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The global atmospheric electric circuit, solar activity and climate change

M.J. Rycroft[a,*], S. Israelsson[b], C. Price[c]

[a] *International Space University, Boul. Gonthier d'Andernach, 67400 Illkirch, France*
[b] *Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala, Sweden*
[c] *Department of Geophysics and Planetary Sciences, Tel Aviv University, Ramat Aviv 69978, Israel*

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Abstract

The study of the global atmospheric electric circuit has advanced dramatically in the past 50 years. Large advances have been made in the areas of lightning and thunderstorm research, as related to the global circuit. We now have satellites looking down on the Earth continuously, supplying information on the temporal and spatial variability of lightning and thunderstorms. Thunderstorms are electric current generators, which drive electric currents up through the conducting atmosphere. They maintain the ionosphere at a potential of $\sim+250$ kV with respect to the Earth's surface. The global electric circuit is completed by currents $\sim$2 pA/m^2 flowing through the fair weather atmosphere, remote from thunderstorms, and by transient currents due to negative cloud-to-ground lightning discharges. The time constant of the circuit, $\sim>2$ min, demonstrates that thunderstorms must occur continually to maintain the fair weather electric field. New discoveries have been made in the field of sprites, elves and blue jets, which may have a direct impact on the global circuit. Our knowledge of the global electric circuit modulated by solar effects has improved. Changes to the global circuit are associated with changes of conductivity linked with the time-varying presence of energetic charged particles, and the solar wind may influence the global electric circuit by inferred effects on cloud microphysics, temperature, and dynamics in the troposphere. We now have a better understanding of how the conductivity of the atmosphere is influenced by aerosols, and how this impacts our measurements of the fair-weather global circuit. The global atmospheric electric circuit is also beginning to be recognised by some climate researchers as a useful tool with which to study and monitor the Earth's changing climate.

Keywords: Atmospheric electricity; Global circuit; Lightning; Climate change

1. Introduction to the global atmospheric electric circuit

One of the first, and certainly the most famous, demonstrations of a reproducible variation with Universal Time is the hourly average curve of electric potential gradient in the lowest atmosphere obtained over the world's oceans on the Carnegie cruises. These curves have long served as de facto standards (see Bering et al., 1998) with which to evaluate the viability of attempts to measure worldwide variations of electrical properties of the atmosphere near the Earth's surface.

The thunderstorm generator hypothesis proposed by Wilson (1920) was based on his observations that, beneath the thundercloud, negative charge is transferred to the Earth and above the thundercloud positive charge is transferred to the conducting upper atmosphere. A subsequent discovery was the close correlation between the diurnal (Universal Time) variation of the thunderstorm generator current (represented by the frequency of thunderstorm occurrence) and the load current (represented by the fair-weather ground electric field, or air-Earth current density), integrated over the surface of the Earth.

* Corresponding author. Tel.: 44-1223-353839; fax: 44-1223-303839.

E-mail address: michael.j.rycroft@ukgateway.net (M.J. Rycroft).

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By making measurements in regions where local diurnal variations of atmospheric conductivity are minor, by excluding data collected during periods of local meteorological influence, and by averaging to remove the day-to-day variability of global thunderstorm activity, a diurnal curve with a peak near 18 UT, a minimum near 03 UT and a range of some 30% of the mean was obtained. This is known as the global, 'fair-weather', diurnal variation, or the 'Carnegie curve'. Bering (1995) gives a comprehensive interpretation of recent advances in this area.

Humans are becoming increasingly concerned about changes — both natural and anthropogenic — in the Earth's environment. Particular attention is being paid to the atmosphere, not only the troposphere, the region of the Earth's weather and climate, but also the stratosphere — above it, which is where the ozone layer is. The springtime Antarctic ozone depletion, the so-called ozone hole, is the most popular example (see Farman et al., 1985; Rycroft, 1990; Solomon, 1999). Changes higher up, in the mesosphere, thermosphere and ionosphere may also be important.

How does atmospheric electricity affect man and his technological systems? Is our electrical environment changing significantly as a result of air pollution, the release of radioactive materials, the construction of high-voltage power lines, and other activities, or by energetic charged particle effects in the atmosphere? It is clear that modern technological advances may be seriously affected by various electrical processes in the atmosphere or in space, and also that man is beginning to affect the electrical environment in which he resides.

2. Physics of the global atmospheric circuit

Atmospheric electricity plays various roles in the highly coupled system representing the Earth's atmosphere and the near-Earth space environment. For further background information, see Herman and Goldberg (1978).

The conductivity of the fair-weather atmosphere near the surface is on the order of 10^{-14} mho/m, and it increases nearly exponentially with altitude up to 60 km, with a scale height of about 7 km. The main charge carriers below about 60 km are small positive and negative ions that are produced primarily by galactic cosmic rays. Above 60 km, free electrons become more important as charge carriers and their high mobility abruptly increases the conductivity throughout the mesosphere. Above 80 km, the conductivity becomes anisotropic because of the influence of the geomagnetic field, and there are diurnal variations due to solar photoionization processes. The arena for the subject is included in the system shown in Fig. 1, which shows the Earth at the centre, surrounded by the atmosphere, ionosphere, the van Allen belts and magnetosphere deformed by the flowing solar wind.

The area for the subject of atmospheric electricity is the electrically insulating concentric shell between the highly conducting Earth and the highly conducting ionosphere

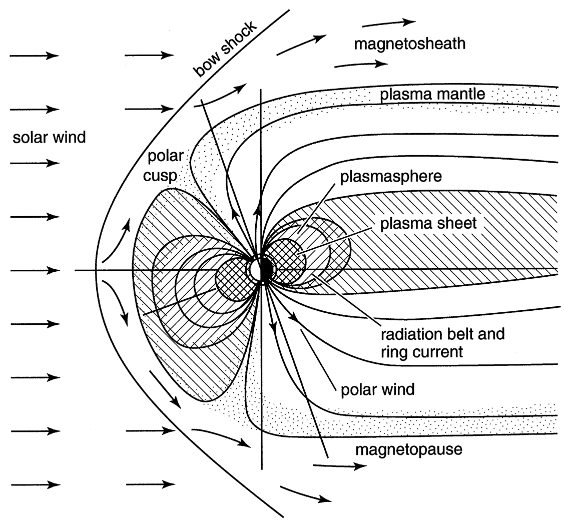

Fig. 1. Diagram showing the Earth at the centre, surrounded by the atmosphere, ionosphere, the van Allen radiation belts and magnetosphere deformed by the flowing solar wind (from Davies, 1990).

(see Fig. 2); this is surrounded by "magnetospheric action". Fig. 3, from Markson (1978), shows that the global electric circuit is believed to be driven by the upward current from thunderstorms, 1000 of them occurring around the globe at any one time. They occur mostly at low latitudes, over tropical land masses, in the local afternoon and evening. The more energetic thunderstorms reach higher into the atmosphere.

It has been known for over two centuries that the solid and liquid Earth and its atmosphere are almost permanently electrified. The surface has a net negative charge, and there is an equal and opposite positive charge distributed throughout the atmosphere above the surface. The fair-weather electric field is typically from 100 to 300 V/m at the surface; there are diurnal, seasonal, and other time variations in this field that are caused by many factors. The atmosphere has a finite conductivity that increases with altitude; this conductivity is maintained primarily by galactic cosmic ray ionization. Near the Earth's surface, the conductivity is large enough to dissipate any field in just 5–40 min (depending on the amount of pollution); therefore, the local electric field must be maintained by some almost continuous current source.

According to the classical picture of atmospheric electricity, the totality of thunderstorms acting together at any time charges the ionosphere to a potential of several hundred thousand Volts with respect to the Earth's surface. This potential difference drives a vertical electric conduction current downward from the ionosphere to the ground in all fair-weather regions of the globe. The fair weather electric conduction current varies according to the ionospheric potential difference and the columnar resitance between the ionosphere and the ground. Horizontal currents flow freely along the highly conducting Earth's surface and in the

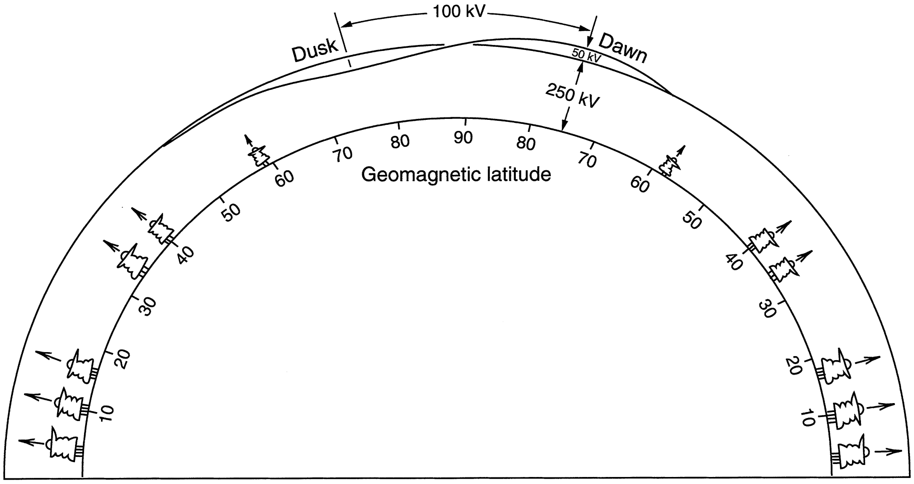

Fig. 2. Diagram showing the upward current to the ionosphere generated by thunderstorms; the ionosphere is approximately an equipotential surface, at +250 kV with respect to the Earth's surface (from Markson, 1983).

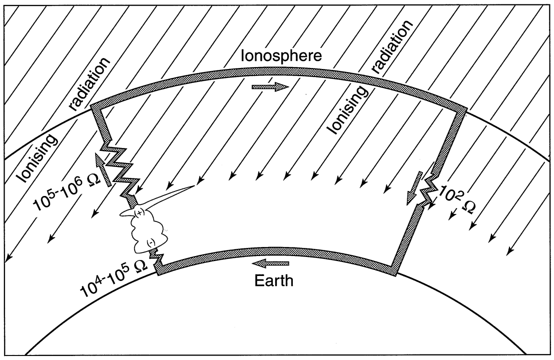

Fig. 3. Diagram of the global electric circuit (bold); the current flowing in the circuit is determined mainly by the current in the generator representing the sum of thunderstorms around the world, in the charging resistor above, and in the resistor representing more than the boundary layer below. Also important are increases in the ionising radiation which, from time to time, reduce the conductivity of the middle atmosphere (from Markson, 1978).

ionosphere. A current flows upward from a thunderstorm cloud top toward the ionosphere and also from the ground into the thunderstorm generator, closing the circuit. The global fair-weather load resistance is of the order of 100 Ω, as indicated in Fig. 3.

A few measurements have been made that give the magnitude of the current flowing upward over the whole area of a thundercloud (Kasemir, 1979). The currents range from 0.1 up to 6 A, with an average between about 0.5 and 1 A per thunderstorm cell (Blakeslee et al., 1989).

The topic is not as simple as it seems initially — there are many variations. It is a problem of global scale, but with spatial variations of important parameters, on the regional scale (e.g. in the geomagnetic latitude, or geographic longitude), on the local scale, and also with altitude. At higher geomagnetic latitudes, the conductivity of the air, σ, is larger due to the larger flux of ionising radiation there due to cosmic rays ($\sim > 1$ GeV ions) or to relativistic charged particle precipitation from the magnetosphere (> 1 GeV ions or > 1 MeV electrons). The cosmic ray fluxes are somewhat reduced at the time of a Forbush decrease and, for certain geomagnetic storms, the fluxes of magnetospheric origin are enhanced.

Fig. 3 illustrates one thunderstorm representing all 10^3 active thunderstorms occurring over less than 1% of the Earth's surface, and each generating ~1 A. Thus, an upward current of ~1 kA is driven through the "charging resistor", of 10^5–10^6 Ω. This current flows through the almost perfectly conducting ionosphere. The return current of 1 kA flows through the fair weather atmosphere, over 99% of Earth's surface remote from thunderstorms; the "discharging resistor", or load resistor, has the value $\sim 2 \times 10^2$ Ω globally.

It is generally convenient to regard the highly (but not perfectly) conducting ionosphere as an equipotential surface locally, at a potential of about +250 kV with respect to the Earth. However, the ionosphere is not an equipotential surface globally, because of

- the dawn-to-dusk potential difference (up to ~100 kV) across the polar cap arising from the interaction of the solar wind with the magnetosphere (see Fig. 2), which causes the two-cell convection pattern of the polar F-region,
- potential differences (up to ~100 kV) associated with auroral/magnetospheric processes,
- unipolar induction, due to the rotation of the Earth's magnetic field, so that the equator is at a potential of −91 kV with respect to the pole, in the centred dipole approximation, in an inertial frame of reference, and

- dynamo action in the ionosphere, such as the Sq process (up to ~20 kV).

The theoretical foundations of the subject of atmospheric electricity are firm, being based on the laws of physics — the Navier–Stokes and continuity equations, and the laws of thermodynamics — which are required to understand and predict atmospheric motions. The atmospheric density decreases exponentially with increasing height, with a scale height, $H{\sim}7$ km. The atmospheric conductivity σ increases with height due to the energy spectrum of the cosmic rays and the charged particles precipitating from the magnetosphere. By Ohm's law, which is valid for linear processes only,

$$J = \sigma E, \tag{1}$$

where J is the vertical electric current density and E is the vertical electric field. This leads us to expect that, in order to maintain current continuity, E is largest near the Earth's surface, where its value is, from observations, ~130 V/m. It decreases upwards, exponentially. By Gauss' law, there is a space charge profile associated with this electric field.

Cho and Rycroft (1998) have presented a simple model profile for the atmospheric conductivity, ranging from near 10^{-13} mho/m near the surface to 10^{-7} mho/m at 80 km altitude in the lower ionosphere. Hale (1994) has presented more complex profiles, which show variations in both space and time.

Only a few mathematical models of global atmospheric electricity have appeared over the years (Kasemir, 1963, 1977; Hill, 1971; Hays and Roble, 1979; Volland, 1982; Ogawa, 1985). Since it is difficult to obtain global measurements to deduce the instantaneous properties of the global circuit, these models provide a convenient means of examining, through numerical experiments, the various interacting processes operating in the global circuit. The overall success of the models may be judged by how well they represent the observed atmospheric electrical properties at any place and time within the circuit.

Thunderstorms are extremely complex, and some simplifying assumptions must be made to represent their properties in a global model. The usual assumption is to consider thunderstorms as dipolar current sources, with a positive source in the could top and a negative source in the cloud bottom.

Ogawa (1985) has considered the simple equivalent circuit for the atmosphere shown in Fig. 4. With R_1 being the charging resistor mentioned earlier, R_2 the resistance of the thunderstorm generator where there exist potential differences ~100 MV between the positively charged top of the thundercloud and the negatively charged bottom, and R_3 the resistance of the boundary layer (first few km) of the atmosphere, all of which are much greater than r, the resistance of the fair-weather atmosphere, it follows that

$$I = R_2 I_0/(R_1 + R_2 + R_3). \tag{2}$$

Eq. (2) relates the current through the fair-weather atmosphere, I, to the current in the thunderstorm generator, I_0.

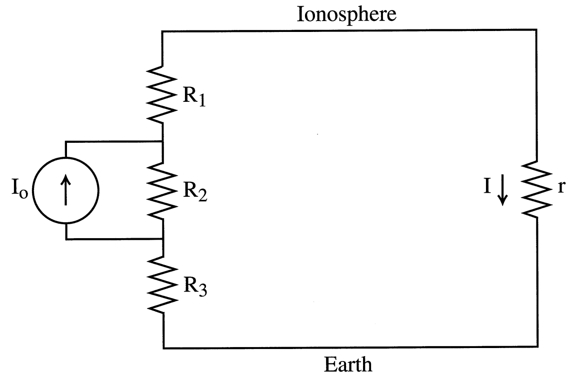

Fig. 4. A simplified equivalent circuit of the global electric circuit, showing the net thunderstorm generator current, I_0, and the fair weather current I (from Ogawa, 1985).

It is clear that R_1 and R_3 are particularly important in this relation; R_3 can be significantly reduced by

- point discharge currents due to the very large electric field below the thundercloud, in the region of updraughts, and
- increasing the height of the ground surface above mean sea level.

In this regard, measurements of I at a high-altitude (mountain) observatory remote from active thunderstorms can give some information on I_0 if R_1 and R_2 can be considered to be constant. Both may, however, be reduced at times of enhanced fluxes of energetic charged particles associated with enhanced geomagnetic activity. And the contribution to R_1 above an active, sprite-producing thundercloud may be greatly reduced due to the ionisation (see Cho and Rycroft, 1998) produced in the rarefied mesosphere by the large transient electric fields due to large, positive cloud-to-ground lightning discharges.

Fig. 5 is a new diagram, the upper part of which attempts to illustrate the electric currents flowing through different parts of the atmosphere, and including the magnetosphere above. The lower part of the diagram shows the equivalent circuit, with three different fair weather regions. One of these is for a high altitude part of the Earth where the profiles of J and E through the fair weather atmosphere will differ from those elsewhere.

From standard electrostatic theory, the capacitance C of the concentric shell of atmosphere between the Earth and the ionosphere, over one scale height of atmosphere rather than over the full height of the ionosphere, is given by

$$C = 4\pi\varepsilon_0 R_E^2/H{\sim}0.7\text{ F}, \tag{3}$$

where R_E is the radius of the Earth and ε_0 is the permittivity of free space.

Hence the time constant for the atmospheric global electric circuit, t, is given by

$$\tau = Cr{\sim}2\text{ min}. \tag{4}$$

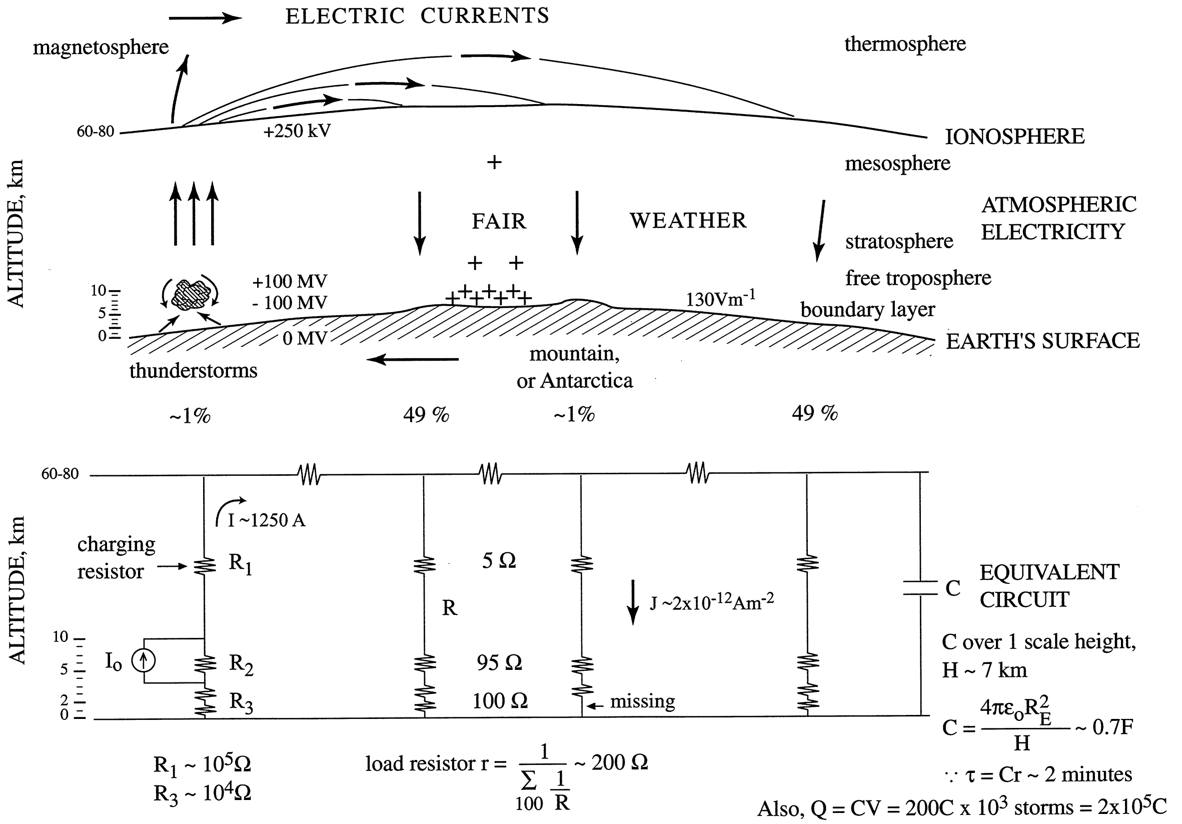

Fig. 5. (a) Top. Diagram, approximately to scale, showing electric currents (bold arrows) flowing up from the net thunderstorm generator over $\sim < 1\%$ of the Earth's surface, through the ionosphere, the fair-weather atmosphere and the Earth, and closing as point discharge currents below the thundercloud. In the centre, the distribution of positive space charge is shown. (b) Bottom. The equivalent circuit for (a), showing components of the fair-weather resistor over different height ranges for 2–3 km above the surface; the boundary layer resistor is "missing" above a mountain or over Antarctica. Typical numerical values are also shown.

With a charge of 200 C associated with each thunderstorm, the total Q on the plates of the spherical condenser is 2×10^5 C. Thus, the energy associated with the global electric circuit is enormous; it is

$$W = CV^2/2 \sim 2 \times 10^{10}\ \mathrm{J}, \qquad (5)$$

inserting $V = 250$ kV.

The electric current density through the fair-weather atmosphere, J, has the value $\sim 2 \times 10^{-12}$ A/m^2. Taking the conductivity of air at ground level, produced by extremely energetic cosmic rays and by radon from the ground, and due to aerosols, to be $\sim 2 \times 10^{-14}$ mho/m, the fair weather electric field at ground level is $\sim 10^2$ V/m, close to the near observed value of 130 V/m. At 20 km altitude, the fair-weather vertical electric field is ~ 1 V/m, and can be well measured from balloons. At 50 km altitude, it is only $\sim 10^{-2}$ V/m.

Following a Forbush decrease, the atmospheric conductivity everywhere could be reduced by $\sim 10\%$. If J is unchanged, the ionospheric potential, and hence also the fair weather electric field, may be increased by $\sim 10\%$. There is some observational evidence to support this concept (see Ogawa, 1985).

After a sprite above one of the thousand active thunderstorms, the ionospheric potential would reduce to 99.9% of its initial value for a millisecond or so. Thus, it is evident that sprites are unlikely to cause an observable effect on the fair-weather electric field.

To consider electrodynamic or electromagnetic effects rather than electrostatic phenomena, Maxwell's equations are involved. They relate electromagnetic fields to charge and current densities in a time-varying situation. Electromagnetic waves of appropriate frequencies can be generated, and these propagate away. The medium through which the energy propagates has a certain refractive index, which is equal to the square root of the relative electric permittivity.

The medium is treated as a conductor at frequencies (ω) such that $\omega \ll \sigma/\varepsilon_0$. Alternatively, the medium behaves as a leaky dielectric when $\omega \gg \sigma/\varepsilon_0$; that is the situation in the ionosphere for VLF waves and for higher frequency waves. However, for waves at Schumann resonance frequencies the lower ionosphere behaves like a conductor. Radiation produced by the current pulse due to a cloud-to-ground lightning discharge (i.e. due to the rapid destruction of the dipole moment formed by the negative charge in the bottom of a thundercloud and its positively charged image in the Earth) ranges from Schumann resonance frequencies up to ~100 MHz.

However, if there are no radiation effects to be considered, the current flowing is the sum of the conduction current and the displacement current. This is termed the Maxwell current. In the atmosphere, there can be other significant contributions to the current density, due to convection, turbulence, precipitation (or settling) or point discharges. Mentioned earlier, and sometimes called St. Elmo's fire, this last contributor to the current through the global atmospheric circuit may actually carry half the current (see Bering et al., 1998). By its very nature, it is variable, and not a great deal is known about it. It is a topic for further research.

A fundamental property of the global atmospheric electrical circuit is the electrical relaxation time at various altitudes, which is defined as the time the electric current takes to adjust to $1/e$ of its final value after an electric field is suddenly applied, assuming that the conductivity remains constant. At high altitudes, near 70 km, the relaxation time is about 10^{-4} s, increasing with decreasing altitude to about 4 s near 18 km and to about 5–40 min near the Earth's surface. The electrical relaxation time of the land surface of the Earth is about 10^{-5} s. The maximum value of about 40 min in the atmosphere near the Earth's surface is the characteristic time that the global circuit would take to discharge if all thunderstorm activity suddenly ceased. Measurements have never shown a complete absence of a fair-weather electric field for any length of time, thereby suggesting a continuous operation of thunderstorms and other generators in maintaining the currents flowing in the global circuit. For time variations longer than about 40 min a quasi-static approximation can be applied when modelling the electrical properties of the global circuit.

3. Solar and cosmic influences on atmospheric electricity

3.1. Solar cycle effects

Variable plasma phenomena from the Sun, such as gigantic coronal mass ejections, can create geomagnetic storms, periods of enhanced geomagnetic activity. Such phenomena exert a profound — often disruptive, and occasionally devastating — influence on humankind's technological systems, such as satellites, telecommunications systems, power lines and pipelines; they may even affect human health.

It is well known that the Sun is not a constant star but one whose radiative output (especially in the ultraviolet and X-ray spectral regions) varies over a solar cycle, of ~11 years period. (Taking account of the Sun's magnetic polarity, it is actually a ~22 year cycle.) The temperature, and hence the density, of the upper atmosphere (thermosphere) vary markedly over a solar cycle. For example, at ~400 km altitude where the International Space Station will operate, the density — and hence the drag force — is almost a hundred times greater at solar maximum than at solar minimum.

The solar magnetic field and its extension through the interplanetary medium (carried by the plasma of the solar wind) to the Earth's orbit and beyond, into the heliosphere, is markedly more variable at solar maximum than at solar minimum. Thus, the flux of galactic cosmic rays (scattered by the irregularities of the interplanetary magnetic field) entering the top of the atmosphere is some tens of percent larger at solar minimum that at solar maximum, whereas the flux of energetic (>0.1 GeV) charged particles (protons) from the Sun at solar minimum is typically many times less that its value at solar maximum. Both types of energetic charged particles and also energetic charged particles precipitating from the inner and outer magnetospheric radiation belts (see Fig. 1, from Davies, 1990) during geomagnetically active periods interact with the Earth's middle and lower atmosphere by depositing their energy in the atmosphere, by creating ionisation directly or via bremmstrahlung radiation, by altering its chemistry (particularly ozone, nitric oxide and sulphate aerosols, see Jackman et al., 1995), or by affecting the nucleation of water droplets to form clouds (see Tinsley, 1996, 2000). There is some recent evidence that energetic solar protons appear to produce small holes in the Arctic ozone layer. They may trigger the formation of cirrus clouds which decrease the flux of solar radiation to the Earth's surface and hence affect the evolution of weather systems (see Pudovkin and Babushkina, 1992), and also affect the Earth's radiation budget by contributing to the greenhouse effect (also see Svensmark and Friis-Christensen, 1997),

Ground-based radars and other instruments in Scandinavia and around the world observe the effects of the ever changing, million Ampere current systems in the auroral ionosphere at heights near 110 km. These cause changing geomagnetic fields which induce large and varying currents to flow in long conductors, such as electrical power lines or oil pipe lines, sometimes with catastrophic effects. These include exploding transformers and power cuts (outages) of several hours duration, or corrosion.

Thus atmospheric electricity plays various roles in the highly coupled system representing the Earth's atmosphere and the near-Earth space environment. There are temporal variations, on time scales varying from microseconds (in lightning discharges), to milliseconds (e.g. sprites), minutes to an hour (e.g. thunderstorm regeneration), hours to a day (e.g. diurnal variations), months (solar rotation and seasonal effects), and to a decade (solar cycle effects), as well as spatial variations.

3.2. Latitudinal effects

Solar influences on the geoelectric field differ between mid-latitudes and the polar regions (Tinsley, 1996).

Increased solar activity reduces galactic cosmic ray fluxes in mid-latitudes, thus reducing the atmospheric conductivity in this region, while at the same time solar protons may be "funnelled" by the Earth's magnetic field to polar regions resulting in an increased atmospheric conductivity there. A dawn-to-dusk potential difference is also applied across the polar regions as a result of the interaction of the solar wind and the Earth's magnetic field (see, for example, Tinsley and Heelis, 1993). The cross-polar potential results from the same interactions that generate auroral activity and typical lies in the range 30–60 kV (Fig. 2). It may, at times of increased solar activity, exceed 100 kV. The cross-polar potential may not be the dominant solar influence on the global geoelectric circuit, but it is of significant magnitude in the polar regions. The diurnal pattern generated as a station rotates beneath the cross-polar cap potential difference also aids its detection.

The global electric circuit is closed by currents flowing in the ionosphere. At high latitudes, within the polar cap, these currents are strongly influenced by parameters of the solar wind, particularly the direction of the interplanetary magnetic field. In the auroral zone, the ionosphere is markedly disturbed when the magnetosphere is buffeted by a cloud of solar wind of enhanced density which is associated with a huge coronal mass ejection event from the Sun. As a result, the potential difference across the polar cap ionosphere can vary markedly.

The measurement techniques applied in magnetospheric and ionospheric research enable the detection of strong, intrinsic effects of the solar wind/ionosphere on the electrical potential distribution and conductivity of the atmosphere, as presented by Michnowski (1998). These manifestations of the solar wind interaction with the magnetosphere and ionosphere are especially evident at high latitudes.

4. Aerosols and the global circuit

4.1. Planetary boundary layer (PBL) aerosols

The planetary boundary layer (PBL) is the lowest few kilometers of the atmosphere, where interactions with the surface, man, and the biosphere are the most pronounced. Near land surfaces the ionization is, beside galactic cosmic rays, produced by the decay of natural and artificial radioactivity. Electrical processes in the PBL are complex, highly variable, and span a tremendous range of space and time scales. The electrical variables respond to many of the lower atmospheric processes but usually have little influence on the phenomena to which they respond. Within the PBL, local turbulent fluctuations of space-charge density impose a time-varying electric field that is comparable in magnitude with, or even greater than, the electric field maintained by global thunderstorm activity. Since the PBL is the region of the atmosphere with the greatest resistance, it is this layer (as well as the thunderstorm generators) that control the currents in the global circuit. Boundary layer processes can have a substantial impact on the fields and currents appearing throughout the entire atmospheric column from the Earth to the ionosphere. Modelling of the atmospheric electricity in the PBL is difficult due to the complicated conditions in the PBL (see Hoppel et al., 1986).

Aerosol particles can change the Earth's radiation budget both directly through scattering and through absorption and indirectly through modification of cloud microphysical properties. It is clear that there is a great uncertainty in assessing the direct and indirect effect of aerosols on climate change. We must understand and be able to quantify the most important sources and characteristics of aerosols in order to assess their effects on climate change. The relatively short residence time of aerosols in the troposphere, of order of a few days, results in significant spatial and temporal variations in aerosol particle concentration, size and composition. The high variability of the atmospheric aerosol leads to one of the largest uncertainties of anthropogenic climate forcing. This variability is compounded by a lack of much information on the properties of the atmospheric aerosols prior to the late 1970's when commercial aerosol instrumentation became more widely available. Thus, it is difficult to assess the influence of anthropogenic aerosols on radiative forcing up to that time. However, a number of researchers have shown that atmospheric electricity parameters can act as a good indicator or surrogate.

Many factors affect the electrical conditions in the PBL. An important area of research is the study of atmospheric ions. According to their physical nature, atmospheric ions with mobilities above 0.5 $cm^2 V^{-1} s^{-1}$ are charged molecular clusters or cluster ions. Tammet et al. (1992), Horrak et al. (1998) and others have shown the importance of these charged particles in atmospheric electricity, particularly in relation to atmospheric conductivity and to space charge formation. Retalis and Retalis (1998) treated the effects of air pollution on the large ion concentration, which indicated the importance of polluted areas (like cities, etc.) on the electrical environment. The impact of Chernobyl in April 1986 on all atmospheric electrical parameters in some parts of Sweden has been significant directly after the accident and several months later (Israelsson and Knudsen, 1986). Martell (1985) and Israelsson et al. (1987) have shown the importance of the ionisation from natural and artificial radioactivity in the charging mechanism of clouds.

Even natural processes over the sea are of importance. Blanchard (1963) indicated that currents as large as hundreds of Amperes flow from the ocean surface into the atmosphere as a result of electrified droplets that are ejected from the bursting of small bubbles.

Modelling of convection currents has shown that they only become important in unstable mixed layers, where the turbulent transport time across the entire PBL can be comparable with the electrical relaxation time. Willett (1978) showed that, on average, the convection currents act as a local generator capable of reducing the total downward current density by as much as 44%.

In order to study the horizontal structure of vertical current densities in the PBL, experiments to examine the covariation of atmospheric vertical electric currents at different stations using long-wire antennas are discussed by Israelsson et al. (1994).

4.2. Volcanoes and aerosols above the PBL

The main source of ionisation in the mid-troposphere and stratosphere (above the PBL) is cosmic radiation. The ionisation rate depends on magnetic latitude and on solar activity. The composition of the ions that establish the bulk electrical properties is relatively unknown. The ion concentration is also affected by aerosols whose distributions are quite variable in both space and time.

The global electric circuit varies over the solar cycle associated with cosmic ray flux changes. Whilst the contributions of thunderstorms may not only be to maintain an upward DC current, an improved understanding is required of the return current ($\sim$2 pA/m^2) flowing through the "fair-weather" atmosphere as part of the global electric circuit, particularly for geographically restricted variations of atmospheric conductivity. Another type of perturbation to the atmosphere results from volcanoes. Their sulphate aerosols and dust particles could nucleate high-altitude clouds, and the sulphates change the atmospheric conductivity and hence the properties of the global electrical circuit.

The character of upper tropospheric aerosols can be temporarily disturbed not only by volcanic eruptions but also by forest fires, biomass burning, and large dust storms. In addition annual variations of their concentrations have also been observed (Hofmann et al., 1975). Another important temporal variation of tropospheric aerosols is associated with the so-called Arctic haze events. New evidence suggests that these events are characterized by high particle loading throughout a large portion of the troposphere. The impact of this extensive aerosol loading on atmospheric electrical parameters is yet to be determined.

Hogan and Mohnen (1979) reported the results of a global survey of aerosols in the troposphere and lower stratosphere. They found that the concentrations were more or less symmetrically distributed about the Earth. More measurements of this type could provide the basis for extrapolating local or isolated observations to characteristic worldwide values. Man-made global ionisation effects reported by Boeck (1983), who studied the effect of krypton 85 released into the atmosphere on the global conductivity, have to be included in the global electric circuit.

The morphology of stratospheric aerosols is dominated by a persistent structure frequently referred to as the 20-km sulphate layer, or Junge layer. It is now known that the character of this layer is highly affected by large volcanic eruptions (Gringel et al., 1986). These volcanic eruptions can result in a rather dramatic increase of the aerosol content up to the stratosphere. The extent to which these aerosols directly affect the atmospheric conductivity, small-ion concentration, and mobility should be investigated to a greater extent. On the other hand, the sulphuric acid content of the lower atmosphere is also drastically enhanced following volcanic eruptions and might influence the ion composition considerably. Air-Earth current density measurements seem to be consistent with the classical picture of the global circuit, with some exceptions. The question of whether there are other global generators in the lower atmosphere, in addition to thunderstorms, could probably be unravelled by ground-based and balloon-borne current measurements at different locations.

5. Thunderstorms and the global circuit

5.1. Spatial and temporal distribution of thunderstorms

In recent decades we have greatly advanced our knowledge regarding the spatial and temporal distribution of thunderstorms and lightning. In the 1960s the first satellite observations of lightning were obtained (Vorpahl et al., 1970). However, in the last five years tremendous advances have occurred with the launch of three separate lightning detectors in space (OTD, LIS and FORTE) (Christian and Latham, 1998; Jacobson et al., 1999). We now know that the vast majority of lightning activity is located over the continental regions of the globe, with little lightning ever being found over the oceans. The reason for this is still debated; however, it is related to the differences in the microphysics of oceanic and continental deep convection (Price and Rind, 1992). Observations have shown significant differences in the updraft intensities in storms, with the oceanic storms rarely having updraft intensities greater than 10 m/s. The intensity of the updrafts is very important for the electrification processes, due to the vertical transport of supercooled droplets and graupel particles (Williams et al., 1992).

As a result of the global distribution of lightning, there are three main centres of lightning activity over the three tropical continental landmasses (South America, Africa, and South East Asia/Maritime Continent). In addition to the tropical lightning, extratropical lightning activity plays a major role in the summer season in the northern hemisphere, resulting in the global lightning activity having a maximum in June–August. Since the daily lightning activity in the tropics maximizes late in the local afternoon (16–18 local time), the combination of spatial and temporal activity produces the well-defined diurnal cycle in measurements of the global electric circuit (the 'Carnegie curve').

Whipple (1929) showed the agreement between the diurnal cycle of the global circuit and the diurnal cycle of global thunderstorm activity. Markson (1986) showed that individual measurements of the ionospheric potential agree well with the 'Carnegie curve', confirming that lightning plays a major role in the global electric circuit. Clayton and Polk

(1977) also showed good agreement between the AC component of the global circuit (Schumann resonances, see below) and global lightning activity. All these studies showed that the global electric circuit has a maximum at approximately 1800 UT, and a minimum at 0300 UT (Price, 1993).

As mentioned above, global lightning activity has a seasonal cycle with a maximum in the northern hemisphere summer. This annual cycle is also observed in the various measures of the global electric circuit. Hence, monitoring the global electric circuit, either via the DC components (ionospheric potential, fair-weather current) or via the AC component (Schumann resonances) provides a good proxy for global lightning activity.

5.2. Sprites

In the last decade, a completely new discovery has been made in the field of atmospheric electricity. Optical flashes have been observed high above thunderstorms, reaching altitudes of up to 100 km. These luminous transient events lasting from 1 to 100 ms have been named elves, sprites and blue jets. In the last few years the research in this area has increased dramatically (see Sentman and Wescott, 1996; Rodger, 1999, and a Special Issue of JASTP (May/June 1998)). It is now believed that all three phenomena are independent of each other, although sometimes they may occur simultaneously. Most of the advances in this field have occurred as the result of dedicated field experiments in the United States. During the summer months, mesoscale convective systems develop over the United States, which provide a natural laboratory for studying sprites. Observations have been taken on the ground (Lyons, 1996), from aircraft (Sentman and Wescott, 1993), and from high-altitude balloons (Bering et al., 1999). It appears that elves occur with all lightning discharges. The electromagnetic pulse (emp) produced by the lightning propagates up into the stratosphere and mesosphere, producing large electric fields that result in a ring of light at the base of the ionosphere (Cho and Rycroft, 1998), similar to the airglow phenomenon. This ring expands outwards as the emp propagates away from the lightning source in the storm below. The elves last only a few milliseconds, and they can only be seen with very sensitive low-light-level cameras. The propagation of elves outward has been observed using high-speed photometers (Inan et al., 1997).

Sprites are the more spectacular events, and are caused by only a small fraction of the lightning discharges within the storm below. We now know that sprites occur simultaneously with positive cloud-to-ground lightning (Boccippio et al., 1995), although recently there has been some evidence of negative cloud-to-ground flashes producing sprites (Barrington-Leigh et al., 1999). Sprites are red in colour as a result of the excitation of the N_2^+ line. The lifetime of sprites is much longer than that of elves, up to 50 milliseconds, and they occupy volumes greater than 1000 km^3. The removal of charge from the cloud by the positive discharge is thought to result in the stressing of the upper atmosphere. The screening layer around the anvil of the cloud immediately after the ground discharge acts as the charged plate of a horizontal capacitor, producing large fields above the storm in the mesosphere. The enhanced field accelerates electrons in the low-density mesosphere, colliding with N_2 molecules, resulting in the emission of red light. The relaxation time of the screening layer is some tens of milliseconds, the time scale of the sprites.

Do sprites influence the global electric circuit? This is still an unanswered question. Although sprites occur in the upward branch of the global circuit above thunderstorms, hence influencing the conductivity of the upper atmosphere (the resistor R_1 in Fig. 5), they occur much less frequently than regular lightning. Observations indicate approximately 1 sprite for every 200 lightning discharges. Therefore, due to their low occurrence rate they may not pay a major role in the global electric circuit. This is a topic of future research.

5.3. Schumann resonances

A paper in this issue (Barr et al., 2000, this issue) describes in detail the history and development of Schumann resonances (SR). The SR are produced by electromagnetic radiation from lightning being trapped in the Earth-ionosphere waveguide. At extremely low frequencies (ELF), very little attenuation occurs, allowing these radio waves to propagate a few times around the globe before dissipating. Constructive interference produces standing resonant waves at $8, 14, 20, 26, \ldots$ Hz, where the 8 Hz mode represents a wave with wavelength equal to the circumference of the Earth (40,000 km); see also Rycroft (1965) and Fuellekrug and Fraser-Smith (1996). Hence, similar to the DC fair-weather global circuit measurements, the SR can also be monitored from a single position on the Earth's surface.

Research on SR is twofold. The background SR signal intensities are well correlated with global lightning activity (Heckman et al., 1998); hence, the SR are used for studying the global variability of lightning activity (Satori, 1996; Nickolaenko et al., 1998). On the other hand, the transient SR signals have been shown to be well correlated with sprite activity (Boccippio et al., 1995; Cummer et al., 1998). Therefore, we are also able to use the SR measurements to study sprites on a global scale (see Fig. 6).

Unlike the DC circuit that is influenced by changes in the conductivity of the atmosphere, the SR are dependent only on global lightning activity. Hence, the AC component of the global circuit is better correlated with global lightning activity than is the DC component.

6. Climate change and the global electric circuit

In recent years a new and important application of the global electric circuit has become evident. The global

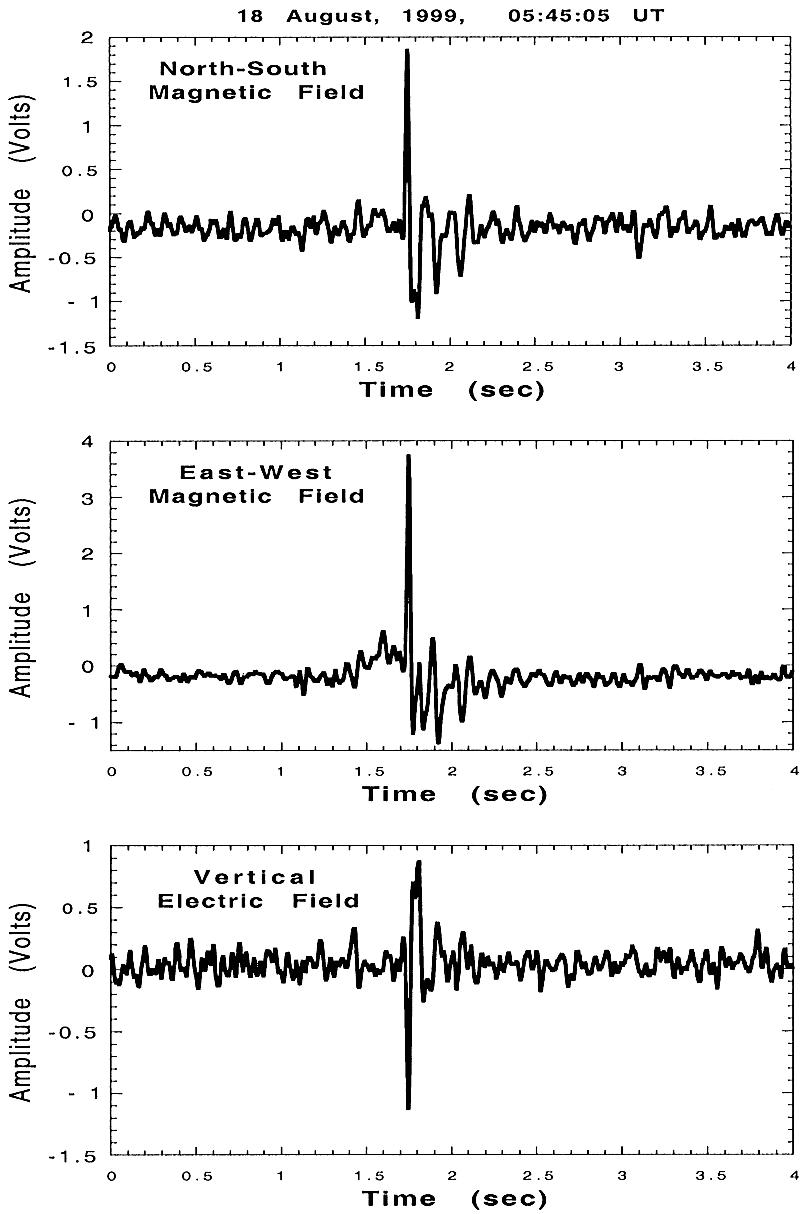

Fig. 6. The ELF radio signals observed in Israel associated with a sprite generated in the United States.

circuit is becoming an important tool in studying the Earth's climate, and climate change. Price and Rind (1990) first proposed the possibility that changes in the Earth's climate could result in more lightning activity around the planet. Since then global lightning activity and the global electric circuit have been shown to be closely related to various important climate parameters.

Williams (1992) showed the close relationship between tropical surface temperatures and the monthly variability of the SR measured in Rhode Island, USA. A similar study was conducted by Fuellekrug and Fraser-Smith (1997), showing a connection between ELF observations in Antarctica and Greenland and global surface temperatures. Price (1993) showed a good agreement between the diurnal surface temperature changes and the diurnal variability of the global electric circuit ('Carnegie curve'). This study also showed a strong link between the frequency/intensity of global deep convection and global surface temperatures. Markson and Price (1999) used direct measurements of the ionospheric potential to further demonstrate the positive correlations between global and tropical surface temperatures and the ionospheric potential. Recently, Reeve and Toumi (1999) used new satellite lightning observations to show the agreement between globally observed lightning activity and global temperatures. Finally, a recent study by Price (2000) has extended the above connections to additional climatic parameters such as upper tropospheric water vapour; the variability of upper tropospheric water vapour is closely linked to the variability of global lightning activity, measured via the SR.

Therefore, by monitoring the global electric circuit, we may be able to study, in a cheap and consistent way, the variability of global lightning activity, which is closely related to surface temperatures, tropical deep convection, rainfall, upper tropospheric water vapour, and other important parameters that affect the global climate system. The advantage of these measurements is that they can be made continuously, for many years, unlike satellite sensors that generally have a relatively short lifetime of only a few years, or even less.

7. Potential applications and recommended atmospheric electricity research

An increased interest in understanding the Earth's electrical environment has resulted from recent advances in different disciplines, along with the recognition that many of man's modern technological systems can be adversely affected by this environment. The cornerstone of our understanding of the Earth's electrical environment and the global electrical circuit is an integration of measurements, theory, and modelling. There should be a concerted effort of coordinated measurement compaigns, supported by critical laboratory experiments, theory, and numerical modelling of processes, to improve our understanding of the Earth's electrical environment.

It is also an opportunity to further investigate relationships/correlations between atmospheric aerosols and electrical parameters, with the advent of more widely available aerosol measurement capabilities. A proper understanding of the impact of aerosols on climate rests both on quality-assessed measurements, and on a predictive modelling capability which enhances our ability to understand complex and nonlinear interactions between aerosols and atmospheric electric parameters. An interesting and novel approach in linking atmospheric electricity parameters and lightning activity to the global electric circuit and to global warming provides the basis for other crucial modelling initiatives.

The global circuit of atmospheric electricity is influenced by meteorological processes. These influences are incorporated in the current that flows in the global circuit. As the electric conductivity of the troposphere and the stratosphere is so much lower than that of the ground and that of the ionosphere, the potential difference between these two highly conducting layers indicates the strength of the global circuit current and its variations with time. In measuring the electric field or the air-Earth current density at any one station, we may obtain information about those meteorological processes that, world-wide, influence the global circuit current. At the same time, the data obtained by measuring the electric field and/or the air-Earth current density are also influenced by local events at and above the measuring stations. These events may be generators for local electric circuits or may cause variations of resistances in the circuit. Therefore, we must basically consider that in the data thus obtained we are witnessing influences both from processes that occur over the entire globe at the same time, as well as from purely local events. If the scientists in atmospheric electricity had the chance to separate these contributions, we might have a tool of significance for global change problems.

The ionospheric potential, electric field and air-Earth current density measurements in the PBL with periods shorter than a few hours are usually attributed entirely to local sources, primarily turbulence and pollution. Recent advances that have been made in independent research areas examine the interrelations between them, and project how new knowledge could be applied for the benefit of mankind. They also indicate needs for new research and for the types of coordinated efforts that will provide significant new advances in basic understanding and in applications over the next few decades. They emphasize a need to consider the interactions between various atmospheric, ionospheric, and telluric current systems to achieve an overall understanding of global electrical phenomena.

Evaluating the present situation from this vantage point, we can perceive three main approaches from atmospheric electricity to the global change monitoring effort:

1. Measure local parameters at many places and attempt meaningful integrations for the results over areas of global importance, optimally for the whole globe.
2. Measure local parameters and follow local processes at locations where they may be representative for larger areas; the expectation is that this will be the case for the oceans far from their shores.
3. Find global contributions to local measurements, and derive global information from a rather small number of local stations.

The global detection of lightning is necessary to determine the global flashing rate and how this rate relates to other parameters in the global circuit. NASA has developed new optimal sensors that could be used to detect and locate lightning in the daytime or at night, and with continuous coverage by using satellites in geosynchronous orbits. These sensors are capable of measuring the spatial and temporal distribution of lightning over extended periods with good spatial resolution; they offer significant new opportunities for research and for many applications.

There are ample reasons for interest in global-scale atmospheric electrical phenomena. For example, valuable information about the distribution and temporal variability of horizontal potential differences in the ionosphere could be provided by monitoring the ionospheric potential simultaneously in different locations. Furthermore, the widely accepted relationship between global thunderstorm activity and ionospheric potential has yet to be verified on anything but the crudest statistical basis. From the present perspective, finally, a detailed knowledge of the forcing from the global circuit would be useful in evaluating the electrical response of the PBL.

Seen from our present state of knowledge and our present priorities, the following atmospheric electricity elements should be investigated. Are they changing over time? If so, how and why?

- Thunderstorm nature, frequency, and geographic distribution; assess secular changes in the number of thunderstorms and/or of lightning.
- Ionosphere-Earth potential difference; assess its changes by direct or indirect measurements of air-Earth current density at the ground or in the air.
- Atmospheric electrical conductivity and its changes at a selection of typical stations, with various local atmospheric and geographic conditions and of types of anthropogenic influences.

In a recently published book, the Board of Atmospheric Sciences and Climate of the US National Research Council (1998) has presented a few Recommended Atmospheric Electricity Research Topics. These are to

- Investigate the possibility that the global electrical circuit and global and regional lightning frequency might be an indicator of climate change.
- Determine mechanisms responsible for charge generation and separation in clouds to understand cloud formation mechanisms and elucidate the fundamental physics of lightning.
- Determine the nature and sources of middle-atmospheric discharges to (1) increase knowledge of these recently discovered phenomena and their possible association with severe weather, and (2) explore their effects on radio propagation and atmospheric chemistry.
- Quantify the production of oxides of nitrogen (NO_x) by lightning to better understand upper-troposphere ozone production or loss.

The European Science Foundation has recently established a Network on "Space weather and the Earth's weather electrodynamic and charged particle effects on the stratosphere and troposphere". The overall aim of that interdisciplinary study, now named Space Processes and Electrical Changes Influencing Atmospheric Layers (SPECIAL), is to

- review and investigate such subjects,
- generate and test some hypotheses on the effects of energetic charged particles on the atmosphere, and
- consider their effects on weather and climate (also see Feynman and Ruzmaikin, 1999).

Thus, it is evident that the "old" subject of atmospheric electricity is very much "alive and kicking" today. Indeed, in the next decade or so, it may experience a renaissance.

8. Conclusions and discussions

The study of atmospheric electricity and the global electric circuit has advanced dramatically in the past 50 years. Our knowledge of the global electric circuit modulated by solar effects has improved, although there are generally more questions than answers in this field of atmospheric electricity. Regarding aerosols and atmospheric ions, advances have been made in studying air pollution using atmospheric electricity, and we have a better understanding of how the conductivity of the atmosphere is influenced by aerosols, and how this impacts our measurements of the fair-weather global circuit.

Perhaps the largest advances have been made in the areas of lightning and thunderstorm research, as related to the global circuit. We now have satellites looking down on the Earth continuously, supplying information on the temporal and spatial variability of lightning and thunderstorms. New discoveries have been made in the field of sprites, elves and blue jets, which may have a direct impact on the global circuit and how we model the global circuit.

Finally, the global atmospheric electric circuit is now starting to be recognised by some climate researchers as a useful tool to study and monitor the Earth's changing climate. The global electric circuit is the only climate-related parameter that can be measured at a single location on the Earth's surface, and yet supply global information. This unique quality should encourage additional research in this field.

Although there have been dramatic advances in the field of sprites, lightning, and even the Schumann resonances over the last decade, there is a need for an increased understanding of the solar-terrestrial connection. How do changes in solar particles and cosmic radiation, and also the solar wind, influence the Earth's climate? How strong is this connection? Is it mainly a high-latitude connection, or can tropical thunderstorms be affected by changes in the solar wind flux? What about variations over the solar cycle? These and many more questions need to be addressed in future research.

Our need to assess environmental impacts on human kind's technological systems requires a better understanding of electrical processes in the Earth's atmosphere than we now possess. Further research is needed to understand better the natural electrical environment and its variability and to predict its future evolution.

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