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Tropospheric-Ionospheric Coupling by Electrical Processes of the Atmosphere

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ABSTRACT

Troposphere-mesosphere coupling features are considered in the case when the effects of strong mesospheric electric fields are allowed for, and electron relaxation cooling in the mesosphere due to disturbances in the tropospheric conductivity is discussed. The effects are considered of these processes on the ionospheric conductivity. Electrical processes occurring in the atmosphere couple the atmosphere and ionosphere, because both DC and AC effects operate at the speed of light. The electrostatic and electromagnetic field changes in global electric circuit arise from thunderstorm, lightning discharges, and optical emissions in the mesosphere. The precipitation of magnetospheric electrons affects higher latitudes. The radioactive elements emitted during the earthquakes affect electron density and conductivity in the lower atmosphere. In the present paper, we have briefly reviewed our present understanding of how these events play an important role in energy transfer from the lower atmosphere to the ionosphere, which ultimately results in the Earth's atmosphere-ionosphere coupling.

Keywords: Lightning discharges, Global electric circuit, Electrical processes, Ionospheric coupling

1. INTRODUCTION

The subject of atmospheric electricity had its origins in the eighteenth century but developed into the concept of the global atmospheric electric circuit in the early twentieth century [1]-[3] and matured considerably in the first decade of the twenty first century [4]. Atmospheric electrical coupling occurs from near the Earth's surface at troposphere up to the ionosphere at ~ 80 km altitude and higher. This coupling takes place rapidly close to the speed of light c [5], contrary to coupling mechanisms involving mechanical waves which propagate at speeds much lower than c. The Earth's atmosphere is a layer of gases surrounding the Earth and is retained by Earth's gravity. On the basis of temperature distribution, atmosphere can be classified into troposphere, stratosphere, mesosphere and thermosphere. The temperature in the thermosphere remains nearly constant. The stratosphere and mesosphere regions are counted as the middle atmosphere above which the atmosphere is marked as the upper atmosphere. At the upper atmosphere the solar radiation and other sources ionize the neutral constituents producing plasma of ions and electrons. The region extending from the mesosphere to the thermosphere is known as the ionosphere where plasma dynamics is controlled by the collisions between the ionized particles and neutrals and also between the ionized particles themselves. The region above the ionosphere is called the magnetosphere wherein the dynamics of charged particles is controlled largely by the Earth's magnetic field as the density collision frequency is very low in this region. There is practically no sharp boundary between the upper ionosphere and the lower magnetosphere region. The study of electrical coupling between the troposphere and the ionosphere is an important assignment related to atmospheric electrodynamics [6]. Observations in mesosphere support strong electric fields of up to 10 V/m [7], [8], indicate that the mesosphere should be treated as an active element in the atmospheric circuit. The formation of transient optical emissions in the mesosphere and lower ionosphere are named as sprites which further supports the concept of strong mesospheric electric fields [9]. All this phenomena demand a critical searching of mechanisms related to electrodynamics caused by the effects of disturbances of tropospheric conductivity on lower ionosphere [10], [11]. It is the purpose of the paper to examine the present understanding of the link between the processes operative in the lower atmosphere and their electro dynamical coupling with the ionosphere.

2. EXTERNAL SOURCES OF FORCING TO THE IONOSPHERE

The ionosphere is largely controlled by different external sources of forcing as well as by a number of mechanisms operative in the system to convert, transport and redistribute the input energy. Extreme ultraviolet (EUV) radiation due to Sun and particle energy from the sun in the form of precipitating solar wind plasma energetic particle are the main factors influence from above. On the other hand, tides, gravity waves, planetary waves, electromagnetic waves in wide frequency range, turbulence, convection and similar many other phenomena contribute from below. Even processes occur below/on/above the surface of the Earth have important role to affect the ionosphere and its processes. In fact, lower atmosphere to magnetosphere behalves as a multi-coupled system under many situation. The coupling is found to form mainly through the chemical, electrical and dynamical processes. The ionosphere reacts with many phenomena like lightning discharges, functioning of high-power transmitters, high-power explosion, volcano eruptions, earthquakes and typhoons through a chain of interconnected mechanisms in the lithosphere-atmosphere-ionosphere interaction system. Thunderstorms formed at the troposphere play a vital role in transferring energy from the atmosphere to the ionosphere [8] and hence to establish electrical coupling through the global electric circuit (GEC). Earth's surface has a net negative charge and so there is an equal and opposite positive charge distributed throughout the atmosphere above the surface. The electrical structures of the lower atmosphere, GEC and conductivity profile have presented in Figure 1.

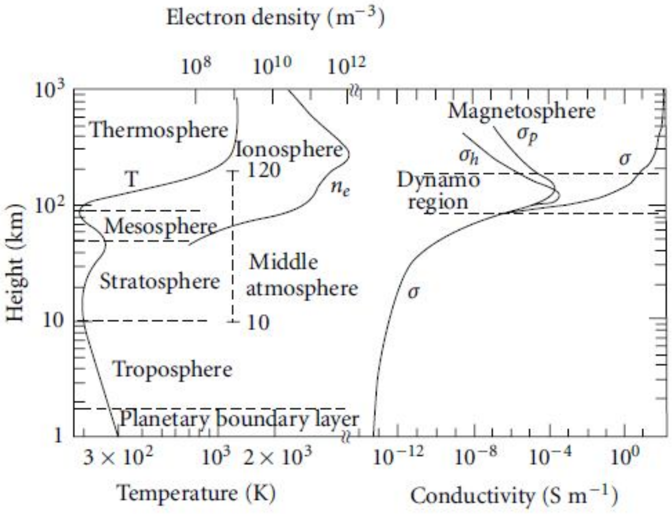

Figure 1 Variation of temperature, electron density and electrical conductivity in different atmospheric layers [6]

The atmospheric layers are significantly influenced by cosmic ray flux [9], high-power transmitted waves [10]–[12] and earthquakes [13]. Lightning-generated whistler mode waves scatter radiation belt trapped electrons to precipitate into the lower ionosphere and formation of ionospheric in homogeneities [14], [15]. Powerful high-frequency transmitted waves produce ionospheric heating to cause generation of ultra-low-frequency (ULF) and extremely low-frequency (ELF) waves [16], the formation of very low-frequency (VLF) ducts [17], [18], the acceleration of ions and the excitation of atmospheric emissions in various spectral bands [19]. The convective activities in thunderstorms are responsible to produce gravity waves which propagate to the lower ionosphere. In course of this propagation they deposit energy and momentum through the mechanism of breaking and absorption and may help to initiate sprites and other transient luminous events [20] – [22]. The associated wave instability generates related field-aligned currents and plasma density irregularities in the upper ionosphere [23]-[25]. The satellite observations anomalous DC electric field, small scale plasma in homogeneities, ULF magnetic pulsations and correlated ELF emissions [26] are considered as important evidences for these processes.

3. AC AND DC VARIATIONS

Above large thunderstorms transient luminous events (TLEs), like sprites, elves and blue jets [27], may occur which may extend up to the ionosphere. It has been reported that the lower ionosphere responds to activity from above in the form of wave-particle interactions between whistler-mode waves from lightning and energetic electrons trapped in the magnetosphere [28].This produces extra ionization in the lowest ionosphere [29]. Figure 2 reveals the broad range of temporal scales involving many phenomena of importance. Out of these electrical discharge phenomena are on the shortest time scales of microseconds order [30]. Lightning radiates all radio frequencies from MHz to ~ 3 kHz where the spectrum shows peaks at 10 kHz [31], [32] to "slow tails" at frequency ~ 100 Hz [33] and to the longest wavelength electromagnetic waves at frequency ~ 10 Hz. These latter waves are responsible to excite Schumann resonances of the spherical shell cavity between the good conducting Earth and ionosphere [34]-[40]. Some stations around the world are recording the radiation at different frequencies generated by lightning and sprites. Williams et al. [41] recorded this for radio signals produced over Africa while Whitley et al. [42] have noted that with four stations around the world sources can be identified to an accuracy of ~ 10 km. Shvets et al. [43], [44], Nakamura et al.[45], Shvets and Hayakawa [46] and Yamashita et al. [47] have also reported interesting results on these aspects.

Figure 2 clearly shows that on the time scale from seconds to hundreds of seconds, blowing space charge related to turbulence in the boundary layer from the Earth's surface up to ~ 2 km altitude generates electrical fluctuations. In order to illustrate the different components associated with both AC and DC variations we have plotted the altitude against the temporal scales. Primarily, the space charge can be ionic in clean air or particulate in polluted air. These particulate space charges are subject to turbulent motions which results in electrical fluctuations. The processes shown in the figure contribute widely to the generation of AC variations in the global circuit.

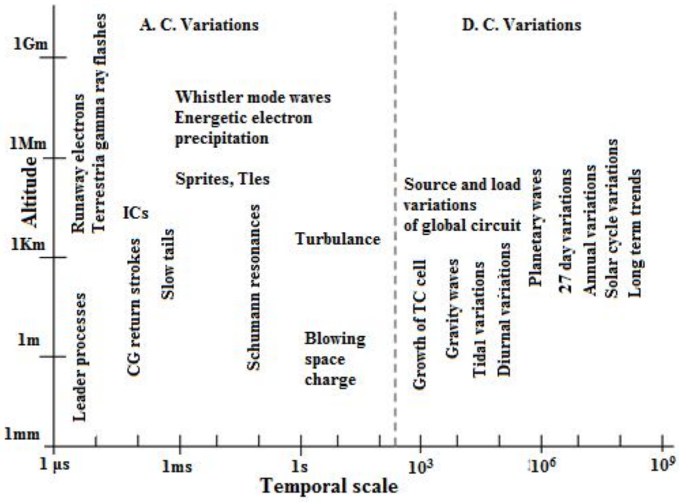

Figure 2 AC and DC variations on time scale from seconds to hundreds of seconds corresponding to different altitudes

The electromagnetic pulses from a large CG discharge deposits energy in the mesosphere to create an expanding ring of light at ~ 90 km altitude which is called elves. The consequent large electrostatic field above the thundercloud produces sprite from about 80 km at the base of the ionosphere down to around 55 km [48]-[52] while blue jets appear from the top of the thundercloud. The DC variations, on time scales of a fraction of an hour, are linked to the development and evolution of thunderstorm cells. Mechanical waves produce in the form of gravity waves, tidal variations (e.g., diurnal, semi-diurnal and two day waves) and long period planetary waves. At longer time scales there are variations associated with the changing energy input over the 27-day solar rotation period, annual variations, variations over the 11 year solar cycle and long term trends. In the figure the boundary between DC and AC phenomena is shown at 200 s which is the electrical time constant of the global atmospheric electric circuit wherein the spherical capacitor is formed between the Earth and the ionosphere [53].

4. UPWARD ELECTRODYNAMICS' COUPLING OF THUNDERSTORMS

There are around 2000 thunderstorms active at any time over the Earth's surface and on average lightning strikes the Earth 100 times per second [54]. About 1000 coulombs of bound space charge are separated and maintained during the active periods of a thunderstorm [55] with CG lightning discharges involving the transfer to the ground of up to 300 coulombs of charge in several ms [56]. This creates a large quasi-electrostatic (QE) field which exist in the mesosphere and lower ionosphere regions over millisecond time scales. These fields combine with intense electromagnetic pulses [57] generated by lightning currents heat the ambient electrons [58] to accelerate energetic runaway electrons [59], [60], producing ionization and optical emissions. Experimental evidence suggests strong upward electro dynamical coupling of thunderstorms to the mesosphere and lower [61]-[66] and optical emissions in clear air above thunderstorms associated with sprites [67]-[73] and blue jets [74] as well as airglow enhancements [75]. The latter are thought to be associated with rapid (< 1 ms) optical emissions at 80-95 km altitudes referred to as "elves" [76]-[78]. Sprites are also uniquely associated with positive CG lightning discharges [79]-[81]. The observations of gamma ray bursts of terrestrial origin [82]-[83], associated with positive CG lightning discharges [84] and intense VHF bursts [85] constitute further phenomena of upward coupling of energy associated with thunderstorms.

4.1 Theoretical Mechanisms

The mechanisms related to transient luminous events are based on heating of the ambient electrons by electromagnetic pulses generated due to lightning discharges [78], [86]-[90] or due to large quasi-electrostatic thundercloud fields [73], [79], [91]-[94] and on runaway electron processes [73],[80], [95]-[96]. It is suggested that the quasi-electrostatic thundercloud fields are capable to maintain the ionospheric electrons well above their ambient thermal energy. Simultaneous observations of early/fast VLF events and sprites [64] indicate that these effects may be a manifestation of the same physical process consistent with model predictions of both optical emissions, heating and ionization changes related to the quasi-electrostatic thundercloud fields [91]-[93], [97]. Wilson speculated that a discharge between the top of a cloud and the ionosphere might be the normal accompaniment of a lightning discharge to ground [98]. Figure 3 illustrates the different phenomena (upper one) and the theoretical mechanisms involved therein (lower one) of lightning-ionosphere interactions operating at different altitudes. The figure clearly shows the optical emissions ($\Delta\nu$) observed as sprites, blue jets and elves, as well as heating (ΔT) and ionization changes (ΔNe) detected as very low frequency (VLF) signal changes.

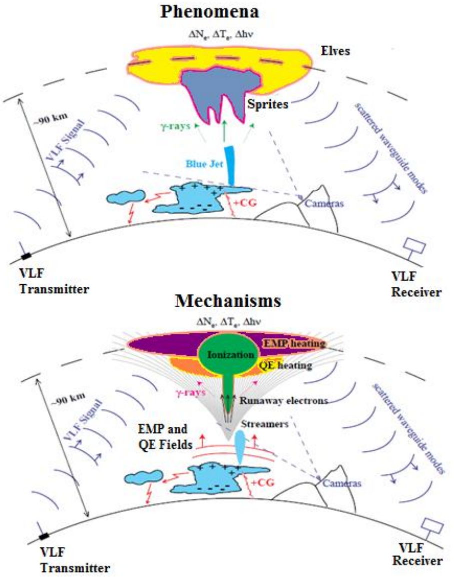

Figure 3 The different optical phenomena (upper one) and the theoretical mechanisms involved therein (lower one)

As illustrated in Figure 4, a cylindrical coordinate system (r, φ, z) is taken with the z-axis representing the altitude. The ground and ionospheric boundaries, taken at z=90 km, are assumed to be perfectly conducting and the whole system is considered to be cylindrically symmetric about the z-axis. Two types of boundary conditions can be used at the cylindrical boundary. If we imagine a perfect conductor at r=60 km, we have $\partial\psi/\partial z = 0$ (or $\psi = 0$), where ψ is the electrostatic potential. This condition was applied by Illingworth [99] for considering the solution of the electrostatic fields in a “tin-can”. Alternatively, one can assume that $\partial\psi/\partial r$=0, following Tzur and Roble [100]. Both the boundary conditions taken in this fashion are artificial and lead to unphysical modification of the electric fields near the boundary. The temporal and spatial evolution of the electrostatic field system does not depend on these edge fields if the boundaries are taken at far enough from the charge sources. The presence of the conducting boundary at r=60 km leads to an error of less than ~10 % on the magnitude of the electric field at r=50 km and z=10 km.

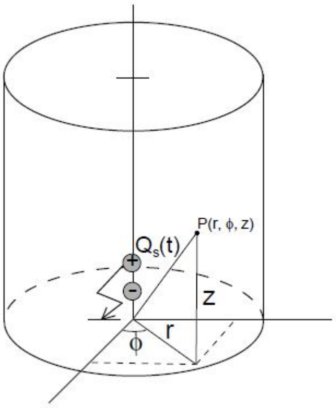

Figure 4 Coordinate system used in calculations

The electrostatic field E, $\vec{E} = \vec{\nabla}\psi$, the charge density ρ, and the conduction current $J = \sigma E$ can be calculated using the following equations:

$$\frac{\partial(\rho+\rho_s)}{\partial t} + \nabla.(\vec{J} + \vec{J_s}) = 0 \qquad \ldots (1)$$

$$\nabla.\vec{E} = \frac{(\rho+\rho_s)}{\varepsilon_0} \qquad \ldots (2)$$

where ρ_s and $\vec{J_s}$ are the thundercloud source charge and current which must satisfy the equation

$$\frac{\partial\rho_s}{\partial t} = -\nabla.\vec{J_s}' \qquad \ldots (3)$$

where $$-\nabla.\vec{J_s}' = \nabla.\vec{J_s} + \frac{\rho_s\sigma}{\varepsilon_0}$$

Here the effective source current J'_s is introduced so as to compensate any change in the thundercloud charges due to the conduction current.
Equation can then be written as

$$\frac{\partial\rho}{\partial t} + \nabla\sigma.\vec{E} + \frac{\rho\sigma}{\varepsilon_0} = 0 \qquad \ldots (4)$$

If in (4) one simply assumes

$$\frac{\partial\rho_s}{\partial t} = -\nabla.\vec{J_s}, \text{ (i. e. } \vec{J_s} = \vec{J_s}') \qquad \ldots (5)$$

It is necessary that ρσ/ε0 be substituted with [(ρ + ρs)σ]/ε0.
In this case if one avoids the effects of the conductivity gradients, the quasi-stationary solution of equation (4) becomes simply $\rho = -\rho_s$ so that the source charge can be totally compensated by charge induced in the conducting medium over a time scale $\sim\varepsilon_0/\sigma$. In fact, ρ_s being a function of time [i.e. $\rho_s = \rho_s(t)$], the quasi-stationary solution $\rho = \rho_s$ has a definite physical meaning when the characteristic time scale of $\rho_s(t)$ is sufficiently greater than $\frac{\varepsilon_0}{\sigma}$. Equation (1) and (2) clearly indicate that the introduction of $\vec{J_s}'$ permits us to specify the charge dynamics inside the cloud as an externally noted function of time.

5. LIGHTNING CURRENT AND CHARGE

The input parameters which are required to specify externally for each model calculation are: (i) the altitude profiles of ambient ion conductivity and electron density; (ii) the magnitude (Q_o) of the charge transferred and the time constant (τ_s) which determines the rate at which the charge is transferred; and (iii) the altitude of the charge removed. None of these parameters can be obtained directly and also some restrictions are there on the magnitude of the removed charge Q and the time scale of the charge removal τ_s.
For the quasi-electrostatic heating model [101], the thundercloud charging and discharging process is considered as two stages. During the pre discharge stage with duration τ_f, the charge Q_o slowly accumulates in the thundercloud. The second stage is the lightning discharge when the thundercloud charge is completely removed very fast over a time τ_s, which is generally of the order of several ms. The continuous thundercloud charge dynamics can be expressed mathematically in the form:

$$Q(t) = Q_0 \frac{\tanh\left(\frac{t}{\tau_f}\right)}{\tanh(1)}, \quad 0 \square t \square \tau \qquad .. (6)$$

$$Q(t) = Q_0 \left[1 - \frac{\tanh\left(\frac{t}{\tau_s}\right)}{\tanh(1)}\right], \tau_f < t < \tau_f + \tau_s \qquad \ldots (7)$$

$$Q(t) = 0, \tau_f + \tau_s < t \qquad \ldots (8)$$

It may be noted that the functional variation as tanh (·) is somewhat arbitrary. For the functional dependence of $Q(t)$ the amplitude of the peak current at $t = \tau_f$ can be obtained from:

$$I_p = \frac{dQ}{dt} = \frac{Q_0}{\tau \tanh(1)}, \quad t = \tau_f \qquad \ldots (9)$$

From knowledge of Ip, the peak electric field at a distance of 100 km from the lightning discharge can be calculated as [102],

$$E_{100} = \frac{I_p v}{2\pi D \varepsilon_0 c^2} \qquad \ldots (10)$$

Here, c is the speed of light in free space, ε_o is dielectric permittivity of free space, $D = 10^5$ m and $v = 1.5 \times 10^8$ m/s

It may be noted that E_{100}=75 V/m corresponds to a peak current of I_p=270 kA and a total charge removed in lightning of Q_o=200 C, if we take into account τ_s=1 ms which is a reasonable data based on experimental result [103].

5.1 ELECTRON MOBILITY

The electron mobility μ_e is a complicated function of the electric field which may be determined by many loss processes each having different cross sections [104]. One may apply a functional dependence of μ_e on the magnitude of the electric field *E* which is derived from experimental data [104], [105]. This function can be expressed in analytical form:

$$\log (\mu_e N) = \sum_{i=0}^{2} a_i x^i, \; EN_0 / N \geq 1.62 \text{ x } 10^3 \text{ V/m} \quad \text{... (11)}$$

$$\mu_e N = 1.36 N_0 , \; EN_0/N \geq 1.62 \text{ x } 10^3 \text{ V/m} \quad \text{... (12)}$$

where $x = \log(E/N)$, $a_o = 50.970$, $a_1 = 3.0260$, and $a_2 = 8.4733 \times 10^{-2}$. The analytical expression can be utilized for computationally efficient calculation of the electron mobility for any combination of electric field and number density of air molecules (i.e., altitude). This method provides results which can be compared well with those obtained from kinetic formulations. The electron mobility μ_e when plotted as a function of the electric field *E* and the molecular number density *N* of atmospheric gas, as shown in Figure 5, interesting variations have been noted [104].

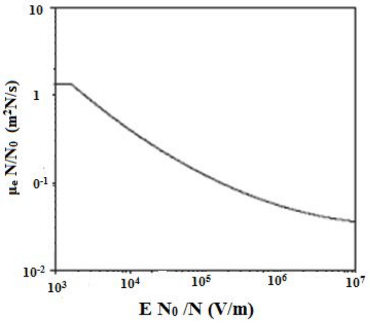

Figure 5 Electron mobility μ_e as a function of the electric field *E* and the molecular number density *N* of atmospheric gas

6. COUPLING MECHANISMS

Thunderstorms have role to couple the atmosphere and the ionosphere. Potential difference between the ionosphere and the Earth is maintained due to thunderstorms' pumping action of lightning discharges. Intense atmospheric disturbances owing to earthquakes, volcanoes, tropical storms, typhoons affect electrical properties of the lower ionosphere. Thunderstorms and lightning discharges produce major current source in global electric circuit (GEC) [106]. Basically, the GEC is based on the concept that the quantity of electric charge has to be conserved in the Earth's atmosphere-ionosphere-magnetosphere regions. The essential features of the global atmospheric electric circuit are shown in Figure 6.

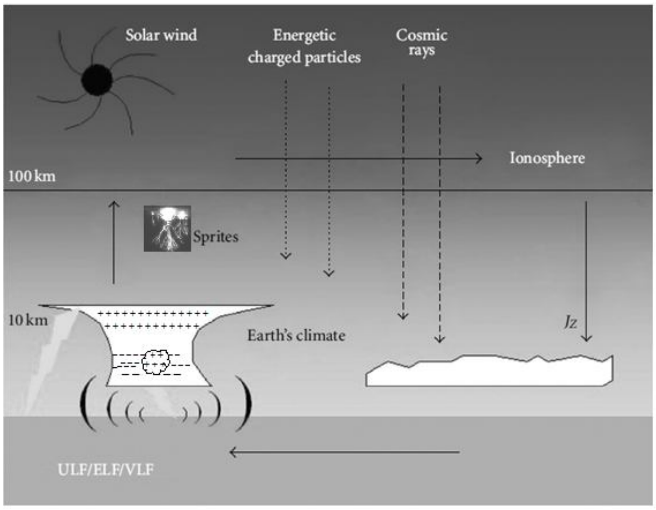

Figure 6 Features of the global electric circuit

Solar wind interactions with the Earth's magnetic field generate additional current [107]; potential gradient modulation may arise owing to coupling of geomagnetically-induced variations in the magnetospheric dynamo through the global circuit. Precipitations from electrified clouds are also act as current driver [108]. Considering the realistic model an equivalent circuit with capacitors, resistors, and switches is drawn in Figure 7 [109]. The switch drawn in the figure is closed for a short time when a certain type of discharge occurs. For example, the switch *S*1 closes for a few ms when a sprite occurs above a particular type of thunderstorm and fair-weather time constant, *r C* ~ 2min (*r* ~ 200 ohms, *C* ~ 0.7F). Generators act over <1% of Earth's surface and rest 99% of the Earth's surface region behalves as a load on the circuit. The total current (I) flowing in the circuit becomes ~1 kA [109], [110]. A schematic equivalent circuit diagram for global electric circuit is shown in Figure 7.

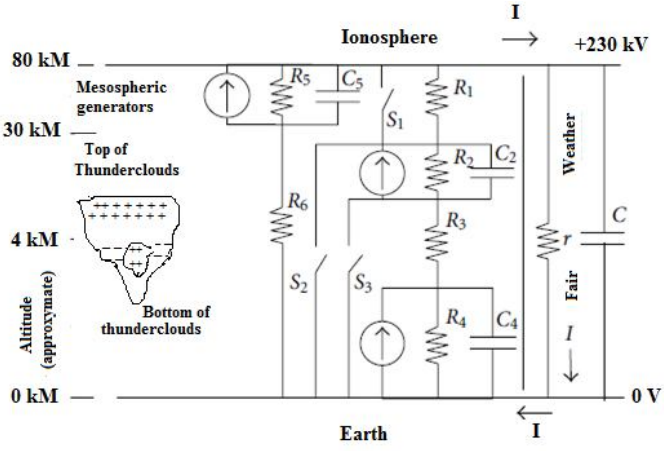

Figure 7 Schematic equivalent circuit diagram for global electric circuits

Both radioactive substances and charged aerosols injected into the atmosphere modify the altitude profile of conductivity, perturbation of electric field, generation of external currents and current in the ionospheric layer. Consequently, the Joule heating of the ionosphere and instability of acoustic gravity waves take place to manifest in the formation of horizontal in homogeneities of ionospheric conductivity. Again the excitation of plasma density fluctuations and ULF/ELF emissions in the ionosphere, upward plasma transport, and generation of field aligned currents and plasma layers, modification of F2-layer and change in the ion composition of the upper ionosphere take place [111], [112]. All these changes affect the GEC and the Earth's climate. Figure 8 shows a schematic diagram which can be applied for computing external currents and enhancement of electrical conductivity in the lower atmosphere which is responsible to produce an increase in the electric field in the ionosphere due to the injection of charged aerosols and radioactive elements [8]. The schematic model shown in Figure 8 can be used to calculate electric field due to the injection of charged aerosols in the atmosphere-ionosphere circuit.

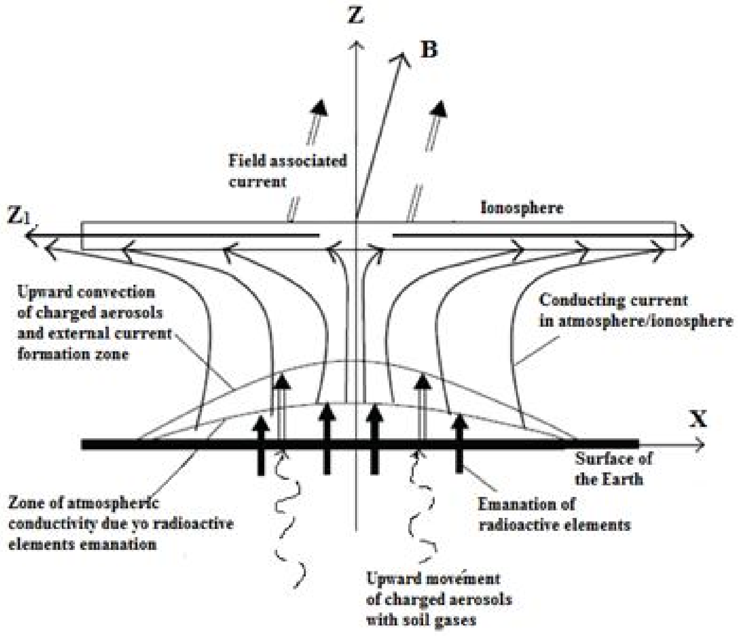

Figure 8 Schematic model used for the calculation of electric field due to the injection of charged aerosols in the atmosphere-ionosphere circuit

It should be pointed out that there are some other complex processes participating in multiple scales of variability. Turbulent mixing and also eddy diffusion are other ways of transport from bottom. In the lowest part of the atmosphere over continental surfaces, ionisation is produced from the escape of radon isotopes [113] as well as by galactic cosmic rays arriving from beyond the solar system [114]-[116].

7. CURRENT FLOW AND IONOSPHERIC POTENTIAL

Integrating the vertical electric field profile derived from aircraft or balloon measurements up to the troposphere one can determines the ionospheric potential. As reported at 12 UT this has the value 230 kV and it rises to 310 kV at 16 and 20 UT which then falls to 200 kV at 24 UT. The curve closely resembles the Carnegie Curve [117] and is considered as one of the “confirming ideas” [119] supporting the behaviour of the Earth-atmosphere global circuit system. A significant generator of the conduction currents up to the ionosphere, also known as Wilson currents, is owing to the action of thunderstorms which serve as batteries. Figure 9 is taken from Harrison and Usoskin [119] wherein the left panel shows the ionospheric potential (V_i) from various data sets. In the figure, the larger circles show monthly averages for months having four or more V_i values, and the neutron count rate at Climax, Colorado, as the grey line, observed from 1966 to 1972. The right hand side figure, on the other hand, shows a plot of the monthly-averaged V_i values against the monthly average neutron count rate. In the figure the error bars show ± two standard errors.

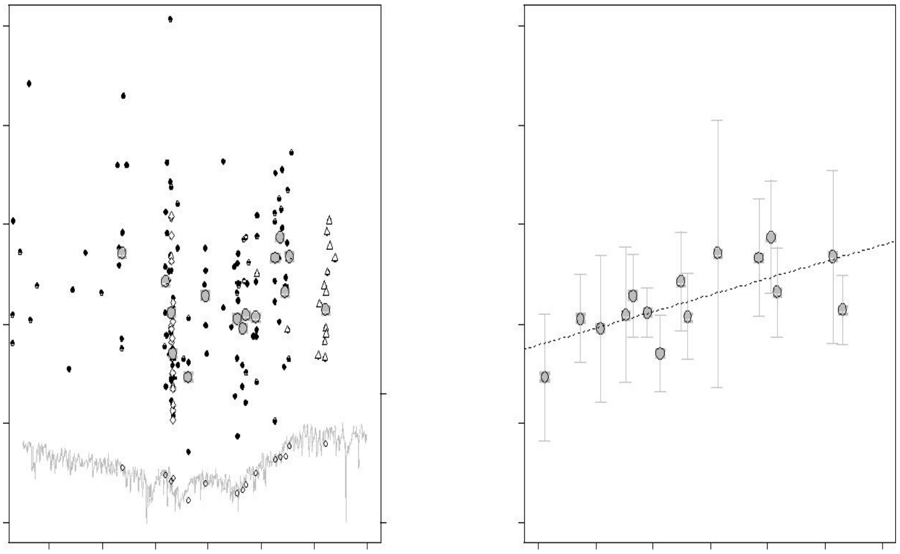

Figure 9 (a) The ionospheric potential (V_i) from various data sets and (b) plots of the monthly-averaged V_i values against the monthly average neutron count rate [119]

8. CONCLUSIONS

The electrodynamics coupling between the Earth’s atmosphere and the ionosphere is very complex and described by the global electric circuit. Currently, many aspects are not well understood.

Scopes for some further studies are outlined below:
(i)More detail investigation is required to find the relative contributions made by thunderstorm generators and by rain/shower cloud generators as drivers of the global electric circuit [120], [121],
(ii) To investigate land-sea interactions and their characteristic differences in detail,
(iii) To analyze the effects of cosmic rays (especially Forbush decreases) on lightning, low level clouds, and their effects in the fair weather (load) part of the global circuit,
(iv) To investigate the energy densities of the many different physical processes involved
(v) To continue the search for signatures in the vertical electric field observed near the Earth’s surface and throughout the atmosphere due to
    (a) Solar flares,
    (b) Forbush decreases, solar proton events,
    (c) Auroral activity and jets, elves and sprites.

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