Area Averaging of Atmospheric Electric Currents

Lothar H. RUHNKE

Environmental Science Services Administration
Atmospheric Physics and Chemistry Laboratory
Boulder, Colorado, U.S.A.

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Abstract

The global atmospheric electric current flow may be determined, if local influences can be eliminated, by measuring the total Maxwell current flowing to the surface of all fair-weather areas. A new method to reduce the effect of locally produced disturbances on surface measurements of the atmospheric electric current density is described. Experiments indicate that in the time domain from a few seconds to a few hours the standard deviation of the total current density decreases approximately with the square root of the sensor size. Locally generated currents may therefore be effectively suppressed by area averaging.

1. Introduction

For many decades investigators have pursued the idea of establishing a network of sites for measuring atmospheric electric fair-weather phenomena. In spite of enthusiasm, and the availability of stations and instrumentation, a long lasting network has not been developed. The reason is that the large contribution of local disturbances significantly overshadows any common measurement made at two distant stations. Global contributions to the locally measured electric field and conduction current density have been revealed through time averages obtained over long periods (*Mauchly* 1923), but no further significant progress on atmospheric electric investigations of synoptic significance has been achieved.

Dolezalek (1967) recently proposed a new synoptic program, using modern means and liberal scientific viewpoints, to investigate the global atmospheric electric current flow. He believes that this program could be accomplished successfully through international cooperation and sustained, concentrated effort. He suggests two parameters as guidelines for this program: 1) consideration of the potential of the assumed high-altitude equipotential layer as the central problem and 2) the choice of an hourly average as the basis for data comparisons.

We believe that the sum of the total Maxwell current, ignoring local effects, flowing to the surface of all fair-weather areas is a better parameter than the high-altitude potential, because of its significance in the search for a worldwide quantity to describe the atmospheric electric current flow. We further believe that a time domain of a few seconds to a few hours is more appropriate than hourly averages for the study of the global atmospheric electric current flow. This domain is likely to contain significant signals of global character produced by thunderstorm generators, as well as important fluctuations attributable to other sources.

Solar, auroral, magnetic, and cosmic ray effects may possibly influence the worldwide current flow. Furthermore, local influences probably can be best eliminated in this time domain.

In this paper a new method of eliminating local influences in surface measurements of the atmospheric electric current density is described.

2. Theory

The usual assumptions for consideration of global atmospheric electric current flow are made: The surface of the ground has zero potential; an equipotential layer with potential ϕ exists at high altitudes; the conductivity $\lambda(h)$ of the air is stratified but variable with altitude; and the supply current is generated by thunderstorms.

Of importance is that the supply current to the global circuit is independent of the resistance R between high altitudes and the ground, which follows from the relatively high resistance between each thunderstorm and either the ground or the high-altitude equipotential layer. Since the potential inside thunderstorms (10^9 V) greatly exceeds ϕ ($3 \cdot 10^5$ V), the supply current is also independent of ϕ . Thus, the sum of all currents generated by thunderstorms and fed into the global circuit must be treated as an impressed current ΣI . Other sources of global current will also be assumed to be impressed currents independent of R and ϕ . Neglecting time variations of ΣI we write simply:

$$\phi = R \cdot \Sigma I \quad (1)$$

Being the product of R and ΣI , ϕ inadequately represents the source current of the global circuit. When time variations occur, ϕ is even less representative, because R must be treated as a complex impedance rather than on ohmic resistance.

We believe that the source current ΣI should be considered the central problem of global atmospheric electricity. This current may be obtained by integrating the sum of the conduction current λE and the displacement current $\epsilon \frac{dE}{dt}$ over the surface F of the globe, excluding thunderstorm areas:

$$\Sigma I = \int_F \left(\lambda E + \epsilon \frac{dE}{dt} \right) dF \quad (2)$$

With the assumption of a stratified medium, the conduction current plus the displacement current (for simplicity called the total current) will be proportional to the sum of the generator currents at any altitude.

If time fluctuations in the supply current occur, the local relaxation time ϵ/λ becomes important. Assume that the conductivity $\lambda(h)$ of air is an exponential function of altitude h , where H is the scale height:

$$\lambda(h) = \lambda_0 e^{h/H} \quad (3)$$

Assume further that the dielectric constant ϵ is independent of altitude. A complex conductivity can then be defined, as well as a columnar impedance $Z(s, h)$, where s is the Laplace-transformed time variable. The columnar impedance as a function of altitude h is

$$Z(s, h) = \int_0^h \frac{dh}{(\epsilon s + \lambda)} \quad (4)$$

Using equation (3):

$$Z(s, h) = \frac{H}{s\varepsilon} \ln \frac{(1 + s\varepsilon/\lambda_0)}{(1 + s\varepsilon/\lambda)}. \quad (5)$$

The columnar impedance between the high-altitude equipotential layer and the earth becomes

$$Z(s, \infty) = \frac{H}{s\varepsilon} \ln(1 + s\varepsilon/\lambda_0). \quad (6)$$

This impedance, together with the Laplace-transformed generator current $\Sigma I(s)$, integrated over the earth's surface F , determines the magnitude and time variation of the potential ϕ at high altitudes:

$$\phi(s) = \frac{H}{s\varepsilon} \ln(1 + s\varepsilon/\lambda_0) \cdot \frac{1}{F} \cdot \Sigma I(s). \quad (7)$$

Even for simple time functions of the generator current $\Sigma I(t)$, such as a step function or a ramp function, the potential ϕ behave in a complex manner and analysis is difficult. We find it unwise, therefore, to use this potential as a basis for global circuit considerations.

By recognizing $\Sigma I(t)$ as the source of the fair-weather electric field and current, we obtain the electric field by differentiating the general potential distribution $\phi(s, h)$:

$$E(s, h) = \frac{\Sigma I(s)}{\lambda \cdot F \cdot (1 + s\varepsilon/\lambda)}. \quad (8)$$

Time variations in the supply current are thus damped with the local relaxation time in the local electric field. The conduction current density behaves, of course, similarly. For a step function in the current supplied by thunderstorms to the global circuit, the local electric field and conduction current develop proportionally with the time constant ε/λ . The potential of high altitudes with respect to the ground, however, will build up in a complex manner difficult to derive from analysis. It would be a misconception, therefore, to suppose that an altitude exists at which the electric field variations or the conduction current follow potential fluctuations directly. For measurements of total currents vs. altitude, we must expect both the mean and the fluctuations to be constant with altitude, neglecting local disturbances and displacement currents produced by sensor movements.

Locally produced rapid current variations of large magnitude usually prevent recording of the total current without proper averaging methods. It is customary to average by eliminating the displacement current, either through integration over a suitable time, as in the *Wilson* (1906) method, or by using *Kasemir's* (1955) matching method. The conduction current so obtained, however, although very important for studies of the local condition, is representative of the global current only when periods longer than the local time constant are considered. This is true even in the absence of local generators.

If a time resolution better than the local time constant is needed, the total current has to be recorded. Consequently, it is necessary either to find locations relatively free of local disturbances or to use a method to separate the global part from that produced locally. In searching for a site of low locally produced disturbances, *Ruhnke* (1966) measured the total

current density with floating balloons in the stratosphere and found a reduction by a factor of 50 in the short-term variations. Such a platform, however, is inappropriate for studies longer than a few hours because of battery limitations, instrumental drifts due to temperature, and the limited range of the telemetering system. Therefore, the problem of measuring current density at ground level should be fully investigated.

Consider that the total current at any point has a global contribution and one produced locally with means m and standard deviations σ . To separate local and global parts, consider many observational sites separated sufficiently so that locally produced currents are independent. By integrating over many such locations, the global part will increase linearly with the number of sites, while the locally produced part will increase with the square root of the number. Our experiments have shown that the site separation required to measure local disturbances independent of each other is very small if time elements of short duration are considered. It is preferable, then, to use a single sensor covering an area larger than the spatial extent of the disturbances. Locally produced variations can be expected to increase with the square root of the sensor area M , while global variations grow linearly with sensor size. Realistically, three operating regimes must be considered (Fig. 1). In regime I the sensors are very small and local variations will affect each part of the sensor equally. A slight increase in sensor area will not change the standard deviation of the measured current. In regime II locally produced fluctuations are different at each part of the sensor and the standard deviation will decrease with the square root of the sensor size. In this regime local disturbances are assumed to be of much larger amplitude than variations in the global contribution. Finally, in regime III the size of the sensor is increased until local variations average out and the global part becomes dominant. In this regime a further increase of sensor size will no longer reduce the ratio of standard deviation to the mean of the recorded current. The minimum size for regime III at any station is determined empirically. In Fig. 1 the three regimes are sketched on a double log scale.

Fig. 1 Expected decrease of the standard deviation in a current density measurement when the effective area of sensors is increased.

To develop a sensor for the total current density we applied the theory of *Kasemir and Ruhnke* (1958), who show that the effective area M of an arbitrarily shaped sensor is determined from its capacity C and height h above ground :

$$M(m^2) = \frac{h(m) \cdot C(F)}{\epsilon}, \quad (9)$$

where ϵ is the dielectric constant (8.859×10^{-2} A sec/Vm).

Long horizontal wires about 1 m above ground require the least mechanical support and insulation per sensing area. Wooden poles spaced 30 m apart with Teflon insulators support a 2 mm diameter stranded copper wire. These antennas are easy to install and it appears feasible to construct sensors with effective areas of 10,000 m².

3. Experiments

All measurements were made at the Mauna Loa Geophysical Observatory, situated at 3400 m altitude on the north slope of Mauna Loa on the island of Hawaii. The tropical high-altitude site is well protected from turbulent exchange and air pollutants at sea level by the trade-wind inversion at 2400 m and is considered an excellent site for atmospheric electric investigations (*Cobb & Phillips*, 1962). The general climate and location of the Observatory have been described by *Price and Pales* (1963), and the atmospheric electrical characteristics of the site have been discussed by *Cobb* (1967).

A block diagram of the measuring circuit is shown in Fig. 2. Four sensors A, B, C, and D with effective areas of 20 m², 70 m², 250 m², and 800 m², respectively, were switched alternately to the input of a vibrating reed electrometer. The electrometer (response time, 0.1 sec) operated in the current mode with a feedback resistor of $10^9 \Omega$. A potentiometric recorder with 0.5 sec needed for full deflection was used as a readout. Each 5 sec average was considered one data point and a different antenna was switched on every 5 min. After about 2 hr, enough data points were collected to measure the same mean current density with all four antennas. The standard deviation σ was taken as a suitable measure of the

Fig. 2 Block diagram of the measuring circuit to determine influence of sensor size on magnitude of fluctuations.

recorded fluctuations, and was calculated from the square root of the mean of the squares minus the square of the mean :

$$\sigma = (\overline{x^2} - \bar{x}^2)^{1/2} \quad (10)$$

As would be expected, the standard deviation varied widely as a result of local weather. High values were recorded when clouds or parcels of fog drifted through the sensor array. Equally high fluctuations sometimes occurred during fair weather and, in particular, when clear skies prevailed and the dark lava surface was heated rapidly by intense solar radiation. It was apparent that turbulence in the unstable surface layer caused rapid fluctuations of high magnitude in the total current density. The daily trend of this type of fluctuation resembled fairly closely the findings of *Israel* (1958) on the atmospheric electric agitation of the electric field. During the night, with clear skies and low wind, the conditions for recording atmospheric electric variables generally were very good. The lowest fluctuation levels

Fig. 3 Sample recording with four different sensors of total current density on August 11, 1967, at Mauna Loa Observatory.

were found shortly after sunrise, during the period of wind reversal from downslope to thermally produced upslope flows.

In all of these cases a reduction of fluctuation was noticed whenever a large sensor was used. As the typical sample of four successive recording periods with each of the four sensors in Fig. 3. shows, rapid fluctuations occur most strongly in the shortest antenna. The area-averaging process is also evident in this figure.

A better analysis of the method can be made by processing data of some typical periods of observation. In Fig. 4 the standard deviation σ and the mean m of a 2 hr period are plotted against the effective area of three sensor sizes on a double log scale. The recording was made on a cloudy day with winds of 5 m sec^{-1} and a light intermittent drizzle. Fog particles drifted over the station and visibility varied in short intervals between 20 m and 20 km. The results show that the largest sensor received a lower amount of fluctuations. The bulk of the fluctuations of the current density apparently extended over areas of about 70 m^2 , making sensors below that size ineffective in the area-averaging process. The 250 m^2 sensor, however, showed a 40-percent reduction in the standard deviation.

Fig. 4 Standard deviation and mean value of a 2 hr period, July 25, plotted as a function of sensor size.

Fig. 5 Standard deviation and mean value of a 2 hr period, July 28, plotted as a function of sensor size.

On July 28, 1967 (Fig. 5), clear weather with 4 m sec^{-1} upslope winds prevailed during the total observation period. Solar heating of the barren lava resulted in a strong temperature gradient close to the surface. The air was unstable but otherwise dry and free of pollutants. There were many gusts and eddies of all sizes. This weather normally would be labeled "fair" in atmospheric electric terminology. The results of the current density recording, however, showed a pattern characteristic of disturbed weather. Only the largest sensor showed a distinct decrease of fluctuations.

A different behavior was observed on most other fair-weather days when turbulence was not excessive. In the early morning hours of August 1, 1967, light winds, clear skies, and stable air provided ideal conditions for fair-weather atmospheric electric investigations. Fig. 6 shows that σ decreased with any sensor size and this behavior can be considered typical of fair-weather conditions. A further attempt to reduce locally produced variations

Fig. 6 Standard deviation and mean value of 2 hr period, August 1, plotted as a function of sensor size. Dotted lines a, b, and c depict the change in standard deviation when averages of 10 sec, 20 sec, and 40 sec, respectively, are used in computations.

Fig. 7 Standard deviation and mean value of a 2 hr period, August 11, plotted as a function of sensor size. Dotted lines a, b, and c depict the change in standard deviation when averages of 10 sec, 20 sec, and 40 sec, respectively, are used in computations.

was made on August 11, 1967 (Fig. 7). Our largest sensor, with an effective area of 800 m^2 , was now ready for testing. The recording was made under clear-sky conditions and early in the morning to avoid local turbulence produced by solar heating. A substantial decrease in the standard deviation resulted from increasing the sensor size. Although the largest sensor used is still not large enough, the results demonstrate the feasibility of averaging out local disturbances to a level below the globally produced signal variations.

4. Discussion

The method of area averaging described is a very simple way of filtering out large-scale variations in the air-earth current density from those produced locally, but its success depends largely on the atmospheric electric climate of the station and the size of the sensor. The physical limitation of sensor size determines the lowest filterable frequency feasible to filter with a single large sensor. Below that frequency range, for daily and seasonal variations, a sufficiently large network of stations seems more appropriate for the averaging process as suggested by *Paramonoff* (1950). For the time domain of a few seconds to about 2 hr, however, single sensors can be successfully employed, as was done in our experiments. Depending on the spectrum of variations produced at each location, a given sensor attenuates local disturbances by a fixed factor. The description of the local atmospheric electric climate requires knowledge of both the amplitude and the frequency distribution of the local disturbances.

Our choice of the standard deviation as a measure of variability in the current measurements necessarily produces a cutoff at a lower and upper frequency. The selection of 5 sec data points in the 2 hr measuring interval indicates roughly the frequency band of interest. To demonstrate that the general results do not change when these limit frequencies are arbitrarily varied, we processed the data of August 1 and August 11, 1967, using 10 sec, 20 sec, and 40 sec averages at data points. Increasing the time period of the data points changes the cutoff frequency and the standard deviation will be reduced. Figs. 6 and 7 show the reduction of σ obtained by using 10 sec, 20 sec, and 40 sec averages.

The global atmospheric electric circuit is best studied at locations with little air pollution, low probability of cloud cover, and low turbulence. The Mauna Loa Observatory must be considered an excellent atmospheric electricity station, yet our records of current density never showed complete freedom from local disturbances: an increase in sensor size always led to a decrease in the standard deviation. This method is thus an excellent indicator of local disturbances.

We can reasonably assume that most locally produced fluctuations in the current density follow the space-time distribution of atmospheric turbulence close to the earth's surface. The turbulence spectrum might well indicate, therefore, the sensor size required to enter regime III of the proposed method (see Fig. 1).

At the Observatory local wind conditions during the night produce eddies within a 40 m thick layer of downslope winds. During the day, eddies of much larger size occur in a 600 m thick upslope air flow generated by local solar heating. Current density measurements reflect

these conditions: the sensor size required to enter regime II increased from only 20 m² at night to more than 70 m² during the day. Nocturnal conditions therefore are preferable for studies of the global component. The level of the global contribution to air-earth current density in the time regime with which we are concerned is not yet known, but we hope to determine it during calm night hours with sensors which exceed the size of local eddies. When increasing sensor size does not lead to a reduction in the standard deviation, we can assume that the remaining fluctuation will be, if not of global nature, at least of very large extent. Experiments at a minimum of two widely separated stations will be required to determine whether these large-scale variations are of global size. If they are, as we expect them to be, the development of a synoptic network and cooperation with other disciplines will inevitably lead to a better explanation of disturbances in the global electric current flow.

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