21 May 1976, Volume 192, Number 4241 SCIENCE

Solar Structure and Terrestrial Weather

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

John M. Wilcox

Claims for a connection between the variable sun and the earth's weather can be found in a literature of well over 1000 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 the earth in connection 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 8 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 framework 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 is that this subject has reached a state in which it merits the consideration of serious scientists (*2*). Such consideration is indeed increasing as witnessed by several symposia on the subject, the most recent of which was held in 1975 at the 16th 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, who are thus beginning to bridge the interdisciplinary gap.

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 W. O. Roberts at the National Center for Atmospheric Research and the University of Colorado in Boulder has been a leading American worker on the subject of sun-weather interactions. Some recent work by Roberts and Olson (*3*) studied days on which geomagnetic activity had a sizable increase, which was assumed to have a solar cause. They also studied the history of low-pressure troughs (cyclones) from the Gulf of Alaska as they moved across the continental United States, and found that troughs associated with geomagnetic activity were significantly larger on the average than troughs associated with intervals of quiet geomagnetic conditions. The vorticity area index, a measure of the size of low-pressure troughs devised by Roberts and Olson, 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 have 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 short-range weather prediction becomes small (that is, little better than a prediction of average properties) within 2 or 3 days (*4*). The vorticity area index devised by Roberts and Olson can be computed from maps of the height of constant-pressure (300-mbar) surfaces by using the geostrophic wind approximation. These maps are prepared twice a day, at 0 and at 12 universal time (U.T.), 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

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now defined as the sum of all areas in which the vorticity exceeds a certain threshold, which is chosen so that all well-formed troughs are included. Once the threshold level (20×10^{-5} sec^{-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 was challenged by Hines (*5*), who suggested 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 of several solar, interplanetary, and terrestrial properties of this structure is available (*6*). 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. For the next several days it will be observed to have a 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 described here, the time at which a sector boundary is observed to sweep past the earth is 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 there is one) 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 rays incident at the 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 joined forces with Roberts and Olson to extend their original investigations. The first results (*7*) of this collaboration are shown in Fig. 1, where the average change in the vorticity area index is plotted against days from sector boundary 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 Fig. 1 that on the average the vorticity area index reaches a minimum approximately 1 day after the boundary passage. The amplitude of the effect from the minimum to the adjacent

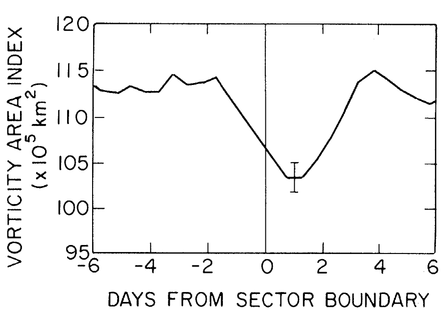
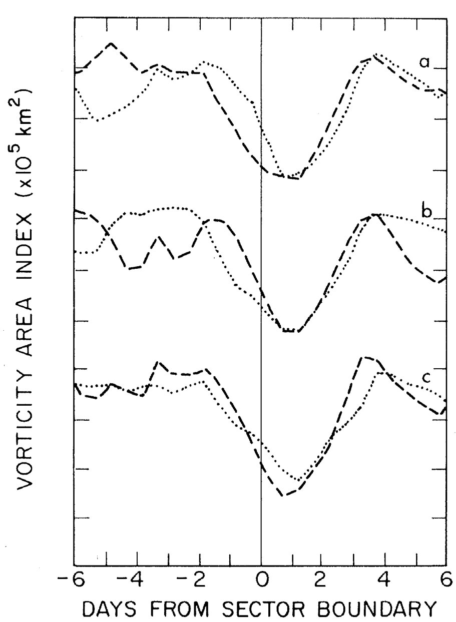


Fig. 1 (left). Average response of the vorticity area index (the area of all the low-pressure troughs in the Northern Hemisphere) about times when solar magnetic sector boundaries were carried past the earth by the solar wind. Sector boundaries were carried past the earth on day 0. The analysis includes 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.



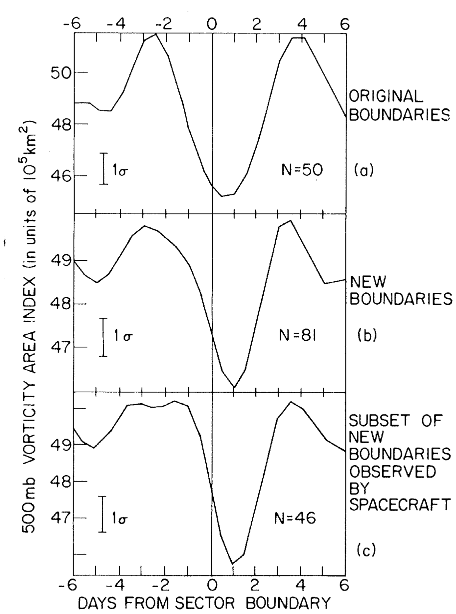
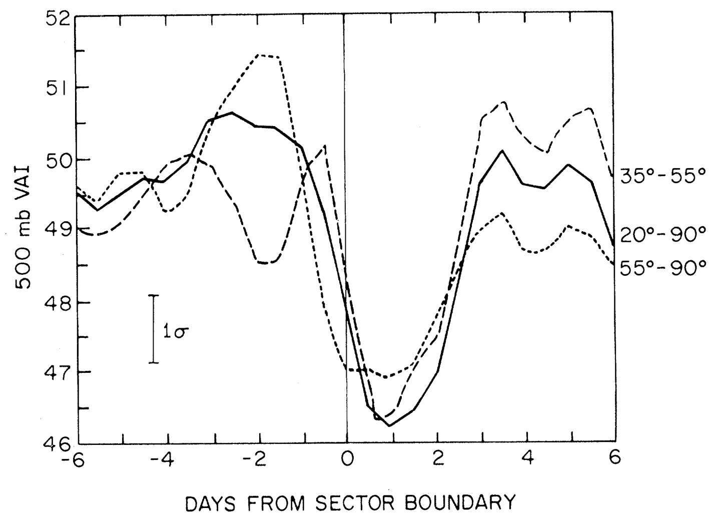


Fig. 2 (middle). Same format as Fig. 1. The list of boundaries used in Fig. 1 was divided into two parts according to (a) the magnetic polarity change at the boundary, (b) the first or last half of the winter, and (c) the yearly intervals 1964 to 1966 and 1967 to 1970. (a) The dotted curve represents 24 boundaries in which the interplanetary magnetic field polarity changed from toward the sun to away from the sun, 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 Fig. 1; that is, each interval is 5×10^5 km^2. Fig. 3 (right). Same format as Fig. 1 for (a) 50 of the boundaries used in the original work, (b) 81 new boundary passages not included in the original analysis, and (c) a subset of (b) in which the times of 46 boundary passages were determined from spacecraft observations.



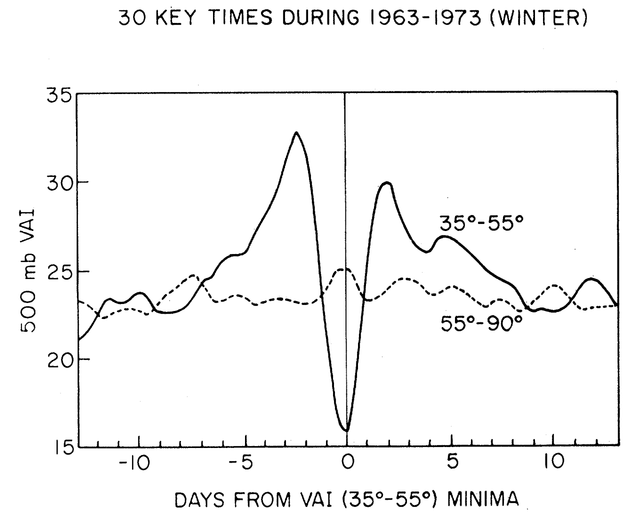


Fig. 4 (left). Similar to Fig. 3, except that the results are shown separately for the latitude zones 35°N to 55°N and 55°N to 90°N, and for the entire Northern Hemisphere north of 20°N. The form of the minimum at 1 day after the boundary passage is rather similar in all of these latitude zones. Fig. 5 (right). Same as Fig. 4, except that the key days are 30 minima in the latitude zone 35°N to 55°N that are not near sector boundaries (see text). The solid curve shows the results for the zone 35°N to 55°N, and the dashed curve shows the results for the zone 55°N to 90°N. The deep minimum in the lower zone does not appear in the upper zone. Abbreviation: *VAI*, vorticity area index.

maxima is about 10 percent. When we consider that weather usually consists of relatively small changes about climate (the average properties), this represents a sizable 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. Figure 1 is computed for 300 mbar, but similar results are found for 200, 500, and 700 mbar.

The result shown in Fig. 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 the earth's atmospheric circulation.

In view of the checkered history of sun-weather influences, the new claim shown in Fig. 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 Fig. 1. This is satisfyingly small, and on formal grounds one might conclude that the minimum near the sector boundary in Fig. 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 to further tests. Figure 2 is in the same format as Fig. 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 Fig. 2 the data have been divided into two parts in three different ways, as explained in detail in the figure legend. We see that the effect persists in all of these divisions of the data set.

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

The last test of significance (*9*) to be described in this article is shown in Figs. 4 and 5. Figure 4 shows the same analysis performed in the latitude zones 35°N to 55°N, 55°N to 90°N, and 20°N to 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 zone 35°N to 55°N it also has a similar minimum in the zone 55°N to 90°N. This possibility has been investigated in the following way. From a plot of the vorticity area index in the zone 35°N to 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 Fig. 3 were tabulated. Figure 5 shows the same analysis performed with the resulting list. The result for the zone 35°N to 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 to 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 1 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 Fig. 1 was made by Hines and Halevy (*11*), who stated, "Reports of short-term Sun-weather correlations have been greeted with skepticism by many." They subjected the data used in preparing Fig. 1 to a variety of statistical tests and requested the analysis of new data shown in Fig. 3. They concluded that "We find ourselves obliged, however, 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 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 11-year sunspot cycle and the 22-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 has any other country. A bilateral agreement between the Soviet Union and the United States 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 of geomagnetic activity is only now beginning to emerge after many years of scientific efforts. 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.

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13. This work was supported in part by the National Aeronautics and Space Administration under grants NSG 5024 and 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 under contract N00014-76-C-0207.

Colligative Properties of a Solution

Enhanced tension in the solvent gives rise to alterations in solution.

H. T. Hammel

When a solute is added to a pure solvent to form a solution, some properties of the solvent are altered. In what way does the solvent in the solution differ from the pure solvent? To answer this question I shall examine here those properties of a solution which differ from those of the pure solvent and are known as the colligative properties. Four of these properties which can be measured experimentally are (i) the osmotic pressure, (ii) the lower vapor pressure, (iii) the lower melting temperature, and (iv) the higher boiling temperature. "Colligative" refers to those properties that depend on, or vary as a function of, the number of solute molecules in solution and not on the nature of the molecules. What reasonable physical explanation can be proposed for these changes which depend only on the number of molecules?

One virtue of thermodynamics is that it provides quantitative relationships between the colligative properties. This success, however, may have hindered the search for an explanation since thermodynamics describes relationships between pressures, volumes, temperature, and numbers and species of molecules in different phases without regard for the mechanisms underlying these relationships. Thus, from the first and second laws of thermodynamics one can, when dealing with homogeneous solutions, deduce that the chemical potential of the solvent depends on the temperature and external pressure to which the solution is subjected and upon the mole fraction of the solute. Suppose we ask what the change in chemical potential of a solvent is when the temperature is changed by dT, when the externally applied pressure is changed by dp, and when the mole fraction of solute is changed by dx_2 (the subscript 1 denotes solvent in solution, and the subscript 2 denotes solute). The basic thermodynamic statement that can be made about these changes is that the change in the chemical potential of the solvent, $d\mu_1$, in a homogeneous solution is given by

$$d\mu_1 = -\overline{S}_1 dT + \overline{V}_1 dp + \frac{\partial \mu_1}{\partial x_2} dx_2 \quad (1)$$

where $\overline{S}_1$ is the partial molar entropy of the solvent, $\overline{V}_1$ is the partial molar volume of the solvent, and x_2 is the mole fraction of solute, which is the ratio of the number of moles of solute (N_2) to the number of moles of solute plus solvent ($N_2 + N_1$). Since we are here concerned only with changes induced by adding solute to a solvent, we can simplify this thermodynamic statement by limiting our attention to the situation in which the solvent is subjected to no change in T or p. Thus, we are left with the statement that the change in μ_1 in a homogeneous solution is given by

$$\Delta\mu_1 = \int_0^{x_2} \frac{d\mu_1}{dx_2} dx_2 \quad (2)$$

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