Investigation of Possible Sun-Weather Relationships

Steven Businger

MASTER

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NCAR Cooperative Thesis No. 49

University of Colorado and
National Center for Atmospheric Research

1978

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Investigation of Possible Sun-Weather Relationships

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*A thesis submitted to the Graduate School of the
University of Colorado in partial fulfillment of the
requirements for the degree of Master of Sciences,
Department of Astro-Geophysics, based on research
conducted in cooperation with the scientific staff
of the National Center for Atmospheric Research,
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ABSTRACT

Statistical correlations between anomalous solar activity (as denoted by large solar flares, active plages, and interplanetary magnetic sector boundaries) and the circulation of the troposphere are reviewed. Two indices (measuring atmospheric vorticity and mean zonal geostrophic flow in the northern hemisphere) are analyzed in an effort to reveal possible sun-weather relationships. The result of this analysis provides no additional statistical evidence for a connection between solar activity and the weather. Finally, physical mechanisms that have been suggested to explain the claimed correlations are discussed.

ACKNOWLEDGEMENTS

The author wishes to take this opportunity to thank the many people and organizations who have contributed to the attainment of this goal.

First I wish to express my sincere gratitude to Professor Julius London whose constructive criticism and encouragement were invaluable to the completion of this thesis. I also wish to thank Dr. Walter Orr Roberts, Director of the Aspen Institute for Humanistic Studies, and Mr. Roger Olson for their helpful support and willingness to discuss any problems.

Financial support was provided by grants administered by the Aspen Institute for Humanistic Studies. Computer time was provided by the National Center for Atmospheric Research. I am indebted to Mr. Edward Gerety and Ms. Linda Theil for their valuable help with computer programming.

Finally I wish especially to thank Ms. Suzanne Parker for her excellent typing of the final manuscript and the many drafts.

DOE Contract ER-78-02-4634. A000

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Introduction

The sun's output is the primary external force controlling the earth's weather. The circulation of the atmosphere is driven by pressure gradients resulting from the differential heating of the earth's surface and atmosphere by solar radiation. Diurnal and seasonal variations are also basically the result of solar radiation. The question has therefore arisen; can variations in this solar output produce predictable variations in our weather? Signs of such a response to solar activity have been sought by researchers since the discovery of sunspots by Galileo more than 200 years ago.

Scientists have, however, remained skeptical of the many statistical correlations found between solar activity and the weather, because the solar heating which provides the driving force for the earth's atmosphere is essentially constant (Fröhlich, 1977).

Relationships between solar activity (evidenced by large solar flares or active plages), fluctuations in the geomagnetic field and the occurrence of aurorae in the upper atmosphere are reasonably well established (Chapman, 1964). However, the high frequency (x-ray and ultraviolet) radiation and the intense corpuscular streams responsible for the variations observed in the upper atmosphere cannot normally penetrate to levels much below 80 km (London, 1956), therefore one must look for indirect processes to influence the lower atmosphere. This may explain why efforts to link responses in the lower stratosphere and troposphere to solar variability have produced no definite physical relationships.

Most of the research in this area has been confined to statistical and/or synoptic analysis. Almost nothing has been done in the way of a physical, dynamical approach to the problem. If a physical theory were advanced that could explain the seemingly solid statistical results of Wilcox et al. (1973) verified by Hines (1975), the field of sun-weather relationships would be on much firmer ground.

Research into sun-weather relationships falls into basically two categories; studies of the possible short-term (on the order of two weeks or less) weather responses to solar activity and studies that attempt to relate longer term climatic trends with the cyclic nature of solar activity.

This thesis will deal primarily with the possible short-term responses in the lower stratosphere and troposphere to solar variability. The first chapter is a review of some recent representative studies aimed at linking anomalous solar activity (denoted by large solar flares and or large fluctuations in the geomagnetic field) to the lower atmosphere. Chapter II will discuss recent work by investigators showing a possible relationship of the solar magnetic sector structure and an index of vorticity in the northern hemisphere. In Chapter III my studies directed at revealing more about the nature of a possible relationship between the weather and anomalous solar activity are presented. In closing, Chapter IV will discuss the problem of physical mechanisms and include an overall conclusion.

CHAPTER I

REVIEW OF RECENT SUN-WEATHER STUDIES

The studies reviewed in this chapter were all directed at finding a relationship between solar activity (as evidence by large solar flares and/or large fluctuations in geomagnetic activity) and the lower atmosphere. The method employed in each case was that of superposed epochs.

The superposed epoch method is useful for studying the relationship between two time series especially if from one of the time series "key" days can be defined representing the occurrence of discrete events. For example when looking for possible influences of large solar flares and/or geomagnetic storms on the tropospheric circulation, "key" days representing the dates when the events in question occurred are selected. The sequence of days just before and after a key day can then be denoted $x_{-m}^i, x_{-m+1}^i, \dots, x_{-1}^i, x_0^i, x_1^i, \dots, x_n^i$; where x_0 denotes the key date. If we have N number of events (key days) then average values of the other variable (i.e., atmospheric pressure, vorticity, etc.) are obtained for each day of the sequence using the formula $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_j^i$ where x represents the value of the other variable on the day of the sequence j .

The purpose of the superposed epoch technique is then to damp short-term variations that are not correlated with the parameter used to determine the key days, while coherently displaying signals which are phase related to the key day. A quantitative evaluation of the results can be carried out by employing methods to test their

significance in comparison with results from another independent sample or with some random distribution.

The gaussian or normal distribution is most commonly used to determine the statistical significance of an excursion in the superposition sequence. In the studies reviewed later in this chapter it has been assumed that deviations of the meteorological data about the mean can be fairly well approximated by a normal distribution. The validity of this assumption is discussed in Chapter II. The standard deviation about the mean can be computed using the equation:

$$S = \sqrt{\frac{\sum_{i=1}^N (x_i - \bar{x})^2}{N-1}}^{1/2} \quad \text{Panofsky and Brier (1958)}$$

where $\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$ is the population mean. In Chapter II, I will discuss in more detail the difficulties in determining just how significant a particular excursion in a superposed epoch sequence is when the resulting excursion is within a few standard deviations of the mean and the data used are noisy, as is the case with sun-weather correlations.

A serious difficulty which has plagued sun-weather research is the inherent by variable nature of meteorological data. The results of the superposed epoch studies described in this thesis indicate that the responses, if they are indeed real, of the weather to solar activity are well within the natural range of day to day weather variation. Thus in studies using few key days and small data samples, especially when the key days are spaced within a day or two of one another, spurious results can give rise to seemingly significant correlations with no physical basis for the observed

correlation. Due to the persistence inherent to meteorological data, care should be taken that the key days are sufficiently well spaced from one another to avoid correlations of the weather with itself. I have used an eight day period as the minimum spacing of key days in my studies described in Chapter III.

Due to the difficulty in establishing the significance of an excursion by statistical means, an important test of statistical correlations between solar activity and the weather, therefore, lies in the consistency of the results of these studies. If the results of various related studies produce signals of coherent timing and nature and can be reproduced using independent data, then the alleged physical reality of the various correlations will be easier to accept, and some of the conditions that a physical mechanism must meet will be well specified.

It is the object of the first two chapters of this thesis to review the more recent investigations of sun-weather relationships to see if a pattern emerges when comparing the various results.

Before turning to the review I wish to make a brief aside about the relationship between large geomagnetic fluctuations (i.e., large geomagnetic storms or bright aurorae) and solar activity. It is generally accepted that these two phenomenon are closely related. This assumption stems from the view that aurorae and geomagnetic storms derive most of their energy from fairly direct interaction of the solar wind with the magnetosphere (Matsushita and Campbell, 1967). Figure 1.1 shows a superposition of Kp values with large solar flares determining key days for the period 1955-1974. Note the clear cut maxima in geomagnetic activity two days following

fig. 1.1

fig. 1.2

fig. 1.1 Geomagnetic Kp index values vs. key days of large solar flares. 92 cases

fig. 1.2 Geomagnetic Kp index vs. key days of large solar plagues. 91 cases

the solar flare.

The Kp index is well suited for the description of auroral zone disturbances as a measure of the solar wind. It is an average of the magnitude of the variation during a three hour period of the magnetic field recorded by magnetograms at 12 northern hemisphere stations between the latitudes 48° - 63° N. Thus it is not entirely satisfactory for representation of disturbances within the polar cap north of 63° N latitude. Figure 1.2 shows a similar result obtained with central meridian passage dates of large and active plages on the sun used to determine the key days. Again the maximum Kp value occurs two days following the key day. The peak in this case is broader, reflecting the fact that the plage region emits radiation for a longer period than flares which emit for periods of a few minutes to a few hours. The establishment of a relationship between weather and geomagnetic activity is, therefore, assumed to have implications for the existence of a sun-weather connection. Geomagnetic fluctuations are however not uniquely related to solar activity, and Hines (1973) has pointed out that meteorological variation in the troposphere may propagate into the upper atmosphere and create a response in the earth's magnetic field, thereby confusing the question of cause and effect when using indices of magnetic activity to deduce sun-weather relationships.

Shapiro (1956) presents statistical evidence which suggests the existence of a relationship between solar corpuscular radiation (measured by rapid increases in geomagnetic activity) and the subsequent behavior of the sea level pressure distribution of most

of North America. The behavior of the pressure distribution was measured by three-day running mean persistence correlations for the period January 1899 through May 1945.

The persistence correlation is a measure of the extent to which the three-day mean pressure distribution for day K, K+1, and K+2 resembles the mean pressure distribution for days K+3, K+4 and K+5.

The results of the analyses show an increase in persistence about four days after the key day, followed by a pronounced decrease in persistence during about two weeks after the large changes in geomagnetic activity. It was found that the minimum in persistence was significant ($\geq 99.9\%$ confidence level using student's t test) only for years of moderate or low sunspot numbers.

Shapiro (1972) further corroborated the earlier results using an independent set of data. He again found a maximum in persistence (99% confidence level) about four days after the key day for a region covering Europe, with a less significant minimum ten days later. For a region covering North America he also finds a maximum in persistence (95% confidence level) followed by a minimum in persistence (99% confidence level) two weeks after the key day (see figure 1.3).

The results of these studies seem interesting since large data sets and many cases were studied, however they contain little specific information concerning the nature of the changes of pressure distribution which are responsible for the low persistence correlations on day fourteen after large geomagnetic disturbances. Both investigations indicate that the average magnitude of the response to solar disturbances is small. Several questions come

fig. 1.3 Average persistence correlations for the 3-day mean sea-level pressure distribution preceding and following large increases in geomagnetic activity. Upper curve refers to the North American region (30°N-60°N, 65°W-124°W); each value represents an average of 564 cases in 47 years of data. Lower curve: European region (35°N-65°N, 30°E-30°W); each value represents an average of 467 cases in 40 years of data (from Shapiro, 1972).

to mind when discussing Shapiro's work with sea level pressures. How are the changes in the persistence correlation reflected in the general circulation of the atmosphere? What does the persistence correlation tell you about the physical nature of the processes involved? Why would sea level pressure be a good parameter to study in looking for a sun-weather relationship?

Shapiro attributes the increased persistence during the first week after increases in geomagnetic activity to increased zonal flow; a finding confirmed by Stolov and Shapiro (1974). One might then conclude that the decrease in persistence two weeks after a magnetic disturbance implies a return to stronger meridional circulation; this effect does not reveal itself in Shapiro's and Stolov's subsequent work. The choice of surface pressure data for analysis was probably based more on the availability of long records of data than on considerations of the possible physical nature of a sun-weather connection.

In trying to draw conclusions from these results as to the physical processes involved the persistence correlation suffers drawbacks. Although it reflects both negative and positive changes in the weather which another parameter may average together, the persistence correlation is not used routinely in atmospheric sciences, therefore there is no background information on the typical behavior of this parameter. Secondly the persistence correlation is an isolated parameter which consequently, cannot provide information about what is happening to other atmospheric parameters while the persistence is responding to variability. These arguments also apply to other meteorological indices designed

for the study of possible sun-weather relationships.

While the number of significant excursions found in Figure 1.3 is only what would be expected by chance (there being 35 individual days being considered in each superposed epoch sequence), the agreement of Shapiro's (1972) subsequent results with the original provides a test supporting the earlier results.

Another study by Shapiro and Stolov (1970) of surface pressure in polar regions failed to reveal any correlation with solar particle emission. Power and cross-power spectra for the daily average station pressure at nine arctic and antarctic stations and various measures of solar variability, such as f_{min} , riometer data, and K_p , were computed for the years 1956-1961. The results seemed to indicate that a small but coherent oscillation of sea level pressure exists between the two polar regions with a period of about sixty days which could be the result of a weak direct exchange of mass between the arctic and the antarctic. However, no associations were found between various indices of solar variability and station pressure in these regions.

Macdonald and Roberts (1960) noted that 300 mb troughs which enter the Gulf of Alaska one to three days after a geomagnetic storm tend to intensify to a greater degree than those troughs which enter the same area at other times (see figure 1.4). The trough index used in their study is essentially the ratio of the trough depth (north-south dimension) to its width (east-west dimension) with certain weighing factors giving stronger emphasis to closed lows. The authors claimed that such a strong chance association is less than 10^{-6} .

fig. 1.4 Average trough amplitude I_1 for the seven days after first appearance in the target area for all troughs that did not move off the maps (past 0° longitude) during the seven days. Dotted curves for troughs that first appeared in target area on second, third, and fourth days after C_p key dates. Solid curves, all others (from Roberts and MacDonald, 1960).

fig. 1.5 Mean vorticity area index for key and non-key troughs, 1964-71 (from Roberts and Olson, 1973).

In a more recent study Roberts and Olson (1973) traced the development of 300 mb level troughs by means of an objectively derived index of high positive absolute vorticity for each trough entering the Gulf of Alaska during the winter half-years of 1964-1971. The vorticity area index (VAI), derived by computer, was defined as the area of the trough for which the absolute vorticity is $\geq 20 \times 10^{-5}$ rad/s plus the area $\geq 24 \times 10^{-5}$ rad/s, thus giving extra emphasis to deep closed lows.

The vorticity was computed from 300 mb height maps using a five point differencing method. The limiting values that went into making up the VAI were arrived at by inspection of many maps of vorticity over the Northern Hemisphere. It should be noted that the anti-cyclonic vorticity was not included in the definition of the VAI.

The results of this more recent study indicate that the response is more pronounced during years of solar minimum than during years of solar maximum, which is consistent with Shapiro's findings discussed earlier. The trough studies show the effect to be stronger in winter than summer, perhaps resulting from the greater natural variability in the vorticity data during winter.

Some results of the more recent investigation, which include the winter half-years of 1964-1971 are given in Figure 1.5. The dashed curve of Figure 1.5 shows the changes in vorticity area index for those key troughs that entered the Gulf of Alaska after a magnetic disturbance, while the solid curve represents the troughs entering the gulf during geomagnetically undisturbed periods. A question which arises when studying Figure 1.5 is what does the 10% higher starting point of the dashed curve mean when trying to

assess the significance of these results. Could this be evidence for an earlier response to the geomagnetic storm which occurred three days earlier? Another observation is that the two curves in Figure 1.5 reach a minimum on day three of the sequence at a time when the slope (response) of the key trough curve in the earlier study was the steepest (see figure 1.4). When considering the entire sequences, however, the larger size of the key trough is apparent in both studies.

The results of the trough analyses indicate an increase in meridional circulation at the same time (about + five days after the geomagnetic storm) Shapiro's work would indicate an increase in zonal circulation. What does this mean?

In a study of the changes in the average height gradient between 20°N and 50°N latitude at the 700 mb level, Stolov and Shapiro (1974) noted an increase in the average height gradient four days after a large geomagnetic disturbance in winter. The maximum effect was found in the quadrant 90° ~ 175°W and corresponded to a 7% increase in the mean westerly geostrophic flow. In summer a less prominent increase was found two days earlier than in the winter case. The study included the years 1947-1970 spanning more than two solar sunspot cycles (see figure 1.6). Although the excursion at +4 days is consistent with Shapiro's earlier work, no response appears on day +14 as was the case in his earlier work.

A similar study by London et al. (1959) of changes in the average zonal geostrophic flow over the United States at the 100 mb level failed to reveal any correlation with large or moderate geomagnetic disturbances. The study included the years 1951-1955

fig. 1.6 The mean height differences (in feet) of the 700-mbar surface between 20° and 55°N for the entire hemisphere in winter from 33 days before to 66 days after the C1 key days. The 21-day continuum is shown by a dark line. Student's t values, corresponding to the departures of each phase day mean from its continuum value, are also shown. (from Stolov and Shapiro, 1974).

which were years of relatively quiet sun.

Stolov and Spar (1968) studied atmospheric sea-level pressures at 31 stations in North America before and after solar flares. The individual analyses show no statistically significant pressure departures following flares, and a composite curve for North American stations also failed to produce any significant signal. Their study included forty relatively isolated flares for the period 1956-1960.

A study by Schuurmans and Oort (1969) of the response of the 300 mb height field to solar flares did reveal a pattern of alternating cells of positive and negative height change which is established within six hours of the flare. The analysis included 81 flares from the period July 1957 - December 1959. The significance of their results was tested by drawing comparison with the results obtained when applying the same analysis to three sets of random key dates selected from the same period. This study agrees with the result of Olson et al. (1975). However, it was not carried out long enough to confirm or negate Shapiro's finding of a decrease in persistence at about day +16 after flare activity.

Olson et al. (1975) in an investigation of 94 large wintertime flares of the period 1955-1969 find a 5-10% increase in the 500 mb "vorticity area index" (VAI) one day after the key date, followed by a 5-10% decrease in VAI three to four days after the flare (see figure 1.7). The VAI is the sum of the "vorticity area index", described previously (page 13) over the Northern Hemisphere north of 20°N latitude. It is therefore, a crude measure of the size and intensity of the troughs in the Northern Hemisphere. Although the two largest excursions in Figure 1.7 are significant at the 95% level

fig. 1.7 Student's t values for 24-h change in Vorticity Area Index (expressed as departure from mean) before and after 94 large flares, 1955-69 (winter season, October-March). Arrows on right indicate labelled confidence limits (from Olson et al., 1975).

fig. 1.8 Number of geomagnetic key days before and after zero days established by the three minimum value days per month of the 500 mbar VAI September-April, 1950-71 (from Olson et al., 1975).

it seems difficult to explain them in terms of a single physical mechanism if one takes the view that the peak and trough are indeed suggestive of a physical link between the two time series. This result is discussed further in Chapter III where I detail my studies of anomalous solar activity and the weather.

In the same paper Olson et al. studied the relationship of the VAI to fluctuations in geomagnetic activity. They designated three days each month where the VAI reached a minimum value as key days, and then constructed a superposed epoch curve plotting the number of geomagnetically active days before and after the key days. The results for winters 1950-1971 show a maximum number of geomagnetically active days one day prior to the minimum value VAI key day (see figure 1.8), thus implying that geomagnetic disturbances result in a decrease in VAI one day later, which is in agreement with their result using flares.

The response time of one day following geomagnetic activity is, however, not a confirmation of Shapiro's finding of increased persistence four days after geomagnetic disturbances, or the work with troughs in the Gulf of Alaska which showed growth five days after the disturbances. In the case of the trough analyses the inconsistency may be resolved by extending the study to include the day of the geomagnetic activity and the days just following.

Further work by Olson et al. (1978, to be published in Nature) using the central meridian passage on the sun of large active plages to define the key days, reveals a tendency for high values of VAI to precede the key day while low values of VAI tend to follow the key day. The study covers the period 1954-1974 and

includes all the seasons. Since the daily VAI values comprise a rather noisy data set, the data were normalized by selecting the three maximum and three minimum value days for each month. (Figure 1.9 shows the results of this investigation.) The curves in Figure 1.9 are the result of doing a superposed epoch study plotting the number of max VAI days minus the number of min days. The cross-hatching was done to show when the number of max and min VAI days are significantly different. Figure 1.9a is the result of a superposed epoch using the central meridian passage of a plage of activity index 10 on the Dodson-Hedeman (1971) list. The bracket marked Mag indicates the days when geomagnetic activity was significantly increased. Figure 1.9b is the same as 1.9a except key days are the three maximum days per month of the 10.7 cm solar radio flux. In Figure 1.9c two criteria are used to define the key days: key days are within $\pm$ one day of maximum 10.7 cm flux; and they are also days of central meridian passage of a plage of any activity index from the Dodson-Hedeman list.

The significance of these results was tested using the χ^2 significance test. Taking into account the possibility that the three key days per month could be consecutive days thus not truly independent, Olson et al. assumed that the three key days per month were consecutive in each case, and corrected for the resulting loss of independence. The probability of obtaining from a random set a distribution as highly skewed as shown in each of the curves of Figure 1.9 was still less than 0.5%.

The choice of three maximum and three minimum days per month has the advantage of normalizing the data which are very noisy,

fig. 1.9a Plages with C.F.I. ≥ 10 as key days.

fig. 1.9b 3 days per month of greatest 10 cm radio flux as key days.

fig. 1.9c Plages with large associated 10 cm radio flux.
(from Olson et al., 1978).

however, much of the information contained in the noise is thus also lost. In Chapter III, I investigate the possible relationship of large flares, large active plages and the circulation in the troposphere independently, using unfiltered meteorological data.

Conclusions

In this chapter I have not made any attempt to verify the reality of the claimed correlations I have discussed. I have merely presented the results of some of the more prominent recent studies. In Chapters II and III, independent examinations of the work by Wilcox et al. (1973, 1974, 1976), by Olson et al. (1975), and by Olson et al. (1978) are presented.

In order to make an easier comparison of the results of the investigations detailed in this thesis, I have summarized the nature and timing of the alleged correlations in Table 1.1.

From Figure 1.1 and 1.2 it is clear that a close relationship exists between solar flares, plages, and geomagnetic activity. The geomagnetic response reaches a sharp maximum about two days after the solar disturbance. If we subtract this two day lag from the timing of the supposed tropospheric responses to solar flares and plages then we can get a reasonable estimate of how well these results coincide with the timing of the results of studies using geomagnetic activity as the key day parameter. (The way in which the key days were defined has already introduced a $\pm$ one day ambiguity in the timing of the responses.)

At the outset it should also be recalled that not all the studies reviewed in this chapter produced "significant" results.

Table 1.1

<u>Author</u>	<u>Period of study</u>	<u>Parameter determining the key days</u>	<u>Atmospheric variable and level</u>	<u>Seasons included</u>	<u>Timing and nature of alleged responses</u>
1. Shapiro (1956)	1899-1945	geomagnetic disturbances	persistence of Sfc. pressure	all seasons	increase +4 days decrease +14 days
2. Shapiro (1972)	1947-1970	"	"	"	"
3. Macdonald and Roberts (1960)	1955-1959	"	300 mb trough index	winter	increase +5 days
4. Roberts and Olson (1973)	1964-1971	"	300 mb vorticity area	winter	increase +5 days
5. Stolev and Shapiro (1974)	1947-1970	"	700 mb height gradient	winter	increase +4 days
6. Wilcox, et al. (1973), (1976)	1964-1970	magnetic sector boundary crossings	500 mb and 300 mb VAI	winter	decrease +1 day increase +2 - +4
7. Schuurmans and Dert (1969)	1957-1959	large solar flares	300 mb heights	all seasons	alternate cells of increase and decrease +6 hrs.
8. Olson, et al. (1975)	1955-1969	"	500 mb VAI	winter	increase +1 day decrease +3-4 days
	1950-1971	geomagnetic dist.	"	"	decrease +1 day
9. Olson and Prince (1978)	1954-1974	large and active plages	500 mb VAI	all seasons	broad increase (several days before) broad decrease (lasting several days after)

Only those that did are included in Table 1.1.

The table format of representing the results, although it aids in acquiring an overview of the data, does not resolve the basic limitations that arise from the difficulty in comparing the various parameters used to describe the weather. Some general observations can be made nonetheless.

First of all, if we make the two day timing adjustment, we notice that all of the solar flare and solar plage studies produced responses preceding the time of the associated geomagnetic activity, while none of the studies involving geomagnetic activity as key days resulted in a response before day zero. (Could it be that researchers do not try to resolve signals produced prior to their choice of key day?)

One might conclude from this brief discussion that the alleged response of the weather to solar disturbances is a separate phenomenon from the responses found to geomagnetic fluctuations, or alternatively the reality of the alleged correlations may be in question.

While the results of studies authored by Shapiro are self consistent and the results of the trough analyses are also self consistent, in comparing the results of the two lines of investigation a clear pattern does not reveal itself. Shapiro's strongest response occurs at about two weeks after geomagnetic storms, yet none of the other studies listed in Table 1.1 reveals an effect this far removed from the key days.

The results obtained by Wilcox et al. (1973) (see Chapter II) have withstood extensive statistical testing by Halevy and Hines

(1977) and are in general agreement with the results of Olson et al. (1975), however, again no obvious pattern emerges when comparing the results of Stolov and Shapiro (1974), or Shapiro (1956, 1972) with the rapid responses found in the former studies.

If all of the alleged atmospheric responses to anomalous solar activity are real, then the physical nature of the signals is indeed even more complicated than generally thought by sun-weather researchers. The brief comparison undertaken here clearly illustrates the controversial nature of the sun-weather field.

In Chapter II, I give additional methods of testing for the statistical significance of a response in discussing the line of investigation pursued by Wilcox et al., 1973, 1974, 1976.

CHAPTER II

THE INTERPLANETARY MAGNETIC FIELD STRUCTURE AND AN INDEX OF VORTICITY IN THE TERRESTRIAL ATMOSPHERE

One of the more interesting associations between solar activity and the earth's weather, which has received a great deal of attention in recent years, is the apparently significant correlation between the dates when magnetic sector boundaries sweep past the earth and the vorticity area index (defined on page 16) computed for various tropospheric levels (Wilcox et al., 1973a,b, 1974, 1976).

In this chapter I discuss in some detail the results of the various studies linking the magnetic sector structure to the weather. The arguments used in this chapter can, in most cases, be generalized to apply to the studies reviewed in Chapter I, and therefore, some of the conclusions drawn may also apply in a broader sense.

The magnetic sector structure was first described by Wilcox and Ness (1965). Within each sector the polarity of the interplanetary magnetic field is predominantly in one direction. Since the interplanetary field lines are rooted in the sun, the entire field pattern rotates with about a 27 day period. The solar magnetic sector structure is extended outward from the sun by the radially flowing solar wind. The sector boundaries are often very thin, sometimes approaching a proton gyro radius in thickness. The time at which such boundaries are swept past the earth by the solar wind can therefore often be defined to within a fraction of an hour. It should be emphasized, however, that although the moment at which a sector boundary is carried past the earth provides a well

defined timing signal, the terrestrial magnetic effects are related for the most part to the large-scale structure existing for several days on each side of the boundary (Wilcox et al., 1974).

Since the polarity within each sector can be of either sign some boundaries will be more clearly defined than others. Svalgaard (1972), has pointed out that just around sunspot minimum the new activity begins rather erratically with no well developed sector structure. After sunspot maximum the sector structure is usually well defined before it disappears again near the next minimum.

It should be stressed (Wilcox et al., 1976), that the dates of sector boundary crossings should be viewed as a convenient timing device rather than as part of a physical mechanism. The sector structure has its origin in the sun and the solar wind, thus avoiding Hines' criticism of geomagnetic indices given in Chapter I on page 7. Figure 2.1 shows the relationship of the sector-boundaries and the Kp index of geomagnetic activity. The minimum prior to the sector boundary appears to be the most significant in the sequence, and implies that the strength of the solar wind diminishes prior to sector boundaries, increasing to above average values just after the boundary crossings. The vertical error bars give the magnitude of an excursion of two standard deviations.

Wilcox et al. (1973a) have extended the Roberts and Olson (1973) line of investigation by summing their "vorticity area index" (defined on page 13 of Chapter I) over the Northern Hemisphere north of 20°N latitude, thereby obtaining a global "vorticity area index". This is the same index used by Olson et al., 1975 and 1978 in their studies of solar flares and plagues (see Chapter I page 3.) They

fig. 2.1 The relationship of magnetic sector boundary crossings and the average Kp geomagnetic index.

then perform a superposed epoch analysis using the time at which the solar magnetic sector boundary passed the earth as the zero-day. Boundaries which were not well defined in time were excluded from these studies, thus leaving 54 sector boundaries for the winter months November through March 1964-1970.

The result of this investigation was a decrease in the VAI at 300 mb reaching a minimum approximately one day after the passage of a sector boundary, followed by an increase of about 10% in magnitude in the next two or three days (see figure 2.2.) (The vertical error bars give the probable error about the mean curve for various points).

Although the authors do not compute a significance for this excursion, they do divide the list of key sector boundary passage days with respect to polarity, time of year from November to March, and year and find essentially the same results. Hines and Halevy (1977), however, point out that in the case of an initially large signal, splitting of the key days into subsets does not necessarily constitute additional evidence for significance. A more appropriate test for significance is discussed later in this chapter. Wilcox et al. (1973b) go on to find evidence for a response at all levels of the troposphere up to the 200 mb level.

Harrison and Businger (unpublished) have taken an independent look at Wilcox's results. We also constructed a superposition curve (upper curve in figure 2.3) similar to that of Wilcox et al. (figure 2.2) using the same VAI data.

The dip seen at two days after the sector boundary crossings is the greatest excursion from the mean shown in this span and it

fig. 2.2 Average response of the VAI to magnetic sector boundaries for the winters 1964-70. 54 cases (from Wilcox, et al., 1974).

fig. 2.3 Upper curve - average response of the VAI to magnetic sector boundaries for the winters 1964-1970. 54 cases.

Lower curve - robust superposition of VAI data and magnetic sector boundaries.

agrees with Wilcox's result. We have extended the abscissa from $\pm$ six days to $\pm$ fifty days, thus revealing several other peaks and dips of nearly comparable magnitude. In doing so it appears that the dip seen in Figure 2.3 is a little less extraordinary than it seems in Figure 2.2. It should be noted, however, that the spacing of sector-boundary passage key dates is about seven days on the average, therefore, in a span of $\pm$ fifty days key days falling on days before or after the zero-day of the superposition sequence may produce spurious excursions in the sequence. This poses a limitation for the method of superposed epochs. Still it is a worthwhile exercise in that it gives another measure of the magnitude of the central excursion relative to other excursions in the superposed epoch sequence far removed from the key day and therefore presumably not influenced (on the average) by any solar geomagnetic event. In addition it provides a second test of significance.

The standard deviation can now be estimated either internally from the 54 crossings contributing to the minimum on the curve, or externally from the 101 points which make up the whole curve. The two methods give essentially the same result in this case. It should be noted that this additional test is not entirely independent from the original since it is derived essentially from the same data.

The nearly central dip on Figure 2.3 is, nevertheless, the greatest excursion from the mean. Its amplitude divided by the standard deviation is about two thus giving the dip a 95% confidence level.

The calculations made to determine this significance assume that the deviations of the data from the mean are normally distributed

and that the sequence of sector boundary crossings is not serially correlated.

It is easy to show, however, that both the sequence of field reversals and the sequence of vorticity indices are not white. The VAI is correlated with itself over periods of several days at least (see table 2.1). The reversal events show a maximum at intervals congruent with the solar rotation period, and considerable power at the first and second subharmonics of the sun's rotation, which is to be expected. The spectral power of the VAI (after filtering out the semi-annual and annual waves) overlaps strongly with the reversal events of periods less than ten days. Due to this spectral overlap something similar to a phase lock between the two might occur accidentally and lead to an abnormally large residual noise in the superposed epoch analysis.

Table 2.1

Interval Between Magnetic Sector Reversals, or Period Interval for Vorticity Power Spectrum	Fraction of Reversal Events Occurring Within Interval	Relative Spectral Power of Vorticity Area Index
(Days)	(%)	(%)
0 - 5	12	54
5 - 10	25	21
10 - 15	28	3
15 - 20	15	7
20 - 25	2	3
25 - 30 (solar period)	12	2
30 -	5	10
	100	100

In order to illustrate this we constructed arrays of random numbers having the same frequency distribution of reversal events as the real sector boundary days. Then Monte-Carlo tests with these random arrays against the real vorticity series exactly as before showed curves resembling the curve of Figure 2.3 roughly 10% of the time, between plus and minus ten days.

Hines and Halevy (1977) also explored the possible phase lock effect in several ways. The results of their investigations go far to dispose of the possibility (except at the 5% probability level) that the sequence of key dates had an accidental correlation with the characteristic variations of the VAI. They conclude that the large excursion produced by the original key half-days was not accountable for simply on the basis of the distribution of intervals between them.

To consider the question of normality, we have computed superposition curves, exactly as before, not only for the mean but for the variance, skewness, and kurtosis. These are shown in Figure 2.4 where it can be seen that near the day of sector boundary crossing the variance and skewness of the vorticity indices are both also at or near minima. This result alerts us to the likelihood that the phenomenon is sensitive to relatively few "outliers" among the points which contribute to the superposition of means. Hines and Halevy (1975) have also remarked upon this and have pointed out that the central dip is greatly diminished if as few as four of the 54 days of sector crossings are omitted from the series. We have shown an equivalent sensitivity to very few points by constructing a "robust" superposition curve, the lower curve of Figure 2.3.

fig. 2.4 Statistical parameters computed for the VAI data (1964-1970) using magnetic sector boundaries as the key day.

This curve differs from that above it by weighting each point contributing to the average vorticity by unity if that point differs from the mean by less than one standard deviation (that is, when t is less than one) and by t^{-2} when t exceeds unity. This procedure discriminates against the 10% or so of least typical points. As can be seen in the lower curve of Figure 2.3, the characteristic dip near zero lag is comparatively diminished with respect to the similar curve above it. Indeed the magnitude of the dip over the standard deviation is close to unity, and the apparent odds against an excursion as large or larger are not very impressive. Perhaps in this test we have thrown out the signal we are seeking in the analysis. Hines and Halevy speculate that this may be so. There is no way to test the significance of these new results, based, as they are, on the arbitrary discrimination of selected portions of the data.

Hines and Halevy also notice the abnormality of the variance near times of zero lag, and they guess that whatever mechanism may be producing the apparent coupling between the atmosphere's vorticity and the sun's magnetic sector fields may be operating by modulating the noise, that is, by dumping the variance into the means. We are unable to comment on the likelihood of this, but do comment that our superposition curve of the variance (second curve in figure 2.4) seems to contradict our understanding of Hines and Halevy in that our reading of their paper leads us to believe that they found a maximum of noise (variance) coincident with the zero-lag days, where we find a minimum.

To continue their examination of the significance of the supposed solar signal, Halevy and Hines (1977) introduce as a parameter the

excursion x , defined as the difference between the maximum and the minimum values of VAI found in a twelve-day interval. The excursion can then be considered a measure of the signal that emerges, or the residual noisiness (or both) as a consequence of the averaging process. The distinction between the noise interpretation and the signal interpretation is the crucial distinction here at issue and was drawn on the grounds of statistical properties.

Although the variation shown in Figure 2.2 is visually impressive, one really has no foreknowledge of what to expect from the superposition of 54 twelve-day intervals of VAI data. Therefore, Hines and Halevy computed 200 superposed epoch curves using random key day sets. The excursion of each curve was then obtained thus providing an ensemble average of 7.57 ± 1.98 where the $\pm$ represents the rms deviations from the mean. The excursion of the original curve would have been produced with at most a 2-3% probability.

The possibility exists that this probability, though low, was just the result of the process of the selection of best data for presentation. The 2-3% value might well represent the degree to which artificial tuning (i.e., leaving out the summer months) of the data had been successful in inhibiting the cancellation of noise rather than producing true signal. This possibility can only be tested by an application of precisely the same rules of tuning to new data.

Wilcox et al. (1976) have subsequently published further superposed epoch analyses using a new set of 81 key days and filtered 500 mb data. Hines and Halevy (1977) have done an independent check of the new results using unfiltered data. They conclude that

the consistency of the new signal that was produced in these analyses with the alleged signal that had been produced in the original analyses was obviously such as would conform to any criteria for consistency that might have legitimately been established.

Larsen and Kelly (1977) have provided independent support of Wilcox's et al. (1973) earlier results. They studied the integrated values of high positive vorticity at the 500 mb level predicted by one of the National Weather Service's prognostic models and found a decrease in the correlation coefficient between the 24 hour forecast product and the observed vorticity of .17 one day following the magnetic sector boundary crossing. In addition, analysis of the integrated vorticity areas for the winter months of the period 1972-1975 provided independent verification of the earlier studies relating sector structure with atmospheric vorticity.

Since the 500 mb VAI response to the sector structure suggests a change in the large scale circulation presumably this change would also manifest itself in the mean zonal geostrophic flow at this level in the atmosphere. In order to investigate this possibility, and also to study possible atmospheric responses to large flares and active plages (discussed in Chapter III), I have computed a daily value for a "zonal index" for the period 1955-1974. The zonal index has the advantage of measuring a tangible atmospheric quantity, the zonal geostrophic wind, for which there is some background information. The zonal index was defined as the average difference in height of the 500 mb pressure level in the atmosphere between 25° and 65° north latitude in the Northern Hemisphere. The height gradient was computed for every 5° of longitude and then averaged

around the globe to obtain a "zonal index". Stolov and Shapiro (1974) used a similar index to study the influence of geomagnetic activity on the average geostrophic flow of the atmosphere at 700 mb. Their results are discussed in the previous chapter.

The result of a superposed epoch study of 98 winter-time magnetic sector boundaries and the zonal index for the years 1964-1974 is given in Figure 2.5. The VAI response shows a dip at about one day after the key day. If low values of VAI correspond to a more zonal circulation (less deep troughs), as one might expect, then the zonal index should reach a maximum at about the same time. Although the zonal index does show a rise after the key day, the first maximum (1.15) following the key day (see figure 2.5) does not occur until day +7 and is followed by an even larger excursion on day +18 (not shown). My conclusion from this exercise is that no relationship is apparent between the zonal index and the crossing of magnetic sector boundaries for this period. This conclusion may reflect the fact that the VAI is more closely related to the eddy flow rather than the zonal flow; the response then manifesting itself in the eddy component of the flow. Work by Williams (1978) addresses this point.

Bhatnagar and Jakobsson (1978) have also looked at atmospheric responses to magnetic sector boundaries. They investigated two dynamical atmospheric indices, kinetic energy density and square of the vorticity of the main motion. The results of their study leads them to conclude that no relationships were found between the solar sector boundaries and these particular atmospheric indices, irrespective of the time within the solar cycle, latitude, season,

fig. 2.5 Zonal index vs. magnetic sector boundaries. 98 cases from winters 1964-1973.

fig. 2.6 VAI values vs. magnetic sector boundaries
a) the dashed curve for 73 cases, 1965-1973 winter
b) the solid curve for 38 cases, 1974-1977 winter

and polarity of the interplanetary magnetic field. The period of study was 1963-1969.

In a recent paper Williams (1978) analyzed four components of the Lorenz energy cycle by superposed epoch method using sector boundary crossings as key days. The Lorenz energy cycle was introduced as a means of attempting to establish a broader physical picture of the atmospheric processes involved in the solar modulation of the VAI. While the Lorenz energy cycle has the distinct advantage of integrating four separate energy parameters, it does suffer the drawback of not including water vapor. The eddy kinetic energy is reported to respond in a similar nature, but to a lesser amplitude and statistical significance than the VAI response (97% at 500 mb). A control experiment using random key days suggests that the statistical significance of these results was actually much less. Thus Williams concluded that no compelling evidence for a solar modulation of tropospheric energetics was found. He does however, point out the possibility that certain wave numbers that make up the eddy kinetic energy may respond more strongly than others. Since the VAI is finely tuned to storm systems, the decomposition of the eddy kinetic energy into wave components may reveal a stronger relationship of select modes with the sector boundaries.

In studying the amplitude of the kinetic energy response Williams found a stronger signal for the earlier years of the analysis (1963-1973) than for the more recent years (1974-1977). This led to an analysis of the VAI for the more recent sector boundaries (1974-1977). It was found by Williams and Gerety that no solar modulation of the VAI revealed itself for these more

recent years. Figure 2.6 shows my superposition of VAI for the years 1974-1977.

Svalgaard (personal communication) found a similar reduction in the strength of the VAI response during the years of solar minimum in the mid-sixties. He notes that the sector structure loses its definition during years of sunspot minimum (Svalgaard, 1972). What this means for the nature or reality of the vorticity response is unclear. Many scientists, myself included, feel that more satellite data are necessary before a firm judgment one way or the other is possible.

Chapter IV will discuss further the implications of this, and other alleged sun-weather correlations discussed in this thesis, for the nature of the physical mechanisms that may be responsible.

CHAPTER III

LARGE SOLAR FLARES, LARGE SOLAR PLACES AND TWO INDICES THAT MEASURE ATMOSPHERIC CIRCULATION

In this chapter my attempts to substantiate and provide further information about the nature of some of the alleged relationships discussed in Chapter I are presented. In particular, plages and solar flares from the Dodson-Hedeman lists are studied with respect to the VAI and a zonal index (defined in Chapters I and II respectively) for the Northern Hemisphere.

Dodson and Hedeman (1971, 1975) have derived activity indices for large flares and large plages for the years 1954-1974. The flares are classified by five components: short wave fade (or other sudden ionospheric disturbance), associated H α flare, 10 cm flux, type II burst, and type IV radio emission. Each of these components is assigned a numerical value depending on the presence (or absence) and strength of the component's effect. The sum of the five components then gives the Comprehensive Flare Index or CFI.

For the plage index, five characteristics are considered; these are: the size and complexity of the accompanying sunspots, the flare productivity, associated sudden ionospheric disturbances, centimetric and metric radio flux emission from the plage.

Using these lists Olson et al. (1975) determined that large winter (October-March) flares with a CFI of ten or greater produced a significant response in the VAI at the 500 mb level (see figure 1.7 in Chapter I) for the period 1955-1969. Since then a new flare list has been published for the period 1970-1974. Using

fig. 3.1

the two lists I have attempted to reproduce the response found by Olson et al.

I constructed superposed epoch curves using all the winter season flares with a CFI of greater than or equal to ten as the key day parameter. For the period 1955-1974, spanning roughly two solar sunspot cycles, 102 flares qualified from the Dodson-Hedeman list. The results can be seen in Figure 3.1 where the upper curve covers cycle #19 (1955-1964), the middle curve cycle #20 (1965-1974), and the lower curve includes the entire period. The vertical error bars represent an excursion of two standard deviations. From this figure it can be seen that no significant excursion resulted from this exercise, though there does appear to be some agreement in the shape of the curves with Olson's et al. (1975) result especially in the lowest curve of Figure 3.1.

In Olson's study it was found that flares near east-and-west limb on the sun and, more generally, flares on the western side of the sun did not produce the response that flares near central meridian, especially those $\leq 45^\circ$ East longitude, produced. They argued that flares near central meridian produce larger geophysical (magnetic) effects and that the effects produced by flares on the far western half of the sun may not reach the earth due to the rotation of the interplanetary magnetic field with the sun.

To test these ideas only those flares of CFI greater than ten within the longitudes $45^\circ\text{E} \leq \text{flare} \leq 25^\circ\text{W}$ on the sun were used as key days. The results of a superposed epoch study again covering the period 1955-1974 are shown in Figure 3.2. In Figure 3.2a, which includes flares occurring in all seasons, a significant peak does

fig. 3.2a

fig. 3.2b

fig. 3.2a VAI vs. large flares ($45^{\circ}\text{E} < \text{flare} < 25^{\circ}\text{W}$ solar longitude) as key days. 92 cases

fig. 3.2b VAI vs. large flares ($<45^{\circ}\text{E}$ and $<25^{\circ}\text{W}$ solar longitude), 1955-74, winter season. 44 cases.

not occur near day zero as in Olson's result, and the magnitude of the dip on day three after the key day is only at the 90% level, thus there is a $\geq 10\%$ chance it is due to random chance; therefore, this excursion is not very compelling for the reality of a physical link. Figure 3.2b, which includes only the flares occurring during the winter months October-April, does show a significant peak on day zero (mostly due to the contribution of the +12 hour (12Z) VAI data). However, when the data were divided into two subsets, including cycle #19 and cycle #20 separately, the effect did not reveal itself.

In choosing the key days I was careful to avoid spurious correlations resulting from the persistence of the VAI data by insuring that the spacing of the key days was at least eight days. Thus if several flares were grouped within eight days of one another I chose the flare with the greatest CPI value to represent the period. Olson et al. chose all flares of CPI $\geq$ ten and longitudes between 45°E and 0° regardless of the spacing of the flares. These differences may account for the lack of a strong correlation in this more recent investigation.

Next I constructed superposed epoch curves using the same list of large flare key days as in the previous study only using values of the zonal index (as defined in Chapter II). The result of this exercise is shown in Figure 3.3 where it again appears that no relationship between the mean geostrophic flow for $25^{\circ} - 65^{\circ}$ north latitudes and large flares is shown for either winter or summer months. (The vertical error bar represent an excursion of two standard deviations from the mean). The winter flare curve (upper

fig. 3.3

curve in figure 3.3) shows the largest excursions prior to the zero day when presumably no response to the flare is possible.

Theoretical work (Markson, 1978, Herman and Goldberg, 1978, and Hays and Roble, 1978) has attempted to link solar activity with parameters of atmospheric electricity and thunderstorm activity. It is thought that the changes in atmospheric conductivity, brought about by changes in cosmic ray intensity and solar corpuscular radiation, may effect the charging processes within prospective thunderstorm clouds. Changes in cosmic ray intensity during solar flares have been discussed in detail by Forbush (1966). Model calculations made by Hays and Roble (1978) indicate that conductivity changes due to a solar flare are capable of altering the electrical circuit on a global scale. The lack of good observations of variations in electrical conductivity at various altitudes, however make critical evaluations of a specific event impossible at this time. I will discuss this and other suggestions for physical mechanisms in more detail in Chapter IV.

Since the changes in cosmic ray intensity and resulting changes in atmospheric conductivity are central to the theories relating solar activity to atmospheric electric parameters, a preliminary study of flares producing large variations in cosmic ray intensity was undertaken.

From the original list of flares two subsets were created. One consisted of flares accompanied by a 5% decrease in cosmic ray intensity (Forbush decrease) measured at the ground by neutron monitors at three North American stations. The control list included flares which were not accompanied by detectable decreases

in cosmic ray intensity.

Superposed epoch curves were then computed for each list of key days. The results are given in Figure 3.4. The curve in Figure 3.4a shows the results for 32 flares with associated Forbush decreases for the years 1959-1974, while Figure 3.4b shows the curve for the control case.

There is a marked difference between the two curves just after day zero. A broad trough of low VAI values occurs after the key day in the case of flares with Forbush decreases, while the control curve exhibits a narrow dip two days prior to the key day of lesser magnitude. The tendency for low values of VAI to follow flares with Forbush decreases would be consistent with the results of Olson et al. (1975 and 1978). However, these results do not provide strong statistical evidence for the reality of a sun-weather effect.

To further investigate the possible influence of Forbush decreases on atmospheric parameters I studied a list provided to me by Mr. Olson of 5% decreases in cosmic ray intensity measured at the Mount Wilson neutron monitor. Using the dates of these decreases for the years 1959-1974 as key days I constructed a superposition curve with VAI data to see if a similar signal would appear as in the case of flares accompanied by Forbush decreases. The results are shown in Figure 3.5. Although there is a hint of low VAI values after the key day the most striking feature of this curve is the maximum at day +16. My conclusion is that no relationship between Forbush decreases and atmospheric vorticity has revealed itself in these preliminary studies. It should be emphasized that the data sets used were relatively small; thus firm conclusions will require further

fig. 3.4a

fig. 3.4b

fig. 3.4a VAI vs. flares with associated cosmic ray decrease of 5% or more. All seasons, 32 cases, 1959-74.

fig. 3.4b VAI vs. large flares without associated cosmic ray decreases of 5% or more all seasons, 22 cases, 1959-74.

fig. 3.5 VAI vs. key days defined by a 5% decrease in cosmic ray intensity at the Mt. Washington neutron monitor.

analysis with data from a larger network of stations with reasonably long measurements of cosmic ray intensity.

Olson et al. (1978), in a paper which I detailed in Chapter I, find a significant correlation between the central meridional crossing of active plage regions on the surface of the sun, and a normalized indicator of the VAI. Since they used the three maximum and three minimum VAI values per month to construct their superposition curves (figure 1.9), it seemed worthwhile to study the unfiltered VAI data directly to see if the response was discernible. By choosing the max and min days of VAI for analysis, Olson and Prince are smoothing the data considerably. This has its advantages especially when dealing with noisy data, as is the case with VAI values. However, much of the information contained in the noise is thus also lost.

The results obtained by Olson and Prince indicate that the alleged atmospheric response of the VAI is a broad increase before the key day followed by a broad decrease following the key day occurring in summer as well as winter though less strongly in summer. This may be the result of the fact that the plage is emitting radiation continuously while a typical flare usually lasts for a matter of minutes to a few hours. Thus the plage is a stronger energy source at the earth (Olson et al., 1978). Olson et al. conclude that plages appear to organize the VAI data better than the flare dates. They suggest that flares tending to occur at various locations on the solar disc at about the same time may obscure the results when studying flares. This contention stems from Olson's et al. (1975) result that the VAI first experiences a

rise and then a fall after large solar flares (see figure 1.7).

Figure 1.2 illustrates the relationship between plage key days and geomagnetic activity. Figure 3.6 shows the response of the Ottawa 10.7 cm radio flux to the plage key days.

To further investigate Olson's and Prince's claims, I have used the same list of plage key days as was used in their study. These dates are well separated in time, thus avoiding some of the problems in estimating the statistical significance of an excursion resulting from the use of flare occurrence as the key days in the superposed epoch analysis. The results of my superposed epoch study correlating the VAI with plage key days is given in the lower curve of Figure 3.7. The most striking feature of this curve is the rather broad minimum found between day two and day seven of the sequence. This excursion is 1.9 standard deviations from the mean, thus one's first estimate of the likelihood that this feature is produced by random processes is <10%. The upper curve of Figure 3.7 shows the result of the same study using zonal index data in place of VAI data. The broad peak from day five to day twelve reaches a maximum 2σ away from the mean, thus making it "significant" at the 5% level.

When the significance of these two results was further tested by dividing the data into subsets corresponding to the solar sunspot cycles #19 and #20 each period produced results in agreement with those shown in Figure 3.7 with excursions of comparable magnitude. Again it should be pointed out that these estimates of significance rely on the assumptions that the data are not serially correlated and the deviations from the mean are normally distributed, as was discussed in Chapter II. Hines and Halevy (1977) have also shown

fig. 3.6 Relationship of Ottawa 10 cm radio flux to central meridian crossing of a large plage.

fig. 3.7

that once an excursion is established as "significant" splitting the data into subsets does not necessarily constitute additional evidence for significance since large excursions produced using random key days usually also retained their identity when the data were divided. The breadth of the excursions, although they may (in part) be a reflection of the fact that the data have a high degree of persistence for periods of several days, tends to support the significance of the features from a statistical point of view. The trough in the VAI curve in Figure 3.7 is in general agreement with the result of Olson et al. (1978), however, I have found no clear evidence for a maximum in VAI preceding the key days as they reported.

To further test the significance of the curves Hines' and Halevy's (1977) technique (described in Chapter II) of computing the excursion for many sets of random key days was applied. I thus computed superposed epoch curves for fifty sets of random key days chosen from the original period 1955-1974. From these curves the mean excursion and the standard deviation from the mean were derived.

The mean excursion for the fifty curves using VAI data was $4.45 \pm .52$ where the $\pm$ refers to the standard deviation from the mean. Thus the excursion of the lower curve in Figure 3.7 of 5 units is 1.0σ away from the mean excursion giving it a 32% probability of occurring through random coincidence, not a very impressive statistic when trying to establish a credible sun-weather relationship. Following the same procedure for the zonal index result (upper curve of figure 3.7), the probability of an excursion of ≥ 34 meters occurring by random processes was only 10%. In five

of the curves produced using a randomly generated set of key days the excursion was as great or greater than that produced using the actual plage key dates. This statistic tends to discredit the confidence (95% level) found earlier for the zonal index curve of Figure 3.7.

For now I leave the question of the statistical significance of the alleged signals and turn instead to a brief comparison of the nature and timing of the excursions shown in Figure 3.7. The first observation one might make is that the duration of each of the two signals is about six days, however, the alleged response of the zonal index is displaced by about three days from the VAI response. Though there is some overlap this fact is nonetheless puzzling if one wishes to explain these two curves as a result of the same forcing. The difference in the sign of the excursions may be easier to explain if one takes the point of view that high values of VAI correspond to strong troughs and a relatively meridional circulation while low values of VAI correspond to a more zonal regime leading to higher values in the computation of the zonal index. Alternatively, one could argue that large values of VAI could result from large latitudinal shear inherent in strong zonal winds.

My conclusions from the study of plages and tropospheric circulation are that the significance of the results given in Figure 3.7 are not compelling evidence for a sun-weather connection. Further attention is, however, warranted, in my mind, in light of the overall magnitude and nature of the excursions. The list of plages can be broken down according to their physical characteristics to perhaps reveal a more significant correlation with the circulation

of the atmosphere. Alternatively it may further be useful to break down the zonal index, as Stolov and Shapiro (1974) have done, to investigate separately the possible response over the oceans versus that over land. The function of further statistical studies of solar flares and plages at this point should be to test particular hypotheses of the physical processes that may be operative in sun-weather relationships.

CHAPTER IV

DISCUSSION OF SUGGESTED PHYSICAL MECHANISMS

In this chapter I discuss some of the physical mechanisms which have been suggested in recent years. It should be pointed out at the outset that none of the physical mechanisms that have been advanced successfully provides an explanation of how solar variations and/or geomagnetic disturbances cause changes in the terrestrial weather. Part of the difficulty in determining the physical causes for an atmospheric response to solar variability lies in the numerous forms of radiation in which solar energy reaches the earth. Some of these fluxes can be deflected by the earth's magnetic field and there are many arrangements as to the altitudes, latitudes, and longitudes where the energy finally becomes available to affect the dynamics of the atmosphere or some component thereof.

Compounding the difficulty is a complex mechanism with many feedbacks and second-order effects apparently not related to solar activity, but which may well obscure its influence. Therefore the study of the effects of solar activity on specific meteorological parameters reveals only part of the picture, and actual effects on weather may be hidden by various feedback processes.

In the search for a physical mechanism there has appeared no prospect of finding a direct heating mechanism to explain the prompt changes in the atmospheric circulation claimed by researchers. (Willis, 1976 gives a good table of the energies associated with various solar fluxes.) The observed time associations can

therefore only be explained by trigger effects based on instabilities, or by time-modulation effects, in which the energy of the change is already stored in the circulation when the solar energy simply accelerates or delays the timing of the event to produce the observed correlation (Hines and Halevy, 1977).

In addition to these restraints provided by consideration of the energetics involved, the physical mechanism must take into account the delay time of the alleged response with respect to the zero day. From Table 1.1 it can be seen that the majority of the responses occurred within five days of the solar or geomagnetic activity. In the well studied case of the VAI's response to the passing of a magnetic sector boundary the lag time is only one day. The magnitude of the signal corresponds to a 10% reduction from the mean VAI level. In the studies of possible responses of the weather to solar flares and plages (Olson et al., 1975, 1978) the greatest effects are seen within a day or two of the key day. Such prompt response times must be explained by the suggested physical mechanism if it is to be successful.

Mechanisms that involve the possibility of downwards propagation of gravity waves which dissipate energy at lower levels would seem more plausible if they were working in the other direction. Energy variations in the regions established as responding strongly to solar variability are less than 10^{-4} the amount of energy required to influence the lower atmosphere (Dickinson, 1975). A more likely suggestion might be a mechanism which upsets the stability condition in such a way that the principle part of the energy is derived from the lower atmosphere itself. Hines and Halevy, 1975, have formulated

a mechanism whereby upward propagating gravity waves are reflected by the upper atmosphere allowing them to travel downward and interfere with the troposphere. If solar activity produces changes in the reflection properties of the upper atmosphere there could be an indirect modulation of atmospheric circulation by solar activity. This mechanism would be consistent with the observed stronger correlations during winter months because of the absorption of the gravity waves at intervening critical levels during the summer months. It should be noted, however, that Hines himself has expressed reservations regarding this mechanism stemming from consideration of the energetics involved.

Hines and Halevy (1975) have suggested another possibility; they propose that rises and declines of the VAI may be shifted in time by a phase modulation introduced by solar activity. By phase shifting vorticity data obtained from randomly selected days Hines and Halevy have been able to simulate the Wilcox results. However, without a physical explanation it is difficult to imagine how the phase shifting can be accomplished except by purely arbitrary means.

Cirrus Cloud Formation

Roberts and Olson (1973) have suggested that very energetic solar protons (>60 meV) and bremsstrahlung may cause ionization at levels in the atmosphere near the upper troposphere. If the ions are subsequently transported to the level of the troposphere they can then serve as condensation nuclei and produce cirrus clouds, provided the air is near saturation. Roberts (1976) argues that sudden cirrus clouding, if a change of state were triggered by

solar activity, could alter the radiation balance of the atmosphere. Dickinson (1975) has, however, argued that ions will not readily nucleate entire water droplets directly because they still require several hundred percent supersaturation, however they may be important in forming aerosols that will, such as sulfuric acid aerosols.

The sudden cirrus clouding hypothesis, however, has a few drawbacks. Mason (1971), discussing the abundance of ice nuclei at various levels in the atmosphere cites several studies that conclude that ice nuclei concentrations near the tropopause are as high as those near the surface. Thus, formation of cirrus would depend on the saturation of air rather than the availability of ice nuclei active at those temperatures. Consideration of electrical transport processes to bring proton-produced ionization from its region of origin (above about 20 km height) down to altitudes where it could influence nucleation (15 km) shows that such processes would be doubtful unless the ion lifetimes are considerably longer than presently believed.

Heating due to cirrus formation would require at least several days to be operative, thus, failing to explain the prompt vorticity response to solar flares and magnetic sector boundaries.

Ozone Variation and Variation of the Solar Constant

Ozone plays an important role in the earth's atmospheric radiation balance. Ozone absorbs and emits infrared radiation at $9.6\mu\text{m}$ and absorbs visible radiation in the Chappuis bands near 6000 Å. Because of its importance, it has been suggested that possible variations in ozone resulting from solar activity

(variability in ultraviolet radiation of wavelengths .17 to .3 μ) may represent a physical mechanism which could link solar activity with the atmospheric circulation.

At the outset it should be pointed out that the question of the relationship between the variations in ozone and solar radiation is controversial. London and Kelly (1974) examine global trends in total ozone and remark that hemispheric differences in the trends of ozone seem to preclude any direct solar influences. Chamberlain (1977) has proposed a mechanism whereby low solar activity and enhanced cosmic-ray production of NO_x in the stratosphere would reduce the ozone abundance. His arguments are, however, directed at secular variations in solar magnetic activity (~ 100 years); longer than the response times addressed in this thesis. Paetzold (1973) does find a correlation between solar activity and stratospheric ozone for the sunspot cycles #19 and #20. His estimation of the variation of total ozone during a solar cycle is on the order of 3% measured at the ground with most of the variation occurring between 20 and 30 km. Angell and Korshover (1976) report that although there appears to have been some decrease in total ozone in north latitudes following intense solar flares the relationship is not conclusive.

Regardless of the outcome of this controversy, it appears that the possible solar modulation of ozone is relatively small compared with geographic and quasi-biennial variations observed in ozone data (Angell and Korshover, 1976). Presuming solar activity does result in a decrease in total ozone, the effect of the resulting decrease in infrared radiation transferred downward from the stratosphere

would be opposite to the effect of the increase in visible radiation reaching the ground (Dickinson, 1975). Therefore it appears unlikely that the net changes in the radiation budget due to solar modulation of ozone can account for the rapid response of atmospheric pressure and wind fields discussed in Chapter I.

Another mechanism which has received attention in recent years is the possible variation of the solar constant. It is obvious that changes in the total solar radiation incident on the earth would affect weather and climate.

Spacecraft measurements offer the best hope of resolving this question. Only in the last few years have we had the capability to monitor the solar constant continuously from above the atmosphere, where all the problems of atmospheric transparency are eliminated. Results from the Mariner spacecraft reported by Plamondon (1969) showed no correlation with sunspot number and that the total variation in solar constant was less than about 0.3%. During the 150 days in which the solar constant was monitored continuously Plamondon found variations in solar flux to tenths of 1%, and states that these variations appear to be random rather than correlated with solar activity. Early results from the Nimbus 6 spacecraft showed variations in the solar constant were less than 0.2% in the first six months of operation.

Numerical experiments to test the sensitivity of the Giss global atmospheric general circulation model to changes in solar constant (two-thirds and three-halves the standard amount) and ozone amount (zero and twice the standard amount) show such small effects during the first twelve days of integrations that the effects of realistic

variations would almost certainly be insignificant on this time scale (Somerville et al., 1976). These results are not surprising considering the integrations are short in comparison with the tropospheric radiative relaxation time of about fifty days (Manabe and Wetherald, 1967) used in the model calculations.

When regarding the implication of the arguments presented in this section for the subject of sun-weather relationships, my conclusion is that other physical processes must be sought in order to explain the rapid responses claimed by researchers.

Atmospheric Electricity

Perhaps the most likely theoretical direction able to explain the alleged correlations between variable solar activity and the weather is the recent work on atmospheric electricity and thunderstorms. The strength of the atmospheric electrical mechanisms lie in the fact that they bypass the difficulties inherent with heating mechanisms, such as changes in solar constant or ozone concentrations, in that they offer the possibility of releasing and redistributing energy already present in the troposphere. The atmospheric electrical mechanisms require no solar energy to change the state of the earth's electric field and stratospheric conductivity (Markson, 1978). With an atmospheric electrical mechanism it is unnecessary to couple energy from the upper to the lower atmosphere as the entire electric field from the ionosphere to the earth would be affected. If the ionospheric potential varied, the largest absolute variation in electric field intensity would occur near the ground, where electric fields maximize (Markson, 1978).

Another advantage of atmospheric electrical mechanisms is that they offer the rapid response times required. While heating mechanisms are presumed to require at least several days before atmospheric dynamics would be affected, a change in ionospheric potential would rapidly affect electric field intensities all over the world (Hays and Roble, 1978).

Observations of air-earth current and the electric field made at high altitude mountain locations (Cobb, 1967, Reiter, 1969, 1972) exhibit significantly large increases following solar flare eruptions. Cobb's observations showed an increase above normal values of as much as 35% over 24 hours and by 70% during one six hour period following a multiple flare burst. Both Cobb's and Reiter's results show an average increase in fair-weather air-earth current of more than 10% occurring on the key day and lasting for three days or so. Cobb's results were, however, greatly influenced by the contribution of a few very large flares that occurred during the month of July 1961. Since long periods ($\sim$ two weeks) of consecutive fair-weather are needed for these studies, the data base used by Cobb and Reiter are not large, therefore, the results of these studies are, as yet, inconclusive. Märcz (1976) has recently shown that the potential gradient measured near the ground in Poland ($\sim 51^\circ\text{N}$) increases by 30-50% in association with geomagnetic storms. The increases occurred one day after the key day, lasting for several ($\sim$ three) days, and were significant at the 98% level, according to Märcz.

Increases in thunderstorm activity four days after the eruption of a major solar flare have been found by Reiter (1969, 1971), and Bossolasco et al. (1972), and Flohn (1950, 1951) noted

increases in thunderstorm occurrence frequency in central and northern Europe three days following central meridian passage of major active sunspot groups. Markson (1971) indicates a 63% increase in thunderstorm-occurrence frequency in the United States, maximizing about seven days after flare eruptions. The long lag time of seven days makes it uncertain whether United States thunderstorm activity is affected by solar flares. Also there is some evidence for modulation of regional thunderstorm activity following the passage of solar magnetic sector-boundaries in which the polarity changes from positive to negative (Markson 1971, Bossolasco et al., 1973). However, while Markson finds an increase in activity in the United States about one day after the crossing, Bossolasco's results show a decrease ($\sim 15\%$) in thunderstorm occurrence in the Mediterranean. No correlations were found by either study near negative to positive sector-boundaries.

An explanation for these atmospheric electrical responses to solar activity is suggested by theoretical work by Markson (1978) and Herman and Goldberg (1978). Central to their treatments of the problem is the hypothesis that cosmic-ray decreases (Forbush decrease) and/or high energy solar protons associated with active solar events may alter atmospheric electric parameters. The protons produce excess ionization near and above 20 km, greatly increasing the atmospheric conductivity and possibly lowering the height of the electrosphere (Herman and Goldberg, 1978). Forbush decreases tend to reduce atmospheric conductivity at all levels resulting in an enhancement of the electric field maximizing at low heights.

Several world-wide variations in cosmic rays have been established. The most notable disturbances on short-time scales are known as Forbush decreases, which last for several days to several weeks and are highly correlated with the occurrence of geomagnetic storms (Forbush, 1966, Lockwood, 1971). Other correlations that have been noted include a 27-day periodicity and an asymmetry between hemispheres depending on solar sector magnetic field (Wilcox, 1968).

Calculations made by Hays and Roble (1978) using a quasi-static model of global atmospheric electricity show that global electrical resistance decreases from 273 to 247 ohms during the Forbush decrease. The ground electric field at both the equator and the pole are also modulated, decreasing first and later increasing. They simulated the Forbush decrease by a 10% decrease in global electrical conductivity, and assumed latitudinally dependent changes in conductivity resulting from the increase in solar protons during flares. It should be stressed, however, that the assumed global variations of electrical conductivity during solar flares are crude and that simultaneous global data at various latitudes are lacking. These results, nevertheless, imply that responses of atmospheric electric parameters to solar activity are of a global scale.

Linking solar activity to changes in atmospheric electrical parameters, although it provides a good first step in explaining a possible sun-weather relationship, does not clarify the resulting problem of how these changes in electric parameters effect cloud physics and ultimately the circulation.

Several charging mechanisms depend on polarization of cloud droplets in the fair-weather electric field during the initial

stages of electrification (Markson, 1978). Sartor (1978) found that the ultimate electric field intensities in developing cumulus are extremely sensitive to the initial electric field strength. For a given fair-weather electric field which results in a weakly electrified cloud ($1,000 \text{ Vm}^{-1}$), if the initial field intensity is increased by 32% (as might occur following solar activity), that cloud would become electrified to thunderstorm intensity ($1,000,000 \text{ Vm}^{-1}$).

The results of a model of Scott and Levin (1975) indicate a close coupling between precipitation growth and electrification. High electric fields enhance coalescence of small droplets into large drops, the most important factor in rain formation. Sartor (1970) calculates that the instantaneous growth rate of precipitation particles goes up approximately proportionately with the increased electric field intensity. Several physical processes that explain why electric fields affect coalescence have been summarized by Mason (1971). If precipitation reaches the ground as a result of these processes, latent heat of condensation would be left in the atmosphere where it could affect the circulation. Markson (1978) has suggested that ice from the anvils of thunderstorms could subsequently seed lower clouds downwind. This might stimulate additional rain.

Perhaps, the key to explaining solar modulation of vorticity may be that oceanic thunderstorms maximize at northern latitudes in winter (Markson, 1978). In contrast, cumulonimbus are not common over continents during disturbed winter weather. However, this does not mean winter storm clouds are not electrified. Snow clouds

are charged, some sufficiently to produce lightning (Markson, 1978). The greatest obstacle in verifying these ideas is the lack of good data on thunderstorm occurrence frequency on a global scale, and especially over the oceans. What is much needed now is the continuous global monitoring of thunderstorms by satellite.

The arguments that solar modulation of atmospheric conductivity would change the earth's electric field intensity seems to be on reasonably firm ground both theoretically and from the results of statistical studies (Markson, 1978). However, the implications of these changes for thunderstorm activity, and other parts of meteorology is speculative and clearly will require further investigation.

Conclusions

The greatly increased understanding of solar, space, and upper atmosphere physics, due primarily to satellite observations, has been conducive to reconsidering the possible solar influence on weather. The most widely discussed sun-weather correlation, possibly because of its apparent high statistical reliability, was the response of the atmospheric vorticity in the Northern Hemisphere to the solar magnetic sector structure discussed in Chapter II. This and other studies detailed in this thesis suggest that there probably are some connections between changes on the sun and changes in the lower atmosphere. The results of studies described in Chapter III have, however, failed to verify previous statistical correlations found between large solar flares and the circulation of the troposphere. Studies using the dates of central meridian

crossing on the sun of active plages did produce results suggestive of a sun-weather connection, although not retaining the statistical reliability of the correlation between the magnetic sector structure and vorticity in the troposphere.

There is still a conspicuous lack of an acceptable physical theory linking solar activity and the weather. It is clear that the subject of sun-weather relationships is a controversial one, and it will remain so until such time as a physical mechanism is advanced which can explain some of the reported statistical correlations.

It is important now to direct effort toward critical statistical experiments designed to test particular aspects of suggested physical mechanisms. For instance, if winter thunderstorms over northern oceans are responsible for VAI variations following sector boundary crossings, a study of VAI over oceans vs. land should reveal a stronger response to the solar sector structure.

The study of isolated cases of intense solar activity may provide clues as to the physical processes involved, and new indices that reflect known dynamical processes of the atmosphere may be useful.

Atmospheric radiation data could help in reaching conclusions regarding the suggested ozone and cloud seeding mechanisms. Synoptic data on atmospheric electrical parameters, especially conductivity and electric field intensities are needed to learn more about solar modulation of atmospheric electricity. A better understanding of cloud physics and cloud electrification are needed to reach definitive conclusions regarding the

atmospheric electrical mechanisms.

This thesis has been directed at providing an overview of the field of sun-weather relations. For those skeptics who find it difficult to accept the likelihood of such relationships, the arguments in this chapter point out several important meteorological processes, about which we know so little that it is not difficult to use them to build speculative links between solar activity and weather.

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