electric Circuit, NO_x/O₃ perturbation, Aerosols and Climate, Streamers and Leaders

Introduction

With growing interest in climate change, over the last few decades much progress has been made in quantifying the global response of lightning and temperature on different time scale. The spatial and temporal distributions of lightning around the globe using lightning sensors (LIS and OTD) on the Tropical Rainfall Measuring Mission (TRMM) satellite have been studied (Cecil *et al.*, 2012 with references therein). The discharges in the atmosphere could be cloud-to-ground, inter cloud, intra-cloud and from the cloud top upwards. The last one involves sprites, jets (blue starter, blue jets, gigantic jets, palm tree, etc.), sprite halos and elves. The discharge activity is related to the stage of convective cloud development (Vonnegut, 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), rainfall rate (Tapia *et al.*, 1998) and surface air temperature (Price, 1993; Siingh *et al.*, 2013a, 2014).

Transit luminous events (TLEs) are short lived discharges in the middle atmosphere (stratosphere and mesosphere) either caused by the electrostatic field of transient nature due to the charge imbalance in the thunderstorm during cloud-to-ground and inter/intra-cloud discharges or by the electromagnetic fields due to the return stroke current. There have been large numbers of research papers and review papers in the last two decades. Some of the review papers are Pasko (2006, 2007, 2008, 2010), Neubert *et al* (2008), Roussel-Dupre *et al.*(2008), Mishin and Milikh (2008), Ebert and Sentman (2008), Siingh *et al.* (2008), Raizer *et al.*(2010), Inan *et al.* (2010), Pasko *et al.*(2011), Fullekrug *et al.* (2013a), Surkov and Hayakawa (2012) etc. The morphological features of TLEs above a mesoscale convective system along with altitude are shown in Fig.1.

Fig. 1: Transient luminous event (sprites, blue jets, gigantic jets and elves) above the mesoscale convective system along with altitude are shown (modified figure after Lyons *et al.* 2000; Pasko, 2003).

The lightning flash rate depends on the surface temperature and cloud top properties (Williams, 1992; Siingh *et al.*, 2013a). The association of lightning flash rate with intense rainfall (Price and Federmeier, 2006), with production of nitrogen oxides (NO_x) and thereby modification of amount of ozone in the atmosphere (Schumann and Huntrieser, 2007), modification of electric field in the atmosphere, are some of the factors which affect atmospheric temperature, humidity and cloud properties and hence the need to understand the relation between lightning, middle atmospheric discharges and climate. The convective processes caused by differential heating at the Earth's surface lead to both rainfall and lightning. The deeper and stronger updrafts in convection may produce lightning (Boccippio, 2001), whereas modest lifting results in rainfall (Williams, 2005).

The analysis of satellite data shows a positive connection between Mediterranean lightning activity and convective rainfall and also between the El Nino cycle and thunderstorms (Price and Federmesser, 2006). The intense thunderstorms in Eastern Africa influence the stability of African Easterly waves, which may result in the Atlantic hurricanes about a week later (Price *et al.*, 2007) and affect climate there.

The influence of lightning on climate also occurs via the production of NO_x and modification of current/electric fields in the atmosphere. Lightning discharges are considered to be the largest natural sources of NO_x production ($\sim 5 \text{ Tg a}^{-1}$) in the atmosphere (Schumann and Huntrieser, 2007). NO_x critically affect the abundances of ozone (O₃) and hydroxyl radical (OH) in the troposphere (Rohrer and Berresheim, 2006), which have an impact on the atmospheric radiative forcing (Hansen *et al.*, 2005). Toumi *et al.* (1996) showed that a 100% increase in lightning activity enhances the global mean radiative forcing via tropospheric O₃ by $\sim 0.3 \text{ Wm}^{-2}$. Global average radiative forcing due to O₃ formed by lightning induced NO_x ($\sim 6.5 \text{ Tg a}^{-1}$) could be $\sim 0.1 \text{ Wm}^{-2}$ (Hopkins, 2003). Change in radiative forcing directly affects climate parameters.

Future projection of climate is computed using climate models. Different climate models yield different future projections (Wang *et al.*, 2009; Yamasaki *et al.*, 2008; Mirchevet *et al.*, 2012; Wyatt *et al.*, 2012). They differ in several aspects such as heat transport schemes, aerosol modeling, cloud parameterization, representation of terrestrial processes, ice sheet dynamics, oceanic dynamics, etc. (Tsonis *et al.*, 2008, 2011; Steinhäuser *et al.*, 2012; Steinhäuser and Tsonis, 2013). Steinhäuser and Tsonis (2013) compared 23 climate models and commented that none of the models could predict the actual observations and therefore, a question arises on the ability of climate models to produce future projections in time and in space.

In the present paper salient features of lightning discharges in the troposphere, transient luminous events in the stratosphere and mesosphere, their probable generation mechanisms and impact on climate are briefly discussed. Section 2 discusses the impact of solar activity on convection and hence on lightning discharges. The role of cosmic rays, streamers and leaders in lightning generation are discussed. The distribution of lightning flashes on land and ocean surface is discussed in section 2.4. Schumann resonances and its applications in lightning studies are discussed in section 2.5. Salient features of TLEs based on recent studies are discussed in section 3. Measurements of TLEs are also very briefly discussed. Section 4 discusses relevance of atmospheric discharges in climate studies. The points touched are atmospheric circulation and lightning, GEC and lightning, atmospheric discharges and NO_x/O₃ perturbation and impact of aerosols. Some unsolved problems are listed in section 5.

Lightning Discharges

Lightning discharges are manifestation of processes that generate separate and lastly neutralize electrical charges in nature through thunderstorms. The charge generation during the thunderstorm developments can be discussed under inductive and non-inductive processes (Yair, 2008; Saunders, 2008). The charge separation process very sensitively depends on temperature and usually occurs between the altitude level of 0°C and – 40°C, may be through the slow hydrodynamic processes (Saunders, 2008). The updraft drag small and light positively charged ice fragments, whereas heavy negatively charged hailstones predominantly fall downward due to gravity. As a result, there is upward current inside the cloud, which is zero outside. Charges may pile up at the cloud boundaries. The charge distribution in thunderstorm is very complex and may involve multi-layers of charges. However, in the simplest form positive charges tend to pile up in the upper portion of thundercloud whereas the negative charges mostly accumulate in the lower part of the cloud (Lyons *et al.*, 2003a).

The pile up charges of certain sign amounts to several tens of coulombs yielding a strong quasi-electrostatic field inside and around the thunderstorm. The intense electric field may lead to gas discharge. Measurement of electric field in the thunderstorm and Monte-Carlo calculation shows that the field strength never reaches the value required for conventional breakdown, which is $\sim 32 \text{ kVcm}^{-3}$ at atmospheric pressure (Marshall *et al.*, 2005; Stolzenburget *et al.*, 2007). In conventional breakdown, electric field produces thermal electron avalanches of mean thermal energy of the order of several electron volts, which aid discharge phenomena.

Another breakdown mechanism operating at a lower breakdown field ($\sim 2.10 \text{ kV cm}^{-1}$) called as runaway mechanism is considered (Gurevich *et al.*, 2009) which are based on the mechanism of relativistic electron avalanches. 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 field. These energetic electrons act as runaway electrons. As a result, one may expect an exponentially increasing avalanche of runaway electrons (Colman *et al.*, 2010), ultimately leading to the breakdown of air. The required threshold breakdown field for the runaway mechanism is one order of magnitude smaller than the conventional breakdown field. Electron acceleration during propagation of lightning streamers and stepped leaders may lead to breakdown and can be considered as an alternative to runaway mechanism (Chanrion and Neubert, 2010). Numerical simulations showed that exponential growth of electric field in streamers can accelerate up to $\sim 100 \text{ keV}$ (Celestin and Pasko, 2011) which may act as runaway electrons. Further, the electric field produced by stepped leaders can accelerate these energetic electrons up to the MeV energies.

Convection in the Atmosphere

The solar heating causes convection, a driving force for small scale motion in the atmosphere. The intensity of concentration determines updraft velocity and hence nature/altitude location of clouds. Clouds with low lightning activity may have maximum updraft velocity $< 10 \text{ m/s}$, while electrically active storms producing good amount of

lightning have updraft velocity up to 50 m/s (Williams, 2005). The amount of liquid water content and the temperature in the charging region of storm govern the polarity of cloud-to-ground (CG) lightning (Saunders, 2008).

The electrification process in thunderstorm depends on the existence of super cooled water, ice crystals, snow, hail and soft hail (graupel), which may lie between the 0°C isotherm and -40°C isotherm (Saunders, 2008). Ice will start melting above 0 °C and all hydrometeors will be solidified below - 40°C. This region can extend from 2 to 10 km altitude. The presence of these ingredients in the mixed phase region is also governed by the large scale circulation of the atmosphere (Zipser and Lutz, 1994). The stronger updraft also enhances the collision between different particles, which result in increased charge transfer between particles, leading to rapid electrification. Convective activity depends on many large scale factors such as outgoing long wave radiation (OLR), surface temperature, convective available potential energy (CAPE), etc. Enhanced OLR modifies thermal profile of the atmosphere, which in association with wind, relative humidity, vertical stability and other factors determines the buoyancy of the air parcel, a parameter most important in the study of cloud development. CAPE is the vertical integration of cloud buoyancy and accounts for the thermal structure and moisture content of the atmosphere.

Kumar and Kamra (2012) showed that in Himalayan region lightning activity is well correlated ($CC > 0.7$) with surface temperature and less correlated ($CC \sim 0.19$) with CAPE and OLR. Recently, Siingh *et al.* (2014) showed that the correlation coefficient in different parts of India between lightning flashes and CAPE varied between 0.23 and 0.81. Good positive correlation with surface temperature is also reported. No correlation is found between lightning flashes and OLR. These results along with other studies (Qie *et al.*, 2003; Toumi and Qie, 2004) demonstrate that convection is also controlled by orography of the region.

Solar Activity Effect

The incident solar radiation affects heat input to the lower atmosphere and the ultraviolet (UV) part of the radiation coupled with changes in the ozone concentration in the stratosphere affects the heat budget there (Gray *et al.*, 2010). Although, UV radiation is a small portion of the total solar irradiance (TSI), it has a relatively large solar cycle (SC) variation. About 100% variation is present at wavelengths near 100 nm, ~ 6% near 200nm (where O₂ dissociation and O₃ production occurs) and ~ 4% in the range 240 - 320 nm (where absorption of O₃ is dominant) (Gray *et al.*, 2010). Gray *et al.* (2009) reported that half of the temperature response in the tropical upper stratosphere is due to the solar irradiance change and half due to the additional ozone feed-back mechanism.

The variations in the heat input due to the variation in solar radiation affect the East-West tropical (Walker) circulation, which is intimately connected with the North-South tropical “Hadley” circulation (van Loon *et al.*, 2007; Meehl *et al.*, 2008). During

the solar maximum period Walker circulation is strengthened. The heating of stratosphere leads to the “top-down” influence (Kodera., 2004; Shindell *et al.*, 2006) and may strengthen tropical convection with pole-ward shifted inter tropical convergence zone (ITCZ) and south Pacific convergence zone (SPCZ) at solar maximum. Solar heating of the sea surface and dynamically coupled air-sea interaction lead to the “bottom-up” mechanism which also strengthens ITCZ and SPCZ circulation at solar maximum (Meehl *et al.*, 2008). The response of the “top-down” and the “bottom-up” mechanism is additive and produce an amplified sea surface temperature, precipitation and cloud response in the tropical Pacific even for a relatively small solar forcing (Rind *et al.*, 2008; Meehl *et al.*, 2009). These circulations are coupled with other circulations of the atmosphere (Gray *et al.*, 2010, and references there in). These large scale circulations play active role in the distribution of lightning and precipitations.

Fig. 2: (a) Yearly variations of cosmic rays, $F_{10.7}$ cm(solar radio flux) and A_p index for the 22 and 23 solar cycle, (b) yearly variations of sunspot number, lightning flash counts for region R₁ South Asia (8° - 34° N, 60° - 95° E) and R₂ Southeast Asia (8° - 34° N, 95° - 120° E). Lightning flash counts for the Indian Peninsular region (India) are also given in the same figure (Siingh *et al.*, 2013a).

The surface heating sets up convection and influence lightning activity (Williams, 1992, Price, 1993). Another parameter involving temperature and humidity, called wet bulb potential temperature has been used in the study of lightning activity (Williams and Renno, 1993; Reeve and Toumi, 1999; Petersen and Rutledge, 2001). The reduced humidity over Africa in comparison with the maritime continent leads to lower wet bulb

potential temperature there (Africa) where cloud base height is found to be higher and relatively more lightning is observed (Williams and Satori, 2004). Siingh *et al.* (2013a) studied the effect of the sunspot number, A_p index, cosmic rays and $F_{10.7}$ cm fluxes 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 (Fig. 2) showed that the sunspot number/ A_p index do not show any statistically significant results. However, when $F_{10.7}$ cm fluxes and cosmic ray fluxes are considered, lightning flashes show negative correlation (correlation coefficient lie between - 0.23 and - 0.16). Schlegel *et al.* (2001) analyzed data for the period 1992 – 2000 over middle Europe and reported a significant correlation between lightning frequency and A_p index and relative sunspot number on yearly basis. They also reported significant negative correlation with CR fluxes. Girish and Eapen (2008) showed an inverse relation between sunspot cycle and thunderstorm/lightning occurrence rates at Trivandrum, India between 1853 and 2005.

The global variation of lightning activity from TRMM satellite data for the period 1995-2010 is shown in Fig. 3 (Cecil *et al.*, 2012). Fig. 3a shows flash count at a high resolution ($0.5^{\circ} \times 0.5^{\circ}$) grid and Fig. 3b represents data for the low resolution ($2.5^{\circ} \times 2.5^{\circ}$) grid. The flash distribution at high resolution is a bit noisy because the sampling rate for such a high resolution is insufficient. The low resolution data over land (in the tropical zone) is much smoother and hence many details of information disappear. The global flash rate varies from ~ 35 flashes sec^{-1} in February (austral summer) to ~ 60 flashes sec^{-1} in August (boreal summer). The mean global flash rate ~ 46 flashes sec^{-1} . The peak monthly average flash rate (at $2.5^{\circ} \times 2.5^{\circ}$ grid scale) is 18 flash $\text{km}^{-2} \text{ month}^{-1}$ from early April to early May in the Brahmaputra valley of eastern India. The annual global lightning activity peaks in summer hemisphere in agreement with the seasonal migration of the ITCZ and the atmospheric circulation patterns (Price, 2006, 2009; Cecil *et al.*, 2012). During the spring and fall, the distribution of lightning is fairly symmetric about the equator.

Siingh *et al.* (2013a) showed similar relation between lightning and convective rain over the South/Southeast Asia with correlation coefficient 0.68 and 0.81 respectively (Fig. 4) and attributed it to the similar meteorological factors having identical effects on lightning and precipitation. This means that the convective processes in the two regions are 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. Siingh *et al.* (2014) have showed that correlation coefficient between lightning flash and CAPE in different regions of India varied between 0.23 and 0.81, whereas the same between convective rain and CAPE lies between 0.68 and 0.86. However, lightning flashes are well correlated with the surface temperature in all the considered regions whereas the same is not true with the convective rain. These studies show that the CAPE and surface temperature partly control the convective process and partly other factors including orography of the region.

Fig. 3: Mean annual flash rate observed from LIS and OTD detectors are given (a) HRFC (high resolution flash climatology, $0.5^\circ \times 0.5^\circ$ grid) (b) LRFC (low resolution flash climatology, $2.5^\circ \times 2.5^\circ$ grid; after Cecil *et al.*, 2012).

Fig.4: Plots for convective rain and lightning flash counts for the South Asia and South East Asia are shown along with correlation coefficient.

Do Cosmic Rays Affect Lightning?

The required electric field for the conventional breakdown is much higher than the measured/simulated field in thunderstorms (Marshall *et al.*, 2005; Stolzenburg *et al.*, 2007). As a result, an alternative runaway mechanism is proposed (Gurevich *et al.*, 1997, 1999), which requires the presence of high energy charged particles such as cosmic rays and smaller electric fields ($\sim 2.16 \text{ kVcm}^{-1}$) (Gurevich and Zybin, 2005). The high energy charged particles generates a considerable number of electron-ion pairs producing an ionized 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). The discharge is driven by low-energy electrons, similar to self-sustained laboratory discharges at atmospheric pressure initiated by sub-nanosecond pulses of runaway electrons (Babich, 2005; Babich and Loiko, 2009). 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 voltage. 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) passes through a thunderstorm. However, it is not yet possible to identify the percentage of lightning is triggered by this process.

Cosmic rays produce ion clusters in the lower atmosphere, which modify the vertical current and causes accumulation of space charges on the upper and lower edges of cloud (Tinsley, 2000; Nicoll and Harrison, 2010; Singh *et al.*, 2011a; 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. Jun-Fang *et al.* (2012) on the basis of synchronous data of neutron monitor and atmospheric electric field during 62 thunderstorms from 2008 to 2010, reported changes in neutron counting rate during 27 cases with significance $S > 5\sigma$ (σ is standard deviation). The measurement clearly showed that changes do not occur when thunderstorm is just over electric field mill. It occurs when field is not exactly below the thunderclouds but in the control of bottom positive charge layer. The change may be due to acceleration of low energy cosmic ray particles to energy level above the threshold value of the measuring system.

Streamers and Leaders

The other mechanism of conventional breakdown is based on streamers and leaders (Pasko and George, 2002; Raizer *et al.*, 2007; 2010). Streamers are narrow filamentary plasma waves driven by non-linear space charge waves (Raizer, 1991). The head of the streamer contains a large amount of net space charge which enhances electric field ($>$ the threshold value) in the region just ahead of the streamer and as a result streamer expands spatially. The leader is a thin conducting channel with conductivity orders of magnitude higher than the streamer channel and transfers the electric potential of the supporting charge reservoir. The leader head contains an intense electric field, which ionizes the medium and creates a conducting channel (Raizer *et al.*, 2007). Both positive and negative streamers in large numbers ($\sim 10^9 \text{ s}^{-1}$) originate from the leader head and $\sim 10^5$ streamers are present in a leader streamer zone at any given time (Bazelyan and Raizer, 2000). Observations indicate a quasi-continuous development of positive leaders and a more impulsive, stepwise development of negative leaders (Bazelyan and Raizer, 2000).

Numerical simulations show that streamers can be initiated in an electric field $\sim 0.2 - 0.6 E_k$ (Liu *et al.*, 2009a,b, 2012,) well below the break down field E_k from an isolated ionizations (small-scale) patch. Electric fields of this magnitude are generally observed in thunderclouds (Stolzenburg *et al.*, 2007; Luque and Ebert, 2009). The initiation of positive streamer is much easier and at relatively lower voltage than negative

streamer (Briels *et al.*, 2008). Modeling studies and observations suggest that, streamers at an altitude may initiate in a form of simultaneously upward and downward propagating system (Stanley *et al.*, 1999; Moudry *et al.*, 2003; McHarg *et al.*, 2002; Liu and Pasko, 2004). Observations show that positive streamers generally propagate downwards direction, whereas negative streamers propagate over a wide range of angles with respect to the local vertical (McHarg *et al.*, 2007). They showed the speeds and acceleration of both positive and negative streamers vary between 10^6 and 10^8 ms⁻¹, and 10^5 - 10^{10} ms⁻².

Streamers grow exponentially and accelerate very fast in an electric field. For example, in the $1.1 E_k$ field at 70 km altitude, a positive streamer would acquire diameter of ~ 110 m and speed of $\sim 2.2 \times 10^7$ ms⁻¹ by travelling a distance of only 1 km (Pasko *et al.*, 1997; McHarg *et al.*, 2002; Moudry *et al.*, 2003). The exponential growth and branching of streamers (Qin *et al.*, 2012a) leads to electron multiplication and acceleration to a few eV (Gurevich *et al.*, 2009; Qin *et al.*, 2012a; Fullekrug *et al.*, 2013b) which may radiate low frequency electromagnetic wave with amplitudes increasing toward lower frequencies (Qin *et al.*, 2012b; Fullekrug *et al.*, 2013a).

In a negative streamer tip, electrons in the presence of modest field can be energized in to the run-away regime (Chanrion and Neubert, 2010), creating a beamed distribution in front of the streamer that affects its propagation and may allow initiation of the relativistic discharge. The streamer head is usually associated with blue emissions due to the excitation of the first negative N_2^+ (1N₂⁺) and the 2nd positive N_2 (2PN₂) band systems. The relatively low electric field in the streamer channels causes red emissions associated with (1PN₂) the first positive band system of N_2 . At certain altitudes 1PN₂ emissions are suppressed due to the strong quenching of the $N_2 B^3\Pi_g$ state. The streamer head typically brightens as they move up or down. For a 25 m streamer head the range of average brightness may be 9×10^8 – 5×10^{11} R and head size may vary between 10 and 100 m (Stenbaek-Nielsen *et al.*, 2007).

Land-Ocean Differences of Lightning

A number of studies have shown higher lightning activity over land surface than over ocean surface (Brooks, 1925; Orville and Henderson, 1986; Christian *et al.*, 2003; Kandalgaonkar *et al.*, 2005; Ranalkar and Chaudhari, 2009; Tinmaker *et al.*, 2010; Siingh *et al.*, 2015). Satellite observations also reveal that the land-ocean contrast also exists in the diurnal variation. The diurnal variation of lightning activity may be linked to the diurnal variation of fair-weather electric fields (Williams and Heckman, 1993; Singh *et al.*, 2004; Siingh *et al.*, 2007, 2013b; Williams, 2009). Mach *et al.* (2009, 2010) using aircraft observations of electrified clouds showed that land storms had greater flash rates than ocean storms but smaller mean conduction or Wilson currents.

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). 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 Hallet, 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. Convective regime, even though, the land surface is inhomogeneous terrain, not even flat. 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 (the 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 to 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 temperatures 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 were attributed to warm water and overlying cold air (Rutledge *et al.*, 1992; Zipser, 1994).

Schumann Resonances

The long term SR data collected at several different stations clearly show diurnal, seasonal and inter-annual variation of SR parameters (Satori *et al.*, 1996, 2003, 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). The finite Difference Time Domain (FDTD) method has been widely used to study the propagation features of ELF waves (Pasko *et al.*, 1998; Berenger, 2002; Simpson and Taflove, 2004, 2007; Soriano *et al.*, 2005; Hu and Cummer, 2006). In addition, several other numerical and analytical techniques have been used to solve SR problems (Huang *et al.*, 1999;; Kirillov, 2005; Morente *et al.*, 2003; Haupt and Haupt, 2004; Greifinger *et al.*, 2007; Ando and Hayakawa, 2007).

The received SR signals can be broadly considered under their 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; Williams *et al.*, 2010). 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 FDTD and other techniques are useful. The continuous back ground noise-like signals produced by many superposed and time-over lapping signals from ordinary convective scale lightning discharges form third category (Nickolaenko *et al.*, 2010; Rycroft and Odzimek, 2010).

The global inversion calculations based on the observation of the Schumann resonances at either a single station or three/more than three stations have been carried-out to study global distributions of lightning activity (Williams, 1992; Satori *et al.*, 1996; 2007, 2009a,b, 2013; Hobara *et al.*, 2006; Williams *et al.*, 2010; Shvets *et al.*, 2010; 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 show peaks at 0700 - 0900 UT, 1400 - 1600UT and 1900 - 2100UT (Betz *et al.*, 2009; Satori *et al.*, 2013) corresponding to strong 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 warm El Nino years and cool La Nina years (Satori and Zieger, 1999; Satori *et al.*, 2013). 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) showed that lightning activity in the African zone dominates over that in South America and that electrified rain/shower clouds are more numerous in South America than in Africa, an important result in the context of global electric circuit studies.

Analyzing the transient SR data, the global distribution of negative and positive CG discharges in the summer season (June to August, 2004) Sato *et al.* (2008) reported that the – CG discharges occur mainly in the middle America, Africa, India and Southeast Asia both over the land and oceanic regions. The occurrence 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 shows that most of the +CG discharges occur over the land region, especially in the North America, equatorial and northwest parts of Africa, India and Southeast Asia (Sato *et al.*, 2008).

The SR frequencies vary with UT time of the day, season and year and with the solar cycle. Satori *et al* (2005) and Betz *et al.*(2009) showed that the frequencies of 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 solar minimum and minimum at 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 Nina phase. These results support the idea that SRs, 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).

Transient Luminous Events (TLEs)

The intense convection inside the cloud with cloud top temperature $< - 50^{\circ}\text{C}$ is usually associated with discharges occurring between cloud top and lower ionosphere, which are grouped as TLEs (Sao Sabbas and Sentman, 2003; Lyons *et al.*, 2003b, 2009; Fullekrug *et al.*, 2006; Sao Sabbas *et al.*, 2010). Some important characteristics features of TLEs are listed in Table-1. The global occurrence rate of sprites, halos and elves are ~ 1 , ~ 1 and 35 events per minute respectively (Chen *et al.*, 2008), which occur in the mesosphere and have spatially averaged brightness 1.5, 0.3 and 0.17 MR respectively (Kuo *et al.*, 2008). Further, sprites are usually found to be associated with positive cloud-to-ground discharges (Williams *et al.*, 2007) whereas the ground flashes with negative polarity dominate the global halos population (Williams *et al.*, 2012).

Measurement of TLEs

Optical Measurements

The optical measurements are carried out during nighttime by Low-Light-Level TV devices (LLLTV), intensified video charge coupled Devices (CCD) cameras, Low-Light-Level Silicon Intensified Target (LLLSIT) monochrome TV on high - altitude sounding rockets (Franz *et al.*, 1990) and cameras on board space shuttle (Vaughan *et al.*, 1992). In the optical measurements, usually camera becomes blinded by the CG flash, which precedes TLEs by a few milliseconds. Cameras are specifically designed with suitable triggering facility so that effect of parent lightning could be avoided.

Following three techniques can be used to improve the sprite to parent lightning intensity ratio (Cummer *et al.*, 2006).

- (a) The spatial separation between the two sources of light can be obtained by observing the flashes near the limb or on the limb.
- (b) Appropriate spectral filtering can be used to maximize the sprite induced spectral bands and cut down the spectral bands produced by the parent flashes.
- (c) Trigger photometer may be used to turn on ISUAL imager at the appropriate time so as to remove some of the parent intensity.

The optical measurements have limitations: (i) these measurements can be made only during night time, (ii) there should not be any obstacles (cloud, etc.) between the camera and TLE event, (iii) limited sky scanning due to limited field of view of the camera (iv)

the fine structures can only be studied if snap shot time (one video frame time) is quite small (< 1 ms).

ULF/ELF Measurements

In the ULF/ELF wave measurements, two horizontal magnetic induction coils are used to record north-south and east-west component of wave magnetic fields and one ball (or any other suitable shape) antenna is used to record vertical component of electric field. These three field components are sampled at a pre-determined frequency (say 2.5 kHz) using a 16/32 bit A/D converter (Whitely *et al.*, 2011) and data are stored in PC. GPS is used for time measurement. The ELF transients are recovered by matching the transient onset time with the optical observation times. The polarity of the parent stroke can be determined from the vertical electric field and the location and the charge moment changes are deduced from the three measured field components (Huang *et al.*, 1999).

An example of sprite observed from the Pic du Midi, France and corresponding ELF wave field recorded at Canberra, (Australia), Sutherland (South Africa) and Pinon Flat (California) is shown in Fig.5 (Whitley *et al.*, 2011). SR measurements indicate that C-sprites are caused by small charge moment change whereas Angel sprites are usually associated with the large charge moment change. ELF measurements also revealed the presence of kA electric current within the body of sprites. Which is consistent with the consequence of dielectric breakdown and qualitatively resemble with the lightning discharge in the lower atmosphere.

VLF Measurements

VLF waves (1 - 24 kHz) radiated from lightning discharges travel long distances (6 to 10 Mm) without appreciable attenuation, allowing the entire globe to be monitored with just 28 receiving stations (Lay *et al.*, 2007). Worldwide Lightning Location Network (WWLLN) using VLF waves detects lightning with a time error of < 30 microseconds and a spatial location error of ~ 15 km, even in those areas for which there is no WWLLN stations in the nearby. Usually two techniques are used for CG lightning location, a direction finder and time of arrival information. The location, the time of occurrence, polarity, multiplicity and peak currents of each stroke are derived.

VHF Measurements

VHF waves radiated from lightning discharges are also used in SAFIR system (van der Velde *et al.*, 2006) operated in France which contain three VHF (~ 100 MHz) receivers located in a triangle at ~ 100 km apart, that measures activity in thunderclouds, giving information on the location (in the horizontal plane) and time of IC and CG activity.

Measurement of Amplitude/Phase Perturbation

The perturbation in amplitude/phase of transmitted VLF waves, (which propagated through the TLE region) is also used to characterize TLEs. TLEs cause ionization and heating of ambient medium at localized level which results in conductivity changes and hence perturbation in amplitude/phase of propagating VLF wave. The measuring principle is shown in Fig. (6a). The transmitters used are either powerful VLF transmitters or MF (0.3 - 3MHz) radio transmitters. Such a system is operative in France (Fullekrug *et al.*, 2006; van der Velde *et al.*, 2006; Neubert *et al.*, 2008). Fig. 6b shows VLF perturbation caused by elves. However, VLF perturbation detection is sensitive to several factors such as the distance of TLEs to the receiver, the altitude of perturbation region and its distance from the path of the VLF wave and the intensity and orientation of the TLE producing pulses.

Fig. 5: Sprites observed at Pic du Midi (France) and corresponding ELF wave field recorded at Canberra (Australia), Sutherland (South Africa) and Pinon Flat (California); (after Whitley *et al.*, 2011).

Sprites

Sprites may occur as a single straight luminous column, in cluster of short lived (~ 50 ms) two, three or more repeated elements with a mixture of complex shapes, sizes and intensities. After initiation at around 75 km altitude, they propagate downward in the form of streamer and shortly after upward (Moudry *et al.*, 2003). The streamers often form beads (Sentman *et al.*, 1995) which develop a few ms after the tendril onset (Stenbaek-Nielsen *et al.*, 2000). The brightness of beads lasts longer (~ 100 ms) than sprite. Sometimes sprites are reactivated with reactivation time as long as ~ 100 ms (Stenbaek-Nielsen *et al.*, 2000).

Fig. 6:(a) Schematic diagram showing how the bottom side ionosphere and the mesosphere above a thunderstorm are probed by the signals from a ground based radio transmitter propagating in the Earth-ionosphere waveguide. (b) An “early/fast” VLF perturbation event (upper panel) detected by the Crete receiver ~ 2000 km from the thunderstorm, and an associated elves observed from the Observatoire Midi-Pyrenees shown in the lower panel (after Neubert *et al.*, 2008).

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; Neubert *et al.*, 2008). Discharges involving small charge moments ($\sim$ hundreds of coulomb kilometer) with sufficiently short ($\sim 10^{-4}$ sec) discharge time may initiate sprite whereas discharges with large charge moments (ten thousand Coulomb km) with relatively longer discharge time $\sim 10^{-3} - 10^{-2}$ sec 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, 2004).

Fig. 7: Sprites detected from Negative CG lightning discharges on 25 October, 2009 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–25 kHz) and Duke ULF/ELF sensor (0.1 Hz–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 halo and the sprite.

Sprites produced by $-CG$ discharges are rare (Lang *et al.*, 2013) and the associated charge moment is usually high. Relatively low $-CG$ flash rates are observed during the time of negative sprite (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-parent and negative sprite-class lightning mainly

occurred in or near intense, deep convection (Lang *et al.*, 2013; Singh *et al.*, 2013). One example along with charge moment, current moment and simulated electric field is shown in Fig. 7 (Li *et al.*, 2012). All negative sprites shows remarkably similar features including relatively simple streamer structure, streamer termination altitudes greater than 55 km and accompany bright halos.

Based on simulation, Li *et al.* (2012) showed that a more impulsive current source with the same amount of charge transferred produced a higher electric field of shorter duration at halo 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; Kosar *et al.*, 2012), which is consistent with observations by high speed camera (Stenbaek-Nielsen *et al.*, 2007; McHarg *et al.*, 2007).

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 (Qin *et al.*, 2011). 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. The inhomogeneity in electron density present in the atmosphere can develop in to positive streamers at lower ($E < E_k$) electric fields (Liu *et al.*, 2012; Kosar *et al.*, 2012). Such inhomogeneity may arise due to meteor trails (Zabotin and Wright, 2001), electrodynamic effects of thunderstorms (Singh *et al.*, 2011b), gravity wave breaking (Fadnavis *et al.*, 2009; Ghodpage *et al.*, 2012).

The red color in sprite is attributed to the first positive band system of N_2 (1PN₂) and the blue color to the first negative N_2^+ (1NN₂⁺) and the second positive N_2 (2PN₂) band system primarily from streamer heads during early time of sprite developments. Summary of emission band system, transition involved, excitation energy threshold, life time and quenching altitude are given (Liu *et al.*, 2006; Pasko, 2007). Details of energy transfer mechanism and involved reactions are discussed in recent paper (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).

Recent observations of halos (Newsome and Inan, 2010; Williams *et al.*, 2012) and modeling studies (Asano *et al.*, 2008, 2009) showed 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). 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 milli-seconds. 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 association of sprites with + CG discharges. Formation and development of streamer involve highly nonlinear processes (Kosar *et al.*, 2012), require further observation and modeling studies.

Fig. 8: Variation of (a) halo brightness and (b) variation of halo 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).

Halos

Halos, sometimes also referred as sprite halos are short lived diffused descending luminous events having lateral extent 40 - 70 kms (Pasko, 2010) and usually observed in the altitude range 75 - 90 kms. They are produced by both + CG and – CG discharges (Frey *et al.*, 2007). 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. 8) (Williams *et al.*, 2012). Halos associated with + CG flashes are brighter and last for longer duration. Negative CG 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).

Blue Starters and Blue Jets

Blue starters are slow moving fountains of blue light emanating from cloud top and terminating anywhere between cloud top and ~21 km altitude (Lyons *et al.*, 2003a; Pasko, 2008). Eden, (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 life span from ~ 27 kms⁻¹ to 180 kms⁻¹ (Pasko, 2008). Blue starter do not coincide with cloud-to-ground (both positive and negative discharges). The blue light is attributed to 1NN₂⁺ emission.

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 kms⁻¹, having a life time ~200 – 300 ms. Observations suggested 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). The upward discharges from cloud top could be explained either using the conventional air breakdown mechanism based on streamers and leaders or relativistic runaway air breakdown mechanism. Pasko and George (2002) carried out three dimensional modeling and showed blue starters to be the critical phase of blue jet and both phenomenon could be considered as positive streamer corona developing from a conventional lightning leaders.

Modeling studies indicated that the presence of screening charges on the cloud top as an essential requirement for the initiation of blue starters/blue jets (Krehbiel *et al.*, 2008; Rioussset *et al.*, 2010). Even a moderate cloud charge of 50C with radius of 3 km could sustain blue jet streamer (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. Rioussset *et al.* (2010) considering time dependent conduction currents and screening charges, simulated the dynamics of the screening charges near the cloud boundaries and showed that prior occurrence of IC discharges prevent the development of blue jet until a CG

discharge enhances the positive charge in the cloud by bringing negative charges to ground. The screening charges gradually developing at cloud top lead to breakdown initiation near the upper boundary of cloud resulting into upward propagating blue jet.

Gigantic Jets

The evolution of gigantic jets can be discussed as the leading jet, the fully developed jet and the trailing jet (Su *et al.*, 2003), which terminate at the lower boundary (70 - 90 km altitude) of the ionosphere. Ground observations carried out in these (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.*, 2002, 2003; Chou *et al.*, 2011; Huang *et al.*, 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 transferred positive as well as negative charges from cloud to the ionosphere. They may involve charge moment change as low as 1000 - 2000 Cam (Su *et al.*, 2003) and as high as ~ 12000 Cam (Cummer *et al.*, 2009; Van der Velde *et al.*, 2010). GJ may originate either from a tall cloud top (Soula *et al.*, 2011 with reference therein) or a winter thunderstorm of only 6.5 km tall (van der Velde *et al.*, 2010). The occurrence of GJ mainly depends on the electrical properties of thunderstorms and related dynamics during lightning discharges.

Analyzing GJ events recorded by ISUAL experiment, Kuo *et al.* (2009) reported that after the GJ reaches 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 (Lee *et al.*, 2012). As a result a current continuously flows between the cloud top and the lower ionosphere. When the boundary recovers its 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 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, 2010).

Elves

Elves are short duration (< 1ms) luminous events with horizontal diameter of up to 700 km observed at the bottom edge (75-105 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) or pancake shape (flat disc shape) with a luminous central part (Mende *et al.*, 2004; Lu, 2006). These events are results of atmospheric heating caused by the electromagnetic pulse radiated by the intense lightning discharge (current > 60 kA). The donut shape elves are explained considering the radiation pattern of CG lightning as a vertical dipole, whereas 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 pancake shape elves.

Three dimensional models of the 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 $\sim 120 \mu\text{s}$. The doublet events are $\sim 5\%$ of the total elves count. They further showed 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.

Atmospheric Discharges and Climate

The general circulation of the atmosphere driven by the Hadley circulation between the equator and the mid-latitude determines the location of sub-tropical and polar jets and strongly influence the climate (Price, 2006). Hadley circulation in combination with jets influences the location and quality of storms. The orography and distribution of land mass influence the distribution of lightning and thunderstorms (Christian *et al.*, 2003; Siingh *et al.*, 2013a, 2014). Lightning activity is a sensitive indicator of surface temperature (Williams, 1992, 2009; Siingh *et al.*, 2013a, 2014), upper tropospheric water vapor (Price, 2000; Price and Asfur, 2006), cloud cover (Sato and Fukunishi, 2005; Siingh *et al.*, 2013a, 2014), ice crystal size (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; Tan *et al.*, 2016). These parameters also affect the state of the atmosphere and hence climate.

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 follows the general circulation patterns of the atmosphere (Williams, 2005). Atmospheric discharges are the main contributor to the global electric circuit. The atmospheric circulation and GEC affect climate and changes in it. Lightning discharges are dominated by land surface areas in the tropics (Christian *et al.*, 2003; Siingh *et al.*, 2011) with Africa, South America and Southeast Asia regions ranking from the most lightning and least rainfall region to least lightning and most rainfall region. These regions dominate the Walker circulation, whereas rain fall is zonally uniform in the upwelling portion of Hadley circulation.

The global circulation is energized by the convective process in the atmosphere. Lightning discharges need stronger and deeper convection, whereas rain fall requires moderate updraft with modest lifting. Both phenomena are associated with the microphysics and dynamics of thunderclouds, which in turn depends on the surface temperature, humidity, orography and geographical location of the region (Williams, 2009; Price, 2009; Siingh *et al.*, 2011, 2013a, 2014). Small changes in surface temperature may result in larger change in thunderstorm and lightning activity (Williams, 2005, 2009) establishing a non-linear link.

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) which shows clear increase in lightning activity (Williams *et al.*, 1992; Siingh *et al.*, 2013a, 2014). While studying the effect of enhanced CO₂ (greenhouse gas) models show ~ 10 % enhancements in lightning activity for every 1⁰C global warming (Grenfell *et al.*, 2003). At tropical stations lightning activity may increase by ~ 25 % for increase of surface temperature by 1K above 296 K (Williams and Renno, 1993).

Convection transports water vapor in the atmosphere which leads to a greater ozone loss, decreases 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 1K increase of temperature in that layer, although the Clausius-Clapeyron equation predicts ~ 6 % enhancement for 1⁰K change (Price, 2000; Dotzek and Price, 2009). Contrary to this during the severe drought period of 1997- 1998 (decreased water vapour) the lightning activity in Indonesia increased by 60% (Yoshida *et al.*, 2007). Results are explained considering that in the El-Nino dry period fewer thunderstorms develop, but they are much more explosive producing much more lightning activity (Price, 2009). Thus ENSO anomaly and its impact on lightning distribution need further study.

Gravity waves

The spatially averaged brightness of sprites, halos and elves is 1.5, 0.3 and 0.17 MR respectively and energy deposition per event is 22, 14 and 19 MJ respectively. Using FORMOSAT-2 data, Kuo *et al* (2008) estimated the global energy deposition from sprites, halos and elves to be 22, 14 and 65 MJ min⁻¹ respectively. Sentman *et al*(2003) estimated that the energy deposited in the mesosphere by sprites to be in the range ~0.001 - 1 GJ. However, the energy deposited in the mesosphere could be much higher than the reported above, because many TLEs remain sub-visual and undetected by current observing technique. Blue starters and blue jets are discharges in the stratosphere, whereas gigantic jets cover both the stratosphere and mesosphere. The deposited energy disperses in the other regions through wind and waves and thus effects become non-localized and non-linear.

Thermal energy deposited in the neutral atmosphere in a volume exceeding 10^4 km^3 by TLEs within a short duration could generate outward propagating gravity waves (Sentman *et al.*, 2003). Gravity waves in the mesosphere and lower thermosphere can also be generated during wave-wave coupling and wave breaking (Sentman *et al.*, 2003). The involved waves could be planetary waves and gravity waves of tropospheric/stratospheric origin. Three dimensional simulation showed circular pattern of gravity waves radiating outward from the most intense convective zone often seen well above the convective sources (Sentmann *et al.*, 2003). Using observed gravity wave signatures, the reverse ray tracing technique is widely used to locate the source region of the observed gravity waves. Wrasse *et al* (2006 a,b) analyzed 326 small scale ($\lambda_h < 50 \text{ km}$) gravity waves observed at Cairi (Brazil) and found that about 76% of these waves had their origin in the mesosphere and remaining 24% belonged to the troposphere. Taylor *et al.* (2009) analyzed 24 small scale gravity waves during spread F experiment and found 71% of the waves had their origin in the mesosphere.

The energy deposited by TLEs in localized volume is transported by the outward propagating waves in the mesosphere and thus can cause perturbation in neutral density and temperature. Gravity waves induced modulation of neutral density may cause spatial variation in optical emissions and ionizations produced by lightning electromagnetic pulses. As threshold electric field required for electrical discharge in the atmosphere is proportional to the density of neutral gas, low density regions will require lower threshold electric field (Wilson, 1925). For a given electric field ($E \sim E_k$) the low density region may produce discharge whereas high density zone may not have discharge (Fadnavis *et al.*, 2009). Thus in a modulated density zone sprites may appear separated by a distance equal to the density modulated scale length. An example of sprite cluster that could have been formed in such a process has been reported by Neubert *et al.* (2008). The reported horizontal separation of $\sim 10 \text{ km}$ between sprite elements lies well within the observed horizontal wavelength range of the gravity waves at that altitude. However, the role of local process in creating medium scale structure could not be ruled out. Using simulation results, Pasko *et al.* (1997) showed that upward propagation and diffraction of gravity waves launched by large area mesoscale convective cells can lead to significant (tens of %) modulation of atmospheric density at mesospheric altitudes in vertically oriented cylindrical structures closely resembling to those observed in optical emissions associated with sprites.

Gravity waves also affect the mesospheric inversion layer (MIL) amplitude and mesospheric ozone volume mixing ratio (Fadnavis *et al.*, 2009). Fadnavis *et al.* (2009) showed evidence for a MIL on those days on which sprites were observed. They proposed that breaking of gravity waves may lead to turbulent heating and aid sprite production and MIL. The interaction of gravity waves with planetary wave results in a sharp transition of planetary waves large enough to create a MIL, which may also aid in the production of TLE (Oberheid *et al.*, 2006).

The gravity wave in the mesosphere can cause local temperature perturbation, which affects the rate coefficients for two body reactions. The temperature dependencies for different reactions are different. The steady state emissivity also becomes temperature dependent. Krassovsky (1972) studied the differential response of the OH emission intensities I_{OH} to small temperature perturbations caused by acoustic waves in the upper atmosphere and showed it to vary with differential temperature perturbations as

$$\frac{dI_{OH}}{I_{OH}} \approx \eta \frac{dT}{T}$$

where η is a factor that depends on the wave frequency and phase speed. Makhlof et al (1995) showed that η ranged between 5 and 10 when phase speed of gravity wave decreased from 140 m/s to 40 m/s. Thus a small temperature perturbation can produce 5-10 times amplified OH emissions. There are very few simultaneous observations of sprites and gravity waves (Sentman *et al.*, 2003). Therefore, it is not precisely known the role of gravity waves in the initiation of sprites. The reverse phenomena i.e. the role of sprites on the spectra and amplitude of gravity waves and its generation/ propagation phenomena are also not studied. Further studies are required using simultaneous measurements of thunderstorm characteristics, gravity waves, sprites and mesosphere characteristics.

Global Electric Circuit (GEC) and Climate

Role of Atmospheric Ions

The electrons produced in the atmosphere during ionization by cosmic rays and other sources attaches to neutral electrophilic molecules, creating a negative ion, e.g. O_2^- . Primary ions form clustering with other polar molecules such as ammonia, water and organics (Harrison and Carslaw, 2003). In addition to modification of cloud properties and electrical conductivity these clusters affect the radiative properties of the atmosphere (Klemperer and Vaide, 2006). For example, the hydrogen bond in the clusters such as water dimer $(H_2O)_2$ may absorb infrared radiation (Ptashnik, 2008). Similarly NO^+ also affects radiative properties of the atmosphere (Rothman *et al.*, 2009). Quantitative prediction of infrared absorption for a large number of different isomers (Likholyot *et al.*, 2007) and their variable mixtures (Harrison and Tammet, 2008) has been studied. Initial measurements of infrared absorption in the $9.15 \mu m$ band (Aplin and McPheat, 2008) from local cluster-ion concentrations of $10^8 - 10^9 m^{-3}$ could be $1 - 10 mWm^{-2}$, which is small but non-negligible contribution.

Role of GEC

The space charges formed at the top and bottom of clouds due to the flow of vertical current (Nicoll and Harrison, 2009a,b, 2010) attach to aerosol particles, cloud condensation nuclei (CCN) and ice forming nuclei (Tinsley *et al.*, 2001) and enhance electro-scavenging and ice formation depending on the droplet size distribution or modify droplet evaporation (Harrison and Ambaum, 2008). The enhanced electro-scavenging of larger CCN and aerosol particles may protect smaller CCN and aerosol particles from scavenging (Tinsley, 2004), and may lead to narrowing of the droplet size distribution. As a consequence of this there may be both reduced precipitation and enhanced cloud life

time. The two processes simultaneously compete and the net result depends on local temperature, aerosol environment, strength of vertical current and cloud dynamics.

The microphysical processes linking space charges at the cloud edge with the cloud properties are illustrated in Fig.9 (Rycroft *et al.*, 2012). In electro-scavenging collision efficiency of charged particles and liquid droplets are enhanced (Tinsley *et al.*, 2001) and formation of ice crystal is facilitated. The other impact of cloud charge 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.

Fig. 9: Schematic diagram of various cloud microphysical processes, which may be affected by electrical charge, (a) electro-scavenging (b) electro-activation, (c) electro-collection (after Rycroft *et al.*, 2012).

Harrison and Ambaum, (2008) reported reduction (by 0.3 Wm^{-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 also causes change in

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 in accordance with the fact that a vertical current effect on cloud microphysical process is expected to take few hours (Zhou and Tinsley, 2007).

Atmospheric Discharges and NO_x /Ozone Perturbation

Atmospheric discharges produce NO_x , which acts as a moderator of ozone distribution in the atmosphere. NO_x has short life time of days in the upper troposphere and hence it does not have effective impact on radiative 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 $35^\circ\text{S} - 35^\circ\text{N}$ region (Neubert *et al.*, 2008; Siingh *et al.*, 2011). Measurements show greatly enhanced concentration of NO_x in thunderstorm anvils and enhanced ozone concentration downwind (Huntriesser *et al.*, 2007).

In addition to usual lightning discharges, the discharges between cloud tops and the ionosphere also contribute to the producing of NO_x (Enell *et al.*, 2008; Sentman *et al.*, 2008). 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} to 7.4×10^{26} molecules and 6.8×10^{23} to 6.3×10^{27} molecules per event, respectively. These results into global TLE- NO_x to be $\sim 7 \times 10^{23}$ to 2×10^{28} molecules per second, corresponding to global TLE- NO_x production of $5.2 \times 10^{-4} - 14.7 \text{ Tg(N) yr}^{-1}$. These estimates are still under debate (Nijdam *et al.*, 2010; Petersen *et al.*, 2010). The production of LNOx by blue jets/gigantic jets is almost similar as that of lightning flashes.

The NO_x production by sprites is of the same order as produced by solar proton event during a quiet year, and two orders of magnitude below its production by cosmic rays (Vitt and Jackman, 1996). These preliminary studies suggest that NO_x production by TLEs may not play significant role in NO_x budget of the stratosphere and mesosphere. However, the non-linear responses in the regional dynamics are not ruled out and further studies are required.

Aerosols Effect

The presence of aerosols in the atmosphere affect different microphysical processes of thunderstorms and radiation budget reaching the atmosphere, thereby affect climate. The enhancement in aerosol loading enhances the local lightning activity (Altartatz *et al.*, 2010 with reference therein). Altartatz *et al.* (2010) also showed that higher values of aerosol loading inhibit deep convection and diminish electrical activity in cloud. High concentration of aerosols absorb the incoming radiation, heat the middle troposphere and cool the Earth's surface leading to stabilization of the local atmosphere and choking the development of convections and thunderstorm cells (Koren *et al.*, 2008). Aerosol loading at global level reduced the global warming directly through

backscattering of solar radiation and indirectly through changes in cloud albedo and lifetime (Lohmann and Feichter, 2005).

Precipitation also follows long term trend in global distribution of aerosols (Wild, 2012). Siingh *et al.*, (2013a, 2014) showed that on the regional basis precipitation increases with the increase in aerosol concentration. The effect of aerosols on cloud properties depend on relative humidity (Fan *et al.*, 2007), CAPE and wind shear (Lee *et al.*, 2008; Fan *et al.*, 2009) and cloud morphology (Lee *et al.*, 2010). Wang *et al.*(2011) using measurements and simulations showed that enhanced aerosol loading suppresses lightning and moderate (<25 mm/day) rainfall and enhances heavy rainfall. Recently, Li *et al.*(2011a, b), Niu and Li. (2011) and Tao *et al.*(2012) discussed the conditions under which clouds and precipitations are either suppressed or enhanced by aerosol concentration.

Summary

The present understanding of lightning discharge in the troposphere, stratosphere and mesosphere and its impact on climate are briefly discussed. It is shown that both mechanisms of lightning discharges, namely runaway mechanism and conventional breakdown mechanism involving streamers and leaders are operative and could explain some properties of lightning discharges. Individually anyone mechanism could not explain all the properties of discharges. It seems that both mechanisms are involved in discharge process. Lightning and convective precipitation are well correlated, and both depend upon meteorological parameter such as convective available potential energy and surface temperature. Flash rate variation showed an almost opposite trend to sunspot number variation. The charge imbalance in the cloud just after CG or IC discharges, leads to jet phenomena. Depending upon the magnitude and nature of charge imbalance, the blue starter, blue jet and gigantic jets are produced above the cloud top. Jets transfer cloud charges to the ionosphere and discharge mechanism is identical to the cloud-to-ground discharges involving streamers and leaders.

The impact of lightning discharge in the lower/middle atmosphere leads to changes in cloud formation, precipitation and atmospheric circulation which directly/indirectly affect climate at the local and global basis. The flash rate distribution and precipitation are correlated at regional scale but they are uncorrelated on the global scale. Long term data for different local time should be analyzed to pin-point the cause of these discrepancies. The role of gravity wave in creating density modulation in the atmosphere and transport of energy /momentum affecting atmospheric circulation during thunderstorm are shown to affect middle atmosphere discharges and climate. Although due to limited studies, the impact on climate is not quantified. Discharges produce NO_x which enhance/reduce the ozone concentration in the atmosphere depending upon the initial ozone density. Ozone is the main constituent which absorbs infra-red part of solar radiation and thus controls temperature at the troposphere/stratosphere and on the Earth surface. Changes in ozone concentration cause change in temperature outside the

perturbation region through dynamical response which exhibits non-linear behavior. Detailed studies involving relevant measurements and modeling work are required to assess quantitative impact on climate.

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 <i>et al.</i> , 1995; Pasko, 2007; Stenbaek-Nielsen <i>et al.</i> , 2007; Inan <i>et al.</i> , 2010.
2	Halo	75-85 km	Transverse dimension ~ 40-70 km, horizontal cross section as large as 700 km ² . Featureless diffuse descending glows of ~ ms duration. Sometimes they accompany/precede sprites.	Stenbaek-Nielsen <i>et al.</i> , 2000; Frey <i>et al.</i> , 2007.
3	Blue Jets	Cloud top to ~ 40 km	Slow moving fountains of blue light emerging from the cloud top, vertical velocity ~ 112 ± 24 kms ⁻¹ and life time 200 - 300 ms. Upward development in conical shape with conical angle $14.7^\circ \pm 7.5^\circ$. 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 <i>et al.</i> , 1998; Lyons <i>et al.</i> , 2003b; Krehbiel <i>et al.</i> , 2008.
4	Blue starters	Cloud top to ~ 25 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 27-53 kms ⁻¹ . In this case also screening charges are required to initiate them.	Wescott <i>et al.</i> , 1996, 2001; Lyons <i>et al.</i> , 2003a; Eden, 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 ~ 1sec.	Su <i>et al.</i> , 2003; Hsu <i>et al.</i> , 2005; Chou <i>et al.</i> , 2010; Soula <i>et al.</i> , 2011.
6	Palm tree	Cloud to ~ 60-70km 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; Marshall and Inan, 2007.
7	Elves	Bottom edge of the ionosphere (80 - 95 km altitudes)	Donut shape (concentric rings) elves of short duration (< 1ms) 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 <i>et al.</i> , 2007; Newsome and Inan, 2010; Chang <i>et al.</i> , 2010; Mende <i>et al.</i> , 2004; Lu, 2006.

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