Solar Structure and Terrestrial Weather

by

John M. Wilcox

January 1976

SUIPR Report No. 652

Office of Naval Research
Contract N00014-76-C-0207,
National Aeronautics and Space Administration
Grant NGR 05-020-559, and
National Science Foundation
Grants ATM74-19007 and DES75-15664

INSTITUTE FOR PLASMA RESEARCH
STANFORD UNIVERSITY, STANFORD, CALIFORNIA

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER SUIPR Report No. 652	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) SOLAR STRUCTURE AND TERRESTRIAL WEATHER		5. TYPE OF REPORT & PERIOD COVERED Scientific, technical
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) John M. Wilcox		8. CONTRACT OR GRANT NUMBER(s) N00014-76-C-0207
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Plasma Research Stanford University, Stanford, California 94305		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Reserach Electronics Program Office Arlington, Virginia 22217	12. REPORT DATE January 1976	13. NO. OF PAGES 17
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
14. MONITORING AGENCY NAME & ADDRESS (if diff. from Controlling Office)		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this report)

Approved for Public Release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from report)

18. SUPPLEMENTARY NOTES

TECH; OTHER

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Solar Structure
Weather

ORIGINAL PAGE IS OF POOR QUALITY

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A detailed knowledge of solar causes for geomagnetic activity is only now beginning to emerge after many years of efforts by able scientists. This suggests that a possible successful solution to the sun-weather problem will require a similar magnitude of effort. #

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SOLAR STRUCTURE AND
TERRESTRIAL WEATHER

by

John M. Wilcox

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

National Aeronautics and Space Administration
Grant NGR 05-020-559

and

National Science Foundation
Grant ATM74-19007
Grant DES75-15664

SUIPR Report No. 652

January 1976

Institute for Plasma Research
Stanford University
Stanford, California

Submitted to: SCIENCE

SOLAR STRUCTURE AND TERRESTRIAL WEATHER

After more than a century of controversy this subject may be moving toward scientific respectability.

John M. Wilcox
Institute for Plasma Research
Stanford University
Stanford, California

The author is an adjunct professor at the Applied Physics Department and the Institute for Plasma Research, Stanford University, Stanford, California 94305.

Claims for a connection between the variable sun and the earth's weather can be found in a literature of well over one thousand published papers during the past century. The subject has been discussed by such illustrious authors as Herschel, Gauss, Sabine, Faraday, Wolf, Stewart, Schuster and Airy. Nevertheless, the subject has tended to remain on the fringes of respectable science.

Observations of the changing sun are not now employed in routine weather forecasting. Many scientists are reluctant to admit the possibility of such an influence. Perhaps the main stumbling block involves energy considerations. The variation of the amount of energy received at earth in connnection with the variable sun is rather small compared to the energy in the general circulation of the earth's atmosphere. By the variable sun I mean any changes on a time scale of a few days in the sun as viewed from the earth. Lacking a knowledge of the physical mechanism(s) that may be involved, I cannot be more specific.

Such concern with energy is undoubtedly valid, but may not be conclusive. It may be instructive to consider the situation at the turn of the century. It had been noted that geomagnetic activity often increased after a large solar flare. Furthermore, days with enhanced geomagnetic activity sometimes recurred at intervals of 27 days, the solar rotation period. This led to suggestions that geomagnetic activity was caused by the sun.

In his famous Presidential Address in 1892 to the Royal Society, Lord Kelvin (1) made a stiff dismissal of such claims. He calculated the energy associated with eight hours of a not very severe geomagnetic disturbance, and concluded that in order to supply this energy to the geomagnetic field "as much work must have been done by the Sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light". Lord Kelvin's calculations were quite correct within the frame work of his knowledge. He did not know about the solar wind, which extends the solar magnetic field away from the sun in all directions and completely changes the energetic considerations. We may wonder if an unknown process comparable in importance to the solar wind may be part of a causal chain between the variable sun and the earth's weather.

It seems possible that sun-weather investigations are finally beginning to move to a position of scientific respectability. The most firm conclusion that I would draw is not related to any specific claim, but rather that this subject has reached a state in which it merits the consideration of serious scientists. Such consideration is indeed increasing as witnessed by several symposia on the subject, the most recent of which was held at the 1975 XVI General Assembly of the International Union of Geodesy and Geophysics in Grenoble. It is encouraging that such symposia have been attended by solar physicists and meteorologists, thus beginning to bridge the interdisciplinary gap.

Recent reviews on the subject are available (2).

Some Recent Work

I will now describe some recent work involving the cooperative efforts of several scientists at several institutions. For a decade or more Walter Orr Roberts at the National Center for Atmospheric Research and the University of Colorado in Boulder has been a leading American worker on this subject. Some recent work by Roberts (3) in collaboration with Roger Olson begins with a study of days on which geomagnetic activity has had a sizeable increase. The increase is assumed to have a solar cause. Roberts and Olson studied the history of low pressure troughs (cyclones) from the Gulf of Alaska as they moved across the continental United States. Troughs associated with geomagnetic activity were found to be significantly larger on the average than troughs associated with intervals of quiet geomagnetic conditions.

A measure devised by Roberts and Olson of the size of low-pressure troughs has been used in several subsequent investigations. A low-pressure trough is a large rotary wind system having a diameter of a few thousand kilometers that is usually associated with clouds, rain or snow. Although the formation and structure of low-pressure troughs has been studied in some detail, it is not possible in general to predict the time and place at which a trough will form. This is one reason why the skill in shortrange weather prediction falls to zero (i.e. no better than a prediction of average properties) within two or three days (4).

The vorticity area index devised by Roberts and Olson to measure the size of low-pressure troughs can be computed from maps of the height of constant pressure (300mb) surfaces using the geostrophic wind approximation. These maps are prepared twice a day, at 0 UT and at 12 UT by the National Weather Service. The circulation of the air mass in a trough is defined as the line integral of the velocity of the air around a closed path. Vorticity is defined as the circulation per unit area.

In our use of the vorticity area index it is computed for the portion of the northern hemisphere north of 20°N. The index is now defined as the sum of all areas in which the vorticity exceeds a certain threshold, which was chosen so that all well-formed troughs would be included. Once the threshold level ($20 \times 10^{-5} s^{-1}$ in our work) has been chosen the computation of the vorticity area index is completely objective.

The results of the investigations to be described in this article will be presented in terms of graphs in which the meteorological input to the investigation is plotted on the ordinate and the solar input is plotted on the abscissa. The meteorological input is the vorticity area index just described. Now we must consider what the solar input will be.

Roberts and Olson (3) assumed that the increases in geomagnetic activity used in their analysis were caused by the changing sun. This assumption has been challenged by Hines (5) who suggests that some geomagnetic activity may be caused by current systems induced by motions of the lower atmosphere. To the extent that this assumption is correct, the assumed chain "sun → geomagnetic increase → weather change" would be replaced by a closed circle "weather change → geomagnetic activity → weather change". In my opinion such an influence on the investigations of Roberts and Olson (3) can probably be neglected. Nevertheless, it is clearly an advantage in this situation if a structure that is clearly of solar origin can be used for the "solar" input in the investigation.

For this purpose we consider the solar sector structure, which is a fundamental large-scale property of the sun. A description (6) of several solar, interplanetary and terrestrial properties of this structure is available. The structure is readily perceived in observations by spacecraft magnetometers of the interplanetary magnetic field that is swept past the earth by the solar wind. For several consecutive days this interplanetary field will be observed to have a polarity directed away from the sun. The next several days will be observed to have interplanetary field polarity directed toward the sun. These two sectors are separated by a thin boundary that typically is swept past the earth during an interval measured in tens of minutes.

In the investigations to be described the time at which a sector boundary is observed to sweep past the earth will be used as a zero phase reference. This sharply defined time is very convenient for the analysis, but it must be emphasized that the sector boundary itself is probably not an important influence on the weather. Furthermore, the large-scale sector pattern of the interplanetary magnetic field (and associated structures in the solar wind) is not necessarily a physical influence on the weather. The solar influence (if such there be) described in this article could be related to variations in the solar ultraviolet emission, in the solar "constant", in some manifestation of the changing solar magnetic field such as energetic particle emission, in an influence of the extended solar magnetic field on galactic cosmic ray incident at earth, or in some other unknown factor. In any event, the extended solar sector structure as observed with spacecraft in the interplanetary magnetic field near the earth is clearly a solar structure that is not influenced by terrestrial weather. We now consider further the possibility that some aspect of the solar structure may influence the weather.

Extension of Earlier Investigations

Our group at Stanford (Svalgaard, Scherrer and myself) joined forces with Roberts and Olson to extend their original investigations. The first results (7) of this collaboration are shown in Figure 1. This shows the average change in the vorticity area index as the sector structure is swept past the earth by the solar wind. Day zero represents the time at which a sector boundary passed the earth. We see in Figure 1 that on the average the vorticity area index reaches a minimum approximately one day after the boundary passage. The amplitude of the effect from minimum to the adjacent maxima is about 10%. When we consider that weather usually consists of relatively small changes about climate (i.e. the average properties), this represents a sizeable and important change. I repeat the warning that the sector boundary passage, although very convenient as a precise timing mark, almost surely does not have an important physical influence on the weather. The large-scale sector structure in the interplanetary magnetic field also may not have a direct causal influence on the weather, but may merely delineate some solar structure that does.

The result shown in Figure 1 is prominent only during the winter months (8). This may be related to the fact that this is the season in which the equator-to-pole temperature differences are the largest, producing the largest stresses on earth's atmospheric circulation.

In view of the checkered history of sun-weather influences, the new claim shown in Figure 1 must be subjected to the most careful scrutiny.

The first test is to compute the standard error of the mean, which is shown by the error bar in Figure 1. This is satisfyingly small, and on formal grounds one might conclude that the minimum near the sector boundary in Figure 1 is significant. However, the textbook instructions for computing an error bar are always subject to assumptions and boundary conditions that are never completely fulfilled in any analysis of real observations. We therefore proceed on to further tests. Figure 2 is in the same format as Figure 1, but in this case the list of times of boundary passages has been divided into two parts, and the same analysis has been performed on each half separately. The extent to which the analysis of parts of the data is similar to the analysis of the entire data set is a further test of significance. In Figure 2 the data has been divided into two parts in three different ways, as explained in detail in the figure caption. We see that the effect persists in all of these division of the data set.

A further test of significance is to inquire if the effect persists in new observations (10). Figure 3a shows our original analysis while Figure 3b shows the same analysis performed with a list of 81 new boundary passage times, none of which are included in the analysis of Figure 3a. The new boundary passage times used in Figure 3b were obtained by increasing the interval examined to 1963-1973, and by supplementing spacecraft observations of the interplanetary magnetic field polarity with inferred polarities of the interplanetary field obtained from analysis of polar geomagnetic variations (9). In response to the suggestion by Hines (5) that some geomagnetic activity could be caused by variations in the weather, we performed the analysis shown in Figure 3c using a subset of 46 of the 81 boundary passage times used in Figure 3b. The analysis of Figure 3c used only boundary passages in which the time was fixed by spacecraft observations. It can be seen from Figure 3 that the effect clearly persists in the new observations.

The last test of significance (10) to be described in this article is shown in Figures 4 and 5. Figure 4 shows the same analysis performed in the latitude zones 35°N - 55°N, 55°N - 90°N, and 20°N - 90°N. We see that the effect is quite similar in these three zones. The possibility might still remain that due to conventional meteorological processes, whenever the vorticity area index has a minimum in the 35°N - 55°N zone it also has a similar minimum in the 55°N - 90°N zone. This possibility has been investigated in the following way. From a plot of the vorticity area index in the zone 35°N - 55°N during the time interval of interest, all those times not near a sector boundary passage at which the index had a minimum resembling the average minimum in Figure 3 were tabulated. Figure 5 shows the same analysis performed using the resulting list. The result for the zones 35°N - 55° N shows a deep minimum, since each individual case was selected to have such a minimum. By contrast the result for the zone 55°N - 90°N is essentially a null result. No trace of a corresponding minimum is to be seen. It thus appears that at times that are not near sector boundary passages minima in the two latitude zones occur independently, whereas some solar influence causes both zones to show similar minima one day after the passage of a sector boundary. If we accept the reality of this result, we can turn the argument around and say that the unknown solar influence causes similar results in the two latitude zones.

The most important test of the significance of the results claimed in Figure 1 has been made by Hines and Halevy (11) at the University of Toronto who say "Reports of short-term Sun-weather correlations have been greeted with skepticism by many". They subjected the data used in preparing Figure 1 to a variety of statistical tests and requested the analysis of new data shown in Figure 3. They conclude that "We find ourselves obliged to accept the validity of the claim by Wilcox et al., and to seek a physical explanation".

What does one conclude from all of the above? The results of the past century suggest that a certain caution would be very appropriate. The one statement that I would make with complete conviction is that this appears to be an interesting subject that should be vigorously pursued.

Summary

If there is indeed an effect of the variable sun on the weather, the physical cause(s) for it remains quite elusive (12). We should keep in mind the possibility that there may be several causes and several effects. The situation may change through the eleven year sunspot cycle and the twenty-two year solar magnetic cycle, as well as on longer time scales.

Work is proceeding at a lively pace at the institutions mentioned in this article and at many others around the world. The Soviet Union has long had considerably more workers interested in this field than any other country. A Bilateral Agreement between the USSR and the USA has considerably increased the interactions between workers interested in this subject, including an exchange of extended visits between the two countries.

A detailed knowledge of solar causes for geomagnetic activity is only now beginning to emerge after many years of efforts by able scientists. This suggests that a possible successful solution to the sun-weather problem will require a similar magnitude of effort. We look forward with interest and optimism to the results of the next few years.

Acknowledgements

This work was supported in part by the National Aeronautics and Space Administration under Grant NGR 05-020-559, by the Atmospheric Sciences Section of the National Science Foundation under Grants ATM74-19007 and DES75-15664, and by the Office of Naval Research Contract N00014-76-C-0207.

References

1. Lord Kelvin, Nature, Lond., 47, 106 (1892).

2. J.M. Wilcox, J. Atmos. and Terr. Phys., 37, 237 (1975).
L. Svalgaard, in Correlated Interplanetary and Magnetospheric Observations, D.E. Page, ed. (D. Reidel Publishing Co., Dordrecht, Holland) (1974), pp. 627-639.
J.W. King, Astronautics and Aeronautics, 13, 10 (1975).
Proceedings, Symposium "Possible Relationships Between Solar Activity and Meteorological Phenomena", NASA Goddard Space Flight Center, November 7-8, 1973. To be published as a NASA Special Publication.

3. W.O. Roberts and R.H. Olson, J. Atmos. Sci., 30, 135 (1973),
W.O. Roberts and R.H. Olson, Rev. Geophys. Space Phys., 11, 731 (1973),

4. C.E. Leith, Rev. Geophys. and Space Phys., 13, 681 (1975).

5. C.O. Hines, J. Atmos. Sci., 30, 739 (1973).

6. J.M. Wilcox, Space Sci. Rev., 8, 258 (1968).

7. J.M. Wilcox, P.H. Scherrer, L. Svalgaard, W.O. Roberts, and R.H. Olson, Science, 180, 185 (1973),
J.M. Wilcox, P.H. Scherrer, L. Svalgaard, W.O. Roberts, R.H. Olson and R.L. Jenne, J. Atmos. Sci., 31, 581 (1974).

8. J.M. Wilcox, L. Svlagaard and P.H. Scherrer, Nature, 255, 539 (1975).

9. L. Svalgaard, J. Geophys. Res., 77,4027 (1972),
L. Svalgaard, J. Geophys. Res., 78,2064 (1973),
L. Svalgaard, J. Geophys. Res., 80, 2717 (1975),
J.M. Wilcox, Rev. Geophys. and Space Phys, 10, 1003 (1972).

10. J.M. Wilcox, L. Svalgaard and P.H. Scherrer, On the Reality of of a Sun-Weather Effect, J. Atmos. Sci., submitted.

11. C.O. Hines and I. Halevy, Nature, 258, 313 (1975).

12. A.J. Dessler, Some Problems in Coupling Solar Activity to Meteorological Phenomena, Proceedings, Symposium "Possible Relationships Between Solar Activity and Meteorolcgical Phenomena", NASA Goddard Space Flight Center, November 7-8, 1973. To be published as a NASA Special Publication.

Figure captions

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

Figure 2 Same format as Figure 1; the list of boundaries used in Figure 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away, and the dashed curve 29 boundaries in which the polarity changed from away to toward. (b) The dotted curve represents 31 boundaries in the interval 1 November to 15 January, and the dashed curve 22 boundaries in the interval 16 January to 31 March. (c) The dotted curve represents 26 boundaries in the interval 1964 to 1966, and the dashed curve 27 boundaries in the interval 1967 to 1970. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is the same as in Figure 1, that is, each interval is $5 \times 10^5 km^2$.

Figure 3 Same format as Figure 1. Figure 3a uses 50 of the boundaries used in the original work, Figure 3b uses 81 new boundary passages not included in the original analysis and Figure 3c is a subset of Figure 3b in which the times of 46 boundary passages were determined from spacecraft observations.

Figure 4 Similar to Figure 3, except that the results are shown separately for the latitude zone $35^{\circ}N$ - $55^{\circ}N$, $55^{\circ}N$ - $90^{\circ}N$, and for the entire northern hemisphere north of $20^{\circ}N$. The form of the minimum at one day after the boundary passage is rather similar in all of these latitude zones.

Figure 5 The same as Figure 4, except that the key days are 30 minima in the latitude zone $35^{\circ}N$ -$55^{\circ}N$ that are not near sector boundaries (see text). The solid curve shows the results for the zone $35^{\circ}N$ - $55^{\circ}N$, and the dashed curve shows the results for the zone $55^{\circ}N$ - $90^{\circ}N$. The deep minimum in the lower zone does not appear in the upper zone.

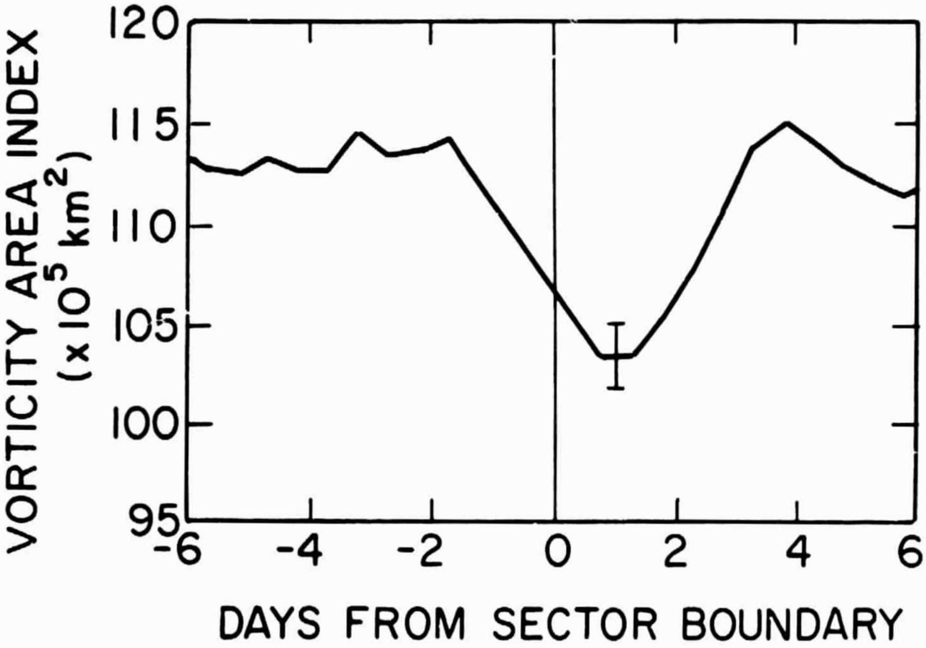
VORTICITY AREA INDEX
(x 10^5 km^2)
120
115
110
105
100
95
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY

Figure 1

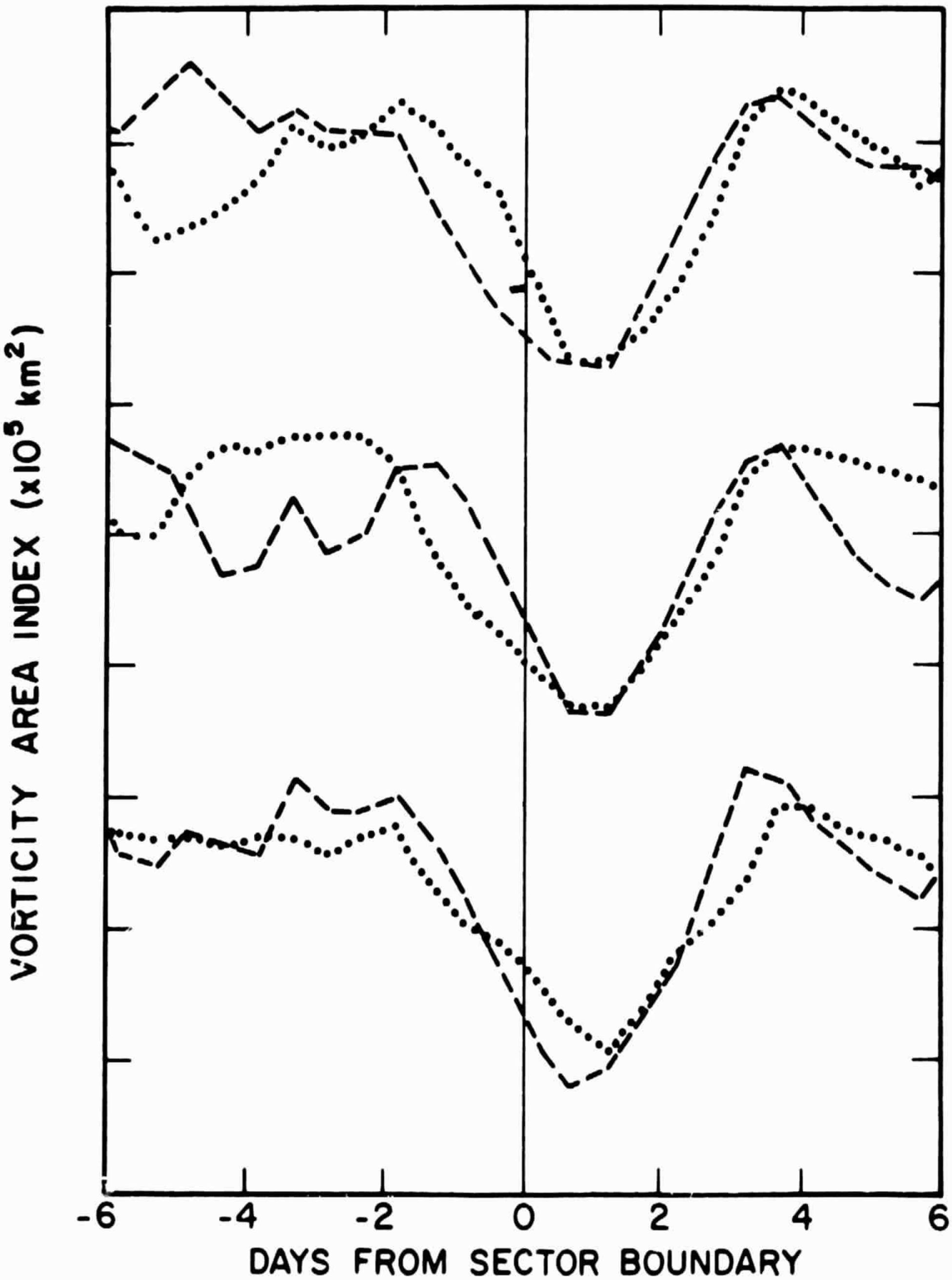
VORTICITY AREA INDEX (x10^5 km^2)
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY

Figure 2

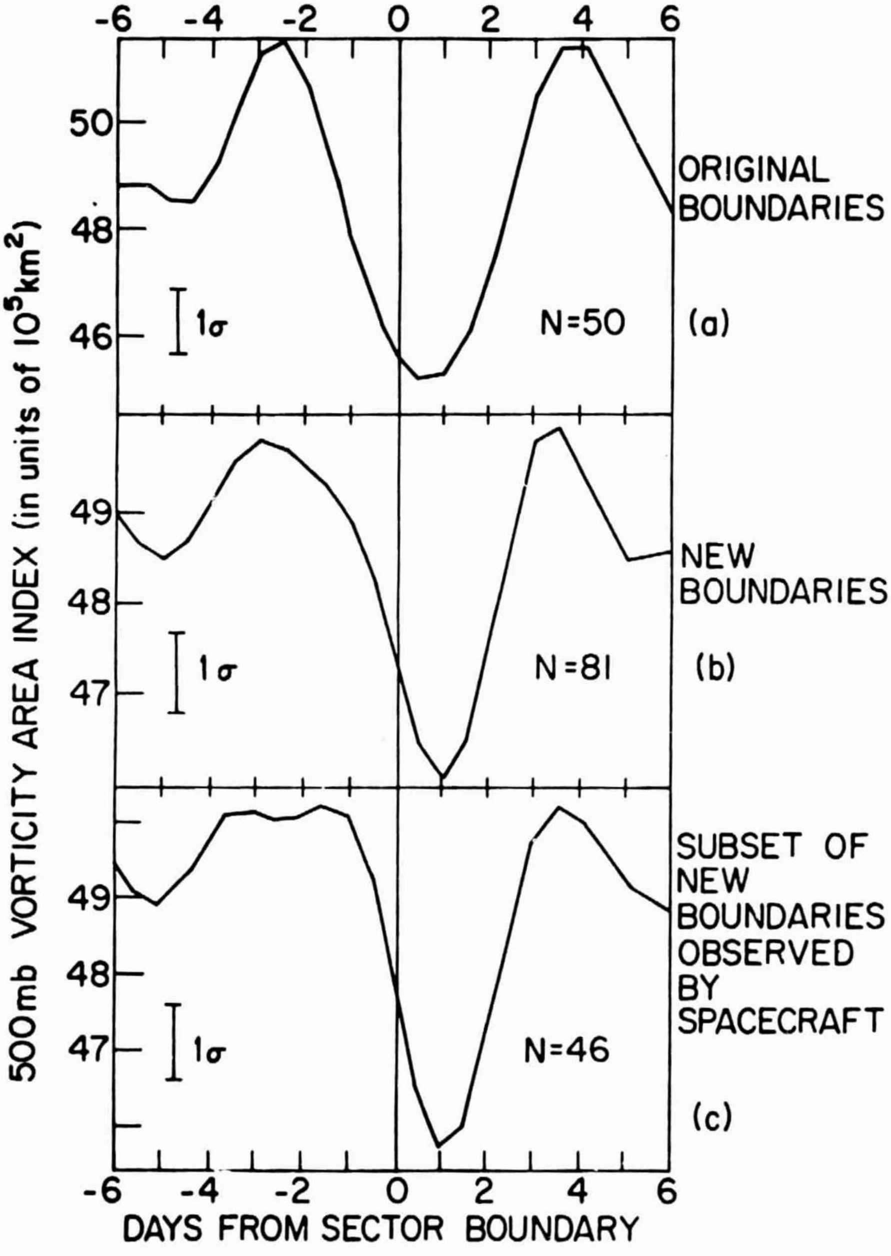
-6 -4 -2 0 2 4 6
500mb VORTICITY AREA INDEX (in units of $10^5 km^2$)
50
48
46
1σ
N=50
ORIGINAL BOUNDARIES
(a)
49
48
47
1σ
N=81
NEW BOUNDARIES
(b)
49
48
47
1σ
N=46
SUBSET OF NEW BOUNDARIES OBSERVED BY SPACECRAFT
(c)
-6 -4 -2 0 2 4 6
DAYS FROM SECTOR BOUNDARY

Figure 3

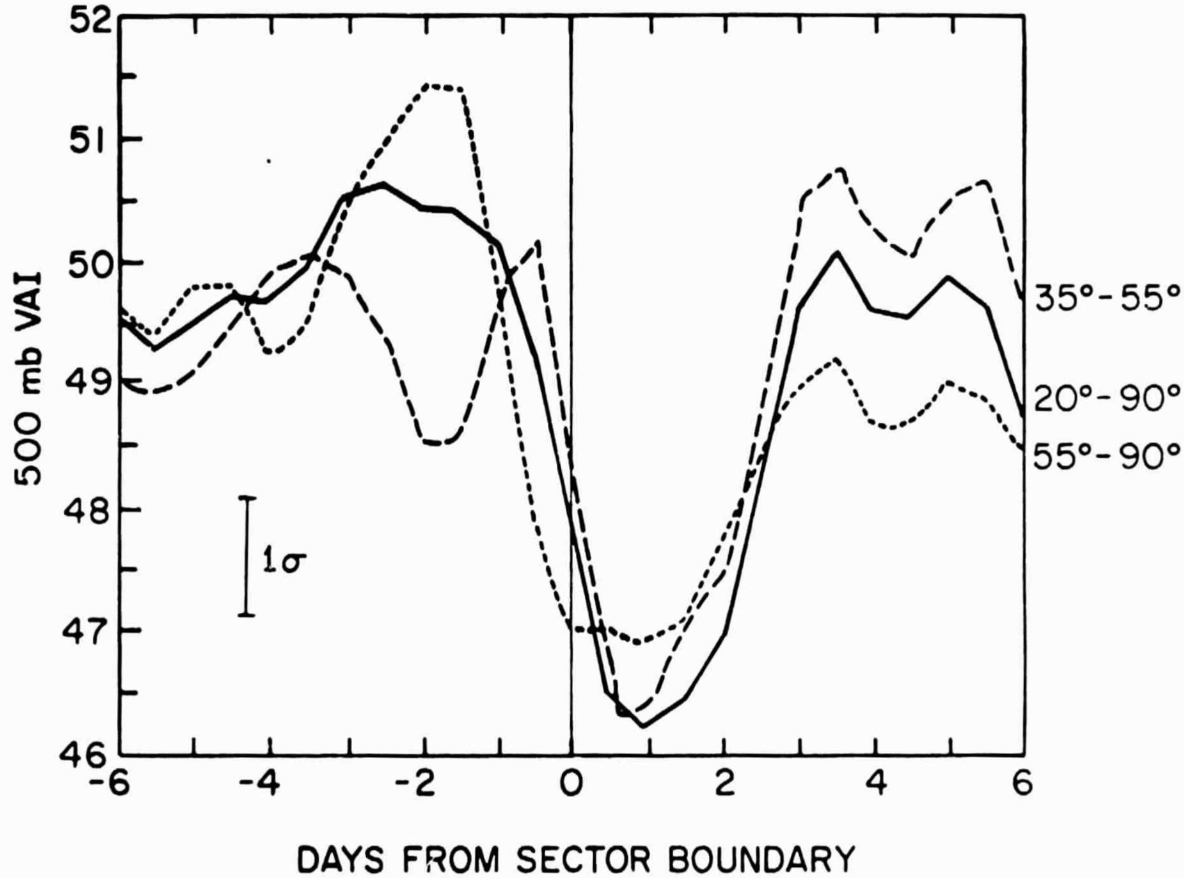
52
51
50
49
48
47
46
500 mb VAI
1σ
-6
-4
-2
0
2
4
6
DAYS FROM SECTOR BOUNDARY
35°-55°
20°-90°
55°-90°

Figure 4

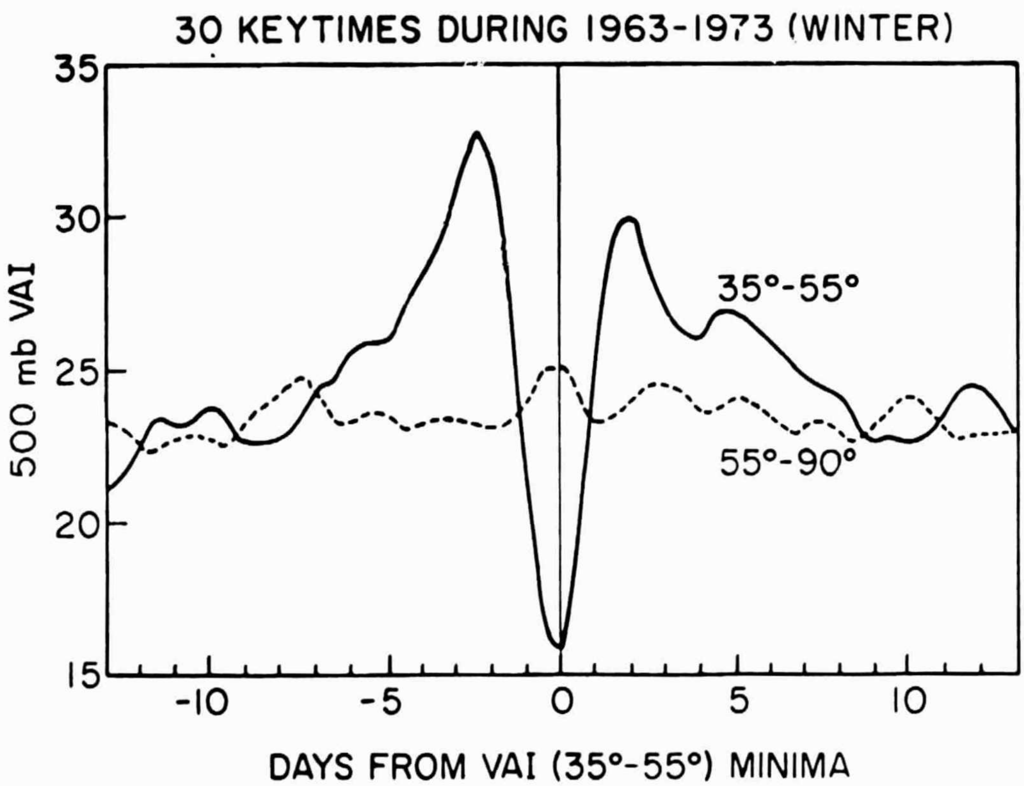
30 KEYTIMES DURING 1963-1973 (WINTER)
35
30
25
20
15
500 mb VAI
35°-55°
55°-90°
-10
-5
0
5
10
DAYS FROM VAI (35°-55°) MINIMA

Figure 5