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A critical review of the Earth's electrical atmosphere

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Abstract

Many investigations have been made towards the understanding of lightning and thunderstorms and in relating them to the global electric circuit. Great attempts have been made towards the study of the electrical environment of the Earth's atmosphere during the past century. The electromagnetic fields and currents connect different parts of the Earth's environment, and any type of perturbation in one region affects another region. The modern theory of the global electrical circuit has been discussed briefly. Interconnection and electrodynamic coupling of various regions of the Earth's environment can be easily studied by using the global electric circuit model. Deficiencies in the model and the possibility of improvement in it have been suggested. Application of the global electric circuit model to the understanding of the Earth's changes of climate has been indicated.

Keywords

Atmospheric electricity; Fair-weather atmosphere; Galactic cosmic rays; Global temperature; Global electric circuit; Electrical conductivity; Ion-aerosol interaction; Weather; Climate.

INTRODUCTION

The atmosphere of the Earth is filled with electrons, negative ions and positive ions, comprising of very low plasma density[1]. These charged particles interact amongst themselves and also interact with electric and magnetic fields present in the medium, leading to the control of space–plasma environments by an electrodynamic process. The outer boundary of the Earth's environment extends up to the magnetosphere, which is formed by interaction of the solar wind with the geomagnetic field[2]. The electric current developed in the magnetopause helps in the creation of the tail. The cavity carved as a result of the deflection of the solar wind by the geomagnetic field and enclosed by the magnetopause is called magnetosphere (Figure 1).

The magnetosphere contains the radiation belt composed of energetic charged particles trapped in the magnetic field. The number density of electron- ion pairs in the magnetosphere is highly variable, ranging in order of magnitude from a low of 10^6 m^{-3} in parts of the tail up to 10^{12} m^{-3} in the densest portions of the dayside atmosphere. As a result of the solar wind's interaction with the geomagnetic field, mass, momentum, and energy are transferred from the solar wind to the magnetosphere, and a complex pattern of several current systems is generated in different parts of the magnetosphere (Figure 1). The

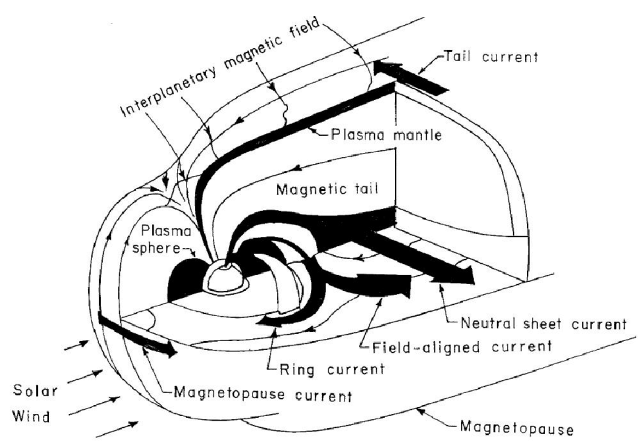

Figure 1 : Three-dimensional schematic diagram of the Earth's magnetosphere (thin arrows indicate the direction of the magnetic field and thick arrows show the magnetopause's current, ring current, field-aligned current, neutral sheet current, and tail current)[14].

variability of solar conditions reflects in the variability of the solar wind, which results in variability of the current system. In the magnetosphere a natural phenomenon involving electric discharge, somewhat like a thunderstorm, occurs which is called a magnetospheric substorm. During substorms the cross-tail current is disrupted and diverted towards the ionosphere as a field-aligned current. The energy stored in the magnetotail is converted into plasma heat and bulk flow energy, and it is dumped towards the inner magnetosphere. Energetic precipitating particles cause enhanced auroral activity.

Various relations between atmospheric electricity and both solar activity[3-11] and volcanic activity[12] have been reported. Any perturbation in the interplanetary or atmospheric environment causes a variation in electrical conductivity and hence variation in the current/electric field system of the atmosphere. The atmospheric electric conductivity depends on the ionization rate, the recombination rate, and various meteorological and solar activity conditions. In the ionosphere ionization is caused mainly by the extreme ultraviolet and X-ray radiation from the Sun. The precipitating energetic charged particles from the magnetosphere can cause significant ionization, mainly at high latitudes. The ionization in the lower atmosphere depends on solar activity in the sense that at a particular height the ion production rate is lower during the sunspot maximum period than during the sunspot minimum period[13]. The mechanism is not fully understood, but it appears that irregularities and enhancements of the interplanetary magnetic field (IMF) tend to exclude part of the lower energy cosmic rays from the inner solar system. The effect becomes more pronounced with increasing height/increasing geomagnetic latitude (L). At $L = 50°$ the reduction of the ion production rate during the periods of sunspot maximum is about 30% at 20 km and about 50% at 30 km[14]. The solar cycle dependence was confirmed by measurement with the open balloon-borne ionization chambers[15]. Analytical expressions for computing the ionization rates dependent on latitude and the period of solar cycles are given by Heaps[16]. Superimposed on the 11 year solar cycle variation are the Forbush decreases, which are somehow related to solar flares and exhibit a temperature reduction of the incoming cosmic ray flux for periods of a few hours to a few days or weeks[17]. The measurements of electric current and fields in the lower atmosphere was found to show variations associated with solar flares[18,19], solar magnetic sector boundary crossings[20], geomagnetic activity[21], auroral activity[22], and solar cycle variations[23]. The physical mechanism for the solar terrestrial coupling through atmospheric electricity has been suggested and studied widely[24-28]. In this paper, the recent results concerning electrical structure of the Earth's atmosphere, source of electric field, and its connection with the global electric circuit (GEC) have been summarized in detail.

ELECTRICAL STRUCTURE OF THE EARTH'S ATMOSPHERE

This is known for over two centuries that the solid and liquid Earth and its atmosphere are almost permanently electrified[27]. The surface has a net negative charge, and there is an equal and opposite positive charge distributed throughout the atmosphere above the surface. The Earth's atmosphere has been studied by dividing it into various regions based on temperature profiles, conductivity, or electron density (Figure 2). Each region has been studied more or less in isolation as far as electro dynamical processes are concerned, although processes operating in one region are influenced by the presence of neighboring regions.

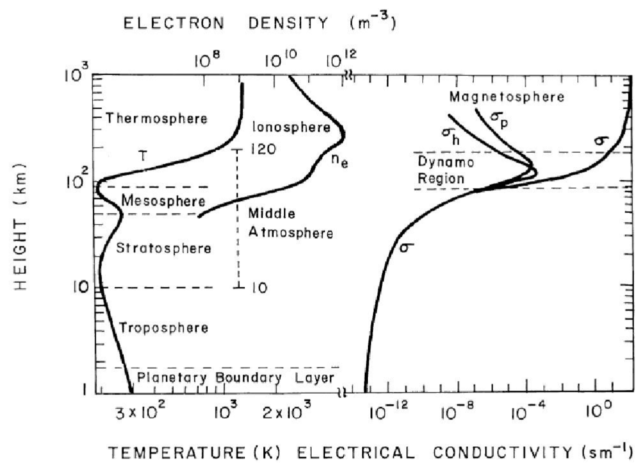

Figure 2 : Profiles distribution of the temperature, conductivity, and electron density of the Earth's atmosphere[42].

The troposphere

The lowest region of the atmosphere, where the temperature decreases with an increase in altitude, is called the troposphere, and which is the chief focus of meteorologists, for it is in this layer that essentially all phenomena to which we collectively refer as weather occur. Almost all clouds, and certainly all precipitation, as well as all the violent storms, occur in this region of the atmosphere. There should be little wonder why the troposphere is often called as the 'weather sphere'. It extends from the surface of the Earth up to about 10 to 12 km. Through out this layer there is a general decrease of temperature with altitude at a mean rate of 6.5°C/km, which is called the environmental lapse rate. This lapse rate is highly variable from place to place, but never exceeds 10 °C/km, except near the ground. Sometimes shallow layers up to about 1 km deep in which the temperature actually increases with height are observed in the troposphere. When such a reversal occurs a temperature inversion is said to exist. The main source of ionization in the troposphere is galactic cosmic rays, apart from radioactive materials exhaling from the soil. The radioactive ionization component depends on different meteorological parameters and can exceed the cosmic rays component by an order of magnitude[29-31]. It decreases rap- idly with increasing height, and at 1 km it is already significantly less than the contribution owed to cosmic rays[12]. The temperature of the Earth's surface rises as a result of absorption of solar radiation. Heat from the Earth's surface is transferred to the air near the ground by conduction and radiation, and is distributed upwards through the atmosphere by turbulent mixing. Convection, which involves the ascent of warm air and downward movement of cold air is effective in transporting heat upward. Owing to this process the average air temperature is usually highest near the ground and decreases with height until it reaches a level called the tropopause, at an average height of approximately 12 km in the tropics and 10 km near the poles. The minimum temperature at the tropopause level can be between "70 °C to "90 °C in the tropics.

The stratosphere

The stratosphere lies between the tropopause and the stratopause (~ 50 km altitude). In the lower part of the stratosphere the temperature is nearly constant with height or increases slowly. Throughout the stratosphere galactic cosmic rays provide the principal ionization source, and the ionization rate does not vary diurnally but does vary with geomagnetic latitude and with the phase of the 11 year solar cycle. Roughly speaking, the ion production rate at 30 km height increases by a factor of 10 from the geomagnetic equator to the polar caps at a sun spot minimum (cosmic-ray maximum) and by a factor of 5 at a sun spot maximum. The solar cycle modulation is near zero at the equator, increasing to a factor of about 2 in a polar cap region. The ionization rate above 30 km is approximately proportional to the atmospheric density. These properties result because of (a) the shielding effect of the geomagnetic field, which allows cosmic ray particles to enter the atmosphere at successively higher latitudes for successively lower energies, and (b) the reduction in cosmic ray flux in the inner solar system as solar activity intensifies. In addition, solar proton events (SPE) provide a sporadic and intense source of ionization at high latitudes. Solar flares produced one of the largest SPE event recorded in terms of the total energy input into the middle atmosphere during 4 – 9 August, 1972. The largest Forbush decrease in cosmic rays intensity that has been observed also occurred during this event[32,33]. The conductivity, which is roughly of the order of 10^{-14} mho/m at the Earth's surface, increases exponentially with altitude in the troposphere - stratosphere region; the main charge carriers are the small positive and negative ions. The warming of the stratosphere results from the absorption of ultraviolet radiation by ozone (at wavelengths between about 200 nm and 310 nm). Although the stratosphere contains much of the total atmospheric ozone, the maximum temperature occurs at the stratopause, where the temperature may exceed 0 °C.

The mesosphere

This is the region of the second decrease of temperature with height, like the tro- posphere, to a minimum of about -90 °C around 80 km. This layer is commonly known as the mesosphere, which literally means the middle sphere and the level corresponding to the minimum temperature is referred to as the mesopause. The mesosphere extends from about 50 km to 85 km, and many of the atmospheric variations encountered in it are linked to complicated processes in the underlying layers. The major sources of ionization are the solar Lyman alpha radiation, X-ray radiation, and the intense auroral particle precipitation. The conductivity increases with height rather sharply. The major day time source of ionization in undisturbed conditions is provided by the NO molecule, whose low ionization potential of 9.25 electron volts allows it to be ionized by the intense Solar Lyman alpha radiation. The concentration of NO in the mesosphere is not well known and is almost certainly variable in response to meteorological factors[34,35].

The ionosphere

The ionosphere starts from above the mesopause and extends to a height of about 500 km. The upper boundary is not well defined, i.e., the so called thermosphere is included in the ionosphere. In this region ionized species do not necessarily recombine quickly, and there is a permanent population of ions and free electrons. The net concentration of ions and free electrons (generally in equal numbers) is greatest at a height of a few hundred kilometers and has a profound effect on the properties and behavior of the medium. The major sources of ionization are EUV and X-rays radiation from the sun, and energetic particle precipitation from the magnetosphere into the auroral ionosphere. The Current carriers are electrons and the positive ions such as NO^+, O^+, and O^+. Electrical conductivity becomes anisotropic in this region with the parallel conductivity (with respect to an Earth's field line) exceeding the transverse conductivity by several orders of magnitude. The ionized medium also affects radio waves, and as a plasma it can support and generate a variety of waves, interactions, and instabilities which are not found in a neutral gas.

The magnetosphere

The magnetic field decreases with altitude as the atmosphere becomes moresparse and its degree of ionization increases. The electro dynamic properties of the medium above the ionosphere are dominated by the geomagnetic field, and this region is called the magnetosphere. The lower boundary of the magnetosphere is the ionosphere and it extends up to magnetopause. At the magnetopause energy is coupled into the magnetosphere from the solar wind, and here is determined much of the behavior of the magnetosphere and of the ionosphere at high latitudes. In the sunward direction the magnetopause is encountered at about 10 Earth radii, but in the anti-solar direction the magnetosphere is extended downward in a long tail, the magneto tail, within which occur plasma processes of great significance for the geo spatial regions.
We have tried to show above that the electrical properties of different regions are linked and that one is not justified in studying the electrodynamics of the Earth's atmosphere region by region, i.e., separately for troposphere, stratosphere, mesosphere, ionosphere, magnetosphere, and interplanetary medium. The electric field and current map from one region to the other, and control the electro dynamic properties of the entire atmosphere. Therefore a global approach is required in order to understand the electrical environment of the Earth's atmosphere[25].

ATMOSPHERIC GLOBAL ELECTRIC CIRCUIT

The concept of a GEC began to evolve in the early twentieth century with the recognition of the following facts: (a) the net positive space charge in the atmosphere between the Earth's surface and a height of ~ 10 km is nearly equal to the negative charge on the Earth's surface; (b) the electrical conductivity of the air increases with altitude and the air–earth current within an atmospheric column remains constant with altitude, which implies that this is being driven by a constant voltage drop between the surface of the Earth and upper atmosphere. The discovery of the ionosphere during the same period provided the means of closing the global circuit through this conducting layer and played an important role in framing the concept of the GEC. According to the classical picture of atmospheric electricity, the totality of thunderstorms acting together at any time charges the ionosphere to a potential of several hundred thousand volts with respect to the Earth's surface[36]. This potential difference drives a vertical current downward from the ionosphere to the ground in all fair weather regions of the globe. The fair weather electric conduction current varies according to the ionospheric potential difference and the columnar resistance between the ionosphere and the ground. The fair weather electric field varies typically between 100–300 V/m at the ground surface and shows diurnal, seasonal, and other time variations caused by many factors. The fair weather conductivity of the atmosphere near the Earth's surface is of the order of 10^{-14} mho/m and shows considerable variations with particulate pollution[37,38], relative humidity[39], and radioactivity of the air and ground surface[40]. The electric conductivity increases nearly exponentially with altitude up to 60 km with the scale length of 7 km (Figure 2). This conductivity is maintained primarily by galactic cosmic rays ionization. These Galactic cosmic rays flux reduces in the mid latitudes, when the solar activity increases, thus reducing the atmospheric conductivity in this region, while in the same period solar protons may be 'funnelled' by the Earth's magnetic field to polar regions resulting in an increased atmospheric conductivity there. A dawn to dusk potential difference is also applied across the polar regions as a result of the interaction of solar wind and the Earth's magnetic field[6]. Cho and Rycroft[41] have presented a simple model profile for the atmospheric conductivity ranging from 10^{-13} mho/m near the surface to 10^{-7} mho/m at 80 km altitude in the lower ionosphere. Hale (1994) has presented a more complex profile, which shows variations in both space and time. He has shown that the conductivity is three orders of magnitude higher at the height of 35 km compared to that at the Earth's surface, whereas the air density at 35 km is 1% of the Earth's surface. Below 60 km the main charge carriers are small positive and negative ions which are produced primarily by galactic cosmic rays, and above 60 km free electrons become more important as charge carriers, and their high mobility abruptly increases the conductivity throughout the mesosphere. However, near the Earth's surface the conductivity is large enough to dissipate any field in just 5 – 40 min (depending on the amount of pollution); therefore the local electric field must be maintained by some almost continuous current source. Above 80 km the conductivity becomes anisotropic because of the influence of the geomagnetic field and shows diurnal variation owed to solar photo-ionization processes. The arena for the subject is included in the system shown in Figure 3 which shows the Earth at the center, surrounded by the atmosphere, ionosphere, the Van Allen belts, and the magnetosphere deformed by the solar wind coming from the Sun. During the geomagnetically active periods the energetic charged particles precipitating from the Earth's inner and outer magnetospheric radiation belts (Figure 3) interact with the middle and lower atmosphere by depositing their energy in the atmosphere, by creating ionization directly or via bremmstrahlung radiation, by altering its chemistry[42], or by affecting the nucleation by electro freezing of water droplets to form clouds, thereby influencing the dynamics of storm, and the atmosphere[6,43]. Thus the electrical behavior of the Earth's environment is controlled by the dynamics of the solar atmosphere.

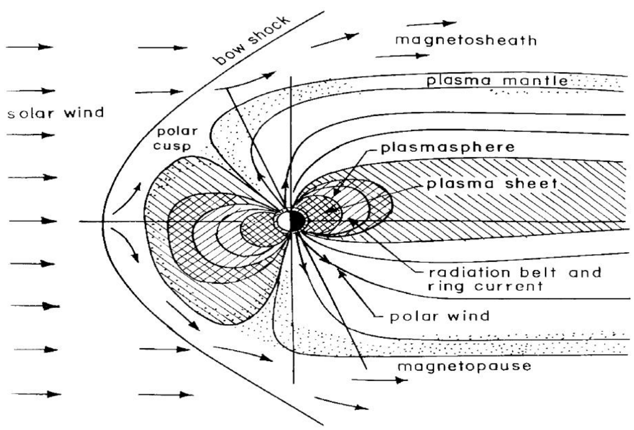

Figure 3 : Schematic diagram of Earth's magnetosphere, showing the Earth at the center, surrounded by the atmosphere, the ionosphere, the Van Allen radiation, and the magnetosphere deformed by the flowing solar wind[68].

The Earth's surface and the ionosphere provide two conducting plates where current flows horizontally. Figure 4 shows that the GEC is driven by the upward current from a thunderstorm's top towards the ionosphere and also from the ground into the thunderstorm generators, thus closing the circuit[44]. Blakeslee *et al.*[45] carried out measurements of air conductivity and vertical electric field with a high altitude NASA U2 airplane flying over thunderstorms in the Tennessee valley region of the United States and reported that the Wilson current varied from 0.09 – 3.7 A with an average of 1.7 A. They have also shown that the relative efficiency of a thunderstorm to supply current to the GEC is inversely related to the storm flash rate. Thus the current generated within the cloud is divided between production of lightning and maintenance of the Wilson current. Intra-cloud discharges do not support the Wilson current. The ratio of cloud to ground and intra-cloud discharge increases from about 0.1 in the equatorial region to about 0.4 near latitude 50[46]. Thunderstorm activity is maximum near the equator and decreases with latitude. Thus the supply of Wilson current varies with latitude and shows a peak at low latitudes. Using the global model of atmospheric electricity, Hays and Roble[3] computed the electric field and air earth current density along the Earth's orographic surface which is shown in Figure 5. They present variation of the calculated electric field and the air earth current density over the Earth's surface caused by the downward mapping of the magnetospheric convection potential pattern. Under the maximum positive ionospheric potential, the calculated surface electric field is +15 V/m (positive ionospheric potential regions; the air – earth current flows into the ground) and under the minimum negative potential the calculated surface electric field is -20 V/m (a negative ionospheric potential; the current flows from the ground towards the ionosphere). The maximum ground current density occurs over the mountainous regions of Antarctica, Greenland and the Northern Rocky Mountains. The calculated air earth current shows considerable variations as a result of the Earth's orography that are associated with changes in the columnar resistance[37]. In the vicinity of the high Antarctic mountain plateau the air earth current has positive perturbations of up to 0.2 × 10"12 A/m^2 on the dawn side and to "2 × 10"12 A/m^2 on the dusk side. This potential pattern moves over the Earth's surface during the day, rotating about the geomagnetic pole. Hays and Roble[3] showed that in sun-aligned geomagnetic coordinates at a ground station, balloon, or aircraft at a given geographic location should detect variations that are organized in magnetic local time. At an early magnetic local time the ionospheric potential perturbations of the Earth's potential gradient are positive, and at a later magnetic local time negative potential overtakes times and the perturbations are negative. Owing to orographic variations the globally integrated ground current varies between net upward and downward values, which in turn causes the difference in the fair weather ionospheric potential to vary between positive and negative values in a diurnal cycle[14]. Analyzing the data recorded at the South Pole and Thule, Greenland, Kasemir[47] showed that the diurnal Universal time (UT) variations of potential gradient are about 30% less than the global low latitude UT variations, which are attributed to variations in thunderstorm frequency. The polar curve has a similar shape to the curve derived from the Carnegie cruise, but at a much reduced amplitude. From these results, Kasemir[48] concluded that another agent, besides worldwide thunderstorm activity, may modulate the global circuit at high latitudes. Kamra *et al.*[49] have studied the concept of the classical GEC on the basis of their electric field observations in the Indian Oceans. Recent observations of Deshpande and Kamra[50] also showed that diurnal variation of the electric field at Antarctica significantly differs from the Carnegie diurnal curve of the electric field. D'Angelo *et al.*[51] have studied the correlation of the vertical electric field with the magnetic activity parameters by analyzing the balloon measurements of magnetospheric convection fields data. During quiet geomagnetic conditions the classical Carnegie curve could be reproduced at the location of the balloon's height, and during more active geomagnetic conditions the dawn–dusk potential difference of the magnetospheric convection pattern was found to clearly influence the vertical fair weather field as it intensified and presumably moved from its quiet time position to over the balloon's height. Measurements of

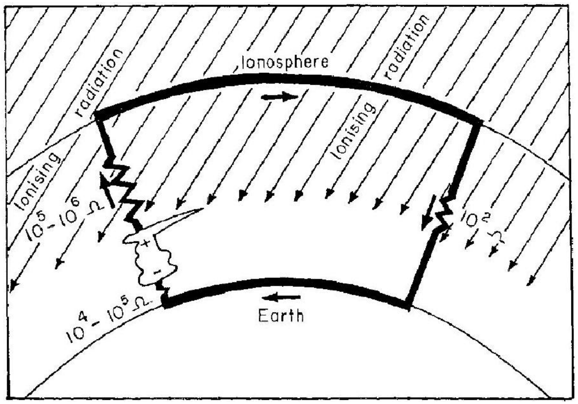

Figure 4 : Diagram of the global electric circuit. Ionizing radiation is mainly owed to galactic cosmic rays in the middle atmosphere[71].

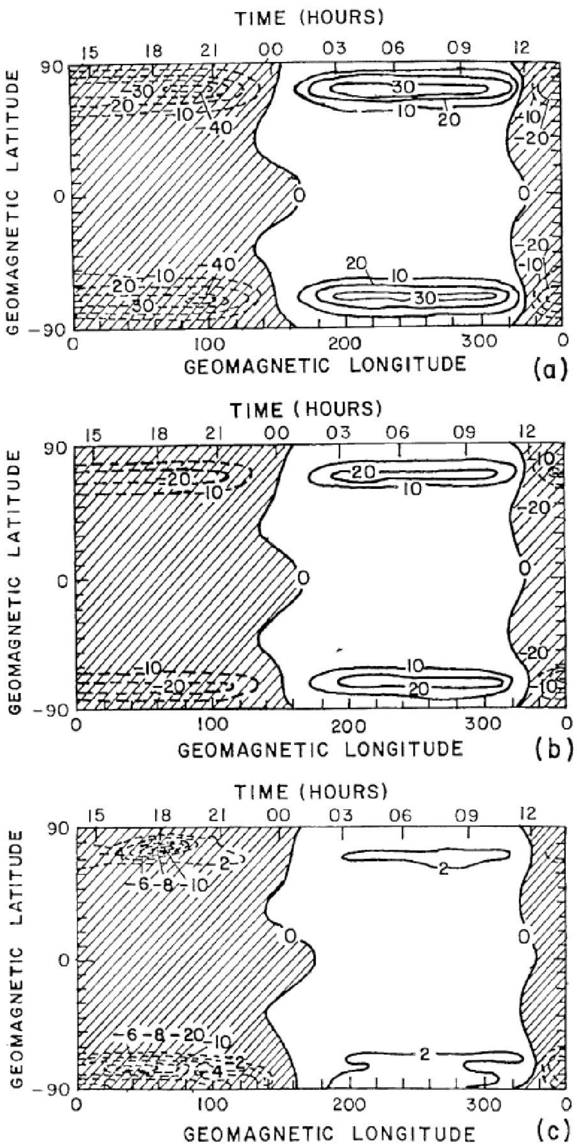

Figure 5 : Contours illustrating the downward mapping of the ionospheric potential pattern: (a) imposed ionospheric potential (kV) at ionospheric height (> 100 km); (b) calculated electric field (V/M) along the Earth's orographic surface; and (c) calculated ground current (A/m^2, multiplied by 10^{-13}) along the Earth's orograpic surface. All figures are plotted at 19:00 UT in geomagnetic coordinates[3].

the vertical electric field at Syowa station (Antarctica) showed that it increases in response to a magnetospheric substorm[20]. All these measurements suggested an electrical coupling between the magnetospheric dynamo and the GEC at high latitudes and indicated a need for more measurements in order to gain better understanding of the nature of the interaction.

Only a few mathematical models of global atmospheric electricity have appeared over the years[52-54]. The widely referred model of Ogawa[53], considering the simple equivalent circuit for the atmosphere and an equipotential surface for the ionosphere, is shown in Figure 6.

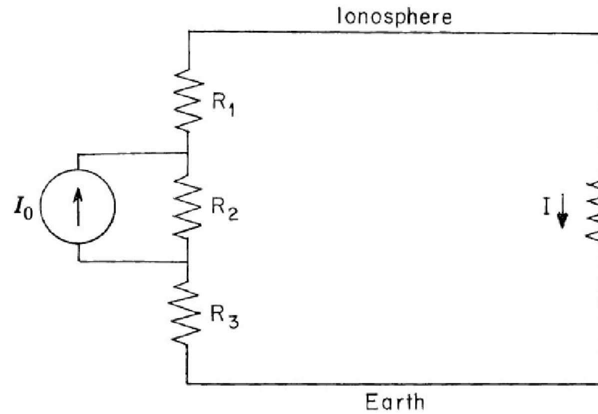

Figure 6 : A simplified equivalent circuit for the global electric circuit showing the thunderstorm as the main generator[53].

The thundercloud is treated as a constant current generator with a positive charge at the top and negative charge at its bottom. Here *r* is the global resistance between the Earth and the ionosphere and R_1, R_2 and R_3 are the resistances between the ionosphere and top of the thundercloud, between two charge centers within the thundercloud and between the bottom negative charge and the Earth's surface, respectively. Since R_1, R_2, and R_3 are much greater than *r*, the upward current from the thundercloud to the ionosphere is given by

$$\mathbf{I} = \frac{\mathbf{R_2 I_0}}{\mathbf{R_1 + R_2 + R_3}}$$

It should the noted that the current *I is* also the fair weather current from the ionosphere to the Earth's surface and it is related to the thunderstorm generator current I0. The measurement of *I* at a high altitude observatory remote from active thunderstorms can give some information about I_0, if R_1 and R_2 are considered as constant. Both may, however, be reduced at times of enhanced fluxes of energetic charged particles associated with enhanced geomagnetic activity. The contribution to R1 above an active, sprite-producing thundercloud may be greatly reduced owing to ionization produced in the rarefied mesosphere by the large transient electric field during large, positive cloud to ground lightning discharges[41].

Recent observations of optical emission between the top of the thunderstorm and the ionosphere suggest the existence of intense current which may be an extension of the return stroke current[55,56]. This current should be included in the mathematical modeling of GEC. Recently Pasko *et al.*[57] have reported a video recording of a blue jet propagating upwards from a small thunder cloud cell to an altitude of about 70 km. As relatively small thunder cloud cells are very common in the tropics, it is probable that optical phenomena from the top of the clouds may constitute an important component of the GEC. Rycroft *et al.*[7] presented a new model of GEC treating the ionosphere and the magnetosphere as passive elements (Figure 7). Three different regions of the fair weather circuit are given. One of these is for the high altitude part of the Earth where the profiles of J and E through the fair weather atmosphere will differ from those of low and mid latitudes. The time constant for the atmospheric GEC is $\tau = Cr \approx 2$ min[7]. The energy associated with the global electric circuit is enormous, $\approx 2 \times 10^{10}$ J[7]. This value has been obtained by considering a charge of 200 C associated with each

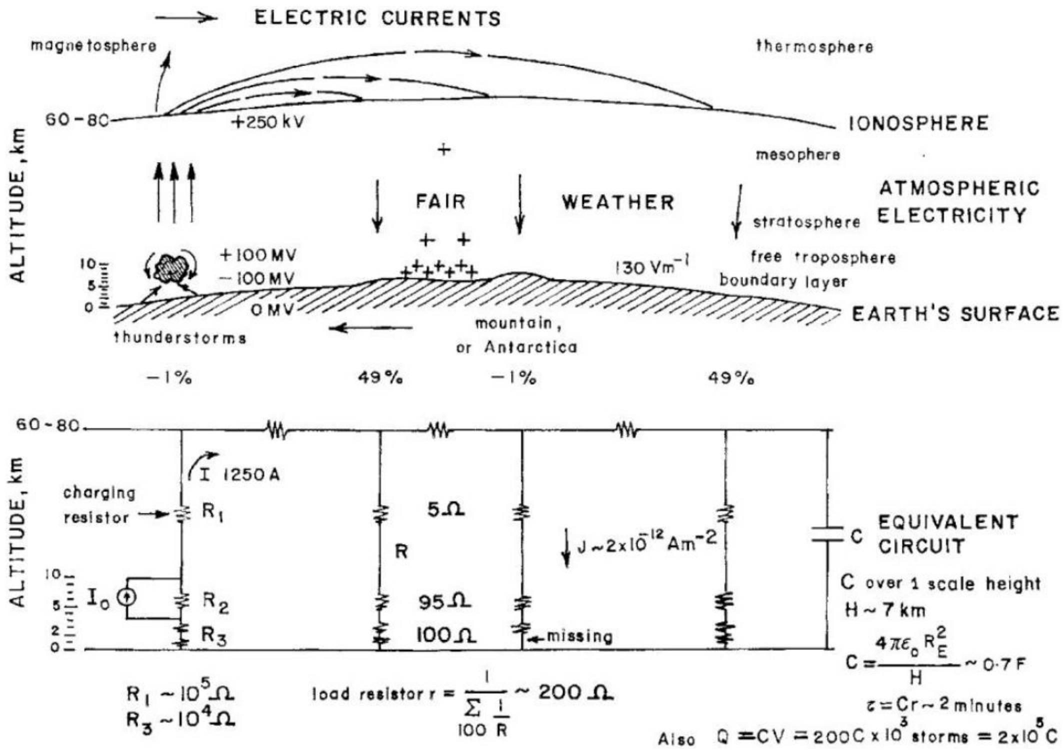

Figure 7 : The equivalent global electric circuit showing typical numerical values[7].

storm and 1,000 storms operating at a time. The electric current density through the fair weather atmosphere $\approx 2 \times 10^{-12}$ A/m^{-2}. Taking the conductivity of air at ground level to be $\approx 2 \times 10^{-14}$ mho/m, the fair weather electric field is $\approx 10^{2}$ V/m at ground level, ≈ 1 V/m at altitude 20 km and $\approx 10^{-2}$ V/m at altitude 50 km[7]. Thus even though the fair weather current remains the same, the vertical electric field goes on decreasing with altitude. The current remaining the same if the atmosphere conductivity changes owing to some reason, then accordingly the fair weather electric field also changes. For example, following a Forbush decrease, if the atmospheric conductivity is everywhere reduced by 10% then the fair weather electric field will be increased by ~ 10%[53]. The ionospheric potential would reduce to 99% of the initial value only for a few milliseconds after sprites, and would have little effect on the fair weather electric field[7]. Is there any affect of sprites on the global electric circuit? This is a completely unanswered question to this date. A sprite occurs over large convective thunderstorms and affects the conductivity of the upper atmosphere[58,59]. The frequency of occurrence of sprits is far less than that of lightning (only 1 sprite out of ~ 200 lightning discharges). Based on such observations Rycroft *et al.*[7] have suggested that sprites do not play any major role in the GEC. However, intensive research into this topic is required in future. In all GEC models electrostatic phenomena have been considered, whereas during lightning discharges electromagnetic waves having frequencies from a few Hz to 100 MHz are generated and propagated through the atmosphere. To account for the effect of these waves electromagnetic effects should be considered by relating electromagnetic fields to charge and current densities in a time varying situation. At higher frequencies ($\omega >> \sigma/\varepsilon 0$) the medium can be considered as a leaky dielectric whereas at lower frequencies ($\omega << \sigma/\varepsilon 0$) it can be considered as a conductor. Even in the absence of radiation displacement current should be considered. In fact, the Maxwell current shown in Figure 3 is by its nature very variable, and not a great deal is known about it. Further studies of this topic are required.

The GEC model has several advantages over the traditional methods, based directly or indirectly on the solar heating mechanism put forward for explaining solar – terrestrial – weather relationships. The main drawback of the solar heating mechanism is that the solar constant variations are very small (< 0.1%). Secondly, they require efficient coupling from the thermosphere to the lower atmosphere, which in reality is rather weak. Thirdly, the solar heating mechanisms are too slow; they require at least several days before atmospheric dynamics would be affected significantly. The GEC model by passes all these difficulties, at the same time it offers a novel approach to understanding the electrical environment of our planet. For example, a change of ionospheric potential caused by solar flares would rapidly affect electric field intensities all over the world. The state of ionization of the lower atmosphere is controlled by cosmic rays of both solar and galactic origins, which again depend upon solar activity. A slight change in the ionization over the cloud top can affect the electric field throughout the lower atmosphere. Theoretical modeling shows that a slight change in the initial background electric field during cloud electrification can lead to an entirely different final voltage being developed[60]. This is because the Earth's atmosphere is a highly nonlinear system.

The main source of electrical phenomena upon the Earth's environment is thunderstorm activity, which is affected by solar activity. Brooks[61] analyzed world- wide data collected from 22 stations and suggested a positive correlation between the frequency of thunderstorms and relative sun spot numbers (*R*). The correlation was low at mid latitudes and increased both towards the equator and the pole. Stringfellow[62] analyzed data collected in Britain between 1930 and 1973 and found the correlation coefficient between lightning frequency and sun spot numbers to be ~ 0.8. Recently Schlegel *et al.*[63] analyzed data from the German lightning detection system (BLIDS) and showed a significant correlation of lightning frequency with AP and *R*, and a significant anti-correlation with cosmic ray flux. However, a similar analysis with data from the Austrian System (ALDIS) yielded inconclusive results, although the two observing regions are quite close to each other. The difference in lightning activity can be understood in terms of the weather system. The operational region of the ALDIS system lies in the south and east of the Alps mountains and is dominated by the continental Mediterranen weather system, whereas the area of the BLIDS system is mostly within the in- fluence of the north Atlantic weather system[63]. The solar activity influences the lower D region[64] and Schumann resonance[63], which in turn affect the electrical environment of the Earth. A modern detection system should be used to explore new aspects of the Sun – thunderstorm/lightning relationship and its variation with solar/geophysical indices. Recently GEC has been being used as a tool for studying the Earth's climate and changes in it[65,66] because of its direct connection with lightning activity. The subject has been recently reviewed by Williams[67]. A close relationship has been shown between: (a) tropical surface temperature and monthly variability of the Schumann Resonance[68]; (b) ELF observations in Antarctic/Greenland and global surface temperature[69]; (c) diurnal surface temperature changes and the diurnal vari- ability of the GEC[70]; and (d) ionospheric potential and global/tropical surface temperature[71]. Reeve and Toumi[72] using satellite data, showed agreement between global temperature and global lightning activity. Aerosols in the atmospheric boundary layer and stratosphere have a strong influence on the electrical phenomenon in the atmosphere. Adlerman and Williams[73] found large effects from several factors such as seasonal changes, variations in mixed layer heights, variations in the production rates and anthropogenic aero- sols, and variations in surface wind speed on the seasonal variations of the GEC. These aerosol particles can even influence the charge generating mechanisms in storms and thus affect the charging currents in the GEC[67]. Williams *et al.*[68] concluded that the conduction currents other than lightning is the dominant charging agent for the Earth's surface. Recently, Price[70] extended this study and showed a close link between the variability of upper troposphere water vapor (UTWV) and the variability of global lightning activity. UTWV is closely linked to other phenomena such as tropical cirrus cloud, stratospheric water vapour, and tropospheric chemistry[74]. These examples suggest that by monitoring the GEC it is possible to study the variability of surface temperature, tropical deep convection, rainfall, upper troposphere water vapour, and other important parameters which affect the global climate system.

CONCLUSIONS

We have summarized the electrical behavior of different regions of the Earth's environment. Sources of electric fields and the electro dynamic processes involved in each region have been discussed briefly. It has been suggested that the GEC model, if properly solved, is able to provide short term and long term variations in the electrical processes of various regions and their inter-coupling. Possible causes of changes in the GEC are discussed and its role in monitoring the Earth's climate is indicated. However, further research is needed to better understand the natural environment and its variability, so that future evolution may be predicated.

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