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STATISTICS AND TRENDS OF GLOBAL ATMOSPHERIC
ELECTRICITY MEASUREMENTS

by

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A THESIS SUBMITTED IN
PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE
MASTER OF SCIENCE

APPROVED, THESIS COMMITTEE

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ABSTRACT

Statistics and Trends of Global Atmospheric Electricity Measurements

by

Erika Cleary

Globally representative atmospheric electric field and current data have been obtained from two sites at Amundsen-Scott South Pole Station at ground level (3 m) with 1 Hz time resolution. The average diurnal variation has been calculated for individual months and seasons, and well known features of the Carnegie curve observed. Amplitude ratios for seasonal curves range between 30-43%, in agreement with other studies. The Northern hemisphere winter is found to be a minimum for global convective-electrical activity and summer a maximum, in contradiction to the original 1929 Carnegie results. Seasonal phase shifts observed in previous studies of the diurnal variation of deep convective activity (DCA) in the tropics also appear in the results of this study. Good correlations between low amplitude peaks suggest our data are highly accurate and could be useful in detecting changes in weather patterns as might occur with global warming.
ACKNOWLEDGMENTS

I am grateful for the always kind encouragement and constant support given to me by my advisor Dr. Arthur Few. Dr. Few along with Dr. Bering from the University of Houston provided me with invaluable help and advice throughout the course of my research. Two students who worked on this project before me, Gary Morris from Rice University and Robert Chadwick from the University of Houston, generously gave their time to help me learn the computer code.

I thank everyone in the Space Physics and Astronomy Department for creating a great working and living environment. I never starved intellectually, socially or physically. In particular, thanks to Vincent Kargatis and Chris Miller for the couch, food and parties, Ben Boyle for the caffeine, Umbe Cantu and Maria Byrne for their nearly unbelievable kindness and everyone else I enjoyed conversations with. Finally, my parents and sisters and brother gave me a great deal of encouragement and empathy during my efforts to meet deadlines.

Financial support came from the National Science Foundation, Division of Polar Programs under grant DPP-8917464 to the University of Houston, from the National Aeronautics and Space Administration under a grant to the Universities Space Research Association to Rice University, and from the Charles L. Conly Research Fund of Rice University.
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INTRODUCTION

The Global Circuit

A downward pointing electric field of roughly 200 V/m and a current flow on the order of pA/m² are maintained in fair-weather regions near the Earth's surface. This phenomenon results from the Earth's atmospheric conductivity profile which increases exponentially with height and from the action of thunderstorms [Wilson, 1920]. A vertical conductivity gradient exists due to ionizing radiation from space and exponentially decreasing density, causing the conductivity near the top of a thundercloud to be approximately 10 times greater than the conductivity at the bottom. Large-scale charge separation occurs within thunderclouds, with updrafts bringing cloud particles with a net positive charge to the top while the larger and negatively charged particles tend to remain in the lower region of the cloud. Because of the much greater conductivity at the altitude of the cloud top, the accumulated positive charge produces a current which flows upwards towards the ionosphere where it is distributed rapidly over the globe. The current then leaks downward through the entire volume of the atmosphere to the Earth's surface and returns to the bottom of the cloud through lightning, conduction and point discharge processes. The electric field and current beneath a thundercloud point upwards, opposite the direction of the fair-weather field and current. The path described is the one of least resistance by at least an order of magnitude except when intra-cloud lightning occurs. A rough illustration of the net positive charge flowing out from around a thunderstorm is shown in Figure 1.

The 'global circuit' is a model of lower atmosphere electricity in which the ionosphere and the ground are considered to be the shells of a spherical capacitor charged to approximately 260 kV which discharge by leaking 1 kA total current through the
atmosphere to ground [Israel, 1973]. Both the ionosphere at 100 km and ground have comparable conductivities on the order of $10^{-2}$ mho/m. This model "capacitor" has a time constant of about 200 seconds; this implies that without a generator in the circuit supplying charge, the ionosphere would discharge within several minutes. The 1,000 - 2,000 active thunderstorms over the globe at any one time [Brooks, 1925] are principal generators in this circuit.

![Diagram](image)

Figure 1. Schematic diagram of global circuit model. Thunderstorms generate a downward pointing fair weather electric field and current.

Wilson’s 1920 global circuit theory was followed by observations of a diurnal signal in the atmospheric potential gradient [Mauchley, 1923]. And throughout the late 1920’s the research vessel Carnegie made thousands of observations at sea of the electric field: again a diurnal signal was evident [Torreson et al, 1946]. The change in global circuit parameters (the ionospheric potential $V_I$, the electric field or atmospheric current density) with Universal Time (UT) is now known as a “Carnegie curve”. When Whipple in 1936 made a crude estimation of daily thunderstorm activity worldwide, it was found to correlate extremely well in phase with the Carnegie data. This study provided the first
evidence that thunderstorm activity results in the observed daily variations in the atmospheric electric field and current. More recent evidence of this connection comes from satellite measurements of lightning frequencies, cloud cover [Markson, 1986], and parameters relating to deep convective activity within clouds [Hendon and Woodberry, 1993], all showing a correlation in phase with the Carnegie curve.

Because the current is distributed to the ionosphere homogeneously and on time scales of tens of milliseconds, one local measurement of the atmospheric electric field, current density or ionospheric potential difference ($V_I$) under appropriate conditions can be representative of the globally integrated value. Observations have borne this out, as measurements of the ionospheric potential taken from aircraft at 30 minute time resolution [Markson, 1986] are correlated with the Carnegie curve at the 99% confidence level. Experiments measuring $V_I$ simultaneously at widely separated locations also show close agreement [Muhleisen, 1971], [Markson, 1985]. The project detailed by this thesis sought to improve upon these results through an increase of the time resolution to 1 second and long-term deployment of instrumentation.

A model Carnegie curve is shown in Figure 2 with the predicted contributions from the major land masses. It is the uneven distribution of land over the Earth which causes the regular diurnal features. Thunderstorms are about 10 times more likely to form over land than over ocean [Orville and Henderson, 1986] because of the increased convective available potential energy when the sun heats a land surface. Land has an effective heat capacity lower than water and goes through more rapid temperature fluctuations. This is because water can “mix” the heat downward whereas the land surface must conduct the heat. As the Earth rotates, the relative fraction of land and ocean receiving radiation changes, leading to temporal variations in global thunderstorm development and in turn, to changes in the measured atmospheric current density and electric field.
Figure 2. Model Carnegie curve with major land mass contributions. Reprinted from Roble and Tzur, 1986.

The lower part of Figure 2 explains the Carnegie curve's characteristic shape. It has a minimum near 0400 UT where the sun shines over the Pacific Ocean and three prominent peaks due to increased convective-electrical activity over continental land masses. The 0800 UT peak is associated with Asia and Australia; the 1400 UT peak takes major contributions from Africa and Europe and the 2000 UT is associated with North and South America.

Thunderstorm development is a random process. Averages are meaningful quantities, providing a way of understanding system behavior; however, predictions of future behavior cannot be made. Variability inherent in the global weather should be reflected in large deviations from the mean on daily and monthly time scales. Also, it is the changes in the daily average values over different time scales which will be useful in understanding global atmospheric processes and trends.
Seasonal differences in the Carnegie curve are expected as well. The greater percentage of land in the Northern Hemisphere would dictate that it has the dominant effect on the globally integrated measurement. The period of time when the Northern hemisphere had the most thunderstorms and convective activity would see the highest magnitude of the daily average electric field and current; likewise, the time when it had a minimum number of thunderstorms (usually winter) would correspond to the lowest. Long-term trends can only be conjectured: it would be of interest to see if any changes in the average amplitude, signal strength, and the phase of the peaks occurred on annual or decadal time scales.

**Recent Research**

*Sources to the Global Circuit*

The amplitude variation of the Carnegie curve has been an important number in atmospheric electricity research. The amplitude variation (or 'ratio') is computed by subtracting the minimum of a curve from the maximum value and dividing by the mean; it is a measure of the diurnal signal strength. The data in the literature show Carnegie curves with amplitude ratios of 35-45% while those of lightning and thunderstorms have been estimated to be approximately 2-3 times higher. Israel [1973] has presented lower values, 20% for the Carnegie curve and 45% for thunderstorms, but the factor of ~2 is still present. Previously, this difference in the amplitude ratios was thought to be the result of ocean thunderstorms which were not taken account of; today this assumption is known to be false.
This discrepancy between the amplitude ratios of the Carnegie curve and of thunderstorm activity has led researchers to conclude that other processes, such as point discharge and conduction currents from electrified, non-lightning producing clouds add to the baseline electric field, decreasing the relative strength of the peaks. Reversals of the atmospheric current under overcast low clouds have been observed [Burke and Few, 1978], indicating that these clouds undergo charge separation and contribute significantly to the global circuit. More evidence comes from Price [1994] who studied the relationship between ionospheric potential measurements and lightning frequencies (which were estimated from satellite data with a flash rate parameterization). The $V_I$ measurements were taken during different years using balloon and aircraft techniques. A linear correlation that was highly significant at the 99% confidence level was found. The intercept was at 159 kV, indicating that lightning accounts for only about 40% of the daily variation in $V_I$. The changes in areal extent of deep convective activity (DCA) across the tropics with Universal Time were also obtained from satellite data [Hendon, 1994]. Agreement in amplitude ratio with the Carnegie curve could only be obtained by including vertical ranges appropriate to both thunderheads and lower lying stratiform clouds producing point discharge.

A combination of currents contribute to the global circuit but there is not a consensus on which of them, if any, dominate. Some have argued that point discharge is the major contributor to the global circuit since calculated ‘single-source’ curves for point discharge have an amplitude ratio closer to that of the Carnegie curve [Williams and Heckmann, 1993]. But conduction currents under thunderstorms are observed to be strongly correlated with the total lightning flash rate [Blakeslee, 1989], suggesting that the current output from various sources may often occur in parallel. So while a cloud with low-level electrification may contribute only through conduction currents, once it develops into a thunderstorm, all types of current output should increase. This issue may
affect the interpretation of the Carnegie curve but not necessarily its worth. Regardless of
the dominant source to the global circuit, the relative changes in net diurnal, seasonal and
annual electrical activity in the atmosphere can still provide important information.

Global Warming

Global warming of 1-5 degrees Celsius by the year 2050 has been predicted by
the Intergovernmental Panel on Climate Change (IPCC) due to the buildup of greenhouse
gases in the Earth’s atmosphere; yet the Earth’s surface temperatures have increased only
a few tenths of a degree Celsius in the last century largely due to the tremendous heat
capacity of oceans. This change is well within the expected variability in the temperature
record; for this reason, the seriousness of the situation and plans for environmental action
are being hotly debated. It has been postulated that global warming studies could be
simplified by making single observations of the global circuit, since surface temperatures
are linearly correlated with thunderstorm activity on diurnal, seasonal and interannual
time scales [Price, 1993].

Some studies have demonstrated a nonlinear response of atmospheric electrical
parameters to slight changes in wet-bulb temperature, a quantity which takes account of
both temperature and moisture content [Williams, 1992]. Global warming would cause
an increase in moisture content as ocean evaporation rates go up. This added heat and
moisture would be reflected in an increase of convective activity and cloud complexes
producing lightning, corona and conduction currents. Williams has examined monthly
averages of lightning and temperature data in the tropics where this relationship would be
most strongly brought out. Data from several stations close to the equator showed
increases of more than one and two orders of magnitude in lightning frequency associated
with average temperature increases of approximately 2 degrees Celsius. Tropical stations at higher latitudes and the mid-latitude station of Orlando, Florida did not exhibit such an exaggerated response to wet-bulb temperature changes, finding only an approximate doubling of lightning output per 1 degree Celsius change. Nevertheless, the fact that the tropical region has the most convective activity on the Earth and is the source of 2/3 of the world’s lightning suggests that monitoring global temperature trends through the Earth’s global circuit is not merely an option but the most effective and efficient means.
THEORY

Convective processes in thunderclouds charge the ionosphere to an average potential of ~ 260 kV. The ionosphere is very nearly an equipotential surface at 100 km; therefore we can apply the following relation:

\[ V_I = I^* R. \]

\( I \) is the net current flowing in the global circuit and invariant with altitude except on small time scales not of interest to this experiment. \( R \) is the total atmospheric resistance. It will exhibit diurnal variations due to its dependence on temperature and aerosol and water content.

The primary quantities measured are \( E_z \), the vertical electric field in units of \( \text{V/m} \) and \( J_z \), the vertical current density in units of \( \text{A/m}^2 \). Data were taken at a height of three meters above the Antarctic Plateau at 1 Hz time resolution. A columnar resistance, \( r_0 \), defined as the resistance of one square meter from altitude \( z \) to the ionosphere, relates \( J_z \) to \( V_I \) and \( I^* \):

\[ J_z = \frac{V_I}{r_0} = I^* (R/r_0). \]

The air-earth current density is altitude invariant for reasons of continuity except where charged clouds or turbulent conditions exist. At the South Pole the climate is very dry and a temperature inversion which has colder air sitting at the lowest altitudes suppresses turbulence of the boundary layer [Dalrymple, 1966]. The absence of diurnal sunrises/sunsets and low pollution levels means that the columnar resistance \( r_0 \) shouldn't experience diurnal variations. The current density measurements \( J_z \) are directly proportional to \( V_I \) and to the globally integrated current \( I \).
By Ohm's Law, the current density is equal to the conductivity multiplied by the electric field. For this study, only the vertical (z-direction) components are important:

\[ J_z = \sigma_z E_z. \]

\( E_z \) is related to the traditional global circuit parameters through the following equation:

\[ E_z = \frac{J_z}{\sigma_z} = \left( \frac{V}{\rho_0 \sigma_z} \right) = \left( \frac{IR}{\rho_0 \sigma_z} \right). \]

The two ground measurements were to be used together to eliminate substandard data and to check that the instruments were functioning properly. When \( J_z \) and \( E_z \) exhibit normal variability but their ratio \( \sigma_z \) stays constant, Ohm's Law is satisfied locally and great confidence is had in the global nature of the data. Unfortunately, this comparison between the two measurements was possible only occasionally, because the \( J_z \) and \( E_z \) data sets were not equal in size or always coincident. Sample daily plots of the current density, electric field and the calculated conductivity are shown in the Appendix.
INSTRUMENTATION

Two identical sites, each with a current sensor, electric field mill and buried vault box were established at Amundsen-Scott South Pole Station in mid-January of 1991. By comparing $J_z$ from array 1 and array 2 and $E_z$ from array 1 and array 2, some local perturbations can be filtered from those of global origin. Array 1 and 2 were set 600 m apart with the latter being closer to the station dome. Both were situated in the Science Quadrant upwind of the dome and downwind from the Clean Air Sector.

The current sensor deployed at the South Pole was one modified after Burke and Few's design [1978]. It consisted of two hollow hemispherical stainless steel shells electrically isolated from each other. The atmospheric current passes from one hemisphere through internal sensing electronics and out the other hemisphere. Because of the simple geometry of the sensor, a linear relationship exists between the current measured and the atmospheric conduction current (providing convection and displacements currents are small) [Burke and Few, 1978]. The sphere was suspended at a height of 3 m by Kevlar cables attached to wooden posts. All cables from the sensor were coated with Teflon to insure that the impedance to ground was much larger than that through the air.

The measured current can be broken up as

$$I_u = \frac{1}{2}I_a + \frac{1}{2}I_h$$

and

$$I_l = -\frac{1}{2}I_a + \frac{1}{2}I_h$$

where $I_u$ and $I_l$ correspond to the upper and lower hemispheres respectively, $I_a$ to the atmospheric current and $I_h$ to the horizontal convection current. Each hemisphere collected ions of just one sign. The difference current, $I_u - I_l$, removes local horizontal
contamination by convection. Vertical convection currents still influence the measurement but comparisons between sites 1 and 2 help identify large local effects.

The rotating dipole type electric field mill was developed at Stanford University. Two 30 cm stainless steel antenna rods rotate in a vertical plane at approximately 1800 rpm. Graphite brushes connect the dipoles to the sensing electronics. Conducting slip rings carry the induced sinusoidal voltage signal to internal electronics which produce a DC voltage which is linearly proportional to the vertical component of the atmospheric electric field.

Various “housekeeping” variables were recorded in addition to the current and electric field: the common mode current, average power in the difference current, the internal temperature and monitors of three power supply voltages. Magnetometer data, $B_x$, $B_y$, and $B_z$ components, are also available for about half the time the equipment was operational. Weather data such as wind speed and direction, pressure, and temperature are available from South Pole Station in addition to estimates of the altitude, type and amount of cloud cover, visibility, and identification of meteorological obstructions. The instruments and their installation are described elsewhere in greater detail [Byrne et al, 1993].
LOCAL CLIMATOLOGY

For non-turbulent steady state conditions, the conduction current is equal to the total current, or Maxwell current. In disturbed weather, other mechanisms contribute to the measurement. Beneath a thundercloud, lightning deposits negative charge to ground; point discharge, or corona current, sends positive charge upwards to the cloud bottom; precipitation tends to bring positive charge downwards to ground. Convection currents may sweep charge upwards and downwards erratically. The displacement current, \( \frac{d\mathbf{D}}{dt} \), also contributes, but on time scales so short that it has no net effect on our data. The various currents are shown in Figure 3.

\[
\begin{align*}
\overline{J}_w &= \overline{J}_c + \overline{J}_l + \overline{J}_e + \frac{\partial \overline{D}}{\partial t} & \text{Below T.S.} \\
\overline{J}_w &= \overline{J}_c + \frac{\partial \overline{D}}{\partial t} & \text{Above T.S.}
\end{align*}
\]

Figure 3. Currents associated with convective clouds. Reprinted from Roble and Tzur, 1986.

At the south pole, the temperature and high pressure greatly limit the development of thunderstorms but a certain number of snowstorms per year do occur. The
temperatures are below freezing all year, and since lightning rarely occurs with snowstorms, it is not a factor.

The greatest additional source to the conduction current is the convection current. This is due to turbulent air flow which blows charged snow particles and positive space charge from the 'electrode layer' [Hoppel, 1967] to the sensors. In a fair weather region the Earth's electric field points downward, accelerating positive charges downwards and negative charges upwards. At the air-ground (or air-snow) boundary negative charge becomes depleted, and positive space charge accumulates. This imbalance of ion flow is termed the 'electrode effect' and causes an increase in the electric field. For non-turbulent airflow with uniform volume ionization and no aerosols, Poisson's equation and an ion-balance equation are solved together to yield an analytic solution for the electric field with height [Hoppel, 1967]. Hoppel's calculations show that deviations exist to a height of 3 m. The instruments sit right at this boundary. When conditions are turbulent, positive charge is carried erratically in eddies of different sizes and the conduction current may be disturbed; on a calm day the signal will not be affected.

For many reasons, Antarctica was the ideal laboratory for this project. At an altitude of 2835 m above sea level, measurements of the air-to-earth current density are enhanced by a factor of two, approximately. The ice sheet is almost 3 km thick and provides a very uniform electrical ground plane. Its conductivity is many orders of magnitude greater than the air and its nearly flat, smooth surface reduces surface wind-shear driven turbulence. The small uniform slope of the ice sheet leads to a down-slope wind almost constant in direction and speed. There are relatively few man-made aerosols and pollutants in Antarctica which distort the electric field, and the experiment was set up in the Clean Air sector which was upwind of South Pole Station. Ground level conductivity is not altered by soil radioactivity and there is one annual sunrise and sunset so diurnal heating and convection effects are not factors to consider. An inversion layer
in which temperature increases with height, leaving denser air at the surface, creates greater stability in the air and reduces the tendency for convection currents to disturb the measurements.

The aforementioned qualities of the South Pole site allowed collection of a quality subset of data for averaging. Nevertheless, more data were discarded than used due to inclement weather and occasional instrument failures. Figure 4 shows by month the amount of data used in units of days. The number of days was determined precisely from the number of 60 second averaged points in the data sets and do not represent continuous periods. The sample of days per month having at least a few good hours was therefore greater than that shown in Figure 4.

- **Current Density Measurements**
- **Electric Field Measurements**

![Graph showing data subsets by month for 1991 and 1993](image)

**Figure 4.** Amount of data used in Carnegie curve analyses in units of days.
METHOD

Data were stored on magnetic tapes at the South Pole site and then shipped to the United States. Using computing facilities at the University of Houston, the data were then processed in block units of a day or less. As the data sets were so large, with each day having its associated variable arrays of 86,400 points, and a great deal of filtering could only be done by hand, IDL was the chosen language for the processing and analysis. Software was written with IDL version 1 and used with a Vax system.

Gaps were identified and removed in the processing. Calibration factors for the two sites were applied for data taken at different times. In order to prevent drifting of the baseline for the current meter, zero-level values (lasting 32 seconds) were recorded every 1024 seconds. The output was adjusted with respect to these values.

The difference current data were recorded in such a way that every 1024 seconds it switched signs. The processing removed the sign-swapping. If the day had calm weather and the equipment was functioning properly, the logical sequence of the +/- alternating series matched perfectly with the sign of the data and the processing was rapid. If weather or mechanical problems developed so that there was a discrepancy between the sign of the current and the sign of the alternating +/- logical sequence, the appropriate range of current data (length of 2048 seconds) would be displayed and the operator would be required to pick the true sign. This was often difficult when the current was rapidly fluctuating.

Most of the difference current data that had uncertain or irregular sign sequences due to turbulence were ultimately rejected and so were not a source of error. Nevertheless, errors in the sign determination might have contributed to occasional inaccuracies. The magnitude of any errors is not easily determined: it would depend on
the number of 1024 second cycles that the sign was reversed and how much the current increased or decreased. Systematic errors in the processing of the current occurred as a result of a failure in the software to latch on to the correct sign sequence during the first hour. As a result, this period of time in the daily averages of the current density must be disregarded.

As a final step in the processing, the data were averaged over 1 minute intervals and written to output files. Plots were made of the electric field, current density and calculated atmospheric conductivity.

Out of a span of available data ranging from January of 1991 to September of 1993, slightly less than one year's worth of data were processed. Out of that processed subset, a smaller selection of data (displayed in Figure 4) believed to be free of local meteorological disturbances was used in the averages for the Carnegie curves. The plots of processed data were inspected visually and compared with weather and wind records. Ultimately a subjective judgment was made as to whether the data were within the realistic amplitude ranges and smoothly varying enough to be a true global measurement. This was most difficult when large peaks appeared in both $J_z$ and $E_z$ measurements on a day with marginal weather.

As stated previously, top quality data were not in continuous blocks. In a given day it was not unusual to have intermittent disturbances by high winds, passing planes or technicians which would distort the true value of the electric field. The most straightforward way to eliminate these and other contaminating effects was to fix the start and stop times of the data going into the Carnegie averaging routine. As many as five or six inputs of start and stop times and calls to the bin averaging routine were made per day in the batch file program to insure that local effects were filtered out. At the same time, the data would be worthless if the selection process was too conservative and only days with low-level, weak electrical activity were included in the average. Every effort was
made to let the data speak for itself and not remove anything that could be a real signal. In general, if a large peak (~ 350-400 V/m) was smoothly varying enough, the data were included with the hope that the effect of any mistakes would be reduced in the averaging. Perhaps criteria could have been developed to automate the procedure for selecting or rejecting data, but it was thought that any such program would have to run through so many checks on the arrays that either computing speed or accuracy would be highly compromised.

The files containing 1 minute averages of the atmospheric electric field and current density were then used to compute the average value in 30-minute bins from 0000 to 2400 UT. The program accounted for gaps in the data and worked with arbitrary start times. The number of values in each half-hour bin was stored for later use in standard deviation calculations.

Carnegie curves were computed for each month with batch files and then summed together for study of seasonal trends. Since the season change occurs about three-quarters through the particular 'transitional' month, the start of the given season was taken to be the 1st of the following month, e.g., January 1st as the start of the Northern hemisphere winter rather than December 22nd.
RESULTS & DISCUSSION

Electric Field

Carnegie curves showing the diurnal variation of the electric field for each of the four seasons are presented in Figure 5. All curves have the characteristic shape with a minima around 0300-0400 UT and maxima spread over a wide time range from 0800-2000 UT. The similarity in shape is striking; inspection shows that even individual half-hour bins exhibit similar changes: for example, small dips are seen at 0900 UT and small peaks at 0200 UT. Linear correlation coefficients (r values) for each pair of seasonal averages indicate probabilities of non-correlation of less than .05%.

Carnegie Curves: Averages By Season

Figure 5. Seasonal trends of global atmospheric electricity. The characteristic shape is maintained as baseline increases are seen from winter to summer (Northern Hemisphere).
The amplitude ratios are all between 30-41%. This is consistent with other studies showing mean amplitude ratios of .47 [Torreson et al., 1946] and .35 [Kasemir, 1972]. The agreement of phase and amplitude is strong evidence that a global electrical signal has been measured.

Our results indicate that the atmospheric processes contributing to the fair-weather electric field are most active during the Northern hemisphere spring and summer, followed by autumn and then winter. The winter to spring change is the largest, a 32% average increase. The spring to summer transition shows a small average decrease of 4%. Summer to fall shows an average decrease of 15% and fall to winter, 17%.

It was predicted that the electric field measured at the South Pole would be at a minimum during the Northern hemisphere winter. A greater percentage of the Earth’s continental land mass is located in the Northern hemisphere and most convective-electrical activity occurs over land as manifested by the fact that lightning occurs about ten times more frequently over land than ocean. So as the temperature and moisture content drop and the occurrence of snowstorms increases in the Northern hemisphere winter, the worldwide signal also goes down. Simultaneously the electrical-convective activity in the Southern hemisphere is at its strongest, but because of the greater percentage of ocean, the Southern hemisphere increase cannot make up for the Northern hemisphere decrease. Backing up these considerations are midnight lightning flash data [Orville and Henderson, 1986] from polar orbiting satellites showing a clear maximum at the longitude range corresponding to the Americas during the Northern hemisphere summer. Thus, there is strong evidence that the Northern hemisphere should dominate the global electrical signal.

The original Carnegie data apparently exhibited the opposite seasonal trend from this data -- a 30% greater winter value over that of the summer [Markson, 1986]. Markson has explained this “apparent paradox” by arguing that 1) atmospheric electrical
processes in the equatorial region contribute the most to the global circuit and 2) that this region shows “maximum activity in winter”. The fact that 2) is not completely correct is shown by recent data of deep convective activity in the tropics and its diurnal variation [Hendon and Woodberry, 1993]. The data are reprinted in Figure 6 as they help to explain the results of this study.

![Graph showing seasonal trends in tropical convective-electrical activity](image)

**Figure 6.** Satellite data showing seasonal trends in tropical convective-electrical activity. Reprinted from Hendon and Woodberry, 1993. The phase shift of the summer is apparent in the global measurements of Figure 5.

Hendon and Woodbury’s data show the diurnal variation of convective clouds across the tropics (30 degrees N to 30 degrees S) in units of $10^5$ Km$^2$. The criteria for determining a “convective” cloud was inclusive of stratiform clouds which do not produce lightning but most likely are producers of point discharge currents. Notably, the data have the same amplitude ratio as the Carnegie curve. The time resolution of 3 hours is more than sufficient to make out the important diurnal and seasonal trends.

Our data are global measurements; Hendon and Woodberry’s are limited to the tropical belt. We can take the global data and mentally subtract off the tropical...
contribution and infer what *must* be coming predominantly from the mid-latitude regions in the Northern and Southern hemispheres. The two experiments are different; their respective units of measurement are not even the same. Nevertheless, here we have two independent seasonal analyses of the Earth’s atmospheric electrical activity and important deductions can be made.

Hendon and Woodberry’s data do not support Markson’s statement regarding maximum electrical activity in winter (Northern hemisphere). The diurnal curves for spring and winter tropical convection have nearly indistinguishable magnitudes (and phases). The “winter maximum” occurs in a 90 degree longitudinal region of the tropics (6 hour UT range), associated with the Central and South American rain forests, while a “summer maximum” is seen for 180 degrees of longitude (or 12 hours of UT). In estimating the area under each seasonal tropical curve it appears that winter and spring are ranked first, followed by summer and then fall. Using Markson’s logic with the recent and improved data, it would follow that seasonal averages of global convection should progress from a *dual* spring-winter maximum to a somewhat lower summer and an autumn minimum.

As was mentioned above, our spring and winter data show differences in magnitude greater than any other seasonal pairs. It is unlikely that our seasonal electric field data sets could be so regular and well correlated with each other and the Carnegie curve, have the correct amplitude ratios and yet have the annual maximum and minimum reversed. This is taken to mean that 1) the original Carnegie data are flawed with respect to seasonal trends, and 2) that convective activity in the mid-latitudes must be strong enough to make up the amplitude discrepancies between the tropical and global convection curves. Specifically, the Northern hemisphere mid-latitude regions must contribute strongly to making the summer a maximum for atmospheric electricity.
The unique phase relationship of the seasonal curves in Figure 6 reappears in our own measurements and confirms that we have measured globally representative values. In the satellite data in Figure 6, the summer is phase shifted earlier in the day while winter, fall and spring are grouped together with their maxima all at 2100 UT. Looking at our Carnegie curves in Figure 5, it is immediately obvious that the summer data set also has its maximum shifted earlier. Finding this feature in two independent data sets was totally unexpected but is clearly an indication that our data are reliable.

Looking at Figure 6, from 0000 to 0600 UT the differences between the seasonal convection strengths are minimal but starting at 0600 UT the summer curve of tropical convection increases over the other seasons. By 1800 UT the summer curve contribution is lower in intensity than the other three seasons. We notice in our data a similar pattern: between 0000 and 0400 UT summer and spring values lie very closely together; between 0400 and 1030 UT summer is actually peaked higher than the spring. Our summer curve starts to decrease gradually around 1200 UT, a bit earlier than Hendon and Woodberry’s tropical summer curve which decreases around 1800 UT, but this is expected since different sections of the globe are being sampled. Moreover, the data sets span different years.

The maximum values of our other three seasons all peak later than the summer: winter array 1 at 2000 UT, winter array 2 at 1230 UT, autumn at 1330 UT and spring at 1900 UT (excluding one point that is probably globally unrepresentative at 1230 UT). Linear correlation coefficients (r values) help bring out the respective phase groupings: between winter and fall r is .92; for winter-spring and spring-fall r is .91. The eastward shift in the phase of peak summer convection is reflected in smaller r values with the other seasons: .63 for summer-spring, .66 for summer-fall and .79 for summer-winter (array 2).
Returning to Figure 5, a well-defined local maximum in the autumn curve is found between 0600 to 0900 UT. As this time corresponds to afternoon in Asia/Indonesia and the seasonal average includes September, a primary monsoon month for India, we attribute this feature of the autumn curve to the monsoons in that region. The summer curve shows a global maximum around this same universal time. Major contributions to this peak are probably divided between thunderstorms in the Northern Hemisphere and those over the subcontinent, as August is the other primary monsoon month.

All high quality data obtained have been included in Figure 5, regardless of year. Inter-annual differences of the monthly averages would seem to be helpful in establishing the mean seasonal values. This has resulted in some uneven weighting. For example, “spring” and “summer” include only two months of data, April and May of 1991, and July and August of 1991 respectively, while “autumn” is composed of October, November and December of 1991 as well as December of 1992, shifting the latter slightly more towards a winter value. We do not have enough data to study how much the seasonal values may change from year to year; monthly values can exhibit changes on the order of ~ 100 V/m in different years as shown in Figure 7, but it is expected that with three times more data this number would drop significantly.
Figure 7. Carnegie curves showing changes in intensity of monthly averages in different years.

Figure 8 shows standard deviation values for representative Carnegie curves. The data sets which have high mean values also have the highest standard deviations from the mean. This characteristic applies to both the value of the baseline of the monthly curve, as well as to the hourly variations, resulting in the fact that the standard deviation values look very much like the calculated averages. Spring and summer (Northern hemisphere) are higher than the fall and winter. The phase shift of the summer maximum and the 0300 UT minima are evident. Consistently, the standard deviation values come close to reproducing the curves for the calculated averages.
Figure 8. Standard deviation values tend to be almost a constant fraction of the mean value for each bin, reproducing the shape of the corresponding Carnegie curve.

The number of data points used in each 30 minute bin does not affect the percentage of standard deviation apparently. Correspondingly, the number of days used in the averaging calculation appears to be of secondary importance: the curves for April and December of 1991 used roughly the same amount of data; however, the standard deviation for December, a relatively inactive electrical period, is about 75 V/m lower.

As a further test, the standard deviation was divided by the mean for all forty-eight half-hour bins, in order to determine the fractional value that it comprised. The average of these forty-eight values was next computed. These average fractional values are listed in Table 1 for each month. It was found that for all monthly data sets but the two of lowest quality, the standard deviation ranged between 84 - 96% of the computed
average. This is a measure of the natural variability in the global weather system and the inability to make deterministic predictions. Large thunderstorm complexes may develop on a given day, greatly contributing to the global electrical activity, and then dissipate within 24 hours. And it seems logical that the development of thunderstorm complexes on all size-scales would occur in parallel. That is, when conditions are generally unfavorable for thunderstorm formation (e.g., 0300 UT, January), the baseline Carnegie curve is lower and the formation of large-scale complexes which would increase the standard deviation is highly improbable. Likewise, when weather conditions are ideal for thunderstorms, small and large systems develop in some particular ratio: the small systems tend to increase the baseline value of the Carnegie curve while the larger ones contribute to the higher standard deviation.

Table 1.

<table>
<thead>
<tr>
<th>Average Values of Standard Deviation Divided by Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 1993: .84</td>
</tr>
<tr>
<td>February 1993: .89</td>
</tr>
<tr>
<td>March 1993:  .89</td>
</tr>
<tr>
<td>January 1991: .94</td>
</tr>
<tr>
<td>February 1991: .62*</td>
</tr>
<tr>
<td>April 1991:  .93</td>
</tr>
<tr>
<td>May 1991:    .88</td>
</tr>
<tr>
<td>July 1991:   .90</td>
</tr>
<tr>
<td>August 1991: .73*</td>
</tr>
<tr>
<td>September 1991: .84</td>
</tr>
<tr>
<td>October 1991: .93</td>
</tr>
<tr>
<td>November 1991: .88</td>
</tr>
<tr>
<td>December 1991: .93</td>
</tr>
<tr>
<td>December 1992: .96</td>
</tr>
</tbody>
</table>

* not used in seasonal averages

It is reassuring that the fractional values of the standard deviation are constant over different time periods and do not depend on the amount of data. Specifically, we can compare the months of October 1991, April 1991 and December 1992. The October subset has only about one week’s worth of data, while April has about double that amount and December of 1992 has three times that amount, yet the average standard deviation fractions are .93, .93 and .96, respectively. If the standard deviation fraction
could be significantly lowered by the inclusion of additional data, that would be an indication that the deviation from the mean was caused by local meteorological disturbances and that there was less variability inherent in the system.

**TYPICAL VALUES OF MEAN ERROR**

![Graph showing typical values of mean error](image_url)

**Figure 9.** The mean error is within 2-5% of the Carnegie curve averages.

The error in the mean for sample Carnegie curves is plotted in Figure 9. This is the standard deviation divided by the square root of the number of data points used in the averaging bin. The mean error is a measure of the reliability of the measurements and ranges between 4-14 volts/m in absolute terms, or between 2-5% as a fraction of the average value.
Strong proof that the electric field measurements are of a global nature comes from the calculated amplitude variations. Past studies have presented amplitude ratios for annual and seasonal curves of about 35-40%. As seen in Table 2, the seasonal Carnegie curves from this study have similar amplitude ratios even though the monthly values may be somewhat higher. Two of the higher amplitude ratios are undoubtedly due to poor statistics, February 1991 and August 1991, while the others are taken as real indicators of the diurnal signal strength.

Amplitude Variation For Seasonal and Monthly Carnegie Curves

<table>
<thead>
<tr>
<th>WINTER ARRAY 1</th>
<th>42%</th>
<th>SUMMER ARRAY 2</th>
<th>32%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 1993</td>
<td>76%</td>
<td>Jul. 1991</td>
<td>37%</td>
</tr>
<tr>
<td>Feb. 1993</td>
<td>45%</td>
<td>Aug. 1991**</td>
<td>86%</td>
</tr>
<tr>
<td>Mar. 1993</td>
<td>73%</td>
<td>Sep. 1991</td>
<td>38%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WINTER ARRAY 2</th>
<th>43%</th>
<th>AUTUMN ARRAY 2</th>
<th>34%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan. 1993</td>
<td>76%</td>
<td>Oct. 1991</td>
<td>47%</td>
</tr>
<tr>
<td>Feb. 1993</td>
<td>45%</td>
<td>Nov. 1991</td>
<td>35%</td>
</tr>
<tr>
<td>Mar. 1993</td>
<td>73%</td>
<td>Dec. 1991</td>
<td>35%</td>
</tr>
<tr>
<td>Feb. 1991**</td>
<td>138%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>SPRING ARRAY 2</th>
<th>30%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apr. 1991</td>
<td>35%</td>
</tr>
<tr>
<td>May 1993</td>
<td>29%</td>
</tr>
</tbody>
</table>

** not included in averages

Figure 10 shows the relationship between the average standard deviation scaled as the percentage of the mean and the amplitude variation (maximum minus minimum value divided by the mean). The encircled data sets were determined to be of high quality by visual inspection: the data varied smoothly and were within acceptable ranges. The best data consistently had amplitude ratios close to 35%, and standard deviation values which were approximately 90% of the Carnegie curve itself. Again, the absolute amount of
data, i.e., the total number of hours or days put into the monthly averages is not of direct
significance: October 1991 which is in the center of the circle has about the same amount
of data as February of 1991.

![Graph showing Amplitude Variation](image)

**Amplitude Variation**

Figure 10. Best data sets with reliable amplitude ratios
(\(\sim 0.35\)) also have highest values for standard deviation as a
percentage of mean, averaged for all half-hour bins.

What seems to be a factor in determining where these monthly values fall on the
graph is the selection process itself during periods where good data are scarce. A few
good hours may be sandwiched between much longer periods where the current and
electric field meter are off-scale due to blowing snow and convection currents. Because
the "real" peaks were harder to distinguish from the off-scale periods, the selection
criteria were necessarily stricter: acceptable values of the electric field tended to be less
than 250 or 300 V/m, as compared to 400 V/m during a calm day. The rejection of large
peaks on turbulent days from the averaging is what causes the percentage of standard deviation to be relatively small.

The explanation of high amplitude ratios is dual: larger values may occur when the diurnal cycle is strong, as is suspected with January and March of 1993 (which could be connected with the spring-winter maximum in tropical convection around 2100 UT), or when the data quality is suspect. While the amount of data in absolute terms is not important, it is true that the lack of well-distributed data have a significant influence on the amplitude ratio. There may be a relatively small amount of data for some half-hour bins while other bins have more points than necessary to get a good monthly average. In this case, one unrealistically low or high bin value directly leads to a skewed amplitude ratio.

The amplitude ratio strongly depends on what the minimum and maxima are -- two points which may not be meaningful if the data are unevenly distributed throughout the day.

It was not always easy or straightforward to isolate the good data from the bad, even when supporting weather reports were available. An electric field peak with a maximum value of 350 V/m and width of three hours UT may represent a local disturbance or a strong global signal from a tropical storm or hurricane. Calculations of average standard deviation as a percentage of the mean can be useful for comparisons between data sets and the determination of whether too much or too little data are being thrown out.

Data from the seasonal calculations are added together to produce an annual Carnegie curve in Figure 11. For each calendar month the best data were chosen. Figure 11 includes January though March of 1993, April and May of 1991 and July through December of 1991. The amplitude variation is somewhat lower than most of the seasonal curves, 27%, but this is not problematic. Decreases in amplitude ratio from monthly to seasonal time scales occur as regional weather patterns are averaged out; it seems
consistent that the UT variation would be slightly more suppressed when averaging data over a year.

**ANNUAL CARNEGIE CURVE**

Electric Field, V/m

UT (30 minute bins)

**AMPLITUDE RATIO: 27%**

Figure 11. Annual Carnegie curve constructed out of eleven monthly data sets obtained from 1991 and 1993.
Current Density

The atmospheric current density measurement is much more difficult to make than the electric field. The global signal is on the order of picoamps and easily obscured by convection currents of charged blowing snow and space charge from the electrode layer. Due to the higher sensitivity to local conditions we have only obtained good data during the Northern Hemisphere fall and winter. The averages grouped by season are presented below in Figure 12.

![Carnegie Curves: Averages By Season](image)

Figure 12. Current data show a winter-to-fall (Northern hemisphere) increase similar to that of the electric field Carnegie curves in Figure 5.

High agreement can be seen between these two curves and the electric field measurements except for the first segment of the day when the electric field values are decreasing while the current density values are increasing. As mentioned earlier, this is
the result of a flaw in the data processing procedure which incorrectly determines the sign for the first hour.

The linear correlation coefficient \( r \) between the Northern hemisphere winter and autumn current density averages is .83, indicating a probability of non-correlation of less than .05%. To quantify the similarity between the current and electric field measurements, the \( r \) values were computed. Between \( E_Z \) and \( J_Z \) for autumn, \( r \) was .82. For the winter curve, \( r \) was .94. It is also noteworthy that the percentage change from winter to fall was comparable in both global circuit variables: the electric field showed a 17% average decrease; the current density 16%.

Magnitudes of the air-earth current density cited in the literature typically range from 2-3 picoamps around sea level. The higher altitude of the Antarctic Plateau increases our observed current signal by a factor of two, approximately. Few and Weinheimer [1986] have further pointed out that their analysis of the electrode effect is applicable to many studies of conduction current and argue that the measurements should be multiplied by a factor of two to compensate for the depletion of ions near a conducting surface in a vertical electric fields as particles oppositely charged will build up. With these considerations our current density averages are not unrealistically high.
Carnegie Curves: Averages By Month

Figure 13. Monthly Carnegie curves for the difference current.

In Figure 13 the seasonal curves are broken up into their monthly contributions. October 1991 is larger than the other monthly averages as it is the month closest to the Northern hemisphere summer.
Figure 14. Comparison between the amplitude ratios of the electric field and current density Carnegie curves by month.

Figure 14 presents the current density amplitude ratios in comparison to the electric field values. In five out of the six cases the current density has a higher amplitude ratio. This difference could result from a greater sensitivity to local weather perturbations or from a falsely low or high value of the current caused by errors in the sign (+/-) identification. The current density is a much more sensitive measurement than the electric field and the sensor has a larger dynamic range than the electric field meter, not going off scale as frequently. As can be seen from Figure 4, the monthly subsets of the current data are also smaller and this probably contributes to the larger amplitude ratios.
Figure 15 shows a peak in electrical activity of relatively small amplitude at various times during the year. Only a sampling of the curves is shown. Just as the 0400 UT minimum is linked with thunderstorm development over the Pacific Ocean and the 2000 UT with the Americas, this two-hour time interval should be strongly correlated with convective-electrical activity in a longitude strip 30 degrees wide. Study of the changes in size of these peaks throughout the year can provide clues as to whether the 'source' is located in the Northern or Southern hemisphere. A peak connected with a
Northern hemisphere land mass would tend to be larger in the summer and smaller in the winter; vice versa for the Southern hemisphere.

The fact that this 0200 UT peak appears in a number of different months and in both the current density and electric field measurements suggests that it is a real signal. Inspection of a globe suggests that it could be due to parts of Australia and to New Zealand; indeed a slight contribution from New Zealand is listed on the model Carnegie curve in Figure 2. Other smaller land masses identifiable through longitude and latitude restrictions may have regular electrical signatures. This could be a rough, but simple and perhaps useful way to monitor changes in regional atmospheric electricity activity.
CONCLUSION

Despite the ruinous effect of the local weather on a large fraction of our data, a small subset of high quality data yielded excellent electric field Carnegie curves. The seasonal increases in baseline matched expectations based on land mass distributions and land/ocean lightning frequencies. The amplitude ratios were consistent with those found in earlier studies. A distinct phase grouping of the seasonal curves was found with summer peaks shifted towards earlier values of Universal Time. The same phase separation was seen independently in satellite data showing the variation of diurnal tropical convection and this strongly suggests that a global signal has been measured.

Averages of the diurnal variation of atmospheric current density were obtained for only two seasons. Amplitude ratios were only slightly higher than those of the electric field and still within appropriate ranges. The average percentage change between fall and winter matched closely that of the electric field. Once problems from local weather perturbations are surmounted, a complete and high quality set of Carnegie curves can be obtained.

A liberal data selection criterion was used, in which any smoothly varying peak under approximately 400 V/m or 2 x 10^{-11} A/m^2 was included in the Carnegie curve averages. High standard deviation values resulted, which are a measure of the weather system's natural variability, but no problems could be found with the averages in terms of peak phases and signal strength. Based on this analysis, it appears that the standard deviation is approximately 90% of the calculated average values.

Further studies of the data are needed. Over a year and half's worth of measurements need to be processed and quality data added to the seasonal averages. Inclusion of just a few good weeks of current data during the austral winter would probably be sufficient to gain an understanding of seasonal trends and make comparisons
with those of the electric field. Interannual changes should be documented with the intention of estimating any effects from global warming. Local weather data should be used to develop a general criteria for which globally representative measurements can be obtained. The latter could help automate data processing of any future experiments of this kind. Further analysis may reveal regular magnetospheric influences on the data. Finally, it would be of interest to use the subset of data that includes both the electric field and current density to calculate the diurnal variation in atmospheric conductivity.
REFERENCES


APPENDIX

South Pole Array 1 and 2

Difference Current, A m$^{-2}$

UT, 18 January 1991 to 19 January 1991