Measurement of atmospheric air-earth current density from a tropical station using improvised Wilson's plate antenna

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We have developed an experimental set-up to measure the atmospheric air-earth current (conduction current). Data obtained with the continuous measurements of Wilson's plate are used to study of air-earth current density, with the aim of gaining an understanding of the experimental set-up's response to different meteorological conditions, including fair-weather days. This paper is a part of the on-going Global Electric Circuit (GEC) studies from Tirunelveli (8.7°N, 77.8°E), a measurement site in the tropical and southern tip of the Indian peninsula. Attempts have been made in past few years to obtain the global signature in this region with this sensor, but on most of the occasions it has been impossible to obtain the global signature during fair-weather days. The data used for February–April, 2007 have the well-defined nature of this global signature, which is in agreement with the well-established classical Carnegie curve of GEC. This paper also deals with very important observations made at sunrise and during those hours when fog existed. It is noted that the resistivity of the atmosphere increased significantly with the onset of fog and later decreased as the fog disappeared, based on the measured value of conduction current density when compared with the electric field measured by horizontal passive wire antenna. Also, during fair-weather conditions, conduction current and electric field variations are similar because the conductivity during this period is more or less constant at this site. Observations made during different meteorological conditions, such as different wind speeds, humidities, and temperatures, are also discussed.
Key words: Global electric circuit, atmospheric electricity, conduction current density, fair-weather, passive antenna.

1. Introduction

Different classes of currents flow in the earth's atmosphere, and these can be classified according to the agency of transport. The conduction current constitutes the actual transport of charges under the influence of an electric field and is almost a direct current, while the displacement current is a fluctuating current that contains a spectrum of frequencies and does not involve any charge transport. The existence of the latter is due to the time variation of the electric field in the medium. This Maxwellian Displacement current density is given by,

$$\mathbf{J}_\mathrm{d} = \varepsilon_\mathrm{o} \frac{\partial \mathbf{E}}{\partial t} \tag{1}$$

where ε_o is the permittivity of free space, and $\partial \mathbf{E}/\partial t$ is the time derivative of the electric field. For air-earth currents, the two main agencies that transport charge in the atmosphere are the electromotive force and the momentum of air. The current due to the electromotive force is the conduction current and is given by Ohm's law

$$\mathbf{J}_\mathrm{cd} = \sigma \mathbf{E} \tag{2}$$

where σ is the conductivity, $\mathbf{E}$ is the electric field, and $\mathbf{J}_\mathrm{cd}$ is the conduction current density. When the charge carriers are driven by air momentum, the current is called the convection current. Convection currents in the atmosphere can occur in different directions and intensities depending on the space charge density, air movement, the stability of the atmosphere, and gravity acting on charged particle suspensions.

Many attempts have been made in recent years to study atmospheric electrical parameters (Byrne *et al*., 1993; Tammet *et al*., 1996; Kar *et al*., 2004). Long-term investigations agree well with the Carnegie curve (Ralph Markson, 1978), but short-term investigations reveal considerable deviations (Clayton and Polk, 1977). Dhanorkar *et al*. (1989) studied the variations in the conduction current during a solar eclipse, while Kamra *et al*. (1997) studied the effect of relative humidity. Datta and Bhattacharya (2004) shed light on the air-earth current during severe meteorological disturbances, while the effects of thermal power plant emissions on atmospheric parameters were studied by Monohar *et al*. (1989) and Monohar and Kandalgaonkar (1995). These studies determined that the site of GEC measurements must be free of atmospheric aerosols and convection activity. Otherwise they lead to noise that will obscure the weak signatures representing the global thunderstorm activity.

In the work presented here, the experimental site is 35 km east of the Bay of Bengal and 45 km from the Western Ghats. The landscape is nearly flat, and there are no trees in the vicinity of the sensors. Pollution is low, and scanty rainfall in this region enables a large number of atmospheric

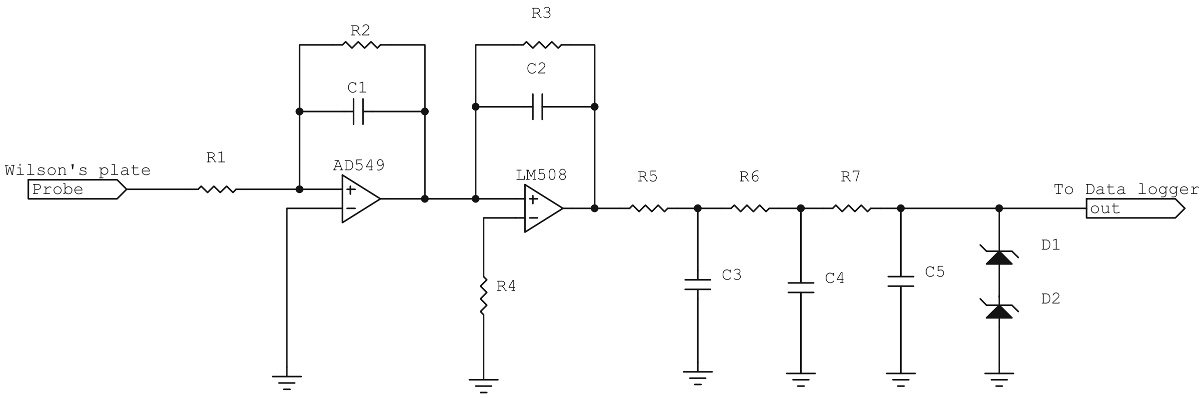

Fig. 1. Circuit diagram of the Wilson's plate experiment.

electricity measurements to be made, including the vertical electric field using a horizontal passive wire antenna, Wilson's plate antenna for conduction current, and the Maxwell current density using a long wire antenna. The results of these studies have been reported earlier (Panneerselvam *et al.*, 2007).

2. Instrumentation and Technique

There are only a few methods suitable for measuring atmospheric electric currents. The common ground-based sensors used for current measurements are Wilson's plate, the horizontal long-wire antenna, and the spherical shell in the form of two hollow hemispheres (Raina, 2002). In the case of Wilson's plate set-up, the current collector is in the form of a metal plate flush with the ground and isolated by an insulator supported by Teflon rods. As soon as the charged particles come in contact with the antenna, the electric field is indicated by an electrometer with AD 549 which converts the current into a voltage.

The electrometer measures the current in the range of Pico-amperes to a few nano-amperes with high feedback resistance. A buffer stage (LM308) is connected to the electrometer output. The output signals are filtered by a low pass filter (3 dB) at the input of an analog-to-digital converter (ADC) that is nearly 50 m away from the preamplifier. The filtered signal is fed to a high-resolution Windows-based data logging system. Averaging of the data samples were carried out during the analysis stage at 1-min and 30-min intervals, respectively.

Wilson's plate is exposed permanently to the atmosphere and kept flush with ground level (zero potential). The charge is accumulated on the plate by the air-earth current. The time-varying component passes through high 50 GΩ resistance (R_2) and capacitance 18 nF (C_1) that constitute the feedback loop of the current-to-voltage converter connected as a parallel combination, as shown in Fig. 1.

The convection current through the surface of an antenna is inherently zero because air cannot pass through this surface. Thus, the total current collected by the plate antenna is the sum of two components—the conduction current and displacement current.

3. Modifications of the Technique Employed

1) To obtain the conduction current component one has to eliminate the displacement current ($\mathbf{J}_d$); this is achieved by making the time constant of the electrometer, in current mode, equal to the relaxation time (ε_o/σ) of the atmosphere. The conductivity is 1.4×10^{-14} to 1.6×10^{-14} mhos/m close to ground level. Therefore, from the above given value, we take the polar conductivity to be half and $\varepsilon_o = 8.85 \times 10^{-12}$ F m^{-1}. Accordingly, the time constant of the electrometer has been set to nearly the atmospheric relaxation time.
2) A significant contact potential exists between the ground and metal plate. Here, we may have 1 V of contact potential in between the Wilson plate and the ground. This potential also varies with the variation in soil moisture and causes a variable error in the measurement of conduction current density. In order to reduce the error due to the contact potential, the Wilson's plate is made of stainless steel (which is supposed to have a minimum contact potential). The side wall and bottom of the pit are covered with the same stainless steel material and are properly earthed. This helps in suppressing the current from the ground due to radioactive sources.
3) Another improvement is in the shape and size of the plate. In the air-earth current receiver, a 1×1-m plate or 1-m^2 circular plates are being used as the air-earth current receiver (Price and Rind, 1992). In the improved design installed at EGRL, the plate is 1×4 m. The length of the plate is also in the direction of the prevailing wind at the site, which reduces the effect of the convection current carried by the wind to the plate and, consequently, the signal-to-noise ratio is increased.

4. Results and Discussion

To investigate the quasi-steady global electric circuit, we require the measurement of the conduction current, while the convection and displacement components can be considered as extraneous signals. The fair-weather atmospheric electric field near the earth's surface is nearly uniform and vertically oriented. Low wind conditions were chosen, and adequate care was taken with the horizontal component of the convection current so that it did not contaminate the conduction current measurements. The experiments were con-

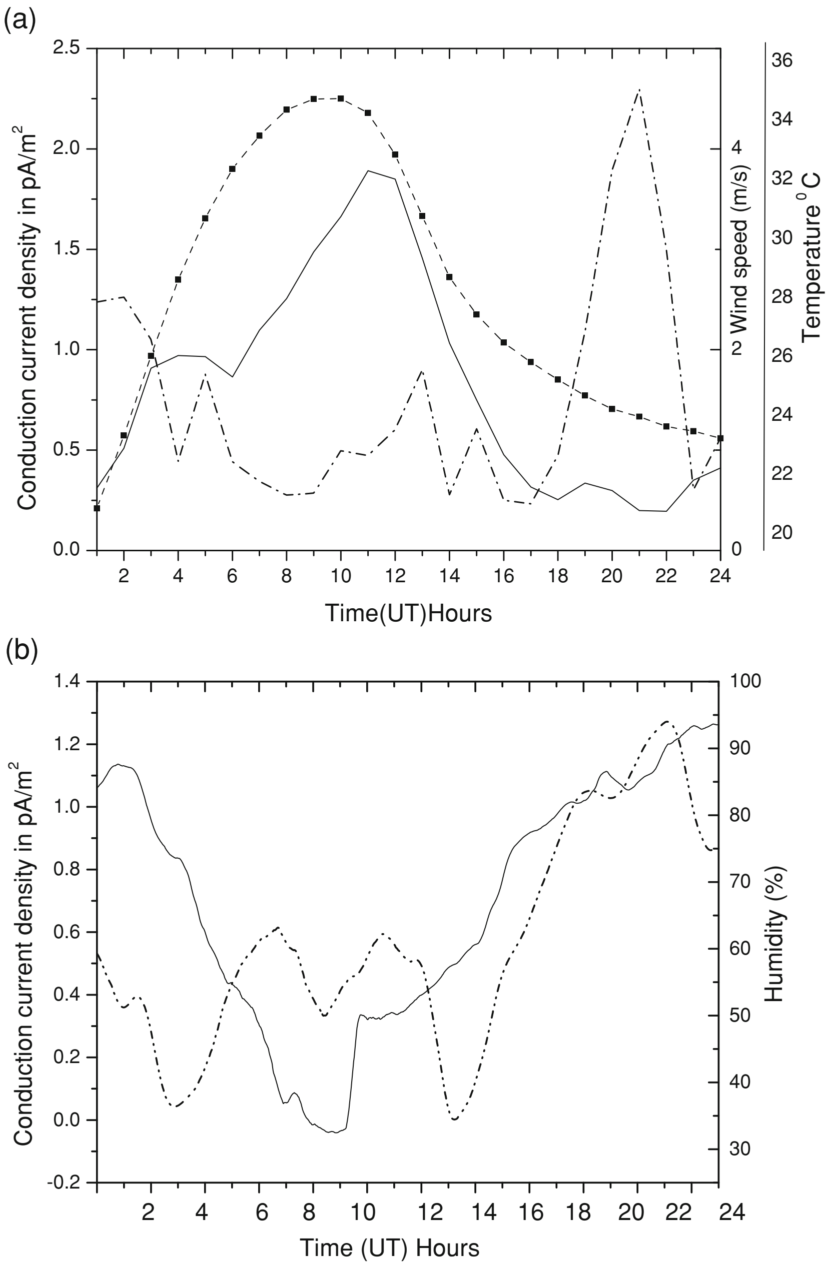

Fig. 2. (a) The variation air-earth current with temperature and wind speed of the troposphere on a fair-weather day, the dotted line represent conduction current, the dashed line plus simple line shows the temperature and the continuous line shows wind speed. (b) Variation in conduction current with local humidity. The dotted line represents the conduction current and the continuous line, the humidity.

ducted mostly on fair-weather days in February, March, and April 2007 at Tirunelveli (8.7°N, 77.8°E), and the data obtained are compared with those obtained at the high-latitude Indian station Matri (70.8°S, 11.8°E) in Antarctica to confirm the validity of the measurements. Whenever the sky was cloudy, the experiment was either stopped, or such data points were eliminated from the fair-weather day analysis. However, disturbed-weather observations were taken round the clock for comparative studies of the cloud physics. Mostly 1-min and 30-min averages were considered for the analyses of the measured parameters. We continued measurements for about 82 days, of which 42 days were fair-weather days and the remaining ones were disturbed-weather days. We define a fair-weather day as one in which there is no rainfall at the measurement site, clouds are less than three octas throughout the day, and the wind speed is less than or equal to 10 m/s. The data are plotted in Universal Time (UT). The mean temperature for the 3 months was 34°C and the minimum was 24°C. An automatic digital weather station operates at this observatory for monitoring the wind speed, wind direction, relative humidity, and rainfall at a sampling interval of 1 min.

In the present study, as stated above, two types of data sets were selected for analyses. For one set, days during which fair-weather conditions prevailed were considered, and 30-min averages of conduction currents were computed to yield the diurnal variation. The other type of data set included days on which disturbed local weather conditions occurred. A comparative study of fair-weather days and disturbed-weather conditions was carried out. We found

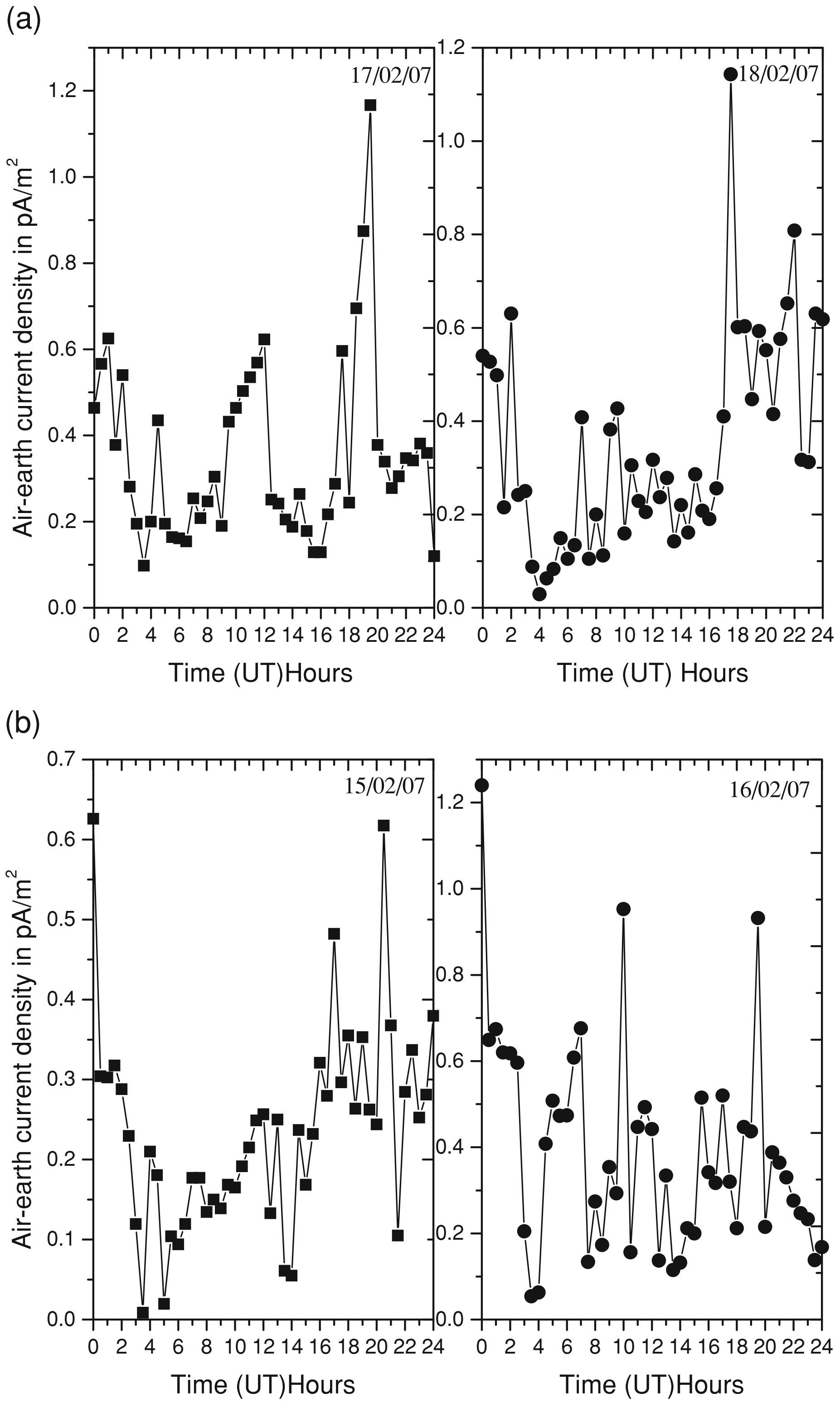

Fig. 3. (a) The air-earth current variation during the morning time with fog or mist. The days are 17 and 18 February, 2007. (b) The figures show the air-earth current on fog-free days of 15 and 16 of February, 2007.

that, in the absence of clouds, atmospheric electricity is almost positive. The change in the sign of the measured current clearly indicates the dominance of lightning current around these times and conforms to the traditional view that the fair-weather electric field changes its direction during thunderstorm activity (Israel, 1961). An electrical potential difference up to the order 25 kV/m was also noted in the electric field meter (EFM) within the vicinity of sensing thunder cells. The air-earth currents owe their origin directly to the atmospheric processes that generate the ionospheric potential (only the global currents). This also gives a clear indication that the plate antenna responded well to the electrical disturbances occurring in the near-earth space environment.

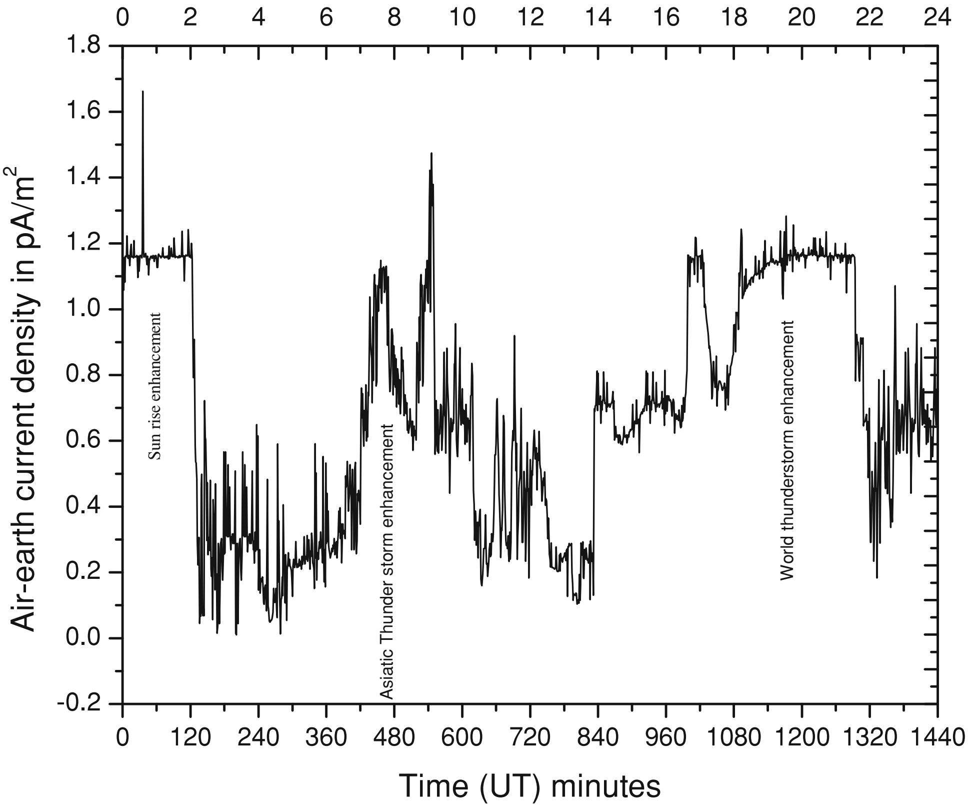

Fig. 4. The figure depicts 1-min average observations of 25 March, 2007, showing the local sunrise effect as well as world thunder storm variations.

The temperature of the troposphere is a minimum during the early morning hours and reaches a maximum during the local afternoon over land; a similar pattern is noted for wind speed over the experimental period, as shown in Fig. 2(a). Humidity also plays a role in the columnar resistance as depicted in Fig. 2(b). Since the surroundings were mostly dry and hot, the field did not vary much.

The effect of fog on the air-earth current was also studied and is depicted in Fig. 3(a). The fog/mist developed as a result of radiation cooling of air in the surface layer. Raw data were selected on 17 and 18 February, 2007 between 00:30 and 01:30 UT; during this period, the current level decreased. This could be due to the fact that the growing droplets capture atmospheric ions, thereby increasing the resistivity of air and thereby leading to a rapid reduction in the density of the current. Also, when the droplets began to fall, the thickness of the fog layer decreased and, consequently, so did the columnar resistance of the air. This observation agrees with results reported earlier (Israel, 1961; Hoppel *et al.*, 1986; Panneerselvam *et al.*, 2003). Figure 3(b) shows the fog-free diurnal variation of the half-hourly (30 min) average air-earth current density on fair-weather days.

The sunrise enhancement observed at 01:00 UT (06:30 IST) is depicted in Fig. 4. The observed day is a fair-weather day, sunrise enhancements in the air-earth current density are local effects associated with the ionization of the ionosphere. A study performed by Israel (1961) had provided a clear indication of the reaction of the potential gradient and air-earth current to sunrise. The increase in the atmospheric electric field and the air-earth current after sunrise is a regular phenomenon in the undisturbed atmospheric electric regime.

The measurement of the air-earth current at this continental station showed an increased conduction current at or soon after sunrise. There is also a simultaneous increase in potential gradient, but little change in conductivity. This effect is often referred to as the sunrise effect (Muir, 1975; Panneerselvam *et al.*, 2003), which is found to be more pronounced in summer than in winter. This effect is believed to be associated with the generation of a pre-dawn layer of positive charges close to the surface and subsequent uplifting of the layer through upward convection generated by surface solar heating (Marshall *et al.*, 1999).

The electric field strength or potential gradient is closely related to the air-earth current and atmospheric conductivity. The field can undergo considerable fluctuations near the ground owing to conductivity variations and local generators. Here, the measured value of air-earth current density was compared with that of the potential gradient measured with a horizontal wire-passive antenna. Resemblances were observed (Fig. 5) when the diurnal variations of atmospheric electrical signatures were compared, implying that the columnar resistance remains almost steady at the measuring site. On the other hand, the measuring site is less polluted. Thus, the variations in Fig. 5 can be seen as (1) partially a world-wide variation associated with the variation of V, the potential of the electrosphere (or ionosphere), and (2) partially a local variation related to the variation in R, the local columnar resistance. The above relation is used to predict the spatial variation of air-earth currents from the known variation of V with universal time and assumed vari-

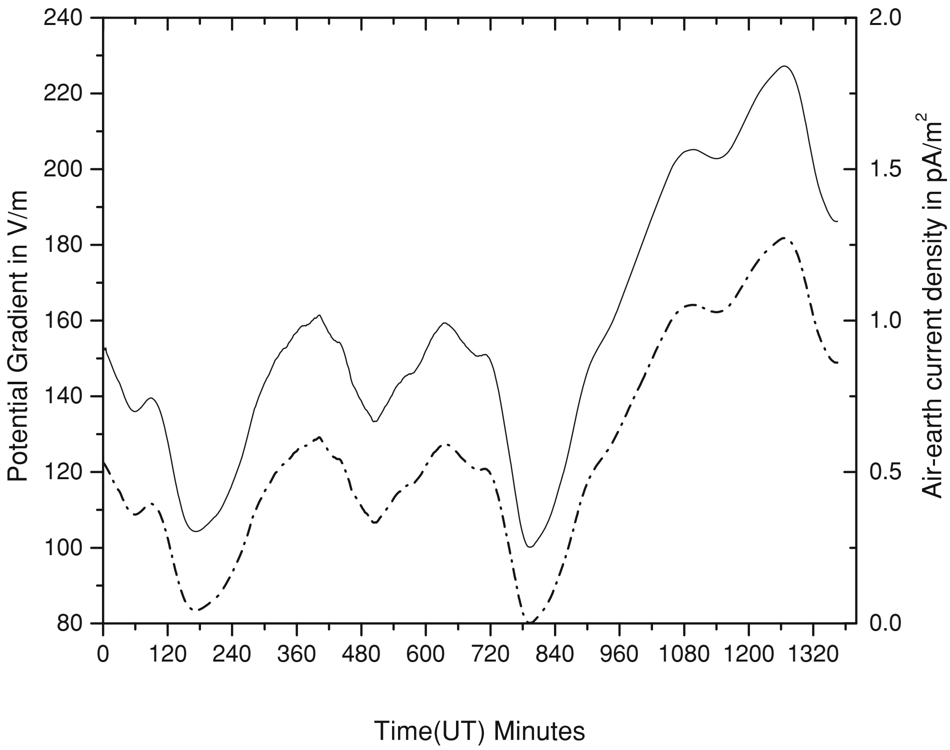

Fig. 5. Plot of 1-min average of the air-earth current values of Wilson's plate (dotted line). The continuous plot shows the potential gradient values of passive antenna at measuring site Tirunelveli on the 25 April 2007.

ation R with local time. Such computed values have been verified from experimental measurements.

There are different disturbed weather source zones world-wide where thunderstorm activity is at a maximum during different time intervals. For example, the thunderstorm activity is a maximum over the Amazon forests in the afternoon, which corresponds to about 18:00 UT. Similarly, the thunderstorm process over the Malaysian Archipelago and the adjoining maritime continent extending from South Asia across the Philippines, Indonesia, and Borneo into northern Australia are active around 08:00–10:00 UT; for Europe, it is 12:00–14:00 UT; for America, 18:00–20:00 UT (Tinsley and Heelis, 1993). Hence, the Carnegie curve shows a maximum value at 18:00 UT. Figure 6 demonstrates the systematic features in the air-earth current for 12 fair-weather days of the observation period. The diurnal variation in the air-earth current over land shows different forms at different times in terms of maxima and minima. At globally representative stations, the air-earth current density shows a diurnal variation with UT, with a minimum around 03:00 UT and a maximum near 18:00 UT; this reflects the diurnal variation of the electrosphere potential.

Figure 7 illustrates the average picture for 42 fair-weather day observations. A general characteristic is that the minimum value lies at 03:00 UT and a broad maximum lies near 19:00–20:00 UT. An air-earth current sensor placed over the continents other than the polar/ocean region may show the variation with respect to local and regional origin. Since the observed site here is a tropical site, the sunrise effect and other diurnal variations are statistically removed in graph shown in Fig. 7, with the vertical bar showing the standard deviation. The observations can be compared with the classical Carnegie expedition curve (Whipple and Scrase, 1936).

As a result of the global distribution of lightning, there are three main centers of lightning activity over the three tropical continental landmasses. In addition to the tropical lightning, extra tropical lightning activity plays a major role in the summer season in the northern hemisphere (Whipple and Scrase, 1936), resulting in global lightning activity being a maximum in June–August. Since the lightning activity in the tropics maximizes late in the local afternoon (14:00–16:00 IST), the combination of the spatial and temporal activity produces the well-defined diurnal cycle in measurements of the global electric circuit, with the ionospheric potential agreeing well with the 'Carnigie curve', thereby confirming that lightning plays a major role in the global electric circuit. There is a good agreement between the fluctuating component of the global circuit and global lightning activity (Tinsley and Heelis, 1993). All of these studies show that the global electric circuit has a maximum at approximately 18:00 UT and a minimum at 03:00 UT. This variation has been widely observed elsewhere and, according to classical theory, this is attributed to the variation with time of day of the thunderstorm activity across the globe.

5. Conclusion

This paper reports our successful attempt at identifying global signals in the air-earth current from a land station. The study was conducted during 42 fair-weather days with the aim of exploring the sensor response as well as the physics of the near-earth electrical environment and the role

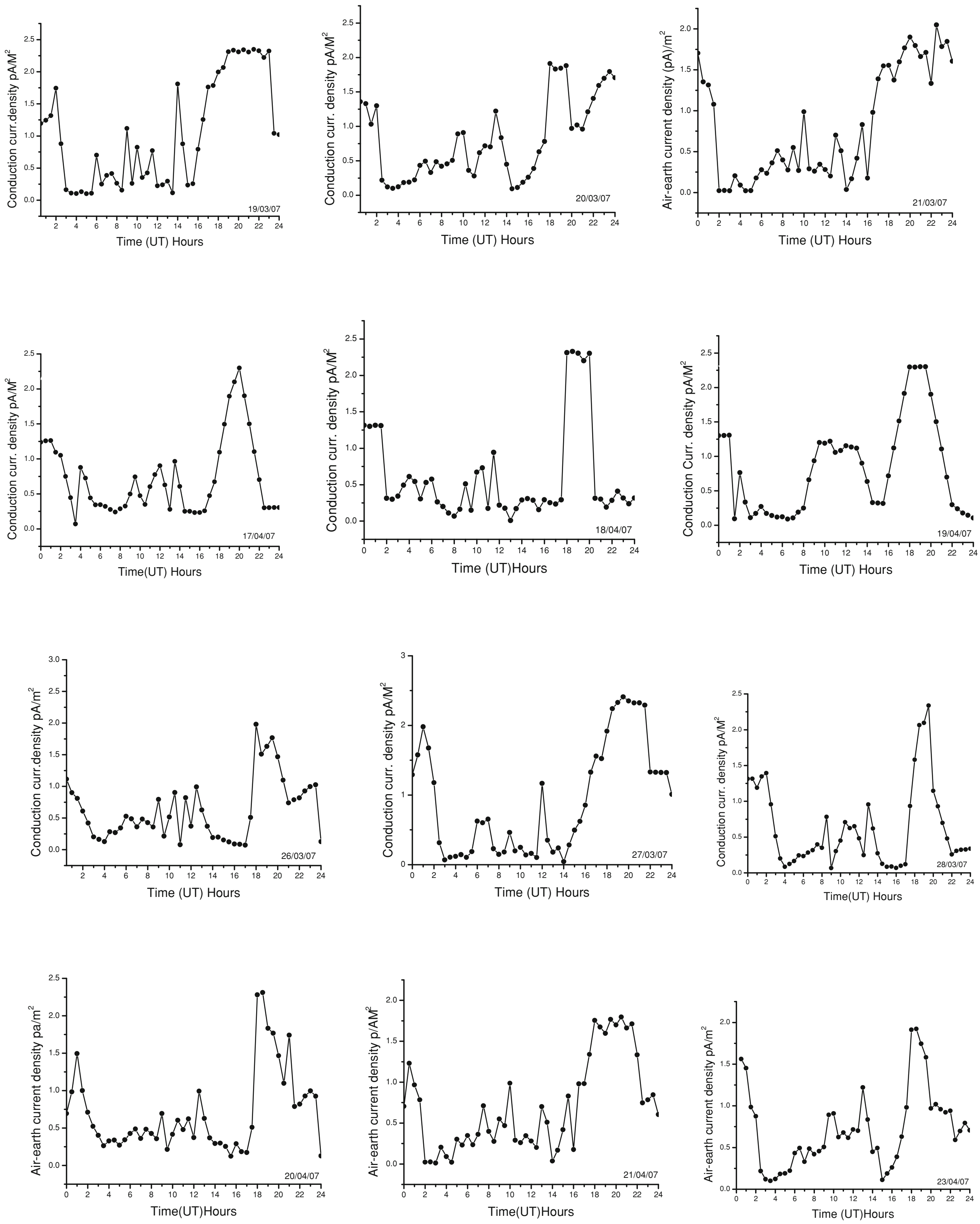

Fig. 6. Day-to-day variability of air-earth current density for 12 fair-weather days.

of conduction current in it. The range in conduction current density is of the order of a few pico-amperes per square meters on fair-weather days.

The existing theory has thus been validated with experimental results. The fog effect on the air-earth current was qualitatively studied, and an increase in the columnar resistance was noted during the time that the fog was present. Our studies on diurnal variation showed two maxima, one at 00:50–01:50 UT and the other at 18:00–19:00 UT. The first may be due to the sunrise effect of the Indian sector. Excluding the sunrise enhancement, the amplitude and phase of the average of 42 fair-weather day curve show an agreement with the well-established Carnegie curve of atmospheric electricity. It is clear from the above discussion

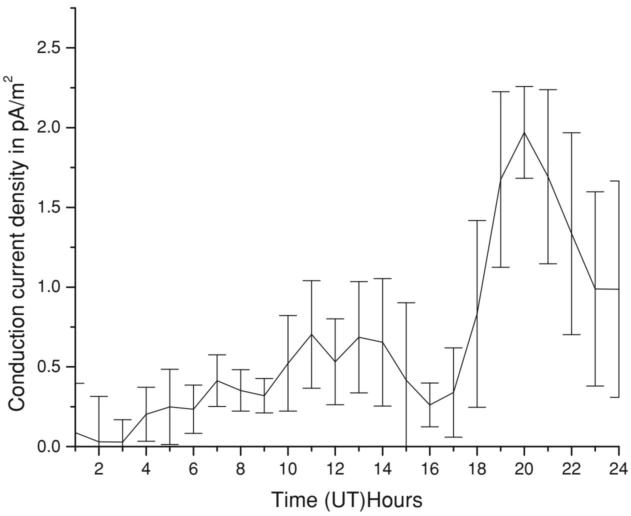

Fig. 7. Plot of average of 42 fair-weather days during the observation period.

and results that thunderstorms play a vital role.

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