SOLAR ACTIVITY AND THE WEATHER

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Abstract. Some new evidence that the weather is influenced by solar activity is reviewed. It appears that the solar magnetic sector structure is related to the circulation of the Earth's atmosphere during local winter. About $3\frac{1}{2}$ days after the passage of a sector boundary the maximum effect is seen; apparently the height of all pressure surfaces increases in high latitudes leading to anticyclogenesis, whereas at midlatitudes the height of the pressure surfaces decreases leading to low pressure systems or to deepening of existing systems. This later effect is clearly seen as an increase in the area of the base of air with absolute vorticity exceeding a given treshold. Since the increase of geomagnetic activity generally is small at a sector boundary it is speculated that geomagnetic activity as such is not the cause of the response to the sector structure but that both weather and geomagnetic activity are influenced by the same (unknown) mechanism.

1. Introduction

The idea that solar activity influences weather and climate on the Earth is nearly as old as the concept of solar activity itself. The Italian Jesuit priest Riccioli suggested in 1651 that the temperature of the Earth falls with increasing spottedness of the Sun. Unfortunately in 1801, William Herschel came to the opposite conclusion from an examination of wheat prices in England. This inconclusiveness has been the mark of the whole field of relations between solar activity and weather ever since. Part of the reason for this is the complexity and variability of both solar and terrestrial parameters over a wide range of time scales. Different regions of the Earth such as oceans and continents may also show different responses to solar events. One author investigates surface pressure patterns in response to solar flares; another examines rainfall and sunspot numbers. Their results can hardly be compared and may even be contradictory to results obtained from other geographical regions. After some initial optimism in the beginning of the century serious research in the solar activity-weather field has since been discouraged, particularly among meteorologists.

Recently, however, a number of rather convincing findings have appeared linking the Earth's weather to solar and interplanetary parameters. For example the IUGG Symposium convened by E. R. Mustel in Moscow during August 1971 summarized many new researches in this field. On a whole it seems that direct solar activity influence on weather is gaining growing acceptance in the Soviet Union, whereas the field still is somewhat suspect to Western researchers. The fact that no plausible mechanism has yet been advanced to explain how solar activity possibly can influence the weather is undoubtedly the main reason for this lack of respectability. A famous case in point, of course, was the slow acceptance of the relationship between solar activity, auroras and magnetic storms. From energy considerations Lord Kelvin concluded in 1892 that it was impossible that terrestrial magnetic storms are due to magnetic action of the Sun or to any kind of dynamical action taking place anywhere near the Sun.

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The existence of the solar wind overcomes Lord Kelvin's objections because the magnetic field of the Sun is brought out to the Earth by the outflowing plasma. But the energy content of the solar wind is many orders of magnitude less than that of the total radiation which is the driving force of the atmospheric circulation; so again from energy considerations, it is hard to see how solar activity can have any measurable influence on the lower atmosphere. Without a plausible theory it is then difficult to organize and interprete the empirical evidence. On the other hand some really firm evidence might stimulate the search for a physical mechanism. In this paper I will discuss a recent investigation (Wilcox *et al.*, 1973) of the apparent response of the atmospheric circulation to the solar magnetic sector structure.

2. Solar Magnetic Sector Structure

The large-scale solar photospheric magnetic field is extended outward from the Sun by the radially flowing solar wind (Wilcox, 1968). Seen from the Earth, the interplanetary magnetic field can be divided into sectors such that within each sector the field polarity is either toward the sun or away from the Sun. Adjacent sectors having opposite field polarities are separated by a very narrow boundary. Most commonly there are four such sectors, each having a width of about 90° in solar longitude, and the whole sector structure rotates past the Earth with a period of approximately 27 days. While the Earth may be within the same sector for several days, it usually takes only a few hours down to a few minutes for a sector boundary to sweep past the Earth. Hence the time of passage of a sector boundary may be used as a precise timing signal to examine the atmospheric response to the sector structure using the superposed epochs technique. The zero days (or key-days) were defined as the times at which the sector boundaries tabulated by Wilcox and Colburn (1972) swept past the Earth. These are boundaries for which the polarity of the interplanetary magnetic field observed by spacecraft near the Earth – but still outside the Earth's magnetosphere – was in one direction (away from or toward the Sun) for at least four days before the boundary, and in the opposite direction for at least four days after the boundary. Similarly defined sector boundaries for the year 1970 (Wilcox and Colburn, 1973) were added to the list of well-defined boundaries. A total of more than 100 sector boundaries were available for analysis. Due to the strict requirement that each boundary must be clearly defined by *observations* only about one-fourth of all possibly existing boundaries went into the analysis.

3. The Hemispheric Vorticity Area Index

The atmospheric parameter in the investigation was the vorticity area index of Roberts and Olson (1973). A basic quantity in hydrodynamics is *circulation*, involving movement around a closed path within a fluid. Circulation is defined as the line integral of the velocity of the fluid around this closed path. *Vorticity* may be defined as circulation per unit area. For a circular disk rotating rigidly with angular velocity

ω the circulation around the outer boundary is $C = 2\pi R \cdot \omega R$, where R is the radius of the disk. Thus $C = \pi R^2 (2\omega)$ or area times 2ω, so that the vorticity of a disk rotating as a solid is twice the angular velocity of rotation. Since the Earth is rotating, it must have a vorticity; the Earth's atmosphere corotates with the Earth, and so its mean vorticity is simply 2Ω, where Ω is the angular velocity of the Earth. However, local variations in atmospheric vorticity occur, and these are of prime significance for both climate and weather. Strictly speaking we have components of vorticity for the three axes of a Cartesian system. Since the vorticity about the rotation axis is by far the most important, we only consider that from now on.

A distinction must be made between relative vorticity, which is the vorticity of the airflow relative to the Earth's surface, and absolute vorticity. The latter is simply the sum of the relative vorticity ζ and the vorticity f of the Earth itself: $\zeta_A = \zeta + f$.

Now it can be shown (e.g., Pedlosky, 1971) that for a rotating air column in the atmosphere the absolute vorticity is conserved for that volume of air. The distribution of absolute vorticity over the surface of the Earth is highly uneven. There are numerous centers or regions with rather high vorticity separated by areas of low absolute vorticity. These high vorticity centers move across the surface with the weather systems but conserve their value of high absolute vorticity. If the pressure is falling in one of these centers its area increases to conserve volume, and the area over which the high vorticity is observed increases accordingly. The high vorticity centers are seen in connection with low pressure troughs associated with increased storminess and precipitation. A deepening of these troughs leads to an increase of the area with high absolute vorticity; and it is possible to define an index indicating the overall severeness of the low pressure systems. This vorticity area index is the total area over which the absolute vorticity exceeds a given treshold.

The vorticity area index can be computed from maps of the height of constant pressure surfaces using the geostrophic wind approximation. These maps – prepared twice a day, at 0^h UT and at 12^h UT for the part of the northern hemisphere north of 20° N – were used to compute the vorticity area index for the years 1964–1970. The original vorticity area index of Roberts and Olson was defined as the area (in km^2) over which the absolute vorticity exceeded $20 \times 10^{-5}\ s^{-1}$ plus the area (also in km^2) over which the vorticity exceeded $24 \times 10^{-5}\ s^{-1}$. For virtually all low pressure troughs there was some area over which the vorticity exceeded the lower value, and for the major troughs there was nearly always some area over which the higher value was exceeded. The pressure level used to calculate the vorticities was the 300 mbar level at about 9000 m height. The area was summed over the entire hemisphere north of 20° N, and two values of the index was obtained per day. Due to systematic (small) differences between the 0^h UT map and the 12^h UT map each vorticity index value was smoothed according to $V_i = (V_{i-1} + 2V_i + V_{i+1})/4$ to remove the systematic variation.

4. Vorticity Area Index Response to Sector Structure

Figure 1 shows the average response of the hemispheric vorticity area index to the sector structure sweeping past the earth during the winter months, November to March. A total of 54 sector boundaries was used to calculate the average response. On the average the vorticity is decreasing until 1 day after the boundary, and then increasing until a maximum is reached about $3\frac{1}{2}$ days after the boundary. A similar analysis covering the summer months showed little or no effect. This may not be too surprising because the atmospheric circulation patterns are quite different for summer and winter. Also it appears to be one of the most persistent empirical evidence emerging from most other investigations that any influence of solar activity or solar parameters on the weather tends to be strongest during the winter season.

The vorticity area index is influenced by many physical effects. The superposed epoch analysis presented here emphasizes one particular effect – the solar magnetic sector. Since the phase (zero day) of the analysis is fixed by the time at which a sector boundary passes the Earth, physical effects on the vorticity index related to the sector structure will tend to be reinforced in this analysis, and other physical effects on the vorticity index will tend to occur at random phases and therefore to be averaged out.

The physical significance and reproducibility of the result shown in Figure 1 have been investigated by dividing the data sample into two parts in three different ways, and performing the same superposed epoch analysis separately on each part. Figure 2 shows the result of analysing separately the boundaries at which the field polarity

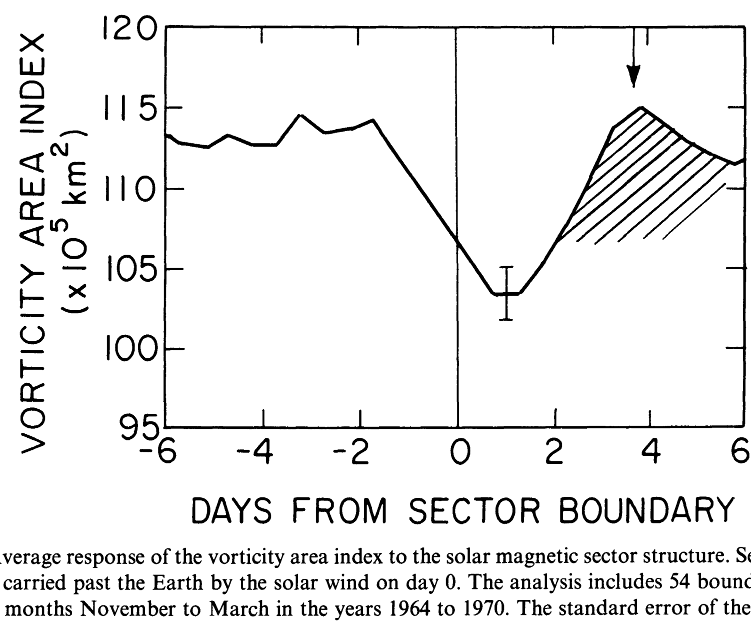

Fig. 1. Average response of the vorticity area index to the solar magnetic sector structure. Sector boundaries were carried past the Earth by the solar wind on day 0. The analysis includes 54 boundaries during the winter months November to March in the years 1964 to 1970. The standard error of the mean (error bar) was calculated after subtracting a 27-day mean centered on each sector boundary, to remove long-term trends. The increase in the vorticity area index $3\frac{1}{2}$ days after the boundary is shaded.

changed from toward the Sun to away from the Sun and the boundaries where the field polarity changed from away to toward. Also shown are the results of separate analyses of the boundaries occurring in the first half of the winter (November 1 to January 15) and those occurring in the last half (January 16 to March 31). Finally, the boundaries occurring during the years 1964 to 1966 and those occurring during 1967 to 1970 have been analyzed separately. We note, that the analyses performed on these various subsets of the data all gave essentially the same results, so that the result shown in Figure 1 is highly reproducible and is quite independent of the way the data was subdivided. In all cases do we see a decline of the vorticity area index until 1 day after the boundary followed by a rise in the index to a maximum about $3\frac{1}{2}$ days after the sector boundary passed the Earth.

The results shown in Figures 1 and 2 were based on the vorticity area index calcu-

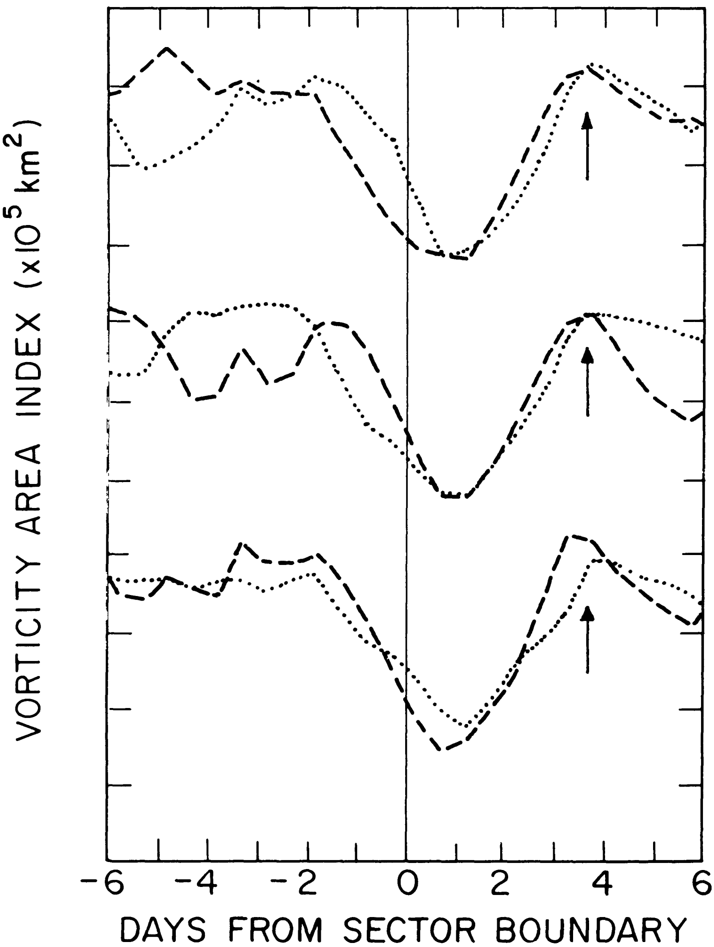

Fig. 2. Same format as Figure 1; the list of boundaries used in Figure 1 was divided into two parts according to (top) the magnetic polarity change at the boundary, (middle) the first or last half of the winter, and bottom) the yearly intervals 1964–1966 and 1967–1970. The curves have been arbitrarily displaced in the vertical direction, but the scale of the ordinate is the same as in Figure 1.

lated for the 300 mbar level, and using the original definition of the index as the sum of two areas corresponding to two different vorticity tresholds. Using only one treshold gives essentially the same results and it was felt an unnescessary complication to proceed with the analysis with the two tresholds. The final vorticity area index may now be characterized by two parameters: (i) the pressure level for which it is computed, and (ii) the treshold or discriminator value used.

To check if the results found at the 300 mbar level could be reproduced at other levels in the atmosphere, the analysis was repeated for each of the so-called standard pressure levels ranging from 850 mbar up to 10 mbar. The vorticity discriminator was first set to the fixed value 20×10^{-5} s^{-1} for all levels. Figure 3 demonstrates that the

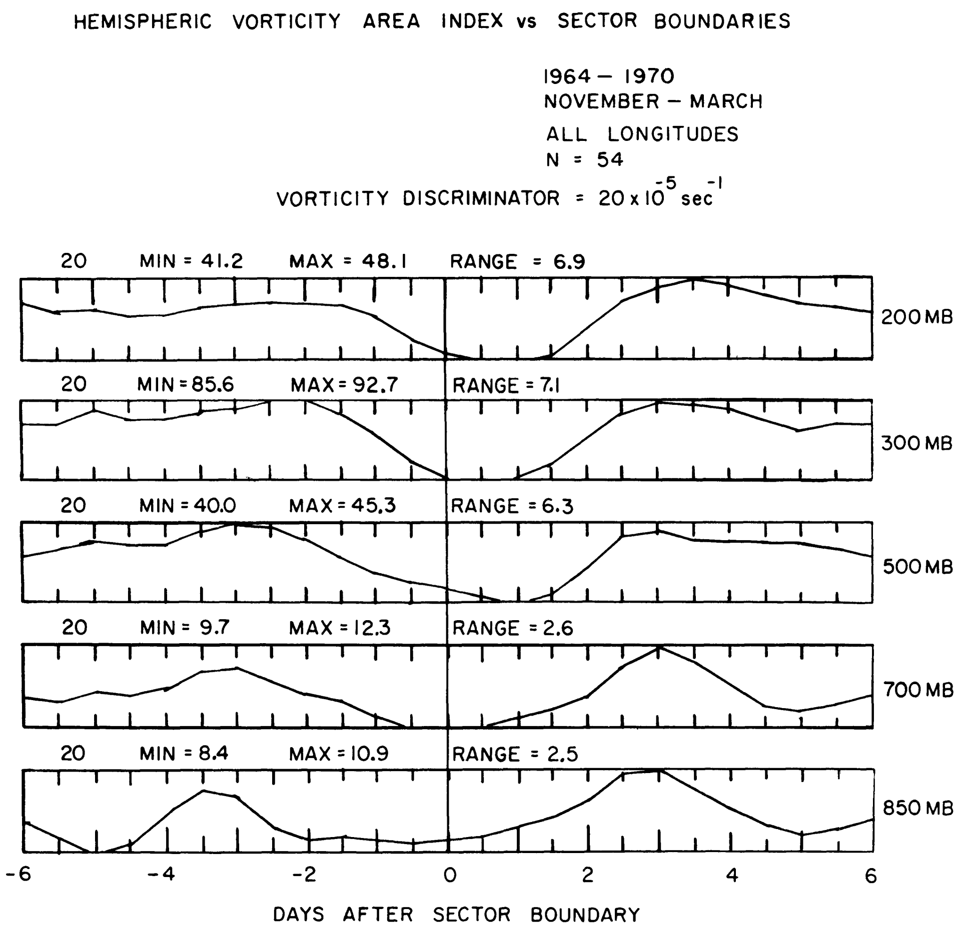

Fig. 3. Superposed epoch analysis using the same list of boundaries as in Figure 1, but with a single discriminator value for the vorticity. The analysis is shown for each of the pressure levels 850 mbar, 700 mbar, 500 mbar, 300 mbar, and 200 mbar. The vertical scale is for each strip given by the maximum and minimum value of the vorticity area index (in units of 10^5 km^2).

effect is present at all levels in the troposphere. It could not be seen at stratospheric levels above 100 mbar. This may simply be a consequence of the fact that the atmospheric circulation is quite different in the stratosphere and in the troposphere. It is quite noteworthy that the effect can be observed as low as at the 850-mbar level. The persistent feature in Figure 3 is the maximum 3–4 days after the boundary. This maximum starts to develop at the same time at all levels, whereas there may be some indication that the decline of the indexvalue starts first at the lowest level and becomes effective later and later as we go to higher levels. It is tempting to ascribe the slower decay as due to decreased friction with altitude.

From Figure 3 it is evident that there is quite a variation of the absolute vorticity from one level to the next; the vorticity area index changes from a minimum of $\approx 10 \times 10^5$ at 850 mbar to $\approx 90 \times 10^5$ km^2 at 300 mbar. Since the atmosphere is basically a *thin* structure, air masses generally have much larger horizontal dimensions compared to their vertical size. Therefore the analysis was finally repeated varying the vorticity discriminator at each level such as to make the areas nearly equal to 40×10^5 km^2 at all levels. The result is shown in Figure 4. We note that again we get essentially the same result as in the previous analysis.

The reproducibility of our results when the parameters of the analysis are varied, for all levels of the troposphere and for different subsets of the data strongly suggests that the effect is real. The fact that the times of the sector boundaries were published long before the analysis precludes wishful selection-effects. Finally the whole analysis is completely objective and may be repeated by anybody using only published data.

5. Pressure and Sector Structure

In a follow-up study of the atmospheric response to the solar sector structure Svalgaard *et al.* (1973) analyzed atmospheric pressure rather than vorticity. Instead of analyzing the pressure at a given height it is costumary in meteorology to examine the height of a given pressure level; many equations in dynamic meteorology are simpler with pressure as an independent variable instead of height. Using the same 54 sector boundaries as zero days in a superposed epoch analysis the quantity investigated was the average height of a given constant pressure level over a latitude belt 10° wide. As for the vorticity area index significant systematic variations of the average heights were found in response to the passage of a sector boundary. In general the heights increased a few days after the boundary at high latitudes, whereas they decreased at mid-latitudes.

A single quantity which incorporates both of these changes of height is the height difference between the levels of constant pressure in the 40°–50° N latitude belt and in the 60°–70° latitude belt. In the free atmosphere there is generally a low pressure area around the north pole in the winter time and a region with high pressure in the subtropics. The height difference defined defined above is a measure of the slope of the surface of constant pressure slanting somewhat downwards toward the pole. This slope is then positive and of the order of 400 m on the average. The response

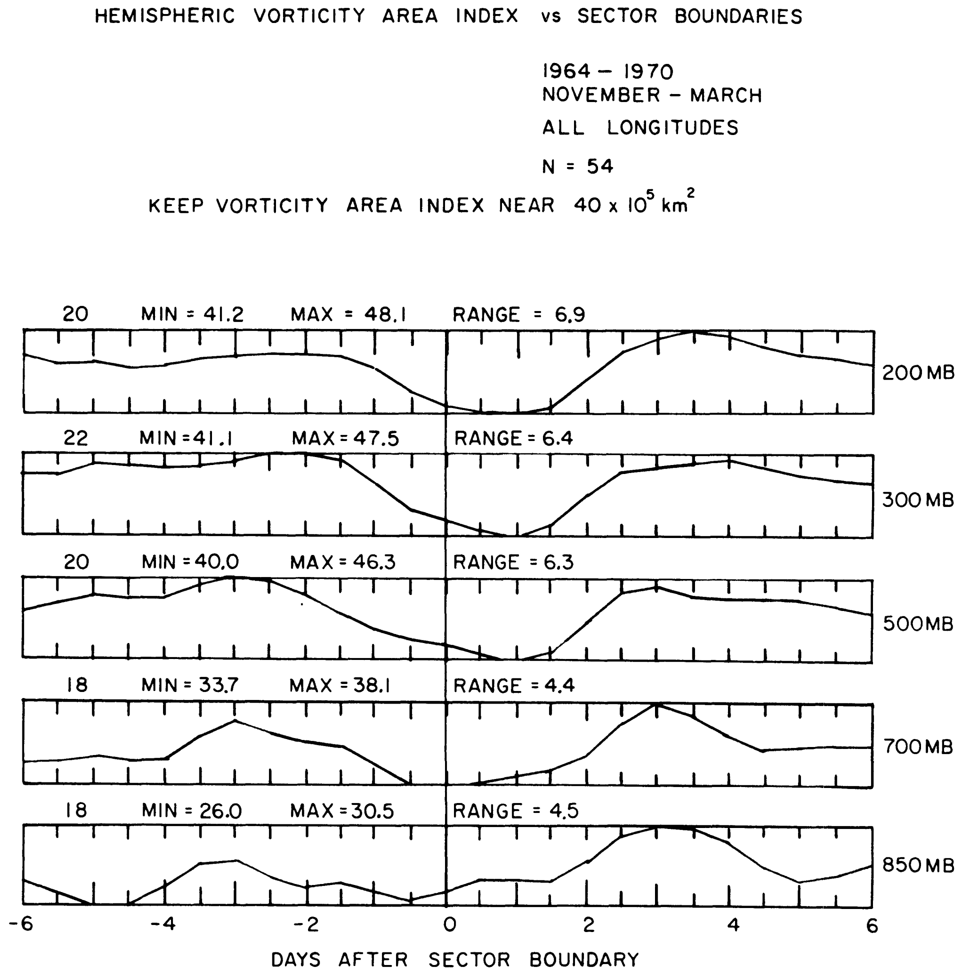

Fig. 4. Same format as Figure 3; the vorticity discriminator has been varied to bring the area index close to 40×10^5 km^2 and is given at the left end of each strip.

of the height difference to passage of a sector boundary is shown in Figure 5 for all standard levels up to 30 mbar. A persistent feature of the response is the decrease in height difference starting at the time of passage of the boundary and being maximal 3–4 days after the boundary. This decrease corresponds to a 'flattening' of the height profile along a meridian. In interpreting Figure 5 two circumstances must be taken into account. First, there is the pronounced seasonal variation of the slope as mid-winter is approached, and secondly it must be remembered that there is often another sector boundary about 7 days before a sector boundary, such that 3–4 days *before* the zero-day of our analysis we may see the effects of the preceding boundary. There are 32 boundaries in the first half of the winter but only 22 in the last half, so that residual trends become apparent: increasing height difference with time at stratospheric levels, but decreasing in the troposphere.

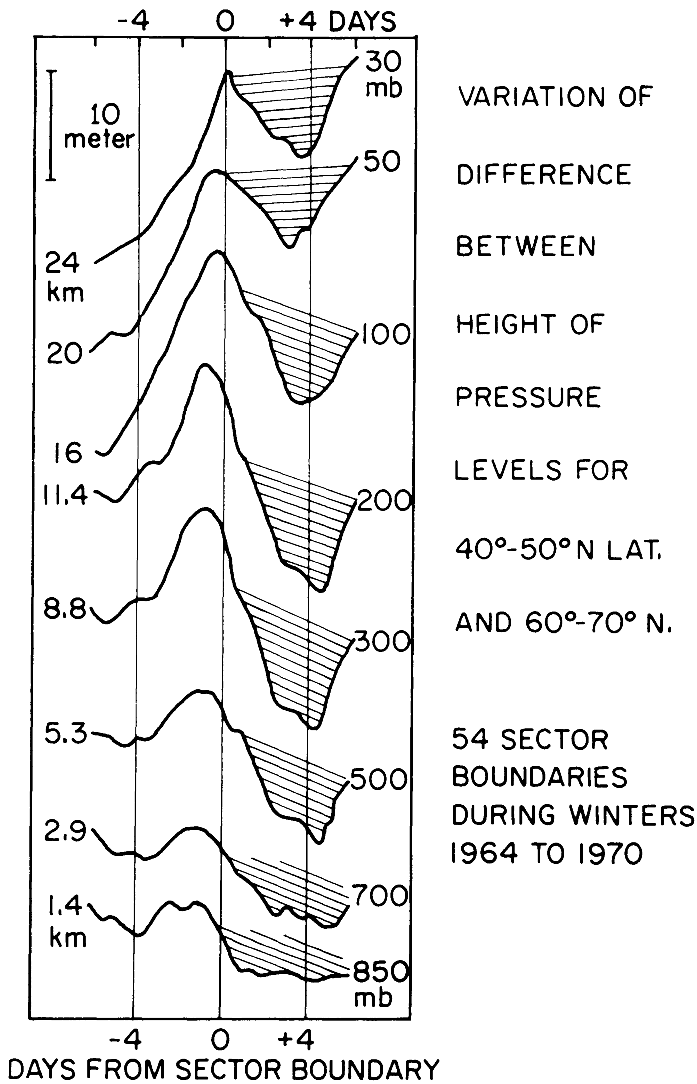

Fig. 5. Superposed epoch analysis of the difference between the height of constant pressure levels for the two latitude belts 40°–50°N and 60°–70°N. The same sector boundaries as in Figure 1 are used. The approximate height of each level is also given.

A crude, schematic picture of the physical changes in the pressure distribution after the passage of a sector boundary is given as Figure 6. Following a sector boundary the height of all pressure surfaces increases at high latitudes leading to anticyclogenesis (high pressure system), whereas at midlatitudes the height of the pressure levels decreases leading to low pressure systems or deepening existing ones with an overall result of increased storminess and precipitation. This picture is quite consistent with the vorticity analysis which indicated an increase in absolute vorticity about $3\frac{1}{2}$ days

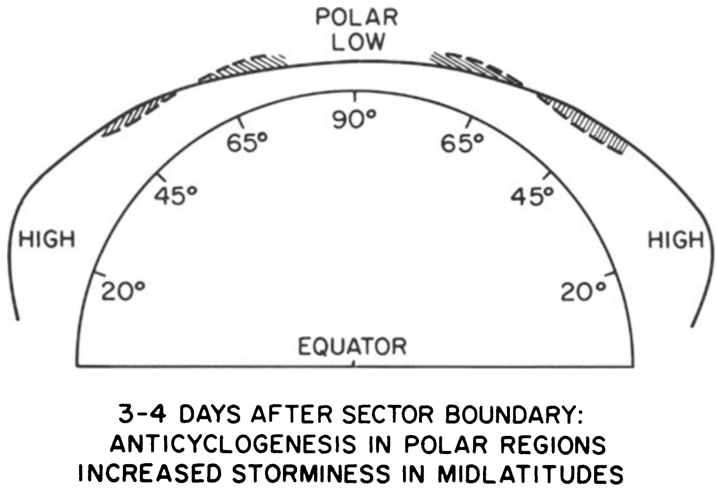

Fig. 6. Schematic of the change in meridional profile for a pressure level in response to passage of a sector boundary.

after the boundary with the same consequences at midlatitudes where most of the vorticity centers are.

6. Geomagnetic Activity and Sector Structure

It is well known that the passage of a sector boundary is associated with a transient increase in geomagnetic activity as measured for example by the K_p index. However, this increase is usually quite small; K_p increases on the average from a minimum of 1_+ just before the boundary to about 2_+ or 3_- a day after the boundary. Numerous authors have searched for atmospheric responses to strong geomagnetic activity and the claims are legio. The effects reviewed here are not particularly associated with strong or not even moderate geomagnetic disturbances. On the other hand, it may well be that many of the effects claimed to follow geomagnetic activity are related to the sector structure. Solar proton flares occur most often near solar sector boundaries. Geomagnetic sudden commencements show a marked tendency to occur near sector boundaries. High solar wind velocities, densities and interplanetary magnetic field strengths also are often observed near sector boundaries. It is not inconceivable that at least some of the many past investigations relating geomagnetic activity and the weather actually correlated sector structure and weather instead.

Rather, the relationship between the sector structure and the weather reviewed in the present paper suggests that it is not geomagnetic activity as such that may influence the lower atmosphere but that geomagnetic activity and some weather changes are results of the same basic mechanism which still waits to be uncovered.

Acknowledgements

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Appendix

List of observed and Well-defined Sector Boundaries

The date, sign change (+away, −toward), and time (in 3-h intervals) is given for all observed sector boundaries with at least four days of opposite field polarity on each side of the boundary. The notation 8-1 means that the boundary occurred between the last 3-h interval of that day and the first 3-h interval of the next day.

Observed and well-defined sector boundaries

Year	Day of Year	Sign	Date	Time
1962	253	+, −	Sept 10	8–1
	269	−, +	Sept 26	3–4
	281	+, −	Oct 8	4–5
	293	−, +	Oct 20	8–1
1963	336	−, +	Dec 2	8–1
	346	+, −	Dec 12	4–3 (gap)
	354	−, +	Dec 20	1–2
1964	007	+, −	Jan 7	7–8
	016	−, +	Jan 16	2–2 (gap)
	023	+, −	Jan 23	3–4
	035	+, −	Feb 4	2–3
	284	−, +	Oct 10	6–7 (1 day gap)
	291	+, −	Oct 17	7–8
	297	−, +	Oct 23	6–8 (1 day gap)
	306	+, −	Nov 1	5–6
	312	−, +	Nov 7	2–1 (gap)
	320	+, −	Nov 15	5–6
	325	−, +	Nov 20	3–2 (gap)
	332	+, −	Nov 27	7–8
	341	−, +	Dec 6	4–5
	345	+, −	Dec 10	8–1

Year	Day of Year	Sign	Date	Time
	349	−, +	Dec 14	8–1
	361	+, −	Dec 26	1–2
1965	002	−, +	Jan 2	1–2
	008	+, −	Jan 8	1–2
	012	−, +	Jan 12	2–3
	032	+, −	Febr 1	8–1
	125	+, −	May 5	4–5
	153	+, −	June 2	8–1
	161	−, +	June 10	2–3
	230	−, +	Aug 18	7–6 (gap)
	235	+, −	Aug 23	5–7 (gap)
	259	−, +	Sept 16	2–3
1966	001	+, −	Jan 1	6–7 (1 day gap)
	032	+, −	Febr 1	4–5
	043	−, +	Febr 12	2–3
	062	+, −	March 3	3–4
	067	−, +	March 8	2–3
	089	+, −	March 30	2–3
	099	−, +	April 9	1–2
	127	−, +	May 7	8–1
	249	−, +	Sept 6	5–6
	257	+, −	Sept 14	6–7
	276	−, +	Oct 3	6–7
	285	+, −	Oct 12	2–3
	303	−, +	Oct 30	5–6
	312	+, −	Nov 8	4–5
	331	−, +	Nov 27	7–8
	338	+, −	Dec 4	3–4
1967	001	+, −	Jan 1	7–8
	013	+, −	Jan 13	3–4
	018	−, +	Jan 18	2–3 (1 day gap)
	081	−, +	March 22	7–8
	216	−, +	Aug 4	5–6
	242	−, +	Aug 30	2–3 (1 day gap)
	249	+, −	Sept 6	6–7
	270	−, +	Sept 27	3–4
	276	+, −	Oct 3	1–2
	297	−, +	Oct 24	2–3
	324	−, +	Nov 20	4–5
	338	+, −	Dec 4	5–6
1968	001	+, −	Jan 1	6–5 (gap)
	028	+, −	Jan 28	8–1
	042	−, +	Febr 11	3–4
	057	+, −	Febr 26	6–7
	070	−, +	March 10	4–5
	083	+, −	March 23	5–6
	096	−, +	April 5	7–8
	112	+, −	April 21	3–4
	123	−, +	May 2	1–2
	138	+, −	May 17	5–6

Year	Day of Year	Sign	Date	Time
	185	−, +	July 3	3–4
	191	+, −	July 9	8–1
	199	−, +	July 17	4–5
	207	+, −	July 25	4–5
	213	−, +	July 31	7–8
	226	−, +	Aug 13	7–8
	234	+, −	Aug 21	2–3
	263	+, −	Sept 19	2–3
	290	+, −	Oct 16	5–6
	318	+, −	Nov 13	2–3
	334	−, +	Nov 29	6–8 (gap)
	345	+, −	Dec 10	2–3
	359	−, +	Dec 24	6–7
1969	006	+, −	Jan 6	5–6
	023	−, +	Jan 23	8–1
	033	+, −	Febr 2	5–6
	050	−, +	Febr 19	2–3
	090	+, −	March 31	6–7
	110	−, +	April 20	7–1 (gap)
	119	+, −	April 29	3–4
	127	−, +	May 7	6–3 (gap)
	132	+, −	May 12	8–2 (gap)
	138	−, +	May 18	6–7
	147	+, −	May 27	1–2
	165	−, +	June 14	3–4
	192	−, +	July 11	2–3
	202	+, −	July 21	5–6
	219	−, +	Aug 7	6–7
	248	−, +	Sept 5	3–4
	303	−, +	Oct 30	8–1
	330	−, +	Nov 26	5–6
	343	+, −	Dec 9	1–2
	356	−, +	Dec 22	7–8
1970	040	−, +	Febr 9	7–8
	067	−, +	March 8	8–1
	120	−, +	April 30	3–4
	131	+, −	May 11	6–7
	158	+, −	June 7	6–7
	243	+, −	Aug 31	8–5 (gap)
	309	−, +	Nov 5	3–4
	328	+, −	Nov 24	3–4