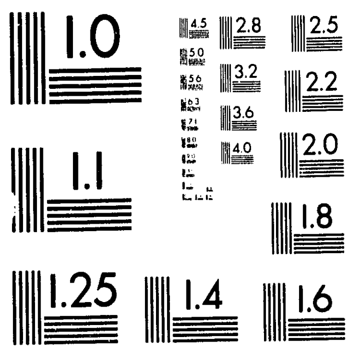
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Lightning, Atmospheric Electricity and Climate Change

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LIGHTNING, ATMOSPHERIC ELECTRICITY AND CLIMATE CHANGE

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1. INTRODUCTION

Temperature records indicate that a global warming of 0.5-0.7°C has occurred over the past century (Hansen and Lebedeff, 1987). Whether this trend is a result of increased trace gas concentrations in the atmosphere, or simply a result of natural variability, is still not known. These temperature trends are derived from thousands of observations worldwide. However, these observations are concentrated largely over continental areas, and then mainly in the northern hemisphere's populated regions. This northern hemisphere continental bias results in large uncertainties in estimates of global temperature trends.

Due to the increasing evidence that the present buildup of greenhouse gases in the atmosphere may result in an additional global warming of 1-5°C by the year 2050 (IPCC, 1990), it is increasingly important to find alternative methods to monitor fluctuations in global surface temperatures. As shown by two recent studies (Williams, 1992; Price, 1993), the global atmospheric electric circuit may provide a promising alternative for monitoring future climate change.

2. SURFACE TEMPERATURES VS. GLOBAL LIGHTNING FREQUENCIES

When looking at trends in global surface temperatures, it is not always vital to know the absolute temperatures, but rather the magnitude and sign of the temperature anomalies. For this reason satellite surface temperature measurements can often provide a valuable substitute for the true surface air temperatures. Two independent satellite temperature data sets were used in this study, each providing skin temperatures of the earth in clear sky regions. The skin temperature corresponds to the observed clear sky infrared radiances (brightness temperatures), which are different to the observed air temperature measured a few feet above the ground. Unlike the surface station temperature data, the satellite data is not biased to northern hemisphere continental regions. The temperature data sets used are:

i) ISCCP: This satellite data set supplies surface (skin) temperatures obtained from the International Satellite Cloud Climatology Project (ISCCP) (Rossow et al., 1988). The surface temperatures used are only for non-cloudy pixels, determined using a cloud detection algorithm (Rossow and Garder, 1994). Approximately 50% of the tropical land area can be observed under clear sky conditions. In the summer hemisphere this drops to approximately 40%. The original satellite radiance data represent measurements over fields of view ranging from 4-8 km in size; however, the ISCCP data are sampled to a spacing of about 25-30 km. The data are collected at a time resolution of three hours, supplying eight global data sets every day from July 1983 to December 1990.

ii) TOVS: This surface temperature data set is obtained from the analysis of data from the TIROS Operational Vertical Sounder (TOVS) system, flown on the NOAA Operational Polar Orbiting Satellite series. To retrieve surface (skin) temperatures the High Resolution Infrared Radiation Sounder (HIRS/2) instrument is used, which has a field of view of approximately 17km at nadir (Kidwell, 1986). As with the ISCCP data, the TOVS surface temperatures are determined from the blackbody radiances in clear sky regions only. Only one global data set is available each day.

Due to the limited availability of global lightning observations, a parameterization to simulate global lightning distributions and frequencies has been developed (Price and Rind, 1992a), using readily available satellite cloud data from the International Satellite Cloud Climatology Project (ISCCP) data set (Rossow et al., 1988). The height of deep convective clouds (H) is the key parameter in the parameterization, with two formulations used: one for continental thunderstorms (flash frequency$\approx H^{4.9}$) and one for oceanic thunderstorms (flash frequency$\approx H^{1.7}$). Deep convective clouds in the ISCCP data set are defined as having optical depths greater than 23 and cloud top pressures below 440mb. The lightning index is therefore also an indicator of the intensity and frequency of deep convection. The link between deep convection and the global electric circuit has been previously suggested by Markson (1986). The calculation of global lightning distributions using ISCCP data is available

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every three hours from July 1983 to December 1990 (Price and Rind, 1992a; 1992b).

2.1 *Diurnal Variations*

As far back as the 1920's the atmospheric global electrical circuit was observed to have a unique diurnal cycle (Mauchly, 1923). Thousands of observations made during the cruise of the Carnegie research vessel show that the average variation of the surface potential gradient over the world's oceans has a maximum at 1830 UT and a minimum at 0230 UT (Whipple, 1929).

The diurnal temperature variations, derived from the ISCCP data, for tropical temperatures (land and ocean) and global temperatures (land and ocean) are presented in Figure 1. The temperature curves are averages of 365 daily curves during 1990. The Carnegie curve is presented for comparison. The maximum surface temperatures occur close to 1200 UT while the minimum values occur around 0000 UT. The temperature maxima occur approximately six hours before the peak in the Carnegie curve, while the minimum temperatures occur 2-3 hours before the minimum in the Carnegie curve. The time lag between maxima is due to the time needed for the adjustment of the boundary layer to temperature perturbations, followed by the development of thunderstorms. In addition, observations show that large conduction currents can flow in the decaying stages of thunderstorms, when lightning rates are low (Livingston and Krider, 1978). Therefore, it is not surprising that there is a six hour lag between peak surface temperatures and peak potential gradients at the surface. The lag between minima is probably due to the time needed for air temperatures in the boundary layer to adjust to the minimum skin temperatures.

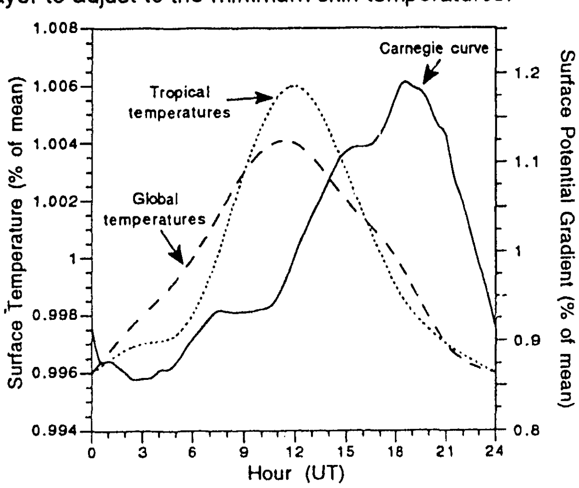

Figure 1. Normalized annual mean diurnal variations of ISCCP surface (skin) temperature for the tropics (±25° land and ocean), and for the globe (land and ocean). The Carnegie curve is shown for comparison (solid line).

It is important to note the amplitude range of the temperature curves (Figures 1). Unlike the 35% variation of the Carnegie curve about the mean, the temperature curves show 1% (tropics) and 0.8% (global) variations about the mean. This implies that if the diurnal temperature variations are related to global thunderstorm activity, and the global electrical circuit, small changes in surface temperatures will result in large responses in the global electric circuit.

2.2 *Seasonal Variations*

To see how seasonal variations in temperature are related to the global electric circuit, the two satellite temperature data sets were analysed for the year of 1990, in conjunction with the simulated global lightning frequencies for the same period. Both temperature and lightning data were sampled at 1500 LST (local standard time) around the world, to remove the diurnal cycle from the data sets. This is also the time closest to the peak lightning activity.

Figure 2 shows the relationship between the global lightning frequencies and the clear sky surface temperatures (60°N-60°S) averaged over consecutive 15-day periods during 1990, using a) ISCCP and b) TOVS temperatures. The arrangement of these points for the annual cycle is repeatable from year to year, with the largest surface temperatures and lightning frequencies occurring during the northern hemisphere summer. It is interesting that the linear regressions in Figure 2 have approximately the same sensitivities and explain similar amounts of the variance. The sensitivities of the correlations imply that a one percent increase in surface temperatures results in a 16-22% increase in global lightning frequencies, similar to what is found from climate model predictions (Price and Rind, 1994).

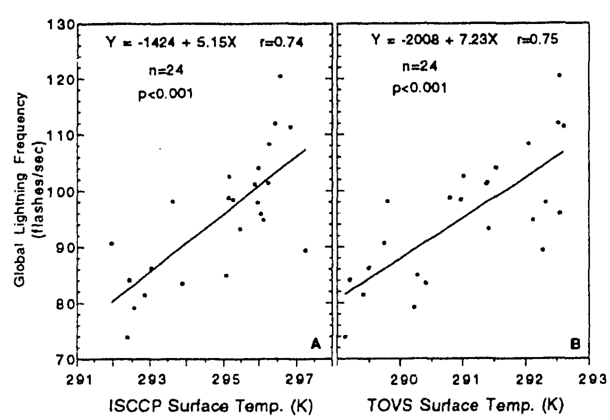

Figure 2. Relationship between 15-day global mean lightning frequencies and clear sky surface temperatures from a) ISCCP and b) TOVS, during 1990.

2.3 *Interannual Variations*

Since temperature variations on seasonal time scales are different in nature to those on interannual time scales, the relationship between global lightning activity and surface temperatures (60°N-60°S) for eight consecutive Julys (1983-1990) is considered (Figure 3). Once again the data were sampled at 1500 LST to remove the diurnal cycle. The interannual variations in global lightning activity are positively correlated with surface temperatures. However, due to the small number of data points (n=8) the correlation is only significant at the 90% level. Nevertheless, the sensitivity of the interannual global lightning frequencies to changes in surface temperatures is very similar to those found for the seasonal variations.

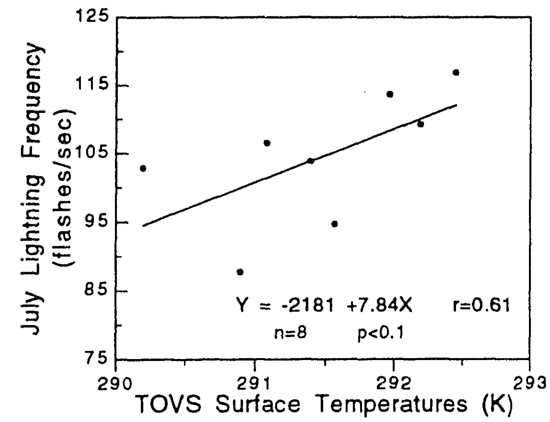

Figure 3. Relationship between simulated global lightning frequencies and TOVS global surface temperatures for eight consecutive Julys (1983-1990).

The correlation coefficient in Figure 4 implies that this global lightning index explains approximately 35% of the interannual global surface temperature variability. It is believed that if the actual lightning frequencies were used, and not an empirically based parameterization, and if surface temperature data in the regions of deep convection (rather than clear sky) had been available, the correlation coefficient would have been larger. Furthermore, since lightning is only a partial contributor to the ionospheric potential, it is likely that ionospheric potential measurements would be better correlated with surface temperatures.

3. GLOBAL LIGHTNING FREQUENCIES VS. IONOSPHERIC POTENTIAL

The ionospheric potential (V_I) is controlled by the intensity of electric currents flowing to and from the earth in regions of thunderstorm activity. Three main processes govern the intensity of these currents: i) Cloud-to-ground lightning that brings negative charge from the cloud to the ground; ii) Point discharge and conduction currents from pointed objects such as trees and buildings. Strong electric fields in regions of thunderstorms result in these objects going into corona, or point discharge. It has been suggested that this mechanism is the dominant charging mechanism for the earth's surface (Wormell, 1930; Williams and Heckman, 1993); iii) Precipitation tends to reduce the effects of point discharge currents by scavenging some of the upward-moving positive ions and returning them to the earth.

To investigate the relationship between ionospheric potential and global lightning frequencies, a comparison was made between the parameterized global lightning frequencies and 29 observed values of ionospheric potential (R. Markson, personal communication). The V_I observations were obtained on 29 different days between July 1983 and December 1990. The observations were sampled at different universal times and at different locations (New Hampshire, New Mexico, Bahamas, Christmas Island, Hawaii and Massachusetts). Some of the V_I data were obtained from aircraft measurements, while some was obtained using balloon borne electric field instrumentation.

The parameterized global lightning frequencies used the ISCCP observed cloud distributions available for the same 29 days. Since the ISCCP cloud detection algorithm uses optical depth values to determine the presence of convective clouds, the parameterized lightning values are available only for daylight hours, unlike the ionospheric potential measurements that are taken at a specific UT, integrating both day and night hemispheres. The correlation between the observed V_I measurements, at a specific UT, and the simulated global lightning frequencies, at 1500LST, is shown in Figure 4.

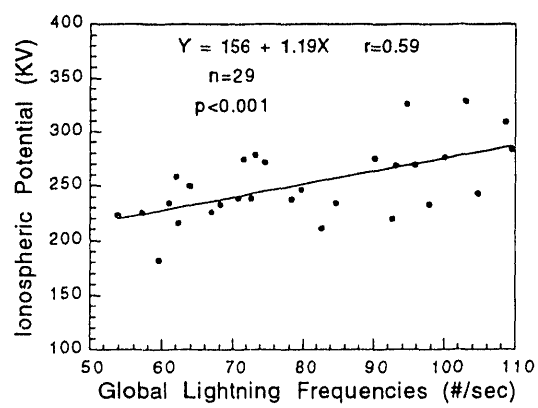

Figure 4. Relationship between 29 independently observed values of V_I and the corresponding globally integrated lightning frequency index.

A linear relationship exists between the simulated global lightning frequencies and the observed values of ionospheric potential. Considering that the lightning calculations are based on a simple parameterization, together with the fact that the lightning is calculated at the same local time around the globe, while the V_I measurements represent different local times at different locations, it is surprising how well these two parameters are correlated.

The relationship implies that this global lightning index can explain 35% of the variability in V_I. This would be expected to increase if actual observed lightning data were correlated with V_I and not a parameterized value. With 29 pairs of data points this correlation is highly significant at the 99.9% level. The slope of the relationship is close to unity, implying that global lightning frequencies and the ionospheric potential vary on a one-to-one basis. The intercept of this regression line implies that if all lightning activity around the globe was to cease, there would still exist an ionospheric potential of 159KV. This implies that point discharge may be the major contributor to the global electric circuit, as suggested by Wormell (1930) and Williams and Heckman (1993). This value of 159KV is very similar to that found by Williams (1992) when values of the Schumann Resonance, another global lightning index, were correlated with V_I observations.

These results imply that the previous relationships, showing a 5-10% increase in global lightning frequencies for every 1°K of global warming, could be translated into a 5-10KV increase in ionospheric potential for each 1°K of warming. Based on the IPCC (1990) report, this would imply a possible 5-50KV increase in the mean ionospheric potential by the middle of the next century.

4. FUTURE CLIMATE CHANGE PREDICTIONS

In order to study future implications of climate change on global lightning frequencies and the global electric circuit, the Goddard Institute for Space Studies (GISS) general circulation model (GCM) has been utilized (Hansen et al., 1983).

The lightning calculations in the model use exactly the same formulations as used with the ISCCP data to calculate the global distribution and frequencies of lightning activity. However, instead of observed convective cloud distributions, the model calculates the convective cloud distributions using a penetrative convective scheme, based on parcel theory. The model's lightning climatology for the present climate is extensively discussed by Price and Rind (1993). The model's spatial and temporal lightning distributions show good agreement with the limited global observations. The annual mean climatology of the model has a global flash frequency of 77 flashes/sec, with the maximum lightning activity occurring during the northern hemisphere summer. Cloud-to-ground lightning makes up approximately 25% of the total global lightning.

To investigate the possible effect of future climate change on global lightning frequencies, the concentration of CO_2 in the model's atmosphere was doubled from that in the control climate. This increase in CO_2 results in an equilibrium global surface warming of 4.2°C. The corresponding annual mean changes in global lightning activity are shown in Figure 5. The largest absolute increases occur in the tropical continental regions, although the percentage increases from the control climate are fairly uniform with latitude. Globally averaged, an increase of 30% in lightning frequencies occurs, implying an increase of 7% in global lightning frequencies for every 1°C of warming. This is in good agreement with the sensitivities found from observations (section 2 above). Although the global increase in lightning frequencies is approximately 30% for a $2xCO_2$ atmosphere, the local increases can be much larger. Some regions have increases of more than 150%. Decreases in lightning activity are also found in the warmer climate due to increases in large scale subsidence in some regions, resulting from the increased convection in other regions. More details of this climate change modeling experiment are presented by Price and Rind (1994).

5. CONCLUSIONS AND DISCUSSION

Observations and model calculations have been presented showing that global lightning frequencies are non-linearly related to global surface temperatures. In addition, evidence has been presented to show that global lightning frequencies are linearly proportional to the ionospheric potential. This implies that the magnitude of the ionospheric potential is probably well correlated with surface temperature fluctuations.

Both empirical and model studies show that a 1°C increase in global surface temperatures should result in a 10KV order of magnitude increase in ionospheric potential. Since ionospheric potential needs only one reliable measurement to monitor global thunderstorm activity, and hence surface temperatures, this method of monitoring global fluctuations in surface temperatures may be a valuable tool for tracking future climate change (Markson, 1992).

Although this method of monitoring climate change sounds promising, it does have a few limitations. The ionospheric potential signal originates in areas of thunderstorm activity. These regions are mainly tropical continental landmasses. Therefore, V_I may not be

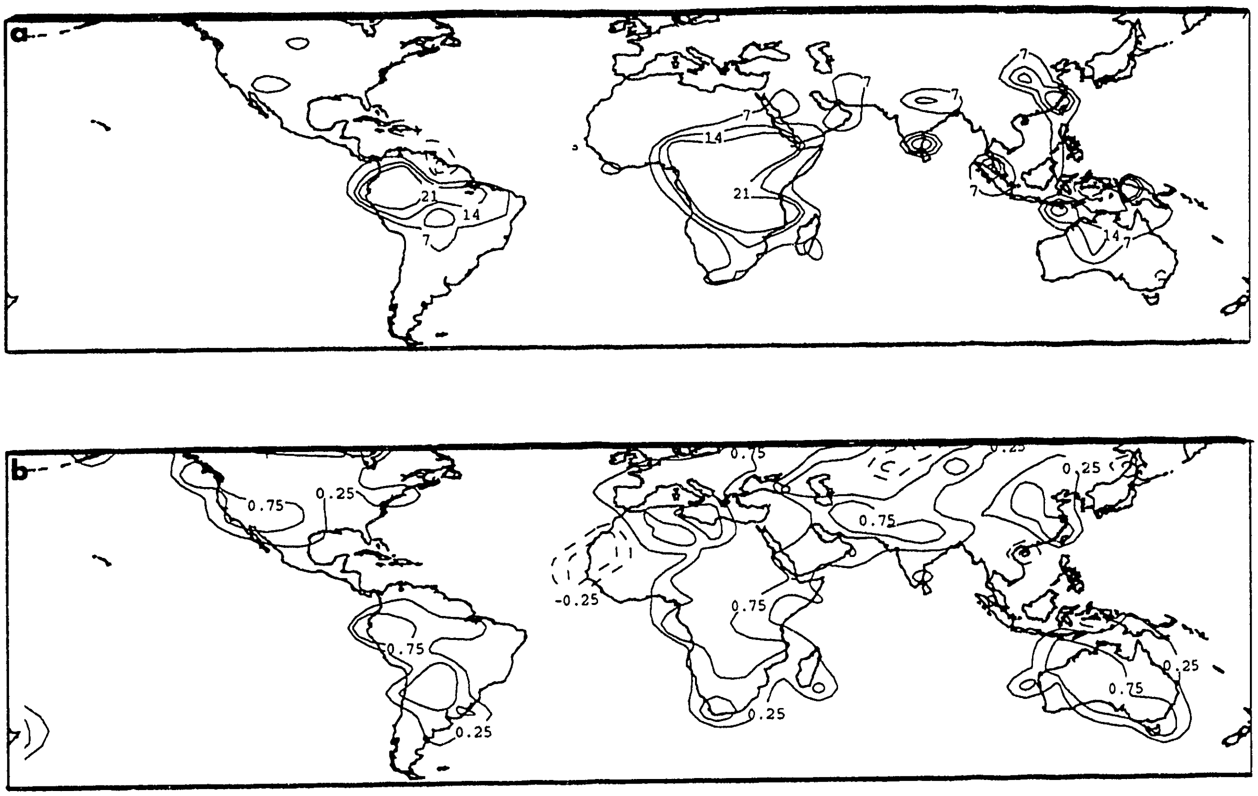

Figure 5. a) Absolute changes (contours range from -21 to 21 flashes/min at intervals of 7), and b) Percentage changes (contours range from -0.75 to 0.75 at intervals of 0.5) in lightning frequencies in a $2xCO_2$ climate, as calculated using the GISS GCM. Solid/dashes contours represent increases/decreases in lightning frequencies.

sensitive to changes in ocean temperatures, midlatitude temperatures (land and ocean) and high latitude temperatures. This is unfortunate, given that climate models predict the largest increases in temperature to occur in high latitudes, due to the snow/ice albedo feedback. Furthermore, V_I depends on the columnar resistance of the atmosphere. If the conductivity of the atmosphere changes as a result of climate change itself, the V_I observations will not depend only on thunderstorm activity. Changes in conductivity could arise from changes in the atmospheric loading of aerosols, ions and water vapour.

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