Solar Modulation of Atmospheric Electrification Through Variation of the Conductivity Over Thunderstorms

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There have been numerous reports indicating that solar activity somehow modulates Earth's electric field and thunderstorm activity. This paper suggests that variations of the current in the global atmospheric electrical circuit can be produced through regulation of the resistance between the tops of thunderclouds and the ionosphere. Long- and short-term changes in the conductivity of this region occur due to changes in the ionization rate resulting from solar activity. Previous suggestions that the phenomena might be due to conductivity variations in the fair weather part of the world or an influx of space charge to the upper atmosphere are discussed and considered unlikely. It might be possible to test the proposed mechanism by measuring the temporal variation of the ionospheric potential during disturbed solar periods. Another approach would be to measure simultaneously the variation in ionization rate and electric current over thunderstorms. Several ways in which changes in atmospheric electrification might influence other meteorological phenomena are mentioned.

Statistical evidence has been accumulating suggesting that the electrification of the atmosphere is controlled to some extent by solar activity. The findings can be divided into two categories:

(1) Long-term (secular) effects in which worldwide thunderstorm activity, as inferred by the ionospheric potential and air/Earth current density in the upper atmosphere, varies inversely with solar activity over a solar cycle.
(2) Short-term effects characterized by increases in potential gradient, air/Earth current density, and thunderstorm activity for several days following solar flares.

It has been difficult to explain how extraterrestrial radiation could modulate atmospheric electrification or the electrical elements near the ground inasmuch as the radiation variations are confined to the upper atmosphere (Markson, 1971).

This paper suggests that solar controlled conductivity variations in the stratosphere could cause the observed atmospheric electrical effects through control of electrical currents flowing between the tops of thunderclouds and the ionosphere.

It will be helpful in the discussion to follow to review the classical picture of atmospheric electricity. The basis of the proposed mechanism is contained in the "global circuit" first defined by Wilson (1920). Figure 1 depicts this dc series circuit. The generator is worldwide thunderstorm activity. There are on the order of 2000 thunderstorms at a given time producing currents averaging about 1 A per storm. This generator maintains the ionospheric potential V_I at approximately 250 kV relative to Earth. Local generators, which contribute minimally to the global circuit current, are also shown. Thunderstorms can be considered as dipoles with the positive pole at the top. Positive charge leaves Earth under thunderstorms due to corona discharge and cloud-to-ground lightning. It is trans-

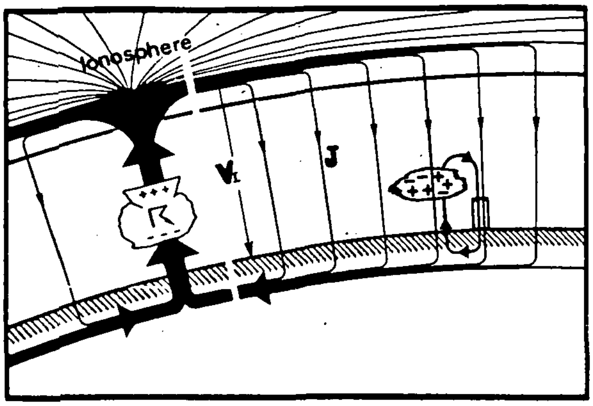

FIGURE 1.—The basic elements of the atmospheric electrical global circuit; thunderstorms, the ionopheric potential, and the fair weather conduction current. (After Mühleisen and Fischer, 1967.)

ported up to the cloudbase and through the cloud by a combination of lightning, precipitation, convection, and conduction currents. The relative importance of each is subject to debate. From the cloud tops, it flows upward by conduction to the ionosphere where it rapidly becomes distributed laterally around Earth. In nonthunderstorm regions, over 99 percent of Earth's surface, the charge returns to the ground in the air/Earth conduction current. The current density J is about 3×10^{-12} A · m^{-2}. Because high conductivity exists in the upper atmosphere, the region at a height of about 60 km, called the "ionosphere" for our purposes, can be considered an equipotential surface and the outer conductor of a capacitor formed by two concentric spherical shells, the inner conductor being Earth. Between the conductors, the atmosphere constitutes a leaky dielectric in which conductivity increases approximately exponentially with height. Conduction currents can flow through the atmosphere because ions are present. The ionizing radiation is mostly galactic cosmic radiation supplemented at times by solar cosmic radiation and near the ground by radioactive gases and emanations from the soil.

The ionospheric potential is a good measure of worldwide thunderstorm activity and the electrification of the atmosphere.

PROPOSED MECHANISM

Because of variations in solar activity, conductivity variations occur in one element of the global circuit which, containing most of the total circuit resistance, would exert strong control over the global circuit current. This element is the path between the tops of thunderclouds and the ionosphere. Thunderstorm clouds generally extend to altitudes in the 10- to 20-km height range. Conductivity variations are sufficiently large in the environment of the tops of thunderclouds that global electrification should be affected.

Long-term conductivity variations at these altitudes through a sunspot cycle, caused by changes in galactic cosmic radiation, are on the order of a few tens of percent (Dubs et al., 1965). However following solar flares, solar corpuscular radiation can cause short-term increases in conductivity to three times the normal value (Hake, Pierce, and Viezee, 1973).

The more the circuit resistance is concentrated in the element above thunderstorms, the better the mechanism will work. Dolezalek's (1972) estimates for a typical thunderstorm of area 2×10^8 m^2 with a cloudbase at 2 km and top at 12 km will be used. The resistance between the top and the upper atmosphere is 2×10^7 Ω. This gives 10^4 Ω for 2000 storms (parallel) constituting the global generator. Under a thunderstorm the estimated resistance is 3×10^5 Ω, or 150 Ω for the global generator. This value was derived by increasing the normal fair weather conductivity by three orders of magnitude because of the presence of point discharge ions. With an ionospheric potential of 250 kV and an air/Earth current density of 3×10^{-12} A · m^{-2}, the resistance of the fair weather return path over the 5×10^{14} m^2 area of Earth is 160 Ω.

Thus, the resistance over the generator is two orders of magnitude larger than the resistance in the other parts of the circuit external to the generator. The thunderstorm's resistance given in the reference was 1.5×10^5 Ω, or 750 Ω for the global generator; but this estimate was intentionally conservative. However, it is questionable whether the ohmic concepts of conductivity and resistance should be applied in more than a qualitative manner to a thundercloud, or the region beneath it, because the flow of charge in these regions depends on many variables other than just the electric field intensity and is not linearly related to the latter (Vonnegut, 1963).

While it is realized that conductivities within and beneath thunderclouds are not accurately known, it seems reasonable to assume a large portion of the total circuit resistance lies above thunderstorms. It is suggested that this region in effect is a variable resistor and can function as a valve controlling current flow in the global circuit. Solar controlled changes in this resistance should therefore regulate the ionospheric potential and the electrification of the atmosphere. The mechanism should be more effective with higher thunderstorms because solar-controlled conductivity variations increase with altitude. However, detailed predictions cannot be made until we have more information about thunderstorm electrification processes.

The question of how an increased flow of charge to the thunderstorm might influence its function as a generator must be considered. Whether this will enhance or diminish the storm's ability to separate charge depends on the electrification mechanism. There is no consensus on this basic problem of atmospheric electricity, and many theories exist. If convection is important, in accordance with the models of Grenet (1947), Vonnegut (1955), or Wilson (1956), the electrification process will be enhanced. If increased currents are dissipative, as stated by Schonland (1932), in accordance with the numerous models where charged particles are produced by hydrometeor interactions (Chalmers, 1967), the generator could weaken.

Finally, we should consider the possible influence of the fair weather field on thunderstorm formation. Several thunderstorm theories (Elster and Geitel, 1885; Sartor, 1965; Vonnegut, 1955; Wilson, 1929) depend on polarization of cloud droplets in the fair weather field during the initial stages of electrification. Thus, a change in thunderstorm currents could lead to a corresponding variation in the number of thunderstorms. In sum, there are two possibilities for feedback in the proposed mechanism.

IONIZING RADIATION

Solar corpuscular particles are more likely to influence atmospheric electricity than solar electromagnetic radiation. Wave radiation with sufficient energy to ionize air molecules (for example, Lyman-alpha and X-rays) does not penetrate below 50 km (Hake, Pierce, and Viezee, 1973). To have a significant influence on the thunderstorm generator, ionizing radiation must reach altitudes below 20 km. Secondary cosmic radiation (created by solar and galactic cosmic radiation) has this property and is almost exclusively the ionizing agent from the top of the mixing layer through the stratosphere. Solar corpuscular radiation also plays a critical role in modulating the flux of galactic cosmic radiation reaching the atmosphere through variation of the screening properties of the interplanetary magnetic field (Hines et al., 1965).

Primary cosmic radiation from the galaxy and its secondary radiation are the ionizing agents in the stratosphere. There is an inverse correlation between galactic cosmic radiation and solar activity through a sunspot cycle. Although the exact cause of this is not well understood, the galactic particles apparently are magnetically deflected by kinks and irregularities in the interplanetary magnetic field (Wilcox, 1968). Therefore, the ionization of the upper atmosphere varies inversely with solar activity over a sunspot cycle. The cosmic-radiation-modulated secular variation in conductivity is minimal in the lower atmosphere but becomes significant at higher altitudes. Comparing ion production rates at solar maximum (cosmic ray minimum) in 1958 to solar minimum (cosmic ray maximum) in 1954, there was a 25-percent increase at 10 km, a 50-percent increase at 15 km, and an 80-percent increase at 20 km (Dubs et al., 1965). Because conductivity is proportional to ion density, and the latter is proportional to the square root of the production rate, the conductivity increases would have been 12 percent at 10 km, 22 percent at 15 km, and 34 percent at 20 km.

However, there are short-period increases in stratospheric ionization of as much as one order of magnitude due to bursts of energetic solar particles (Hake, Pierce, and Viezee, 1973). A series of solar flares over tens of hours or several days such as might occur during a period of intense solar activity could maintain enhanced conductivity in the stratosphere over a similar period with a delay for the transit time of the particles.

ATMOSPHERIC ELECTRICAL RESPONSES TO SOLAR ACTIVITY

Secular Variations

In searching the literature, it is possible to find both positive (Bauer, 1926), negative (Rao, 1970); and null (Hogg, 1955) correlations between long-term time series comparing atmospheric electrical parameters measured on the ground and solar activity. Because atmospheric electrical data gathered at Earth's surface are sensitive to local influences, they are relatively unreliable indicators of global electrical activity compared to measurements of ionospheric potential and air/Earth current density well above Earth's surface.

An inverse relationship between ionospheric potential and long-term solar activity is suggested by figure 2. These data from Mühleisen (1969) depict the variation of ionospheric potential over a solar cycle. Similarly, an inverse correlation between air/Earth current density in the stratosphere (directly proportional to ionospheric potential) and solar activity during the period of 1965 to 1972 has been observed (D. E. Olson, personal communication, 1973). Because galactic cosmic radiation is inversely correlated with solar activity, and because this radiation is the primary source of atmospheric ionization, these findings suggest the importance of galactic cosmic radiation in modulating the intensity of the global electric generator through conductivity variations.

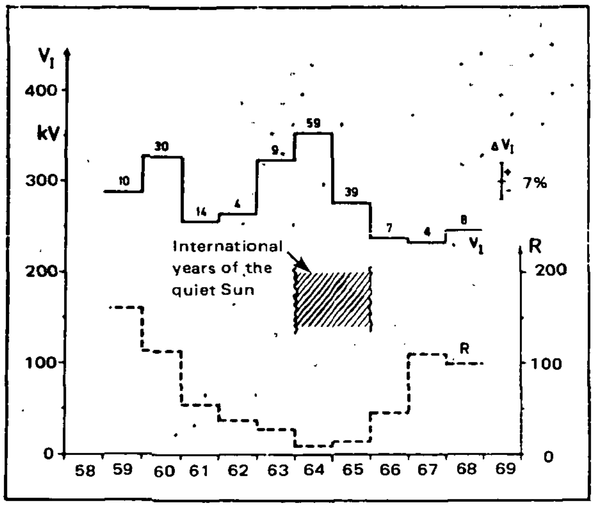

FIGURE 2.—The variation of ionospheric potential through a solar cycle; numbers on the line are total balloon soundings for the year. (After Mühleisen, 1969.)

Additional support for this conclusion is seen in Lethbridge's (1969) comparison of galactic cosmic radiation, as monitored by neutron counts at Chicago, with U.S. thunderstorm frequency. This study shows that high counts correspond to high thunderstorm frequency and low counts to low thunderstorm frequency:

Short-Term Variations

While the secular variation in solar activity seems to be inversely related to ionospheric potential, the opposite is noted for short-term variations. Increases in potential gradient and air/Earth current density on 3-km high mountains in Hawaii and Germany following solar flares have been reported by Cobb (1967) and Reiter (1960, 1969, 1971). Sao (1967) shows a correlation between 1000-MHz solar flux (a measure of solar activity) and potential gradient measured in the arctic. Bossolasco et al. (1972) report an increase in thunderstorm activity in the Mediterranean area 3 and 4 days after solar flares. These reports indicate an increase in terrestrial electrical activity apparently associated with the radiation from solar flares. There is a lag of one to several days between the occurrence of flares and the electrical effects on Earth in agreement with the time it would take solar corpuscular radiation to reach Earth.

Thus, the evidence suggests that both galactic cosmic radiation as well as solar corpuscular radiation modulate the electrification of the atmosphere. This could explain the apparent contradiction that long-term variations in global electrification appear to be inversely correlated with solar activity while short-term electrical variations are positively correlated with solar activity. If the electrical charge of the atmosphere is controlled by conductivity over thunderstorms, the variation of galactic ionizing radiation controls the secular change in atmospheric electrification, while short-term atmospheric electrical increases are due to the enhancement of conductivity caused by particles from solar flares.

DISCUSSION OF PREVIOUSLY SUGGESTED MECHANISMS

Variation of Columnar Resistance

In trying to explain how solar radiation might influence atmospheric electricity, Sao (1967) suggested that, during times of enhanced solar activity, increased ionization in the upper portion of the columnar resistance in fair weather regions would concentrate the ionosphere-to-Earth potential difference in the lower portion of the atmosphere and increase the potential gradient there. This seems unlikely. Because 90 percent of the columnar resistance lies below 10 km and 98 percent below 20 km, an increase in conductivity in the stratosphere would not significantly change the total columnar resistance and thereby the electrical conditions in the lower atmosphere. The ionizing radiation would have to penetrate to about the 3-km level, through one-third of the columnar resistance, to have an appreciable influence on atmospheric electricity through fair weather columnar resistance variations; such occurrences are rare. It would be necessary for the columnar resistance above 3 km to undergo an unrealistically large 30-percent decrease to produce a 10-percent increase in air/Earth current and potential gradient near the ground. This line of reasoning led Cole and Pierce (1965) and Cobb (1967) to speculate that because solar-induced atmospheric electrical effects in the lower atmosphere could not be caused by conductivity variations, they might be the result of an influx of space charge to the stratosphere; for example, from a stream of polar protons.

Space Charge

The ionization of the atmosphere above the mixing layer is caused by secondary cosmic radiation showers produced in the 15- to 35-km region when primary cosmic radiation in the billion-electron-volt energy range contacts air molecules. Some of the charge carried by the primary cosmic radiation is deposited in this region, and a fraction of it is carried to lower altitudes. However, the flux of galactic cosmic radiation is about 1 particle $\cdot$ cm^{-2} $\cdot$ s^{-1}. While flare-produced solar corpuscular radiation (sometimes called solar cosmic radiation) can have flux densities in the thousands, these are mostly in the low million-electron-volt energy range and would be screened by the magnetosphere from the atmosphere except in the auroral zones. As previously mentioned, some of the solar particles (mostly protons) have sufficient energy to produce an increase in stratospheric ionization of, at the most, one order of magnitude lasting a few hours (Hake, Pierce, and Viezee, 1973). This means that a maximum flux of 10 elementary charges $\cdot$ cm^{-2} $\cdot$ s^{-1} might reach the stratosphere. Because of high conductivity in the upper part of the columnar resistance, most of the incoming charge would be conducted toward the ionosphere and not significantly contribute to the air/Earth conduction current in the lower atmosphere. Considering that this current is about 1500 elementary charges $\cdot$ cm^{-2} $\cdot$ s^{-1}, the small influx of space charge to the upper atmosphere that could be carried by extraterrestrial radiation is orders of magnitude too small to influence atmospheric electricity near the ground. About 1500 positive elementary charges $\cdot$ cm^{-2} $\cdot$ s^{-1} would have to reach 10 km to cause a 10-percent increase in the fair weather conduction current and potential gradient in the lower atmosphere.

TESTING THE MODEL

Measuring the Variation of Ionospheric Potential

It may be possible to identify the extraterrestrial particles and mechanism(s) that modulate atmospheric electricity by correlating the variation of ionospheric potential, a measure of the intensity of the global generator, with geophysical parameters. Reiter's (1972) attempt to do this with data obtained on a 3-km high mountain indicates that even under the most ideal circumstances, it is very difficult with electrical data taken at Earth's surface. Kasemir (1972) reports that with measurements made on a ship in mid-ocean (the cleanest air possible), at least 1 week's data were necessary for statistical averaging to detect the well-known diurnal variation that follows worldwide thunderstorm activity. The noise in ground-level measurements is caused by variations in columnar resistance plus local conductivity and space charge fluctuations. These are due to many natural and manmade elements such as radioactive gases, condensation nuclei, and pollution transported by the wind and convection. An additional limitation with ground data is that the response time of the local electric field, here defined as the time to reach 90 percent of the new equilibrium value, is about 30 min.

Most of the noise in such measurements can be eliminated by making them from an airplane flying at constant altitude well above the mixing layer under selected meteorological conditions over the ocean (Anderson, 1969; Markson and Vonnegut, 1971). With this technique, the diurnal variation in potential gradient and air/Earth current density is seen in just 1 day's record, and simultaneous measurements made from two aircraft 7000 km apart showed high correlation (Dolezalek, 1972). These results demonstrate the possibility of recording continuously the temporal variation of ionospheric potential. The temporal resolution is determined by the altitude of the measurement; at airplane flight levels the response time is less than 1 min.

Airplane Measurements

It may be possible to test the proposed mechanism in two different ways utilizing atmospheric electrical measurements from aircraft platforms. The first approach would be to measure the variation of ionospheric potential and ionization rate at one location and altitude in fair weather regions over extended periods following solar flares. This would allow comparison of global electrification with solar-controlled geophysical events. An increase in ionospheric potential at the time of a magnetic storm or polar cap absorption event would suggest the importance of solar corpuscular radiation. A decrease coincident with a Forbush decrease (in galactic cosmic radiation) would point to this as the cause. If the measurements were made at a location reached by ionizing radiation, increases in the ionization rate might accompany increases in ionospheric potential. However, increases in ionospheric potential alone might occur if the radiation enters the atmosphere in an area remote from the aircraft where it increases thunderstorm currents. The correlation of stratospheric ionization and ionospheric potential may only be observable at low latitudes because most of the world's thunderstorms, particularly the largest ones, reside in the tropics, and magnetic screening allows only the most energetic cosmic radiation access to this region.

It also would be of interest to examine the variation of ionospheric potential as a function of Earth's position in a solar magnetic sector. Markson (1971) suggested because the sector structure of the solar magnetic field controls extraterrestrial particles, the analysis of extraterrestrial effects on weather should consider Earth's position in a solar sector. Using this approach, a relationship was found between solar sector position and thunderstorms in the United States. Subsequently, Wilcox et al. (1973) found striking evidence for atmospheric vorticity relating to Earth's solar sector position. Solar and galactic cosmic radiation reaching Earth is a function of Earth's position in a solar sector (Wilcox, 1968).

A second approach would be to measure electrical currents and ion production rates above thunderstorms. If the model is correct, thunderstorm currents for comparable storms (height, depth, and location) would be positively correlated with ionization. Comparisons between solar maximums versus solar minimum would be of considerable interest; if conductivity controls thunderstorm currents, they should be greater at solar minimum.

It is recognized that making such an evaluation may be difficult because of noise in the data. Previous investigators have observed considerable structure in flights across the tops of thunderclouds (Gish and Wait, 1950; Stergis et al., 1957). Many measurements may be required for statistical evaluation. The noise may be lessened by using a slow-flying airplane capable of remaining over one thunderstorm location—preferably a turret where the masking effect of the screening layer is minimized (Vonnegut et al., 1966). This would have the additional advantage of minimizing variations due to changes in the aircraft's position relative to charge in the thunderstorm, thus allowing the temporal variation to be observed better. If the noise is not too great, measurements made at judicious times after solar flares may "catch" the arrival of ionizing radiation for comparison with the thunderstorm current.

THE INFLUENCE OF ATMOSPHERIC ELECTRIFICATION ON METEOROLOGY

As previously discussed, a variation in the global circuit current would be expected to affect the electrification of the thunderstorm generator as a function of the charging mechanism. Changes in electric field intensity could influence microphysical processes within a thundercloud. Vonnegut (1963) has assembled from the literature several different ways in which precipitation formation and cloud dynamics might be affected.

It is difficult to estimate the influence of thunderstorm activity on synoptic meteorology, but several large-scale physical processes occur that could have consequences in atmospheric dynamics. Thunderstorms transport momentum, heat, and water from the lower atmosphere to the stratosphere. Ice crystals from their tops can form extensive cirruslike cloud shields that would modulate radiational heating.

Variations in solar activity controlling the weather through modulation of thunderstorm activity would be important to the extent that thunderstorms are an important part of Earth's weather.

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DISCUSSION

DESSLER: Would the fair weather electric field at the surface of Earth (in terms of your model) be maximum at sunspot maximum? The way you have it now, the total potential is minimum at sunspot maximum, is that correct?

MARKSON: The ionospheric potential?

DESSLER: Relative to Earth, is the minimum at sunspot maximum?

MARKSON: That is correct.

DESSLER: What is the fair weather electric field in volts per meter at Earth's surface?

MARKSON: This is also essentially proportional to ionospheric potential.

DESSLER: This would not necessarily be true. If you are lowering the effective height of the ionosphere, which I understand you are doing, then it could go the other way.

MARKSON: Assuming I maintain the same kind of conductivity distribution in both cases (solar maximum and minimum), the potential gradient near Earth would be less when the ionospheric potential is less.

DESSLER: I thought you were changing the conductivity distribution.

MARKSON: No. The point is that the big variations occur in the 10- to 20-km region. This increases the current. If you have a thunderstorm model in which enhanced current in the external circuit does not drain the thunderstorm generator and if you can maintain its potential, the lowering of resistance above the thunderstorm would increase current flow to the upper atmosphere and thus raise the ionospheric potential and potential gradient in the lower atmosphere. According to several thunderstorm theories, an increase in fair weather potential gradient would enhance thunderstorm activity.