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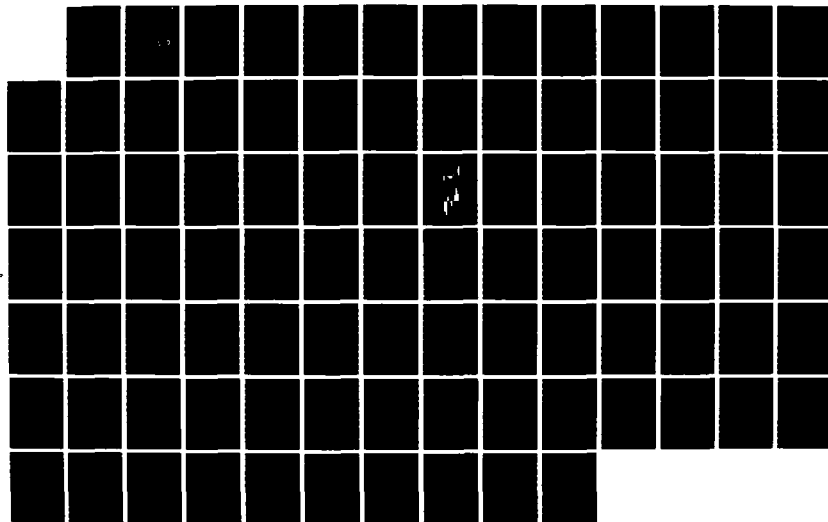
EXTRATERRESTRIAL FORCING ATMOSPHERIC ELECTRICITY AND
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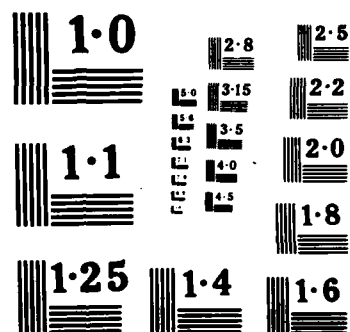
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The Pennsylvania State University

The Graduate School

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Extraterrestrial Forcing, Atmospheric Electricity, and
the Occurrence of Thunderstorms

A Paper in

Meteorology

by

Angelo M. Nuzzo

Submitted in Partial Fulfillment

of the Requirements

for the Degree of

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ABSTRACT

It is generally accepted by many scientists that a cause-effect relationship exists between solar activity and weather. Statistical evidence is provided to support this concept; atmospheric electricity and stratospheric-tropospheric exchange are highlighted. Although many accept the idea, there are those who are skeptical about such a relationship because no definite physical mechanism exists between the two. This is a topic of much discussion and debate. It is believed that the shielding of the Earth from galactic cosmic rays during increased periods of solar activity plays a key role in the process. Several of the mechanisms discussed rely on this concept. The emphasis will be on the atmospheric electrical mechanism since it has received much of the attention in this area. On the topic of the atmospheric electrical mechanism, two hypotheses are presented: those of Markson and Hale. Finally, the stratospheric-tropospheric exchange mechanism is introduced. This mechanism is similar to the atmospheric electrical mechanism in that it also depends on the possible modulation of the thunderstorm generator by solar activity. Tropopause folding events are presented as a vital link in the stratospheric-tropospheric exchange mechanism.

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Chapter 1

INTRODUCTION

1.1 Background

Evans (1982) defines solar-terrestrial relationships as the response of the Earth's upper atmosphere, ionosphere and magnetosphere to the Sun's energy and its variations. However, this paper will extend this definition to include the response of the middle and lower atmosphere as well. More specifically, this paper treats the coupling of ionospheric and tropospheric responses to solar activity, including sunspots, solar magnetic sector structure, solar flares, and their effects on galactic cosmic rays.

It has been determined that solar heating is essentially "constant" since it varies by only a few tenths of one percent over several days (Evans, 1982). Most of the energy (~ 95%) reaching the Earth's surface is within the visible and infrared wavelengths. The energy emitted by the ultraviolet and X-ray portion of the spectrum (~ 5%) never reaches the Earth's surface (with the exception of the near ultraviolet at 3000-3800Å) but is absorbed in the middle atmosphere and higher. However, it is this portion of the spectrum that becomes important when dealing with solar activity. How then does solar activity affect the weather?

The question presented above is one that is not easily answered. The relationship between solar activity and meteorological phenomenon has certainly been well documented statistically. The uncertainty in the relationship arises because physical mechanisms linking solar

activity to weather are lacking. There are many theories dealing with linking mechanisms. The problem is finding mechanisms that can modify tropospheric processes. The amount of the energy from solar activity reaching the troposphere is negligible compared to the energy needed to drive the processes (the solar constant). For this reason, many scientists are skeptical about the effects of solar activity on weather.

1.2 Outline of Paper

In Chapter 2, several statistical relationships between solar activity and meteorological phenomenon are presented. In addition, a few of the proposed mechanisms linking extraterrestrial forcing to weather are discussed in that chapter.

Chapter 3 provides a more indepth look at two proposed linking mechanisms: atmospheric electricity and stratospheric-tropospheric exchange. A discussion of each topic is presented to introduce the reader to the terminology involved. This is followed by a section providing statistical evidence of extraterrestrial forcing on both parameters. The last section is a discussion of each parameter as a possible linking mechanism between extraterrestrial forcing and weather. The emphasis is placed on the atmospheric electrical mechanism since most scientists suggest this as the most probable linking mechanism. The classical global electric circuit is presented as well as Markson's (1978, 1979a, 1983) concept of the atmospheric electrical mechanism based on the classical model. Hale's (1983) model is also presented to further emphasize the variety of ideas involved

when dealing with not only the atmospheric electrical mechanism but with Sun/weather linking mechanisms in general. Finally, the stratospheric-tropospheric exchange mechanism is introduced, as Herman and Goldberg (1978b) suggest. Their idea is then modified to include tropopause folding as a more appropriate trigger for this mechanism.

Chapter 2

REVIEW OF EXTRATERRESTRIAL FORCING

2.1 Evidence for a Sun/Weather Connection

There have been many statistical correlations presented relating solar activity and meteorological parameters. Wilcox (1974) reviews several of these relationships. In addition, a few others not mentioned by Wilcox will be discussed. (Since much of the work in solar-terrestrial research deals with solar magnetic sector boundaries, further discussion on this topic can be found in the appendix.) Wilcox et al. (1973) found a 10% variation in the amplitude of the 300-mb low pressure trough vorticity area index (VAI), a measure of the intensity of cyclonic circulations. The VAI reaches a minimum one day after solar sector boundary passage, increasing thereafter to a maximum on the fourth day after boundary passage (Fig. 1).

The results of Wilcox were an extension of the work of Roberts and Olsen (1973b) on VAI and geomagnetic activity. Their results indicated a subsequent deepening of 300-mb troughs moving into or forming in the Gulf of Alaska two to four days after a sharp rise in geomagnetic activity than for troughs preceded by a geomagnetically quiet period (Fig. 2). Schuurmans and Oort (1969) also investigated tropospheric circulation but in connection with solar flares. The study deals with average height changes of several constant pressure levels in the troposphere and lower stratosphere following strong solar flares. The analysis period runs from July 1957 through December 1959 and covers the

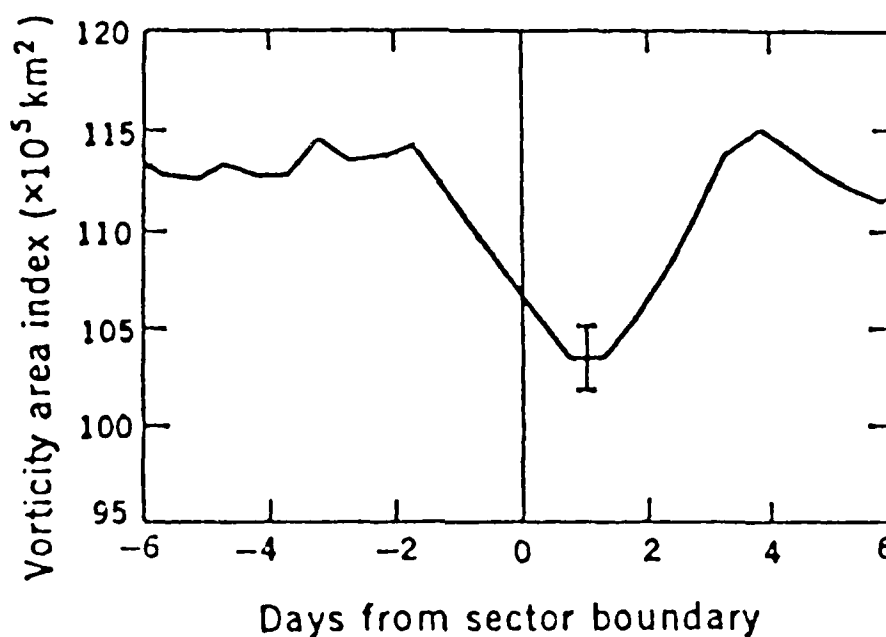


Figure 1 Average response of the vorticity index to the solar magnetic structure. Sector boundaries were carried past the Earth by the solar wind on day 0. The analysis includes 53 boundaries during the winter months November to March in the years 1964 to 1970. The standard error of the mean (error bar) was calculated after subtracting a 27-day mean centered on each sector boundary to remove long-term trends. The deviations corresponding to the individual boundaries are consistent with a normal distribution about the mean (Wilcox et al., 1973).

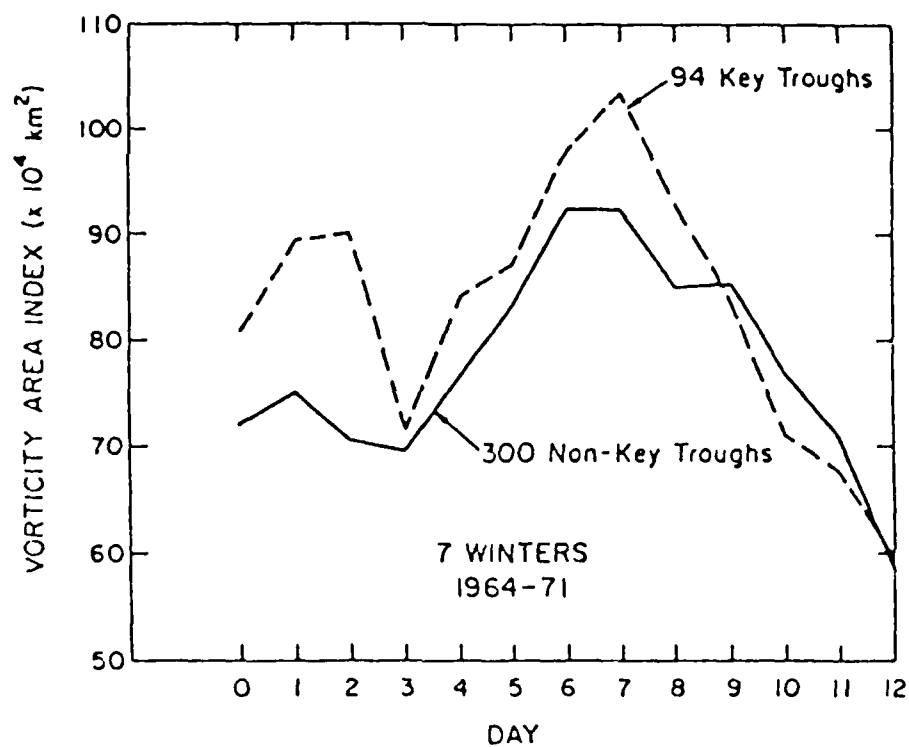


Figure 2 Mean vorticity area index for troughs preceded by a sharp rise in geomagnetic activity (key troughs) and for troughs preceded by a geomagnetically quiet ten-day period (non-key troughs). The "0-day" is the day of first appearance of the trough in the Gulf of Alaska region (Roberts and Olsen, 1973b).

Northern Hemisphere north of 10°N . Some characteristics of the height changes indicate:

- (1) a maximum response near the tropopause
- (2) significant height changes of the 500-mb level at all latitudes
- (3) the changes are well established within six hours after the flare
- (4) the strongest reaction pattern occurred in the winter sample.

The dependence of drought and growing season (the portion of the year when the daily averaged air temperature at 1.25 meters above ground exceeds 5.6°C) on the sunspot cycle presented by King (1973) indicates a correlation between temperature and the sunspot cycle. The results of his investigation reveal an increase in the growing season at Eskdalemuir, Scotland on the average to be approximately 25 days longer near sunspot maximum than at sunspot minimum (Fig. 3). By comparing the length of the growing season to the day number the season began and ended (the first and last day of the year the temperature reached 5.6°C), King concluded that the sunspot cycle influences the temperatures in spring rather than autumn. King also compared the smoothed sunspot cycle to the comprehensive temperature measurements of Starr and Oort, and found the decline in the temperatures from May 1958 to April 1963 was highly correlated with the smoothed sunspot cycle (Fig. 4).

On further examination, King found a correlation between the sunspot cycle and the monthly rainfall totals of Wales-Smith from

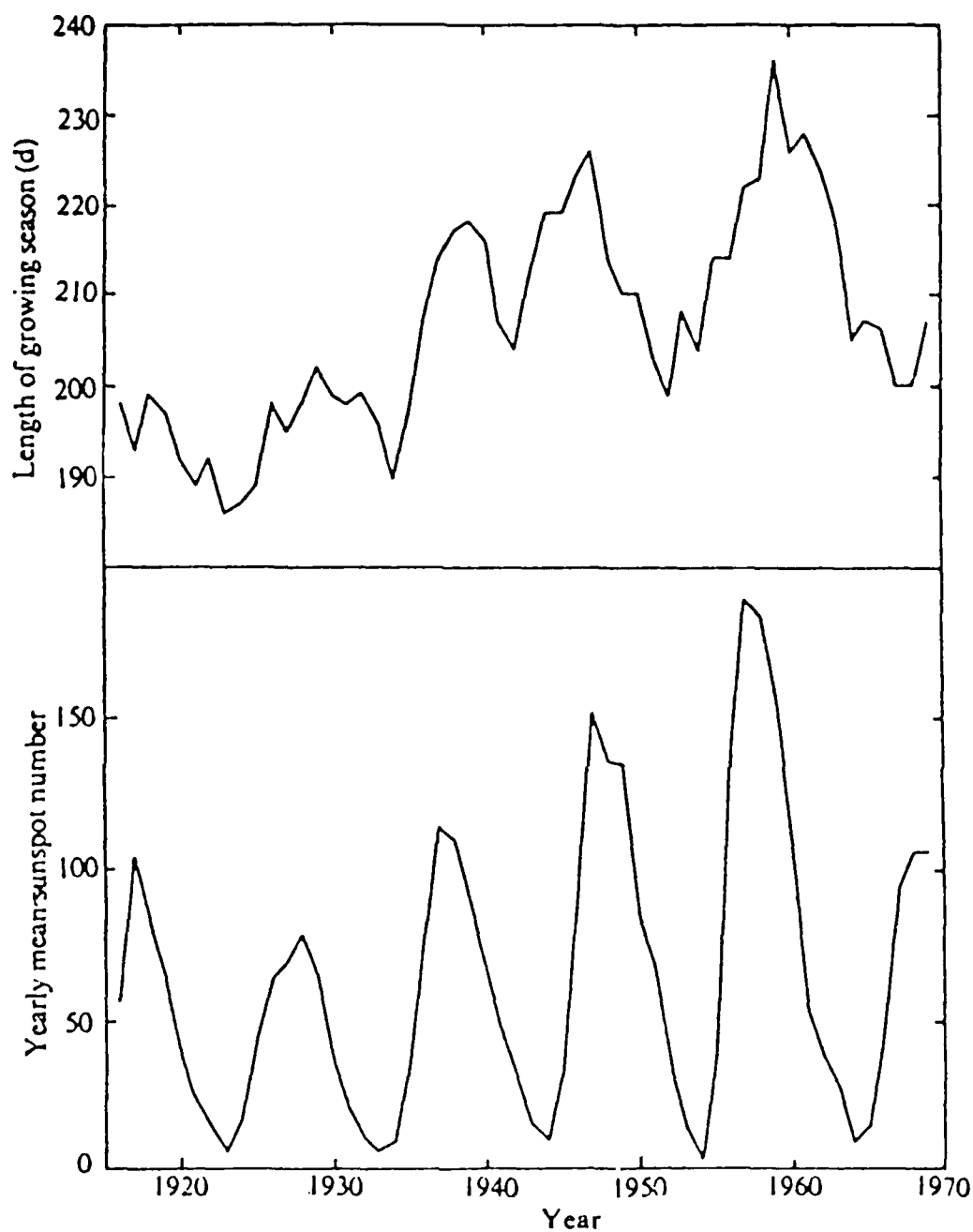


Figure 3 The upper portion is the length of the "growing season" (that is, the number of days in the year on which the averaged temperature exceeds 5.6°C) at Eskdalemuir (55°N , 3°W). The lower portion is the yearly mean sunspot numbers (King, 1973).

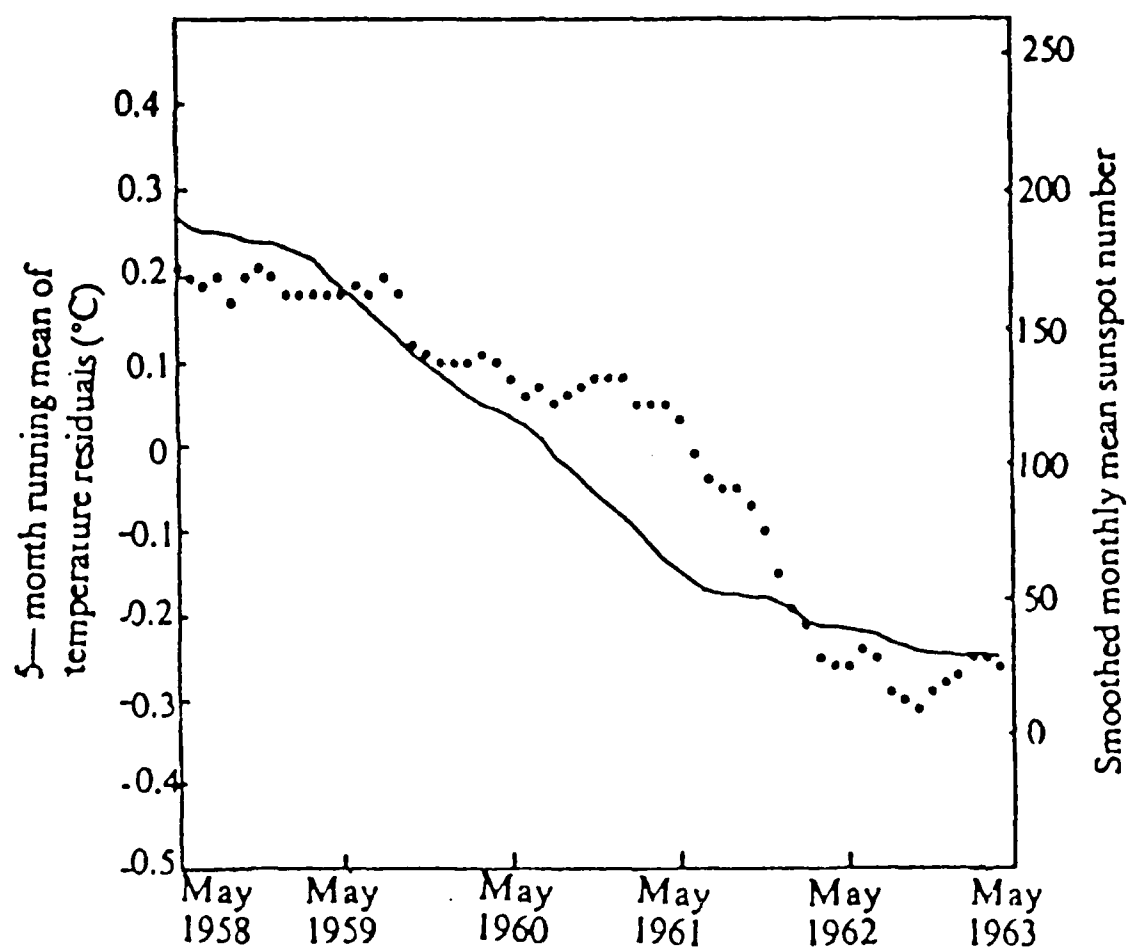


Figure 4 Smoothed variations of monthly temperature residuals show a declining trend in the average temperature of the lower atmosphere in the Northern Hemisphere. Also plotted are the smoothed variations of the monthly mean sunspot numbers. The two points at the beginning and the end of the temperature curve are not necessarily quite accurate. The smoothed sunspot numbers are the conventional 12-month running means. •, temperatures; ---, sunspot numbers (King, 1973).

1697-1970 at Kew, England. The results are as follows:

(1) the driest winters appeared to be associated with low sunspot numbers.

(2) the driest springs, summers and autumns occurred during high solar activity.

(3) abnormal winter and annual rainfalls occurred around sunspot minimum.

(4) the wettest springs occurred at sunspot minimum and the driest springs tended to occur around sunspot maximum.

In addition to these results, he also detected a high negative correlation between sunspot numbers and rainfall at Beirut (as reported by Winstanley (1973) during the winter-spring seasons for 1951-1969) (Fig. 5). Certainly, this is only a few of the many correlations that have been observed. The point is, as King (1974) states it, "Even the most skeptical scientist who investigates the literature thoroughly will be forced to concede that important aspects of lower-atmosphere behavior are associated with solar phenomena ranging from short-lived events such as solar flares, through 27-day solar rotations to the 11-year, 22-year and even longer solar cycles." The following topics will further develop the role of solar activity in Sun/weather relationships.

2.2 Several Proposed Coupling Mechanisms

The statistical findings presented in the previous section certainly indicate a possible link between solar activity and weather. The problem is as Markson (1979a) states it, "there is no obvious

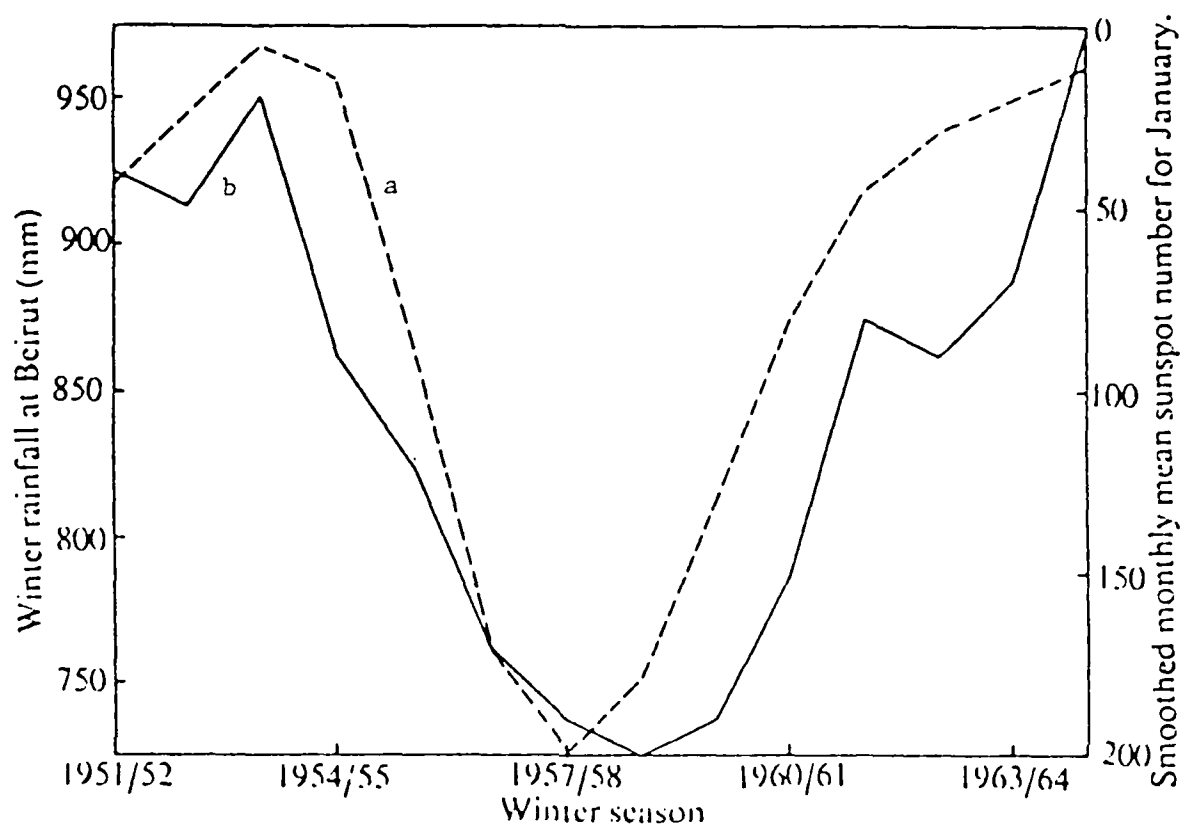


Figure 5 Plot showing, for October-May periods, the rainfall at Beirut (34° N, 36° E) (Winstanley, 1973). Also plotted are the 12-month running mean sunspot numbers centered on January. (a) sunspot number, (b) rainfall (King, 1973).

physical mechanism to explain the findings." There has been much speculation over the linking mechanism. A review of several proposed mechanisms will be presented here. Chapter 3 focuses on the atmospheric electrical and the stratospheric-tropospheric exchange mechanisms.

Evans (1982) discusses three possible mechanisms that have been suggested. One of the mechanisms proposed by Volland (1979) and discussed by Evans deals with the 27-day variation of the solar radiation reaching the ground. The coupling mechanism Volland proposes suggests an alteration of the stratospheric wind and temperature profile or a change in the albedo as a result of the enhanced solar radiation absorbed in the stratosphere. These changes would affect the planetary wave propagation within the troposphere. Volland feels this mechanism may be responsible for the long term effects on the weather (time scales on the order of a month or longer) since the ultra-long waves are important in the total poleward transport of heat in the northern mid-latitude winter.

A second mechanism treats the production of NO molecules in the stratosphere at high altitudes. The transport of NO to lower latitudes and altitudes by winds and diffusion affects the concentration of ozone. The proposal is for modulation of the solar ultraviolet radiation reaching the ground by variations in the ozone layer concentration. This leads to changes in heating and temperature and finally to changes in atmospheric circulation patterns. The section on stratospheric-tropospheric exchange will address the NO-ozone topic again.

The third mechanism presented by Evans is based on atmospheric electrical properties. This hypothesis states that changes in the electrical conductivity modulate the strength of the fair-weather electric field produced by thunderstorms. There are several schools of thought on the atmospheric electrical mechanism. Two models will be presented in that section, those of Markson (1978, 1979a, 1983) and Hale (1983).

Still another proposed mechanism is cirrus cloud shielding (Roberts and Olsen, 1973a,b). High energy solar corpuscles produce ionization down to the 300-mb level and below either directly or by secondary (Bremsstrahlung) radiation. The atmospheric ions produced then act as additional condensation nuclei to form cirrus clouds. Roberts and Olsen suggest a 1°C per day increase in temperature in the upper troposphere during the high latitude winter over a relatively warm ocean surface is likely. The heating results from the absorption of infrared radiation emitted from the Earth. Such an increase could again lead to changes in the atmospheric circulation.

Ionization by galactic cosmic rays is the process in the lower atmosphere most dependent on solar activity. For this reason, ionization by galactic cosmic rays in the lower atmosphere is a concept often addressed in connection with coupling mechanisms. This will become evident as the following chapter is presented.

Chapter 3

FURTHER EVIDENCE FOR A SUN/WEATHER CONNECTION

3.1 Atmospheric Electricity

3.1.1 Introduction

Many scientists feel that atmospheric electricity is the link between solar activity and weather. Thus, it is essential to identify the effects of solar activity on atmospheric electrical properties and to discuss the atmospheric electrical mechanism. However, a discussion identifying the atmospheric electrical properties to be considered in this section precedes the aforementioned topics.

Two fields must be considered when describing the global electric circuit; the fair-weather and storm-generated electric fields (Pierce, 1986). The fair-weather atmosphere is at a positive potential (V) with respect to the Earth, increasing with height above the Earth's surface. The potential gradient is positive and the electric field (E) is the negative of the potential gradient and thus, it is negative and points in the direction positive charge moves. The electric field at the Earth's surface under polluted conditions is $E_0 \sim -100 \text{ Vm}^{-1}$ with the corresponding bound charge $\sigma_0 \sim -9 \times 10^{-10} \text{ Cm}^{-2}$.

The lower atmosphere is weakly conducting due to the ions produced by ground radioactivity, radioactive gases and cosmic rays. The conductivity increases approximately logarithmically with height up to 40 km. Above 40 km the increase in conductivity with height is more pronounced because the effects of free electrons become significant due to both a solar ultraviolet ionization source and local effects on

ion composition and recombination rates. For unpolluted conditions, the surface electrical conductivity is $\lambda_0 \sim 3 \times 10^{-14} \text{ mhm}^{-1}$ and the current density is $j = \lambda_0 \times E_0 \sim -3 \times 10^{-12} \text{ Am}^{-2}$, carrying positive charge into the Earth's surface. From Table 1, the magnitude of the air-Earth current ($I = V/R$, where R is the columnar resistance) is approximately constant with altitude ($3 \times 10^{-12} \text{ Am}^{-2}$). The positive charge carried to the Earth's surface should neutralize the bound charge in approximately 300 seconds (Pierce, 1986). However, this is not the case as the Earth retains its negative charge. It is for this reason that the storm-generated electric fields must be considered in the global circuit.

According to the global circuit concept (Pierce, 1986), a thunderstorm transfers positive charge toward the conducting upper atmosphere (Fig. 6). The charge is distributed laterally to the fair-weather regions. Thus, thunderstorms act as generators supplying the driving potential for the fair-weather currents. The average current per storm is approximately 0.7 amps toward the electrosphere.

In addition, there is an exchange of electricity with the Earth below the cloud. The three main processes responsible for this exchange are:

- (1) cloud-to-ground lightning
- (2) point discharge and conduction currents
- (3) precipitation.

The average current per storm from these three processes is estimated to be about one amp to the ground. The discrepancy between the currents above and below the cloud indicates possible leakage and

Altitude h (km)	Conductivity λ_h (mho m^{-1})	Columnar resistance R_h (ohm m^2)	Field E_h (V m^{-1})	Potential V_h (V)
0	3×10^{-14}	0	-100.00	0
2	5×10^{-14}	5×10^{16}	- 60.00	1.5×10^5
12	4×10^{-13}	9×10^{16}	- 7.50	2.7×10^5
40	10^{-10}	10^{17}	- 0.03	3.0×10^5

Table 1 Representative values of the fair-weather electrical parameters (Pierce, 1986).

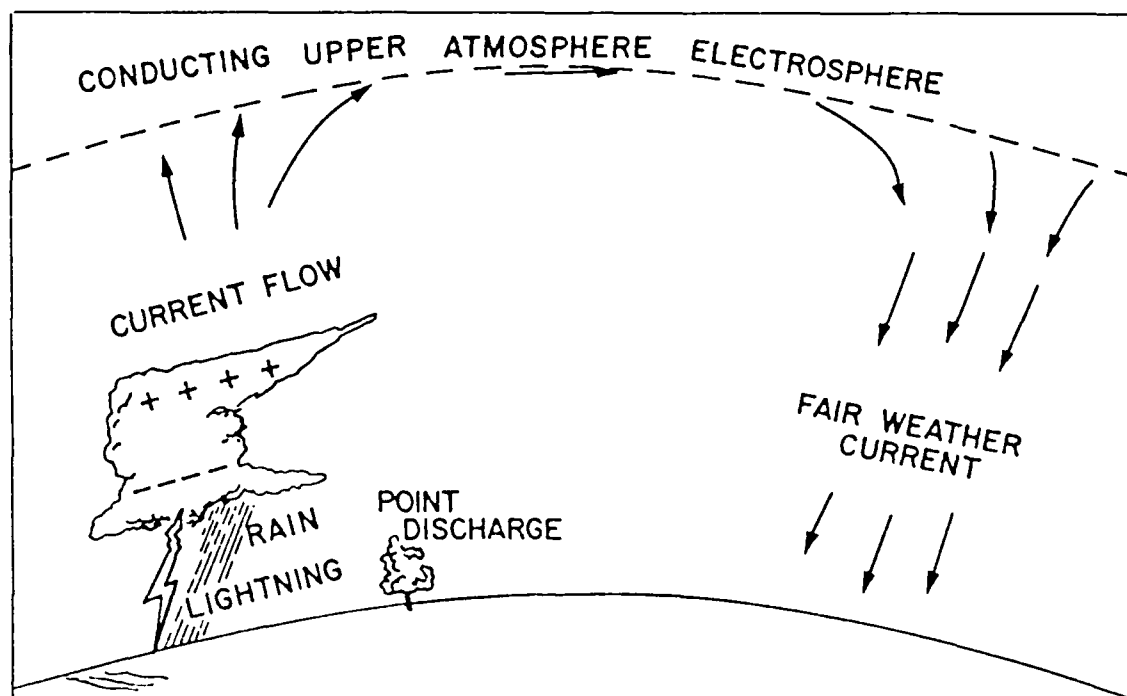


Figure 6 An illustration of the classical global circuit model (Pierce, 1986).

losses within the thunderstorm. On the average, there are about 2,000 thunderstorms active simultaneously over the Earth's surface; each storm generates about one amp. Hence, about 2,000 amps are continuously generated from all global thunderstorms. This roughly balances the fair-weather current integrated over the Earth's surface. Therefore, consideration of the storm-generated electric fields is necessary to explain the excess negative charge on the Earth's surface and to produce a balance of currents. Statistical evidence of extraterrestrial forcing on the atmospheric electrical properties described here will be presented in the next section.

3.1.2 Statistical Evidence for an Atmospheric Electrical Connection

The measurements of air-Earth conduction current (I) and electric field (E) during fair weather by Cobb (1967) at Mauna Loa Observatory, Hawaii (3400 m asl) usually increased following periods of solar flare activity. These measurements confirmed the earlier investigations of Bauer in 1924 and Reiter in 1964. The measurements were taken over a one-year period from September 1960 to September 1961, with one-third of the days considered disturbed solar days due to solar flare activity. The measurements were made above the mixing layer, preventing large fluctuations of the fair-weather electrical parameters due to space charges. The values of the air-Earth conduction current (I) and the electric field (E) for "quiet and disturbed solar days" (Cobb, 1967) were an average taken over the one-year period. The average values of these parameters were found to be about 10% larger on the disturbed solar days than on quiet solar days. For 80% of the

flares, the air-Earth current density increased during the first 24 hours following a flare (Fig. 7).

Of greater significance was the occurrence of solar flares in July 1961. During the last twenty days of the month, twelve flares occurred. The air-Earth current and electric field reached their highest values of the year and exceeded the normal 24 hour values by 35%. On July 15, the air-Earth current density exceeded the normal value by 75% in one six-hour period! Cobb suggests that it is indeed a result of solar flare activity and not the global thunderstorm distribution. He concludes that the suggestion concerning the association of large values of the air-Earth current to the "natural abundance of thunderstorm activity during the Northern Hemisphere summer" cannot be responsible for the high air-Earth current densities in July 1961. Even though July is the peak thunderstorm month for the Northern Hemisphere, likewise January is the peak thunderstorm month for the Southern Hemisphere, but no flares were observed in January 1961 and the air-Earth current density was mostly below normal for the month. An alternate idea for this increase in current density and fair-weather electric field will be discussed in the section on stratospheric-tropospheric exchange.

Reiter (1972) also confirms the existence of a correlation between solar flares and the fair-weather electric field (E) and air-Earth current (I). Measurements of E and I for five periods in 1968 and 1969 were used in the study. The measurements were made at Zugspitze peak (3000 m asl) in the Bavarian Alps. As was the case for Mauna Loa, the measurements were made above the mixing layer. The results of this

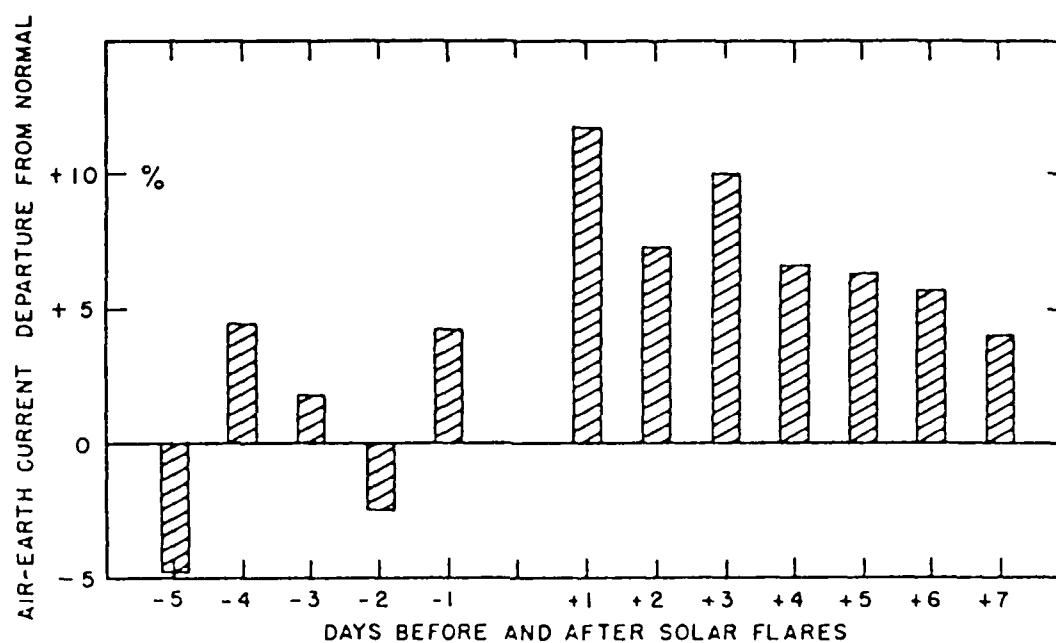


Figure 7 The average daily departure from normal of the fair-weather air-Earth current before and after solar flares (Cobb, 1967).

study showed a 10-30% increase in E and I three to four days after the flare event. This is in agreement with the travelling time from Sun to Earth required of particles travelling with the solar wind velocity. Similarly, Sartor (1980) discovered a correlation between flare events and the air-Earth current and the electric field. Upon re-examination of the atmospheric electrical data taken on Niwot Ridge, Colorado (3744 m asl) from 1966 through 1968, Sartor found an increase in the electric field strength one day after flare occurrence with the maximum occurring three to four days after flare occurrence (Fig. 8a,b).

Reiter (1977a, 1979a) investigated the relationship of solar sector boundary passages to atmospheric electrical properties (E and I). The measurements of E and I were taken from May 1964 to February 1975 during fair-weather days on Zugspitze peak. The results were as follows:

(1) a significant increase in E and I one day after the towards/away (-/+) boundary passage

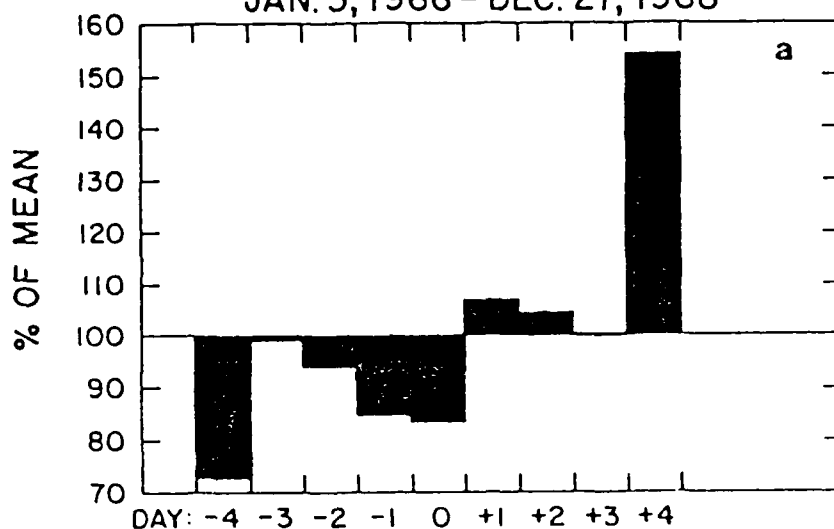
(2) a decrease of E and I prior to the away/towards (+/-) boundary passage and a significant increase on the day of the passage.

When the solar sector boundary data is divided into years of maximum and minimum solar activity, the results are more pronounced during periods of maximum solar activity despite the reduction of data. The results were:

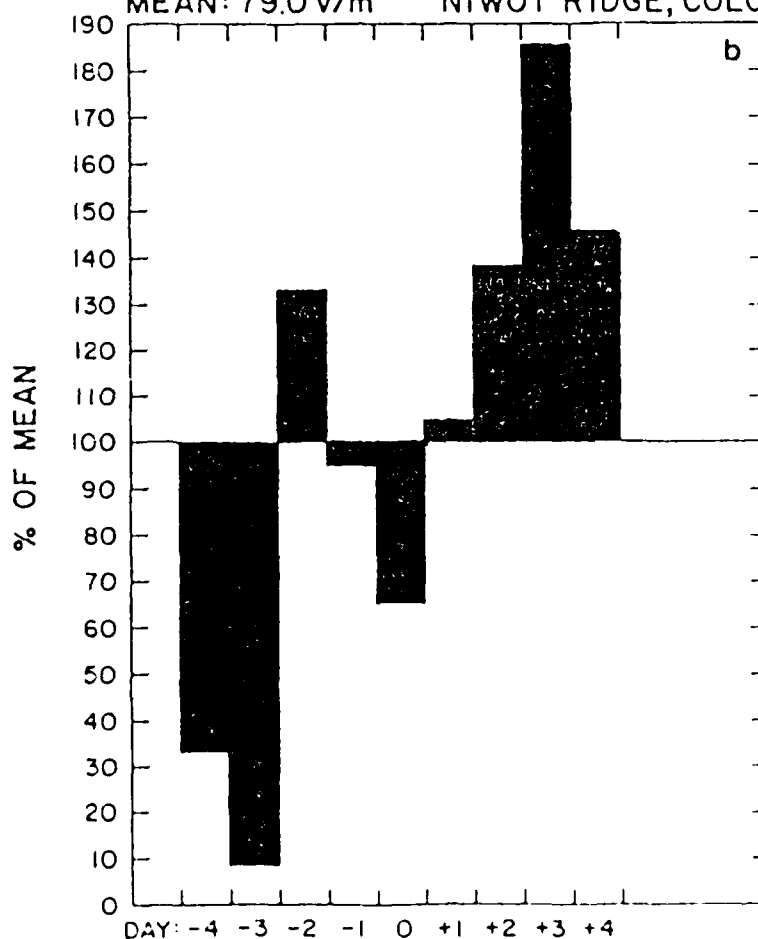
(1) a 20-30% increase in E and I one day after the towards/away passage. A more significant increase than when all the data was considered

Figure 8 (a) Nine cases of consecutive days (81 total days) with fair weather selected from the 408-day sample. The reference day is an actual flare day. (b) Same as (a) except that the reference day is chosen randomly (Sartor, 1980).

MAJOR FLARE DAYS
 ALGEBRAIC VALUES - 9 CASES
 MEAN: 79.5 v/m NIWOT RIDGE, COLO.
 JAN. 5, 1966 - DEC. 27, 1968



E-FIELD - RANDOM "O" DAYS
 ALGEBRAIC VALUES - RANDOM CHOICE
 MEAN: 79.0 v/m NIWOT RIDGE, COLO.



(2) for the away/towards passage, the increase was approximately the same as when all the data was considered (a 15% increase) and the increase still occurred on the day of the passage.

The report of Park (1976) is of interest since his results were different from those of Reiter. Park obtained atmospheric electric field measurements at Vostok, Antarctica (3488 m asl) which is located at the southern geomagnetic pole. His investigation showed a 15% decrease in the electric field one to three days following a boundary passage (Fig. 9). The data also indicated a seasonal variation, with the electric field larger during the Southern Hemisphere winter than during the equinoxes (Fig. 10). Although the difference in Reiter's and Park's results are not clear, Herman and Goldberg (1978a) suggest some ideas for the difference. The first possibility may be the small data sample used by Park compared to the 11-year sample used by Reiter, while a second possibility is that of a latitudinal effect. Another reason for the difference may be that the locations used were in opposite hemispheres and thus, the response lag is dependent on the "difference in coupling of the IMF to the geomagnetic field during different dominant solar field direction periods". The next subject deals with extraterrestrial forcing on thunderstorms. This will give a clearer picture of the thunderstorm-atmospheric electrical connection before discussing the proposed atmospheric electrical linking mechanism.

Many forms of extraterrestrial forcing have been identified with thunderstorm activity over the past 15-20 years. The effects of solar flares on thunderstorm activity are considered first. Using the

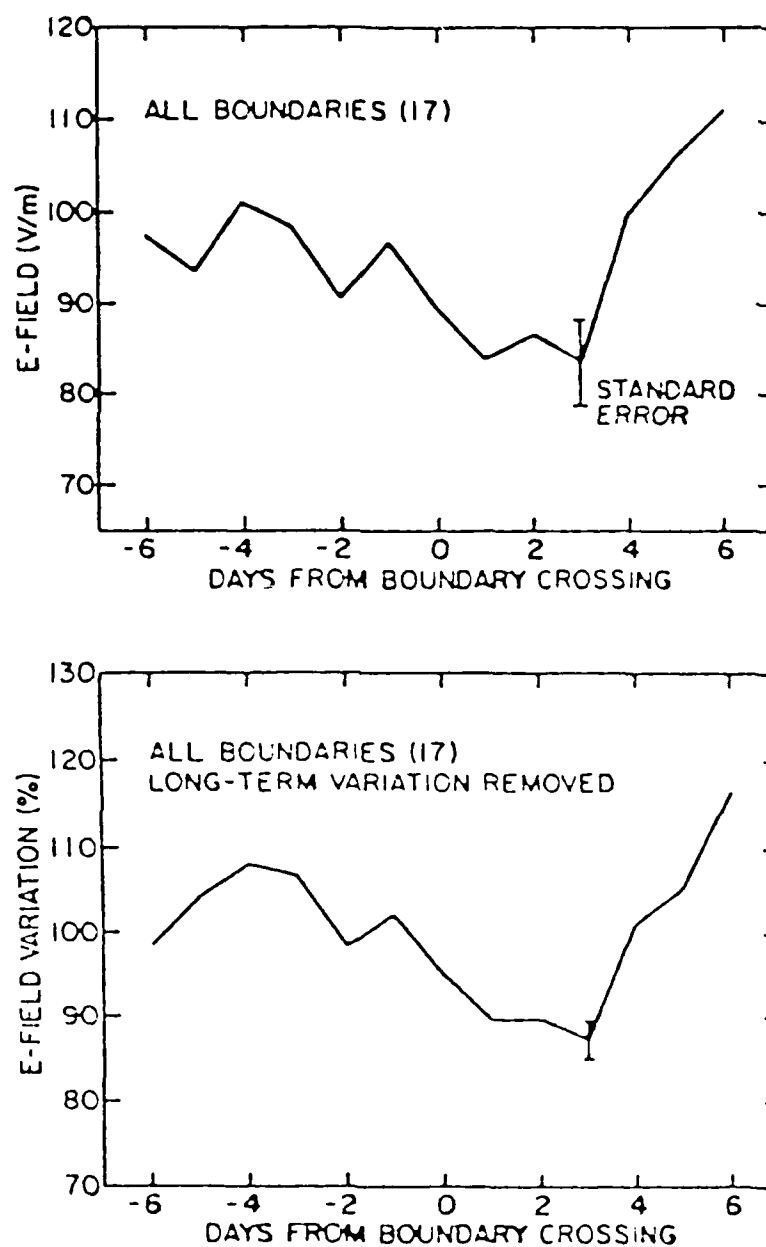


Figure 9 The upper figure is the average behavior of the Vostok electric field about the times of solar magnetic sector boundary crossings. The number in parenthesis indicates the number of cases. The bottom figure is the same as the upper figure except that long-term variations have been removed (Park, 1976).

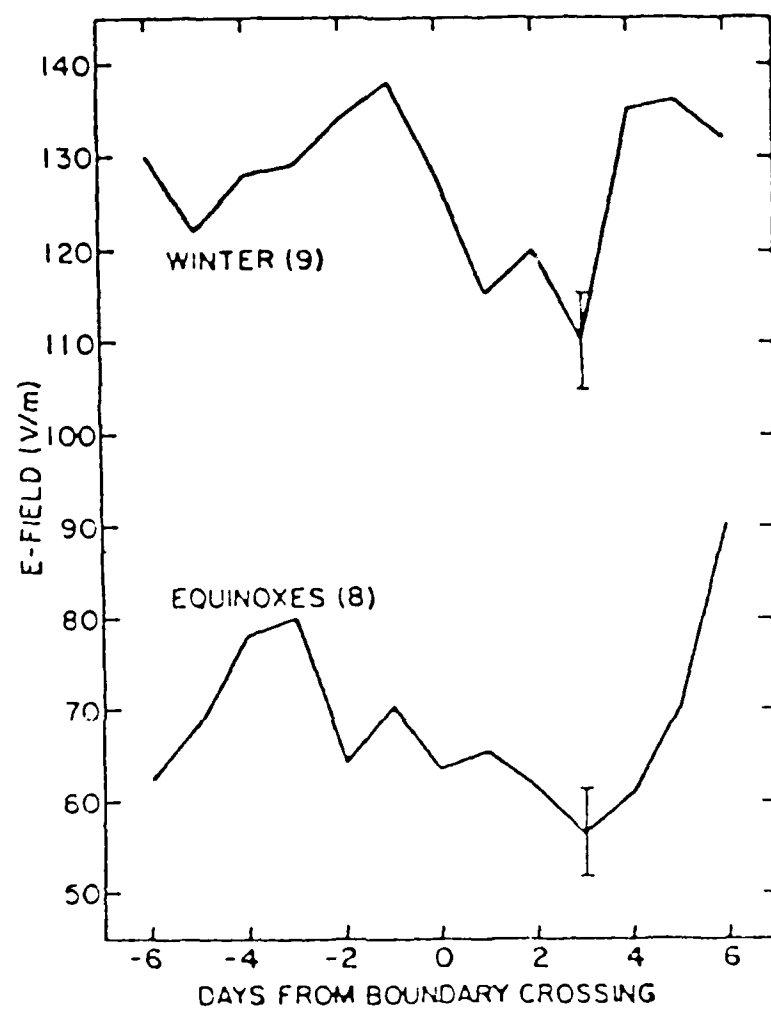


Figure 10 Same as Fig. 9 except that the winter data are separated from the rest (Park, 1976).

electric field measurements of Cobb and Reiter and the thunderstorm data from Lethbridge, Markson (1971) found an increase in thunderstorm activity three to four days after solar flares. Markson indicated the probable cause is "solar cosmic rays" (the high energy component of solar corpuscular radiation consisting mostly of protons). The solar cosmic rays are able to penetrate deep into the atmosphere thereby modulating the Earth's electric field or creating secondary cosmic radiation which could penetrate deeper into the atmosphere, increasing the fair-weather electric field near the ground. The results of Bossolasco (1973a) were similar to those of Markson. Bossolasco found thunderstorm activity over the Mediterranean area to be correlated with solar corpuscular radiation emitted by strong solar flares (those H_{α} -flares with an importance of two or greater) during the time period from 1961 to 1971. The daily planetary geomagnetic index, A_p (a measure of the solar corpuscular activity emitted by the flare), was compared with thunderstorm activity (Fig. 11). The results showed an increase in the A_p index after strong solar flares, reaching a maximum on the third day, while thunderstorm activity showed an increase on the third and fourth day (by almost 38% and 55%, respectively) following the flare.

Markson (1971) also proposed the solar sector boundary passage relationship to thunderstorm activity. He discovered that thunderstorm activity maximized when the Earth crossed from a positive sector to a negative sector. On further examination, it is noted that "most of the increase in thunderstorms for the positive sectors came from only one of the two which had contained a long-lived stream of solar protons"

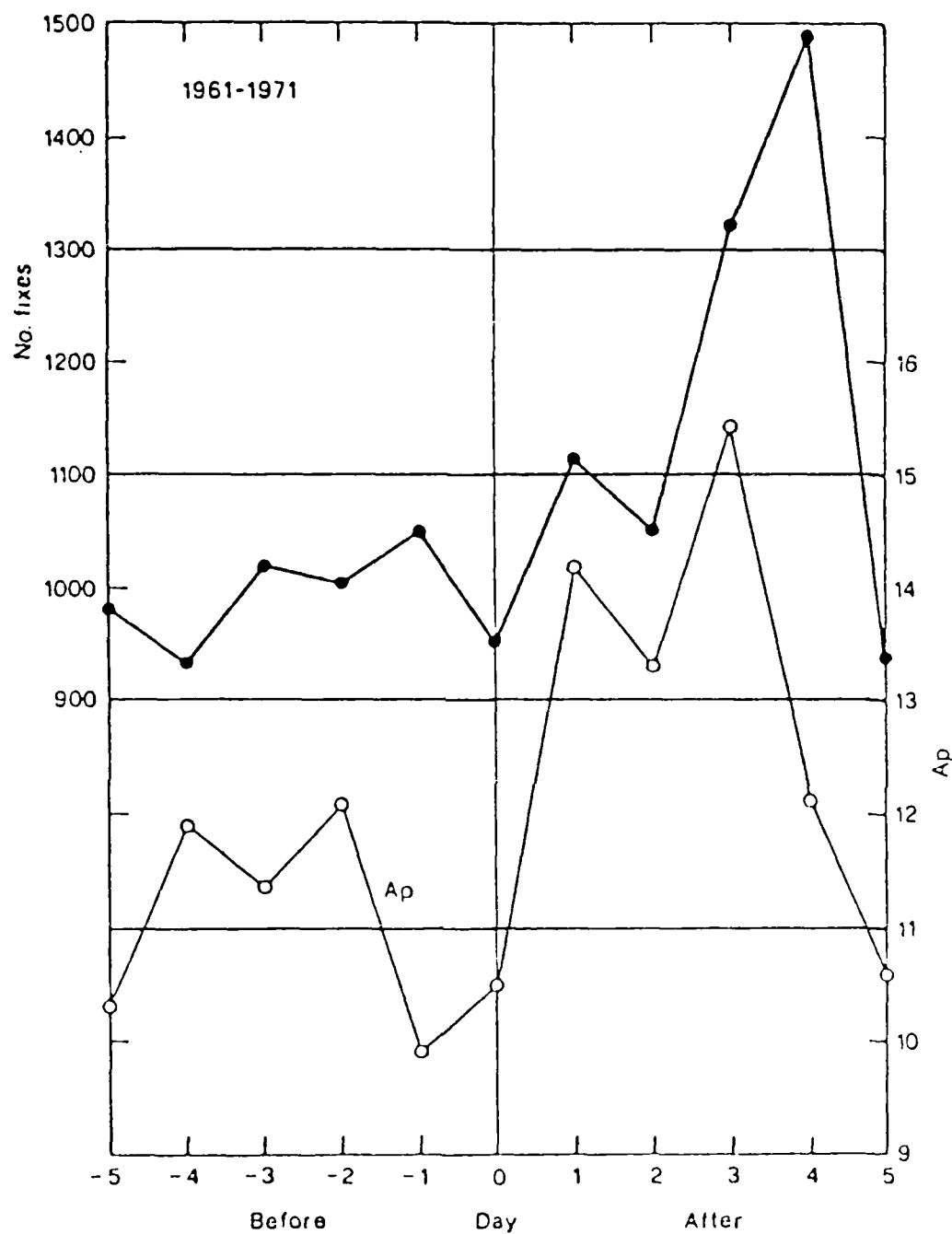


Figure 11 Superposed epoch analysis of the daily thunderstorm activity (heavy line) and of the corresponding planetary geomagnetic index A_p before and after a strong H_α -flare, assumed as key-day (1961-1971). The number of fixes are representative of the thunderstorm activity (Bossolasco, 1973a).

(Markson, 1971). Again, Bossolasco's (1973b) results were similar. He found a correlation between the thunderstorm activity over the Mediterranean area and boundary passage for the 1961-1971 data (Fig. 12). The data revealed a minimum in thunderstorm activity one day before a positive to negative boundary crossing the Earth, and a maximum two days after the crossing. Lethbridge (1979) also found a correlation between solar sector boundaries and thunderstorm frequency in the winter for the eastern two-thirds of the United States from 39°N to 45°N latitude. Thunderstorm frequency maximized one day after passage. More important, however, is the work of Lethbridge (1983, 1986) dealing with galactic cosmic rays and thunderstorm activity. A brief discussion on galactic cosmic rays precedes that discussion.

Primary galactic cosmic rays are produced within our galaxy. Their energies range from tens of MeV to hundreds of GeV and they are nearly isotropically distributed near the Earth (Herman and Goldberg, 1978a). The energies are more than large enough to penetrate into the atmosphere where they interact with atomic nuclei to produce secondary cosmic rays which may reach to the Earth's surface. More importantly, the interaction with atomic nuclei produce on the order of 10^7 ions per particle (Dickinson, 1975). The height where maximum ionization occurs is at the point where only $1/e$ of the initial particle energy remains. Maximum ion production peaks at about 13 km altitude (near the tropopause) at high latitudes and at about 13 km altitude near the magnetic equator. Since particles with energies less than several GeV cannot reach equatorial latitudes, the ionization rates are lower at the magnetic equator than at high latitudes.

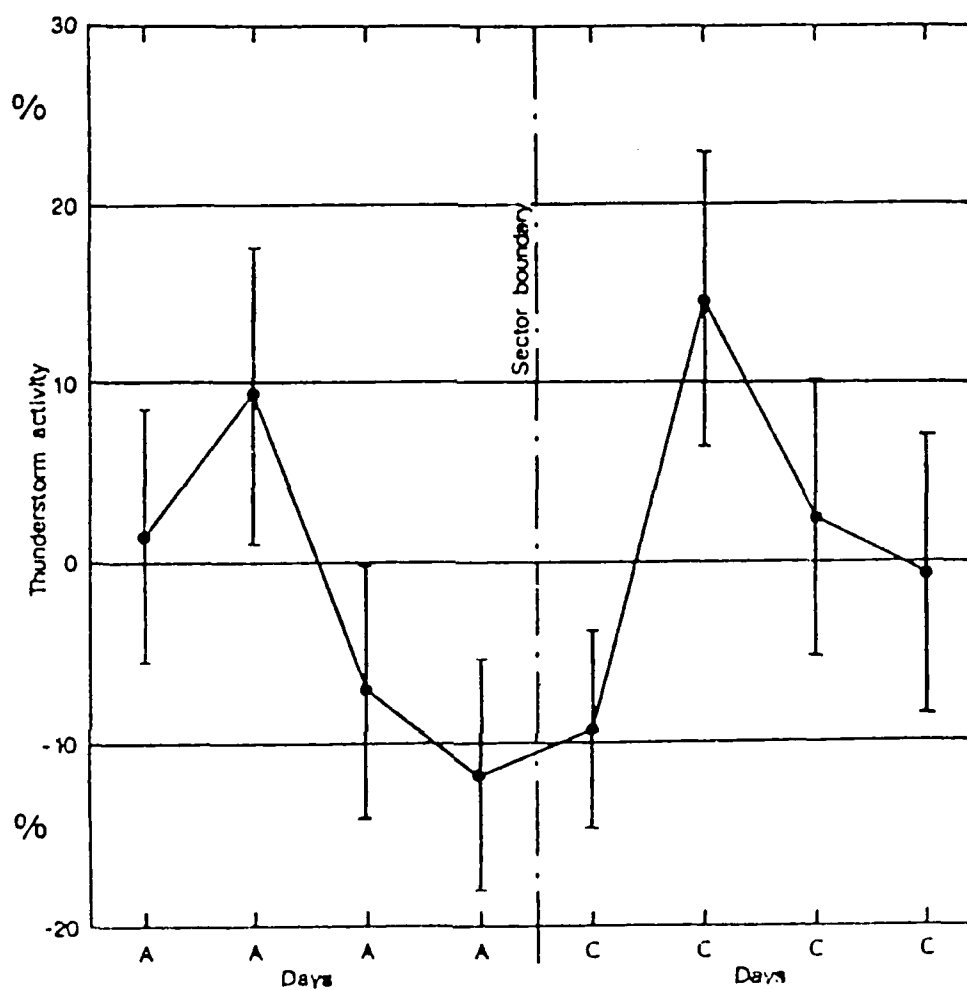
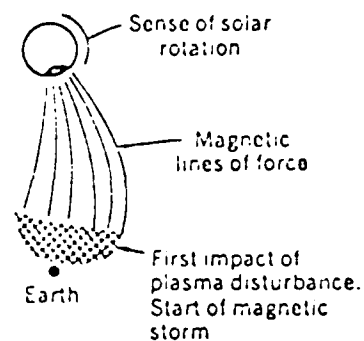
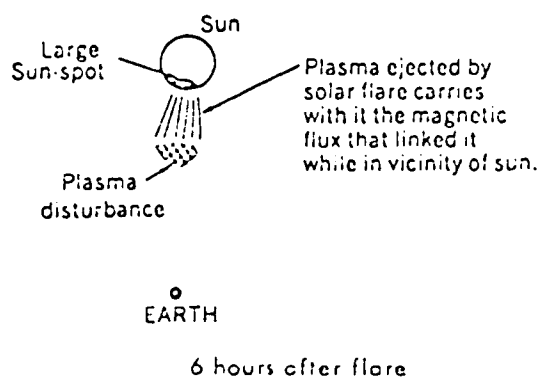


Figure 12 Average response of the thunderstorm activity (as expressed by the daily percentage deviation of sferics rate) to the IMF sector structure sweeping past the Earth, in the case of Earth crossing from an A-sector to a C-sector. (A = away sector, C = toward sector). The standard error of the mean is indicated by an error segment (Bossolasco, 1973b).

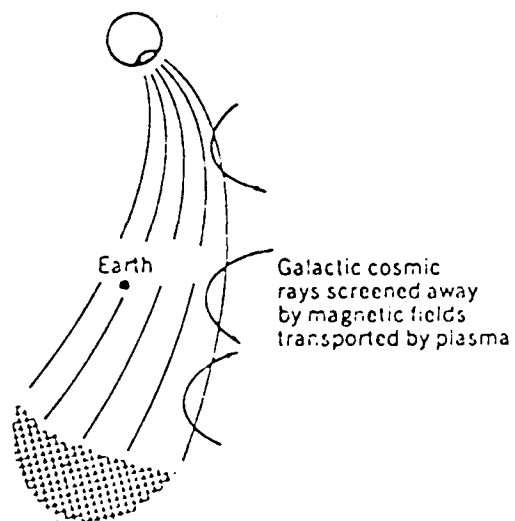
The intensity of galactic cosmic radiation has been shown to vary inversely with solar activity. Short-term variations in cosmic ray intensity have been detected following solar flares (Forbush decrease) and solar magnetic sector structure crossings. Markson (1971) mentions decreasing galactic cosmic radiation associated with the 11-year sunspot cycle. Markson suggests the mechanism responsible for the decrease in cosmic ray intensity is the shielding of the Earth "by an enhanced solar plasma strengthening the interplanetary magnetic field" during periods of solar activity (Fig. 13).

Returning to the investigation by Lethbridge, she proposes a possible connection between cosmic rays, solar sector boundaries and thunderstorm frequency. A summary of her results indicates a significant increase in thunderstorm activity almost three days after high cosmic rays over the eastern two-thirds of the United States from 39°N to 45°N latitude (Fig. 14a), and over the eastern two-thirds of the United States as a whole (Fig. 14b). Furthermore, high latitude thunderstorms were compared to solar sector boundary days which had high cosmic ray deviations one day before boundary passage. The result was nearly the same as in the above situation, except the result was statistically more significant.

However, these conclusions were in disagreement with those of Ney (1959). Ney hypothesized that an increase in solar activity decreases the cosmic ray flux and atmospheric ionization leading to an increase in thunderstorm activity. Upon re-examination of her cosmic ray data, Lethbridge (1986) used days of high values of cosmic ray deviations from the annual mean which changed her results significantly. The



About 24 hours after flare



About 48 hours after flare

History of a solar proton event.

Figure 13 Schematic illustrating how an enhanced solar wind plasma shields the Earth from some galactic cosmic radiation (Hess et al., 1965).

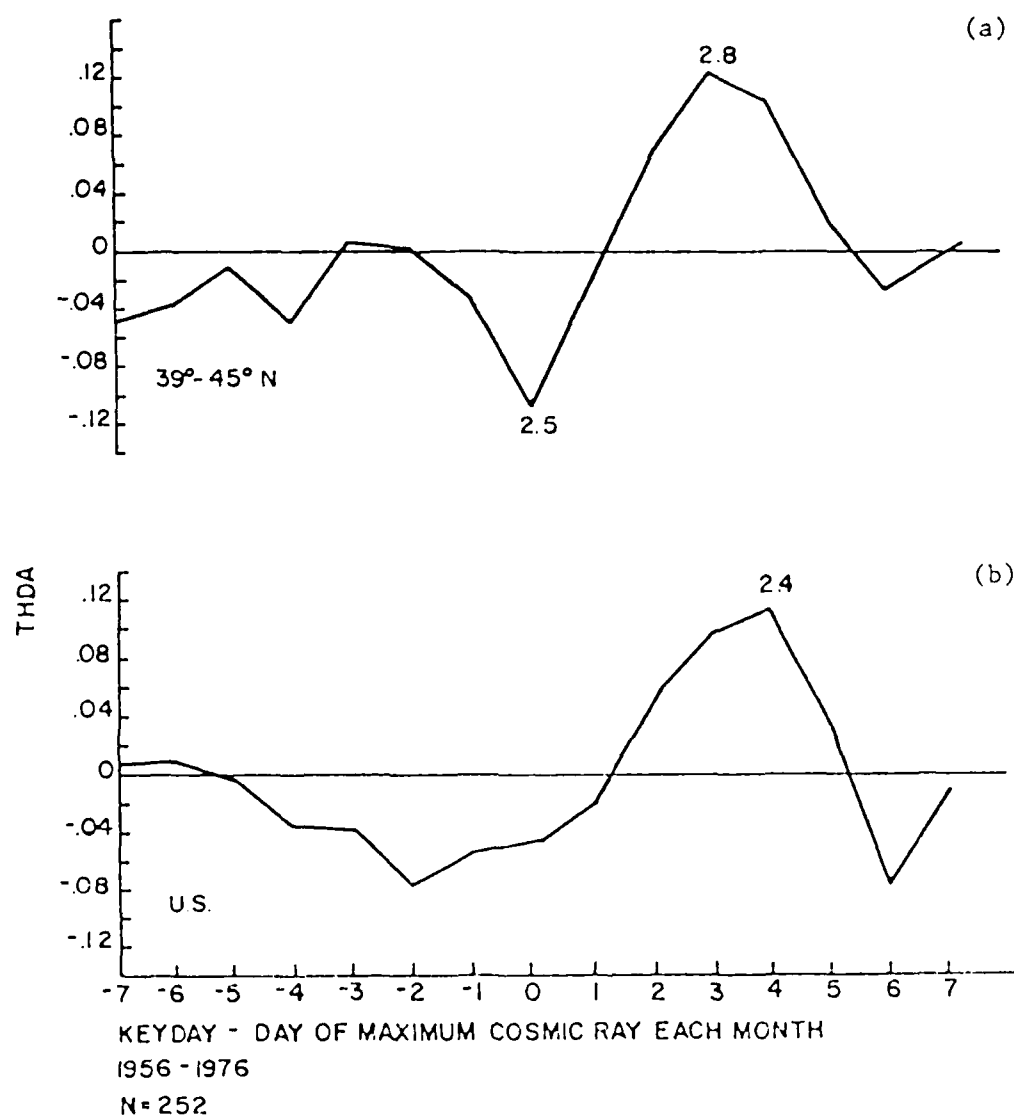


Figure 14 (a) Thunderstorm frequency index, THDA, for 39°N to 45°N latitude shows a maximum three days after the day of maximum cosmic rays for 1965-1976 with $N = 252$. (b) THDA for the United States shows a maximum three to four days after the day of maximum cosmic rays for 1956-1976 with $N = 252$ (Lethbridge, 1983).

maximum in thunderstorm activity two to four days after high cosmic rays was not as pronounced. However, there was a significant decrease in thunderstorm frequency on the day which had high values of cosmic ray deviations itself. This investigation brings her work in line with the hypothesis of Ney.

Furthermore, Ely's (1984) interpretation of Lethbridge's results is based on the strong cosmic ray minimum that occurs after a boundary passage preceded by a cosmic ray maximum. Ely contends the increase in thunderstorm activity two to four days after high cosmic rays coincides exactly with the cosmic ray minimum. Ely suggests "that the cosmic ray decrease causes the lightning maximum." Although this is based on a magnetic coupling model, this point will be important when considering the proposed stratospheric-tropospheric exchange mechanism.

Finally, Stringfellow (1974) reported a correlation between the 11-year sunspot cycle and the mean incidence of lightning in Britain. The five-year means of the annual values of mean lightning index and the mean sunspot number (from 1930-1973) were positively correlated despite the year to year variations (Fig. 15). The amplitude of lightning incidence is $\pm 30\%$ of the mean with an 11-year period.

3.1.3 The Atmospheric Electrical Mechanism

The advantage the atmospheric electrical mechanism has over the others is it does not depend directly or indirectly on solar heating as most of the others do. According to Markson (1978), the atmospheric electrical mechanism has three distinct advantages over heating related mechanisms. They are as follows:

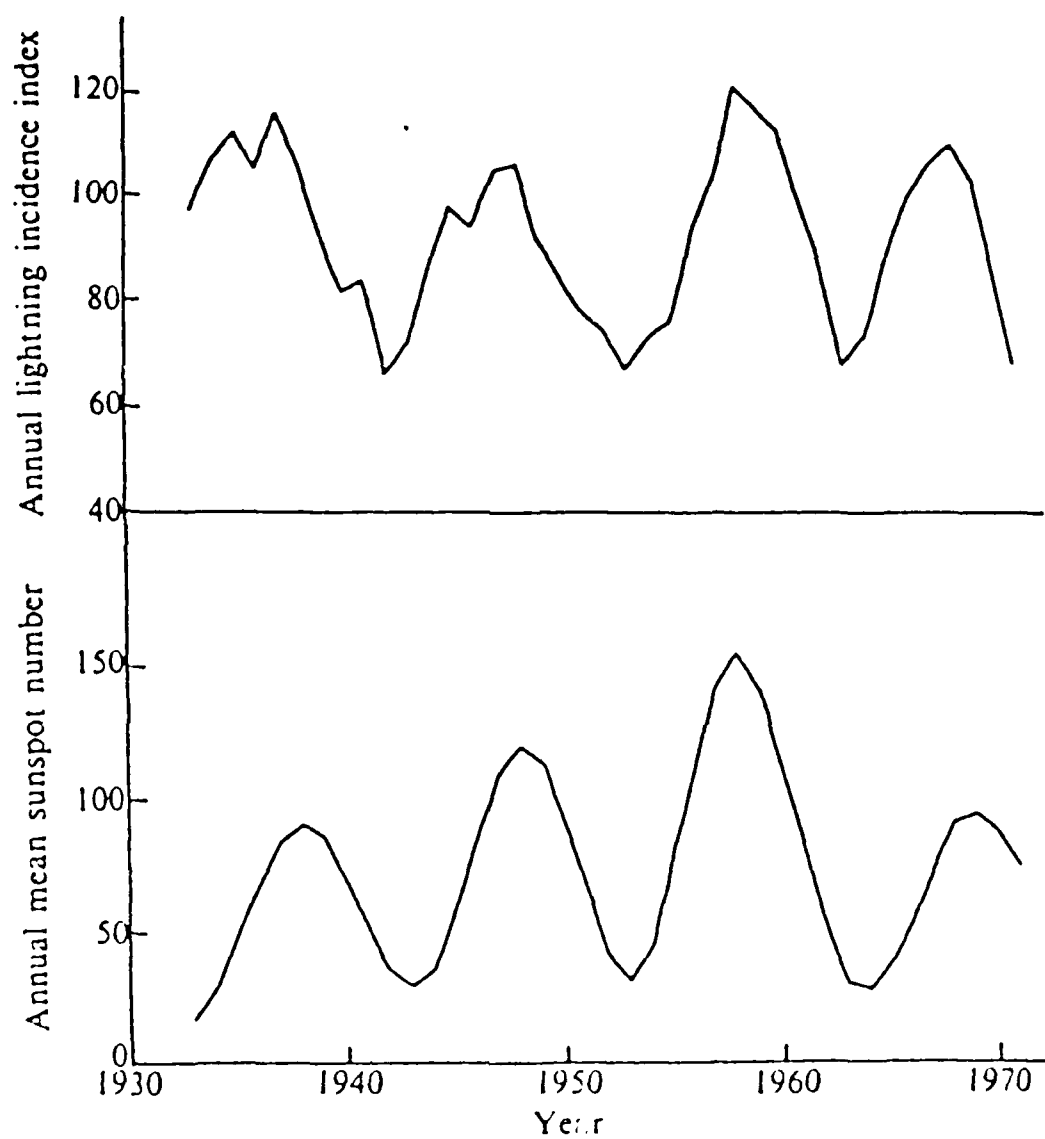


Figure 15 Annual variation of the five-year running means of lightning incidence and sunspot number (Stringfellow, 1974).

(1) energy - no solar energy is required to alter the Earth's electric field and stratospheric conductivity, yet the mechanism offers the possibility of releasing and redistributing large amounts of energy already in the troposphere.

(2) coupling - the largest temperature variations due to solar activity occur in the upper atmosphere; these may be very weakly linked to the troposphere at best. The atmospheric electrical mechanism requires no coupling of energy from the upper to the lower atmosphere since the entire electric field from the ionosphere to Earth will be affected. And

(3) time delays - heating mechanisms may require several days before the lower atmosphere would be affected. The atmospheric electrical mechanism provides a rapid response since a change in ionospheric potential rapidly affects the global electric field intensities.

3.1.3.1 Markson's Model

This discussion of atmospheric electricity as a linking mechanism begins with a review of the classical global circuit by Markson (1978, 1979a, 1983). The main charge structure within a thundercloud is similar to an electric dipole (Uman, 1969) with positive charge at the top and negative charge at the bottom of the cloud (Fig. 16). The worldwide thunderstorm activity acts as a d.c. generator, causing current to flow through the circuit and maintaining the Earth's electric field. Conduction currents exist because the atmosphere is ionized. The isotropic flow of galactic cosmic rays maintains the

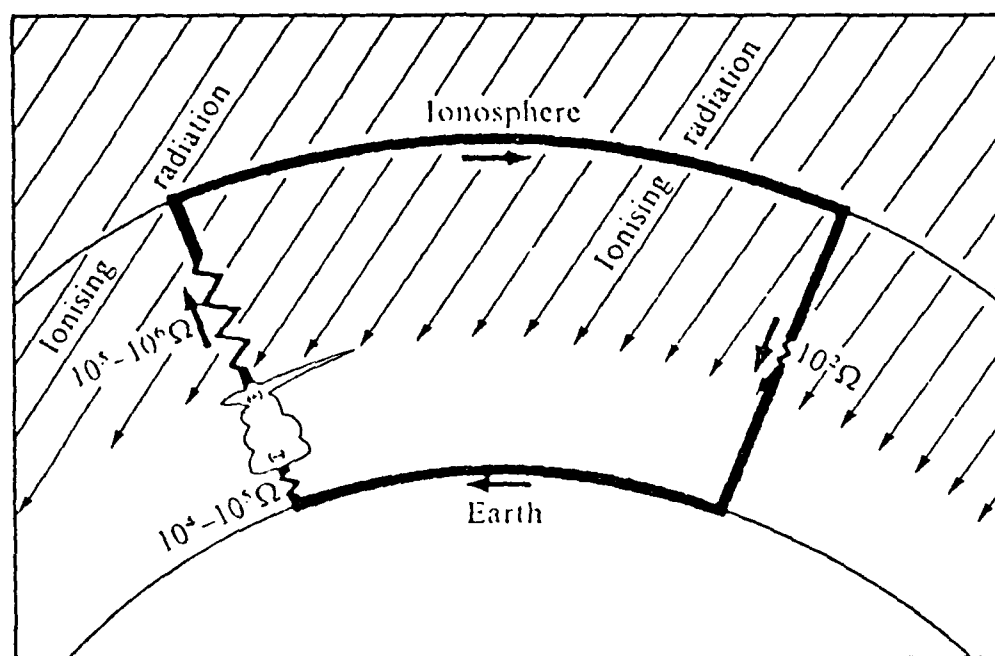


Figure 16 Model of the global circuit. Large arrows indicate flow of positive charge. Estimated resistances of circuit elements are given. The thunderstorm depicted represents the global electrical generator, that is, the totality of all global thunderstorms. The arrows indicate the accessibility of the controlling resistive element above the thunderstorm generator to the varying component of the ionizing radiation (Markson, 1978 and Markson and Muir, 1980).

atmospheric conductivity augmented in the stratosphere by solar corpuscular radiation and Bremmstrahlung X-rays from magnetospheric and auroral particle precipitation.

Over the surface landmass, two-thirds of the ionization at the surface is due to radioactive gases and emanations from the ground. The conductivity increases exponentially with altitude above the planetary boundary layer due in part to the increase in cosmic radiation. As the conductivity increases, the potential gradient decreases (Chalmers, 1957), and at 60 km an equipotential surface is considered to exist due to the large conductivities and very small potential gradients. In terms of the global circuit, this equipotential surface is the "ionosphere" (Markson, 1978) and it is characterized as the outer shell of a spherical capacitor. The Earth's surface is the inner conductor with the atmosphere ("leaky dielectric" (Markson, 1978)) between the two. A charging resistor exists above the thundercloud and a conduction current flows from the thundercloud tops to the ionosphere. Vonnegut et al. (1966) found a negative potential gradient existed from measurements taken over the cumulus turrets (overshooting tops) of thunderstorms which is in agreement with the classical theory. The charging current maintains the ionospheric potential (the overall intensity of global atmospheric electrification) at about 250 kV relative to the Earth. For the return portion of the circuit, a conduction current flows through the "load resistor" (Markson, 1978) in the fair-weather regions; positive ions drift downwards, the negative ions drift upwards. The complete circuit includes the area between the Earth and the thundercloud base, where

the current flow is maintained by precipitation, conduction (including corona), convection and lightning.

A closer look at the resistive elements shows that about 90% of them are above the thunderstorm (Markson, 1978). Again considering Vonnegut's work, we see that the current flows from the thunderstorm turrets. Since this area covers generally less than one tenth of a percent of the Earth's surface, the charging current must flow through a larger resistance ($10^5 - 10^6$ ohms) (Fig. 16). The fair-weather return flow covers most of the Earth's surface area, therefore the resistance is very small (about 150 ohms). The resistive elements between the thundercloud and the ground would be the largest if not for charge transfer. Although difficult to estimate, Markson suggests an order of magnitude increase in the conductivity beneath the thundercloud and therefore an order of magnitude decrease in the resistance ($10^4 - 10^5$ ohms). This is nearly 10% of the total global circuit resistance. Therefore, most of the resistance of the circuit is above the thunderstorm (about 13 km in mid-latitudes). Referring to the discussion of galactic cosmic rays, the maximum ion production peaks at about this height. Ionization in the fair-weather portion of the circuit at this altitude would be of little consequence since the resistance is small in this element. How then does atmospheric electricity link solar activity to weather?

Markson (1978, 1979a, 1983) and Markson and Muir (1980) propose the following mechanism: that changes in the resistance above the thunderstorm generator occur through solar controlled variations in the ionizing radiation. The resistive element above the thundercloud acts

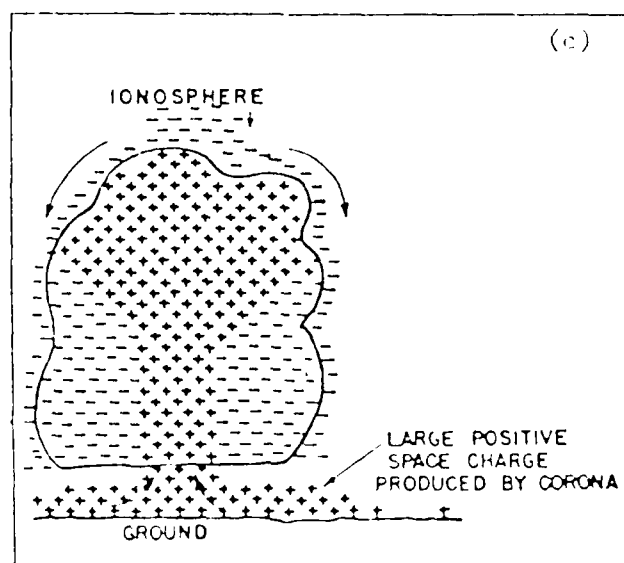
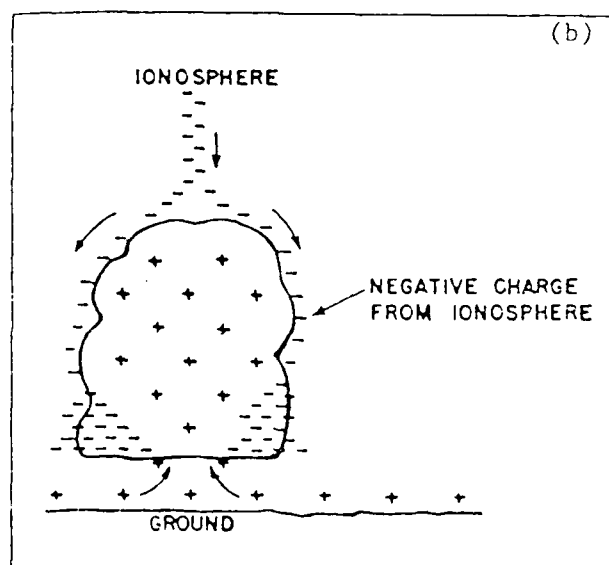
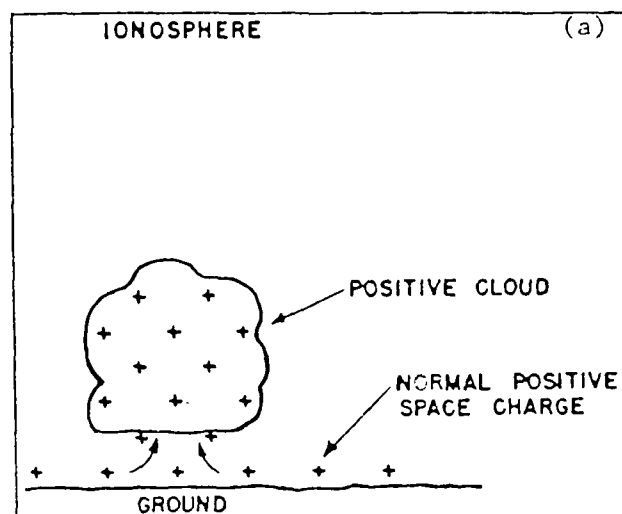
as a valve regulating the global circuit flow. The ionospheric potential and fair-weather electric field adjust proportionally to the modulating charging currents. Markson (1979b) clearly indicates that the ionizing radiation need not reach the thundercloud tops to increase the current flow. The ionizing radiation need only lower the total columnar resistance (increase the conductivity) above the thundercloud in order to increase the current flow to the ionosphere. Markson (1971, 1979a, 1979b) also discusses the high latitude variations of ionization and conductivity throughout a solar cycle. At 10 km the ionization rate increase is 30%. By 15 km, the ionization rate increases 51%, with a 23% increase in conductivity while at 20 km the ionization rate increases 76%, with a 33% increase in conductivity from solar maximum to solar minimum. Markson (1978) also illustrates the average conductivity variation through a solar cycle for the mid-latitudes and the equator. The mid-latitude variation is ~ 18%, and near the equator it is ~ 10%. Since these are the average values, he infers that larger conductivity variations must exist at times.

Markson and Muir (1980) discuss the misconception of this proposed mechanism. The mechanism explains the variation of the global electric field by solar activity, not a solar-controlled variation in thunderstorm activity. Markson (1978) suggests an increase in stratospheric ionization and/or electric field intensity in order to amplify cloud electrification and increase thunderstorm frequency. However, Markson and Muir (1980) note, "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". Nevertheless, Markson (1978) and Markson and Muir (1980) proposed two possibilities for increasing thunderstorm electrification. The first is a direct local effect caused by increased ionization above the thundercloud which enhances the ionospheric conductivity. The second is an indirect worldwide effect due to an amplified electric field in the troposphere.

Markson and Muir base their ideas on the convective theory of thunderstorm electrification (Vonnegut, 1955). Because the ionosphere is maintained at a positive potential with respect to the Earth, a positive current flows continuously from the ionosphere to the Earth as a result of this potential difference. The positive ionosphere potential is maintained by worldwide thunderstorm activity. The current establishes a slight excess of positively charged Aitken nuclei in the lower atmosphere. Vonnegut (1955) postulated that the initiation of the electrification process in developing clouds can be attributed to these small positive space charges. Furthermore, convection of fair-weather positive space charge into developing cumulus clouds may be responsible for the initial development of the positive space charge center in the cloud (Fig. 17a). Ionization over the developing cloud provides a source of negative charge. As the cloud grows, it reaches an altitude where the electrical conductivity is greater than at lower levels. The potential gradient at the cloud top is considerably greater than the normal positive gradient at that height and in the opposite direction. Consequently, the small negative ions flow from the ionosphere to the cloud top where the positive space charge resides (Fig. 17b). The negative charge becomes attached to the

Figure 17 The convective theory of thunderstorm electrification. (a) The formation of the cloud containing small positive charge; (b) the development of the negative charge center in the lower part of the cloud; (c) The intensified electrification resulting from point discharge on the ground (Vonnegut, 1955).



cloud particles and Aitken nuclei at the cloud surface where they are then transported to the sides of the cloud by the divergent wind field. The downdrafts carry the negative charge to the bottom of the cloud, thus becoming the negative charge center in the thunderstorm electrical dipole.

The negative charge center continues to grow until it finally produces a field large enough to cause point discharge (corona) from the Earth's surface (Fig. 17c). The positive ions are prevented by the wind from moving towards the negative charge that induced them. Thus, the positive charge center grows as the positive ions are carried aloft by the updrafts. This reinforces the rate at which the negative ions are attracted to the cloud top and carried to the lower part of the cloud. The charge centers grow until the potential gradient is large enough to produce lightning.

An increase in the ionospheric potential would increase the space charge since space charge is formed by the air-Earth conduction current flowing through a medium of varying conductivity. This increase in space charge may affect the initial electrification process of developing cumulus clouds. Therefore, increased ionization above the developing cloud would increase the flow of charge to the cloud and enhance electrification. An enhancement in electrification may lead to enhanced cloud physical processes, which may ultimately lead to changes in the Earth's radiation balance. Markson and Muir (1980) conclude: "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."

3.1.3.2 Hale's Model

In light of experimental observations gathered to date, Hale (1979, 1983) perceives the classical global circuit model and hence, Markson's theory on the atmospheric electrical linking mechanism as inadequate. The criticism of Markson's model is based on Hale's contention that ionization events do not produce the required conductivity changes above the thunderstorm tops that Markson's model requires except during rare solar proton events. Hale (1983) suggests a mechanism whereby "auroral events whose radiation penetrates only to the mesosphere may influence lower latitude and altitude electrical phenomena." The modified global electric circuit as proposed by Hale will be discussed prior to discussing this mechanism.

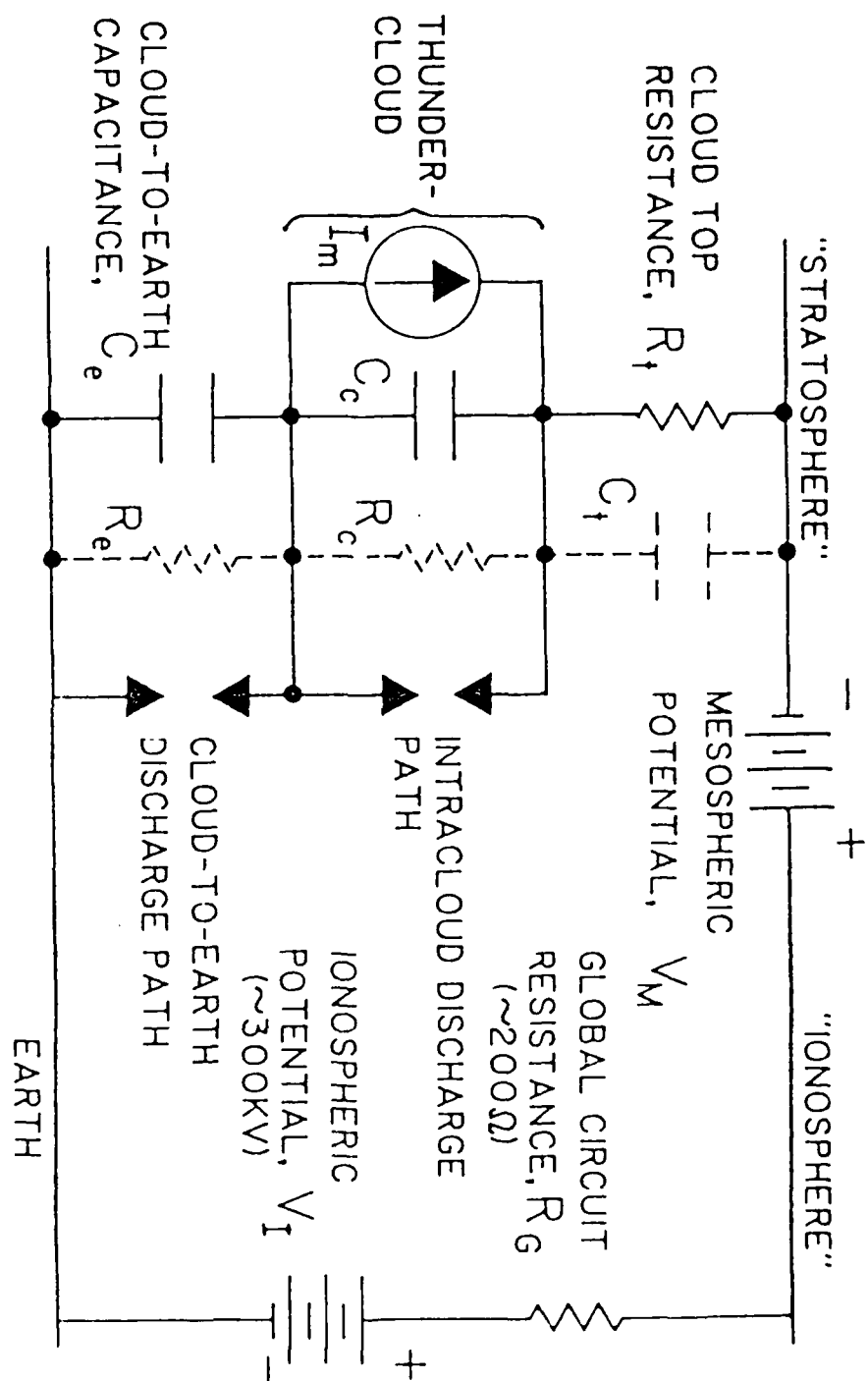
Hale (1983) proposes a modified global circuit that considers capacitive as well as resistive elements. With regard to the thunderstorm generator, the model accounts for lightning transients and the highly non-uniform global ionosphere. Measurements made by Hale above a small off-shore thunderstorm indicated "that lightning causes a large pulse of conduction current to flow to the ionosphere and global circuits and, if the result is generally true of most thunderstorms, cloud-to-Earth lightning represents a major fraction of the global

circuit current." He further suggests the total global circuit current (~ 2000 amps) can be represented by the estimated charge displaced (~ 20 coulombs/flash) by the global cloud-to-Earth lightning rate (~ 100 flashes/second). Hale's model suggests the thunderstorm current generator (I_m) charges capacitor C_c directly and C_e through R_t , the ionosphere and the global circuit (Fig. 18). When C_e or C_c reaches breakdown, lightning occurs. The three components of current to the global circuit are:

- (1) the current charging C_e through R_t and the global circuit
- (2) plus the transient discharge of C_c when C_e discharges
- (3) minus the transient discharge of C_e when C_c discharges.

Hale (1983) points out that most global circuit models do not consider the horizontal gradients in the ionospheric conductivity. Because of the small contribution of the upper atmosphere to the columnar resistance, the thunderstorm currents that flow to the high ionosphere and the magnetosphere have not been considered very important. However, Hale (1983) contends "that the effects of non-uniform mesospheric conductivity on current paths in the upper atmosphere provide a mechanism for coupling between individual thunderstorms and high-latitude phenomena, and a means for high-latitude ionospheric fields to penetrate to lower latitudes." The conductivity variations are produced during very large solar proton events, however, these events are infrequent compared to the events (i.e., the Sun rising and setting) that produce the large conductivity changes at high altitudes. The nighttime conductivities are low compared to daytime or disturbed conditions, yet they are probably

Figure 18 A modified version of the classical global circuit model. Note the inclusion of the capacitive elements and the mesospheric potential. Their inclusion accounts for lightning transients and the non-uniform mesospheric conductivities, respectively (Hale, 1983).



never low compared to the troposphere. Thus, the thunderstorm currents will generally reach the higher ionosphere unobstructed (Hale, 1983). The nighttime thunderstorm currents will follow the line of least resistance in returning to the Earth. The tendency is for these nighttime thunderstorm currents to flow downwards to the lower atmosphere in higher conductivity regions around either day-night or quiet-disturbed boundaries, the latter usually occurring in the auroral zone. "Moderately high-latitude nighttime thunderstorm" (Hale, 1983) currents occurring well away from the dawn or dusk terminator might then return through the auroral zone. Hence, as Hale (1983) suggests: "the non-uniform mesospheric conductivity provides a mechanism for direct coupling between the thunderstorm circuit and auroral currents. This would be enhanced when auroral radiation penetrates more deeply, such as during relativistic electron precipitation (REP) events."

Another facet of Hale's model concerns the large vertical electric fields measured in the mesosphere. Hale suggests two sources for the vertical fields; the poleward or equatorward auroral fields may "turn the corner" (Hale, 1983) and map to lower latitudes as large vertical mesospheric fields. This would explain the high latitude fields, however, the low and mid-latitude mesospheric fields are more likely internally generated by an active mesosphere, with an internal e.m.f. generator, probably related to aerosol. The significance of these large vertical mesospheric fields is described by Hale (1983) as this: "The potential associated with vertical mesospheric fields will add or subtract from the true ionospheric potential at higher altitudes to determine the potential applied across the lower atmosphere, commonly

mis-named the "ionospheric potential". Since this potential is much more easily modulated by frequently occurring solar-geomagnetic events, this provides a much more prevalent coupling effect than events which directly affect the tropospheric thunderstorm circuit. In particular, radiation events which decrease the downward mesospheric field, possibly by shorting it out due to enhanced conductivity, will increase the lower atmosphere fair weather field ..."

In conclusion, Hale is much less certain that this could be a cause or effect of Sun/weather relationships and hence, he suggests looking at more subtle atmospheric electrical relationships.

3.2 Stratospheric-Tropospheric Exchange

3.2.1 Introduction

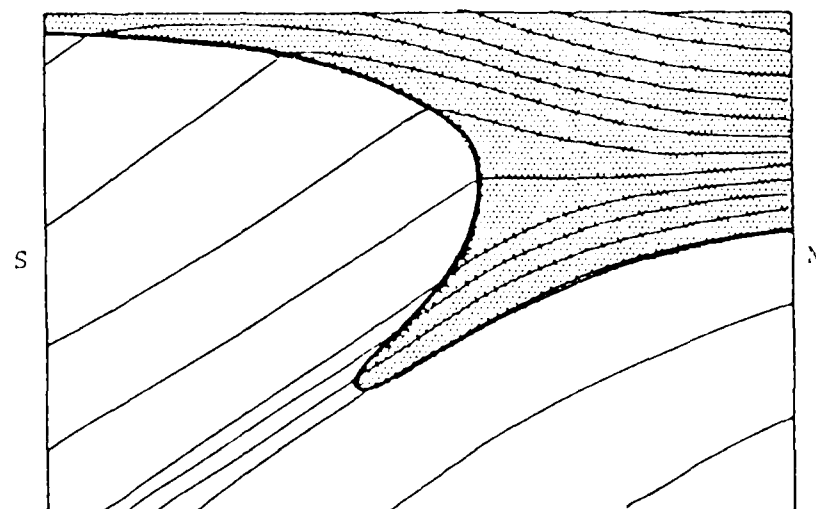
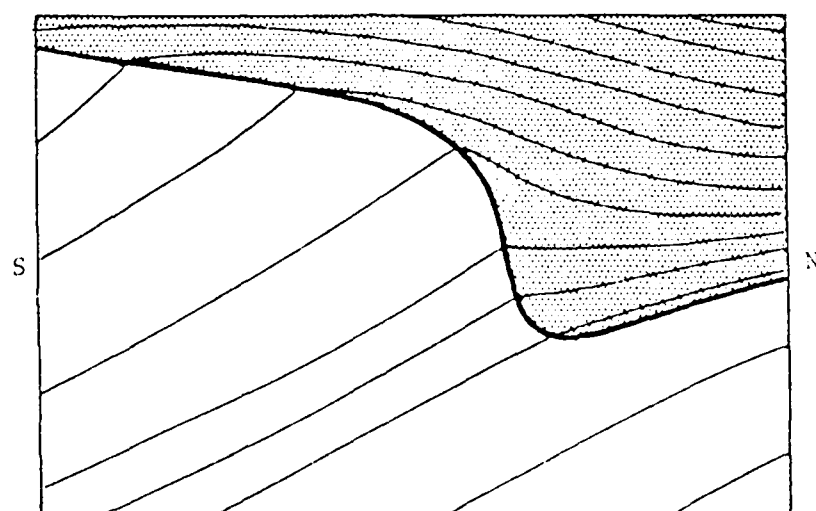
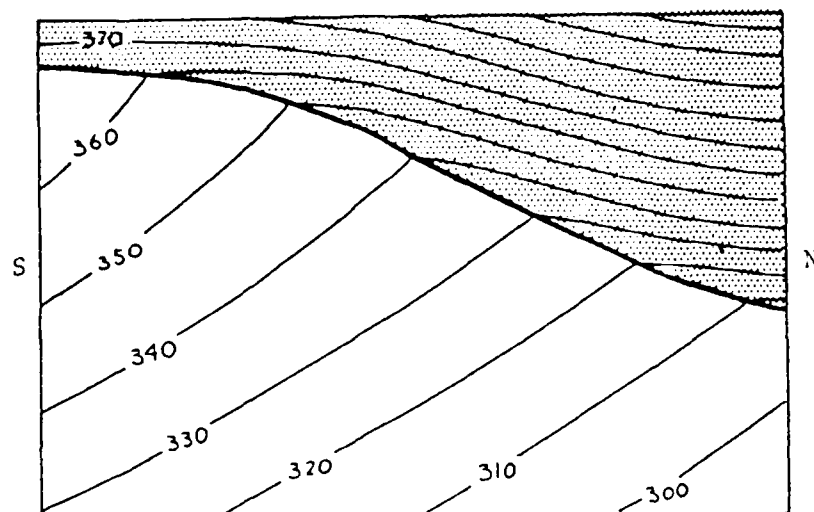
This section introduces the hypothesis that stratospheric-tropospheric exchange may be a linking mechanism between solar activity and weather. The decrease in galactic cosmic rays during increased periods of solar activity plays a major role in the mechanism. The proposed trigger is tropopause folding and thus, the introduction discusses the characteristics of the folding process. The next section provides statistical evidence of extraterrestrial forcing on the exchange process and the final section presents the hypothesis.

Danielsen (1964) states: "As the tropopause folds, air from the stratosphere is drawn out to form a thin layer in the troposphere". Thus, the concept of mass transport from the stratosphere to the troposphere is based on this principle of tropopause folding. Reed (1955) postulated that one possible mechanism for upper-level

frontogenesis is tropopause folding, and indeed, Danielsen's work (1964, 1968) supported Reed's hypothesis. According to Danielsen (1968), "the fold develops in the baroclinic troposphere and stratosphere where the troposphere is initially inclined and where there is a large gradient of θ along the tropopause" (where θ is the potential temperature, Fig. 19). (Note: For the purpose of this section, the tropopause as Danielsen describes it, is not that determined by conventional radiosonde data. Rather, it is a generalized criterion where the location of the tropopause is determined by large spatial changes in the potential vorticity). Furthermore, initiation of the tropopause fold by the quasi-geostrophic shears in the baroclinic atmosphere occurs to the west of developing troughs and vortices. The ageostrophic motions, although frequently too small to measure, produce important stability, vorticity and velocity changes in the stratosphere and troposphere (Danielsen, 1964). The folding process occurs beneath the jet core along the axis of confluence between the direct and indirect circulation cells (Fig. 20). These circulations are responsible for the momentum transport (downward and southward along the warm boundary of the folding layer) which renders the folding process irreversible.

Figure 20 illustrates the mean flow with respect to the tropopause. The mean flow is predominately from the troposphere to the stratosphere (Danielsen, 1968). The concentrations of ozone, radioactivity and potential vorticity are diluted by subsynoptic-scale mixing. The large gradients of these quantities at the tropopause are maintained by the inflow to the stratosphere. These gradients extend

Figure 19 A vertical cross section of a tropopause folding event and tropospheric frontogenesis. The bold line is the tropopause and it separates the stratospheric air (stippled region) from the tropospheric air. The thinner lines are lines of constant potential temperature. The vertical scale extends roughly from 1000-mb to 150-mb (Danielsen, 1964).



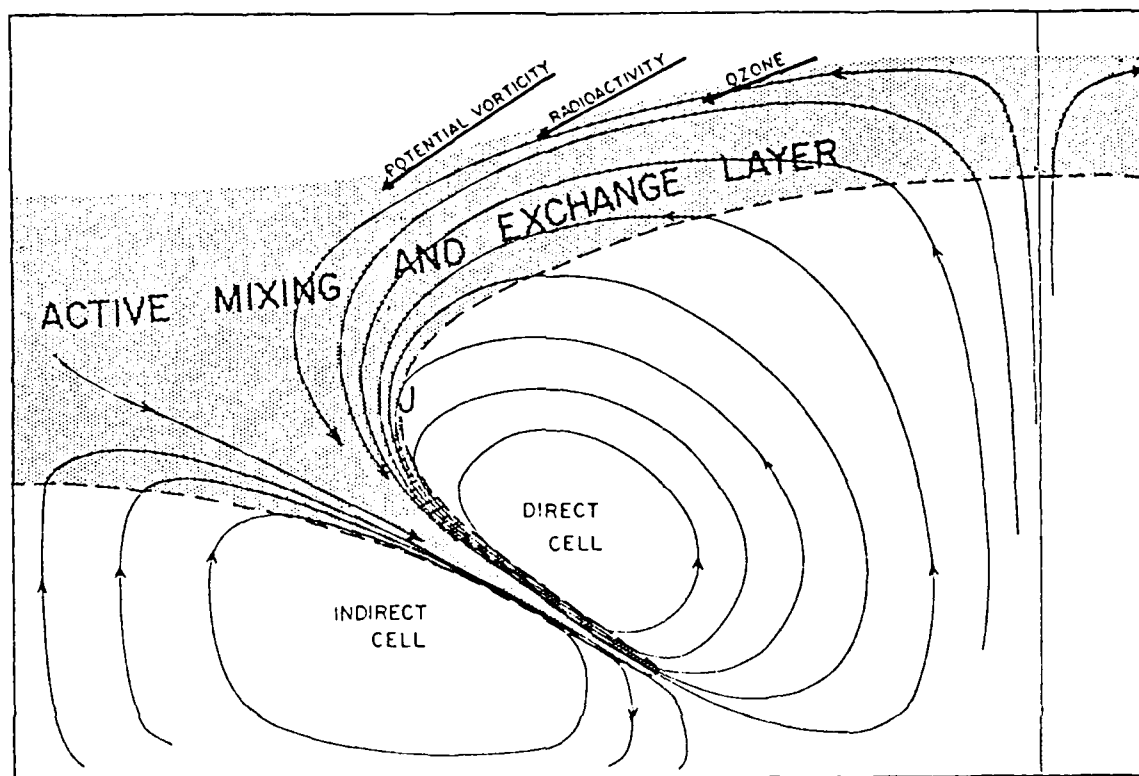


Figure 20 A schematic of the mean circulation relative to the tropopause. Note the folded tropopause and the intrusion of stratospheric air well into the troposphere (Danielsen, 1968).

several kilometers into the lower stratosphere acting as a deep transition layer. The mass of the stratosphere also increases as a result of this inflow. However, any increase in mass in the stratosphere is offset by a mass outflow associated with the folding process.

In order for the folding process to be considered a transport process and not a diffusion process, properties of the stratospheric air (i.e., concentration of ozone, radioactivity and potential vorticity) should be approximately conserved during the formation of the fold. If diffusion was the dominant process, any conservative stratospheric property would enter the troposphere across the tropopause or along the "break lines" (Danielsen, 1964) in the tropopause introduced along the axis of the jet. Furthermore, assuming vigorous mixing in the troposphere would disperse any conservative stratospheric property, then high concentrations of these properties would be present only in the stratosphere. However, this is not the case as Reed (1955), Danielsen (1964, 1968) and several other investigators have shown.

Consider Danielsen's work (1964) using potential vorticity (P_θ) as an example. Neglecting mixing, $\frac{dP_\theta}{dt} \propto -\frac{\partial \dot{\theta}}{\partial p}$ where $\dot{\theta}$ is the diabatic heating term, such that heating above and cooling below increases the potential vorticity and vice versa. The ozone layer acts as a heating source producing large values of potential vorticity while heating at the Earth's surface produces low values in the troposphere. The process is more pronounced when radiational cooling due to clouds or

moist layers extend to the tropopause. However, in the free atmosphere (neglecting radiational cooling) $\dot{\theta}$ is small and potential vorticity is conserved. Therefore, as Danielsen states, "when the tropopause folds, tropospheric air with small values of P_θ folds over an extruded layer of stratospheric air with large values of P_θ . Since each parcel conserves its value of P_θ during the folding process, the air of stratospheric origin can be readily identified even after it is considered part of the troposphere. Ozone and radioactivity have also been shown to be quasi-conserved during the process, thus, strongly indicating that the folding process is indeed a transport process. This suggests that "the stratospheric air moves diabatically down through the stratosphere on the cyclonic side of the jet. Then it is extruded from the lower stratosphere into the troposphere where it passes beneath the jet as it descends and moves to lower latitudes," Danielsen (1964).

3.2.2 Statistical Evidence for a Stratospheric-Tropospheric Exchange Connection

The work of Reiter (1973, 1976, 1977b, 1979b, 1979c) has lead to some interesting results regarding the influence of solar activity on the stratospheric-tropospheric exchange processes. The results indicate an increase in the frequency of stratospheric intrusions after solar flares and to a lesser extent after solar sector boundary passages. A more detailed discussion regarding the results follows, whereas the causal relationship will be discussed in the next section.

Reiter's (1979c) paper is a continuation of his previous publications which analyzed the dependence of stratospheric intrusions on solar events. He based the analysis on eight years of recordings of stratospheric radionuclides and the ozone concentration at Zugspitze peak (3 km altitude) in the Bavarian Alps. The data also included the atmospheric profile of the ozone concentration and the total ozone concentration. The eight-year period analyzed occurred during a period comparable to an eleven-year solar cycle. The sequence included:

- (1) November 1969 through 1972 - a period of maximum solar activity
- (2) 1973 through 1975 - a period of decreasing solar activity and
- (3) 1975 through 1977 - a period of minimum solar activity.

In addition, the data was further subdivided according to seasons (winter/spring and summer/fall). The frequency and intensity of stratospheric intrusions, as identified by the concentration of Be^7 (and other radionuclides) and the local ozone concentration at Zugspitze, were studied using solar H_α -flares (those flares with importance one and near the central meridian of the sun), solar sector boundary passages, and the Forbush decrease among others as key days.

The frequency of stratospheric intrusions after solar H_α -flares were significant and unrelated to the phase of the solar cycle and seasons. The maximum occurred two to three days after the flare day and varied slightly in amplitude from solar maximum (increase of 50%) to solar minimum (increase of 80%). Also, the concentration of local ozone at Zugspitze rose significantly from the third day before the flare until the fifth day after the flare. The atmospheric total ozone

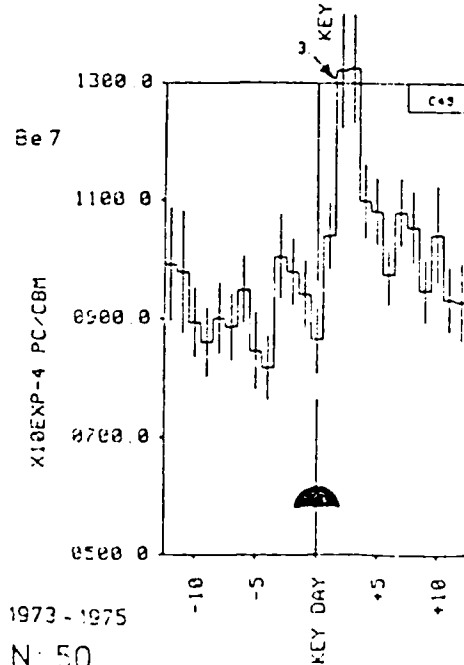
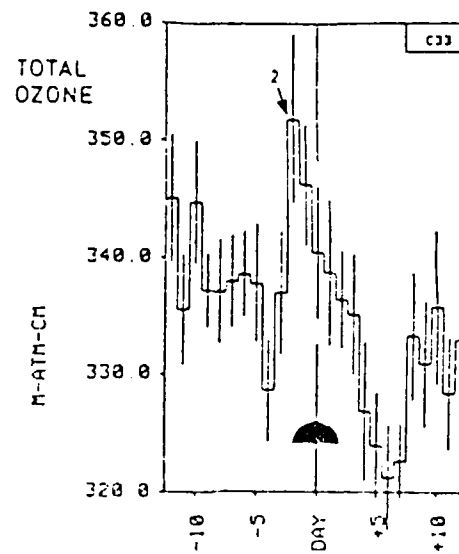
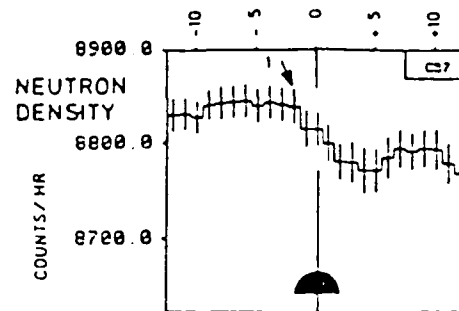
decreased from the day preceding the flare until the fourth or fifth day following the flare. In both instances the correlations were significant during solar maximum but the correlation could no longer be observed at solar minimum.

The influence of solar sector boundary passages on the frequency of stratospheric intrusions were not nearly as significant as the influence of H_{α} -flares. Nevertheless, a significant correlation between the $-/+$ boundary crossings and stratospheric intrusions existed. In the winter/spring a maximum occurred on the day of the passage but in the summer/fall a minimum occurred on the day of the passage. The boundary passages showed no effects on the frequency of the intrusions during solar minimum.

In addition, Reiter related the stratospheric intrusions to days with maximum Forbush decrease (an attenuation of galactic cosmic rays by an enhanced solar wind), which occurred a few days before the actual flare. The neutron density was used as an indicator for the Forbush decrease, such that a minimum in the daily means of the neutron density corresponded to a maximum Forbush decrease. The minimum of neutron density was found on the fourth or fifth day after the flare. The concentration of Be^7 (the indicator of stratospheric-tropospheric exchange) reached a maximum on the day before the maximum Forbush decrease, thus the intrusions occurred generally two to three days before the maximum Forbush decrease.

Using the period of decreasing solar activity (1973-1975), Reiter noted an interesting dependence of neutron density, total ozone and Be^7 concentrations on solar H_{α} -flares (Fig. 21). The dependence occurred

Figure 21 A conspicuous time sequence around H_{α} -flare key days during a period of decreasing solar activity.
Point 1. Beginning decrease of neutron density;
Point 2. Steep increase of the total ozone to a maximum; Point 3. Significant maximum of Be^7 two to three days after the key day (Reiter, 1979c).



1973 - 1975

N: 50

H α FLARE

as follows: As soon as the neutron density started to decrease (point 1 in figure), the total ozone concentration reached a local maximum (point 2) and four to five days later the maximum concentration of Be^7 was found (point 3). The significance of this sequence of events will be discussed in more detail in the next section where attention is focused on the stratospheric-tropospheric exchange mechanism.

3.2.3 The Stratospheric-Tropospheric Exchange Mechanism

Herman and Goldberg (1978b) proposed that because non-tropical thunderstorms are usually associated with frontal boundaries, stratospheric ions may be swept downward along with neutral air ("bulk transport") near the frontal boundaries. And because storm systems are often associated with the jet stream, Herman and Goldberg suggest that stratospheric air penetrates into the troposphere at the tropopause break lines near the jet stream (Fig. 22). As noted earlier, maximum ion production due to galactic cosmic rays peaks near the tropopause in mid-latitudes. The ionized particles produced (as indicated by the charge signs in Fig. 22) would be transported downward with the neutral air by subsidence along the front. Furthermore, wind speeds in the vicinity of the break lines coupled with strong downdrafts may bring the ions to thunderstorm heights within their lifetime. For the larger ions (i.e., small ions that attach themselves to aerosols), Herman and Goldberg estimate the half-life of these large ions to be approximately 8500 seconds. If the speed of the air transporting the ions was only

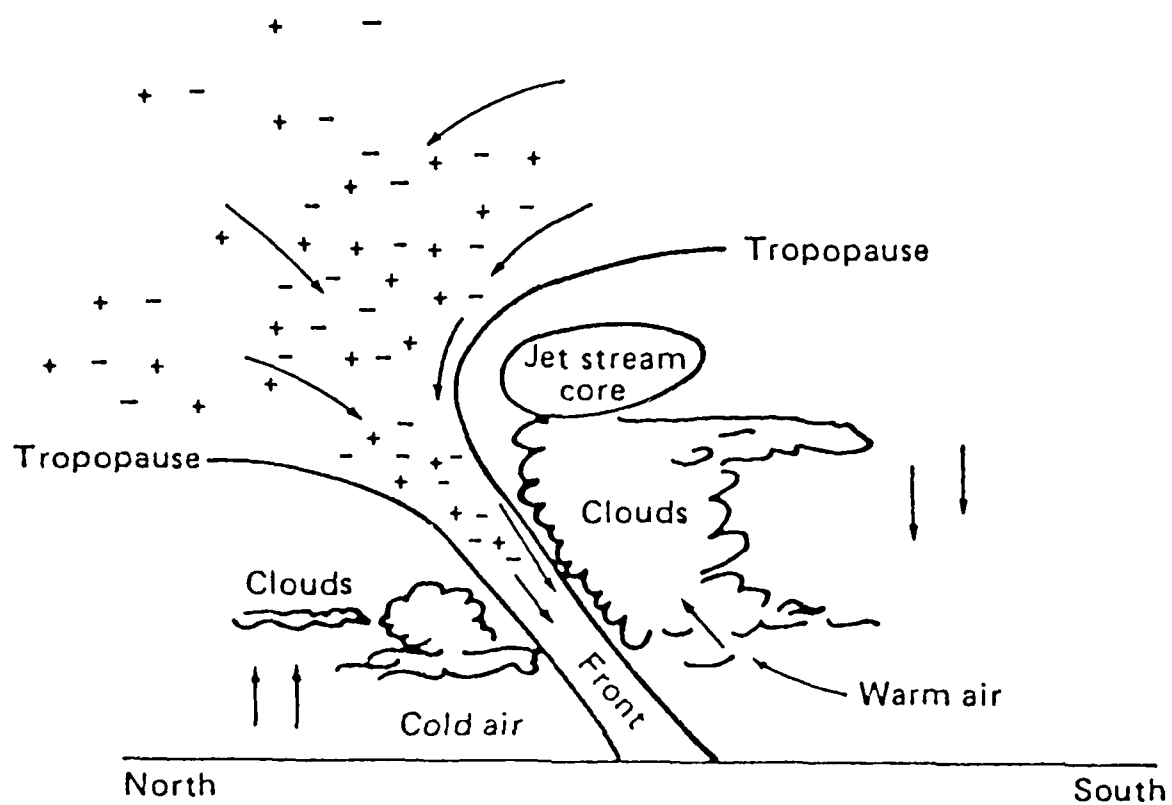


Figure 22 Intrusion of stratospheric air and ions into the troposphere through the tropopause break line (Herman and Goldberg, 1978b based on Reiter, 1967).

1 ms^{-1} , then the ions would be swept downward 8.5 km and one-half of the ions would still exist to be entrained by the cloud system along the front.

However, Danielsen (1968) found "negative evidence" for the assumption that radioactivity or other stratospheric properties are displaced from the stratosphere to the troposphere at these tropopause break lines. Therefore, the next viable alternative is to consider tropopause folds as the process for ion transfer into the troposphere from the stratosphere. The problem of transferring ions down to thunderstorm heights was possibly solved by Reed (1955) who found that "an intense portion of the frontal zone consisted of a thin wedge of stratospheric air which had descended to very low levels (700 to 800-mb)".

In addition, Danielsen's (1964) discussion of wet fallout provides a valuable piece of information concerning this hypothesis. In Fig. 23, Danielsen (1964, 1980) sketches the three-dimensional structure of a typical tropopause folding event. Note how the central and left portions of the extruded flow descends until it reaches the trough. Danielsen (1964) continues: "After it passes the trough it ascends. The ascent may begin to the west of the surface front but continues well in advance of the front. At its leading edge the ascending dry, stable stratospheric air flows above ascending moist or saturated air. The high stability of the stratospheric layer suppresses vertical cloud development but the presence of the dry layer over saturated air is potentially unstable. As ascent continues, the latent heat release at the base of the layer by the condensing water vapor decreases the stability.

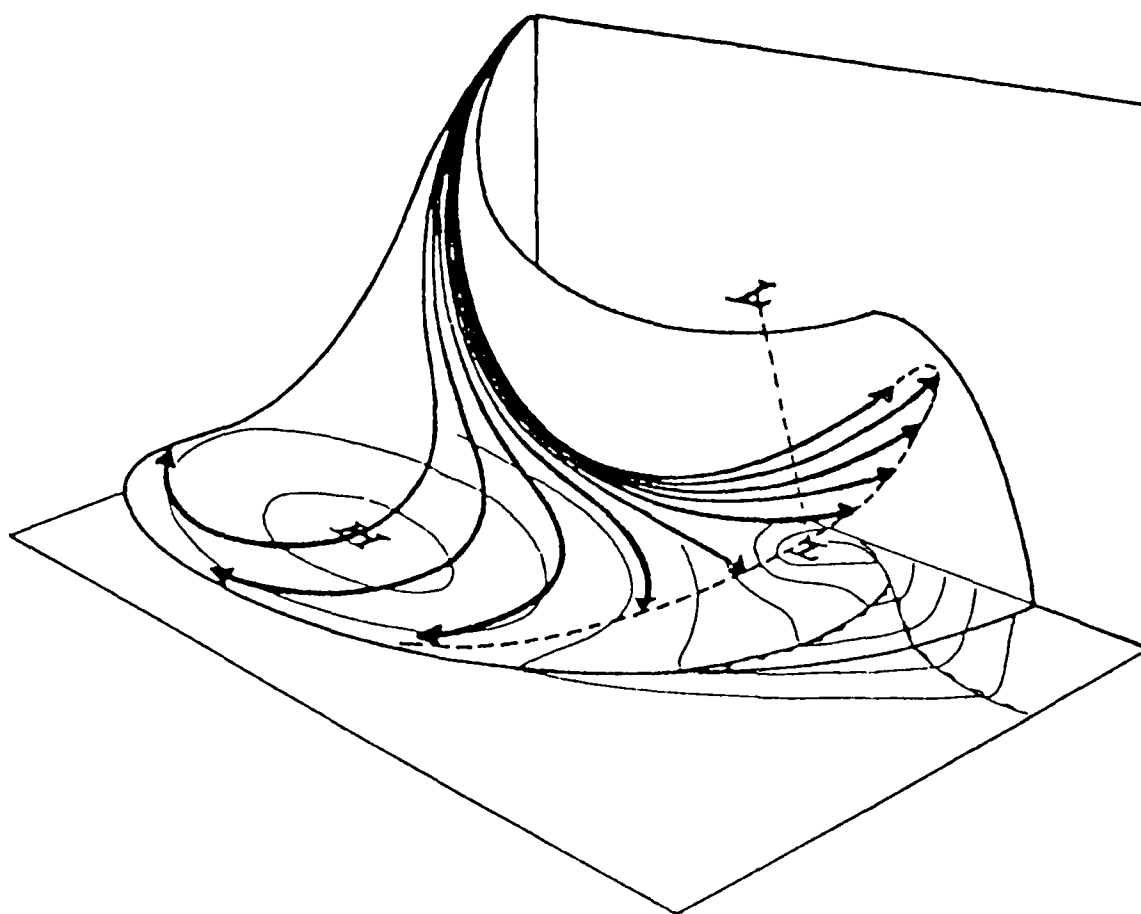


Figure 23 A representation of typical trajectories and deformations associated with a tropopause folding event (Danielsen, 1964, 1980).

When the stability is reduced to a critical value, the cumulus clouds break through the layer and are then accelerated upward by strong buoyancy forces. A line of rain showers and thunderstorms quickly develops along the leading edge of the destabilized layer. As the cumulus clouds penetrate and break through the layer torroidal circulations entrain the stratospheric air into the growing cloud. If the radioactivity in the stratospheric air is attached to freezing or condensation nuclei, the radioactivity will then enter the precipitation cycle."

Therein lies the key to the stratospheric-tropospheric exchange mechanism proposed here. Any ions from the folding process entrained into the cloud could enhance cloud electrification increasing the chances for lightning discharge. Referring back to the discussion of atmospheric electricity, an increase in thunderstorm electrification would enhance the fair-weather electric field. Such a feedback process could explain why atmospheric electrical properties show a dependence on extraterrestrial forcing. Furthermore, ions entrained into a well-developed thunderstorm could possibly increase the electrical potential within the thunderstorm enough for intense lightning discharges to occur. These intense lightning discharges, or "superbolts" (Turman, 1977, 1979) as they are commonly referred to, are positive lightning discharges from near the top of the thunderstorm cloud to the ground. They have an optical power in the range of 10^{11} to 10^{13} watts (approximately 100 times more powerful than a typical lightning discharge). Superbolts have been recorded by both the Vela and DMSP (Defense Meteorological Satellite Program) satellites and tend

to occur more often in the winter than in the summer. They are infrequent and very powerful and thus, if superbolts were dependent on stratospheric intrusions for development, they could provide valuable evidence for the Sun/weather problem.

A major problem remains finding a way to relate extraterrestrial forcing to stratospheric-tropospheric exchange in a causal sense. Reiter (1979c) suggests that the sequence of events discussed in the previous section (Forbush decrease, temporary increase in total ozone, infrequent maximums in the lower stratospheric ozone concentrations and triggering of stratospheric intrusions) "is possibly due to a physical link". The postulate here is that the sequence of events should be looked at as a possible Sun/weather linking mechanism rather than as a result of some mechanism as Reiter suggests. Further insight into this sequence of events is needed to support this postulate.

Table 2a details the 9-20 April 1978 case study by Reiter (1979c) in which two intrusions occurred and Table 2b is the 10-19 February 1978 case. The following sequence is noted in both tables: solar flare occurrence (1), decline of neutron density (5), enhancement of total ozone (7,8), warming in the region of the tropopause (9), a lowering of the tropopause height (11), an increase in the Be^7 and local ozone concentration and fallout (12). The first case beginning on 11 April took one to two days to complete (13). The second case beginning on 13 April took four days and the February case took two to three days (13). In all cases, the neutron density decrease and total ozone enhancement occur at approximately the same time. Of greater importance is the significant increase in the ozone concentration

(a) DAY:	9	10	11	12	13	14	15	16	17	18	19	20
1. H_a FLARES			2B	1B	1B		1N			2B		
2. SUNSPOT NO	126	111	109	107	93	75	61	85	99	100	107	115
3. SOLAR FLUX 107cm	156	155	180	155	145	138	140	137	132	133	145	139
4. RADIO PROP INDEX	129	123	109	134	132	118	135	135	139	129	138	122
5. NEUTRON DENSITY		65585	63617	63433	64682	64840	61928	60593	55130	56653	58021	55539
6. GEOMAGN IND Ap	6	10	64	29	24	51	19	8	7	19	38	23
7. RADIO TOTAL O ₂ SPECTROM AIRC												
AROSA	-	391	-	414	417	413	-	-	433	385	-	389
GARMISCH	-	-	-	-	-	425	-	-	461	425	431	442
HOMENPEISS	385	388	-	426	422	421	-	422	425	359	395	402
8. RADIO TOTAL O ₂ SOND. GAP. nb	-	-	-	-	435	429	508	-	385	425	375	426
O ₂ FROM TROPOP 10-150mb	-	-	-	-	125	119	146	-	84	117	119	105
9. TROPOPAUSE TEMP °C	-64	-63	-59	-55	-56	-52	-59	-61	-49	-58	-57	-54
10. INTERDIURNAL TEMP CHANGE		+1	+4	+4	-1	+4	-7	-2	+12	-9	+1	+3
11. TROPOPAUSE HEIGHT km	113	110	95	91	95	90	91	95	75	98	102	92
12. AUGSPITZE 3km												
O ₂ ppb	490	488	417	413	443	442	372	412	399	434	522	456
E ₀₇ 10 ³ pcie m ³	121	49	52	165	157	77	36	45	65	169	109	67
FALLOUT 10 ³ pcie m ³	37	13	13	27	22	17	11	08	12	22	16	10
REL HUMIDITY %	81	98	96	87	95	80	95	99	75	40	20	75
13. TIME LAG				1-2 DAYS			4 DAYS					

(b) DAY:	10	11	12	13	14	15	16	17	18	19
1. H_a FLARES			1B	2B						
2. SUNSPOT NO	96	95	92	93	82	59	64	56	55	53
3. SOLAR FLUX 107cm	153	158	163	155	152	140	133	129	128	122
4. RADIO PROP INDEX	129	130	130	129	128	126	131	132	134	137
5. NEUTRON DENSITY	63500	63613	63308	63324	62736	57028	60247	61312	62270	62334
6. GEOMAGN IND Ap	7	5	9	8	11	48	11	10	10	12
7. RADIO TOTAL O ₂ SPECTROM AIRC										
AROSA	390	-	376	352	-	393	-	-	320	360
GARMISCH	-	-	-	335	313	410	-	-	-	-
HOMENP	-	-	400	359	348	439	-	-	352	-
8. RADIO TOTAL O ₂ SOND. GAP. nb	-	-	-	331	296	362	343	342	-	-
O ₂ FROM TROPOP 10-150mb	-	-	-	63	95	131	75	85	-	-
9. TROPOPAUSE TEMP °C	-	-	-	-58	-55	-52	-63	-66	-	-
10. INTERDIURNAL TEMP CHANGE	-	-	-		+3	+3	-11	-3		
11. TROPOPAUSE HEIGHT km	-	-	-	95	95	80	105	110		
12. AUGSPITZE 3km										
O ₂ ppb	353	329	292	320	307	339	279	270	370	334
E ₀₇ 10 ³ pcie m ³	17	18	43	62	48	77	062	065	259	050
FALLOUT 10 ³ pcie m ³	014	004	002	008	007	004	008	002	006	020
REL HUMIDITY %	88	92	91	88	84	89	92	99	89	96
13. TIME LAG				2-3 DAYS						

Table 2 Tables depicting the events related to stratospheric intrusions. (a) The April 1978 case and (b) the February 1978 case (Reiter, 1979c).

between the tropopause and the 150-mb level that occurs on the second day (15 April) after the flare and on the third day after the flare in the February case (8). The implication is that the warming at the tropopause height and the subsequent lowering of the tropopause height are a result of the ozone concentration increasing between the tropopause and the 150-mb level.

The next logical step in the process is to relate this sequence to extraterrestrial forcing. The key to the entire sequence may be galactic cosmic rays. The effects of solar activity on galactic cosmic rays have been documented in previous sections. Reiter points out that the generation of ion pairs and excited nitrogen in the lower stratosphere are caused exclusively by galactic cosmic rays. The formation of NO_x occurs when nitrogen and excited nitrogen molecules react with oxygen molecules. Although this source of NO_x is relatively small, it does catalytically destroy ozone (Chamberlain, 1977). Chamberlain also states: "A long period of low solar activity and enhanced galactic cosmic-ray production of NO_x in the stratosphere would reduce the ozone abundance." Likewise, during periods of high solar activity and decreased cosmic ray production of NO_x in the stratosphere, one would expect an increase in ozone abundance. Increases in the ozone concentration in the lower stratosphere would lead to a rise in temperature above the tropopause. This would alter the structure of the tropopause possibly triggering stratospheric intrusions and ultimately initiating cyclogenesis (Reiter, 1979c). Reiter is quick to point out that these are "first assumptions" based on the findings in that paper.

Thus, the sequence of events involved with this hypothesis begins with an enhanced IMF due to increased solar activity. This shields the Earth from galactic cosmic rays and results in a decrease production of NO_x . An increase in ozone concentration in the lower stratosphere follows which produces a warming in the layer above the tropopause. The warming triggers stratospheric intrusions and cyclogenesis at upper levels of the troposphere. This stratospheric air (after a transport period of several days) is entrained into developing thunderstorms along the frontal boundary. The increase in thunderstorm electrification enhances the fair-weather electric field.

Several observations presented in previous sections provide additional support for this hypothesis. For instance, Ely (1984) (Section 3.1.2) suggested (based on Lethbridge's work (1983, 1986)) that the minimum in cosmic rays after solar activity causes a lightning maximum. Lethbridge found a minimum in cosmic rays occurred two to four days after high cosmic rays preceded a solar sector boundary passage. The minimum also occurred at a time when thunderstorm activity was increasing. Referring to Reiter's (1979c) work, (Table 2a,b), the maximum in neutron count that occurred the day preceding the flare would lead to an increase in ion production in the lower stratosphere. More importantly, on the day with minimum neutron count, the maximum in Be^7 is recorded at Zugspitze peak two to four days after the maximum in neutron count. Thus, incorporating Ely's and Reiter's ideas indicate stratospheric air would be available at the time thunderstorm frequency is increasing. This would explain the increase in thunderstorm frequency two to four days after solar activity that

Markson, Bossalasco, and Lethbridge found (Section 3.1.2). Therefore, Ely may be correct in his observation that the minimum in cosmic rays causes a lightning maximum.

Cobb's (1967) work (Section 3.1.2) may also provide support for this hypothesis. Recall that Cobb found significant increases in fair-weather electric field (E) and the air-Earth current density (I) during July 1961. Specifically, on 15 July, the current density exceeded the normal value by 75% in one six-hour period leading Cobb to suggest solar activity as the cause and not the global thunderstorm distribution. To further substantiate his claim, he notes that in January (the peak thunderstorm month for the Southern Hemisphere) the current density was below normal at a time when no solar flares were observed. However, if in July the solar flares triggered stratospheric intrusions that increased the thunderstorm frequency, then it is possible that it may very well be the global thunderstorm distribution in conjunction with solar activity that was responsible for the increase in the current density. In addition, if there were no flares in January, then there would be few stratospheric intrusions and thus, no enhancement in thunderstorm frequency, air-Earth conduction current or fair-weather electric field. Whether this process could be responsible for such a large deviation (75%) remains to be seen, but it could explain the smaller deviations and the two to four day time lag that Reiter (1972) and Sartor (1980) found.

Chapter 4

SUMMARY

Wilcox (1974) reviews the "few common threads" in the solar activity-weather relationship. These relationships are:

(1) meteorological responses tend to occur two or three days after geomagnetic activity

(2) meteorological responses to solar activity tend to be most pronounced in the winter

(3) some meteorological responses over continents tend to be opposite from the responses over oceans.

In summarizing the relationships presented in this paper, one generally sees a delay in the meteorological responses two to four days after the solar flares and one to three days after solar sector boundary passage. The tendency is for a more strongly defined response in the winter, during solar maximum conditions, and after the +/- boundary passage.

Many scientists have difficulty accepting a relationship between solar activity and weather because of the lack of a definite physical mechanism linking the two. Dressler (1974) discusses the two main difficulties in coupling solar activity to meteorological phenomena. These are:

(1) devising a mechanism that can modify the behavior of the troposphere while employing only a negligible amount of energy compared to the energy necessary to drive the normal meteorological system; and

(2) determining how such a mechanism can effectively couple some relevant magnetospheric process into the troposphere in such a way as to influence the weather.

Many scientists believe this linking mechanism is atmospheric electricity, although there exist different schools of thought concerning the details. For instance, Markson's proposed linking mechanism attempts to explain the variations in the global electric field by variations of the stratospheric ionization due to solar activity. Alterations in the global electric field may lead to enhancement of thunderstorm electrical properties. Consequently, there may be changes in cloud dynamics which in the end, may lead to changes in the global heat budget. However, Hale's proposed mechanism deals with large horizontal gradients of mesospheric conductivity that cause nighttime thunderstorms to couple with the high-latitude auroral fields. These auroral fields are able to map to lower latitudes as large vertical mesospheric fields thus modulating the fair-weather electric field. The concept of a stratospheric-tropospheric exchange mechanism is introduced because it also depends on the possible modulation of the thunderstorm generator by solar activity. Stratospheric air is injected into the troposphere by tropopause folding events where it is then transported above the surface frontal boundary to be entrained by the developing thunderstorms. The advantage of this model is that an increase in thunderstorm electrification may also explain the observed variation in some atmospheric electrical properties during solar activity.

An inherent problem in these models is the question of cloud electrification processes. Because much is still unknown about these processes, it is unclear whether solar activity affects cloud electrification during the cloud's initial development, during the latter stages of cloud development or even at all. This problem, along with those mentioned by Dressler above, is the reason why these mechanisms (as well as many others) are speculative at this time and why most scientists refuse to accept them. However, Wilcox (1974) reminds us of past history. Lord Kelvin, in his presidential address to the Royal Society in 1892, emphatically concluded that there was no connection between geomagnetic storms and magnetic waves emanating from the Sun. Today, we know there is a connection between magnetic storms and the solar wind. Wilcox (1974) states: "We may perhaps learn a lesson from history at this point."

APPENDIX

REVIEW OF THE SOLAR MAGNETIC SECTOR BOUNDARY STRUCTURE

The solar wind carries the magnetic field structure radially outward from the coronal regions of the Sun (Fig. A-1). The different polarities of the interplanetary magnetic field (IMF) suggests that the solar wind emanates from coronal holes of differing magnetic polarities (Svalgaard, 1974). The structure rotates with the 27-day period of the Sun (however, this varies with solar latitude) with narrow boundaries separating the different polarities of the structure (negative IMF is directed towards the Sun and positive IMF away from the Sun). The boundaries can be characterized by Archimedes spiral lines coming from the Sun. According to Svalgaard (1974), "the flow speed and magnetic field strength tend to be a low near the sector boundary, rising to a maximum one or two days after the boundary, and then declining towards the end of the sector." The boundaries are very thin and can be determined to within a fraction of an hour as they sweep past the Earth (Wilcox, 1974).

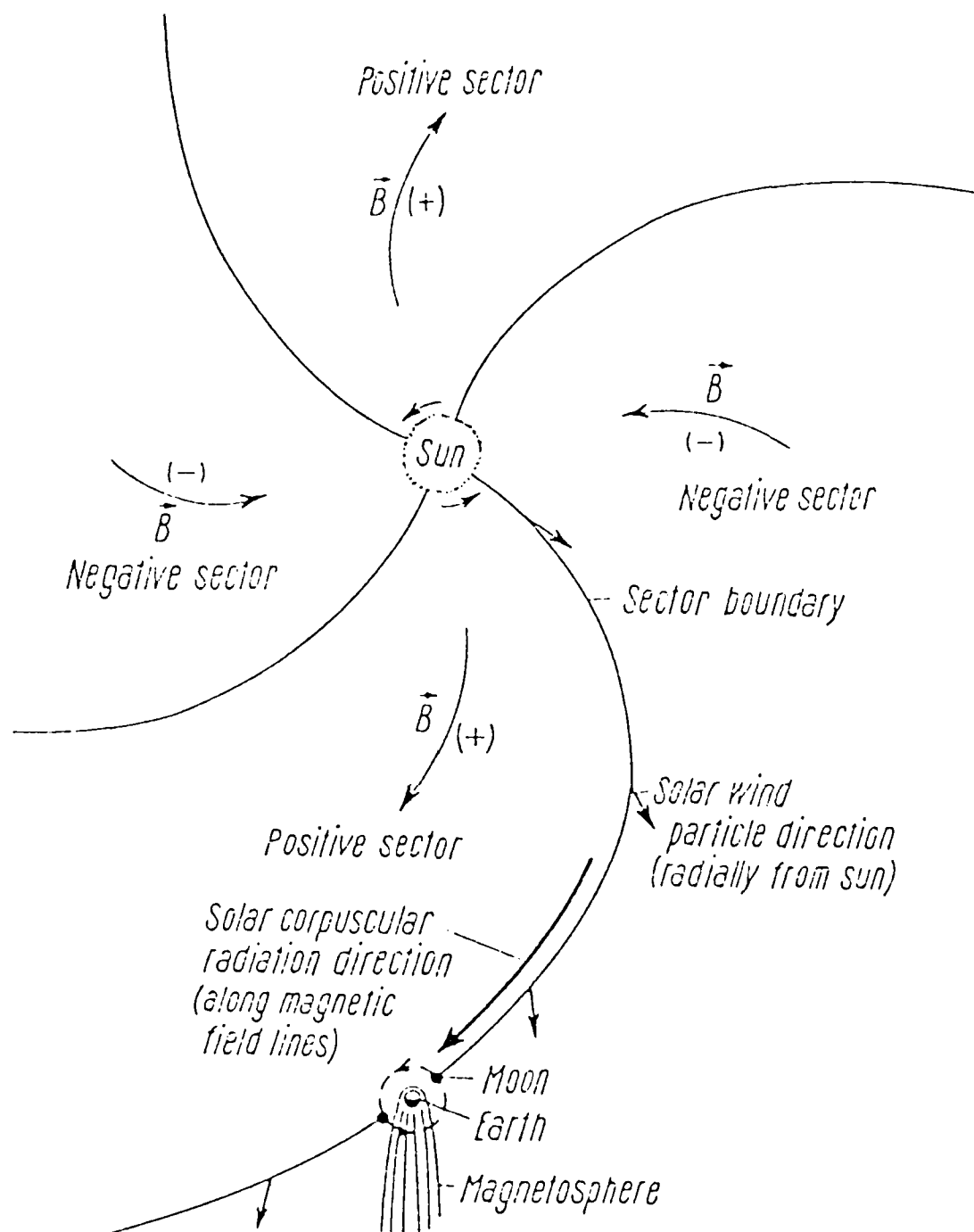


Figure A-1 Schematic of the solar wind structure illustrating the interplanetary magnetic field and the spiral sector structure. The solar wind carries the magnetic field structure radially outward from the coronal region of the Sun. The arrows in the four sectors indicate predominant direction of the field (Markson, 1971).

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