The Global Electric Circuit

An electric current totaling one kiloamp worldwide flows from thunderstorms in the troposphere into the ionosphere and magnetosphere, eventually returning to the ground through the fair-weather atmosphere and closing via lightning.

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On a clear day, there is a downward electric field of 100 to 300 volts/meter at Earth's surface, although this field is not noticeable in daily life.[1] That is, one does not encounter a 1 kV potential difference when getting into a car on an upper floor in a parking garage, and electrocution is not the major hazard associated with jumping out of trees. The major reason why we don't notice the fair-weather field is that virtually everything is a good conductor compared to air. Objects such as tree trunks and our bodies are excellent ionic conductors that short out the field and keep us from noticing it. But the field is there.

To explain the fair-weather electric field, William Thomson (Lord Kelvin) proposed that the ionosphere be viewed as the positive plate of a spherical capacitor charged to a potential of about 260 kilovolts with respect to the ground, which is the negative plate.[2] Today, we know that this capacitor discharges through the atmosphere, with an average current of about 1 kiloampere integrated over the Earth.[3,4] Three quasi-DC sources of electromotive force drive the global circuit: thunderstorms, a dynamo interaction between the solar wind and the magnetosphere, and the dynamo effect of atmospheric tides in the thermosphere.[5]

Thunderstorms are thought to be the most powerful of these sources by a factor of three.[5] The electric current that flows upward from thunderstorms into the ionosphere is known as the Wilson current, named for Charles T. R. Wilson, who in 1920 first suggested that thunderstorms play this role. This current spreads out over the globe through the ionosphere and also through the magnetosphere along magnetic field lines to the opposite hemisphere. The current returns to the surface of the Earth as the fair-weather air–Earth current. Cloud-to-ground lightning strokes, such as the one shown in figure 1, return the charge to the thunderstorms and close the global circuit. This global process is summarized in figure 2, which also shows the location of the relevant layers of the atmosphere. Many attempts have been made over the years to confirm the Wilson hypothesis.[6]

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In addition to the DC circuit, the neutral atmosphere between Earth's surface and the ionosphere behaves like a waveguide when excited with ultralow-frequency electromagnetic radiation. The elements of the discrete spectrum of transmission frequencies at 8, 14, 20, . . . Hz are called the Schumann resonances, after W. O. Schumann, who first proposed them in 1952. These resonances are excited by electromagnetic emissions from lightning strokes and can be regarded as excitations of an AC global circuit. The Schumann spectrum is observed with induction coil magnetometers deployed at remote locations far from artificial electrical interference.

The global electric circuit is an old subject that has recently experienced a renaissance. Thus, mature models exist for both the AC and DC global circuits. However, owing to the difficulty of making measurements, these models rest on a small database. New instruments have allowed a critical reexamination of atmospheric electricity, and the results have challenged the standard paradigm of the global circuit.[3–5,7]

The conducting atmosphere

The "wires" in the global circuit are literally made of thin air. The exception is the "ground wire," which is the ground itself. Thus, we look first at the conductivity of the atmosphere. Ions strongly influence the electrical properties of the atmosphere, because positive and negative ions can be separated from each other to produce large-scale electric fields and because their presence in air produces conductivity. The principle source of ionization in the atmosphere below 30 km altitude is galactic cosmic rays. Collisions between cosmic rays and neutral molecules produce both positively and negatively charged molecules, mostly oxygen and nitrogen. (In the dense atmosphere, free electrons are almost nonexistent.) Within a few milliseconds, these $O_2^{+/-}$ and $N_2^{+/-}$ ions undergo ion chemical reactions and become hydrated with several water molecules (typically 6 to 8, but at cold temperatures as many as 20) to form "small ions" such as $NO_3^-(H_2O)_8$ or $H_3O^+(H_2O)_6$. In the lower atmosphere, the recombination lifetime for these ions is typically five minutes. If aerosols such as cloud or fog droplets, haze or pollution particles are present, small ions attach to them, forming "large ions," thereby reducing their mobility and the atmospheric conductivity. Measurements inside clouds have shown that the conductivity is reduced to 5% of its value at the same altitude outside the cloud.

FIGURE 1. TYPICAL CLOUD-TO-GROUND LIGHTNING FLASH. The five-minute average current delivered to the surface of the Earth is about 2 kiloamperes. Half of this current closes to the cloud tops through the ionosphere, part of a current path known as the global electric circuit. Without the global circuit, flashes such as this would be a much less frequent occurrence. (Photograph by Arthur A. Few.)

Figure 3 shows the conductivity profile of the atmosphere and ionosphere. The atmospheric density decreases with altitude with an exponential or e-folding scale height of 7 to 9 km. The mobility of small ions is governed by collisions with neutrals, and so the conductivity increases roughly exponentially with altitude, but with a smaller e-folding scale height of approximately 5 km, due to the increase in the cosmic-ray ionization rate with altitude in the lower atmosphere. In the stratosphere, conductivity and neutral density scale heights are the same—about 7 km. At the top of the middle atmosphere, above 65 km, the neutral density is so low that the lifetimes of the primary electrons become long enough for them to participate in conduction. This change produces a "knee" in the conductivity profile as the conductivity increases rapidly up into the ionosphere. The air near the surface has a conductivity on the order of 10^{-14} siemens per meter; at 100 km altitude the conductivity is 10^{-3} S/m, eleven orders of magnitude greater.

The conductivity of the ground is approximately that of the lower ionosphere. Because there is a current flowing from the lower ionosphere to the ground, the altitude profile of the electric field is the inverse of the conductivity profile, which means it decreases exponentially with increasing altitude, implying a net space charge in the air. The model of the spherical capacitor is appropriate if one recognizes that the "charge on the outer plate" of the capacitor is distributed throughout the atmosphere rather than being concentrated at a single level. The accumulation of charge in the fair-weather atmosphere above any point is inversely proportional to the local conductivity. Therefore, the distribution of charge on the "atmospheric plate" of the spherical capacitor is a mirror image of the conductivity profile in figure 3.

Vertically integrated resistivity is called the columnar resistance and is measured in units of $\Omega\ \mathrm{m}^2$. One consequence of the increase of conductivity with altitude is that the columnar resistance of the atmosphere is concentrated near the surface. Roughly one-half of the total columnar resistance occurs in the lower 3 km of the atmosphere. Hence, high-altitude surfaces such as the interior central plateau of Antarctica have smaller columnar resistances than do sea-level surfaces. Over the whole Earth, the resistance between the surface and the ionosphere is about 200 ohms. To calculate the capacitance of the spherical capacitor, a separation equal to the scale height (5–7 km) must be used rather than the height of the ionosphere. The result is a capacitance of 1 farad and a time constant for Earth's spherical capacitor in the range of 1000 to 3000 seconds:

$$T = \frac{1}{f} = 2\pi RC = 1200\ \mathrm{s}$$

Because this decay time is short, we know that the charging of the global capacitor must be nearly continuous or the global electric field would disappear.

Without radiation, Maxwell's equations can be re-

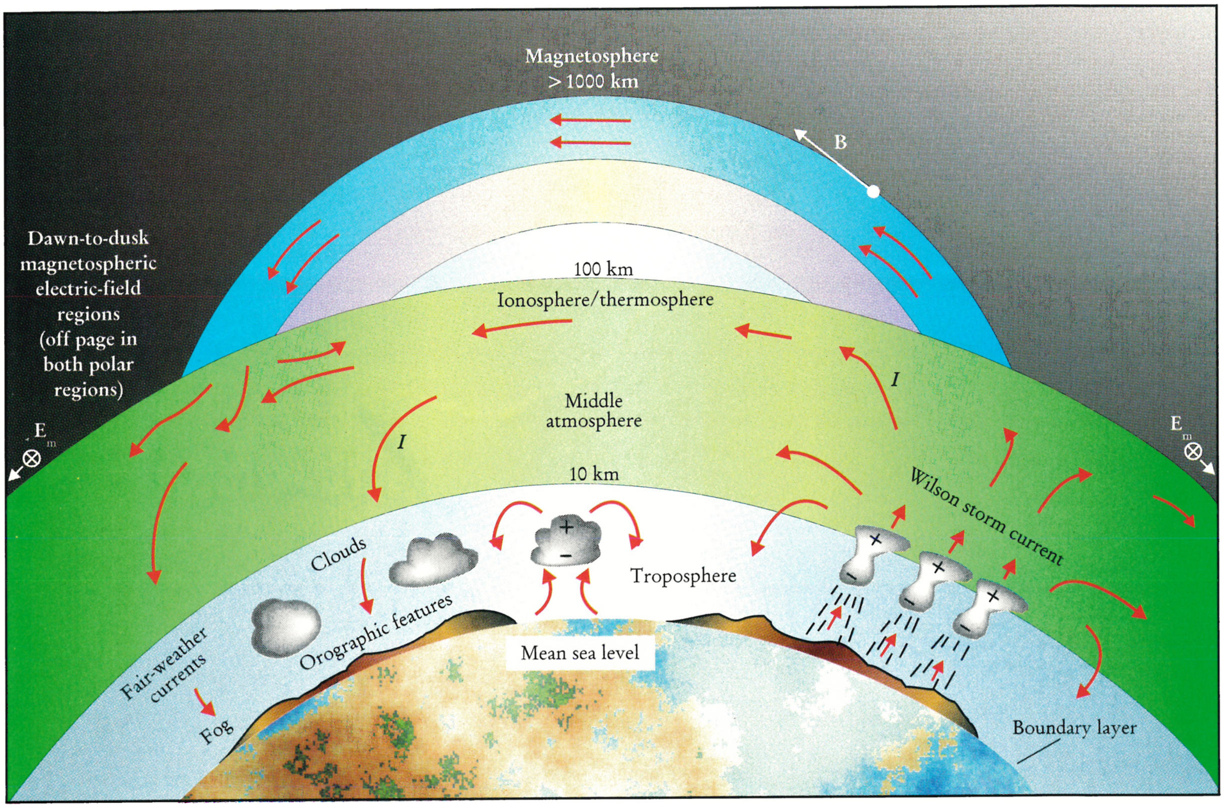

FIGURE 2. FLOW OF ELECTRIC CURRENT in the global circuit. All of the unlabeled arrows represent current flow. The strongest batteries in the circuit are the thunderstorms indicated on the right. They produce the Wilson current. The fair-weather currents are indicated by downward-pointing arrows away from the thunderstorms. (Based on a diagram by Ray G. Roble.)

duced to a single equation, which expresses conservation of the total or Maxwell current.[4,8] The Maxwell current is the sum of the mechanical currents (such as convection) that are the drivers of cloud and boundary layer charging, the conduction current and the displacement current. The boundary layer is the atmospheric layer adjacent to the surface. Turbulence in this layer causes the physical properties of the boundary layer air to be modified because of its contact with the surface. Because the lower atmosphere has a net space charge, turbulent vertical air flows carry part of the current in this layer. Outside of the clouds and above the boundary layer, only the conduction and lightning-driven displacement currents are important. Conduction currents are driven by the large electrostatic fields generated by the charged clouds.

Generators and sources

One problem in understanding the global electric circuit is identifying the active elements in the circuit. There is agreement that tropospheric weather systems are the dominant energy source—the difficulty is in determining the details.[9]

The conductivity of the atmosphere has an important impact on the electrical behavior of charged clouds, especially tall cumulus clouds. The top of a thunderstorm is positively charged and is at a typical altitude of about 12 km, where the conductivity of air is ten times greater than it is just above the surface. The cloud's negative charge is near about 5 km altitude but is concentrated inside the cloud, where the conductivity is decreased by the cloud droplets. It is helpful to make some rough estimates of resistances in this system. For a cylinder of clear air 20 km in radius and extending from Earth's surface to a height of 10 km, the resistance between the top and the ground is roughly 400 MΩ. In cloudy air, however, the resistance is several gigaohms. In contrast, a cylinder of the same radius extending from 10 km altitude to the ionosphere would have a resistance of 40 MΩ, and the return path to the surface through the global atmosphere with its resistance of about 200 Ω is a comparative dead short.

Placing a thunderstorm in the atmosphere will necessarily produce Wilson currents from the cloud top into the ionosphere, back down through the global atmosphere, along the surface and underneath the thunderstorm. The values of the conduction currents observed above individual thunderstorms were found in one study to vary between 0.09 and 3.4 A, with an average value of 1.7 A. Approximately half of this current flows through the overlying magnetosphere to the magnetically conjugate region in the opposite hemisphere. (See figure 2.) Because the time constant for discharge through air from the top of a thunderstorm is an order of magnitude smaller than that of the global capacitor, some of the positive charge ends up being stored in the global capacitor.

When a lightning flash occurs from the bottom of the cloud to the ground, it is completing the global circuit. All charged clouds exhibit this behavior to some extent, but very tall clouds contribute a greater share to the global circuit. Within active thunderstorms, strong updrafts transport cloud particles upward to the growing tops of the thunderstorms. Heavier precipitation particles lag behind and eventually fall out of the updrafts. The small ice particles at the cloud tops have a net positive charge and the larger particles lower in the cloud carry a net negative charge.

Thunderstorms deliver negative charge to Earth in several ways: negative cloud-to-ground lightning flashes; quasi-DC point discharge currents such as St. Elmo's fire; conduction current; and negatively charged precipitation. Attention has focused on the first two mechanisms because they are consistently larger. The most frequent form of lightning is the intracloud discharge, which connects the cloud's upper and lower charged regions, temporarily short-circuiting the charging mechanism. The usual negative cloud-to-ground lightning discharge occurs between the lower negative charge and the surface, and is a primary participant in the global circuit. Occasionally there will be a positive cloud-to-ground discharge that conveys positive charge from the upper charged region to the ground.

Prior to the discovery of the magnetosphere, the standard paradigm treated the ionosphere as an equipotential surface. Modern space research has shown that this assumption is incorrect at all latitudes. A dawn-to-dusk horizontal potential drop of 20–100 kV is impressed upon the geomagnetic polar cap owing to the dynamo interaction of the solar wind and Earth's magnetic field. The cross-polar-cap potential is directly coupled through the currents driven across the polar cap to the global circuit and is one of the three main sources for the circuit, along with thunderstorms and thermospheric winds. Horizontal electric fields with scale sizes on the order of 500 km map down to the ground from the ionosphere and change the air–Earth current and vertical electric field[4] by ±20% at high latitudes during periods of geomagnetic quiet and by greater amounts during geomagnetic storms.[8]

Monitoring the global electric circuit

Measuring the fair-weather electric field is a challenging task. Atmospheric electricity measurements are often made with "field mills," using electrostatic induction. The detecting plate is placed perpendicular to the direction of the field. Gauss's law tells us that a layer of electric charge will be induced by the action of the field on the outer surface of a conductor such that

$$E_n = \frac{\sigma}{\epsilon_0},$$

where E_n is the normal component of the electric field, σ is the surface charge density and ϵ_0 is the permittivity of free space. A rotating grounded disk with holes in it is used to alternately shield and expose the plate. This arrangement produces an alternating voltage on the plate that is proportional to the field.

Continuous measurement of the atmospheric electric field was begun by Kelvin at Kew Observatory in 1861. If there is a global circuit, then one should detect the same fair-weather electric field time variation anywhere on the globe. Local topography will amplify the field on mountain tops, but the shape of the temporal variations should be the same and should have a Universal time (UT) dependence that follows global thunderstorm activity. The thunderstorm rate is not a constant because continents are irregularly distributed in longitude. However, the records obtained at continental observatories show that variations in cloud cover, humidity, total aerosols and vertical convective air currents combine to produce varying electric fields of local origin that can completely mask the electric field of global origin.[4] It is only by careful data rejection that one can obtain hints of the global circuit at such stations.

On the other hand, data found over open ocean waters by the research vessel *Carnegie* during 1915–29 established that a common, UT-dependent variation in the

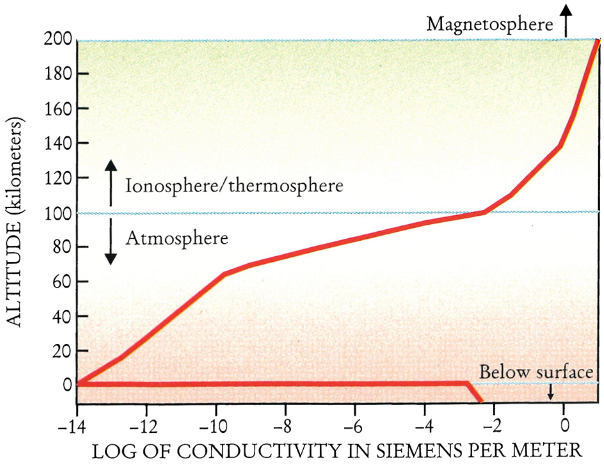

FIGURE 3. CONDUCTIVITY PROFILE. The electrical conductivity of Earth's surface and atmosphere is plotted as a function of altitude.

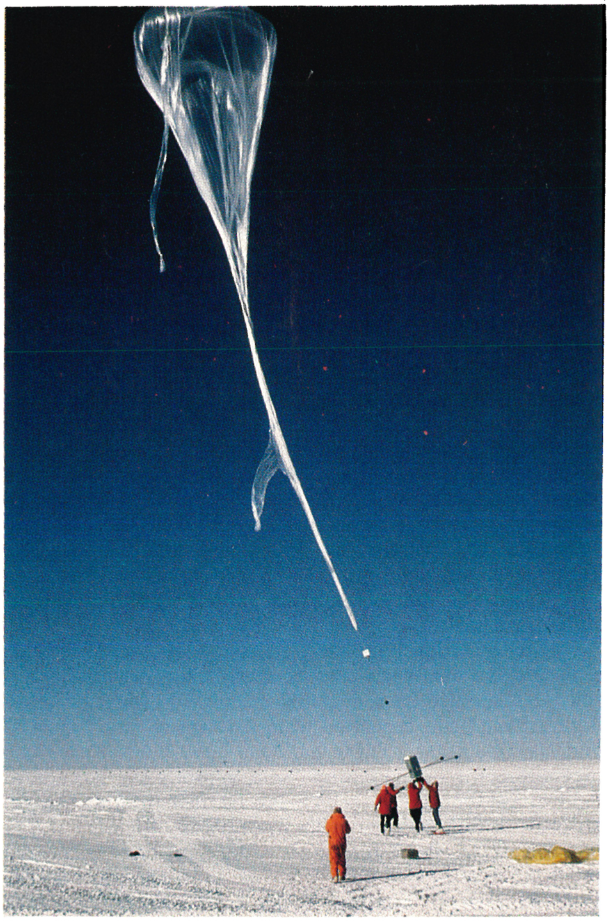

FIGURE 4. LAUNCH of a high-altitude research balloon from South Pole Station on 21 December 1985. This balloon was launched by a University of Houston team as part of the 1985–86 South Pole Balloon Campaign. The payload included a three-axis double-probe vector electric field detector. The antennae of this detector are the six black spheres that surround the central payload body. The black color is produced by a coating of a colloidal carbon suspension. (Photograph courtesy of Eugene G. Stansbery.)

FIGURE 5. CURRENT AND FIELD SENSORS at site 1 near South Pole Station, 15 January 1991. The sphere is an air–Earth atmospheric current sensor. The 17.8 cm split sphere, located about 4 m above the snow, contains a differential ammeter for measuring the difference in current flowing to the two hemispheres. The device on the framework in the foreground is an electric field sensor. It is a vertically oriented 30 cm dipole electric-field mill about 3 m above the snow surface. (Photo by Gregory J. Byrne, copyright 1993 American Geophysical Union, reproduced with permission.)

electric field can be detected at any oceanic site if enough data are taken to give a good signal-to-noise ratio.[6] The diurnal variation of the global electric field that was observed is now called the Carnegie curve. It showed a daily maximum at 1900 UT, a time that corresponds to mid-afternoon in the Amazon basin and noon in the central US. This response can also be observed from mountaintop sites at altitudes above the planetary boundary layer, particularly on oceanic islands.

In recent years, airborne studies of atmospheric electricity have enabled researchers to avoid the turbulence of the planetary boundary layer. Balloons and aircraft have been used to make ascent profiles of the electric field using passive probes that measure the potential differences between electrodes. The field can be integrated over height to give the electrostatic potential difference between the extreme altitudes of instrument operation. Since half of the resistance of the atmosphere is in the lower 3 km, most of the potential drop occurs near the surface. Extrapolation gives an estimate of the potential difference V_I between the ionosphere and the surface. Simultaneous measurements of V_I at separated sites have shown that the spatial variation of V_I is less than 20% at subauroral latitudes.[10]

Long-duration balloons that stay aloft for more than a week have also been used to study time variations and spatial structure in the global circuit.[7,11] Most of these flights have been launched from Antarctica (see figure 4) and New Zealand. These balloons have made three-axis measurements of the electric field to study the horizontal field in the ionosphere, which can be measured at balloon altitude in fair weather with little attenuation.

The $E_{vertical}$ data from these campaigns have been used to study the global circuit. For example, during the 1992–93 austral summer, there were six balloons with electric-field and conductivity detectors aloft at the same time. Indirect measurements of vertical current were made over a geographic latitude range of 28° to 80° S. The current density was about 2 picoamperes per square meter, a value that implies a current in the global circuit of about 1 kA. At subauroral latitudes in good weather, simultaneous $E_{vertical}$ signals were often seen at all balloons. In agreement with prior results, correlated variations were seen on time scales as short as a few minutes.[3,7] This remarkable result is in disagreement with the classical picture, which predicts a global atmospheric electric time constant of at least 10–15 min.

During the 1985–86 South Pole Balloon Campaign, the average diurnal variation of the electric field in geomagnetic quiet times was a 24-hour amplitude modulation of 30–40% of the DC average, with a minimum absolute value near 0300 UT, and a peak near 1800 UT. The diurnal modulation was reduced by about 25% on geomagnetically disturbed days, in agreement with predictions of magnetospheric coupling models and in disagreement with the assumptions of the standard paradigm of the pre-space age. In contrast, a balloon launched at Siple Station, Antarctica (at geomagnetic latitude 62° S), at the start of the intense magnetic storm of 19–20 December 1980, found geomagnetic perturbations in $E_{vertical}$ that were so large that there was no diurnal variation at all, a result that was not predicted by any model.

The best place on Earth for making ground-level observations of the global circuit is arguably on the Antarctic plateau.[4,8,12] That is because the weather on the plateau is clear about 70% of the time, local atmospheric convection is suppressed by a deep temperature inversion and the topography results in an amplification factor of two or more in the electric field strength and current density. From 1991 to 1993, we operated a suite of atmospheric electricity instruments at South Pole Station.[12] The suite consisted of two identical sets of detectors located 600 m apart. The detector sets each measured the electric field and the air–Earth current density. Figure 5 depicts one of our detector sets.

The upper panel of figure 6 shows 10 days of data from the electric-field mills at the South Pole, taken during good weather in December 1992. The figure shows that the data were in agreement, indicating that we measured global effects and that local processes, which would not be correlated over a distance of 600 m, were making a negligible contribution. We see a quasi-sinusoidal modulation each day with substantial day-to-day variation. The lower panel of figure 6 shows seasonal averages of our Antarctic data. The difference between summer and winter as defined in the Northern Hemisphere is a result of the fact that there is more land in the Northern Hemisphere. Because thunderstorms occur primarily over land, this distribution means that there are more thunderstorms during the northern summer than during the southern summer. The sign of the difference between the Northern Hemisphere winter and summer is consistent with the predictions of the global temperature proxy model discussed below. There were seasonal differences in the UT of maximum field strength. These differences point to changes in the longitude of maximum thunderstorm activity.

Challenge to established views

The difficulty with the cloud-to-ground flash mechanism for delivering negative charge to the ground is that the diurnal modulation amplitude of averaged electric field data is modest (about 40% of the mean), as shown in figures 6 and 7. The diurnal variation of total area covered by thunderstorms (bottom panel of figure 7) shows a modulation amplitude that is at least twice as large as the modulation of the Carnegie curve.[6,9] The classic picture solved this problem by assuming a uniform population of oceanic thunderstorms that satellite data have shown do not exist.

In a controversial 1993 paper, Earle Williams and Stan Heckman of MIT constructed a model by adding the global sum of point discharge currents from St. Elmo's fire and corona produced by electrified rain clouds to the current from lightning activity and produced a curve with a modulation amplitude that is in better agreement with the Carnegie curve.[9] They concluded that a significant fraction of the current flowing in the global circuit is more likely carried by point discharge currents than by lightning flashes. A related study can be interpreted to mean that if all lightning activity were to stop, other processes would maintain V_I at 60% of the present average.

Another controversial new idea is that the global electric circuit integrates global thunderstorm activity into proxy variables for the mean global surface temperature and that these proxy variables are much more sensitive to global warming than a measure of the mean global temperature itself.[13]

Although this idea remains unproven, the logic behind it is intriguing. The vigor of the vertical convection of the air increases when the temperature gradient (lapse rate) steepens. All global atmospheric circulation model results for an Earth with increased greenhouse gases yield increases in the planetary surface temperature and decreases in the tropopause temperature; this combination should increase the lapse rate and therefore be destabilizing. Furthermore, increasing the surface temperature should exponentially increase the water vapor flux into the atmosphere, as described by the Clausius–Clapeyron equation. During global warming, increases in energy at the surface go into both the sensible heat of the air and the latent heat of the water vapor. The latter energy is released in cloud convective activity.

The power in the 8 Hz Schumann resonance emission line, and the total current in the global circuit, have been found to correlate with global temperature changes on time scales ranging from the diurnal, through the seasonal, to the El Niño Southern oscillation scale.[13] The UT dependence of the electric field (see figures 6 and 7) demonstrates the response of the circuit to changes in Earth's surface temperature. The modulation amplitude of the electrical response is about 40% of the mean, whereas the diurnal temperature change over the land is less than 10%. Both parameters must be monitored, because Schumann resonance intensity depends upon the height of the ionosphere,[13] which is known to have a solar cycle dependence and to respond to solar flares, geomagnetic storms and solar proton events.[4] If 60% of the average V_I arises from electrified rain cloud currents, the possibility exists that a combination of Schumann resonance power level and V_I monitoring could be used to infer proxy measures of both global temperature and global rainfall rates.

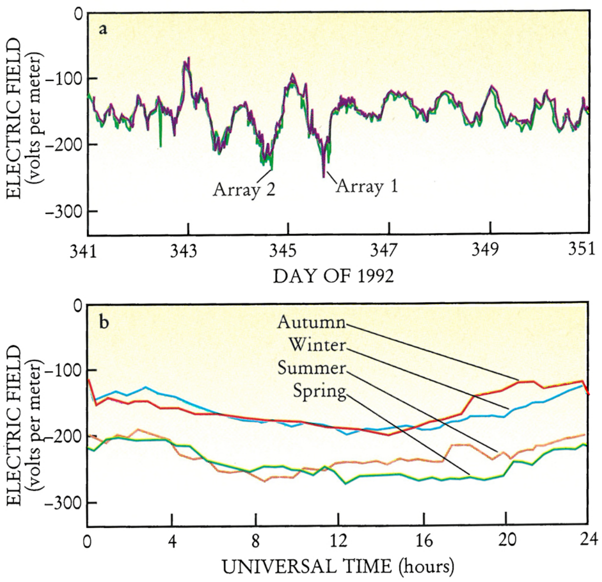

Figure 6. Electric field data collected at South Pole Station. **a:** Ten days of fair-weather readings taken 6–16 December 1992, Universal time. Data from two arrays separated by 600 m are shown. The vertical component is plotted, positive upward. **b:** Carnegie curves showing seasonal averages of Antarctic electric-field data from about one year of operation. All intervals of local bad weather have been removed. Labels indicate Northern Hemisphere seasons. The Carnegie curves were produced by Erika Cleary for her master's degree thesis at Rice University.

A third controversial question about the global circuit concerns the existence of coupling mechanisms that give the circuit a larger role than that of a passive load on the troposphere. In a provocative series of papers, Brian Tinsley and his coworkers at the University of Texas at Dallas[14] have reemphasized the role of the global circuit in Sun–weather coupling[15] and suggested mechanisms whereby the low modulation power provided to the global circuit by the solar wind is amplified enough to affect the weather. For example, to intensify a winter storm in the Gulf of Alaska with a global circuit fluctuation,[14] a successful model must provide for a power amplification factor of about 10^7. Tinsley assigns a critical role to an increase in the rate of ice crystal formation caused by the accumulation of electrostatic charge on droplets and ice crystals, with the accumulation being attributed to poorly understood processes known as ionization nucleation and electrofreezing. This step occurs prior to the generation of strong electric fields within clouds by microphysical ice processes. According to Tinsley, the air–Earth current, which transports charge to the cloud and polarizes the particles in the cloud, can act to increase the net charge on cloud particles and thus play an active role in this coupling process.[14]

As we have seen, one result of the renaissance in the study of the global electric circuit consists of findings that are inconsistent with the standard paradigm. We believe that these anomalies make it clear that more measurements are needed to refine models of the global circuit.

We have based this article in part on a recent review in the technical literature that one of us (Bering) undertook.[3] Our research was

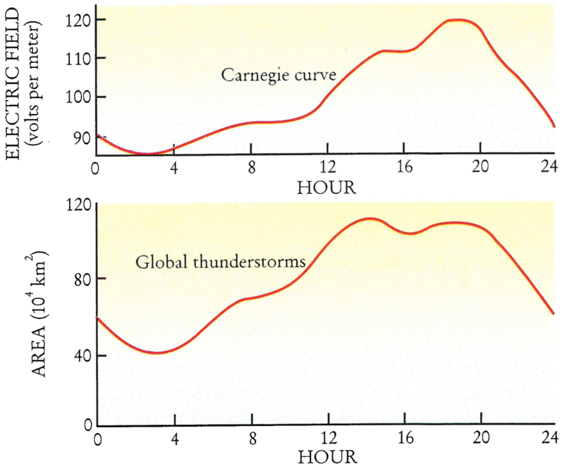

FIGURE 7. DIURNAL VARIATION of electric-field strength and storm area. The top curve is the average potential gradient (the negative of the quantity in the previous figure) measured by the research vessel *Carnegie* during fair weather, plotted as a function of Universal time. The bottom curve is the inferred continental thunder area, also shown as a function of UT. The quantity plotted is the area that would be covered by thunderstorms if thunderstorms occurred only over land and if the probability of thunderstorm occurrence were globally identical to the probability observed as a function of UT at Kew Observatory.

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