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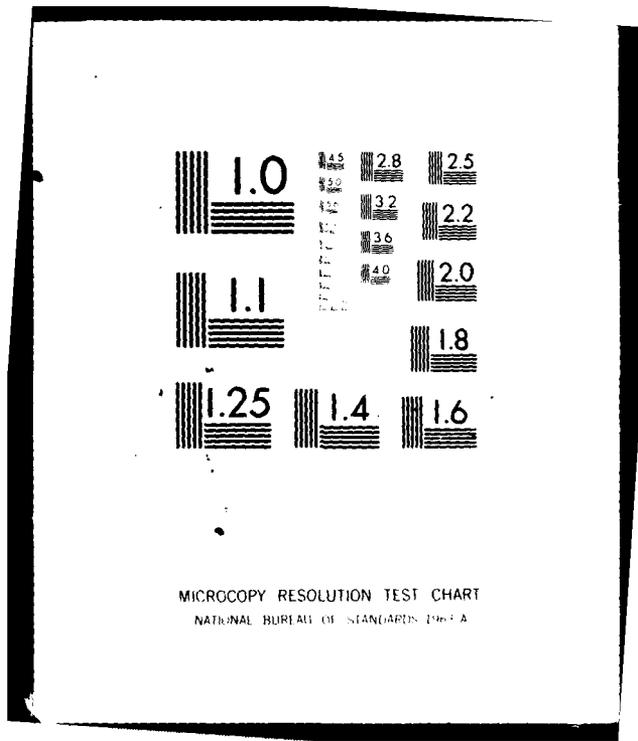
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**POSSIBLE INFLUENCE OF SOLAR ROTATION
ON TROPOSPHERIC CIRCULATION**

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By

J.M. Wilcox

Office of Naval Research
Contract N00014-76-C-0207

National Aeronautics and Space Administration
Grant NGR 05-020-559 and Contract NAS5-24420

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POSSIBLE INFLUENCE OF SOLAR ROTATION ON
TROPOSPHERIC CIRCULATION

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ABSTRACT

A large-scale structure observed in the photospheric magnetic field is carried out into the heliosphere by the solar wind. At earth the resulting interplanetary magnetic field has polarity away from the sun for several consecutive days followed by an abrupt reversal and several days with field polarity toward the sun. This sector structure appears to be related to some effects in the tropospheric circulation. Low-pressure troughs near the Gulf of Alaska appear to have significantly larger area when the interplanetary field is away from the sun than when it is toward the sun. This relation persists during most of the winters of 1951 to 1973. A considerable research program to extend this result will be described. Surface pressures around the Gulf of Alaska during some winters were in anti-phase for interplanetary field toward and away from the sun. The well-known result that the area of all troughs in the northern hemisphere is a minimum about one day after the change of polarity of the interplanetary field will be updated. During the two days after a polarity reversal the accuracy of the best weather forecasts for the continental United States appears to be significantly lower than at other times. Polarity reversals that are accompanied by energetic interplanetary conditions appear to be associated with a larger decrease in the area of the low pressure troughs. Intervals of several days during which the tropospheric circulation is more disturbed also appear to have a deeper minimum in trough area. Theoretical ideas for a physical mechanism will be discussed in terms of atmospheric electricity and constructive and destructive interference of reflected planetary waves.

Daily observations of the photospheric magnetic field using the Zeeman effect at Mt. Wilson Observatory and at the Stanford Solar Observatory have revealed a large-scale structure in the sun's magnetic field. This structure is the source of an electric current sheet in the heliosphere. The current sheet is warped north and south of the sun's equatorial plane. During the past eleven years (i.e. from about sunspot maximum to sunspot maximum) the interplanetary field north of the current sheet has had polarity away from the sun, while south of the current sheet the field polarity was toward the sun. During the next eleven years we are quite sure that

these polarities will be just the opposite. We note therefore that the large-scale polarity of the interplanetary magnetic field therefore has a twenty-two year solar magnetic cycle variation. There is also an eleven year sunspot cycle variation in the extent in latitude to which the heliospheric current sheet is warped. Near sunspot minimum the current sheet is fairly close to the sun's equatorial plane, with the extent in latitude being fifteen or twenty degrees north and south. This is the case shown in the artist's conception in Figure 1. Near sunspot maximum the warp in the current sheet increases very much reaching latitudes of perhaps fifty degrees north and south of the solar equatorial plane.

As observed by spacecraft orbiting the Earth this means that the sun's rotation period of 27 days is typically divided up into four sectors of interplanetary magnetic field polarity, each lasting for about one week. In one sector the field polarity is away from the sun, then there is a rather sharp boundary and in the next sector the field polarity is toward the sun. During some intervals, particularly during the rising portion of the eleven year sunspot cycle, this four-sector 27-day pattern is supplemented by a two-sector structure with a period of about 28 and a half days. We are beginning to have some understanding of the solar origin of these structures (Svalgaard and Wilcox, 1978), but that is beyond the scope of the present discussion.

As observed at Earth the sector structure organizes many important components of the solar-terrestrial environment (Wilcox, 1979a). Near a sector boundary the velocity of the solar wind and the magnitude of the interplanetary magnetic field have minimum values, while two or three days after a boundary transit they reach maxima. The flux of cosmic rays received at Earth is a maximum near the sector boundary and a minimum two or three days later. The extreme ultraviolet radiation received from the sun tends to be a maximum when a sector boundary is near central meridian on the sun.

We first examine some possible correlations between the polarity (toward or away from the sun) of the interplanetary magnetic field observed at Earth and the tropospheric circulation. During most of the winters from 1951 to 1973 it was found that the area of low pressure (300-millibar) troughs near 180° W longitude was significantly larger when the field was directed away from the sun as compared with when the field was toward the sun. The difference in area persisted during a five-day interval in which the troughs moved from 180° W to the North American continent (Wilcox et al., 1979). The size of the troughs was measured by using the vorticity area index (VAI), which is defined as the area of the trough where the absolute vorticity (circulation per unit area) at 300 mb exceeds a value of $20 \times 10^{-5} \text{ s}^{-1}$ plus the area where the vorticity exceeds $24 \times 10^{-5} \text{ s}^{-1}$. These vorticity values correspond to a well-formed trough. The VAI was recorded for a trough on the first day after it had crossed 180° W during the course of its eastward motion (occasionally a trough was formed east of 180° W and was similarly counted). After a trough had been identified east of 180° W, its VAI was measured twice a day for the next 12 days (during some winters the area was recorded for only the first 3 days and during some early years data were available only once a day).

Figure 2 shows the result of dividing the wintertime troughs near 180° W into two groups. The "away" troughs are those for which the interplanetary magnetic field was directed away from the sun on the day when the



Figure 1. Artist's impression of the warped heliospheric current sheet. The region above the current sheet has interplanetary magnetic field directed away from the sun and the region below has field directed toward the sun during the past 11 years. (Artist: Werner Heil) (Wilcox et al.,1980)

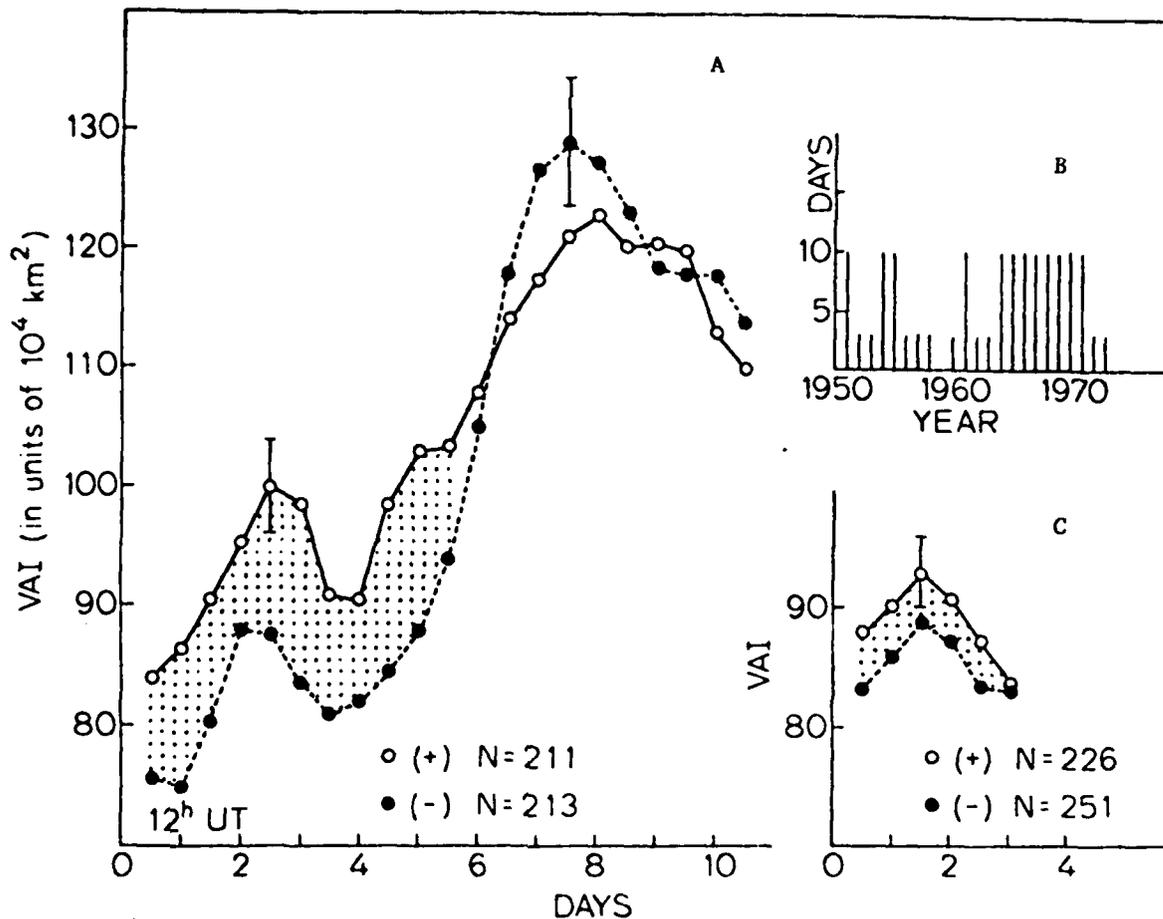


Figure 2. (A) Average area of low-pressure troughs (cyclones) during the 10 days after the troughs crossed 180°W : (O) away troughs and (●) toward troughs (see text for explanation). During the first 5 days after the troughs crossed 180°W , the area of the away troughs is significantly larger than the area of the toward troughs. Error bars are plus or minus the standard error of the mean. (B) Indication of winters during which trough area data were available for 10 days after the troughs crossed 180°W and of winters during which the data were available for only 3 days. (C) Same as first 3 days in (A) but computed for years in which trough area data were available for only 3 days. The area of the away troughs is again larger than the area of the toward troughs. (Wilcox et al., 1979)

trough was first identified east of 180° W. The average VAI of these away troughs during each of the next 10 days is shown in figure 2A. The "toward" troughs are similarly defined. Figure 2A shows that on day zero the average area of the away troughs was significantly larger than the area of the toward troughs and that this difference in area persisted for 5 days during which the troughs moved to the North American continent.

Figure 2A was prepared by using trough observations during the 12 winters for which data out to at least 10 days after day zero were available, as indicated in Figure 2B. During most of the other winters in the interval 1951 to 1973 data were available for only the first 3 days after day zero. Figure 2C shows that the same excess area associated with away troughs was found when these winters were analyzed separately.

The relation described here is sturdy. It persists when the data set is divided into two parts by using the first half and last half of the data or by using every other trough in sequential order. The resulting four graphs are very similar to Figure 2A and so are not shown here.

The persistence of the relationship through most of the winters of 1951 to 1973 is shown in figure 3A. For each winter in this interval the number of months in which the away troughs had a larger area and the number of months in which the toward troughs had a larger area are indicated. Figure 3A shows that in most of the individual winters there were more months during which the away sectors were larger. Figure 3B shows the combined distribution during all the winters shown in Figure 3A. The distribution representing away polarity is clearly considerably separated from the distribution representing toward polarity.

The relationship described here has led us to devise an improved data set describing the area of low-pressure troughs. We plan to identify each trough when it first appears in the northern hemisphere and then at 12-hour intervals to record the time, latitude, and longitude of the central portion of the trough, the VAI computed with several values of vorticity, and other related quantities such as the maximum value of vorticity within the trough. The limitation in the present data set to wintertime troughs near 180° W will thus be removed. It should be possible to define the geographic area in the northern hemisphere in which this relationship exists.

Based on the above results we may ask whether other meteorological conditions near 180° W are different when the interplanetary magnetic field is directed away from the sun as compared with toward the sun. This question has been examined by Rostoker and Sharma (1980) who first looked at surface pressure at Fairbanks, Alaska for the years 1957-1968. Fairbanks is located at 148° W longitude and 65° N latitude so that it is within the area in which the away troughs were larger than the toward troughs. Figure 4 shows the variability of the surface pressure during winter months (November-February) for away-toward sector boundaries (top) and for toward-away boundaries (bottom). The pressure variation patterns for the away-toward boundaries are almost antiphase to those for the toward-away boundaries. The summer (March-October) data yielded no discernable effect, which is consistent with the fact that earlier workers were unable to detect any evidence for sun-weather effects using summer data.

Rostoker and Sharma (1980) expanded their analyses to include three Canadian stations that ring the Gulf of Alaska, Inuvik, Norman Wells, and

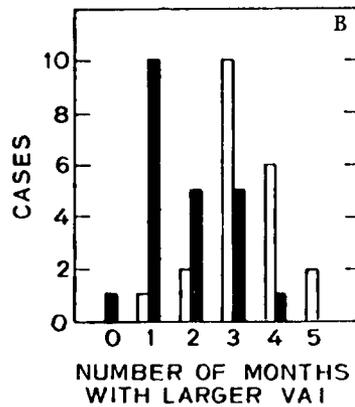
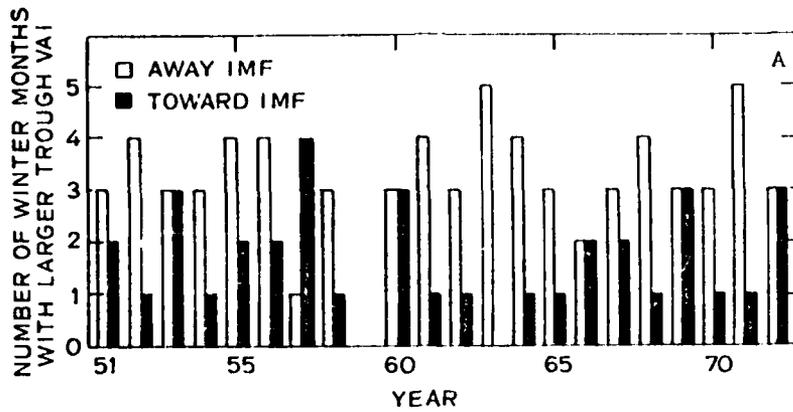


Figure 3. (A) Number of months in the winters of 1951 to 1973 (except 1959, for which no data were available) in which the away troughs (open bars) had a larger area and toward troughs (shaded bars) had a larger area. Away troughs had larger area during more months than toward troughs in almost all these winters. The first 3 days after day zero were used. (B) Distribution of number of months in which away troughs (open bars) had a larger area and toward troughs (shaded bars) had a larger area during all the winters examined. The distribution of open bars is centered at a larger number and is well separated from the distribution of shaded bars. (Wilcox et al., 1979)

Whitehorse. This produced conflicting results. The plots shown in Figure 5a for the interval 1959-1966 appear to reproduce the results from Fairbanks (Figure 4) rather faithfully. The fact that the stations are separated from one another by a minimum of 500 km suggests that these meteorological trends are not localized and are probably associated with planetary wave activity. However, the pattern breaks down completely for the interval 1967-1975, as shown in Figure 5b. After considering the repeatability and non-repeatability of the antiphase relationship from station to station for away-toward and toward-away sector boundary crossings Rostoker and Sharma "are tempted to suggest that there is a tendency for the surface pressure to react significantly at the time of a sector boundary crossing, although the reaction may be modulated by other long-term changes in terrestrial meteorological wind and pressure patterns".

Further studies of the situation in the Gulf of Alaska are clearly indicated. In collaboration with Walter Orr Roberts we are studying such things as the influence of cold northerly winds into the Gulf of Alaska and the importance of the ridge with regard to the centers of vorticity that move around it.

We now turn our attention to analyses of the VAI in the entire winter-time northern hemisphere as related to the time of sector boundary transits. We emphasize two differences between the following discussion and the above discussion: First, the above discussion concerns individual troughs and the geographical area of the Gulf of Alaska while the following discussion concerns the VAI and the entire northern hemisphere, and second, in the above discussion the solar parameter was the direction of the interplanetary magnetic field observed at Earth, while in the following discussion the solar parameter is the time of sector boundary transit past the Earth. In the following discussion no distinction between away-toward and toward-away boundaries will be made, since the results have been approximately the same in both cases.

Figure 6 shows the much-discussed response of the VAI at 500 mb to 162 interplanetary magnetic sector boundary transits past the Earth during the winter months from 1 November 1963 to 31 March 1976. The previously reported (Wilcox et al., 1976) minimum in VAI approximately one day after the boundary transit is clear. Perhaps the most important sun-weather analysis performed so far is shown in Figure 7 from the work of Larsen and Kelly (1977). They analyzed the accuracy of the forecast VAI based on the Limited Fine Mesh prognostic model during October through March 1972-74 and January 1975. A correlation coefficient between the forecast and the observed VAI was computed for the 12-hour (solid line) and 24-hour (dashed line) forecasts for the day of sector boundary crossings and for a number of days before and after the crossings. A marked decrease in the correlation coefficient during the 2 day interval from plus 1/2 to plus 2 days after the sector boundary crossing is immediately evident in Figure 7. This is true for both the 12 and 24 hour forecasts. The average value of the correlation coefficient for all other days outside this 2 day period was 0.84 for the 12-hour forecast and 0.78 for the 24-hour forecast. These are typical results for the Limited Fine Mesh forecasts. Decreases in the coefficient at +1 days of 0.15 and 0.17 were found for the two forecasts. If the decrease in correlation is physically real then the sun-weather effect is physically real. The magnitude of the decrease suggests that the magnitude of the sun-weather effect may be substantial.

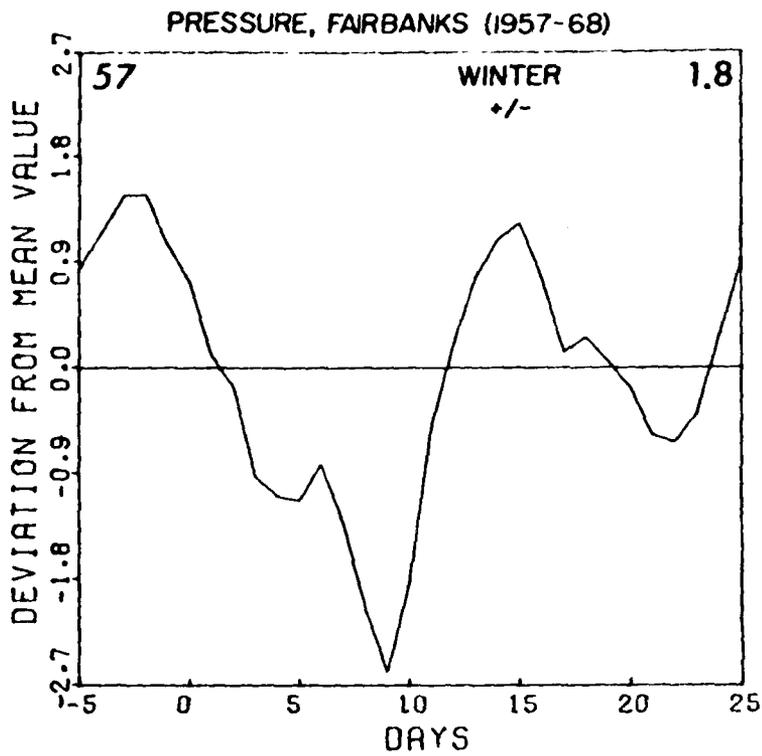
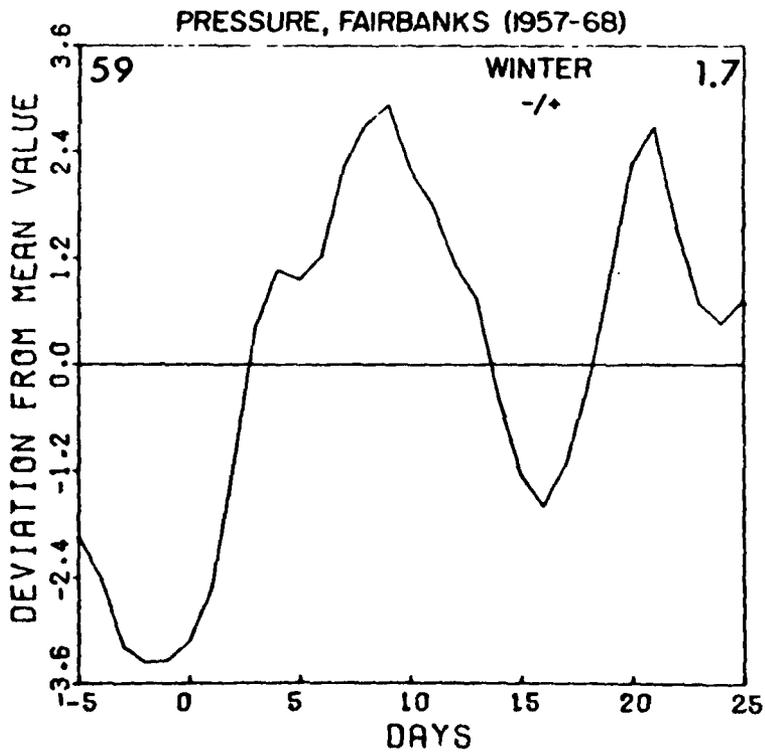


Figure 4: Superposed epoch analyses for Fairbanks surface pressure data shown separately for away-toward (top) and toward-away (bottom) sector boundary crossings recorded during the winter months November-February 1957-68. Deviations for the average pressure are shown in millibars. The estimator of variability of the data is shown in the top right-hand corner of the plot, while the number of sector boundary crossings used is shown in the top left-hand corner of the plot (Rostoker and Sharma, 1980).



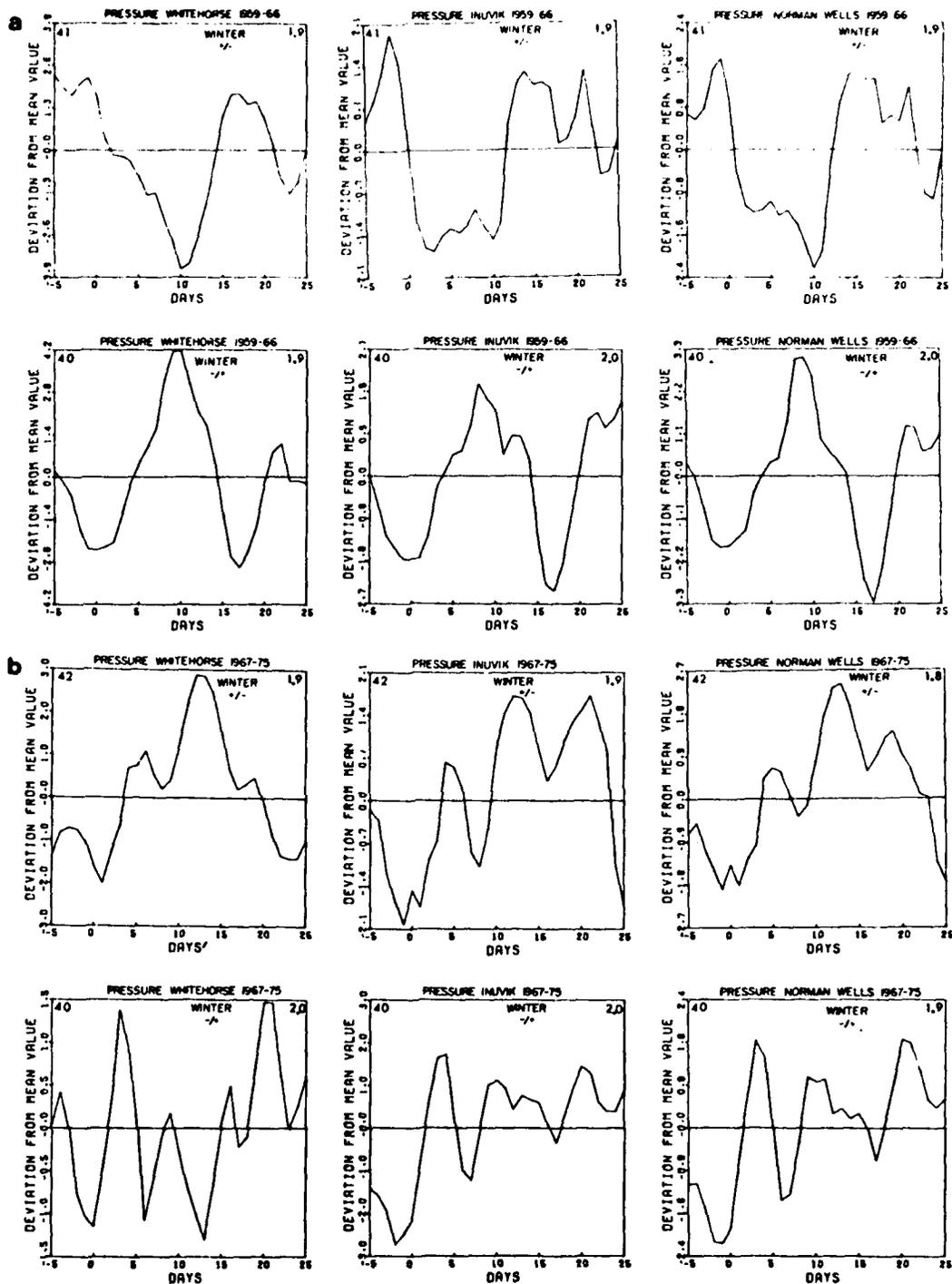


Figure 5: Same as Figure 4, but for Inuvik, Whitehorse, and Norman Wells surface pressure data shown separately for away-toward and toward-away sector boundary crossings: (a) 1959-1966, (b) 1967-1975 (Rostoker and Sharma, 1980).

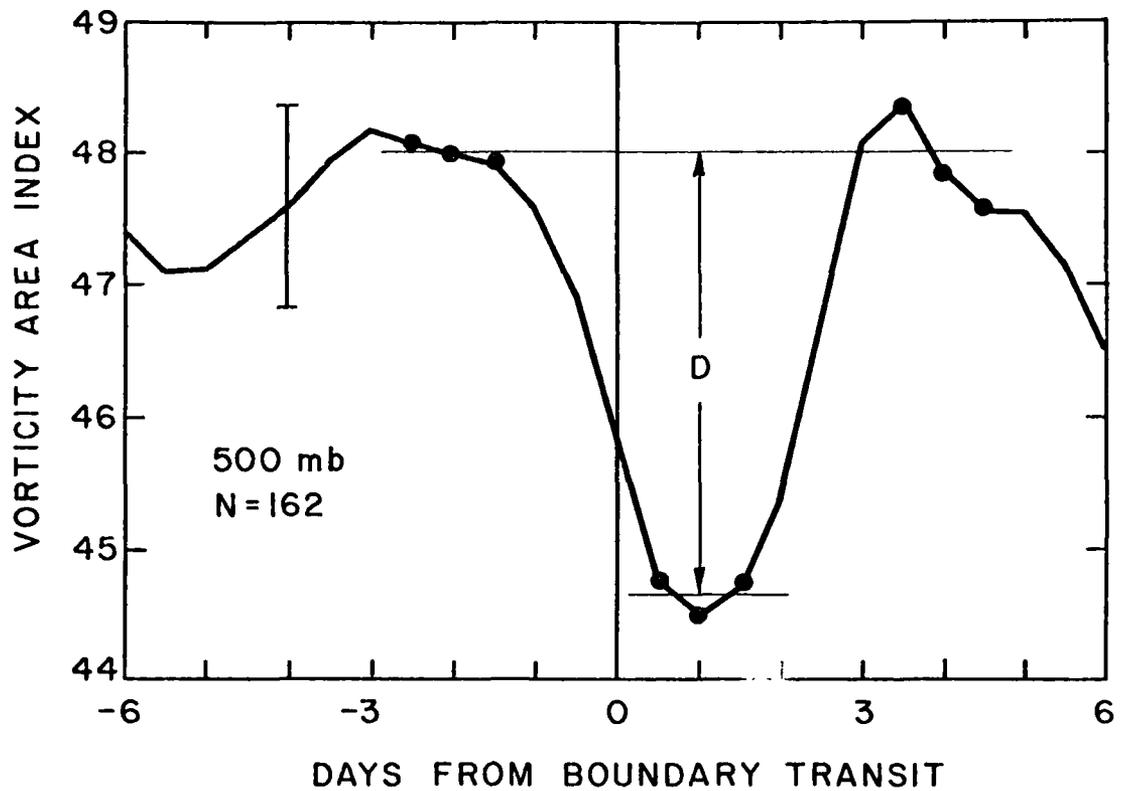


Figure 6. A superposed epoch analysis of the vorticity area index at 500 mbar about 162 times of interplanetary magnetic sector boundary transits during the winters in the interval 1 November 1963 to 31 March 1976 for which spacecraft observations of boundary transits are available. A typical error bar (twice the s.e.m.) is shown for the point at day -4. (Wilcox and Scherrer, 1979).

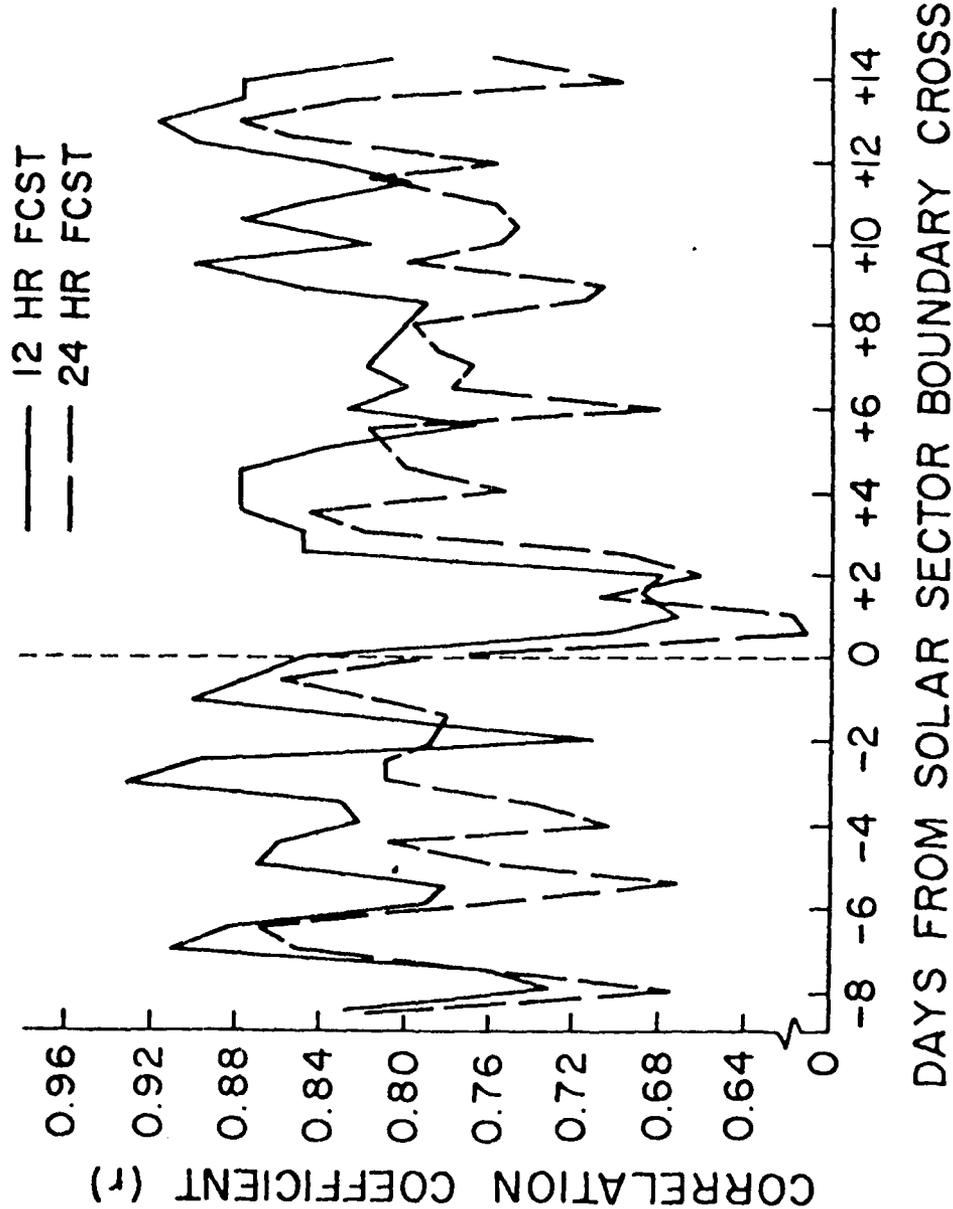


Figure 7. An analysis of the accuracy of forecasts of tropospheric vorticity in a time frame related to the passage of the warped heliospheric current sheet. The ordinate is a cross correlation between the forecast and observed vorticity indices. During the first two days after the passage of the current sheet the correlation coefficient appears to be systematically lower by about 0.15 units. (Larsen and Kelly, 1977)

Finally, we consider evidence for the importance of the initial conditions of tropospheric circulation and of energetic interplanetary conditions on the response of the VAI. Hines and Halevy (1977) discovered that wintertime sector boundary transits that came when the variance of the VAI was large (a more disturbed tropospheric circulation) produced on the average a larger sun-weather effect. This was later confirmed in a much larger data set by Wilcox and Scherrer (1979). Hines and Halevy (1977) introduced the Excursion, which was defined as the difference between the maximum and minimum values of the VAI found in a 12-day interval centered on the time of boundary transit. The amplitude of the sun-weather influence was small when the Excursion was small and large when the Excursion was large. In the past few years the observed Excursions have been considerably smaller than in previous years.

Wilcox and Scherrer (1979) defined a value of Excursion such that half of the 162 wintertime boundary transits during the interval 1 November 1963 to 31 March 1976 had larger Excursions and half had smaller. The sun-weather effect was examined separately for each group. Consider the three-winter interval from 1 November 1963 to 31 March 1966. Figure 8 shows for this interval (plotted at 1965) the average value of the size of the sun-weather effect (D, defined in Figure 6) associated with the group of boundary transits having larger Excursions, and the average D for the group of boundary transits having smaller Excursions. The analysis is repeating stepping one year at a time so that the final point plotted at 1977 represents the three-winter interval from 1 December 1975 to 31 March 1978. We see in Figure 8 that between 1963 and the present the size of the sun-weather effect associated with a group of boundaries having larger Excursions is rather constant, while in most years boundaries associated with smaller Excursions show no significant effect. This confirms the discovery of Hines and Halevy (1977) that this sun-weather effect is most prominent when the tropospheric circulation is most disturbed. A trigger mechanism would probably be most effective in a disturbed circulation.

Some sector boundary transits are followed by energetic solar wind streams that are able to accelerate some protons to energies of a few MeV. Figure 9 shows an analysis similar to that of Figure 6 of the average northern hemispheric VAI as a function of time near a sector boundary transit (Wilcox, 1979b). The solid line represents 18 boundaries that were followed by streams of MeV protons as tabulated by Svestka et al. (1976), while the dashed line represents the 62 other boundary transits observed during the same winters (1963-69). We note the minimum VAI associated with the MeV proton boundaries is almost twice as deep as the minimum associated with the other boundaries. Although the statistical significance of this result is not overwhelming it is a suggestion that disturbed interplanetary conditions may lead to a larger sun-weather effect.

Markson and Muir (1980) have recently discussed the solar wind control of the Earth's electric field, which was established by observations of Reiter (1977) and Park (1976). The Earth's electric field intensity is maintained by world wide thunderstorm currents. Markson and Muir (1980) show that this electric field varies in phase with the flux of cosmic radiation received at Earth. Since cosmic radiation is the primary source of atmospheric ionization, this supports a proposed mechanism in which solar control of ionizing radiation modulates atmospheric electrification and thus possibly cloud physical processes. If the latter occurred, atmospheric energetics would be affected.

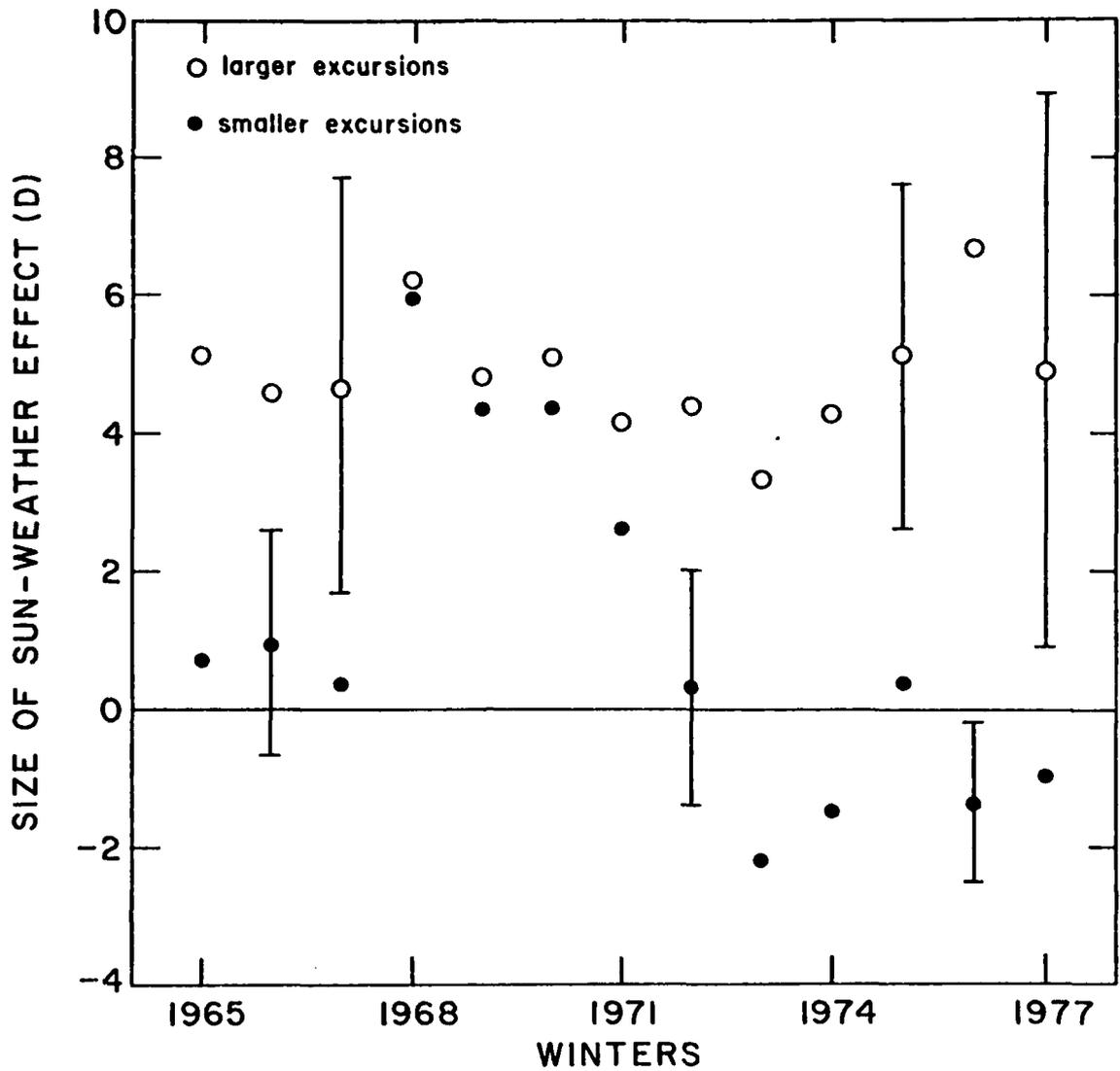


Figure 8. The size D of the sun-weather effect for the groups of boundary transits having larger Excursions (open circles) and for the groups of boundary transits having smaller Excursions (filled circles). The total length of the error bar is twice the standard error of the mean (Wilcox and Scherrer, 1979).

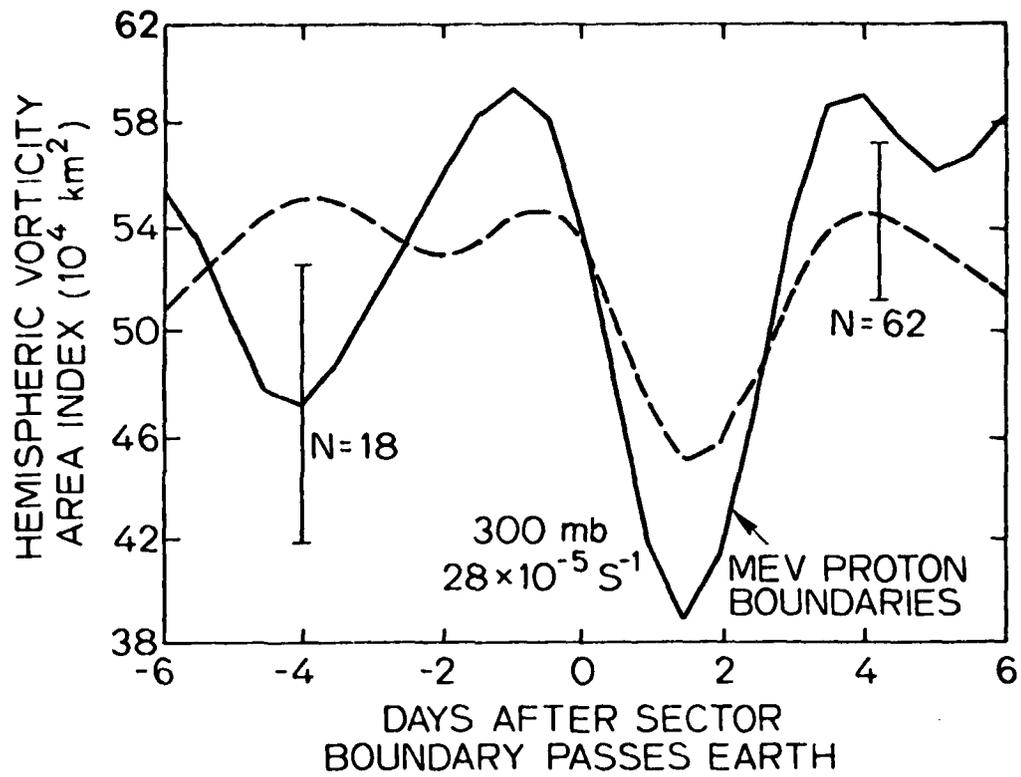


Figure 9. Similar to Figure 6, but computed for sector boundary passages accompanied by MEV proton streams (solid line) and for all other boundary passages in the same winters (dashed line) (Wilcox, 1979b).

I would support efforts to measure a geoelectric index in the belief that such measurements would lead to important advances in our understanding of the solar-terrestrial environment. Much has been learned about the solar-terrestrial environment from studies using the familiar geomagnetic indices. From the symmetry of Maxwell's equations, the geoelectric and geomagnetic fields are inferred to be equally fundamental to understanding of couplings between solar and terrestrial phenomena. Desiderata are the need for measurements on an hourly basis of the atmospheric potential (if possible, together with current density and conductivity) at two or more heights (for example, 5 km and 10 km) and at two or more widely separated locations. Measurements at two or more heights will help to decide among competing models of vertical electric field structure, and measurements at widely separated locations will help to establish the degree of global coherence of the structure. The geoelectric index should be measured for a period of years.

In discussing the interplanetary field polarity correlation with surface pressure in the Gulf of Alaska shown in Figure 4, Rostoker and Sharma (1980) start by suggesting that, for away sectors, there is an average northward electric field of ~ 500 mV/m existing across a strip of latitudinal extent of ~ 500 km and longitudinal extent of ~ 12 h of local time centered on noon. For toward sectors the average electric field in this strip is southward. The direction of this electric field can be maintained for several days at a time, consistent with the sector structure of the interplanetary field resulting from the current sheet shown in Figure 1. Rostoker and Sharma show that such large scale electric fields map essentially unattenuated into the troposphere. Assuming that energy transfer from the electric field to the neutral background gas is by collisional effects only they calculate that if the direction of the interplanetary field is unchanged for five days, an elementary volume of gas at an altitude of 30 km would travel only about 0.3 km. It seems clear that this should yield little or no detectable change in tropospheric parameters unless some instability is triggered. Considering that during the polar winter the meridional component of the winds is minimal they suggest that it is possible that the small change noted above to that component of wind motion may lead to triggering of instabilities which cause changes in the planetary wave configuration. In this concept, virtually all of the energy involved in the reconfiguration of the planetary wave system would be stored in the neutral atmosphere prior to the triggering of the instability. In fact, one might consider that the instability would have taken place in any event regardless of whether or not electromagnetic energy has been coupled into the neutral atmosphere. In this case the polarity of the interplanetary field could be construed as influencing the "phasing" of the planetary wave reconfigurations causing them to show a tendency to occur at the time of sector boundary crossings. Such an approach to the understanding of the sun-weather correlation has already been suggested by Hines and Halevy (1977).

In closing I make a few remarks on statistical proof versus statistical motivation, following Schatten (1980). Some staunch critics appear to want statistics to "prove", or find "unequivocal empirical evidence" for a sun-weather connection. Statistics cannot do this; as in a mathematical proof, it can only guide and provide motivation. For example, the work of Mitchell, Stockton and Meko (1979) on drought cycles since 1700 in the western U.S. suggests that for nearly 300 years a drought cycle follows the Hale magnetic double sunspot cycle (22 years). This effect is

statistically highly significant, but given enough random simulations, it could be duplicated and, therefore, may not be unequivocal statistically. The statistics only provide motivation for study. In my opinion the most significant sun-weather investigation is yet to be done.

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