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Solar Wind Control of the Earth's Electric Field

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The possible influence of variable solar activity on weather and climate has attracted increasing interest in recent years (1). Several factors have contributed to this. We have learned a great deal about solar variability and the magnetosphere. Coronal holes, the solar wind, and the interplanetary magnetic field have been discovered. With the rapid development of space and solar physics, and because of the great potential importance to society, more researchers are starting to consider how solar variability and solar modulation of the interplanetary medium and magnetosphere might provide new inputs to meteorology. However, the mechanism or mechanisms by which solar variability may be influencing weather remain a mystery.

Summary. The sun-weather problem is placed within an electrical framework subject to experimental investigation. An explanation is suggested for how solar variability modulates the earth's electric field. The solar wind velocity is inversely correlated with the electrical potential of the ionosphere, a measure of the overall intensity of the earth's fair-weather atmospheric electric field. In seeking a physical cause of this relationship, galactic cosmic radiation was studied and it was also found to be inversely correlated with solar wind velocity. Thus, the earth's electric field intensity which is maintained by worldwide thunderstorm currents—a meteorological phenomenon—varies in phase with cosmic radiation. Since cosmic radiation is the primary source of atmospheric ionization, these findings support a proposed mechanism in which solar control of ionizing radiation modulates atmospheric electrification and thus possibly cloud physical processes. If the latter occurred, atmospheric energetics would be affected. Sun-weather research need no longer only consist of statistical correlations; an experimental approach is described. Establishment of a proposed geoelectric index would add a new dimension to solar-terrestrial studies.

Statistical evidence accumulated during the last decade indicates that around the time the earth crosses magnetic discontinuities in the interplanetary magnetic field (IMF), there appear to be significant variations in certain meteorological parameters. However, it is unlikely that these discontinuities, which are called magnetic sector boundaries, can themselves directly affect the weather, as they are merely indicators of the sign of the IMF. Since the IMF is maintained and structured by the solar wind, we have examined variations in solar wind velocity in relation to atmospheric electricity. In this article evidence is reported linking the solar wind itself with a meteorological parameter. It is concluded that solar modulation of the flux of ionizing radiation to the atmosphere is responsible for changing the intensity of the earth's fair-weather electric field, which is maintained by worldwide thunderstorm activity. Increases in stratospheric ionization or the intensity of the fair-weather electric field, or both, may affect thunderstorm electrification and thus may lead to physical effects on ice particles and droplets within clouds that could result in changes in the earth's albedo and transformations of atmospheric energy. These could affect air motions on all scales, from convective cells in clouds to the general circulation.

Inasmuch as previous investigations of sun-weather relationships have been statistical studies and correlations alone cannot prove causality, the time has come to define physical mechanisms that are subject to experimental verification. It is important to remember that a hypothesis is not a hypothesis unless it is subject to critical experiments that are capable of disproving it. In this article we suggest an experimental approach to the sun-weather problem.

Why the Current Interest in the Sun-Weather Problem?

New tools and understanding. We now have the technology to investigate sun-weather relationships. This includes unmanned satellites, manned space observatories, interplanetary space probes, atmospheric research vehicles (rockets, balloons, aircraft), new optical solar observing techniques (both from the ground and in space), radio telescopes, and upper atmosphere research radar. We have the capability of monitoring continuously the spatial and temporal variation of fundamental properties of the atmosphere: the morphology of weather systems, cloud cover, and cloud heights (2); the distributions of water vapor and liquid water (3); the electrical potential of the ionosphere (a measure of the overall intensity of the earth's fair-weather electric field) (4-6); and worldwide lightning activity (a measure of thunderstorm activity) (7, 8). These terrestrial variations can be related to solar

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Fig. 1. X-ray photograph of the sun taken from Skylab on 1 June 1973, showing a well-defined coronal hole (dark area) where magnetic field lines extend into space and thus allow fast solar wind particles (high-speed streams) to propagate into the interplanetary medium. The bright plage regions and magnetic structure defined by the closed loops are also seen. [Courtesy of A. S. Krieger and R. Haggerty, American Science and Engineering, Cambridge, Mass., and NASA]

parameters and conditions in the interplanetary medium, magnetosphere, and ionosphere, which are observed routinely. The large quantities of data involved can be handled rapidly because of the availability of computers and microprocessors.

This technology has given us new understanding of the sun, interplanetary space, and the atmosphere. Coronal holes were discovered (*9*) through x-ray observations from Skylab. We have learned that the sun's magnetic structure, most easily depicted in photographs of coronal holes (Fig. 1), configures the interplanetary magnetic field and thus regulates the access of galactic cosmic radiation to the atmosphere. Ionization by galactic cosmic radiation is the dominant element maintaining conductivity throughout the atmosphere. The solar wind in addition controls electric fields in the magnetosphere and ionosphere. But changes in the electric fields and conductivity in the upper atmosphere have little effect on electrical conditions in the lower atmosphere, where weather occurs, because they do not appreciably influence the earth's overall fair-weather electric field.

It is a basic postulate of the classical picture of atmospheric electricity that the ionosphere is, in effect, an equipotential surface (*10, 11*) except in the auroral zone (*12, 13*). This assumption is supported by experimental evidence; the ionospheric potential has been shown to vary simultaneously at widely separated points on the earth's surface (*5*). This could not occur unless the ionosphere had the characteristics of an equipotential surface. Because we now have techniques for measuring the variation of ionospheric potential, we can monitor changes in global electrification. By correlating changes in atmospheric electricity measured well above the earth's surface with solar-controlled variables in space, it should be possible to identify the radiation and processes by which solar variability modulates atmospheric electrification (*14*). The atmospheric electrical parameters (ionospheric potential and lightning activity) can be compared with spatial and temporal changes in the atmosphere sensed from meteorological satellites (such as cloudiness, convection, water vapor, and liquid water) to study possible interactions between atmospheric electricity and weather. The fact that an atmospheric electrical sun-weather mechanism explains how solar variability might control atmospheric energetics without the need to transfer energy from the sun or upper atmosphere (*15*) has helped stimulate interest in atmospheric electricity and the sun-weather problem.

Maunder minimum and climatic change. Interest in the possibility that solar variability modulates weather has been enhanced by Eddy's rediscovery and documentation (*16*) of Maunder's finding (*17*) that the sun is not a regular and predictable environmental factor. There is evidence that sunspots, the classical indicators of solar activity, nearly disappeared for the 70 years between 1645 and 1715—the Maunder minimum—and for extended periods during earlier epochs. Possible climatic implications of such behavior follow from Eddy's report that the Maunder minimum occurred at the time of the coldest period during the Little Ice Age as well as from the correlation between solar variability and glaciation over long periods (*16*). It appears that at times solar activity can nearly disappear, and these times seem to coincide with cold periods in the earth's climate.

The 22-year solar magnetic cycle, tree rings, and drought. Numerous relationships between solar variability and weather have been reported and, although the quality of many of these studies has been criticized, as discussed by Pittock (*18*), some appear to be well done and are convincing. Climatic variation associated with the quasi-periodic solar magnetic cycle (Hale double-sunspot cycle), which averages about 22 years, has provided some of the better evidence for a sun-weather relation. Roberts (*19, 20*) summarizes several independent analyses which indicate that drought in the U.S. High Plains varies in phase with this cycle. King (*21*) refers to the double-sunspot cycle as being present in weather records from various parts of the earth. Mitchell *et al.* (*22*), in an investigation of the periodicity of drought in the United States, have examined the variation of indices derived from tree-ring records for the western United States back to A.D. 1600. They find that the 22-year cycle is the outstanding feature in the spectral analysis of their drought area indices, and furthermore the latter are locked in phase with the quasi-periodic Hale magnetic cycle.

Development of the solar sector approach. Statistical studies of sun-weather relationships go back more than a century, but, as noted by Hines (*23*), a new era was opened when the structure of the IMF was introduced to this work (*24*). In this new approach, solar magnetic sector boundary crossings were used as timing marks (key days) in statistical analysis. Using this procedure, Wilcox *et al.* (*25*) found that an aspect of atmospheric circulation, the vorticity area index developed by Roberts and Olson (*26*), appeared to decrease significantly around the time when the earth crosses a solar magnetic sector boundary. These results were confirmed by others (*27*) and have become a central issue in modern sun-weather research. Sector crossings are now routinely used as key days in statistical analysis by many investigators seeking sun-weather correlations.

In view of the current importance of the solar sector structure in this research, it is of interest to describe how this approach originated. Up to about 10 years ago, sun-weather studies had consisted mostly of correlations between some meteorological parameter and sunspot number, the occurrence of solar flares, or geomagnetic variations. However, as a result of measurements from spacecraft, a new picture of the interplanetary medium was emerging. The flux of solar particles that Parker (*28*) had predicted and named the solar wind had been measured directly. Wilcox and Ness (*29*) had discovered that the IMF was generally ordered, being divided into adjacent magnetic sectors that reverse polarity at the relatively sharp boundaries between them. Since the sun rotates about its axis (about once every 27 days), the earth periodically passes from one sector to the next. The solar-terrestrial parameters in general appeared to vary in an orderly fashion as a function of the earth's position within a sector (*30*); systematic changes occurred in the geomagnetic index, solar wind velocity and number density, and cosmic-ray rate as the sectors swept past the earth.

In 1969, one of us (R.M.) was invited to prepare a paper reviewing extraterrestrial influences on weather for a symposium on atmospheric electricity (*24*). Since the solar-controlled variables that might be influencing weather were unknown, it was decided to examine the variation of meteorological time-series as a function of the earth's position in solar sectors (*31*) by analyzing an index of U.S. thunderstorm activity compiled by Lethbridge (*32*). The results indicated that U.S. thunderstorm frequency was maximal at or shortly after times when the earth crossed from positive to negative sectors (*24*).

This article is thus a continuation of the initial work relating the interplanetary medium to weather through atmospheric electricity. While at first magnetic sector structure was used as a generalized solar-controlled variable, we now focus specifically on the solar wind.

Solar Wind and Interplanetary Medium

Solar wind. Solar activity arises from two basic properties of the sun; it is an ionized gas (a plasma), and it undergoes intense thermal convection (*33*). The combination of convection and solar rotation sets up complex cyclonic motions within the sun. Free electrons and ions in the solar plasma are organized into electric currents by the motions of the gas. These electric currents cannot be detected directly, but their accompanying magnetic fields can. Just above the visible surface of the sun (photosphere) lies an extremely hot layer, the base of the corona, which is heated by the solar gas. Because of the million-degree temperature in this region, the corona expands outward, sending a flux of electrons and

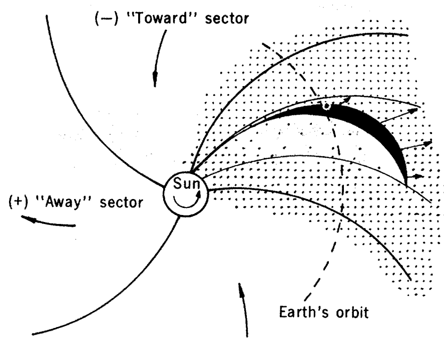


Fig. 2. Idealized magnetic blob (black region) moving radially out with velocity indicated by the arrows (*41*). Two spiral magnetic field lines bounding the blob are shown within one sector. A typical four-quadrant sector structure is also depicted. The dots (shown for one sector only) represent the conjectured cosmic-ray intensity.

protons (the solar wind) into space. The flows of these charged particles constitute electric currents, whose associated magnetic fields are the source of the IMF.

Interplanetary magnetic field. The IMF is generally of one polarity for about 1 or 2 weeks at a time and then abruptly changes sign (*34*). Within solar sectors there are solar wind streams in which for a few days the velocity of the particles increases by 50 to 100 percent. Changes in solar sector polarity occur at the minima between high-speed stream excursions (*35*). In the plane of the ecliptic, the IMF has an overall spiral configuration caused by a combination of radial particle ejection from the sun and solar rotation. It is similar to the shape of water streams emitted by a garden hose sprinkler and rotates with the sun as the water pattern rotates with the sprinkler. Recent work (*36*) has tied the morphology of the solar wind to the topology of solar magnetic fields. The x-ray photographs that revealed the coronal holes illustrate the configuration of the magnetic field near the sun at the base of the corona. The solar wind and the IMF constitute the medium linking the sun and the earth.

Solar modulation of atmospheric ionization. How does the interplanetary medium modulate electricity within the earth's atmosphere? In this regard, the important characteristic of the medium is that it controls the primary galactic cosmic radiation striking air molecules, and thereby controls the flux of secondary cosmic radiation generated in the stratosphere. The latter is generally responsible for atmospheric ionization. Within the lowest 2 kilometers of the atmosphere over land, radioactive gases from the ground are about as important as cosmic rays in ionizing the atmosphere. Cosmic radiation is augmented at times by protons from solar flares, which can penetrate down to altitudes of 20 to 30 km (*37*) and sometimes lower (*38, 39*). It is well known that solar activity can modulate the flux of galactic cosmic radiation. Forbush (*40*) found that the flux of galactic cosmic radiation reaching the earth's surface was inversely correlated with the 11-year sunspot cycle and that some solar flares cause decreases in this radiation which may last several days. These are called Forbush decreases. Barouch and Burlaga (*41*) showed that magnetic "blobs" associated with rapid increases in solar wind velocity screen cosmic rays from the earth. Figure 2 illustrates the decrease in cosmic radiation following a magnetic discontinuity corotating with the sun; a typical four-quadrant solar sector structure is also depicted.

Global Circuit and Ionospheric Potential

Wilson (*42*) realized that the earth's electric field must extend from its surface to the highly conductive ionosphere and is sustained by currents driven by thunderstorm electric fields. If global thunderstorm activity were to stop, the atmospheric electric field would decay to nearly zero within 1 hour. This does not happen because thunderstorms are always occurring at various locations over the earth's surface (*10*, pp. 297–299; *11*, vol. 2, pp. 363–370). There is a global circuit, sometimes referred to as the Wilson circuit, in which the ionosphere is maintained at a positive potential, generally in the range 200 to 300 kilovolts, relative to the earth (*5, 43*) (see Fig. 3). In the nonthunderstorm (fair-weather) portions of the atmosphere a return conduction current flows between the ionosphere and the earth, and the circuit is completed between the conducting earth and the bases of thunderclouds through a combination of conduction, convection, lightning, point discharge, and precipitation currents (*44*). The charge put on the earth by thunderstorms maintains the earth's electric field and the ionospheric potential.

A fundamental assumption of the global circuit hypothesis is that the upper atmosphere (lower ionosphere) is so highly conductive that it can be considered an equipotential surface (*10, 11, 45*). Thus its electrical potential relative to the earth should vary simultaneously all over the world—it is, in effect, the outer shell of a spherical capacitor with the highly conductive earth's surface being the inner conductor. The conduction currents can flow because the atmosphere is conductive, primarily due to ionization by galactic cosmic radiation. Electric fields in the fair-weather portion are a consequence of the vertical air-earth conduction current flowing through the finite resistance of the atmosphere. The summation of worldwide thunderstorm activity (regardless of location) is the electrical generator of the global circuit, since it is the primary agent charging the earth and the only generator connecting the earth to the upper atmosphere. Measurements of vertical currents above thunderstorms have shown their sign and magnitude to be in agreement with the global circuit hypothesis (*46*). Thus, both theory and experiment have led most scientists working in atmospheric electricity to believe that the global circuit concept is essentially correct (*10, 11, 13, 47*).

Role of Atmospheric Electricity in Sun-Weather Relationships

Advantages. In trying to understand how variable solar activity might influence weather, three basic questions can be formulated: (i) Where does the energy come from? (ii) How does the energy reach the lower atmosphere? (iii) If upper atmosphere heating is involved, how can the lower atmosphere respond as quickly as it does? In view of these questions, several factors make an atmospheric electrical mechanism attractive.

Because the energy output of the sun is essentially constant, within the 1 percent accuracy of past measurements (*48*), scientists have been skeptical about the possibility that solar activity might affect the weather, at least on a shorter than climatic time scale (*49*). Although the upper atmosphere above 120 km (the thermosphere) undergoes significant solar-controlled temperature changes, it is separated from the troposphere by two temperature inversions and essentially cut off from the weather-producing part of the atmosphere (*50*). An atmospheric electrical mechanism bypasses the problems of energy and coupling because potential energy already present in the lower atmosphere is released through electrically stimulated cloud physical processes—no upper atmosphere to lower atmosphere energy transfer is necessary. Below 25 km only one atmospheric parameter is strongly and directly controlled by solar activity; this is ionizing radiation (*51*). Two time scales and types of radiation must be considered. In the long-term (secular) time frame there is an inverse correlation between galactic cosmic radiation and the 11-year sunspot cycle, which is caused by scattering off magnetic discontinuities in the interplanetary medium. Superimposed on this long-term variation are short-period changes, lasting hours to days, in which particles associated with solar flares directly ionize the stratosphere.

Another factor favoring an atmospheric electrical mechanism is that of time delays. Some sun-weather studies show rapid atmospheric responses to solar variability; the vorticity area index (*52*) and atmospheric electric fields (*53, 54*) both increase within 1 day after solar flares. Such rapid responses are difficult to explain in terms of present heating models of atmospheric circulation, which do not include atmospheric electrical effects. Somerville *et al.* (*55*) concluded that "any causal relationship between solar variability and terrestrial weather on time scales of two weeks or less will have to rely on changes in parameters other than the solar constant or ozone amount, or on mechanisms not yet included in our model." Ramanathan (*56*) estimated that it would take 2 to 6 weeks for stratospheric temperature changes to affect dynamics in the troposphere. Schneider (*57*) pointed out that since climatic response near the earth's surface is controlled by the thermal inertia of the oceans, weather effects forced by changes in solar emission require that a solar variation must occur over a period generally much greater than 1 month. The effect of ionizing radiation on the global circuit would occur as soon as the radiation reached the atmosphere—less than 1 day after a flare for the more energetic particles (*58*). Because a rapid meteorological response is expected (a predictable time delay), it should be possible to design critical experiments to test an atmospheric electrical sun-weather mechanism. Similarly, a rapid mechanism has the potential of being useful in weather forecasting. On the other hand, it would be difficult to experimentally verify long, imprecisely known time delay mechanisms (such as might result from changes in the solar constant) that could affect weather on the climatic time scale, and these would be of limited value for forecasting.

Atmospheric electrical sun-weather mechanism. Figure 3 illustrates how solar modulation of ionizing radiation would affect the overall intensity of the earth's electric field. This is the basis of a proposed sun-weather mechanism (*15*) that operates within the framework of the global circuit. This circuit can be broken into resistive elements with worldwide thunderstorms lumped together as the global generator. Because the strongly electrified parts of thunderstorms cover less than 0.1 percent of the earth's surface, the charging current of the global generator (the sum of worldwide thunderstorm currents) flows through a relatively large resistance of about 10^5 to 10^6 ohms. The ionosphere is considered a conductor. The return flow in the fair-weather regions of the earth (most of its surface area) can be considered to be conducted through many vertical resistances in parallel (columnar resistances), and hence the overall resistance to the return flow is relatively small, about 150 ohms. The current return path to the area under the generator is through the conductive earth. Charge transfer between the earth and the bases of thunderclouds takes place because of the various currents previously enumerated. Strong electric fields under thunderclouds cause ionization around points on the earth's surface; the ions produced increase the conductivity in the subcloud region and their transport to the cloud by air motion contributes to the net current flow. It is difficult to estimate the resistance of this complex part of the circuit, and since much of the charge transfer in this region is not due to conduction it is in part non-ohmic. However, conductivity measurements beneath thunderstorms suggest an order-of-magnitude increase due to point-discharge ions (*59*), and therefore the resistance of this element of the global circuit is estimated to be 10^4 to 10^5 ohms. Thus, most of the resistance in the global circuit lies between the top of the thunderstorm generator (about 13 km at mid-latitude) and the ionosphere, a height range that is accessible to the varying component of ionizing radiation (*37, 38*) (see Fig. 3). Equivalent ionization changes above 13 km in fair-weather parts of the global circuit (including the auroral oval) would have little effect on the flow of charge in the circuit because the resistance in that element is relatively small. Resistive elements within the thunderstorm generator have not been discussed because thunderclouds are for the most part non-ohmic; ions of high mobility rapidly attach to cloud hydrometeors (raindrops and ice particles) and then they are transported by air motions and gravitation. There are no charge separation theories in which charge is carried by conduction. Therefore the concept of resistance in the thunderstorm generator has little meaning.

These considerations led to the conclusion that the resistive element over the global generator can act as a valve controlling the current flow in the global circuit (*15*). It can thus control the ionospheric potential and the intensity of the earth's electric field. If, as reported by Vonnegut *et al.* (*60*), the vertical conduction current over thunderclouds flows mostly over the turrets where an electrical screening layer is swept away by the unfolding motion of the cloud surface, then the current would flow over only a small fraction of the cloud-top area. This would increase the resistance of the charging resistor and make it even more effective as the element controlling the global circuit current. The cover photograph shows a convective turret in the structure at the top of a thunderstorm penetrating into the lower stratosphere.

Although cosmic radiation affects ionization down to the earth's surface, generally solar flare particles do not penetrate to below about 20 km (*37*). However, measurements made from balloons after solar activity indicate that solar protons on occasion can enhance conductivity by an order of magnitude down to 15 km (*38*) and the most energetic solar particles can even reach the earth's surface (*61*). Even if the ionizing radiation penetrated only into the 20- to 30-km region over thunderclouds, it would decrease the charging resistance sufficiently to increase the charging current. This would result in an amplification of fair-weather electric field intensity throughout the atmosphere—from the ionosphere to the ground and from pole to pole. For a further discussion of solar-controlled variations of atmospheric ionization, including an explanation of the fact that stratospheric variations are much greater than, more frequent than, and generally opposite in sense to ground level "Forbush decreases," see (*62*).

An amplified fair-weather electric field in the troposphere or enhanced conductivity in the lower stratosphere introduces the possibility of positive feedback through an increase in cloud electrification. According to the convective theory of thunderstorm electrification (*63*), a positive charge center initially forms within the upper portion of the cloud. One way this initial electrification might occur is through convection of fair-weather positive space charge into the cloud by the updrafts that create the cloud. Since this space charge is formed by the air-earth conduction current flowing through a medium of varying conductivity, an increase in ionospheric potential would cause more fair-weather space charge and improve the probability of initial electrification of developing cumulus clouds. In the convective mechanism, fast ions created by ionization over the developing cloud provide the source of negative charge which, attracted to the upper cloud surface by the diffuse region of positive charge within the top portion of the cloud, become attached to cloud particles at the cloud surface. They are transported to the sides of the cloud by the divergent wind field at the cloud top and are carried to its lower regions by downdrafts. Accumulation of this negative charge near the bottom of the cloud forms the negative charge center of the classic thunderstorm vertical electric dipole. According to this concept, greater ionization over the cloud top would increase the flow of charge to the cloud and enhance electrification.

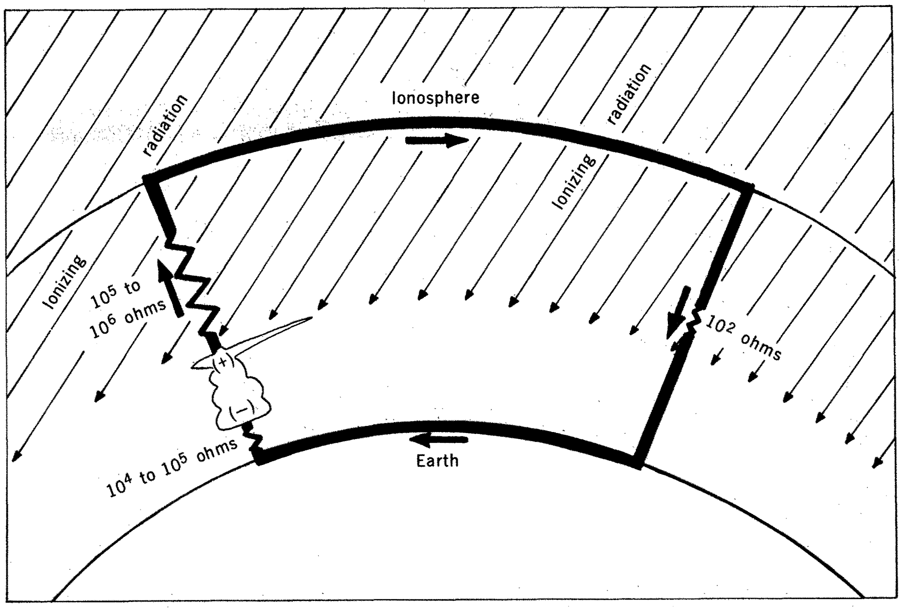


Fig. 3. Schematic of the global atmospheric electrical circuit illustrating relationships between resistive elements. The arrows indicate the accessibility of the controlling resistive element above the thunderstorm generator to the varying component of the ionizing radiation (*15*).

Other cloud-charging mechanisms have been proposed, and several of them depend on the initial electric field to polarize cloud particles during the first stages of electrification (*10*, pp. 408–411; *11*, vol. 2, pp. 527–534). Therefore, with the convective theory, or any of the inductive charging mechanisms, the ultimate electric field intensity in developing cumulus clouds depends on the initial intensity of the ambient fair-weather electric field. If any of these charging mechanisms is valid, modulation of the ionization rate in the lower stratosphere over thunderstorms would lead to positive feedback to the global circuit generator and enhance the efficiency of the process by which solar variability influences the earth's electric field. Moreover, it could provide a way for atmospheric electricity to influence atmospheric dynamics.

While the earth's electric field is a fundamental part of meteorology, atmospheric electrical changes by themselves should have no effect on dynamics unless they influence cloud physics. The effects of electric fields on cloud physical processes are not well understood, although laboratory experiments and modeling indicate they may play an important role in cloud electrification and the coalescence of droplets into raindrops or condensation of water vapor into droplets (*44*, *64*), even for electric fields of much smaller than thunderstorm intensity (*65*). If that is the case, they would affect rainfall and changes of phase of water and result in the addition of heat to the atmosphere. If rain reaches the ground before evaporating, the latent heat of condensation, which was released when the droplets grew from water vapor, is left in the atmosphere. Also, the rate of growth of ice crystals from water vapor is reported to accelerate with increasing electric field intensity (*44*, *64*).

In the realm of cloud dynamics, if water is removed as rain from convective cells in developing cumulus clouds or thunderclouds before evaporative cooling occurs, the cells would gain thermodynamic buoyancy and the cloud's circulation would be enhanced. According to some models, a few intense convective cells (called hot towers) in the intertropical convergence zone near the equator play a dominant role in driving the low-latitude Hadley cell and thus the general circulation. Cloud dynamics could also influence the formation of cloud hydrometeors and cloud electrification. Ice crystals from the tops of thunderstorms have been reported to seed lower clouds downwind, causing more rain (*66*). The cirrus "blowoff" from thunderstorm anvils produce long-lived (hours to a day or longer) cloud shields, which are spread out downwind hundreds of miles from their source regions by the upper level winds; this could be an important factor in the earth's radiation balance, since clouds dominate the albedo of the earth (*67*).

Evidence that solar variability modulates the earth's electric field. Evidence showing a rapid increase in ionospheric potential within 1 day after solar flares is seen in Fig. 4. These data, from Reiter (*53*) and Cobb (*54*), suggest a short-term direct solar influence on atmospheric electricity caused by particles from solar flares. The long-term indirect effect due to modulation of galactic cosmic radiation is illustrated through the results of the balloon sounding program of Olson (*68*), summarized in Fig. 5a. These data show a negative correlation between the fair-weather air-earth conduction current density (proportional to the ionospheric potential) and the sunspot number. The data in Fig. 5a are divided into two sets depending on whether the soundings were made in the time interval centered on the maximum or minimum of the universal time (U.T.) diurnal variation of ionospheric potential (to be discussed later). Figure 5b is a scatter diagram of the data set for 1100 to 2200 U.T. The correlation coefficient $r = -0.667$, with a confidence of 98.9 percent that the correlation is not due to chance (*69*). Figure 5c is a scatter diagram of the data for 2300 to 0800 U.T.; r -0.742, and here the probability has a confidence of 99.7 percent. Olson's data indicate a 30 percent maximum-to-minimum variation of ionospheric potential around its mean value with maximum coming at the minimum in the sunspot cycle. Since galactic cosmic radiation is inversely correlated with the 11-year sunspot cycle and is the main source of atmospheric ionization, Olson's measurements support the conclusion that increased ionization causes a rise in ionospheric potential (*70*).

A misinterpretation of the proposed atmospheric electrical sun-weather mechanism (*15*) is that it postulates a solar-controlled change in thunderstorm occurrence (*71*), whereas it only explains how solar variability modulates the earth's electric field. The discussion of possible cloud physical effects is speculative, since there is no consensus regarding the importance of atmospheric electricity on cloud physics or thunderstorm electrification. However, if thundercloud charging were enhanced there should be additional meteorological consequences; it is difficult to imagine that thunderstorm-intensity electric fields would not influence cloud physics.

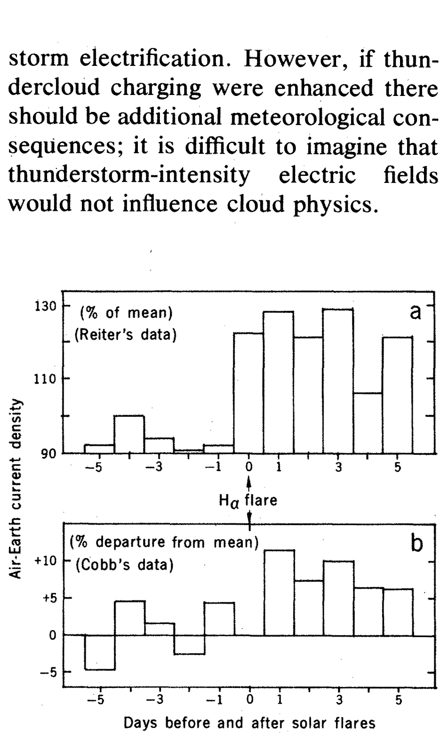


Fig. 4. Variation in air-earth conduction current density before and after the occurrence of solar flares, showing the rapid increase in ionospheric potential. (a) Composite of Reiter's data (*53*) obtained on the Zugspitze mountain peak in Bavaria; (b) summary of Cobb's analysis (*54*), using measurements from Mauna Loa volcano in Hawaii.

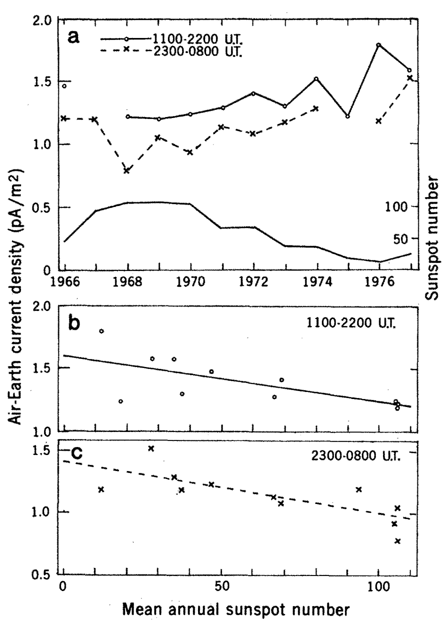


Fig. 5. Variation of air-earth conduction current density (a measure of ionospheric potential) through a solar cycle period. These are the results of more than 300 balloon ascents by D. E. Olson (Department of Physics, University of Minnesota, Duluth). The data were divided into two sets, one corresponding to the hours of maximum electric field due to the U.T. diurnal variation, the other to the hours of minimum in this cycle. Scatter diagrams showing the inverse correlation between current density and sunspot number have been made for each data set.

New Findings Relating the Solar Wind to Atmospheric Electricity

To investigate how the interplanetary medium might be modulating the earth's electric field, the ionospheric potential was compared with the solar wind velocity and a highly significant inverse correlation was found. Since the solar wind itself cannot directly affect ionospheric potential (*72*) and atmospheric ionization is maintained mostly by galactic cosmic radiation, the relationship between solar wind velocity and cosmic radiation was analyzed, and they also were strongly inversely correlated. Thus the ionospheric potential and associated intensity of the fair-weather atmospheric electric field vary in phase with atmospheric ionization.

The solar wind data were obtained by a series of satellites and compiled at NASA Goddard Space Flight Center (*73*). The ionospheric potential measurements were obtained as follows. Several years ago, in order to investigate the hypothesis that the ionosphere is an equipotential surface and to develop a technique for following the temporal variation of ionospheric potential (to study possible effects of extraterrestrial radiation on the global circuit), an extensive measurement program was conducted from an aircraft (*5*). A series of 120 potential gradient soundings was made and used to estimate ionospheric potential (*74*). The temporal variation was determined by comparing a sequence of soundings made on a time scale of hours during 1 day or less; finer resolution (on the order of 1 minute) was obtained through continuous measurement of the vertical potential gradient at constant altitude well above the atmospheric exchange layer during flights lasting several hours. To reduce atmospheric electrical noise due to convection and pollution, most of the measurements were made in the trade wind region over the ocean in the Bahamas in an air mass that had come across the Atlantic. The same aircraft and instrumentation were used to obtain all the data, improving consistency in the data base.

Solar wind velocity and ionospheric potential. Of the 120 soundings obtained in the program outlined above, 60 were made at the same times (within 1 hour) that satellites recorded values of the bulk solar wind velocity (*73*). The corresponding values of ionospheric potential and solar wind velocity are listed in Table 1. Figure 6 is a scatter diagram showing the correlation between solar wind velocity and ionospheric potential.

The solid regression line represents all 60 data points and shows a negative correlation ($r = -0.509$; percent confidence = 99.99). Because the group of points on the right of the diagram may be regarded as somewhat removed from the main body of the data, suggesting lack of normality in the distribution, the analysis was repeated omitting points corresponding to velocities greater than 500 km/sec. The resulting dashed regression line also shows a negative correlation ($r = -0.449$; percent confidence = 99.95).

Since many of the soundings were made on the same day, there would be some persistence in both parameters; that is, they would tend not to change as much over a short period (hours) as over a longer one (days). This is a characteristic problem of meteorological statistics and it introduces some uncertainty regarding the degrees of freedom, necessary information for testing the correlation for significance (*75*). To remove this uncertainty, the data were grouped into single days, or sets of consecutive days, and then the average value of all ionospheric potential estimates within a group and corresponding solar wind velocities were used to represent each group. The resulting 15 average values are shown in the two right-hand columns of Table 1. These averages represent soundings obtained a minimum of 2 days apart, and all but two of the time intervals were longer. Since autocorrelation analysis of the daily U.S. thunderstorm index shows that there is no persistence beyond 2 days (*76*), these data should be independent. The scatter diagram for these grouped data is presented in Fig. 7 ($r = -0.739$; percent confidence = 99.95). The regression line indicates the ionospheric potential has a 30 percent maximum-to-minimum variation around its mean and minimizes when the solar wind velocity is at its maximum in high-speed streams. The correlation of these data is most easily visualized, as shown in Fig. 8, by plotting them chronologically with the solar wind velocity inverted. The results of this study show that the solar wind velocity is negatively correlated with ionospheric potential.

Solar wind velocity and cosmic radiation. It is possible to investigate how solar wind velocity might be modulating ionospheric potential by examining its relationship to cosmic radiation. For this analysis, bulk solar wind velocities were compared with cosmic-ray data from the Mount Washington, New Hampshire, neutron monitor (*77*). To obtain a reasonably large data base for each year, it

Table 1. Ionospheric potential soundings and nearest-hour solar wind velocities plotted in the scatter diagram in Fig. 6. To minimize the uncertainty associated with determining the number of degrees of freedom to use when establishing the significance of the correlation, the averages in the last two columns were computed; they are plotted in Fig. 7. See text for discussion.

Date	Time (nearest hour, U.T.)	Bulk solar wind speed (km/sec)	Ionospheric potential (kV)	Average bulk solar wind speed (km/sec)	Average ionospheric potential (kV)
2 November 1970	2000	421	218		
2 November 1970	2300	378	232	400	225
1 June 1971	1600	507	197	507	197
29 December 1971	1900	420	186		
29 December 1971	2200	417	188		
29 December 1971	2300	420	179	419	184
7 January 1972	1500	368	213		
7 January 1972	1700	380	206	374	210
11 February 1972	1900	463	211		
11 February 1972	2100	444	226	454	219
13 February 1972	1500	576	183		
13 February 1972	1700	585	192		
13 February 1972	2100	620	197	594	191
15 February 1972	2000	560	178		
15 February 1972	2200	541	186	551	183
17 February 1972	1900	411	183		
17 February 1972	2100	399	177		
17 February 1972	2300	391	211		
18 February 1972	0100	394	215		
18 February 1972	0300	398	193		
18 February 1972	0500	396	206		
18 February 1972	0600	389	191		
18 February 1972	0900	404	203		
18 February 1972	1200	397	186		
19 February 1972	1300	432	208		
19 February 1972	1700	395	199		
19 February 1972	1900	426	197		
19 February 1972	2300	431	205	405	198
22 February 1972	1800	404	222		
22 February 1972	1900	400	214		
22 February 1972	2000	399	213	401	216
24 February 1972	1700	520	201		
24 February 1972	1800	521	188	521	195
29 February 1972	1600	308	246	308	246
2 March 1972	2200	411	208		
2 March 1972	2300	419	202		
3 March 1972	1900	386	232		
3 March 1972	2000	384	223		
3 March 1972	2100	396	247		
3 March 1972	2200	400	244	399	226
13 March 1972	1800	357	225		
13 March 1972	1900	355	245		
14 March 1972	1500	358	220		
14 March 1972	1600	359	229		
14 March 1972	1700	357	238		
14 March 1972	1900	347	240		
14 March 1972	2000	349	264		
14 March 1972	2100	350	280		
14 March 1972	2200	348	273		
14 March 1972	2300	348	306	353	252
17 March 1972	2100	502	243		
17 March 1972	2200	472	248		
18 March 1972	1500	436	212		
18 March 1972	1800	420	234		
18 March 1972	1900	429	255		
18 March 1972	2100	409	252		
19 March 1972	1800	352	229		
19 March 1972	1900	345	239	421	239
21 April 1972	2000	383	251		
21 April 1972	2100	382	215	383	233

was necessary to use solar wind data for days with fewer than 24 hourly values listed. Inspection of the data showed that generally an average of as few as 21 hourly values gave a figure that was representative of the day's average. If as few as 18 hourly values were used, significant errors in the average sometimes occurred. Thus daily averages of solar wind velocity were calculated only for days that had 21 or more hourly values listed. Data from 1967 and later were used as the earlier data were too sparse. For instance, in 1966 only 25 days met the minimum requirement of at least 21 hourly values.

Table 2 shows the results of this study, which covers almost a solar cycle period. In each year there is a negative correlation between solar wind velocity and cosmic radiation, although in 2 of the 10 years the correlation does not exceed the 95 percent confidence level. However, there is little question regarding the validity of this relationship. Some evidence suggests that the relationship is weakest near solar minimum (1976 was the year of minimum sunspot number) and strongest roughly midway between solar maximum and minimum, but more data are necessary to clarify this. These findings are consistent with ideas that both solar wind velocity and cosmic-ray variations are associated with magnetic blobs, or discontinuities, in the IMF (*41*).

Since the bulk solar wind velocity is negatively correlated with both ionospheric potential and cosmic radiation, ionospheric potential varies in phase with cosmic radiation. This is in agreement with the atmospheric electrical

Table 2. Yearly correlations between solar wind velocity and cosmic radiation, as represented by Mount Washington, New Hampshire, neutron monitor data. The negative correlations imply that increasing solar wind speed results in a decreasing cosmic-ray flux.

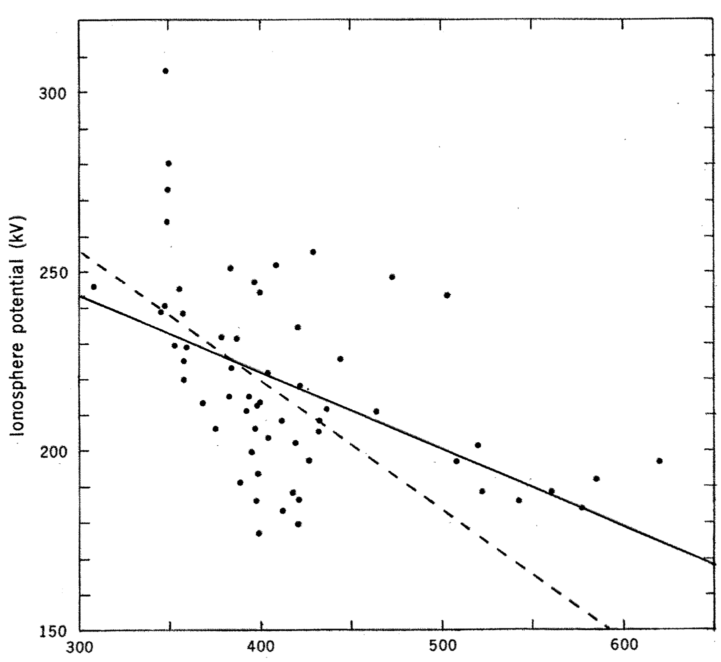
Year	Average sunspot number	Days*	r	P
1967	94	244	−0.338	< .01
1968	106	198	−0.106	
1969	106	184	−0.342	< .01
1970	105	121	−0.338	< .01
1971	67	96	−0.328	< .01
1972	69	136	−0.495	< .01
1973	38	259	−0.444	< .01
1974	35	337	−0.197	< .01
1975	18	140	−0.055	
1976	12	178	−0.272	< .01

*Days with at least 21 hourly solar wind values.

mechanism discussed here which postulates that an increase in stratospheric ionization over thunderstorms would cause an increase in ionospheric potential. If conductivity in the fair-weather return portion of the global circuit was the controlling resistive element, an increase in ionizing radiation over the nonthunderstorm area of the earth would lower its iR drop and the ionospheric potential would decrease.

Proposed Experiments; Geoelectric Index

Global characteristics of the earth's electric field. The current flow through the global circuit, the ionospheric potential, and the fair-weather electric field intensity are the only known meteorological parameters that are synchronized in universal time instead of local time. When local sources of atmospheric noise and local atmospheric electrical generators are excluded from the measurement, the fair-weather field intensity varies synchronously all over the world because the ionosphere behaves as an equipotential. This variation follows a characteristic diurnal cycle—the same one as defined by the research vessel *Carnegie* half a century ago. The average of recent aircraft measurements depict almost exactly the same diurnal variation as the well-known "Carnegie curve" (*5*); the correlation coefficient is 0.96. This variation occurs because the integrated sum of global thunderstorm activity is strongly controlled by the distribution of land masses. When the sun is heating the ground over Africa, Central America, and South America most strongly (local afternoon), the curve has a maximum at about 1800 U.T.; when the sun is over the Pacific, it has a minimum at about 0400 U.T. The maximum-to-minimum amplitude of this variation is about 35 percent of the mean. A comparison of simultaneous time-series records of the vertical electric field made by two aircraft flying at constant altitude at locations widely separated in distance and longitude (the Bahamas and the Gulf of Alaska, 7000 km apart) showed the ionospheric potential to vary synchronously (*5*). If magnetospheric and ionospheric generators were controlling the ionospheric potential, it would follow local time, as in the dawn-to-dusk potential difference perturbation imposed on the ionospheric potential across the auroral



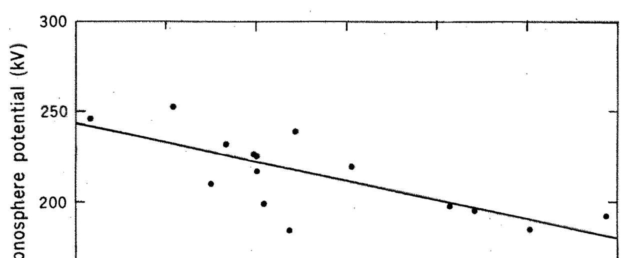


Fig. 6 (left). Scatter diagram showing the relationship of ionospheric potential to solar wind velocity. The solid regression line refers to all the data points ($N = 60$); the dashed line represents the data when points corresponding to velocities greater than 500 km/sec are excluded ($N = 51$). Fig. 7 (right). Scatter diagram showing the relationship between averages of grouped ionospheric potential measurements and corresponding solar wind velocities. This was done to ensure independence of the data (see text). The groups are separated from each other by at least 2 days to eliminate possible effects due to persistence.

oval (12, 13). The Carnegie curve variation of electric field intensity is observed in fair-weather regions all over the earth's surface, including the auroral oval and polar cap regions (78).

Geoelectric index. By measuring the earth-ionosphere potential difference at mid- to low latitudes to minimize possible influences from upper atmosphere generators (79) it is possible with one instrument at one location to characterize the electrification of the earth and resulting atmospheric electric field (which is concentrated in the lower atmosphere) over its entire surface. We routinely monitor electrical conditions on the sun and in space, and it would seem reasonable to continue such measurements within the earth's atmosphere. Even if it is found that solar variability does not affect weather the experiments would provide a more complete description of the state of the atmosphere and information of importance to magnetospheric and ionospheric research.

The elegance of this approach can be appreciated by comparing it with the procedure used to determine such meteorological parameters as temperature, humidity, and wind fields as a function of altitude. To obtain these, hundreds of simultaneous balloon soundings are made over a large portion of the earth's surface every 12 hours. The meteorological term synoptic arises from this requirement for many simultaneous measurements over a large grid. By adding a few more radiosondes instrumented to measure the vertical electric field, conductivity, and ion production rate, we would be able to monitor the intensity of the earth's electric field and atmospheric ionization, thus providing new key global parameters to our observations of the atmosphere. Such measurements would provide a record of ionospheric potential and stratospheric conductivity variations with a temporal resolution dependent on the frequency of the soundings. These could be compared with solar-terrestrial parameters that are routinely monitored, such as solar flares, proton events, sector crossings, and solar wind characteristics. The objective of such a program would be to identify the radiation, interplanetary medium conditions, and processes by which solar variability modulates atmospheric electrification. It would be necessary to obtain a long, preferably unbroken, time series of ionospheric potential measurements made at least once a day at the same time to minimize the U.T. diurnal variation. Such a time series would constitute a geoelectric index patterned after and complementary to the geomagnetic indices which have been of great importance in solar-terrestrial research.

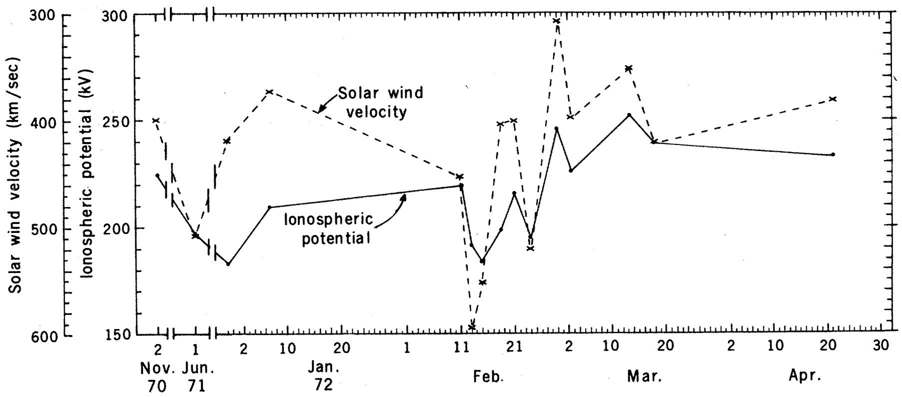


Fig. 8. Temporal variation of ionospheric potential and simultaneous solar wind velocity for the grouped data of Fig. 7 and Table 1. The solar wind velocities are plotted increasing downward to illustrate the negative correlation.

While routine balloon soundings made once or twice a day could be used to follow the gross daily variation of ionospheric potential and would provide much useful information, the lack of higher temporal resolution would be a serious limitation, as would be the case if the geomagnetic indices were determined from measurements made that infrequently. The balloon soundings have been discussed to illustrate that the earth's overall electric field can be measured relatively easily. However, it would be much preferred to measure the ionospheric potential variation continuously. The variation of the air-earth conduction current density could be recorded from a constant-altitude aircraft (5, 80), tethered balloon, or kite platform (81). They could make periodic ascending and descending electric field soundings to establish the absolute value of ionospheric potential (5, 43). The minimum altitude for monitoring ionospheric potential variation from a tethered balloon or kite would be about 5 km (82), and the measurements could most easily be made from a ship at sea (83). The conductivity and ion production rate measurements would have to be made from free balloons in the stratosphere.

Investigations of atmospheric electrodynamics and the global circuit through simultaneous measurements. Besides the application to the sun-weather problem, the capability for measurement of the temporal variation of the earth-ionosphere potential difference will be important for studying the electrodynamics of the upper atmosphere. Through simultaneous measurements along a meridian, such as the pole, auroral zone, mid-latitude, and equator (ideally in both hemispheres), it would be possible to verify models and remote measurements of ionospheric electric field distributions caused by magnetospheric and upper atmosphere generators. Similarly, with two measurements it would be possible to directly measure the dawn-to-dusk potential difference across the auroral oval that has been inferred from incoherent scatter radar data and satellite electric field mapping. There are still differing views regarding the extent to which the ionosphere is an equipotential (45, 62), and this question could be answered with simultaneous measurements.

Atmospheric ionization. Conductivity and ion production rate profiles up to 25 or 30 km could be obtained on a routine basis once or twice a day with free balloons that also measured the absolute value of ionospheric potential. It would be desirable if these measurements were obtained along a meridian. While local meteorological conditions (such as clouds) can severely affect electric field soundings of ionospheric potential, the conductivity and ion production measurements in the stratosphere would be unaffected. These measurements would provide considerably more information on the spatial and temporal variation of atmospheric ionization than is presently available. They would answer the questions of whether at thunderstorm latitudes solar-controlled conductivity variations occur sufficiently low in the atmosphere and frequently enough to significantly modulate the current output of the global circuit generator (15), an issue that has been debated (62).

Lightning detection from satellites. The ability to observe the earth from space makes it possible for the first time to observe the spatial and temporal variation of global thunderstorm activity. Photoelectric systems are capable of sensing lightning during the day as well as at night. In the past, lightning observations from satellites were made incidentally when photoelectric sensors flown for other purposes detected lightning-generated signals (*7*). Recent work (*8*) has stimulated interest in this area, and there has been a conference to define technical capabilities and scientific requirements for satellite lightning-detection systems (*84*). Since optical sensing alone will probably not detect much of the lightning from the middle or lower portions of deep clouds, such as in low-latitude thunderstorms, it will be necessary to sense lightning-generated electromagnetic radiation at other frequencies as well. A new interferometric technique seems particularly attractive (*85*). Three or more geostationary satellites could give full-time coverage of most of the earth's surface (*86*).

Although lightning frequency and intensity must be some sort of indicators of the electrification of thunderclouds, it should not be assumed that a simple correlation exists between a thunderstorm's lightning activity and its ability to electrify the atmosphere. It will be necessary to define this relationship. If satellite lightning detection can provide a method for monitoring the integrated current output of global thunderstorms, then comparison of this with the variation of ionospheric potential will make it possible to critically test the global circuit hypothesis. Such measurements would also provide a means for investigating the speculative part of the proposed sun-weather mechanism in which cloud electrification may be influenced by solar-controlled changes in atmospheric electricity.

Testing classes of cloud electrification theories. Although thunderstorm research has been going on for decades, the processes by which clouds become electrified are not understood very well. Because a thunderstorm cannot be replicated in the laboratory, it must be studied in the field. However, it is so large and complex that it is difficult to make the necessary measurements simultaneously and continuously throughout its entire volume and the surrounding region.

The proposed measurements of global electrification and lightning may offer a new, indirect approach to the problem of thunderstorm electrification. Classes of cloud-charging mechanisms can be broken into two categories: (i) those in which external atmospheric electrical conditions control cloud electrification and (ii) those in which the electrification is due solely to interactions among the ice particles and water drops within the cloud. In case (i), enhanced conductivity over thunderstorms and developing cumulus clouds, or larger fair-weather electric fields near the developing cumulus, should enhance electrification. In case (ii), the increased conductivity near the clouds would allow charge to leak to the surrounding atmosphere more rapidly, which might inhibit electrification. Thus, observation of an increase in ionospheric potential and lightning activity after a solar flare would constitute evidence for the first class of charging mechanisms, while decreased cloud electrification would support the second class.

Because the earth's magnetic field screens solar particles from the atmosphere with increasing efficiency from low to high latitudes, ionization over thunderstorms will be more strongly controlled by solar variability at high latitudes. This may offer another method of testing classes of thunderstorm charging mechanisms. If, after atmospheric ionization caused by a solar flare or bremsstrahlung x-rays, high-latitude thunderstorms produce more lightning and equatorial ones remain unaffected, this would support the convective electrification theory. If electrification increased in low-latitude storms after high-latitude ionization events and an increase in ionospheric potential (world-wide electric field intensity), this would imply that the initial ambient electric field was important in cloud electrification. Such an observation would be in agreement with the induction theories as well as the convective theory, but it would not support electrification theories dependent on processes within the cloud.

Conclusion

An explanation is offered for how solar variability controls the electrification of the atmosphere. A highly statistically significant relationship (with confidence limits greater than 99.9 percent) has been found between the solar wind and the earth's fair-weather electric field intensity. It is inferred from the inverse correlations between solar wind velocity and both ionospheric potential and galactic cosmic radiation that solar variability modulates the earth's electric field by controlling ionizing radiation. Since the ionospheric potential is maintained by the integrated currents from global thunderstorm activity, this implies that enhanced ionizing radiation causes larger currents to flow from existing thunderstorms and may also cause an increase in the number and electrification of cumulonimbus clouds. The extent to which atmospheric electricity might be influencing atmospheric circulation and other aspects of the weather remains an open question. The fact that the earth's electric field is modulated by solar variability is in itself of considerable scientific importance. However, thunderstorm activity also may be affected, and, whether or not they influence atmospheric circulation, thunderstorms are of major meteorological importance over much of the earth's surface.

It is no longer necessary to investigate the sun-weather problem only through statistics and correlations. We now have the tools to observe the details of chains of events by which solar activity may influence meteorology in the lower atmosphere. With existing technology it should be possible to clarify how solar variability causes atmospheric electrical responses. The problem of possible effects on other aspects of meteorology may be more difficult, but it is approachable through analyses of changes in cloud heights and patterns, rainfall, and water vapor distributions (sensed by satellite instrumentation), relative to atmospheric electrical records (sensed from balloons and kites). The highest priority should be placed on field, laboratory, and theoretical studies to determine the extent to which electric field intensity affects cloud physical processes. An atmospheric electrical effect on cloud electrification, rainfall intensification, and cloud dynamics seems the most likely way that solar activity can rapidly influence the spatial and temporal variations of atmospheric energy.

The most obvious application of this research is for weather forecasting, where it has the potential for improving both short- and long-range prediction. Despite the considerable effort expended in weather research during the last few decades, predictive skill still extends to at most 5 days (*20*). There undoubtedly are factors that are not included in present numerical models. Some aspects of solar activity are predictable much farther in advance (months and years) than meteorological conditions, and solar flares are generally observed hours to several days before their particles reach the earth's atmosphere.

Although we are concerned with electrical processes, other ways in which solar variability might influence weather and climate have been suggested, and on a short time scale all may be small effects. Meteorological processes are complex and highly nonlinear and sun-weather research is not intended to provide an ultimate answer to the forecasting problem. Aside from weather prediction, we are interested in studying the relationship of solar variability to atmospheric processes in order to expand our basic understanding of the earth's environment. The potential importance of this research is difficult to assess. For example, while changes in the earth's electric field resulting from a solar flare modulating conductivity may have only a barely detectable effect on meteorology, the situation may be different in regard to electric field changes caused by manmade ionization from radioactive material (*87*).

Parker (*88*) has suggested that sun-weather research may not be a luxury. He notes that "if the sun can play games once (during the Maunder minimum), it certainly can play games with us a second time, perhaps not anything like the first time around. It is conceivable that the sun might become extremely active." Eddy (*89*) reports that the sun has been significantly more active in the past, during the "medieval maximum" (A.D. 1120 to 1280), than in recent times.

The question of how solar variability affects the atmosphere is most timely as we turn to the sun and space for possible answers to the problems resulting from increasing population in a world with limited food, energy, and natural resources—all of which are directly or indirectly affected by atmospheric conditions. Thus if solar activity affects meteorological processes, and there is increasing evidence suggesting that it does, and if society is going to develop the capability of predicting and rationally planning its future, the sun-weather problem becomes a matter of considerable importance.

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(1972)] during the interval 1959 to 1971. These have been cited as displaying an inverse correlation between sunspot cycle and ionospheric potential [R. Markson, *NASA Spec. Publ. SP-366* (1975), p. 174]. Although we tested this negative correlation and found it to be at less than the generally accepted 5 percent confidence level, there appears to be an inverse relationship. Error would have been introduced into these data because the U.T. diurnal variation was not removed, as it was to some extent with Olson's data through stratification, depending on the time of the measurement. Recently, W. Gringel (University of Wyoming, Laramie; personal communication) provided information showing that the average of 80 ionospheric potential measurements made by Mühleisen and Fischer during the sunspot minimum periods (1962 to 1966 and 1967 to 1972) was 301 kV; while the average for 142 measurements made during the sunspot maximum periods (1959 to 1961 and 1967 to 1972) was 234 kV. These data thus display a 25 percent peak-to-peak variation around a mean of 267 kV (unadjusted for the U.T. variation), with ionospheric potential inversely correlated with solar activity through a sunspot cycle period.
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83. Besides removing the tethered balloon or kite from the airspace over land, where it could be a hazard to aviation, another advantage of this approach is that the ship's velocity could be used to counteract the adverse affects of wind on a tethered balloon, or to provide lift for a kite.
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87. Aircraft measurements in the troposphere over Maine 15 days after thermonuclear explosions over the Pacific Ocean in 1956 indicated a conductivity increase of up to 75 percent due to the cloud of radioactivity carried by the westerly winds [R. V. Anderson and G. P. Serbu, *J. Geophys. Res.* **65**, 223 (1960)]. Secular decreases of as much as 50 percent in electric field intensity at ground level apparently were caused by increased ionization due to radioactive fallout following the initiation of thermonuclear testing in 1952 [E. T. Pierce, *ibid.* **77**, 482 (1972)]. If future atmospheric releases of krypton-85, an inert radioactive gas with a half-life of 10 years, takes place according to the scheduled introduction of nuclear fission reactors, it could ionize the atmosphere over the oceans (71 percent of the earth's surface) at a rate comparable to that due to the natural background cosmic radiation. It has been estimated that this condition would significantly modulate the atmospheric electric global circuit by lowering the total resistance of the atmosphere [W. L. Boeck, *Science* **193**, 195 (1976)].
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Biopolyester Membranes of Plants: Cutin and Suberin

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Living organisms are packaged in envelopes that consist of polymeric structural components; in terrestrial organisms a waterproofing mixture of lipids, collectively called waxes, are associated with this outer layer. The structural component in animals is either an amino acid polymer (protein) or a carbohydrate polymer (chitin), whereas in higher plants it is a biopolyester, cutin, in the aerial parts, and suberin, a polymer containing polyester domains, in the underground parts and at wound surfaces. Such polyesters not only constitute the major protective barrier between the plant and its environment but also function as a rather permanent biological barrier within a variety of organs so that diffusion of molecules can be controlled, a role essential to plant life. During the past decade considerable progress has been made in our understanding of the composition, biosynthesis, and biodegradation of these phytopolymers. In this article I summarize these recent findings (*1-4*).

Location and Ultrastructure

Cutin is the structural component of the plant cuticle, which is attached to the outside of the epidermal cell wall in the aerial parts of both angiosperms (*1*) and gymnosperms (*5*). Even primitive plants such as liverworts (*6*) and the moss *Mnium cuspidatum* (*7*) have cutin. Cutin is present on virtually every aerial organ of plants such as stem (except possibly the bark of woody plants), petiole (*8*), leaf, including substomatal cavities (*1*), flower parts (*8, 9*), fruits (*1*), seed coats (*8*), and even internal parts such as juice sacs of citrus (*7*). The thickness of the polymer layer varies among the different species and among organs within the same species. In leaves, thickness and mass were reported to be in the range of 0.5 to 14 micrometer and < 20 to 600 micrograms per square centimeter, respectively (*1*). In special cases such as interstomatal cavity, a very thin cutin layer (0.15 to 1.0 μm) might be found, whereas in organs such as fruits with well-developed cuticle, the cutin content may reach 1.5 milligrams per square centimeter (*4, 10, 11*). Development of cuticle may have been a crucial factor in the colonization of lands by plants (*12*). However, the occurrence of cutin does not appear to be limited to land plants since the polymeric material from a sea grass, *Zoestra marina*, which grows submerged on coastal shorelines contains covalently attached hydroxy fatty acids identical to those found in the cutin of land plants (*7*). Cutin in land plants is embedded in wax, and in some instances the wax occurs in layers so that the cuticle shows a lamellar structure, although more often the cuticle presents an amorphous appearance under the electron microscope (*1, 9, 13*) (Fig. 1).

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