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**Electrical Structure of the Stratosphere and Mesosphere**

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Motions in low latitudes of the sunlit hemisphere. These vertical motions are powered by meridional oscillations in the stratospheric circulation produced by solar heating of the stratopause region and serve as the energy source of electrical current systems which are postulated to result from an impressed electromotive force produced by charged particle mobility differences in the lower ionosphere as the tidal circulations tend to force these particles across the earth's magnetic field. These dynamo currents are variable with geometry and time variabilities of the tidal circulations as well as variability in the solar-induced conductivity of the E region. The semiconducting lower atmosphere and highly conducting earth's surface occupy the near field of the lower side of this current system, with a resulting complex tropospheric electrical structure. Paths of low impedance electric current along magnetic field lines result in development of currents in the exosphere that are driven and controlled by the electrical structure of the primary dynamo circuit and that exert a control of their own through interaction with the solar wind. The basic physical process providing the required electromotive force for maintenance of the earth's atmospheric envi­ronment electrical structure is thus indicated to center in thermally driven tidal motions in the lower ionosphere, with locally observed structure, such as the fair-weather electric field, thunderstorms, lightning discharges, aurora, airglow, electrojets, and radiation belts, playing supporting roles.

Introduction

The electrical structure of the earth remains today one of the most interesting problems faced by the geoscientist. The earth's permanent magnetic field is generally believed to result from electrical phenomena in the earth's interior, and certain small variations in that magnetic field have been demonstrated to be related to direct electromagnetic interaction of the earth system with the local solar environment. Also, some systematic variations are believed to originate in motions of the weak ionospheric plasma through the permanent magnetic field. Electrical manifestations of this comprehensive magnetoelectrodynamic system are commonly noted in thunderstorm electrification, the fair-weather electric field and current, aurora, airglow, and numerous other facets of an obviously complex system. The certainty that these puzzling phenomena (viewed individually) must fit into a satisfying global electrical structure has led to inspection of new information on the physical structure of the atmosphere for clues that will serve to bind the currently fragmented picture together.

In October 1959, a new system for synoptic exploration of the earth's upper atmosphere using small rocket vehicles was initiated to extend the region of meteorological study to higher altitudes. This meteorological rocket network (MRN) has expanded the atmospheric volume currently subject to meteorological scrutiny from limitations of the order of 30-km peak altitude to a current synoptic data ceiling of the order of 80 km. A number of very important findings have resulted from MRN synoptic exploration of the upper atmosphere, the most notable (for our current purposes) being the discovery of large diurnal variations of the temperature, wind, and ozone fields of the stratosphere, that are driven and controlled by the solar induced heat pulse downward and upward from the stratopause level is then accomplished by secondary physical processes. Consideration of this new information has led to the realization that above 40-km altitude circulation systems exist in the atmosphere that exert a profound influence on upper atmospheric structure by dynamically altering physical processes and by mixing and transporting atmospheric constituents of the upper atmosphere.

An important result of these synoptic meteorological studies of the upper atmosphere concerns the fact that vertical motions of considerable magnitude in specific locales are indicated by the data. Upward motions in the summer high-latitude nighttime sky indicated by the data imply the presence of downward motions in polar regions of the opposite hemisphere and in middle and low latitudes of both hemispheres on a diurnal basis. Downward motions are indicated to be located in the sunlit hemisphere from early morning until early afternoon with maximum intensity in low latitudes. Such vertical motions exert pronounced influences on the electrical structure of the atmosphere because they transport charged particles of the atmosphere vertically through regions where differing mobilities of the positive and negative charge carriers produce electromotive forces. Charge separation caused by this basic mechanism is indicated to occur in a predictable fashion in the mesosphere and lower ionosphere, and such a separated charge can be shown to result in electric fields and currents that modify the normal ionosphere in accord with the observed global electromagnetic structure.

Electrical Structure

Motion of a gas containing a mixture of electrons and ions through a magnetic field will result in production of an electromotive force oriented in the direction of flow as a result of differing mobilities of the charge carriers. Peierls has stated the general relation.
where $E$ is the electric field, $\mathbf{v}$ is the velocity of the charged ($q = 1.6 \times 10^{-19}$ coulomb) particles, $B$ is the magnetic field, $M$ is the mass of the particles, $g$ is gravity, $v$ is the collision frequency, $\omega$ is the gyrofrequency of the charged particles relative to the neutral gas, and $v_{\text{p}} n_1$ is the pressure gradient of the charged molecules of n particles m$^{-3}$. He derived the vertical component solution for the case of a vertical wind exerting a force ($F$) through collisions between neutral and charged molecules to obtain the charged particle speed ($v$) relative to the neutral gas:

$$v = \frac{F}{\omega (\omega^2 + \omega_0^2)}$$

where $\omega$ is the gyrofrequency for the particular charged particles involved. The gyrofrequency is given by $\omega = qBm$, which indicates that the gyrofrequency of electrons will be significantly greater than that for the ions as a result of the difference in mass ($9.1 \times 10^{-31}$ kg for electrons and $1.67 \times 10^{-27}$ kg or greater for ions). When the gyrofrequency is greater than the collision frequency, the charged particle will be effectively bound to the magnetic field, whereas in the opposite case, the charged particle will move with the neutral wind. The gravitational and pressure gradient terms of (1) and (2) can be considered negligible in the 70- to 150-km region.

Collision frequencies are significantly different for ions (assumed to be molecular oxygen) and electrons in the D and E regions. In both cases the collision frequency decreases with increasing altitude in accord with the usual density scale height. Available data would then indicate that, in the 70- to 150-km altitude region particularly, electrons would be restrained in their motion and their partner positive ions would move with the neutral wind ($\mathbf{W}$). The force producing this separation will increase with decreasing height as a result of an increasing collision frequency until the collision frequency becomes high enough to carry the electrons along with the wind also.

The electrical structure of the atmosphere varies with time and space in a complex fashion and thus can only be represented in a limited fashion by a particular model or set of data. Although some general features of electron structure are adequately portrayed by the Chapman theory of layer formation, it is apparent that many important features can only be explained by significant deviations from this assumed radiational and static equilibrium condition. It is thus desirable to make gross generalizations about the general electrical structure to obtain a first look at the nature of important physical processes that may occur and then to compare the expected results of these processes with deviations from the static electrical structure that are observed to exist. This procedure is reasonable as long as it is clearly remembered that a uniformity has been assumed that does not exist.

A magnetic field exerts a complicating influence on the conductivity structure of an ionized gas. Typical vertical distributions of specific, Pederson and Hall conductivities for a mean midlatitude noon time atmospheric model are illustrated in Figure 1. The very low conductivity of the lower atmosphere ($2 \times 10^{-14}$ mhos m$^{-1}$) results from the high collision frequency (and thus low mobility) produced by high air density and the small number of charged particles. The conductivity increases rapidly with altitude to values of the order of $10^{-9}$ mho m$^{-1}$ at the base of the D region, partly because of an increase in number density of charged particles. Above about 50 km the presence of free electrons becomes important as a result of gross differences in mass and collision cross sections of the charge carriers, and the conductivity becomes anisotropic, with a component structure like that illustrated in the upper parts of Figure 1. At low latitudes the specific conductivity ($\sigma_1$) is most applicable meridionally, the Pederson conductivity ($\sigma'$) is most applicable vertically, and the Hall conductivity ($\sigma''$) is most applicable zonally.

Vertical downward motions produced by the tidal circulations will, in low latitudes of the morning and early afternoon sunlit hemisphere, result in electrical charge separation in the vertical direction with positive charges forced downward by collision between those ions and molecules of the neutral flow. Using an open circuit approximation (in the absence of an effective return circuit path) with vertical speeds of 1 m sec$^{-1}$ at 80 km and 10 m sec$^{-1}$ at 100 km acting on ions of molecular weight 32, a vertical upward-directed equilibrium electrical field of the order of 0.066 v m$^{-1}$ at the 80-km level is obtained, decreasing in strength below and above that level with a value of 0.015 at the 100-km level. The charge separation process and its opposing electric field will rigidly maintain a positive space charge in the stratosphere region and a negative space charge in the ionosphere during the morning and early afternoon. This region of separated charge will exhibit a diurnal structure under control of the tidal circulation which continuously rotates around the earth at a speed of approximately 460 m sec$^{-1}$ at 15° latitude.

The same reasoning may be applied to
evaluate the electrical structure that will result from the tidal upward flow as the heat wave recedes locally from 2 P.M. until sunrise. With vertical circulation values of 0.4 of the morning values (from mass continuity considerations) for the late afternoon period from 2 P.M. to sunset, mean values of the vertical electric field will be approximately one-fourth the noontime values, with the principal additional difference being that the direction of the resulting electric field will be reversed. The efficiency of this source of electric field generation will decrease during the evening as a result of the diurnal decrease in electron density.

Juxtaposition of electric and magnetic fields in an ionized gas will result in imposition of forces on charged particles in the direction of the cross product of the electric and magnetic vectors. In the D and E regions the ions are immobilized (relative to motions through the gas) by collisions so that electrons are the principal carriers of this 'Hall' current. Velocity of electron motion (unhampered by collisions) constituting such a current is given by

$$v = (\mathbf{E} \times \mathbf{B})/B^2 \quad (3)$$

Using values of $B = 0.34 \times 10^{-4}$ weber m$^{-2}$ directed northward and $E = 0.066$ v m$^{-1}$ directed upward as obtained during the morning hours a westward velocity of electron motion of approximately $2 \times 10^4$ m sec$^{-1}$ is obtained for 80-km altitude.

Fig. 2. Hall current produced in low latitudes by the tidal downward motion as the heat wave approaches. The direction of current flow is to the east.

The current density carried by such a system can be calculated, yielding an 80-km value of $2.6 \times 10^7$ amp m$^{-2}$ as is illustrated in Figure 2 when a concentration of $10^9$ electrons m$^{-3}$ is used with the motion derived above. Similar calculations at other altitudes indicate that the vertical distribution of the midday Hall current of low latitudes is of the type illustrated in Figure 2. Integration of this current density over the suspended cross section yields a total dynamo current of the order of 10$^6$ amperes, which is in general agreement with estimates obtained from variations in the magnetic field.

Now the electric fields associated with these dynamo electric currents can be calculated from values of conductivity obtained from Figure 1. This calculation yields an eastward-directed horizontal electric field at 80 km of 0.043 v m$^{-1}$, which, over the longitudinal span of 1.5 $\times$ 10$^7$ meters in which the downward flow occurs, indicates a potential difference of 650,000 volts between sunrise and early afternoon along the longitude circle at 15$^\circ$ latitude. These considerations lead to the conclusion that in a longitudinal belt at low latitudes ($\pm 15^\circ$) there will be a region of electromotive force (emf) generation with a potential difference of the order of $6 \times 10^5$ volts at the base of the E region between the early morning sector and the early afternoon sector (Figure 3) for each meter per second of vertical down wind of the tidal circulation at 80-km altitude. The direction of this potential gradient is such that the early morning sector (b) is depressed in potential relative to the early afternoon sector (A).

In the afternoon and evening the tidally generated electric fields that drive the Hall currents will reverse direction and be orientated downward. The Hall current will then flow westward after 2 P.M. The electron density of the E region decreases throughout this period to make the process generating Hall current ineffective during the late nighttime (smaller than noontime by two orders of magnitude). It is clear, then, that the sunset dynamo current is weaker than the morning current.

Flow of these dynamo currents in the E region ($\pm 100$ km) of the atmosphere will result in development of a diurnal pattern of electrical potential distribution in that region. The above analysis indicates that the maximum potential will be located geographically near the point marked A in Figure 3 (near 2 P.M. at low latitudes). Minimum potential should be located near the point marked B. Significant diurnal differences will be induced in the hemispheric dynamo currents even at equinox times as a result of asymmetries between the rotational and magnetic axes, and, as a result of hemispheric separation of the vertical tidal circulations over the rotational equator, there will be a region of reduced potential between the low-latitude emf regions of the two hemispheres. More substantial hemispheric differences will develop as the sub-solar point moves away from the equator, with the summer hemisphere being favored with a stronger tidal circulation and enhanced electron concentrations and thus with stronger dynamo currents and greater potential differences. All these factors indicate that potentials in equatorial regions will be different between hemispheres for similar geomagnetic latitudes and make it probable that transequatorial currents of diurnal character will flow between the hemispheric emf zones, probably with an annual bias from the summer toward the winter hemisphere.

Such currents will flow along magnetic field lines, so that the specific conductivity (solid curve) of Figure 1 would be applicable. These currents would start near the 100-km level in one hemisphere on a magnetic field line, progress upward in a divergent field to cross the magnetic equator at an altitude of a few hundred (and/or thousand) kilometers, and converge back to the 100-km level at the same low latitudes of the other magnetic hemisphere.

This current will have the principal characteristics of a conduction current in the middle and upper ionosphere, where charge carriers are plentiful, and will be characterized by fast individual transients of a few particles along magnetic field lines in the relatively collision-free exosphere. This low-latitude interhemispheric dynamo current circuit is in the location...
Fig. 3. Equatorial plane projection of the dynamo current system. Regions 1 and 2 (inclosed by dash-dot curves) represent regions of electromotive force generated by vertical tidal motions. Positions of the rotational (RP), magnetic (MP), and auroral (AP) poles for the northern hemisphere are indicated. The dashed circular curve represents the center line of the auroral zone.

...of the inner Van Allen radiation belt and presumably provides the basic energy for that phenomenon. The inner radiation belt electric current path then smooths inequalities in the hemispheric tidally produced emf regions. There should be marked diurnal variations in the basic low-energy currents flowing in the region of the inner radiation belt. Some of the electrons and ions taking part in these exospheric currents will, because of their favored initial trajectory angles and kinetic energies, be trapped in the magnetic field for short or long periods. These trapped particles will drift longitudinally (electrons drifting to the east and positive ions to the west) along L-shells, to envelop the entire low-latitude global region in a few tens of minutes in the case of particles with high energies. Thus, the daytime dynamo regions supply the inner Van Allen radiation belt with ions and electrons that then interact with the nighttime upper atmosphere of middle and low latitudes as they drift around the globe, resulting in enhanced ionization and heating in low and middle latitudes of the nighttime ionosphere.

For these hemispheric generators of dynamo currents in the 100-km region to be effective in current transport, it is necessary that there be return current paths in the E region. Such paths will be minimum resistance paths from the high to low-potential regions. At low altitudes resistivity, which results from a high collision frequency of neutral ions in the D region, will limit ionic currents that could constitute return flows at altitudes below the emf zone, and rigidity of the magnetic field will preclude an effective electron current flow above. Positive and negative ions in low latitudes will move longitudinally as a result of this horizontal electric field in the 100- to 140-km region, and this current flow will weaken the tidally generated emf.

An important return current path is available in the direction of the magnetic field lines. Along the field lines the meridional conductivity will be that indicated by the solid curve of Figure 1, decreasing with increasing magnetic latitude until in polar regions the conductivity will be reduced to essentially the Pederson values (\(a'\)) representative of those regions. In high latitudes the dynamo current paths will be along the high-conductivity zones of the auroral ovals. These current paths are illustrated by curves a, h, and c of Figure 3. The impedance of these paths will be of the order of \(10^{10}\) ohms m, an order of magnitude less than that offered by the Pederson conductivity (Figure 1) of possible longitudinal paths.

It is clear that the electric potential distribution of the lower ionosphere, which is established by the dynamo currents, will, in general, not be the same in the two auroral zones. Asymmetry of magnetic and geometric axes will produce a diurnal variation in the direction and intensity of these polar potential differences for various conjugate locales. This important diurnal variation will be further modified by the seasonal structure of the dynamo currents.
it, however, coronal discharges from the earth's

Fig. 4. Equinoctial cross section of the earth's geomagnetic field when the sun is over 160° west longitude. The light dashed curves represent projections of hemispheric circuit elements of the tidally generated dynamo current. The heavy dashed curves represent the plasmapause.

Differences in potential of as much as $10^4$ volts are to be expected at opposite ends of some high-latitude magnetic field lines.

The results of these high-latitude electric potential differences are immediately apparent on inspection of Figure 4. Currents will flow along magnetic field lines through the exosphere in response to these potential differences, forming additional circuits through the opposite hemisphere for return flow of currents generated by the tidally driven dynamo emf. As an example, in Figure 4 the potential of point b of the northern hemispheric dynamo circuit (dashed curve) will be higher than the potential of b' because b is electrically closer to the high potential at d than b' is to the high potential at d'. Using a potential difference of $10^4$ volts with an assumed path impedance of $10^{10}$ ohm m$^2$, a current flow of the order of $10^{-6}$ amp m$^{-2}$ should result along the magnetic field lines connecting b and b'. Precipitation currents in excess of this value have been observed in the auroral zones 13, 14.

Twelve hours later in the situation illustrated in Figure 5, the electric potential positions of b and b' will be reversed, with b' at a higher potential than b. The exospheric current flow in the outer Van Allen belt region will thus exhibit a marked diurnal reversal in direction as the asymmetric positions of the auroral zones alter the relative potentials of the ends of high-latitude magnetic field lines. These currents apparently form the basic power source for the outer Van Allen belt.

It is important to note that the regions involved in the currents of both radiation belts will be firmly tied to the earth's rotation. Since most particles are charged above an altitude of roughly 1 earth radii and thus participate in the currents, the effective captive mass of the earth will then be enclosed in the volume contained within the plasmapause surface and high-latitude lower ionosphere indicated by the heavy dashed curves of Figures 4 and 5. These charged particles (electrons and ions) will always be transient, so that the electrical structure of the upper ionosphere and exosphere will be the result of dynamic processes.

Geomagnetic field lines of polar regions extend beyond the plasmapause to sufficient distances from the earth for their energy density ($\sim B^2/8\pi$) to be reduced to near the order of the solar atmospheric plasma ($\sim nkT$). Interaction of high-latitude field lines with the solar wind will thus become important in the relevant physical processes. This extraterrestrial mode of electrical processes would appear from experimental evidence to occur poleward from a variable region near 70° magnetic latitude (beyond the 8 L-shell). The magnetic field lines in these regions will be tied to the electric potential of the lower ionosphere in the region through which they pass. This will result in the earth's exhibiting important nonsymmetrical electrical aspects to the solar wind. The north polar region will generally be at a higher potential (maximum of the order of $10^4$ volts) when the sun is over the western hemisphere (300°E to 150°W longitude, Figure 4), with a maximum where the difference in latitude of the magnetic and rotational equators is maximum. The reverse polarity will be observed in the case illustrated in Figure 5.

Under such conditions an external electric current will flow through the earth system under the control of the dynamo circuits\(^{15}\). The internal part of this current will flow from south to north when the sun is over the western hemisphere (Figure 4) and in the opposite direction during the following diurnal period (Figure 5). The internal path segment of this external electric circuit will almost surely be through the low-impedance path of the outer radiation belt. The reason for the fast response of the outer belt and its precipitation regions\(^{16}\) to variations in the solar wind is thus obvious, and the gross source of charged particles of various energies from the solar wind observed in that region is more easily understood. It is important to note, however, that the impetus for this external current system is from the potential field set up by the dynamo currents.

Fig. 5. Similar to Figure 4 except that the sun is over 20° east longitude.
The kinetics of charged particle transport between the solar and earth environments should exhibit interesting physical characteristics. Positively charged particles (protons) precipitating from the solar wind will, as a result of their greater mass, penetrate deeper into the earth's atmosphere than will electrons. The magnetic pole at a lower potential (the winter pole) will then be the recipient of a flux of these solar protons, the quantity of which will be deposited below the dynamo currents. The electrons involved in this current will, on the other hand, interact (arrive or depart) at a higher altitude as a result of their small mass. These factors are well illustrated by winter polar cap absorption events. A segment of this external circuit must be established in the earth's near space, probably through the action of a Hall current produced by the ambient magnetic and electric fields.

It is interesting to note, then, that the current flow discussed above represents the earth's electrical connection with the solar environment. In the same way that the tropospheric region of high impedance evidences electrostatic phenomena, the earth-solar plasma circuits may cause the internal electrical system of the earth to operate at a different potential from that of the external parts of the circuit. This would be caused by differing mobilities of the charge carriers that take part in the polar segments of the external circuit. A downward flux of electrons into the positive pole should be observed. Over the negative pole, however, it is possible that the current is constituted by a downward flux of protons from the solar wind and an upward flux of ambient electrons from the ionosphere because of gross differences in mass, gyrofrequency, and collision frequency of the two carriers.

It may well be, then, that the earth's integral rotational system (inside the plasmapause) is maintained at some electrical potential different from the solar plasma of the earth's near space by this differential impedance. If so, that difference would be such that the earth would be negatively charged and thus at a reduced electrical potential. It should be again noted that, although the earth's orbital motion and flow of the solar plasma past the earth may supply some of the energy required for this charge separation, the principal source of energy and the control agent will be the tidal circulation, which derives its energy from solar heating of the ozonosphere.

An interesting aspect of upper atmospheric electrical and magnetic phenomena concerns the annual cycle. Magnetic and electrical phenomena generally exhibit maximum intensity near the equinox and minimum intensity near the solstice. The cause of this periodicity is apparent on inspection of Figure 6. The conductivity of the winter high-latitude ionosphere is reduced in the absence of photoionization so that the usual low impedance of high-latitude field lines will be high and these paths are essentially opened. In addition, the dynamo currents of the winter hemisphere do not extend to high latitudes, with a subsequent reduction in the potential difference achieved between the poles.

Tropospheric Electrical Structure

Resistance to the flow of an electric current in the atmosphere is maximum near the earth's surface. Bulk resistivities of the order of $10^{13}$ ohm meters are the rule over most of the globe in the boundary layer, with a rapid decrease with altitude of more than an order of magnitude in the first ten kilometers. The earth's crust and water surface stratum exhibits a resistivity range from 100 to 0.1 ohm meters, and the 100 km region of the ionosphere has values between 10 and $10^5$ ohm meters. The tropospheric electrical situation is thus characterized by a thin spherical layer of high impedance to electrical current flow bounded by relatively
highly conducting layers above and below.

This state of affairs results principally in this dense lower atmosphere from a very low mobility of charge carriers, which in turn is produced by their relatively large mass and high collision frequency. Near the earth's surface, mobilities of approximately $2 \times 10^{-4} \text{ m}^2 \text{ volt}^{-1} \text{ second}^{-1}$ are characteristic of the charge carriers, and values of three orders of magnitude slower are most common. Even the small (fast) ions appear to be clusters of molecules, while the large (slow) ions appear to be attached to condensation nuclei and other atmospheric particulates. This reduced mobility of the charge carriers in the lower atmosphere allows eddy transport phenomenon to dominate the electrical structure on occasion. Clouds are particularly efficient in this process, with vertical upward motions of cloud particles in convective storms and downward motion of precipitation particles actively redistributing tropospheric space charge on a gross scale.

Lightning discharges from cloud to ground under thunderstorm conditions introduce a different mode of transporting electric charge across the high impedance lower atmosphere. The resistivity in the lightning paths is reduced below the fair-weather values at the same altitude by a factor of more than $10^3$, with resulting short time constants and large current flows. Observations of lightning discharges indicate that a net mean upward flow of approximately 1500 amperes across the troposphere is characteristic of global thunderstorm systems. This current flow is roughly equal to the integrated fair-weather current which is observed to flow onto the earth.

Electric "telluric" currents flow toward low latitude in daytime and toward high latitude at night, with continental intensities of $10^{-7} - 10^{-8}$ amperes m$^{-2}$. The lower resistivity of ocean areas indicates that these telluric currents easily carry the approximately 1500 amperes of the fair-weather electric current to the thunderstorm segments of the tropospheric circuit.

The tropospheric electric current system is then characterized by a weak, high potential downward flow across the troposphere over large areas of the globe, lateral convergence to thunderstorm regions as telluric currents in the earth's surface layers, strong upward flows in restricted low impedance lightning paths of thunderstorms and lateral spreading of the current system in the dynamo circuits of the highly conducting upper atmosphere.

The fair-weather electrical structure of the lower atmosphere has been extensively explored. It is variable, with a general resistivity vertical structure of the type illustrated in Figure 7. Here the bulk resistivity of the air exhibits its characteristic high value near the surface, decreasing rapidly with height so that the vertical path resistance is established by the resistance of the lower few kilometers. Almost 98% of the total vertical path resistance of roughly $1.8 \times 10^4 \text{ ohm m}^2$ is obtained in the first 10 km, and almost 50% is obtained in the first 5 km.

In the stable fair-weather case, the vertical distribution of atmospheric space charge which produces the observed change in potential gradient can be calculated approximately from the relation

$$\rho = \varepsilon_0 \frac{\partial^2 V}{\partial h^2},$$

where $V$ is the electric potential, and $\varepsilon_0 = 8.854 \times 10^{-12} \text{ farads per meter}$ is the permittivity of free space. Neglecting horizontal currents, the fair-weather electric current of the lower atmosphere will be conservative with height, and, to a good approximation (Ohm's law), the potential distribution has the inverse character of the resistivity curve of Figure 7, with an overall potential difference of approximately $3 \times 10^3$ volts.

By applying Equation 4 to these data, a representative vertical fair-weather space charge distribution is obtained as illustrated in Figure 8. Clearly, the positive space charge of the atmosphere which must face the observed surface charge density of approximately $-8.8 \times 10^{-10}$ coulombs m$^{-2}$ is principally contained in the lower troposphere. The traditional leaky capacitor concept of fair-weather electrical structure is thus modified to include a diffuse upper plate located in the lower troposphere. The fair-weather troposphere capacitor plate contains a total positive space charge of approximately 400,000 coulombs, with a roughly equal negative charge on the surface of the earth. In addition, the vertically integrated space charge of the dynamo region (75 - 120 km) of roughly $10^{-14}$ coulombs m$^{-2}$ is negligible compared to these tropospheric charges.

The very low electrical mobility of most tropospheric ions in the boundary layer indicates that, in the presence of the general fair-weather potential gradient, electrically forced molecular
diffusion will be, on occasion, exceeded in intensity by eddy diffusion. Mixing produced by thermal and frictional effects may dominate electrical physical processes under certain conditions so that the electrical structure which results frequently deviates from the simple picture of a homogenous, stratified, static fair-weather field which is assumed above.

Certain features of the tropospheric electrical structure are comparatively static. This is true of any high impedance circuit, however, and does not alter the basically dynamic nature of earth electrification. The gross capacitance and charge of the earth's tropospheric electrical system (\(C_0 \approx 1\) farad) and small vertical current densities (approximately \(2 \times 10^{-12}\) amperes \(\text{m}^{-2}\)) of the troposphere effectively filter the variable aspects of atmospheric electricity, shielding the surface layers from the very dynamic aspects of higher levels.

The fair-weather capacitor electrical structure described above is effectively disrupted by occurrence of convective systems. Air that is rich in positive charge (Figure 8) is assembled by the lateral flow, immobilized by the droplets at low levels (1-2 km), and transported vertically by these convective systems in a thin column which spans the lower 10-25 km of the atmosphere as is illustrated in Figure 9. The relatively low mobilities of electrical charges are generally reduced drastically by condensation processes so that the characteristic surface boundary layer electrical time constants of tens of minutes are effectively extended to beyond the half-hour lifetime of the average convective storm. If a 14 mps mean vertical flow through a 7 km diameter throat of the storm with \(10^6\) excess positive charges per cubic meter (Figure 8) is assumed, the more intense convective systems will transport approximately \(10^4\) coulombs of resident positive charge upward each second. A first response to this positive convective current will be an intensification of the fair-weather type field under the cell as the positive space charge converges. Rapidly, however, neutralization of this positive space charge will be accomplished by negative ions in the upper atmosphere so that the negative image charge on the ground under the cell will stabilize.

Introduction of this charge structure into the upper troposphere and lower stratosphere will result in strong response by the highly conducting upper atmosphere. Relaxation time constants (\(T = \frac{\varepsilon_0}{\sigma}\), \(\sigma\) - conductivity, Ref. 19, p. 39) of approximately 100 seconds at 5 km, 20 seconds at 10 km, 4 seconds at 15 km and one second at 30 km in clear air around the thunderstorm may be expected. Upward transport of a cylindrical column of air containing roughly one coulomb of positive charge into the 5-15 km region of the storm can be expected to very quickly result in flow of an equal negative charge onto the edge of the cloud in the lower atmosphere. The mobility of the charge carriers in this conduction current will also decrease drastically when they enter the cloud as a result of capture by cloud droplets. This process will result in development of a thin sheath of negative charge around the positive core of the storm. The positive space charge may then be eliminated by discharges within the cloud between these centers of charge concentration or by recombination at the top of the cloud where the cloud particles evaporate.

The capacitance of this vertical cloud system per unit length can be estimated by the relation for

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**Figure 8.** Typical low latitude vertical structure of the atmospheric fair-weather positive electric space charge.

**Figure 9.** Initial space charge distribution associated with a convective cell before the dynamo potentials become involved. The dashed curve indicates the structure of the cloud, and the arrows indicate net motions of charged particles.
specific capacitance of a cylinder

\[ c = \frac{2\pi \varepsilon \varepsilon_0}{\ln\left(\frac{b}{a}\right)} \quad \text{(farads per meter)} \quad (5) \]

Using values of \( \varepsilon = 1 \), \( a = 3.25 \text{ km} \) and \( b = 3.5 \text{ km} \), the capacitance of this vertical cloud system is found to be approximately \( 7 \times 10^{-10} \text{ farads per meter} \). These estimates indicate that the positive space charge of the fair-weather field near the surface will supply a specific positive charge concentration \( q \) of approximately \( 2 \times 10^{-6} \text{ coulombs per meter length of the cloud} \). The equilibrium electric potential of the inner cylinder which results from this central charge can be approximated by

\[ V_n = \frac{q}{2\pi \varepsilon_0 c} \ln\left(\frac{b}{a}\right) \quad \text{(volts)} \quad (6) \]

which yields approximately \( 3 \times 10^3 \text{ volts} \).

The boundary of the storm cloud will acquire a neutralizing negative charge resulting from a downflow of negatively charged particles from the highly conducting dynamo region above the storm. This electric current, which is directed upward, must have a magnitude of \( 10^{-4} \text{ amperes} \) to match the upwelling positive current in the cloud. This vertical current has important implications for the electrical structure of the lower atmosphere and the earth's surface. Our electrostatic structural assumptions of the fair-weather situation are immediately invalidated as this upward current punctures the earth-troposphere capacitor, and the following two major conditions will prevail:

a. There will be a \( V = IR \) voltage drop along the current path from the storm cloud to the dynamo circuit above. Nominal values of \( I = 10^{-12} \text{ amperes} \) and \( R = 10^{15} \text{ ohm meter}^2 \) give potential drops of \( 10^3 \text{ volts} \), with the top of the storm at the higher potential.

b. The top and sides of the cloud will assume the potential of the dynamo current above the storm plus the difference of \( V \). This latter item is of major importance, since it has been shown that the potential drops of the dynamo currents introduce gross horizontal potential variations of the order of \( 10^6 \text{ volts} \) into the global electrical structure of the lower ionosphere. Thus, the storm cloud upwelling of positive charge from the fair-weather field discussed above will have the net result of adjusting the potential of the outer margins of a convective cloud down to altitudes of 1-2 km toward the gross potential of the dynamo region above the storm.

Stergis, Rein and Kangas have measured the potential gradient and conductivity near 20 km above thunderstorms from the direct current point of view, obtaining results indicating an upward current of the order of one ampere over each storm with negative potential gradients of a few hundreds of volts per meter. Using 200 volts m\(^{-1}\) at 20 km, 50 volts m\(^{-1}\) at 25 km and the resistivity curve of Figure 1, the potential drop in this current path approximates \( 10^5 \text{ volts} \) under steady-state conditions.

When the dynamo potential above a convective cloud is negative (late afternoon and nighttime) a positive image charge will be impressed on the earth's surface in the vicinity of the convective cloud, and the tropospheric electric field will reverse sign relative to the general fair-weather situation and the potential difference between the earth's surface and the outer margins of the cloud will be double that of the dynamo circuit to which the storm is connected. Introduction of negative dynamo potentials of the order of \( 6 \times 10^7 \text{ volts} \) or greater to near the earth's surface will induce coronal discharge of positive charge (Ref. 19, Chapter 9). With development of convective systems, enhancements of such space charge by more than three orders of magnitude above the fair-weather values have been observed. Thus, the \( 10^{-4} \text{ amperes} \) vertical current mentioned above as produced by the fair-weather space charge will be increased to more than \( 10^{-1} \text{ amperes} \), and the captive charge of the cloud condenser will be increased to more than \( 10^{-9} \text{ coulombs} \) per meter for a total cloud charge of the order of \( 10^{10} \text{ coulombs} \). These values imply general potentials across the cloud condenser system of \( 10^6 \text{ to } 10^7 \text{ volts} \), and it is likely that inhomogeneities in the entire process can easily produce the local potentials of \( 10^6 \text{ volts} \) and greater which appear to be required to initiate observed lightning discharges.

The tropospheric return current through thunderstorms must then consist of three modes. The first is upward transport of positive charge in the convective current, and the transport of these charges may represent an electromotive contribution to the troposphere electrical circuit. The second is a conduction flow upward outside the convective system involving positive coronal charges migrating upward from the surface and combining with downward moving negative charges, moving in the forced diffusion mode at higher altitudes and in convective downward motions around the cloud system at low altitudes. The third mode is high intensity upward current flow across the lower atmosphere in intermittent low resistance lightning discharge paths. Convective cells thus establish local electrical structures in which the approach of negative charges from above polarize the earth's surface, producing a negative potential gradient and an upward current flow.

The concept of thunderstorm electrification presented above is parallel to the concepts developed by Grenet, Vonnegut and Moore with the major exception of addition of the 100 km region dynamo circuit potential to induce corona and activate the electrical processes of convective cloud systems. Convective energy is necessary in initiating this series of events, but the impact of the dynamo electric potentials is overwhelming. These considerations indicate that the partial agreements which have been obtained by numerous thunderstorm electrification theories are simply fortuitous, with the basic charge separating mechanism centering on vertical eddy transport of captive space charge.

The tropospheric electrical circuit elements discussed above require that a portion of the circuit lie in the earth. The global fair-weather current must converge to a few local storm areas for the return trip through lightning discharges. Elementary physical considerations (Gauss' law) indicate that these telluric currents will flow in the surface layers of the earth. Since thunderstorms and their associated lightning events exhibit maximum occurrence at
low latitudes in the afternoon and evening, these telluric currents must be generally directed equatorward during the daytime and poleward at night.

Electric currents have been known to exist in the earth's surface since the mid-19th Century. Use of long copper telegraph lines over land regions (a $10^7 - 10^9$ ohm meter reduction in resistivity) indicated the presence of low latitude potential differences in the $10^{-5} - 10^{-1}$ range over the surface of the earth with their associated currents. Chapman and Bartels have summarized the early studies of this phenomenon. They indicate resistivities of a few tenths of an ohm meter in sea water and 1-50 ohm meters in moist loam, with an average value of 100 ohm meters for the general topsoil. Increased resistivity with depth in the ocean results from the colder waters of ocean depths. All considerations indicate that telluric currents are a shallow surface phenomenon.

If a 1 km layer is considered representative, the $10^{-7} - 10^{-8}$ amperes m$^{-2}$ which Chapman and Bartels reported for continental areas yield integrated half-day hemispheric telluric currents in the $10^2 - 10^3$ amperes range. This value is low since high conductivity ocean paths will provide partial shorts for the continental currents. The intensity of telluric currents may thus be considered adequate to supply the consolidated flow from the global fair-weather charge accumulation to the bases of lightning paths. Redding has pictorially described the diurnal structure of low latitude telluric currents, showing that they do indeed flow toward low latitudes during the day and toward the poles at night, indicating that they flow toward the region of principal thunderstorm activity.

Severe complications in telluric current observations caused by technique difficulties, local impedance variations and image charges prevent detailed association of this current segment with the vertical components of the tropospheric electric circuit. Much more information is also required relative to the location of lightning return paths before an adequate understanding can be obtained. It is concluded, however, that telluric currents are indeed adequate to provide the earth circuit segment for the tropospheric current path of the dynamo circuits.

A schematic diagram of the tropospheric electrical circuitry in a vertical low latitude longitudinal plane from the high dynamo potential point at 2 P.M. into the low potential region of nighttime is presented in Figure 10. The principal electromotive force (with potential differences of the order of $10^6$ v) is located at the base of the horizontally stratified dynamo circuit near 80 km altitude. This emf causes current to flow from low to high potential and result in accumulation of a diffuse positive space charge in the region marked A (n $\sim 10^6$ m$^{-3}$). The principal leakage return path for this potential difference is the dynamo current (approximately $10^5$ amperes) circuit through high latitudes at the 100 km level, but a secondary tropospheric return path (I, approximately 1500 amperes) circuit is established in the tropospheric mode illustrated in Figure 10.

The fair-weather vertical portion of the tropospheric circuit is represented by the resistance $R_f$ and the capacitance $C_e$. Nominal values of electrical circuit elements in this region are path resistances of $10^{17}$ ohm m, specific capacitance of $10^{-15}$ farads m$^{-2}$, current densities of $2 \times 10^{12}$ amperes m$^{-2}$ and $3 \times 10^5$ volts overall potential difference (lower at the ground) as was discussed in Section 2. Telluric impedances ($R_t$) yield potential drops of $10^{-6}$ volts m$^{-1}$ with continental current densities of $10^{-7}$ amperes m$^{-2}$ in the general case. Stratospheric impedance ($R_s$) above convective storms appears to be equivalent to that of the stratosphere in other locations (Figure 7), but the area above a convective storm is the site of larger current densities and thus of larger electric fields.

While the conductivity in a cloud is subject to debate, it will be assumed here that in strong convection high cloud droplet concentrations ($> 10^{17}$ m$^{-3}$) will prohibit effective molecular diffusion of charges so that resistance to electrical current flow in the cloud will become very great, with general cloud characteristics of a condenser $C_c$. Figure elements $10^{-7}$ this region are for a 20 km length cloud. During initial stages of convective development, the electromotive force provided by convective eddy motions will be limited to supplying current flows of the order of $10^{-5}$ amperes in individual systems. When the convective cloud system becomes effectively connected to the dynamo electrical potential above
it, however, coronal discharges from the earth's surface into the lower level air which serves as the source for convective mass transport will strongly enhance the electrical transport process. In this case the convective transport current will become very strong, possibly contributing significantly to the total current flow of the tropospheric electrical system. On occasion lightning discharges (S2, Figure 10) may negate this contribution.

Observations indicate that lightning discharges may act as switches (S1 and S2 in Figure 10) to short the charges which accumulate in the cloud-generated open circuit. During the period in which a lightning path exists, the path resistance of the convective segment of the tropospheric portion is reduced many orders of magnitude, and the upward tropospheric current flow will then be through the resistance R. When lightning paths exist in the ionosphere, the exospheric leakage current path of the dynamo circuit is

$$ R = R_f + R_t + R_s $$

which reduces to \( R_f + R_s \) to a good approximation.

These are known to be approximately \( 10^{18} \) and \( 10^{16} \) ohm m2, respectively (Figure 7).

Current densities through these two portions of the tropospheric circuit will be different, however, due to the significant difference in cross-sectional areas of these circuit elements. Peak current densities over severe storms appear to be of the order of 10 times the fair-weather values, but reasonable mean storm areas would be of the order of ten times greater. This would indicate that the potential drop of the fair-weather leg \( (R_f) \) is several times that of the stratospheric leg \( (R_s) \). Flow through this voltage divider thus maintains the earth near the average negative potential of the portion of the dynamo circuit under which the convective storms operate.

Since the fair-weather current flow is generally toward the earth even relatively close to thunderstorms, it is clear that the intermittent nature of lightning is of considerable importance. Thoroughly the mechanism, the earth is closely related to the mean electrical potential field of the dynamo region above active storms, but the brevity of the events (milliseconds) does not allow the sluggish troposphere (tens of minutes) to approach equilibrium with the new circuit parameters during this special event. The average potential of the earth is thus maintained at a negative value relative to the tropospheric condenser plate by the local dynamic characteristics of this tropospheric circuit.

Transport of electricity invariably results in heating of the medium. This heating is the familiar ohmic process if collisions occur, such as is the case in the ionosphere. In the exosphere the energy of electrified particles will be governed by the electrical structure of the environment. The thermal structure of the upper atmosphere will then partly depend on the flow of these complex currents, and a cursory examination of the magnitudes involved indicates that this source of energy will be important, particularly above the dynamo levels where the heat capacity is relatively low.

Conclusions

The earth's general electric structure is found to have its basic origin in charge separation in the lower ionosphere, which is produced by differential transport of charged carriers by low-latitude vertical winds of the stratospheric tidal circulations. Vertical electric fields are generated in the E region in low latitudes of each hemisphere, and in conjunction with the earth's permanent magnetic field, power Hall current circuits that flow longitudinally at low latitudes toward the early afternoon sector and have their principal return paths through high latitudes.

These primary dynamo currents produce gross structure in the horizontal electrical potential distribution of the E region that is not symmetrical between the magnetic hemispheres, with a resulting development of interhemispheric currents along magnetic field lines that provide the basic particle fields and power sources forming the radiation belts. Variations in these potentials caused by irregularities in the tidal circulations and by inhomogeneities in charged particle densities provide mechanisms for accelerating charged particles which are a principal feature of the radiation belts. The inner radiation belt current equals hemispheric differences between the emf regions, and the outer radiation belt current equals differences in potential between auroral zones.

An external current circuit is indicated by these considerations to exist through polar regions of the upper atmosphere, which may result in a net negative charge on the earth system, with a corresponding positive charge in the near space of the solar atmosphere. The internal path of this current will be through the outer radiation belt, and control of the current will be exercised by the dynamo circuit potentials of high latitudes and the conductivity of the solar wind.

An electrical circuit is formed between the lower ionosphere and the earth's surface by the relative short circuit of thunderstorms and their lightning discharges that connect the earth's surface to the polar potentials of the midlatitude afternoon and nighttime auroral regions.

The electron density of the ionosphere and the exosphere is in large part controlled by the electrical structure of the E region. The charged particles of the exosphere and the nighttime upper ionosphere are generally in transit under the direction of the electric fields of the primary dynamo circuits. It is necessary to this concept that these exospheric currents exhibit a diurnal reversal in direction.

The thermal structure of the upper atmosphere will necessarily be strongly dependent on the electrical structure, with ohmic dissipation of electrical energy providing a principal source of thermal energy in certain regions.

This initial look at the global electrical structure of the earth's atmosphere has clarified some aspects of atmospheric physical processes. It has pointed the way toward investigations that should illuminate some of the points that, for experimental or theoretical reasons, remain as
difficulties in the clear understanding of the earth's electrical structure. Progress has come from the application of synoptic principles, emphasizing the fact that in a complex system, such as the earth's atmosphere, isolated investigations depend on sheer luck for success.

References