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Lightning Discharges, Cosmic Rays and Climate

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Abstract The entirety of the Earth's climate system is continuously bombarded by cosmic rays and exhibits about 2000 thunderstorms active at any time of the day all over the globe. Any linkage among these vast systems should have global consequences. Numerous studies done in the past deal with partial links between some selected aspects of this grand linkage. Results of these studies vary from weakly to strongly significant and are not yet complete enough to justify the physical mechanism proposed to explain such links. This review is aimed at presenting the current understanding, based on the past studies on the link between cosmic ray, lightning and climate. The deficiencies in some proposed links are pointed out. Impacts of cosmic rays on engineering systems and the possible effects of cosmic rays on human health are also briefly discussed. Also enumerated are some problems for future work which may help in developing the grand linkage among these three vast systems.

Keywords Cosmic rays and human hazards · Cosmic rays and thunderstorm electrification · Thunderstorms/lightning discharges and climate · Global electric circuit and climate

1 Introduction

General circulation of the atmosphere strongly influences the global distribution of lightning discharges through its effects on surface temperature, humidity, boundary layer stability and cloud properties (Williams 1985, 1992). The association of lightning flash rate with intense rainfall (Price and Federmesser 2006), with production of nitrogen oxides (NO_x) and thereby modification of the amount of ozone in the atmosphere (Schumann and

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Huntrieser 2007), with convective activity are two of the factors which affect atmospheric temperature and other climate variables. Lightning discharges are considered to be the largest natural sources of NO_x production (~ 5 Tg per year) in the atmosphere (Christian et al. 2003; Galloway et al. 2004; Schumann and Huntrieser 2007) which critically affect the abundances of ozone (O_3) and hydroxyl radical (OH) in the troposphere (Rohrer and Berresheim 2006; Siingh et al. 2015a). These 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 O_3 by $\sim 0.3 \text{ Wm}^{-2}$. Lightning-induced NO_x is found to have an ozone production efficiency of 6.5 ± 4.7 times that of surface NO_x sources (Finney et al. 2016). A change in radiation forcing directly affects atmospheric circulations leading to changes in climate parameters.

Cosmic rays (CRs) entering into the Earth's lower atmosphere produce ionization and thereby affect the atmospheric electrical conductivity (Tinsley 2000; Rycroft et al. 2008), global electric circuit (Tinsley 2000, 2008), nucleation rates in cloud (Arnold 2006; Tripathi et al. 2008), lightning discharges (Tinsley 2008; Kudela 2009), space weather phenomena (Kudela et al. 2000), human health (Shea and Smart 2000; Singh et al. 2011), etc. In turn, cloud formation (Sun and Bradley 2002, 2004), lightning discharges (Price 2009) and other space weather phenomena (Kudela et al. 2000; Kudela 2009) affect climate and, hence, a link between CRs and climate is presently being studied. The initial results of the CLOUD (Cosmics Leaving OUtdoor Droplets) experiment at CERN, Geneva, Switzerland, are encouraging in the study of the possible influences of CRs on cloud (Duplissy et al. 2010). Recently, Kumar et al. (2017) using measurements in Antarctica during fair-weather conditions showed that low-level (pressure > 680 h Pa) cloud coverage is positively correlated with the galactic cosmic ray (GCR) flux, the maximum correlation being 36% during long solar minimum of 2007–2009. During this period, snow fall increased by 14%. The results are discussed in terms of formation of ion–aerosol-mediated cloud condensation nuclei (Harrison 2000; Tinsley 2000; Wang and Panner 2009; Yu and Luo 2009; Svensmark et al. 2009; Siingh and Singh 2010; Kirkby et al. 2011). Cosmic rays are thought to affect the total cloud cover of the Earth and thus provide a driver for the terrestrial climate, although the physical mechanism underlying the link is still poorly understood (Svensmark and Friis-Christensen 1997).

Wilson (1916, 1920) for the first time, using ground-based electric field measurements, tried to understand both the charge structure in the thunderstorm and the individual charges involved in the lightning discharge. Since then, a large amount of work has been done using improved high-speed photographic techniques and correlated electric field/current measurements to understand different aspects of thunderstorm charge structure (Stolzenburg et al. 2007; Saunders 2008), electric field (Stolzenburg and Marshall 2009), initiation of lightning discharge (Rakov and Uman 2003; Krehbiel et al. 2008; Dwyer and Uman 2014), associated current (Petersen et al. 2008), etc. One of the problems still unsolved is the initiation of lightning, because for the dielectric breakdown to occur inside thunderstorm the required electric field is about 23 kV cm^{-1} (Gurevich et al. 2009), whereas measured electric field in thunderclouds falls far short of this value (Marshall et al. 2005; Stolzenburg et al. 2007). Gurevich and Zybin (2001, 2005) proposed the runaway breakdown mechanism operating at a lower threshold voltage ($\sim 2.16 \text{ kV cm}^{-1}$) which involved the passage of high-energy particles (cosmic rays) through the thundercloud. Cosmic rays interact with the atmosphere, directly change the concentration of atmospheric ions and indirectly affect the charges in the troposphere through the modulation of current flow in the global electric circuit (Tinsley 2008). They may affect cloud formation and cloud cover rates (Svensmark 1998) and hence may impact the climate (Svensmark 1998; Erlykin et al. 2010).

Different aspects of lightning discharge, global electric circuit, the role of cosmic rays in cloud nucleation and impacts of all these on climate have been discussed at several places (Tinsley 2000, 2008; Rycroft et al. 2000; 2012; Singh et al. 2004; Siingh et al. 2005, 2007, 2008, 2015a; Markson 2007; Anisimov and Mareev 2008; Aplin et al. 2008; Williams 2009; Mareev 2010; Rycroft and Harrison 2012; Dwyer and Uman 2014; Williams and Mareev 2014). In the present paper, salient features of roles of the studies explore the relations between the particle nucleation and cosmic rays (Sect. 2), thunderstorm electrification and cosmic rays (Sect. 3), triggering of lightning by cosmic rays (Sect. 4), high-energy radiations and thunderstorm ground enhancements (TGEs) and terrestrial gamma ray flashes (TGFs) (Sect. 5), the global electric circuit and climate (Sect. 6), atmospheric general circulation lightning and climate (Sect. 7). Section 8 briefly presents the impacts of lightning discharges on engineering systems. A brief description of the possible influences of cosmic rays on different organs of human body is discussed in Sect. 9. Only the studies emphasizing on the links between the respective topics are discussed. Some unsolved problems and gaps in our understanding of these problems are listed in Sect. 10 for future work in this area. The objective of this paper is to present a framework of interactions between these topics which could facilitate in finding an effective linkage among the systems of cosmic rays, lightning and climate.

2 Ion Nucleation, Cloud Cover and Cosmic Rays

Ionization in the troposphere and stratosphere is mainly produced by CR, whereas in the ionosphere the main player is solar extreme ultraviolet (EUV) radiation. The effect of solar EUV radiation is in the ionosphere height, whereas ionization in the troposphere and stratosphere is caused by cosmic rays (Marsh and Svensmark 2000; Viggiano and Arnold 1995). Different types of ions produced in the lower atmosphere directly influence conductivity, electric field and vertical current in the atmosphere. Cosmic ray-produced ions may enhance the formation and growth of new particles by the process of ion-induced nucleation (Yu and Turco 2000, 2001; Yu 2002; Laakso et al. 2002; Eichkorn et al. 2002; Lee et al. 2003; Pierce and Adams 2009; Siingh et al. 2013a; Kamra et al. 2015).

The presence of ions stabilizes the cluster of newly formed particles through Coulomb attraction and reduces the critical size required for further growth to cloud condensation nuclei (CCN) sizes. Cluster of particles smaller than the critical size may be lost by scavenging on existing aerosols (Tripathi and Harrison 2002). Yu and Turco (2000) and Turco et al. (2000) suggested that ~20% variation in ionization of the lower atmosphere may lead to a change of ~5–10% in aerosol concentration of 3–10 nm diameters. Some of them may be converted into CCN. The fraction of CCN originating from CR ionization will depend on many factors including CR intensity and its energy spectra, availability of condensable gas and cloud processes. Cosmic rays are also linked with increased cloud water in the mixed-phase region of moist convection (Williams et al. 2002; Mansell and Ziegler 2013). However, Kulmala et al. (2010) based on observation of atmospheric aerosol formation measurements at the SMEAR II station, Finland (1996–2008), showed that none of the quantities related to aerosol formation correlates with the cosmic ray-induced ionization intensity.

The vertical conduction current in the presence of high-conductivity gradients near the cloud may generate highly charged droplets, which after evaporation will leave behind charged and coated “evaporation nuclei” (Kirkby 2007). These nuclei may become ice

nuclei and may induce ice formation (Harrison 2004; Sastry 2005). The CLOUD (Cosmic Leaving Outdoor Droplets) experiment at CERN, Geneva, Switzerland, showed that ions (proton beams equivalent to galactic/solar cosmic ray intensities) increase the nucleation rate by an additional factor lying between 2 and more than $10 \text{ cm}^{-3} \text{ s}^{-1}$ (Kirkby et al. 2011). The CLOUD experiment provided continuous measurements of molecular composition from single molecules to stable aerosol particles. It is shown that the cluster grows by a stepwise accretion of basic molecules each stabilizing a distinct additional number of acid molecules in the cluster, depending on the presence of vapor concentration. The CLOUD experiment showed production of negative ion clusters containing the HSO_4^- , HSO_5^- or SO_5^- (Kirkby et al. 2011). At higher ammonia concentrations, positively charged nucleation involving the NH_4^+ ion is also observed. The measurements support the additional formation of CCN, and hence, the role of cosmic rays in cloud formation/cloud cover is demonstrated. However, the percent contribution of CR in the CCN formation is not quantified.

Figure 1 summarizes the range of processes that can result from cosmic rays interaction with the atmosphere in the presence of solar radiation. Cosmic rays could change climate by affecting electric field, current, conductivity in the atmosphere, cloud condensation nuclei, thunderstorm electrification, ice formation in cyclones, etc. Svensmark and Friis-Christensen (1997) and Marsh and Svensmark (2000) reported correlation between the cosmic rays and low (<3 km) altitude clouds around the cosmic rays minimum of 1990. However, many workers could not find statistically significant correlation between cosmic

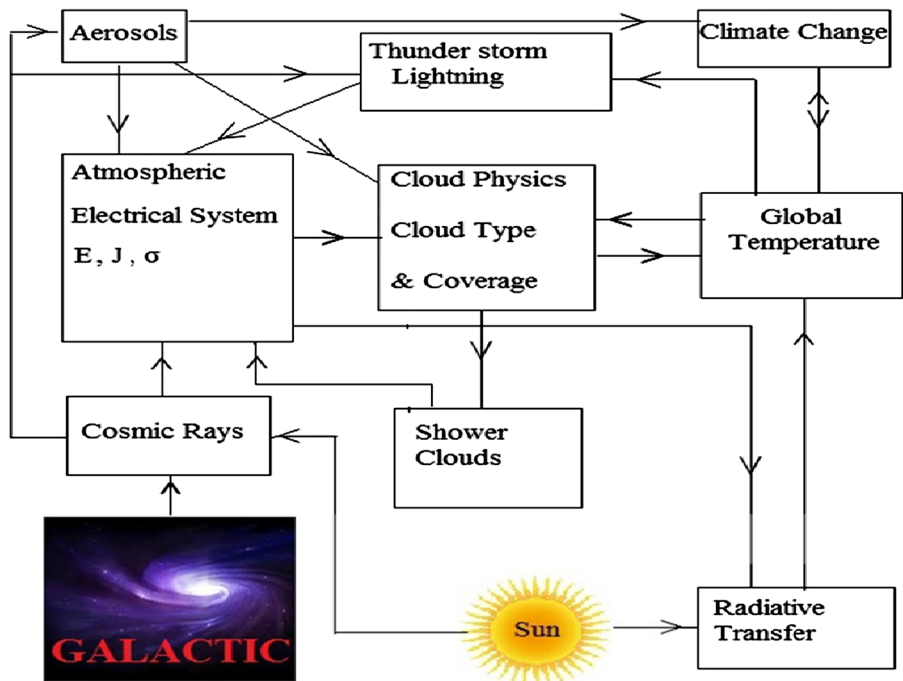


Fig. 1 Range of processes that can result from cosmic ray's interaction with the atmosphere in the presence of solar radiation. (Modified, after Harrison 2004)

rays and cloud cover (Kerenthaler et al. 1999; Sun and Bradley 2002, 2004; Laut 2003). Kuang et al. (1998) studied the variation of cloud optical thickness and their relationship with cosmic ray intensity and El Nino-Southern Oscillation (ENSO) activity over the period 1983–1991 and reported that the variation in optical depth could easily be explained by the ENSO activity rather than a variation in cosmic ray intensity.

Based on satellite observations and numerical modeling, Rossow and Cairns (1995) suggested that ~1% change in the Earth's cloud cover corresponds to ~0.5 Wm⁻² change in the net radiation forcing. This means that ~3% change (Marsh and Svensmark 2000) in cloud cover may correspond to ~1.5 Wm⁻² radiation forcing during 1987–1990. In the same period, cosmic ray intensity changed by ~3.5% (Marsh and Svensmark 2000). These numerical computations and discussions assume that the whole cloud volume is only affected by solar activity, which is not true in the real situation. Local meteorological parameters such as humidity, aerosols, pollution and temperature also affect cloud formation/cover. Further, an increase in cloud cover may result in lower temperatures.

3 Thunderstorm Electrification and Cosmic Rays

Usually, cloud charging mechanisms are grouped under inductive and noninductive processes (Yair 2008; Saunders 2008). In the inductive process, the existing vertical electric field induces polarization charges in suspended hydrometeors. Wilson (1929) hypothesized that falling rain drops in the presence of a prevailing positive field selectively capture negative ions. The electric field is further enhanced due to reinforcement of the field from the gravitational separation of the falling negatively charged drops and the positive net charge on ions located upward in the cloud. The charging process will depend on the rate of production of ions in the lower atmosphere and the possibility of the disintegration of a drop due to an isolated charging (Taylor 1964). Latham and Mason (1962) provided mathematical description of charging of hail pellets in a polarizing electric field. Abbas and Latham (1967) demonstrated that a drop carrying an initially small negative charge acquires an increasingly greater negative charge with an increasing electric field and reaches a critical value which depends on the radius of the drop irrespective of potential and electric field. Taylor (1964) showed that this critical value is about 0.38 times that required to disintegrate a charged drop. Moreover, the maximum electric field that could be generated by this mechanism in a cloud with the prevailing ionization in the troposphere may not exceed ~600 V m⁻¹ (Chalmers 1962). Cosmic ray generated ions in the lower atmosphere also play a key role in the initial stages of convective mechanism for cloud electrification (Vonnegut 1963).

Sartor (1967) proposed that collision between large and small hydrometeors then imparts negative charge to the larger hydrometeors and positive charge to smaller hydrometeors. Gravitational separation of larger and smaller hydrometeors in the presence of an updraft then generates a positive dipole. However, this mechanism could not explain the presence of highly charged particles in the early stages of thunderstorm electrification (Christian et al. 1980; Marshall and Winn 1982). In the noninductive process, charge transfer occurs during collisions of small and large particles but is independent of any pre-existing electric field. In the widely accepted mechanism of thunderstorm electrification, graupel particles colliding with millimeter size ice crystals at temperature above -10 °C acquire positive charge, corresponding negative charge being given to ice crystals (Takahashi 1978). Gravitational separation in the presence of convective circulation graupels and ice crystals builds up the positive dipole in thunderclouds. In a theoretical model of

large-scale electric field generation in thunderstorms, Mareev and Dementyeva (2017) have recently shown that while turbulences can significantly amplify the electrification in case of inductive charging, it has little impact in case of noninductive charging as compared to the impact of convection.

In addition to the above mechanisms, Ermakov and Stozhkov (1999) proposed that cosmic rays could be responsible for thunderstorm electrification and initiation of lightning discharges. In the lower atmosphere, cosmic rays produce fluxes of secondary charged particle which attach to available aerosols in the atmosphere. The electrons take a few microseconds to attach to O₂ molecules and ions take milliseconds to attract polar molecules to become light cluster ions (Hoppel et al. 1986). During the development stage of a thunderstorm, aerosols (charged and neutral) are swept upward with the updraft. The ascending air mass is cooled, and at the condensation level, water molecules start to condense. The rate of condensation is charge dependent (Rusanov and Kuzmin 1977). Negatively charged aerosols grow faster (~10⁴ times) than positively charged ones (Stozhkov et al. 2001). As a result, the massive negatively charged aerosols move with lower velocity than lighter positively charged ones creating charge separation in the cloud (Ermakov and Stozhkov 1999; Stozhkov et al. 2001).

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 layers of cloud (Tinsley 2000; Nicoll and Harrison 2010). Space charges could influence microphysical processes such as droplet–droplet collision (Khain et al. 2004), droplet–particle collision (Tripathi and Harrison 2002) and droplet formation (Harrison and Ambaum 2010). In turn, these may influence cloud lifetime, cloud radiative properties, precipitation and lightning activity. Cosmic rays also aid in initiation of lightning discharges.

Rycroft et al. (2012) discussed charge mediated cloud microphysical processes such as electro-scavenging, electro-activation and electro-collection. Theory and laboratory experiments showed that particle charging considerably enhances the collection of aerosols in electro-scavenging by water droplets (Tripathi 2000; Tinsley et al. 2001; Tripathi and Harrison 2001). Tinsley and Zhou (2015), based on simulation results, showed that size and concentration distribution of CCN may change due to scavenging process which is dependent on size and charge of CCN in the presence of charge/electric field. Electro-scavenging of large CCN may also occur in the region where there is no net charge. Scavenging by supercooled droplets in clouds above the freezing level leads to contact ice nucleation, which then grows by capturing water vapor and thus lowers the vapor pressure causing evaporation of nearby droplets. The size and concentration distribution of aerosols (and hence CCN) controls the process of storm invigoration by the release of latent heat of freezing (Rosenfeld et al. 2008; Lam and Tinsley 2015). Droplet formation can be achieved by reducing vapor pressure, inhibiting evaporation and lowering the super saturation (Harrison and Ambaum 2008). The electro-scavenging, nucleation and electro-collection processes may occur simultaneously in real clouds and, therefore, 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.

4 Triggering of Lightning by Cosmic Rays

The measurements/simulation results of electric fields in or near the thunderstorms/clouds clearly show that the electric field is about one order of magnitude smaller than the

required field for dielectric breakdown of the atmospheric gas (Marshall et al. 2005; Dwyer et al. 2006; Stolzenburg et al. 2007). To initiate lightning discharge process in thunderclouds, some additional process is required. Cosmic rays of both solar and galactic origins have also been proposed to influence atmospheric processes (Gray et al. 2005, 2010; Siingh and Singh 2010). The processes responsible for initiation and propagation of lightning discharge in thundercloud have been extensively discussed by Dwyer and Uman (2014).

According to one idea, lightning can be initiated from streamers developed in the enhanced electric field around hydrometeors (Loeb 1966; Phelps 1974). Theoretical simulation of Babich et al. (2016, 2017) with charged drops of 1–3 mm diameter or needle-shaped ice located in electric field shows that, while the required charge on hydrometeors is within the range of measured precipitation charges, the required electric field is higher than observed in thunderclouds. Thus, a second mechanism must operate to amplify the local electric field. Laboratory experiments of Karma et al. (1993), however, show that corona can be initiated at the distorted surface of very large uncharged drops of > 6 mm diameter suspended in the horizontal electric field of the magnitudes observed in thunderclouds.

Another mechanism proposed for the lightning initiation is the start of a lightning leader with relativistic runaway electron avalanches (RREAs) seeded by high-energy electrons (Ermakov 1993; Gurevich et al. 1997). In this mechanism, RREAs produce an ionized domain by generating considerable number of electron ion pairs. Polarization of this domain in the electric field of thundercloud leads to a local rise in the electric field at the edges of the domain. The enhancement of this local electric field may be up to value required to initiate the spark-type local electric breakdown and thus trigger a lightning discharge. 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 CR showers and RREAs even in the presence of precipitation particles.” On the contrary, the RREAs seeded by low-energy CR produce a plasma domain, at the edges of which the electric field of the cloud is enhanced above the breakdown field. The hypothesis that lightning discharges are caused by high-energy cosmic ray particles ($E \geq 10^{14}$ eV) was suggested by Ermakov (1993). In the atmosphere, these high-energy particles give extensive air showers with many ionized tracks. The lightning discharges propagate along one of these tracks. The flux of high-energy cosmic rays and extensive air showers produced by them is enough to cause the observed number of lightning discharges. Gurevich et al. (2009) confirmed this hypothesis. However, it is not yet possible to identify the percentage of lightning flash triggered by this process.

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 did not occur when thunderstorm was just over an electric field mill. It occurred when field mill was not exactly below the thundercloud, but its reading was damped by the bottom positive charge layer of thundercloud. The change may be due to acceleration of low-energy cosmic ray particles to energy level above the threshold value of the measuring system.

The pile up charges of certain sign amounts to several tens of Coulombs resulting in a strong quasi-electrostatic field inside and around the thunderstorm. Measurements of electric fields in thunderstorms and Monte Carlo calculations show that the field strength never reaches the value required for conventional breakdown of air, which is ~ 32 kV cm⁻¹

at the atmospheric pressure (Marshall et al. 2005; Dwyer et al. 2006; Stolzenburg et al. 2007). Therefore, it was proposed that the thermal electron avalanches (of mean thermal energy \sim several eV) produced by intense electric field of thunderstorm may aid discharge phenomena.

Alternate breakdown mechanism operating at a lower breakdown field ($\sim 2.1 \text{ kV cm}^{-1}$) called runaway mechanism based on the relativistic electron avalanches is also proposed (Gurevich and Zybin 2001, 2005; Gurevich et al. 2009). A high-energy charged particle (cosmic ray, solar proton/electron) moving through the cloud 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. These 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), ultimately leading to the breakdown of air. Gurevich et al. (1992, 1999) proposed runaway mechanism in which a relativistic electron is accelerated in the presence of thundercloud electric field, which generates secondary electrons of various energies due to ionization of neutral molecules. Those secondary electrons of sufficiently high energy are accelerated in the presence of thunderstorm electric field to act as runaway electrons (Fig. 2). The losses of energy in air at the altitudes of thunderstorms exceed the increase in energy obtained by electrons in the electric field of thunderstorms if the strength of electric field is $< 3 \text{ kV/cm}$. The process is cascaded, and an exponential growing avalanche of runaway electrons develops. These runaway electrons moving upwards (downwards) become the source of TGEs (TGFs) thunderstorm ground

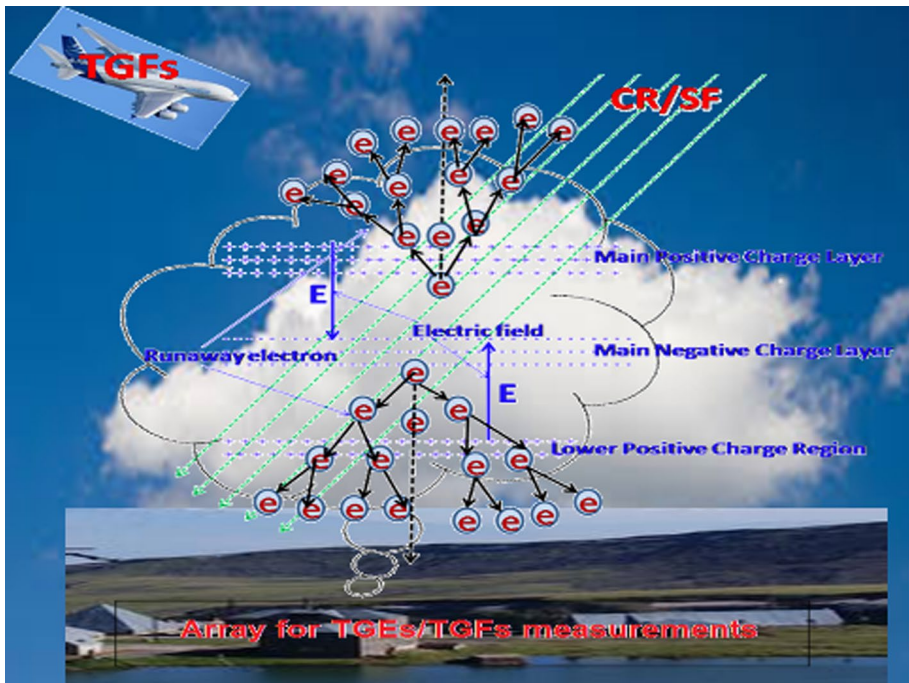


Fig. 2 Cascaded runaway electrons produced by cosmic rays moving upward (downward) become the source of TGEs (TGFs) during thunderstorm activity

enhancements (terrestrial gamma ray flashes). In this model, generation of TGEs requires the presence of lower positive charge region in cloud (Chilingarian 2014). Simultaneously, a large number of slow electrons is generated which leads to electric breakdown at lower electric fields ($E \sim 2.16 \text{ kV cm}^{-1}$) as compared with the conventional breakdown field ($E \sim 32 \text{ kV cm}^{-1}$) (Gurevich and Zybin 2005; Gurevich et al. 2009).

5 TGEs and TGFs

Measurements with ground-based equipments showed the presence of intense fluxes of electrons, gamma radiation and secondary neutrons correlated with thunderstorms/lightning discharges which are termed as thunderstorm ground enhancements (TGEs) (Dwyer et al. 2004, 2012; Chilingarian et al. 2010, 2012, 2013, 2015; Chilingarian 2014). TGEs are second to minute long X-ray and gamma ray emissions originating in or near thundercloud and are observed at mountain heights (Dwyer et al. 2012). The enhancement in gamma ray fluxes has been measured to be $\sim 10\%$ above background level (Suszcynsky et al. 1996), although Torii et al. (2002) reported enhancement up to 70 times the local value during a winter thunderstorm in Japan when the thunderstorm charge center was at lower altitudes. Chilingarian et al. (2010) reported that count rates doubled at Aragats when a thundercloud was 100–200 m above the detector. Modeling studies (Torii et al. 2002, 2004, 2009; Tsuchiya et al. 2007, 2009, 2011; Chilingarian et al. 2010; Babich et al. 2010; Karapetyan 2012) showed that most of the observed spectra are consistent with Bremsstrahlung emission from relativistic runaway electron avalanche (RREA) model. Parks et al. (1981) and McCarthy and Parks (1985) based on observations inside active thunderstorms reported X-ray emissions lasting tens of seconds and extending to greater than 110 keV. They also reported that lightning generally terminated before the X-ray glows. Although TGEs are proposed to be caused by RREAs, their duration, intensity and the conditions present inside the thunderstorms are not well understood. Further measurements and numerical studies are needed.

Terrestrial gamma ray flashes (TGFs) distinct from TGEs were observed at ~ 500 km altitude in correlation with thunderstorms (Fishman et al. 1994; Tavani et al. 2011; Smith et al. 2011). TGFs are millisecond long bright pulses of gamma rays and have harder energy spectra than gamma ray bursts of cosmic origin. The geographical occurrence of TGFs as measured from NASA small explorer spacecraft Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) is shown in Fig. 3 (Splitt et al. 2010), which shows that TGFs are observed predominantly at low latitudes and are associated with the regions of high lightning activity. Radio observations of lightning associated with TGFs showed that TGFs are associated with the early stage of positive ground-to-cloud (negative charge moving upward) discharges (Stanley et al. 2006; Lu et al. 2010; Shao et al. 2010).

Cummer et al. (2005) measured 30 kHz and lower-frequency radio emissions during TGF events and showed that TGF-associated charge moment changes were 50–500 times too small to drive the relativistic runaway electron avalanches (RREAs) process at high altitude as has been considered by early (before 2005) workers (Kulak et al. 2012). Dwyer and Smith (2005) combined the Monte Carlo simulation of RREAs and simulation of gamma ray emissions and propagation through the atmosphere and compared it with the average TGF spectrum measured from the RHESSI spacecraft. They reported that the observed spectra were consistent with the simulation results when the source region was considered at 21 km altitude and below and the derived spectrum was inconsistent for sources above 21 km altitudes. This supports the theory that TGFs are produced either

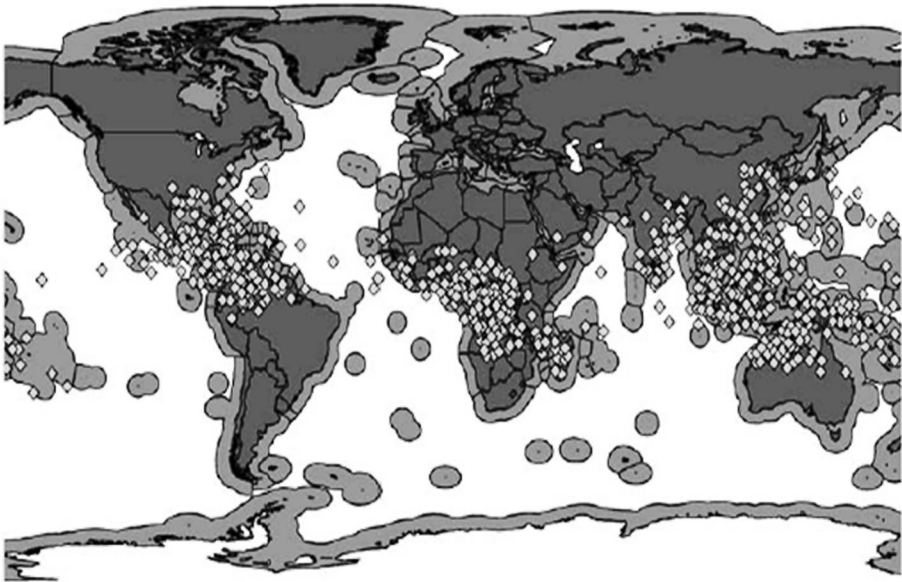


Fig. 3 Location of the RHESSI spacecraft at the time of TGF observations for 805 events from March 2002 through December 2007. The grey shaded regions near land masses are the coastal regions defined by a 200 nautical mile (370 km) distance from shoreline. (After Splitt et al. 2010)

inside a thundercloud or just above a thundercloud, and anyway they are not associated with high-altitude discharges (sprites) as claimed before 2005. Recent measurements of Cummer et al. (2014), however, locate origin of TGF's to lower altitudes of 11–12 km. Comparing lightning location measurements from the World Wide Lightning Location Network (WWLLN) and TGF measurements by gamma rays burst monitor (GBM) onboard the Fermi spacecraft, Connaughton et al. (2010) suggested that the thermal runaway electrons from lightning leaders could be the probable source of TGFs. Connaughton et al. (2013) using recent theoretical and observational results suggested that some of the TGFs may have been produced by very large discharges directly caused by the runaway electrons and their ionization. These discharges may also make large current pulses in the atmosphere which may damage objects near to them.

The TGF observations have been interpreted by two main mechanisms. In the first mechanism, relativistic seed electrons, positrons and X-rays are accelerated and multiplied to produce RREA's (Gurevich et al. 1992; Dwyer and Smith 2005; Dwyer 2008). The second mechanism is based on production of thermal runaway electrons by the negative corona flash stages of stepping lightning leaders (Gurevich 1961; Moss et al. 2006; Celestin and Pasko 2011). The second mechanism has been supported by the modeling studies of Xu et al. (2012, 2015) and Celestin et al. 2012).

Dwyer et al. (2008) proposed a mechanism in which energetic electrons (not runaway electrons) and positrons created by Compton scattering and pair production of gamma rays in a TGF event could propagate along geomagnetic field lines and may form a beam of particles which may be observed at a large distance away from the thunderstorms. Such beams are known as terrestrial electron beams (TEBs). An artist's conception of TGFs and TEBs is given in Fig. 4 (Dwyer and Uman 2014).

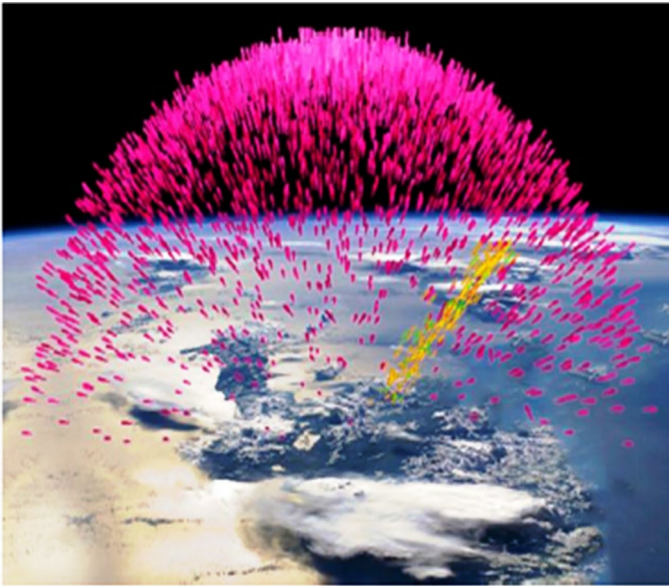


Fig. 4 Artist's conception of a TGF shown by pink and TEB in which electrons are shown by yellow and positrons by green. (Source: Image courtesy NASA, Dwyer and Uman 2014)

6 Global Electric Circuit and Climate

The sources of charge within the GEC in the lower atmosphere are thunderstorms, shower clouds, point discharge currents, ionization by radon isotopes and galactic cosmic rays. There are variations in the estimated contribution of thunderstorms and electrified rain/shower clouds to the upward current: 60 and 40%, respectively (Wilson 1925; Rycroft et al. 2007), 80 and 20% (Odzimek et al. 2010) and 90 and 10% (Mach et al. 2011). Shower clouds generally transport negative charges to the ground via raindrops (Liu et al. 2010). Mareev et al. (2008) using numerical simulation showed that 55–75% of the charges neutralized during lightning discharges are transferred to the ionosphere during 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). Mallios and Pasko (2012) discussed 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 the cloud dissipation phase.

Based on a large number of aircraft measurements (~850 flights over electrified clouds), Mach et al. (2010) reported upward positive current in 93% cases and negative polarity currents in 7% cases. The negative current may be from inverted polarity thunderstorms (Tessendorf et al. 2007). The upward positive current from storms with lightning over oceans was larger (~1.0 A) as compared to land (~0.43 A), whereas the negative current was 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 electrified showers make a finite (+ 0.19 and – 0.17 A over ocean and 0.09, – 0.12 A over land) contribution to the GEC (Mach et al. 2009, 2010), which is 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 and ocean to be 1.1 and 0.7 kA, respectively, and that from rain/shower clouds 0.04 and 0.22 kA, respectively. This turns out to be approximately 55% from land surface and 45% from ocean surface.

In recent years, several theoretical models with different approaches have been developed to study the performance of the GEC. Such attempts are partially successful have shown great potential in explaining some salient features of the GEC. For example, Peterson et al. (2015) developed an algorithm to characterize the electric field above clouds employing passive microwave observations. The algorithm is shown to estimate electric field strengths within a factor of 2. Peterson et al. (2017) applied this algorithm to observations from Tropical Rainfall Measuring Mission (TRMM) and Global Precipitation Measurement (GPM) satellites to estimate the generator current for the GEC. The diurnal distribution of the retrieved generators current was found to be in excellent agreement with the Carnegie curve (Harrison 2004). Kalb et al. (2016) compared model outputs of the Community Earth System Model (CESM) with conduction current and other data derived from TRMM satellite. Using model parameterizations, the derived global measurements agreed well with the geographical patterns of TRMM currents. The model results suggest that the cloud parameters can represent the global distribution and strength of current in a global model framework. To compare the performance of previously developed models when these are executed under similar conditions, Jansky et al. (2017) have recently analyzed the diurnal variation of the GEC obtained from different numerical models.

The discharges in the middle atmosphere commonly known as transient luminous events (TLEs) also act as generators situated in the stratosphere and mesosphere and affect the vertical conductivity distribution and charge transport (Rycroft and Odzimek 2009, 2010; Siingh et al. 2012, 2015a). A single sprite may lower the ionospheric potential by ~1 V (Rycroft and Odzimek 2009, 2010) and could have space charge 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; Siingh et al. 2012). 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 (GJ) (GJ produced by a normally electrified storm and therefore resembled negative cloud-to-ionosphere discharges originating in the mid-level negative storm charge) transferred ~136 C negative charge in short duration (~120 ms) from the ionosphere to the cloud. Recently, Singh et al. (2017) also observed four GJs over Indian subcontinent and they have been calculated net negative charge 17–23 C transporting to the lower ionosphere within 40–80 ms. The leader process in blue starter and blue jets terminates before reaching the lower edge of the ionosphere and thus affects the vertical conductivity above the thunderstorm. However, GJs transfer charge to the ionosphere and thus affect ionosphere potential.

The current flow in the GEC may be affected by cosmic rays which produce ionization in the lower atmosphere and modify conductivity and potential. Harrison and Usoskin (2010), based on observations from 1966 to 1972, demonstrated a positive relation between the ionospheric potential and neutron count rate at Climax, Colorado. The ionospheric 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 in ~23% less fair-weather current at solar maximum than at solar

minimum. Changes of the cloud cover at Vostok, Antarctica, are found to be associated with an extreme increase in the vertical electric field there (Kniveton et al. 2008). Harrison and Ambaum (2008) reported a median 10% decrease in cloud amount at Lerwick Observatory, Shetland Islands, Scotland, associated with a 10% decrease in the Climax neutron rate. Thus, monitoring changes in 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.

Electrical properties of the 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 (Harrison 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) show 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 colocated cloud cover with thin and thick overcast conditions (Nicoll and Harrison 2009). Including the tropospheric and stratospheric aerosols in modeling the GEC in the CESMI model, Baumgaertner et al. (2013, 2014) found that an intra-annual cycle exists in the total global resistance which varies between 220 and 245 Ω and this cycle is driven by seasonal aerosol and cloud variations. Even the presence of turbulence in the troposphere affects droplet charging by the vertical current (Tinsley 2008).

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. One needs 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. The environment of measurement should be selected in such a way that the role of aerosols can be deciphered. This also requires much more effort in the field of related simulation studies.

Thunderstorms affect the global ionospheric potential, which in turn affects the surface atmospheric pressure. Burns et al. (2007, 2008) showed a correlation between daily average surface atmospheric pressure and daily average near surface vertical electric potential gradient with high statistical significance at seven stations in the Arctic and eleven stations in the Antarctic. Thunderstorms affect the GEC, vertical current density and cloud charging and hence cloud and aerosol microphysics. As a result, cloud microphysics, indirect aerosol effect, cloud cover, precipitation and latent heat are affected (Tinsley 2008). These in turn affect radiation balance, temperature, pressure, Rossby wave generation/propagation, cyclone dynamics, etc. Hebert et al. (2012) showed a positive correlation between small changes in high-latitude winter vorticity area index (VAI—an indicator of cyclones) at 500 hPa and changes in vertical current density measured at low-latitude Mauna Loa Observatory. This shows that vertical current could act as a driver for VAI and hence cyclones. Microphysical and dynamical effects produced by condensation, coagulation, ice production, latent heat release, cloud cover, albedo, precipitation and storm invigoration affect global circulation and spatial/temporal variations of Rossby waves (Rosenfeld et al. 2008).

In addition to the thunderstorm generators in the troposphere, the ionospheric potential is also determined by the ionospheric generator in the tropics and by the magnetospheric generator in the polar regions (Roble and Tzur 1986). Existence of these generators is due to the ionization produced by the solar and galactic cosmic rays, EUV radiation

and other energetic particles entering the atmosphere from outer space. While the ionospheric generator is strongly influenced by the tidal waves generated by thunderstorms, the magnetospheric generator is strongly affected by solar activity. The area of solar-terrestrial effects on weather and climate has been widely studied. The current flowing from the upper atmosphere to the Earth's surface, especially in the polar regions where high-energy particles in cosmic rays can penetrate to tropospheric heights, provides a good link to study the effects of changes in the ionospheric potential on the weather and climate in the troposphere. However, secondary particles from high-energy cosmic rays with energy > 10 GeV can penetrate to the tropospheric heights at all latitudes except equatorial ones.

The general circulation of the atmosphere, driven by the Hadley circulation between the equator and the midlatitudes, determines the location of subtropical and polar jets and strongly influences the climate (Price and Federmesser 2006; Price and Asfur 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; Ramesh Kumar and Kamra 2012a). Lightning activity is a sensitive indicator of surface temperature (Williams 1992, 2009; Ramesh Kumar and Kamra 2012b), upper tropospheric water vapor (Price and Asfur 2006; Saha et al. 2017a), cloud cover (Sato and Fukunishi 2005), ice crystal size (Sherwood et al. 2006), ice water content in thunderstorms (Petersen et al. 2005), convective available potential energy (CAPE) (Williams 2009; Ramesh Kumar and Kamra 2012b), aerosol concentration (Williams et al. 2002; Price 2013; Mansell and Ziegler 2013), trough zone and inter tropical convergence zone (ITCZ) (Penki and Kamra 2013a), El Nino and La Nina (Sátori et al. 2009; Ramesh Kumar and Kamra 2012c; Kulkarni and Siingh 2014, 2016; Saha et al. 2017b; Siingh et al. 2017), cyclones and land–ocean contrast (Ramesh Kumar and Kamra 2012b; Ranalkar et al. 2017), Hadley and Walker circulations (Rasmusson and Carpenter 1982; Rasmusson and Wallace 1983). These parameters also affect the state of the atmosphere and hence climate.

The electrons produced in the atmosphere during ionization by cosmic rays and other sources attach to neutral electrophilic molecules, creating negative ions which form clusters 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 radiation properties of the atmosphere (Klemperer and Vaida 2006; Ptashnik 2008; Thaddeus et al. 2008). 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 (Thaddeus et al. 2008). Quantitative predictions of infrared absorption for a large number of different isomers (Likholyot et al. 2007) and their variable mixtures (Harrison and Tammet 2008) have been studied. Initial measurements of infrared absorption in the 9.15- μm band (Aplin and McPheat 2008) from local cluster-ion concentrations of 10^8 – 10^9 m^{-3} could be 1–10 m Wm^{-2} , which is a small but non-negligible contribution.

The space charges formed at the top and bottom of clouds due to the flow of vertical current (Nicol and Harrison 2009, 2010) attach to aerosol particles, 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 the 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 proposed microphysical mechanisms explaining effects of cloud droplet charge on precipitation efficiency, ion-assisted formation of ultrafine aerosols, electro-scavenging of ice-forming nuclei, ice nucleation capability of charged aerosols, etc., are not quantitatively understood and evaluated. Tinsley et al. (2007) reported dependence of macro-physical responses on the vertical current in the GEC, which needs to be studied quantitatively.

The entirety of the Earth's weather system is confined in the region of the GEC, and thunderstorms/lightning discharges are the main contributor to the GEC. Williams (1992), based on observations of a temperature dependence of lightning activity, proposed that surface temperature controlled the degree of instability and CAPE-controlled deep convections and ice particle population believed to be responsible for lightning production. Positive correlations between global circuit parameters and temperature were observed on both semiannual and annual timescales (Williams 1994). On longer timescales, the global circuit response to temperature variation is not yet properly understood (Williams 2005, 2009; Satori et al. 2008). Further, current sources in the GEC are dominated by low-latitude current sources, and hence, a latitudinal trend in global warming should be considered. Williams (2009) reported a trend in global warming to be less by a factor of four in the tropics (~ 0.1 °C per decade) than at higher latitudes (0.4 °C per decade) in the Northern Hemisphere. Considering the temperature response of the ionospheric potential to be 10% per °C (Williams 1999; Markson 2007) and the tropics to be dominant controller, about 1% per decade increase in ionospheric potential is expected which is small enough to go undetected in the presence of natural variability in the ionospheric potential on the short/long timescales (Williams 2009).

Harrison and Ambaum (2008) reported a reduction (by 0.3 Wm^{-2}) in long-wave radiation underneath a stratocumulus layer during a solar flare event and suggested it was due to a change in the height of the 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 a few hours (Zhou and Tinsley 2007).

7 Atmospheric General Circulation, Lightning and Climate

The global distribution of lightning 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). Lightning discharges dominate over the land surface areas in the tropics (Williams and Stanfill 2002; Christian et al. 2003; Kandalganekar et al. 2005; Ranalkar and Chaudhuri 2009; Saha et al. 2017a) with Africa, South America and Southeast Asia regions ranking from the greatest lightning and least rainfall region to least lightning and most rainfall region. These regions dominate the Walker circulation, whereas rainfall is zonally uniform in the upwelling portion of Hadley circulation.

The global circulation is energized by the convective processes in the atmosphere. Lightning discharges need stronger and deeper convection, whereas rainfall 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, orographic nature and geographical location of the region (Carey and Buffalo 2007;

Williams 2009; Sători et al. 2009). Small changes in surface temperature may result in larger change in thunderstorm and lightning activity (Williams 2005, 2009) establishing a nonlinear link.

The increasing greenhouse gases in the atmosphere may lead to a warming at local/global level. More (less) warming at the surface than in 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 a clear increase in lightning activity (Price 2009; Saha et al. 2017a). Numerical studies shows that there is ~10% enhancement in lightning activity for 1 °C global warming caused by enhancement into CO₂ concentration (global warming) (Price and Rind 1992). Williams and Renno (1993) showed that at tropical stations lightning activity may increase by ~25% for an increase in surface temperature by 1 K above 296 K.

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). Climate models predict 10–20% enhancement in water vapor for every 1°K increase in temperature in that layer, although the Clausius–Clapeyron equation predicts ~6% enhancement for 1 °K change (Price 2013). 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). Mareev and Volodin (2014), based on numerical simulations using a GCM INMCM4.0 model, suggested that if the ionospheric potential is decreased by 10% the surface temperature will increase by 2.5 °C and the mean flash rate will increase by 20% during the twenty-first century if the global warming follows the assumed greenhouse emission scenario RCP8.5. The results are correlated with the mean sea surface temperature in the Pacific Ocean (El Nino area). These results can be explained by considering that in the El Nino dry period fewer thunderstorms develop, but they are much more explosive producing much more lightning activity (Ramesh Kumar and Kamra 2012c; Price 2013). Thus, the ENSO anomaly and its impact on lightning distribution affect general circulation and climate.

Using TRMM satellite data, Penki and Kamra (2013b) demonstrated that the lightning flash rate in the dry environment of northwest India and Pakistan (NW) is better correlated with convective parameters (surface temperature, CAPE, outgoing long-wave radiation) than in the moist environment of northeast India (NE). Using the empirical orthogonal function analysis of flash rate, surface temperature and CAPE, they reported that variation of lightning activity in these regions may not be fully explained by the variance in the surface temperature and CAPE alone. Some other factors such as orographic lifting, topography and precipitation may also contribute to this variance in these mountainous regions.

7.1 Thunderstorms, CAPE and Lightning

Thunderstorms with updraft velocity < 10 m/s usually have low lightning activity, while electrically active storms producing a good amount of lightning have an updraft velocity up to 50 m/s (Williams 2001, 2005; Deierling and Peterson 2008). Thunderstorms derive their energy from CAPE which is the upward integration of buoyancy force and depends on the vertical profile of temperature difference between a warmer rising air parcel within an updraft and a relatively cooler air outside the air parcel (Williams 1985). Low buoyancy force leads to low-altitude clouds, and convection is referred to as shallow convection.

Deep convection leads to towering clouds with their tops extending 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 (Zipser 1994). One of the reasons may be difference in the conversion efficiency of CAPE to updraft kinetic energy. Williams and Stanfill (2002) explained the large contrast of lightning distribution in terms of the Bowen ratio (ratio of sensible heat to latent heat flux) which is high for the continent (Williams and Stanfill 2002). Qie et al. (2003) analyzed lightning imaging sensor data over the 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 the plateau between 6 and 18 flashes per kg J^{-1} . In most parts of the plateau, the flash per CAPE is 2–3 times higher than that in Florida and Congo (Williams et al. 1992), although CAPE is low over the plateau. 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.

Convective activity depends on many large-scale factors such as outgoing long-wave radiation (OLR), surface temperature and CAPE. Enhanced OLR modifies the 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. The dependence of lightning activity on surface temperature, CAPE, humidity and OLR are studied using correlation analysis for different parts of India (Siingh et al. 2014; Saha et al. 2017a) including the Himalayan region (Ramesh Kumar and Kamra 2012a), which varied from region to region. Surface temperature is well correlated with lightning flashes throughout the Indian region. CAPE and OLR showed large variations from region to region. These results, along with other studies (Qie et al. 2003; Toumi and Qie 2004; Weckwerth and Parsons 2006; Qie et al. 2014), demonstrate that the development of convection is an interesting and complex problem, which is also controlled by orography of the region.

Siingh et al. (2013b) showed a similar relation between lightning and convective rain over the South/Southeast Asia with correlation coefficients of 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 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) showed that the 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 convective process are controlled not only by CAPE and surface temperature but

also depend on other factors such as sensible heat flux, total surface heat flux, orography of the region and thermodynamic state of the boundary layer.

Cecil et al. (2014) showed that 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 is ~ 46 flashes sec^{-1} . The peak monthly average flash rate (at $2.5^\circ \times 2.5^\circ$ grid scale) is 18 flash km^{-2} 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 (Cecil et al. 2014). Thunderstorms usually 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 period, distribution of lightning is fairly symmetric about the equator.

7.2 Solar Activity and Lightning

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 affects the heat budget in the stratosphere (Gray et al. 2005; Siingh et al. 2011). Half of the temperature response in the tropical upper stratosphere is due to the solar irradiance change and half due to the additional ozone feedback mechanism (Gray et al. 2009). The heat input variations 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, the Walker circulation is strengthened. The heating of the stratosphere leads to the “top-down” influence (Kodera 2004; Shindell et al. 2006) and may strengthen tropical convection with a poleward-shifted 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. 2003, 2008). The response of the “top-down” and the “bottom-up” mechanisms is additive and produces 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 therein) and play an active role in the development and intensification of convective process, thereby changing distributions of lightning and precipitation.

Earlier studies showed both positive and negative correlation between solar activity and thunderstorm activity at different stations (Brooks 1925; Sen 1963; Kleymenova 1967; Schlegel et al. 2001). Some of the results showing positive/negative correlations are given in Table 1. The effect of sunspot number/*Ap*-index on lightning activity during period 1998–2010 over South Asia and the Southeast Asia region was insignificant (Siingh et al. 2013b). However, when solar radio fluxes ($F_{10.7}$ cm) and cosmic ray fluxes were considered, lightning flashes showed negative correlation. Stozhkov (2003) and Pinto 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 number. This means a larger number of thunder days with larger flux of CRs. CRs and sunspot numbers show anti-phase behavior on the 11-year periodicity. The enhanced magnetic field frozen in the solar plasma during high solar activity scatters CRs in the interplanetary medium; as a result, CR entering the Earth’s environment reduces substantially (Duggal et al. 1981; Partamies 2004). These results suggest that

Table 1 Influence of solar activity on thunderstorm activity (correlation studies)

Place	Period	Correlation coefficient		References
		Positive	Negative	
South Germany	1888–1923		0.55	Aniol (1952)
	1923–1944	0.74		
	1889–1944		0.02	
Britain	1930–1973	0.80		Stringfellow (1974)
Siberia	27 Years	0.91	–	Brooks (1934)
Norway	56 Years	0.18		
Sweden (Inland)	35 Years	0.38		
Sweden (Coast)	25 Years	0.21		
Scotland	47 Years	0.20		
Ireland	50 Years	0.13		
England and Wales	47 Years	0.05		
Holland	37	0.00		
Germany	24	0.06		
Japan	24	0.26		
USA—	42			
Northeast	42	0.26		
Lake States	42	0.19		
Southeast	42	0.36		
North Central	42	0.06		
South Central	42	0.09		
Rocky Mountains	42	0.08		
Pacific Coast	43		0.16	
West Indies	55	0.34		
Southern Asia	43	0.40		
Tropical Pacific	–	–		
Australia	36		0.14	
New Zealand	–	–		
Middle Europe	1992–2000			Schlegel et al. (2001)
Trivandrum, India	1853		0.56	Girish and Eapen (2008) Remark: Only significant values are given
	1857		0.57	
	1861		0.62	
	1863	0.54		
	1987		0.47	
	1992	0.30		
	1994		0.60	
1999		0.30		
South Asia	1998–2010		0.09: SSN	Siingh et al. (2013b)
			0.05: Ap	
			0.16: CR flux	
			0.18: $F_{10.7}$	
Southeast Asia			0.07: SSN	
		0.01: Ap	0.23: CR flux	
			0.16: $F_{10.7}$	

SSN smooth sunspot number, CR cosmic ray, Ap Ap-index, $F_{10.7}$ solar radio flux

convective thunderstorm activity in relation to solar activity also depends on the location of observing station on the Earth where cosmic ray flux and local meteorological conditions may dominate. Their selected stations lie within the South Atlantic Anomaly (SAA) zone. Vieira and da Silva (2006) showed evidence for correlated behavior between the cloud-mediated radiation flux and cosmic ray within the SAA zone. Therefore, more work is needed to understand the cosmic rays–cloud relationship in the context of the 11-year solar cycle.

The variations in the solar wind conditions may result in lightning activity variations. Owens et al. (2014) reported a large (~50%) difference in average lightning rates between days when heliospheric magnetic field (HMF) points toward or away from the Sun and explained the results in terms of perturbation in the atmospheric electric circuit through changes in the local ionospheric potential and shifting in atmospheric foot points of various magnetospheric energetic particles. Scott et al. (2014) reported an increase in daily medians of lightning flash rate following the passage of corotating interaction regions (CIRs) in near-Earth space. They speculated that the increase in lightning activity could be the result of variation in the solar energetic particles and GCR fluxes. The changes may occur due to changes in atmospheric conductivity and hence atmospheric electric circuit. Owens et al. (2015) showed that the CIR effect on lightning is either the result of compression/amplification of the HMF or that energetic particle preconditioning of the Earth system prior to HMF polarity change. However, more studies are required to understand the impact of HMFs and CIRs on thunderstorm activity.

7.3 ENSO and Lightning

El Nino and La Nina phases, respectively, describe the warm and cold phases of the tropical land region (Williams 1992). As a result, surface temperature and water vapor distribution will differ in the two phases, which may result in differences in the distribution of lightning activity. Sători et al. (2009) reported more lightning activity in the Pacific Ocean in the La Nina phase as compared to the El Nino phase. Interestingly, the observed response was opposite in the coastal region. The results are discussed in terms of CAPE variation (Sători et al. 2009; Siingh et al. 2017; Saha et al. 2017b).

Penki and Kamra (2013b) studied the role of CAPE on lightning activity in the dry environment (NW) and moist environment (NE) and showed that in the NW region the flash per CAPE is 19 times of that in NE region. This indicates that CAPE is 120 times more efficient in the NW than the NE region in producing lightning. They further showed that the variance in flash rate in the region of mountains cannot be fully explained by the variance in the surface temperature and CAPE and that some other factors such as orographic lifting, rainfall and topography may also contribute to the variance of lifting. Computational results showed that the variance in CAPE due to orographic lifting in the Himalayan foothills (NE region) may contribute to 7.5% variance in lightning activity.

7.4 Land–Ocean Contrast

The observation of higher lightning activity over land surface as compared to ocean surface (Brooks 1925) is attributed to the stronger cloud up draughts over land surface as compared to ocean surface for the same input of heat energy. This may arise because the heat capacity of water is much larger than that of soil. 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 current (up to the ionosphere).

The heat input on the surface of the Earth varies with time of the day. As a result, convective process and hence lightning activity also show diurnal variation. This has been studied over major continents and oceans (Mach et al. 2011; Siingh et al. 2015b). The diurnal variation over the ocean surface does not show significant change, whereas different continents peak around 1600 LT. Sato et al. (2008) reported global distribution of positive and negative cloud-to-ground discharges and showed dominant occurrence of negative CG discharges over the ocean as compared to the land surface. In the context of the difference in lightning discharges, Williams and Stanfill (2002) proposed that a larger concentration of cloud condensation nuclei over land surface may lead to numerous smaller cloud droplets which could suppress coalescence process and thereby provide more supercooled droplets in the mixed-phase region where they participate in the charge generation processes. Williams et al. (2004) also suggested that the sensible heat flux over the land surface is stronger than over the ocean surface, providing stronger updrafts required for more lightning. Ramesh Kumar and Kamra (2010) tested these mechanisms over islands of different areas. Ramesh Kumar and Kamra (2012b) studied the lightning flash features over the Arabian Sea, the Bay of Bengal and the Chinese Sea and showed that flash features were different in different sea regions. Flashes were most frequent but least energetic in the Bay of Bengal. This was attributed to warmer sea surface temperature of the Bay of Bengal (Sikka and Gadgil 1980).

Another interesting example of land–sea contrast of an order of magnitude in lightning activity is observed in a small area almost parallel to the Western Ghats (India) during the onset and withdrawal phases of the monsoon (Kamra and Nair 2015). Lightning activity undergoes a dip in the monsoon months of maximum rainfall. Convection in this region frequently occurs due to modulation of low-level westerly flow by the Western Ghat mountains, which arrives almost perpendicular to the mountain range in the monsoon season. The low-level flow enriched in moisture and marine aerosols during its passage over the Arabian Sea is further enriched by the continental aerosols and anthropogenic aerosols released by big cities (Mumbai, Pune). The decrease in lightning activity during the active phase of the monsoon may be attributed to the reduction in aerosol of continental and anthropogenic origins in the airflow (Kar et al. 2009; Yuan et al. 2011). Cooling of the Earth's surface by the rainfall and increased cloudiness during the monsoon period may also reduce lightning activity.

8 Impact on Engineering System

Thunderstorms are the main driver of the GEC, influencing the ionosphere-to-ground resistance of which is nearly 90% is in the troposphere. Conductivity in the troposphere changes by change in thunderstorm activity and also from external influences on the upper atmosphere (Harrison 2004; Rycroft 2006) such as galactic cosmic rays and solar activity (solar wind, cosmic rays, solar flares, CMEs, etc.). Disturbances caused by the above sources have noticeable effects on engineering systems in the geosphere through space weather phenomena (Tinsley 2000; Thomson et al. 2007, 2010; Duro et al. 2012 and references therein). Space weather can disturb the communication, use of global positioning system (GPS), pose risk to spacecraft operations and satellites (Pirjola et al. 2005; Thomson 2007; Eastwood 2008). Space weather also causes geomagnetically induced currents (GICs) which may damage power grids, ocean cables and pipe lines (Boteler et al. 1998;

Pirjola 2002; Kappenman 2004, 2005). Barlow (1849) for the first time reported erratic behavior of telegraph cables coincident with auroras and magnetic disturbances, which are now believed to be due to induced voltages caused by solar disturbances. The problem is more serious with ocean cables because they act like a large antenna with limited tolerance on repeaters concentrated around low-frequency phenomena (Lanzerotti et al. 1986, 1993; Thomson et al. 1986, 1995). Analyzing power spectrum of induced voltage data, Thomson et al. (2007) showed the presence of acoustic standing waves in the frequency range ~ 250 to > 5000 μHz , termed as p-modes (p-pressure). Periods of p-modes range from about an hour to few minutes. p-modes are supposed to be associated with the internal systematic motions of the Sun. It has been proposed that p-modes are either generated by magnetic excitation (Moretti et al. 2001) or turbulence in the solar convective zone (Komm et al. 2000). Solar p-modes depend on solar activity (Woodard and Noyes 1985; Libbrecht and Woodward 1990; Elsworth et al. 1994).

A large number of events are recorded on power grid damage (Bolduc 2002; Molinski 2002; Pulkkinen et al. 2005; Thomson et al. 2007). A domain-oriented catalog of the systems affected by space weather, and their effects and measurable parameters are presented in tabular form by Koskinen et al. (2001). Thomson et al. (2010) summarized the principal “ten well known” and “ten unknowns” facts about GIC risk to power grids. The unknowns include the proper knowledge of signatures of interplanetary events and their possible extremes. Even damage of different components of power grid is not properly measured, specified and reported. As a result, systematic analysis of factual grid failures, extent of damage and their relations with GICs (solar activity) are not quantified. Duro et al. (2012) analyzed long-term transmission failures in Southeastern Brazil and reported that the largest number of failures occurred at the peak of solar activity in cycle 23 and then decreased substantially with the decrease in sunspot numbers. The reduction is 67 and 70% for the 138 and 140 kV grids in good correspondence with the decay in the sunspot numbers. They suggested that the increase in atmospheric conductivity caused by larger cosmic ray flux may have reduced the threshold voltage required to produce a lightning stroke and thus reduce their effectiveness in disrupting high-voltage power lines.

Solar wind drivers of geomagnetic induced current could be divided into shock, interplanetary coronal mass ejections (ICMEs) and corotating interaction regions (CIRs). Huttunen et al. (2008) analyzed 7-year (1999–2005) data of the large GIC (amplitude > 10 A) events at the Mantsala station, Finland (part of the Finish pipeline network), and showed that $\sim 91\%$ of them were associated with ICMEs, two events with CIRs and one event with a shock. They further showed that in most of the cases sheath regions of ICMEs were responsible for the largest number of GICs $> 10\text{A}$, whereas ejecta was found to be least efficient part of an ICME in driving significant GIC activity.

9 Cosmic Rays and Human Hazards

The spectrum of cosmic rays (of both galactic and solar origin) contains highly energetic and fully ionized nuclei (hydrogen, nuclei and small part of electrons), which are known to induce a variety of biological effects such as cell killing, mutation, chromosome aberration and carcinogenesis. The natural background radiation exists in addition to GCR in the atmosphere. The revised world population weighted annual effective dose is 0.32 mSv with in the range of 0.23–0.70 mSv covering 99% of world population (Sato 2016; Singh et al. 2011). Cosmic rays, being ionized charged particles, are deflected/scattered by the

geomagnetic field, and hence, their intensity increases with altitude and latitude. Cosmic ray flux at Earth also varies with the solar cycle. Hence, exposure dose depends on solar activity, height from sea surface and geomagnetic latitude. Usually, the GCR intensity increases by a factor ~ 70 , when altitude changes from sea level to 24 km (Shea and Smart 2000). Solar cycle effect maximizes at high latitudes, whereas altitudinal variation shows high value at polar latitudes. The worldwide distribution of calculated absorbed dose rates in air at ground surface due to cosmic rays is shown in Fig. 5 (Sato 2016). The dose rates increase at higher latitudes and altitude regions. The highest dose rate is 502 nGy/h around Mount Everest and the Tibetan Plateau, and the lowest dose rate is 26.8 nGy/h around Car Nicobar Island in the Indian Ocean. The world average including sea area is 33.7 nGy/h, while the average value over land area only is 42.8 nGy/h. Radiation exposure variations with altitude due to different nucleons of cosmic rays at geomagnetic latitude 55°N are shown in Fig. 6. Near the Earth's surface, muons are most effective, whereas electrons, protons and neutrons have dominant effect at higher (>5 km) altitudes. With the increase in population and enhancement in technology, air traffic increases nonlinearly and aircraft is bound to fly at higher altitudes for fuel efficiency which endanger crew members and passengers with enhanced dose of radiation. Copeland et al. (2008) reported dose rates to be 0.15, 0.52 and 1.3 mSv h^{-1} at 30,000, 40,000 and 50,000 feet. Considering flight level 10 km altitude, the accumulated radiation exposure from a flight schedule of 100 h per month for 6 months comes out to be 2.4 mSv, which is higher than the recommended limit of 2 mSv for a pregnant women (Shea and Smart 2000). General recommended limit for human being is about 20 mSv per year.

Cosmic ray particles penetrating tissues of the body produce a trail of dense ionization along particle trajectories. The ionization events damage a variety of critical molecular targets, produce complex lesions that hampers cellular repair processes and protracts the

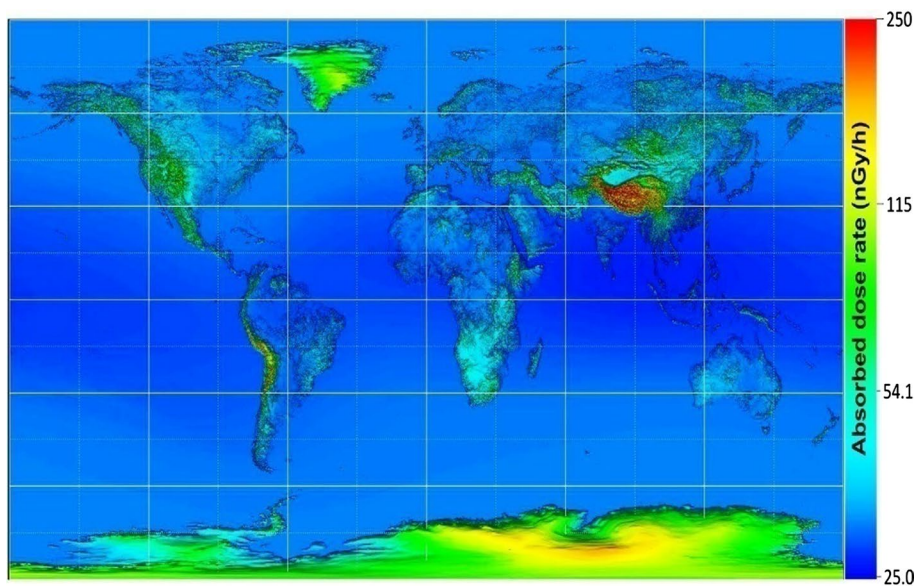


Fig. 5 Map showing the geographical distribution of calculated dose rates due to cosmic rays exposure in outdoor air at ground level for 2.5 arc-minute cells. The colors are expressed in logarithmic scale of dose rate. (Reproduced with permission from Sato 2016)

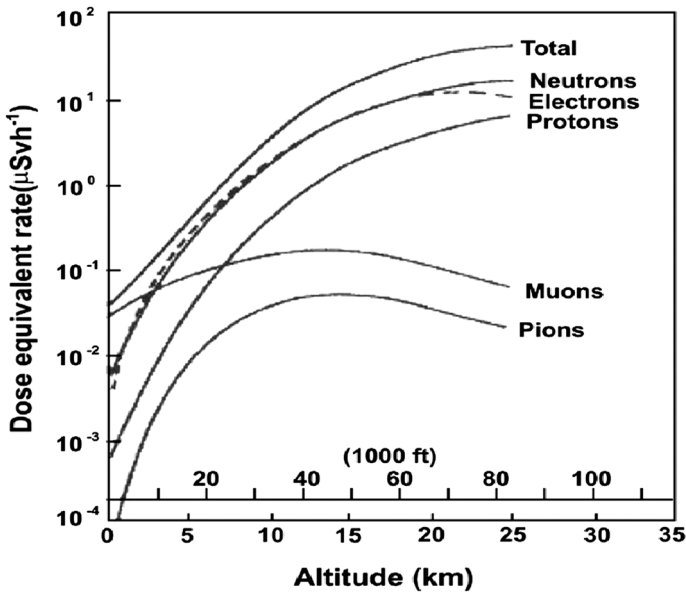


Fig. 6 Radiation exposures due to cosmic rays as a function of altitude at 55°N geomagnetic latitude. The exposure for different nucleons is also indicated. (Reproduced with permission from Reitz 1993)

recovery of irradiated tissues. The recovery processes are further confounded by the secondary ionization caused by delta rays emanated from primary particle tracks. The secondary ionization considerably increases the range and amount of cellular damage (Plante and Cucinotta 2008).

Exposure due to ionization variation may result in pulmonary fibrosis and cancer (Yarnold and Brotons 2010; Maddams et al. 2011). Recent studies showed that exposure to relatively low doses of protons and heavy ions (^{28}Si , ^{48}Ti , ^{56}Fe , ^{16}O) may lead to development of chronic lung injury and lung tumors (Christofidou-Solomidou et al. 2015; Nzabarushimana et al. 2015), reduction in functional activity of the brain (Britten et al. 2012), changes to the structural and synaptic integrity of neurons throughout different regions of the brain (Parihar et al. 2015a, b). It is important to note that the changes are found to persist for a longer time and showed almost no signs of recovery, regeneration and repair (Parihar et al. 2015a). The fluencies of charged particles can elicit significant and persistent reduction in the structure of neurons and dendritic spine density. Attempts are being made to understand radiation-induced changes in neuronal morphometry to behavioral performance (recognition, etc.) in terms of structural changes in neurons (Parihar et al. 2015a). In addition to the above changes, charged particles may cause alteration in the prevalent proteins (Christofidou-Solomidou et al. 2015).

Exposure of protons or heavy ions has strong genotoxic potential and can also affect the cellular epigenomilo DNA methylation (Goetz et al. 2011; Jangiam et al. 2015). DNA methylation plays a critical role during development in the maintenance of cellular homeostasis and is the primary regulators of the proper expression of genetic information in sex tissue and cell type-dependent manner. It also serves as a key mechanism in the silencing of repetitive elements (Jones 2012). Nzabarushimana et al. (2014) reported that alterations in global DNA methylation primarily originate from the repetitive elements rather than

from specific genes. Loss of repetitive elements—associated DNA methylation and their reactivation, may lead to genomic instability, which is one of the driving forces of carcinogenesis (Rodríguez-Paredes and Esteller 2011; Miousse and Koturbash 2015). The role of epigenetic events in radiation-induced pulmonary fibrosis has also been recently recognized (Weigel et al. 2015).

10 Recommendation for Future Research

Cosmic rays being highly energetic charged particles from the solar and galactic origin interact with the terrestrial atmosphere and as a result influences different processes occurring in the magnetosphere, ionosphere, lower atmosphere and biosphere. We have briefly discussed present understanding of cosmic ray impacts on thunderstorm and lightning discharges, global electric circuit, engineering systems and human health. Some of the problems which are still not properly understood are listed below:

- Cosmic ray-mediated cloud microphysical processes such as electro-scavenging/electro-freezing, electro-activation and electro-collection have been proposed for the formation/growth of cloud condensation nuclei. Laboratory experiments/simulations suggest formation of CCN by these processes, but field measurements give conflicting results, especially about the fraction of CCN formed by this process in addition to the conventional sources, such as sea salt mineral dust, volcanic eruptions and dust storms, present in the atmosphere. Wilson (1929) suggested lightning served as an important source of CCN formation. More studies are required with varying flux and energy of charged particles to study the formation of CCN under different atmospheric and aerosol conditions.
- Based on experimental/theoretical studies, it has been proposed that cosmic rays may influence cloud life time, cloud radiation properties, precipitation and lightning activity. However, quantitative estimates studies are not available. It has not even been demonstrated as to what percentage of lightning is triggered by cosmic rays.
- The basic physics of cloud formation and involved thermodynamics is known, but detailed cloud microphysics and the complex connection between climate and ecosystems are not fully understood which is important and essential for a nonlinear system. Clouds being a nonlinear system (Tsonis 2013) are very sensitive to the initial conditions and to changes in parameters. Therefore, further work is needed to improve our understanding of the formation of clouds and dependency of climate system on clouds and its components. For example, the influence of the electrification on cloud microphysics could be investigated using simultaneous high-resolution measurements of electrical properties, particle and droplet parameters, water and water vapor distribution from cloud top to the bottom.
- Thunderstorm electrification mechanisms generally include cosmic ray-generated charged particles in the lower atmosphere and their attachment with aerosols. As different mechanism of cloud charging may operate simultaneously, the contribution of such charged particles separately in such mechanisms should be studied using modeling work. Even in the lightning initiation process, cosmic rays have been proposed to be one of the likely candidates. Much more precisely planned observations and simulation work are needed to support this hypothesis. At present, it is not known what fractions of lightning discharges are caused by cosmic rays.

- TGFs are found to be associated with the early stage of positive intra-cloud discharges. The relation of TGFs with negative intra-cloud discharges should be explored. The source of TGFs is not properly understood. Whether they are produced inside the cloud or outside the cloud and whether they are generated by the highly energetic runaway electron discharges or not. The proposal of Dwyer et al. (2008) about terrestrial electron beams (TEBs) should be examined with suitably planned measurements and modeling studies.
- The main contributor to the GEC is thunderstorm/lightning which varies with latitude/longitudes and seasons. Pollution also affects thunderstorms and lightning. Even cosmic rays and solar energetic proton events perturb GEC which varies with latitudes. Therefore, short-term perturbations in GEC parameters over a wide latitudinal range along with lightning, CR and SEP (solar energetic particle) measurements are required to understand changes in GEC globally.
- Aerosols affect climate parameters, both directly through modification of solar radiation reaching the surface and indirectly through the modification of cloud nucleation, thunderstorm electrification and precipitation. Estimates of the indirect effect of aerosols on climate have large uncertainties, and accurate assessment of the same is urgently required for its incorporation in models for climate and climatic change.
- Available studies showed that convection depends on surface temperature, CAPE, sensible heat flux, total heat flux, orography of the region, thermodynamic state of the boundary layer, etc. However, the precise nature of the dependence of convection on these parameters is not well understood. Further modeling work is required in this field.
- Lightning discharge activity acts as a global thermometer for the surface temperature (major climate variable). Lightning and TLEs are linked to the production of NO_x that leads to the production of O_3 , a strong greenhouse gas. Also, lightning can ignite fire in temperate and boreal forests leading to emission of greenhouse gases, aerosols and warming the atmosphere. Further, thunderstorms transfer water vapor (a greenhouse gas) from the boundary layer to the upper atmosphere. All these may act as a strong feedback to climate. Quantitative assessment of these effects and their relation with lightning/thunderstorm characteristics are lacking.
- Solar-terrestrial effects are still poorly understood. The vertical electric current flowing down from the upper to lower atmosphere in polar regions provides a good link to study the interactions between the global electric circuit and climate. Observational programs and modeling efforts to investigate such linkage between the global electric circuit and the weather and climate in the polar regions needs are needed.

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