Electrodynamic coupling between different regions of the atmosphere*

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Electromagnetic fields and currents connect various parts of the Earth's atmosphere extending up to the magnetosphere boundary. Traditionally, the electrodynamics of a part of the atmosphere has been studied more or less in complete isolation from the other parts. An integrated approach in terms of a Global Electric Circuit (GEC) is emphasized for investigating the electrical environment of the Earth's atmosphere. This approach can provide a good framework for exploring interconnections and coupling of various regions of the atmosphere, and also for explaining the solar-terrestrial-weather relationships.

THE Earth's atmosphere extends up to the magnetopause which acts as a boundary between the Earth and Space. The magnetosphere is formed by the interaction of the solar wind (which is an ionized and highly conducting gas consisting mainly of electrons and protons) emitted from the Sun with the geomagnetic field. The geomagnetic field forms an obstacle to the solar wind flow. As a result the geomagnetic field on the dayside is compressed (to about 10 R_E, where R_E is the radius of the earth) and the solar wind flow is deflected carving a cavity (extending about 1000 R_E on the nightside) in which the geomagnetic field is more or less contained. This cavity is called the magnetosphere and the boundary of the magnetosphere is called the magnetopause (see Figure 1). As a result of solar wind-geomagnetic field interactions, mass, momentum and energy are transferred from solar wind to the magnetosphere, and a complex pattern of several current systems is generated in different parts of the magnetosphere as shown in Figure 1.

The Earth's atmosphere is always and everywhere electrified. In the fair-weather region a downward current of the order of a few pico ampere per meter square flows all the time. The atmosphere is filled with charged particles everywhere. In the lower atmosphere the cosmic rays are mainly responsible for ionizing the atoms and molecules thus making the lower atmosphere electrically conducting. Thunderstorms in which electric charge is separated act like current generators and maintain the potential gradient in the lower atmosphere. In the ionosphere ionization is caused mainly by the extreme-ultraviolet (EUV) and X-ray radiation from the Sun. In the high latitudes, the energetic particle precipitating from the magnetosphere can cause significant ionization in the ionosphere. The magnetosphere itself is filled with charged particles of solar wind and that of ionospheric origin. In the magnetosphere, a natural phenomenon involving electric discharge, like in thunderstorms, occurs. This phenomenon is called magnetospheric substorm. During magnetospheric substorms, the cross-tail current (which is responsible for the elongated magnetotail in the nightside) is disrupted and diverted towards the ionosphere as field-aligned current. Magnetic 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. The analogy between the thunderstorm and the magnetospheric substorms is illustrated in Figure 2. The field-aligned currents and the currents produced in the ionosphere are shown in Figure 3.

The Earth's atmosphere occupies volume of space some million times greater than the volume of the solid earth. In this huge system the charged particles of the plasma react strongly to electric and magnetic fields. Electrical processes in one part of the system could,

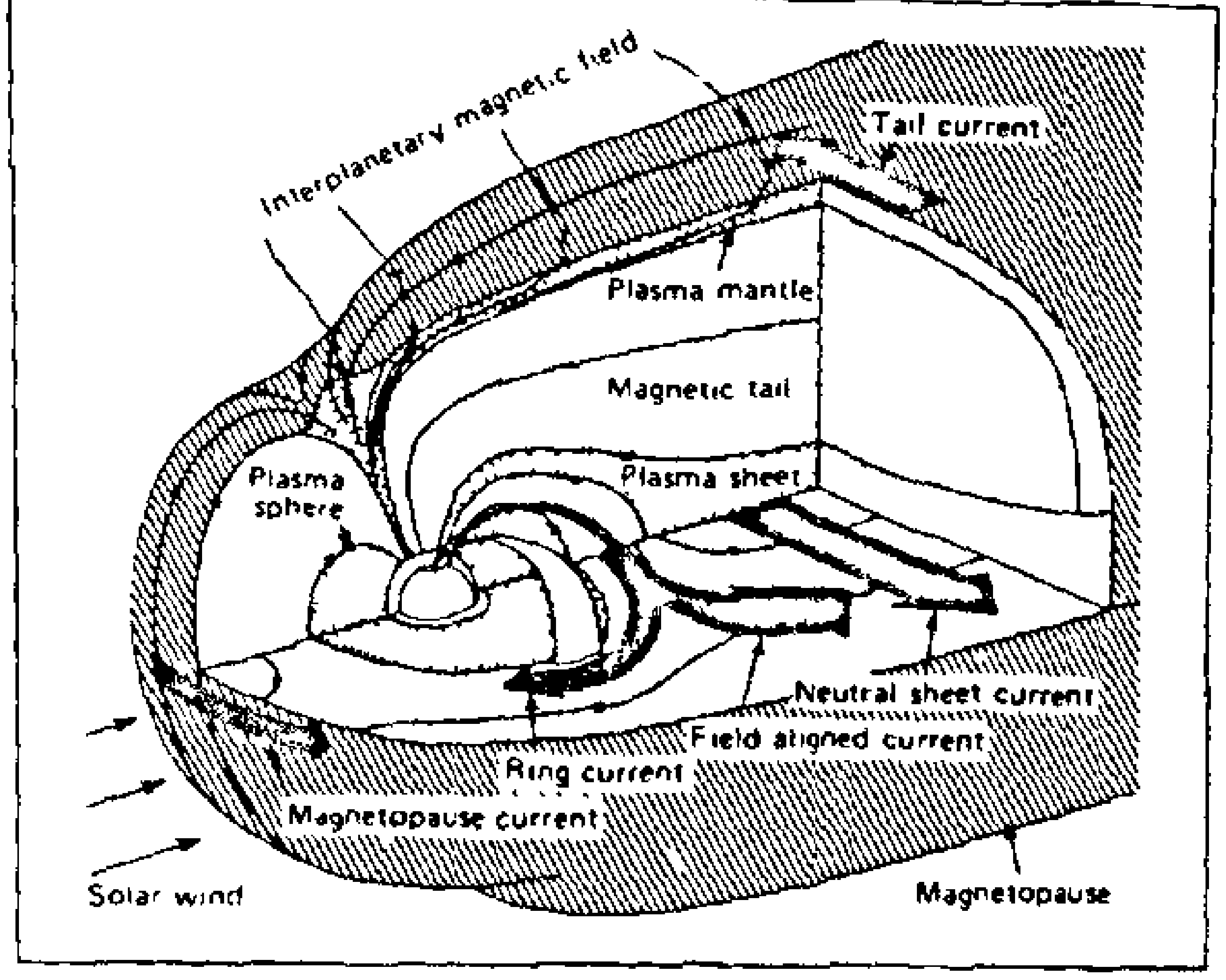

Figure 1. Schematic illustration of a 3D view of the Earth's magnetosphere. Small arrows indicate the direction of the magnetic field lines. Thick arrows show the direction of electric currents. Various current systems present in the magnetosphere are indicated.

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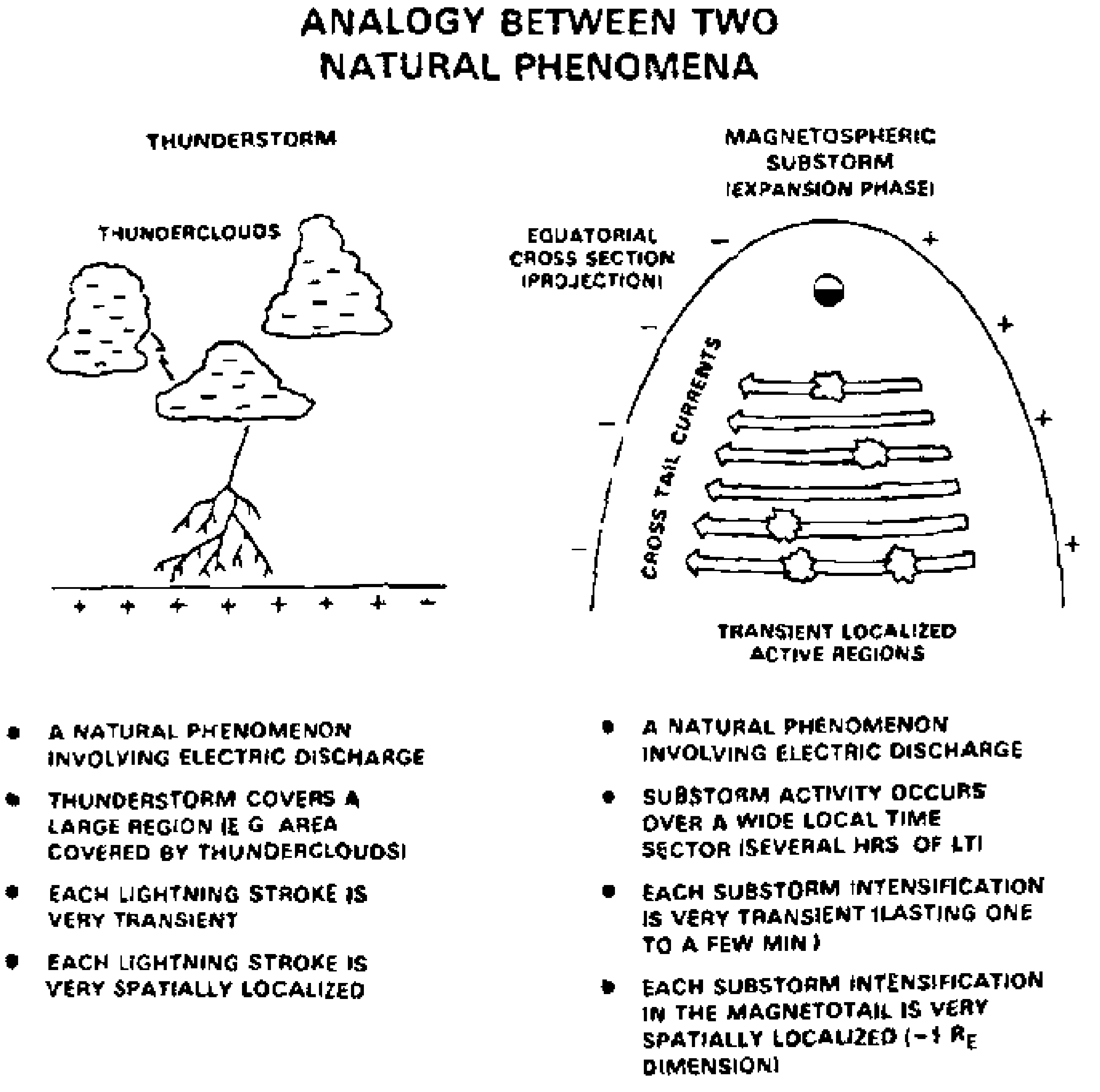

Figure 2. Similarities between the thunderstorms and the magnetospheric substorms (taken from the article by A. T. Y. Lui, in *Geophysical Monograph 64*, American Geophysical Union, Washington, D. C., pp. 43–60, 1991).

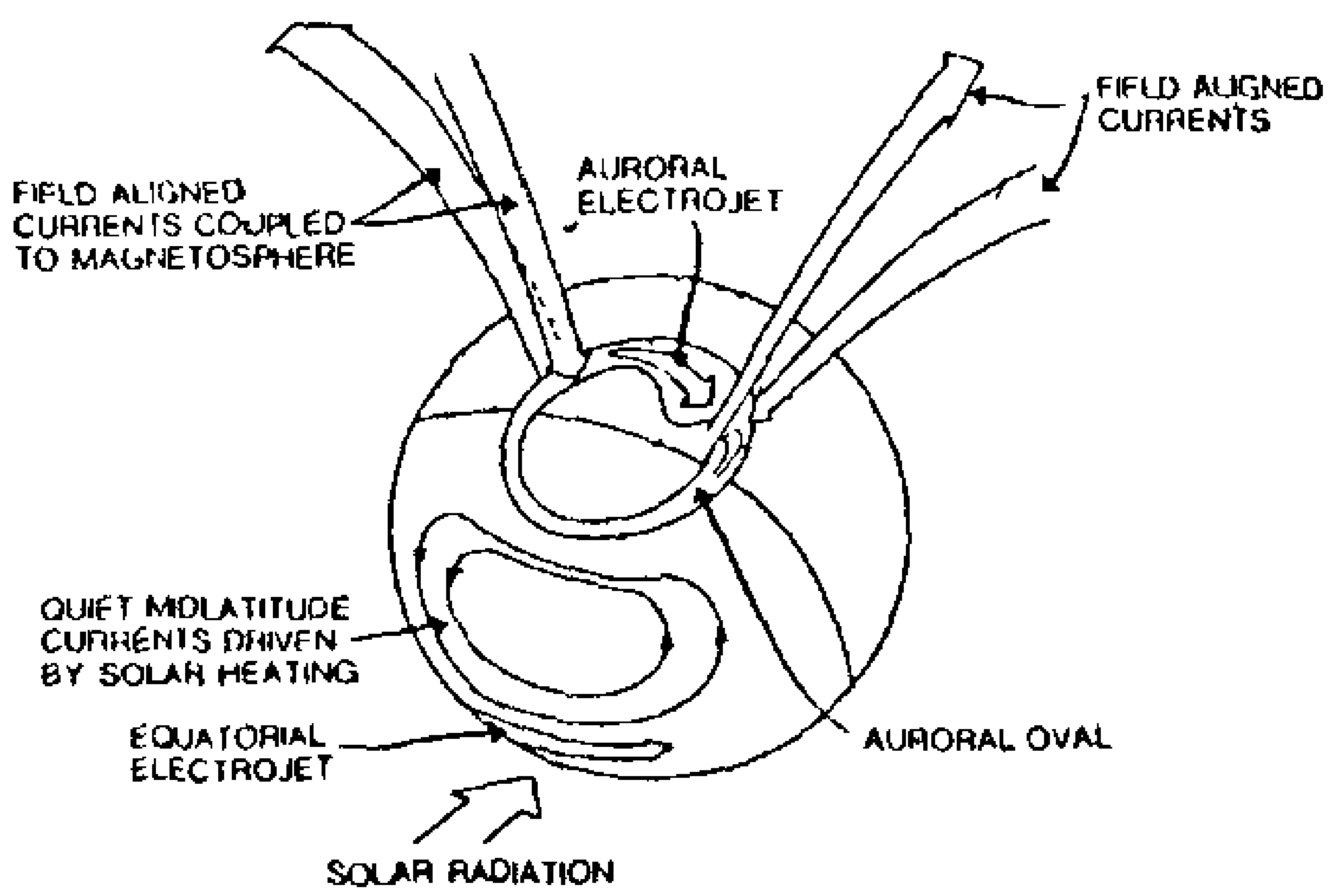

Figure 3. Schematic view of the field-aligned currents flowing between the magnetosphere and the ionosphere. These currents are mainly responsible for sustaining auroral electrojets and also play an important role in magnetosphere-ionosphere-mesosphere coupling in the high latitudes. Solar quiet (SQ) current system and the equatorial electrojet current system are also shown.

therefore, influence the electrodynamical processes in the distant parts of the system. The redistribution of the charged particles in turn can modify the existing electric and magnetic fields in the atmosphere. Hence an investigation of electrodynamical processes in various regions of the atmosphere and their coupling is very important for understanding the state of electrical environment of the Earth's atmosphere.

Traditional view

Structure of the atmosphere

Traditionally, the Earth's atmosphere has been studied by dividing it into various regions based on temperature profiles, conductivity or electron density (see Figure 4). Each region has been studied more or less in isolation as far as the electrodynamical processes are concerned. The main regions are:

(i) *Troposphere.* It extends from the surface of the earth to about 10 km. Galactic cosmic rays and the radioactivity of the earth are the main sources of ionization in this region. The temperature decreases with height and attains a minimum at the tropopause.

(ii) *Stratosphere.* It starts from above the tropopause (~10 km) and extends up to stratopause (~50 km), where the temperature profile attains the maximum value. Galactic cosmic rays are the prime source of ionization in this region. In addition, solar proton events (SPE) provide a sporadic and intense source of ionization at high latitudes. 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; main charge carriers being the small positive and negative ions.

(iii) *Mesosphere.* This is the region of second decrease of temperature profile as seen from Figure 4. It extends from about 50 km to 85 km in altitude. The major sources of ionization in the mesosphere are the solar Layman-alpha radiation, X-ray radiation and the intense auroral particle precipitation. The conductivity increases rather sharply in this region. The main charge carriers are electrons, positive ions (e.g. N_2^+, O_2^+, NO^+) and the negative ions (e.g. O_2^-, O_2^-).

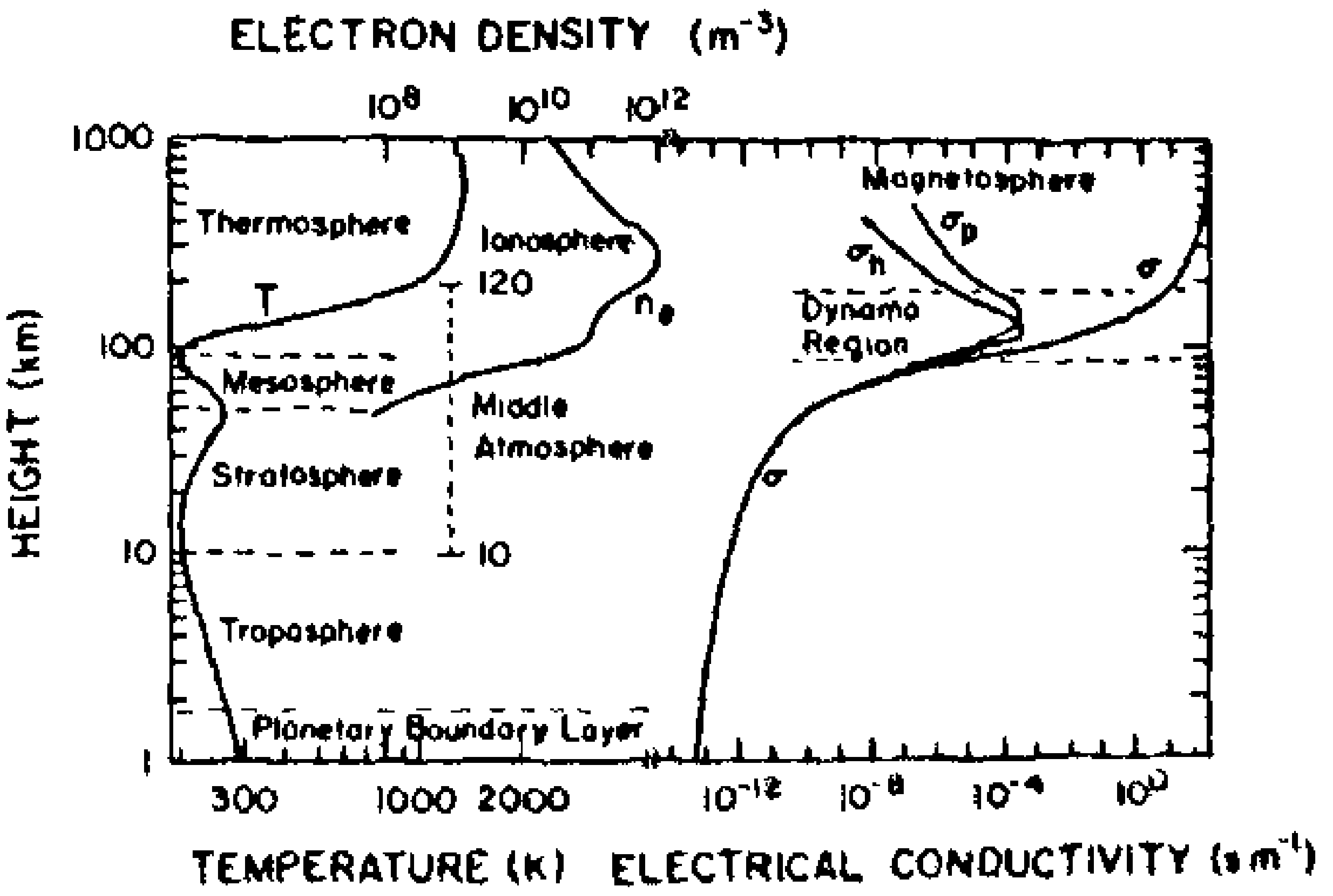

Figure 4. Divisions of the Earth's atmosphere based on the profiles of the distribution of temperature, conductivity, and electron density through the atmosphere.

(iv) *Ionosphere.* The *D*-region of the ionosphere extends from about 60 km to 90 km. The ionosphere proper (i.e. *E* and *F* regions) starts from above the mesosphere, and extends to about 500 km. The upper boundary is not well-defined. The so-called thermosphere is included in the ionosphere. The major sources of ionization in the ionosphere are EUV and X-ray radiation from the sun and energetic particle precipitation from the magnetosphere into the auroral ionosphere. The current carriers are electrons and the positive ions like NO^+, O_2^+ and O^+. Electrical conductivity becomes anisotropic in this region with the parallel conductivity (with respect to geomagnetic field) exceeding the transverse conductivities by several orders of magnitude.

(v) *Magnetosphere.* The lower boundary of the magnetosphere is the ionosphere. The magnetosphere extends up to magnetopause. Here the plasma is fully ionized. The characteristics of the plasmas vary from region to region due to different physical processes occurring thereof. The entire magnetosphere is energized mainly by the energy deposited by the solar wind via complex processes occurring during solar wind-magnetosphere interaction.

Sources of electric fields

Thunderstorms have been considered as the main source of electric fields in the lower atmosphere comprising of troposphere-stratosphere and mesosphere. The thunderstorm activity produces vertical electric fields on a global scale.

In the ionosphere, the electric fields are produced by dynamo action. Atmospheric winds and tides pull the weakly ionized ionospheric plasma across the geomagnetic field. This movement produces an electromotive force and generates electric currents and fields. This is the ionospheric wind or Sq (For solar quiet) dynamo. The electric field, **E**, driving the dynamo current, is related to the wind velocity, $\mathbf{V}_n$, and the geomagnetic field **B** by the relation

$$\mathbf{E} = -\mathbf{V}_n \times \mathbf{B}. \qquad (1)$$

Solar wind/magnetosphere dynamo is the major generator of electric fields in the magnetosphere. This dynamo results from the flow of the solar wind across the open geomagnetic field lines. The electric field produced by the solar wind/magnetosphere dynamo is given by

$$\mathbf{E} = -\mathbf{V}_{sw} \times \mathbf{B}, \qquad (2)$$

where $\mathbf{V}_{sw}$ is the solar wind velocity. The geomagnetic field lines become open rather easily when the interplanetary magnetic field (IMF) points southward. The plasma flows antisunwards over the magnetic polar cap and a sunward flow (via reconnection in the far tail region) in the inner magnetosphere (see Figure 5). The electric fields due to solarwind/magnetosphere (SM) dynamo map down to the auroral ionosphere and produced potential difference across the polar cap of the order of 50 kV to more than 200 kV depending on geomagnetic conditions.

Modern view

The study of electrodynamics of the earth's atmosphere by region-wise is not desirable. The electric fields and current do not care for artificial boundaries, like tropopause, stratopause, mesospause, ionosphere etc. The electric fields and current can propagate from one region to another and affect the electrodynamic processes occurring there. Hence the electrodynamical processes of one region cannot be studied in complete isolation from the electrical state of the other region. An integrated approach, such as global electric circuit is required to understand the electrical environment of the earth's atmosphere.

Global electric circuit

Global electric circuit (GEC) is a model which describes the electrical environment of earth's near space. It links the electric fields and currents flowing in the lower atmosphere (comprising of troposphere, stratosphere

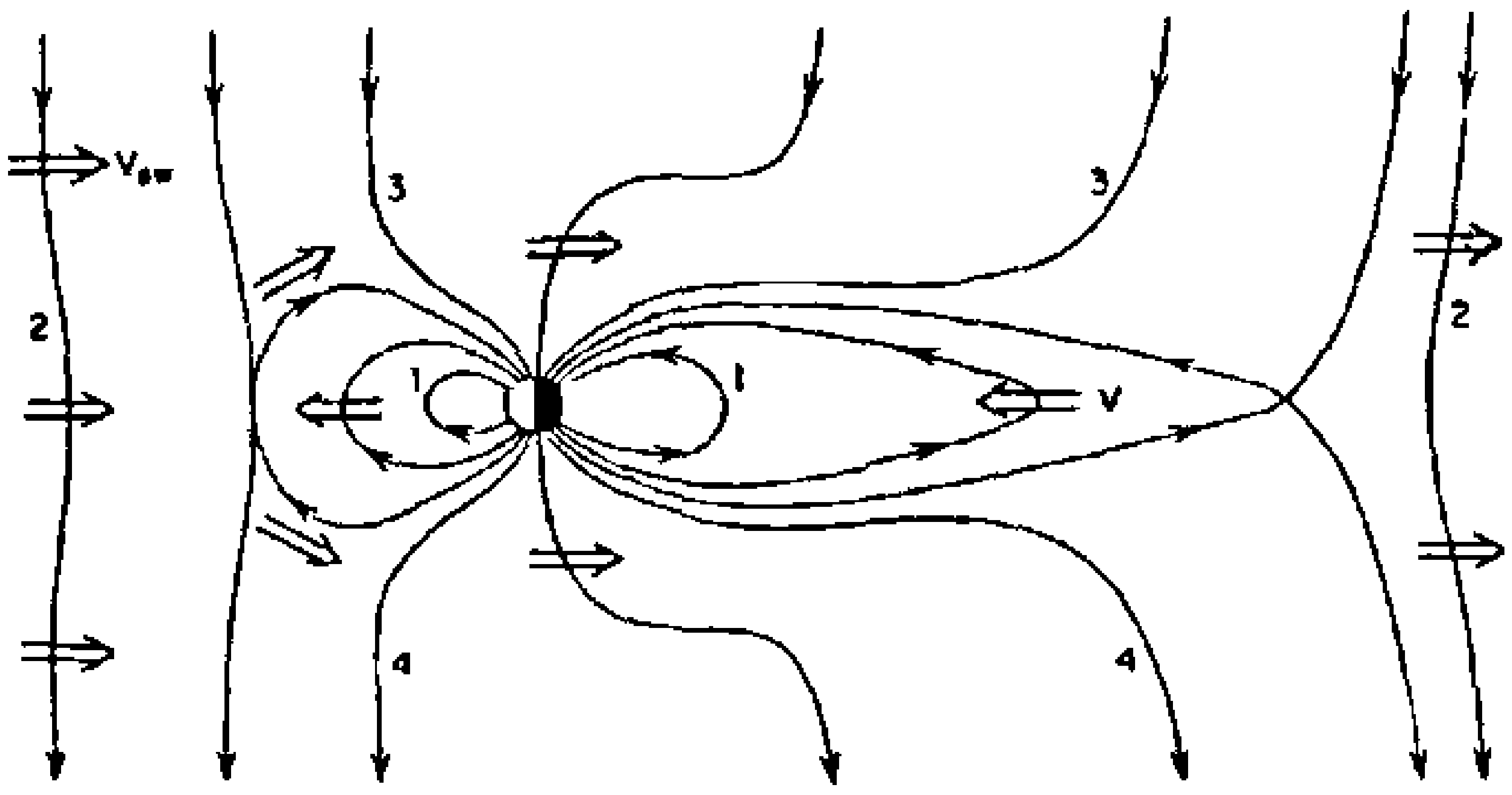

Figure 5. Schematic illustration of magnetic field and plasma flow in the solar wind-magnetosphere environment. Continuous lines show the magnetic field for the case when the interplanetary magnetic field (IMF) is purely southward. Open arrows show the plasma velocity direction. Numbers 1 to 4 denote four classes of the magnetic field line; 1) the closed field lines connected to the Earth in both northern and southern hemispheres, 2) the interplanetary magnetic field lines unconnected to the Earth, 3) open field lines connecting the northern polar cap to the interplanetary medium, and 4) open field lines connecting the southern polar cap to the interplanetary space. The large scale antisunward and sunward plasma flows produced in the magnetosphere are commonly called *plasma convection*. The process of magnetic reconnection occurring on the dayside magnetopause as well as in the magnetotail region is believed to be a major source for the plasma convection.

and mesosphere), the ionosphere and the magnetosphere forming a giant electrical circuit. This could, therefore, form a natural basis for studying the electrodynamical processes occurring in the entire earth's atmosphere. Interestingly enough, GEC can provide a good framework for understanding the solar-terrestrial-weather relationships.

The earth's near space electrical environment as well as its weather are affected by the solar disturbances. It has been postulated for over 100 years that solar activity controls the thunderstorm activity and atmospheric electricity by some complex processes which are not understood even now. Recent studies on sun-terrestrial-weather relationship relate the solar sector boundary crossing to the increased lightning frequency, thunderstorm activity and vorticity area index[1]. Lightning frequency and the tropospheric electric fields are found to increase shortly after solar flares (within a day or so). A strong correlation has been found between occurrence of optical pulses of lightning origin and geomagnetic activity and cosmic ray intensity[2]. Large horizontal potential drops in the ionosphere correlate well with solar flare occurrences with the delay of about 2 days or less[3]. Furthermore, some studies indicate penetration of interplanetary electric fields to the equatorial ionosphere.

The GEC model has several advantages over the traditional methods, based directly or indirectly on solar heating mechanism, put forward for explaining solar-terrestrial-weather relationships. The main drawback of the solar heating mechanisms is that solar constant variations are very small, i.e. less than 0.1%. Secondly they require efficient coupling from thermosphere to the lower atmosphere which in reality is rather weak; and thirdly the solar heating mechanisms are too slow. They require at least several days before atmospheric dynamics would be affected significantly. GEC model bypasses all these difficulties, at the same time offering a novel approach to understanding the electrical environment of our planet. To give some examples; a change in ionosphere 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 clouds top can affect the electric field throughout the lower atmosphere. Theoretical modelling shows that a slight change in the initial background electric field during cloud electrification can lead to entirely different final voltages developed[4]. This is because of the fact that the Earth's atmosphere is a highly nonlinear system. Application of a large amount of energy to the atmosphere is not always necessary to get a violent response, rather a minute amount of energy applied at proper time and location can easily do the same job!

Classical GEC model

The classical model of atmospheric global electric circuit (see Figure 6) proposed by Wilson[5] considers the Earth's surface and the ionosphere (situated at 60 km) to form two plates of an electrical condenser in which ionosphere (the outer plate) is maintained at a uniform positive electrical potential of a few hundred kilovolts with respect to the Earth (which forms the inner plate), by the worldwide thunderstorm activity. The atmosphere acts as a leaky dielectric between these two conductors. The basis for the formulation of this classical model was the observations that the vertical electric field had globally uniform diurnal variations similar to that of global thunderstorm activity. This model considers the thunderstorms as the only generator of GEC and neglects all other sources. It also hypothesized that ionosphere is an equipotential surface and that the thunderstorm electric field cannot go beyond the ionosphere.

New developments

Over the past few decades, with the advent of satellites and the availability of modern sophisticated instruments, there has been a rapid advancement in our knowledge about electric fields and currents in the near Earth environment. Some of the important findings are listed below:

Effects of lower atmosphere electric fields/currents on ionosphere-magnetosphere. Measurements of conductivity on balloons and rockets, and the modelling of current flow above thunderclouds show that the thunderstorm currents flowing vertically into the ionosphere do not spread out homogeneously. Rather, above 70 km a substantial part flows into the magnetosphere along the geomagnetic field **B** and into the opposite hemisphere[6,7]. This is due to the effect of anisotropic conductivity.

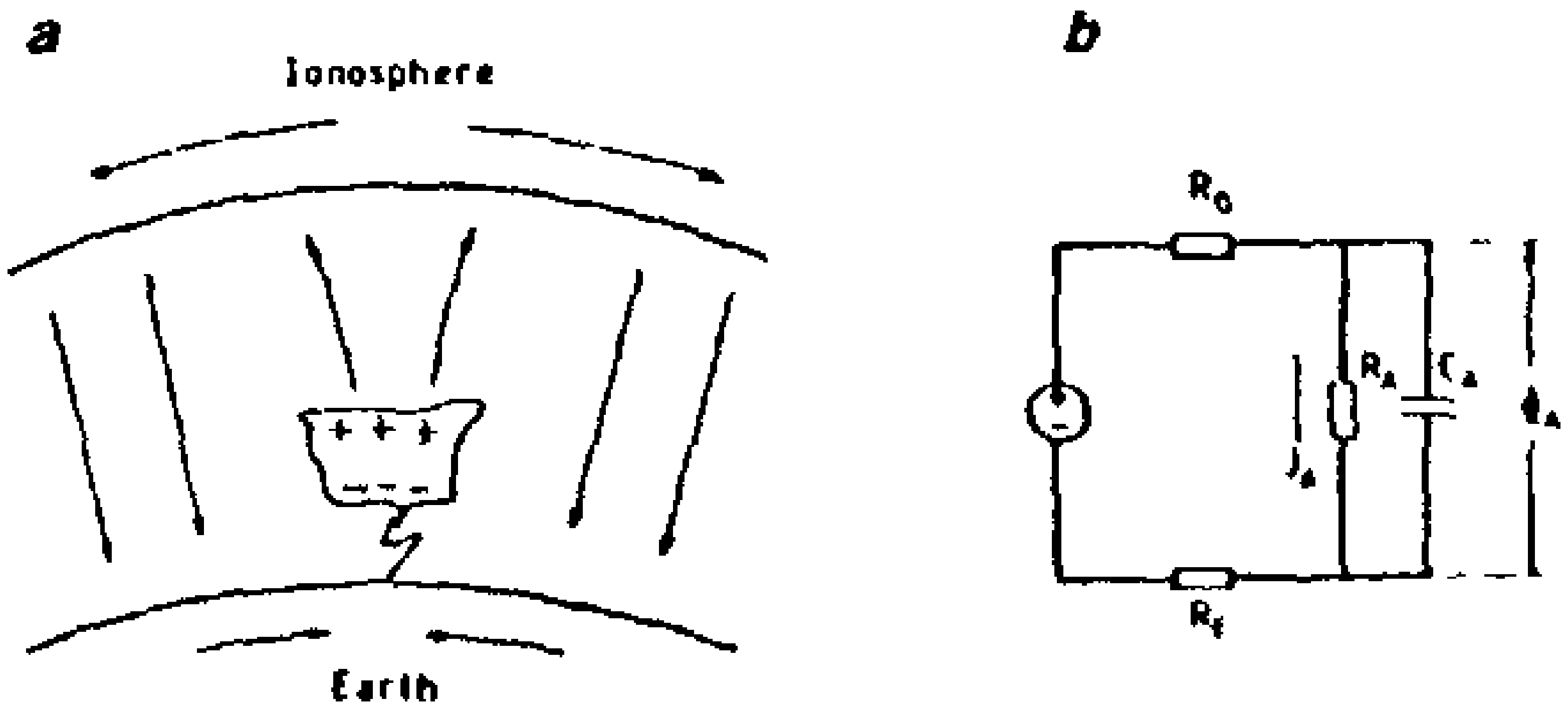

Figure 6. Schematic diagram of the classical global circuit (GEC) model proposed by Wilson. The earth and the ionosphere are treated as two plates of a condenser. The thunderstorms act as a sole generator maintaining the ionosphere at a uniform positive potential of a few hundred kilovolts with respect to the Earth. The atmosphere acts as a leaky dielectric between these two conductors.

It has been observed that lightning strokes can cause transient electric field pulses of several tens mV/m in the ionosphere[8,9]. They can also cause precipitation of energetic electrons from the magnetosphere, which in turn change the conductivity in the mesosphere by impact ionization[10,11].

The passage of a thunderstorm can cause an increase in the sporadic-E ionization in the ionosphere[12,13]. The electric fields of large thunderclouds can penetrate deep into the magnetosphere and lead to the formation of field-aligned electron density irregularities in the ionosphere/magnetosphere[14].

Mesospheric electric fields. During recent years, there have been several observations by rocket and balloon experiments of surprisingly strong horizontal electric fields in the mesosphere[15]. Holzworth[16] reported electric fields of the order of 10–50 mV/m, rotating counter clockwise with a period of about 18 h, in the southern hemisphere. Coriolis force-driven inertial wave has been suggested as a probable cause for these strong fields.

Strong horizontal electric fields ~30 mV/m have been reported[17,18] in the northern hemisphere which rotate in clockwise sense with period of several hours.

Effects of magnetospheric/ionospheric electric fields/currents on the lower atmospheric electrodynamics. It is now more or less established that magnetospheric and ionospheric horizontal electric fields can penetrate as low as 35 km[19].

The ionospheric/magnetospheric currents can couple to the neutral atmosphere currents and cause Joule heating in the mesosphere. This effect is limited mostly to the high latitude. During solar proton events the rate of heating can be of the order of 1°–3° K/day[20–22].

It has been reported that flux transfer events (FTE) arising from dayside magnetopause reconnection can affect the fields and plasma flows in the ionosphere and in the neutral atmosphere[23,24].

Theoretical mapping of ionospheric dynamo field to lower altitudes shows[25] that the horizontal electric fields turn into vertical fields at the surface of the earth with magnitude of the order of 1 V/m. The downward mapping of polar cap electric fields shows that these fields can cause 20% perturbation in air currents and ground electric fields[26]. Both the above mapping studies neglect the possible coupling with the mesospheric electric fields.

Need for new GEC model

The new discoveries stated earlier make it clear that electric fields and current do not feel the artificial boundaries encompassing the regions of the lower atmosphere, or the ionosphere or the magnetosphere. Hence the mutual coupling and interconnections between these regions, which have been traditionally studied separately so far, are essential to understand the complexities of our planets' electrical environment. Such an approach would yield new light in identifying the physical causes of solar-terrestrial-weather relationships. Such a study has been strongly recommended by several ambitious international programmes, like *solar terrestrial energy programme* (STEP), *geospace environment modelling* (GEM), *global atmospheric electrical measurement* (GAEM) and *international geosphere-biosphere programme* (IGBP). The latest GEC model[27] shown in Figure 7) treats the ionosphere and the magnetosphere as passive elements. Hence, there is an urgent need to devise new GEC models where the ionosphere and the magnetosphere are the active elements providing current and voltage sources. A conceptual diagram for the future GEC model is shown in Figure 8. The portion below the dotted line in Figure 8 is the usual classical electric circuit, where thunderstorm and other generators in the lower atmosphere are plugged together as a current source I_{TS}. The ionospheric electrical generator is denoted by V_{SQ}, and the magnetosphere generator by V_{SM}. The variable resistor R_{IM} represents the ionosphere-magnetosphere coupling, and L_T represents the energy stored in the magnetotail. Some of the challenging problems related to GEC which would help in quantifying the value of various elements shown in Figure 8 are:

(i) To quantify the solar wind-magnetosphere interactions under various interplanetary magnetic field (IMF) conditions. This is necessary for estimating the efficiency of solar wind-magnetosphere dynamo, and for the energy and mass transferred to the magnetosphere. Generation and distribution of parallel electric fields

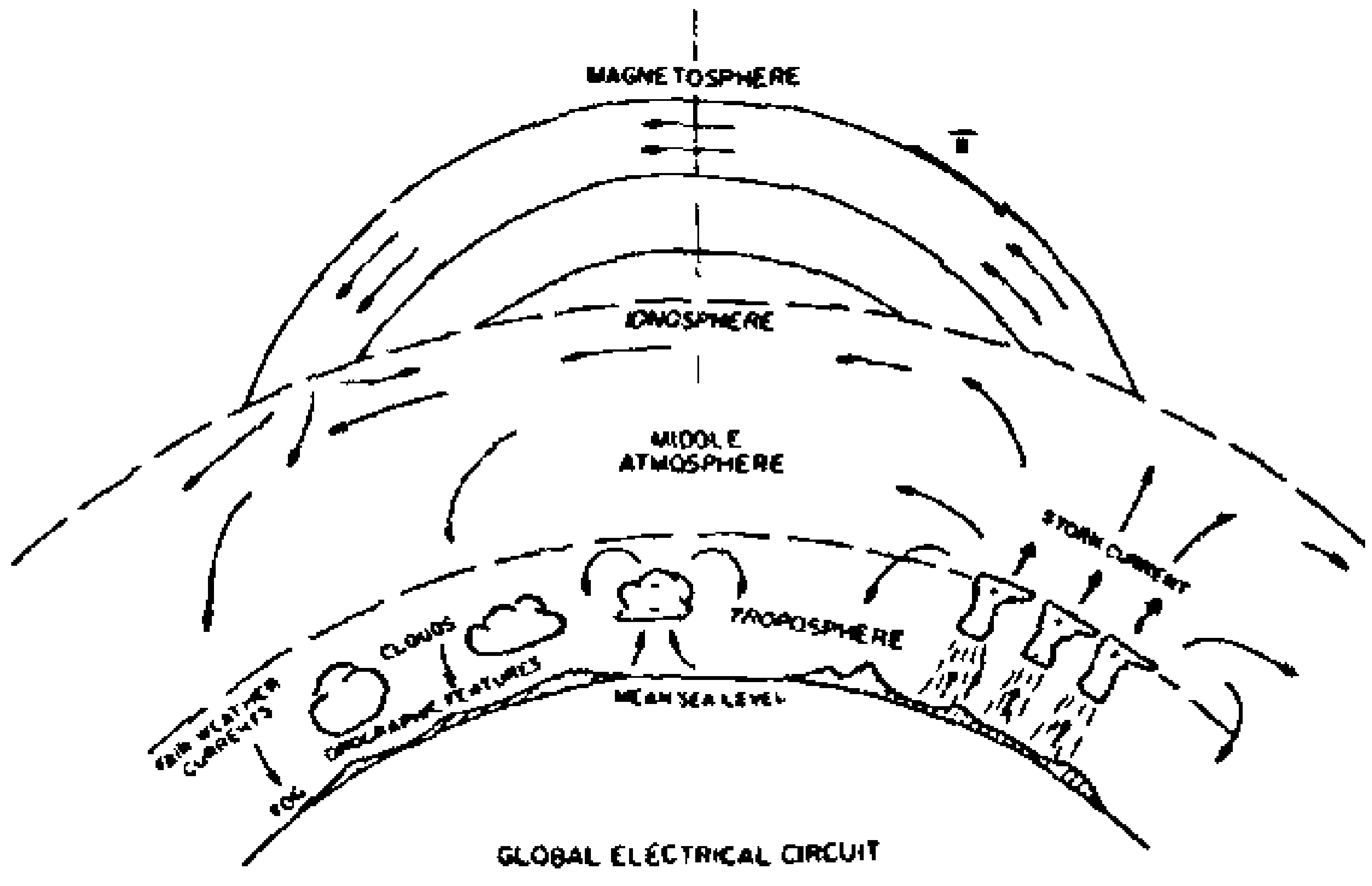

Figure 7. Schematic illustration of a model of the global electric circuit due to Roble and Hayes[27]. The model takes into account the *orography of the Earth, but treats the ionosphere and the* magnetosphere as passive elements of the circuit.

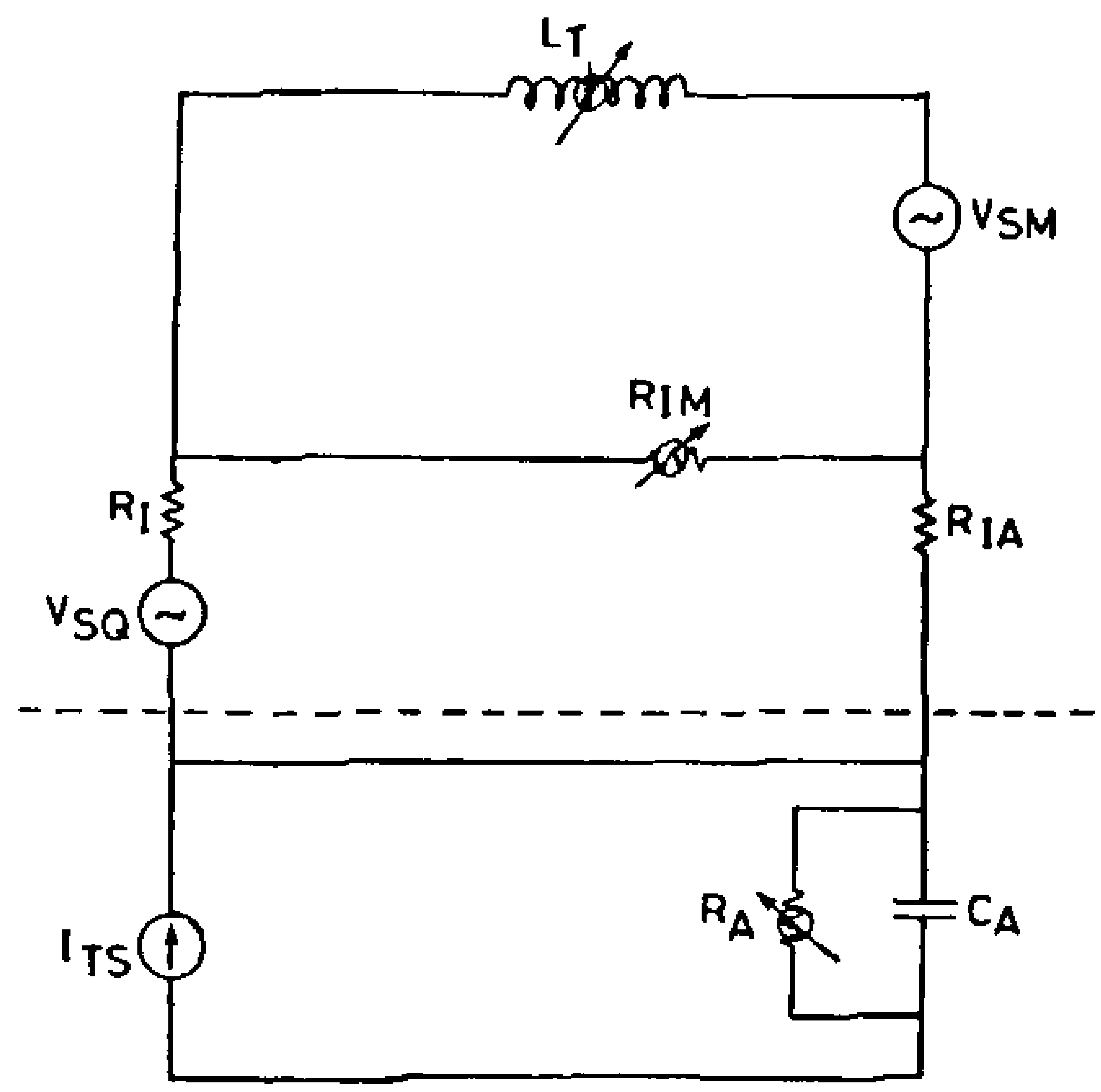

Figure 8. Schematic diagram of a conceptual future model of GEC where the ionosphere and the magnetosphere are treated as active elements. The portion below the dashed line is similar to the classical type GEC models, but incorporates all the known generators in the lower atmosphere clubbed together as I_{TS}. The ionospheric and the magnetospheric generators are shown as V_{SQ}, and V_{SM} respectively. Variable resistor R_{IM} and inductor L_T represent respectively the ionosphere-magnetosphere coupling and the energy stored in the magnetotail. Quantifying the values of various elements shown in this figure imposes a challenging problem for realistic GEC models.

must be understood for proper estimation of magnetosphere-ionosphere coupling[28,29].

(ii) To map electric fields of magnetosphere/ionosphere to the lower atmosphere and finally their coupling to the mesospheric electric fields and, then, estimate their influence on the air-earth current density, and on the processes of charge transport, specially between thundercloud base and the earth.

(iii) To understand the role of external fields, air pollutants, aerosols, cosmic rays etc. on the process of thunderstorm electrification[30-32].

(iv) To integrate all the above as well as other effects together and develop a viable GEC model which can explain the solar activity control of our electrical environment.

Benefits to society

The study of electrodynamical process in the earth's atmosphere via the GEC approach may have many far-reaching and long-term benefits for mankind. First comes the aesthetic requirement of understanding the electrical environment in the same way as one would like to understand the meteorological environment. Secondly, as this study explores interconnection between the electrical environment and weather, it is hoped that the outcome from GEC studies would be relevant for long-term weather forecasting. It may even be possible, in the near future, to modify weather by controlling some of the electrical parameters of GEC. Thirdly, this study would have important implications for communications worldwide, and between the ground to satellite, for satellite charging affecting the lifetime of the satellite and its proper functioning; and for the safety of the astronauts. Fourthly, the study would also be useful for assessing the harmful induced currents set-up in powerlines and long cables under varying solar and geomagnetic activity.

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Role of middle atmosphere coupling processes in ozone change

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The earth's middle atmosphere is a complex region where processes like radiative transfer, chemistry and dynamics are nonlinearly coupled. The relationship between ozone concentration and temperature at stratospheric level and the solar UV irradiance and the total ozone column density are shown as examples of coupling processes. One of the recent findings on the role of stratospheric aerosols in depleting ozone concentration through heterogeneous chemistry is highlighted.

THE altitude region extending between 10 and 100 km of the Earth's atmosphere is generally defined as the 'middle atmosphere'. It can be said that the middle atmosphere couples the upper ionospheric region with the meteorologically significant lower part of the atmosphere, as it is influenced from both above and below. It is a complex region where processes like radiative transfer, chemistry and dynamics are nonlinearly coupled. Systematic observations of this region have begun only in the last ten to twenty years using rocket, balloon and satellite-borne sensors and also using more versatile ground-based techniques such as lidar. Atmospheric ozone is a very important constituent of the middle atmosphere whose global distribution is determined by several chemical as well as physical processes. Detailed experimental and theoretical studies of the behaviour and transport of ozone started way back in the 1940s, and attempts were made to bring out the dependence of ozone distribution on meteorological parameters[1–3]. Extensive literature is available on ozone studies conducted since then (WMO Report[4] and references cited therein). However, over the past few years there has been a greater concern about the anthropogenic influences which are found to play a major role in depleting the ozone abundance. The major consequence of ozone depletion is an increase in the biologically active ultraviolet (UVB) radiation received at the surface apart from its impact on climate through radiative forcing. In this work some of the recently found middle atmospheric processes which influence the ozone chemistry are presented. Particularly the recent finding on the significance of stratospheric aerosols in depleting the ozone concentration through heterogeneous chemistry is highlighted.

Examples of coupling processes

The classic example of a coupling process going on in the earth's middle atmosphere is between two regions, the troposphere and the stratosphere, through meridional circulation. The rising motion of air in the tropics and the descending motion at the mid-latitude regions, referred to as the 'Hadley cell' is used[5] to explain the observed latitudinal increase in the column density of ozone although the ozone production is maximum at the tropical upper stratosphere. Thus the spatial and temporal distributions of ozone depend not only on the chemical reactions which produce and destruct the ozone molecules but also on dynamics which can transport ozone as well as other minor constituents involved in the ozone chemistry.

The temperature field which determines the rates of many chemical reactions is also found to play a role in