On the Annual Variation of Magnetic Disturbance

D. H. McIntosh

Phil. Trans. R. Soc. Lond. A 1959 **251**, 525-552
doi: 10.1098/rsta.1959.0010

ON THE ANNUAL VARIATION OF MAGNETIC DISTURBANCE

By D. H. McINTOSH
Edinburgh University

(*Communicated by N. Feather, F.R.S.—Received 5 February* 1959)

CONTENTS

Statistical features of the annual incidence of magnetic disturbance, over a very wide range of disturbance intensity and latitude, are exhaustively investigated by means of the *K* index and related 'planetary' indices.

Two distinct and physically significant components are identified: (*a*) an annual component, with summer maximum and winter minimum; (*b*) a semi-annual component with equinoxial maxima. Both components are found in all parts of the earth. The amplitude of the annual component increases markedly with latitude, while that of the semi-annual component changes little with latitude.

The physical causes of the two types of variation are finally considered. The conclusions reached are (*a*) that the annual component is probably caused by an atmospheric dynamo effect; (*b*) that the semi-annual component arises because of a systematic annual variation of the angle between the earth's magnetic axis and the sun-earth line, along which travel the solar particles which cause magnetic disturbance.

1. INTRODUCTION

A systematic annual variation of the incidence of magnetic storms is among the best-known features, and its explanation is one of the oldest problems, of geomagnetism. A similar, though less well-documented feature, also without satisfactory explanation, is found

Vol. 251. A. 1001. (Price 10*s*.) 66 [Published 15 September 1959

in the incidence of auroral displays, ionospheric storms, and other geophysical phenomena closely linked with magnetic storms.

The existence of an annual variation of magnetic storminess was already known when Cortie (1913), using disturbance indices for a single observatory, summed over 23 years and arranged in twenty-four consecutive half-monthly periods, found maxima in late February and late August. Cortie considered the cause of the variation to be the fact that the sun's equator is not coplanar with the ecliptic but is inclined at a small angle (7·2°) to it: the earth attains its maximum south and north heliographic latitudes on about 5 March and 6 September, respectively, and is then most likely to lie in the path of particle streams ejected radially from or near sunspots which, averaged over a sunspot cycle, are most frequent in solar latitudes higher than 7°. Cortie considered that sampling effects were the cause of the departure of the actual dates of maxima from the 'theoretical' dates. Cortie's hypothesis, depending essentially on the angle between the solar axis and the ecliptic, has since been termed the 'axial' theory.

The validity of Cortie's theory was not supported by the results of two independent tests applied by Bartels (1932). First, using 'planetary' indices of magnetic disturbance, u_1 and C, extending over periods of 59 and 25 years, respectively, he found dates of mean maxima near the two equinoxes. Secondly, he found no evidence that magnetic disturbance has a pronounced March (September) maximum during those 'favourable' years in which faculae are conspicuous predominantly in the southern (northern) solar hemisphere.

The axial explanation has, however, received support from several workers in more recent years. Thus Gnevishev & Ol (1946), seeking geomagnetic evidence of the width of solar particle streams, considered certain of their findings to accord with this theory. Naqvi & Bhargava (1954), Naqvi & Tandon (1955) and Tandon (1956), claim to have identified 27-day recurrence sequences showing an intensity variation of period 12 months which they considered to be directly related to the tilt of the solar axis with reference to the ecliptic. Bell & Glazer (1956, 1957) studied geomagnetic fluctuations in relation to coronal line intensity observed in the 'favourable' and 'unfavourable' solar hemispheres and obtained a result which they considered lends support to Cortie's theory. In a later work, however, these same authors (Bell & Glazer 1958) have found in magnetic storminess no effect associated with the solar hemisphere grouping of sunspots.

In all this work, including the use of 'planetary' indices by Bartels, the various measures of disturbance have in fact referred to conditions in those areas lying equatorward of the auroral belts. Chree (1915, 1927) has shown, however, that different conditions obtain in very high geomagnetic latitudes, disturbance there having a summer maximum and winter minimum. Analyses by Stagg (1935) and Nikolsky (1947) of the *diurnal* incidence of activity in high latitudes showed that there is a twofold form of local time (l.t.) control of variation in these latitudes. Mayaud (1956) has delineated the zonal boundaries of the two types of diurnal variation of disturbance in terms of the magnetic inclination at a height above the earth of about 5 km, and has shown that they are associated with different general forms of annual variation: the type with maximum night incidence lies equatorward of the transition zone and has March and September maxima, while that with maximum day incidence lies poleward of the transition zone and has a summer maximum and winter minimum.

The annual variation of magnetic disturbance, viewed on a true planetary scale, is thus seen to be complex and it is very improbable that a single cause will serve to explain the two quite distinct features of variation referred to above.

2. Procedure

The measures of disturbance used throughout the investigation are the 3 h range index K and the related Kp and Ap 'planetary' indices, which are now established in international practice as the most convenient measures of disturbance on the local and geographically wider scales, respectively. For definitions of K, Kp, Ap indices see, respectively, Bartels, Heck & Johnston (1939); Bartels & Veldkamp (1949); Bartels & Veldkamp (1954).

Attention is very largely concentrated on the annual variation of disturbance in those latitudes lying on the equatorial side of the auroral zone for the reasons: (*a*) that much the greater part of the earth's surface is thereby included, (*b*) ample data are available for consideration, (*c*) previous discussion and controversy have been almost entirely confined to this region. Conditions obtaining in the remaining (poleward) regions are, however, also examined.

The paper is divided into five sections. The statistical features of annual variation are examined on the planetary, local and regional scales in turn. The relation between the phase and amplitude of a universal time (u.t.) component in the diurnal incidence of disturbance and a semi-annual component in the annual variation is then investigated. Finally, the main results are summarized and possible causes of the identified components of annual variation are discussed.

3. Planetary variation

The K indices observed at selected observatories are compounded to form two closely related measures of disturbance on the so-called planetary scale, Kp and Ap. The former is semi-logarithmic like the K index itself, while the latter is linear in force units and was here preferred to Kp because of the difficulties of precise interpretation of average values of a semi-logarithmic measure.

The distribution of those observatories selected to contribute to Ap (or Kp) is very uneven in both latitude and longitude. A complex statistical procedure is therefore required to remove the effects, diurnal and seasonal, of such unevenness from the derived index. Ap is thus incapable of providing an answer to various queries which arise on a true planetary scale, e.g. the possibility of a perigee-apogee effect in disturbance, or of an effect arising from the non-uniform distribution of land and sea. The ability of Ap to discriminate between the solstices and equinoxes, is, however, not invalidated and it was for this purpose that the Ap measure was here employed. Since all the observatories contributing to Ap lie on the equatorial side of the auroral zone, conclusions concerning the equinox-solstice relationship reached by a study of the Ap index are strictly valid only in these regions.

In order to increase the 'resolving power' beyond that possible with monthly values, the available Ap data were considered in separate calendar weeks, 1 to 7, 8 to 14 January, etc.; fifty-two values spanning the year were thus obtained, the additional day of a normal year being assimilated in an 8-day week, 25 June to 2 July, and the further additional day of a leap year in an 8-day week 26 February to 4 March. In the counting of frequencies and calculation of averages appropriate account was taken of these procedures.

A primary aim in the investigation was one of determining the nature of the annual variation of disturbance from the very low level normally termed 'quiet' up to the highest level of disturbance: it is not *a priori* certain that the form of the variation is independent of the general level of disturbance.

3·1. *Graphical results*

Twenty years of daily *Ap* indices (1937–56) were available for analysis. The computed annual variations of *Ap* are shown graphically in figures 1, 2, 3: figure 1 in terms of average weekly *Ap* at three levels of disturbance; figure 2 in terms of *Ap* frequency at two high levels of disturbance; figure 3 in terms of *Ap* frequency at three low disturbance levels. Each of these levels was arbitrarily chosen.

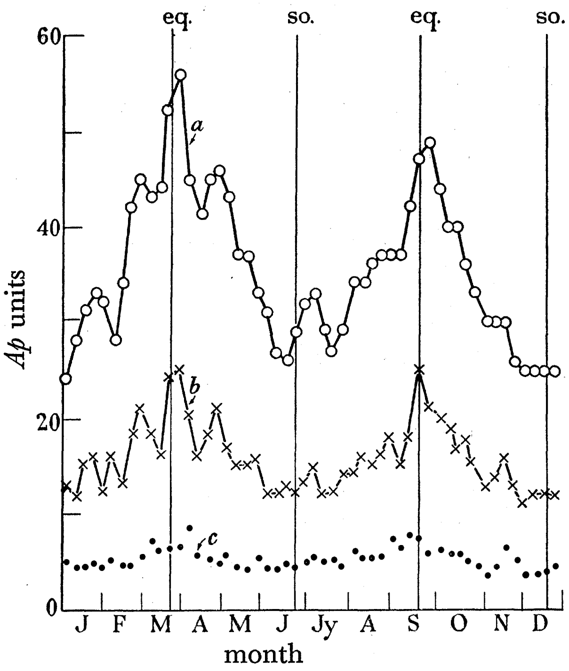

FIGURE 1

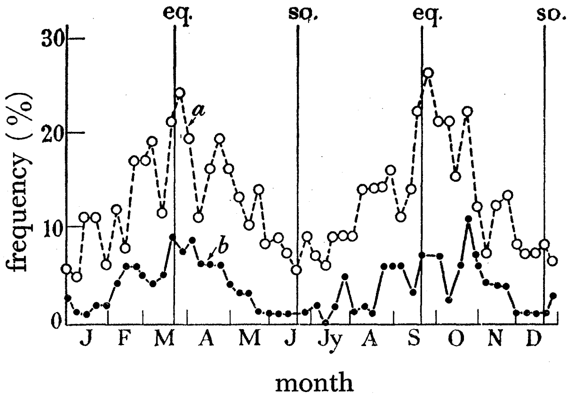

FIGURE 2

FIGURE 1. Annual variation of daily *Ap* index, 1937–56. *a*, weekly mean maximum; *b*, weekly mean; *c*, weekly mean minimum. Equinox (eq.) and solstice (so.) epochs are shown.

FIGURE 2. Annual variation of percentage frequency of occurrence of daily *Ap* index, 1937–56. *a*, $Ap \geqslant 30$; *b*, $Ap \geqslant 50$.

The eight curves of figures 1 to 3 show, with one exception, that magnetic disturbance is at a maximum, and quietness at a minimum, near the equinoxes. The failure of any marked annual variation to emerge at the lowest level of disturbance ($Ap \leqslant 3$) is caused almost certainly by the inability of the *K* (and thus also the *Ap*) index to operate efficiently at so low a level of disturbance—lower, in fact, on average than that of the selected monthly 'international quiet' days. Further comment is made later on this defect of the *K* index. The remaining frequency curves give good cause for the belief that if a magnetic disturbance index capable of discriminating at the lowest level of disturbance between solar particle and wave effects could be devised, such an index would reproduce the form of annual variation displayed by *Ap* at higher disturbance levels.

Importance is attached, in figures 2 and 3, to the fact that the excess of disturbances at the peaks as compared with the troughs, is, within the limits of casual error, the same at each of the three intermediate levels of disturbance, which jointly cover a wide range. The excess is smaller at the highest level ($Ap \geqslant 50$) because this level is higher than that in which zero frequency in the troughs has already been attained.

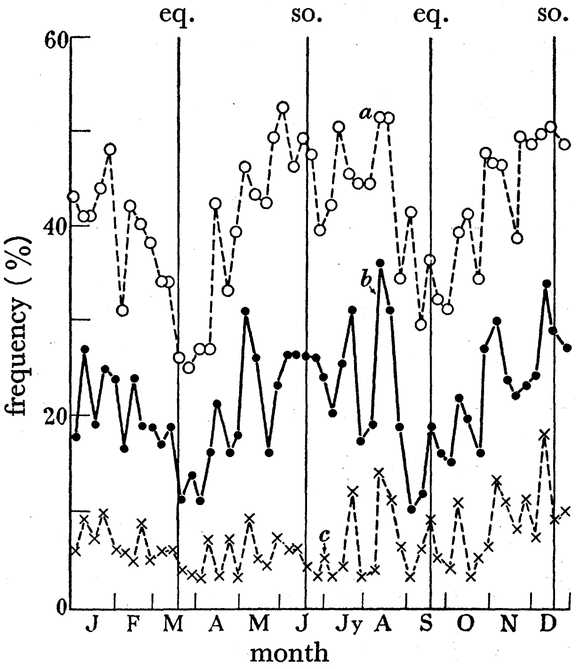

FIGURE 3. Annual variation of percentage frequency of occurrence of daily *Ap* index, 1937–56. *a*, $Ap \leqslant 8$; *b*, $Ap \leqslant 5$; *c*, $Ap \leqslant 3$.

The amplitude of the average *Ap* variation curve increases markedly with disturbance level. *Ap* is a linear measure which, when averaged, tends perhaps to give undue weight to the major storms. It is shown later that a similar, though less marked, feature of amplitude increase is shown by the *Kp* index, despite the logarithmic nature of the latter.

3·2. *Harmonic analysis*

The results of applying harmonic analysis (first two components) to the derived weekly *Ap* indices are shown in table 1.

In table 1 are shown the amplitudes (A) and phases (θ) in the Fourier series

$$A_0 + A_1 \sin(t+\theta_1) + A_2 \sin(2t+\theta_2),$$

obtained by analysis of daily values of *Ap*, arranged (according to various criteria) as fifty-two consecutive weekly values. θ is reckoned from midday on 4 January. A_1 and A_2 are the values corrected for smoothing. Dates of maxima or minima corresponding to θ_1, θ_2 are given. A' represents the size of the larger of n (in this instance, 2) evaluated harmonic components required for significance at the 5% level, computed from the relation $A' = 2\sqrt{(\ln 20n)}\,\sigma/\sqrt{N}$, where N is the effective number of independent values, with standard deviation σ, in the analyzed series.

Insignificant components (as judged by comparison with A') are bracketed in table 1. None of the first harmonics is significant. This fact merely confirms that the statistical procedure adopted to eliminate the effect of a preponderance of northern hemisphere observatories, among those participating in the Ap index, is effective; as previously stated, it does not of itself confirm that no significant first harmonic would be found in a true planetary index, if it were possible to evaluate such an index.

All the computed second harmonics are of statistically significant amplitude except that for the $Ap \leqslant 3$ series, at which very low level of disturbance the K index is unlikely to operate efficiently.

TABLE 1. HARMONIC ANALYSIS OF Ap INDICES, 1937–56

criterion applied to Ap	A_0	A'	A_1	θ_1	date of max.	A_2	θ_2	dates of max.	dates of min.
mean	16	1·8	(0·6)	(325°)	(11 May)	5·5	283°	28 Mar. 29 Sept.	—
mean max.	36	5·1	(4·1)	(305°)	(31 May)	9·5	289°	25 Mar. 26 Sept.	—
mean min.	5·3	0·6	(0·4)	(226°)	(9 July)	1·0	302°	18 Mar. 19 Sept.	—
% frequency $\geqslant$ 50	4	1·6	(0·3)	(338°)	(28 Apr.)	3·2	282°	28 Mar. 29 Sept.	—
% frequency $\geqslant$ 30	13	0·3	(3·0)	(141°)	(14 Nov.)	6·3	281°	29 Mar. 30 Sept.	—
% frequency $\leqslant$ 8	41	3·9	(2·6)	(291°)	(14 June)	7·4	110°	—	25 Mar. 26 Sept.
% frequency $\leqslant$ 5	22	3·3	(1·7)	(146°)	(9 Nov.)	5·8	113°	—	23 Mar. 24 Sept.
% frequency $\leqslant$ 3	7	1·6	(1·4)	(159°)	(26 Oct.)	(1·0)	(117°)	—	21 Mar. 22 Sept.

3·3. *Discussion*

The curves of figures 1 to 3 show clearly that, down at least to the lowest limit at which the K index is capable of measuring solar particle disturbance and probably beyond this limit, essentially the same form of annual variation exists throughout the whole spectrum of disturbance size. The disturbances which are 'missing' at times other than March and September, and most conspicuously missing near the solstices, are at the top end of the disturbance scale. It is inconceivable that big potential disturbances score misses on the earth preferentially near the solstices, while at the same time smaller disturbances show no such preference. These variation curves therefore rule out, as the cause of the annual variation of disturbance, a corresponding annual variation of probability of simple hit-or-miss of solar particle streams on the earth, in the way in which the axial hypothesis is usually stated.

There is, however, a further factor which may save the axial hypothesis. It is probable that the density of particles in a solar particle stream ejected within a solid angle is greatest near the central axis of the stream and least near the edges. If this should be so, and if, less probably, this particle distribution were to persist during the time of travel of particles from sun to earth, then the degree of directness of hit by the stream on the earth would enter as an important factor in storm intensity. Solar particle 'aiming' conditions may be such that direct or near-direct hits on the earth are most frequent in March and

September, with corresponding maximum frequency of great storms in these months; while, at the other end of the disturbance scale, partial hits may in March and September be scored on the earth under particle stream-width conditions which would result in 'misses' in June and December. Such an explanation would fit the characteristics of annual variation at different disturbance levels shown in figures 1 to 3. Since, however, it is not difficult to conceive of a true equinox-solstice effect which would also satisfy these characteristics, discrimination between the two main possibilities, axial or equinoxial, must be made on the basis of the dates of maxima and minima which emerge statistically.

The average dates of maximum disturbance computed from the various criteria are approximately 25 March, 26 September, i.e. a few days later than the equinoxes. It is difficult to assess the standard error of these average dates because the various criteria are highly interdependent, and also because there is no analytical expression for the standard error of a phase angle computed from a single Fourier series. Approximate experimental determination of the standard error in the first series of table 1 (mean Ap) yielded a value of about 6 days in that instance. The conclusion drawn from these results is that the dates of statistical maximum 'planetary' disturbance very probably lie between the equinoxes and 7 days later. There is no possibility that the large departures found from the dates required by the axial theory can be explained by sampling effects: on the contrary, if the true dates of maxima precede the equinoxes it can only be by a few days at most.

It may thus be concluded from the 'planetary' analysis that the dates of maxima are very probably the equinoxes themselves, and that the axial mechanism does not play even a subsidiary part in the disturbance mechanism.

4. Potsdam K variation

The longest available series of K indices is that for Potsdam and its auxiliary observatories, Seddin and Niemegk. Use was made of the individual daily sums of K for the period 1900–51, prepared for a previous investigation, in order to examine the characteristics of annual variation at that station.

4·1. *Graphical results*

Figure 4 illustrates the course of the Potsdam K annual variation, based on mean weekly values of daily sum, in a fourfold division of the 52 years according to sunspot epoch, as judged by the mean annual sunspot relative number:

(*a*) 14 sunspot minimum (N) years,
(*b*) 10 sunspot ascending (A) years,
(*c*) 15 sunspot maximum (X) years,
(*d*) 13 sunspot declining (D) years.

The curves illustrate the well-known solar cycle variation of disturbance and in particular the lag of magnetic disturbance in the sunspot cycle: maximum disturbance occurs not within the sunspot average X year but within the sunspot average D year, while a lag at the minimum end of the scale is also indicated. The four variation curves are each subject to a curvature effect, a smoothed representation of which (based on 12 month running means in order to eliminate annual variation) is shown in each case. When the

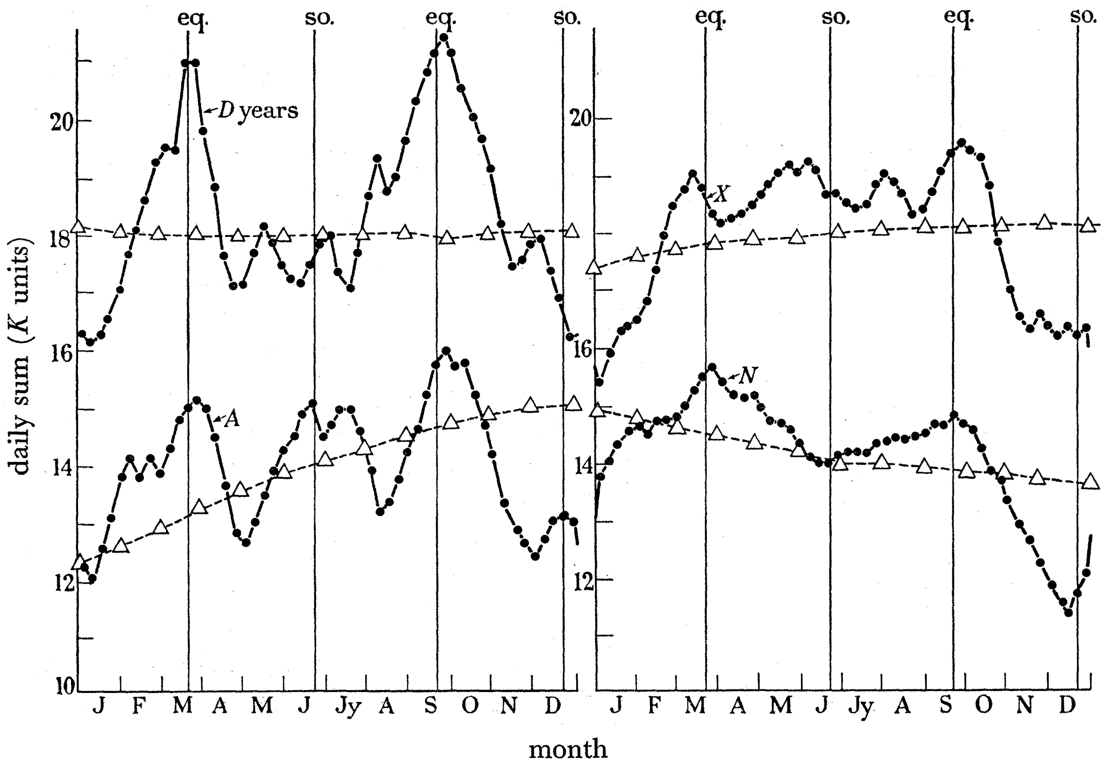

FIGURE 4. Annual variation of Potsdam daily *K* sums 1900–51, at each of four sunspot-cycle epochs. △– – –△ indicates non-cyclic change.

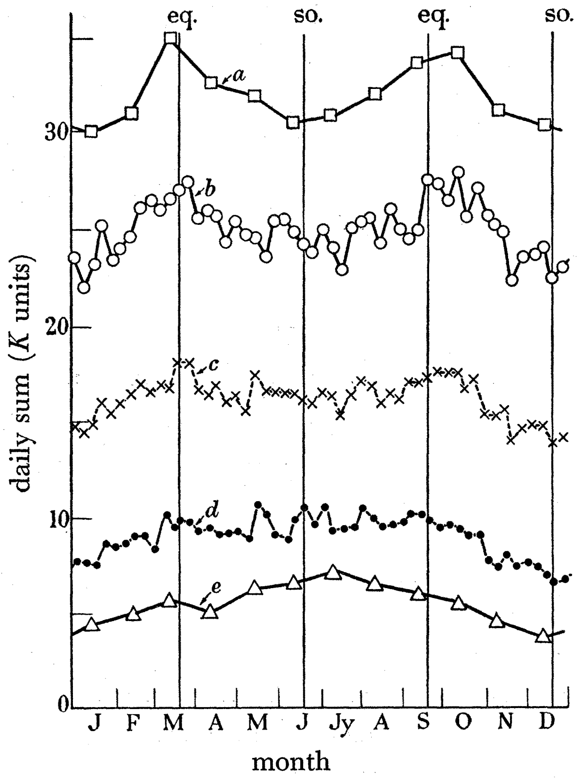

FIGURE 5. Annual variation of Potsdam daily *K* sums, 1900–51, expressed in weekly or monthly mean values. *a*, monthly mean maximum; *b*, weekly mean maximum; *c*, weekly mean; *d*, weekly mean minimum; *e*, monthly mean minimum.

individual curves are studied in relation to these average trends, a two-fold type of annual variation is strongly suggested: (*a*) primary maxima near the equinoxes, (*b*) a secondary maximum near the summer solstice and a minimum near the winter solstice.

The four variation curves of figure 4, corresponding to an over-all average level of daily K sum at Potsdam, are jointly represented in curve c of figure 5. The other four curves of figure 5 represent the type of variation obtained at higher- and lower-than-average levels of disturbance. It is strongly indicated that there is a progressive change in the form of the annual variation with rise in level of disturbance. At low disturbance levels the period of variation is 12 monthly, while at high levels it is 6 monthly: at intermediate levels both types of variation are seen.

4·2. *Harmonic analysis*

The indications of figure 5 are confirmed by the results of harmonic analysis applied to the five sets of Potsdam K index, as shown in table 2.

TABLE 2. HARMONIC ANALYSIS OF POTSDAM K INDICES, 1900–51

criterion applied to daily K sums	A_0	A'	A_1	θ_1	date of max.	A_2	θ_2	dates of max.	ratio A_1/A_2
monthly mean min.	5·4	1·1	2·0	276°	11 July	(0·3)	(29°)	14 Feb. 15 Aug.	6·7
weekly mean min.	8·9	0·5	1·1	279°	26 June	0·7	313°	13 Mar. 14 Sept.	1·6
weekly mean	16·2	0·5	0·7	287°	18 June	1·0	297°	20 Mar. 21 Sept.	0·7
weekly mean max.	24·9	0·7	(0·4)	(265°)	(10 July)	1·4	287°	26 Mar. 27 Sept.	0·3
monthly mean max.	31·9	1·6	(0·3)	(256°)	(1 Aug.)	2·0	304°	29 Mar. 30 Sept.	0·2

In table 2, θ is reckoned from midday on 4 January for weekly values and on 16 January for monthly values. Those components of computed amplitude less than A' are bracketed, as being statistically insignificant.

The first harmonic is the only significant component at the lowest level and the second harmonic at the highest two levels: at the remaining intermediate levels both components are significant. The ratio A_1/A_2 is seen to decrease rapidly with increase of disturbance. Where the analysis is based on 52 weekly values, the calculated dates of maximum of significant first and second components are close to the summer solstice and the equinoxes, respectively. The poorer calculated agreement with these dates at the lowest and highest disturbance levels is readily accounted for by the relatively poor phase resolution obtained by analysis of 12 monthly values.

4·3. *K index frequency*

(*a*) *General*

Further evidence of the nature of the twofold form of annual variation of Potsdam K index deduced above is here presented in the form of a comparison of K index frequency in the two solstice months. A single solar cycle 1926–36 (selected at random) is long enough to reveal the essential features.

The simple frequency distribution contained in table 3 shows that the difference between the Potsdam December and June K index activity, previously deduced from mean values, is to a close approximation accounted for by a deficit of indices 0 and 1 and an equal excess of 2 and 3 in June relative to December.

If the frequency distribution of table 3 is examined on the assumption that the June-December effect, whatever its cause, is unlikely to effect a change of K by more than one unit (i.e. 0 to 1, 1 to 2, etc.), the results shown in table 4 are obtained.

Table 3. Total frequency of Potsdam K indices 1926–36 in December (first 30 days) and June

K index	0	1	2	3	4	5	6	7	8	9
Dec.	309	858	704	430	238	90	9	2	0	0
June	132	737	861	551	275	70	12	2	0	0
Dec. minus June	+177	+121	−157	−121	−37	+20	−3	0	0	0

Table 4. Percentage frequency of change by 1 unit of Potsdam K index from December to June ‘standards’ 1926–36

K index change	0 to 1	1 to 2	2 to 3	3 to 4	4 to 5	5 to 6	6 to 7
% frequency of change	+57	+29	+14	+3	−7	+4	0

In table 4 a positive sign indicates an excess of December changes in upwards sense (e.g. 1 to 2), a negative sign an excess of June changes in upwards sense (e.g. 4 to 5).

Examination of the approximate standard errors involved in table 4 shows that the values at levels of change 3 to 4 and higher are probably no greater than may be accounted for by sample fluctuations from zero. In contrast, the changes at lower K levels are highly significant.

It may thus be concluded that, to a high degree of approximation, the June-December effect in Potsdam K index operates in one sense only and up to the level of effecting changes from 2 to 3: 57 % of the K values ranked 0 in December are ranked 1 in June, 29 % of December index 1 are ranked 2 in June, and 14 % of December index 2 are ranked 3 in June.

(*b*) *Diurnal variation*

The question naturally arises whether the annual component of Potsdam K evident at low disturbance levels is physically real or is a spurious effect arising from contamination of K by the ‘solar quiet day’ (S_q) magnetic variation. An answer to this question is here sought by a consideration of the diurnal variation of frequency of Potsdam K index 0 and 1 in June relative to December.

The range, in force units, of the most disturbed of the three elements H, D, V in each 3 h period determines the corresponding values of K: in general it is found that D makes a minor and V an insignificant frequency contribution to such maximum range values. In the measurement of the 3 h ranges the S_q variation is (largely) eliminated by using as a reference line the appropriate average seasonal and sunspot-epoch S_q curve for each element. A purely objective procedure of scaling the K index would necessarily fail to eliminate S_q entirely, because of the presence of marked day-to-day variations of S_q intensity. Instructions on the scaling procedure therefore stress the importance of recognizing and allowing for such variations: success in carrying out this procedure is, however, unlikely to be complete.

Chapman & Stagg (1929, 1931) have shown that the day-to-day variability of S_q involves the range but not the form of the variation, and also that the range variability is about the same in each of the magnetic elements. It follows that the average form of the S_q variation, or more particularly of the time rate of change of the magnetic elements H and D (ignoring element V which is unimportant in K scaling) will indicate those local times of the day in which the danger of K contamination by S_q is greatest.

As a measure of the seasonal and diurnal variability of 'contamination risk', the S_q composite range curves (γ per 3 h) for winter and for summer at a typical mid-latitude station (Eskdalemuir)are shown in figure 6(*a*): the larger range ΔH or ΔD (equivalent force units), in each 3 h period 0 to 3, 3 to 6 h, etc., was that selected for contribution to the composite curves. These curves have a pronounced diurnal variation with maximum somewhat before midday. If the actual occurrence of the low Potsdam K index values is heavily contaminated with S_q, such contamination would be expected to be most marked around midday in summer. In particular, subtraction of the June and December composite curves would accord closely with the 'December minus June' diurnal variation of combined frequency of K index 0 and 1. Such a comparison is shown in figure 6(*b*), the 'contamination risk' (S_q) curve being shown necessarily on an arbitrary vertical scale.

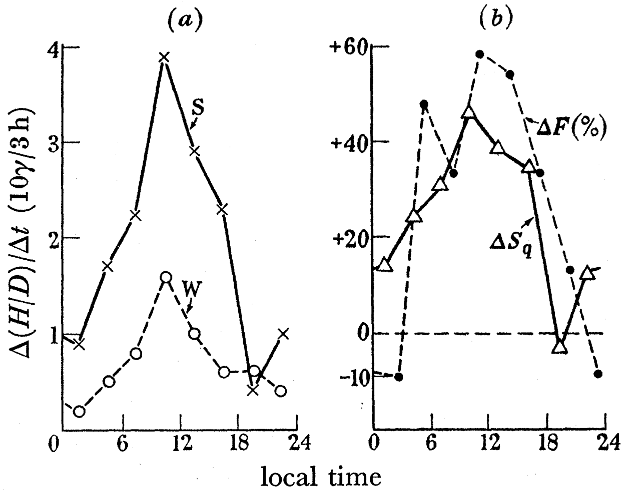

FIGURE 6. (*a*) Combined 'maximum' time rate of change of magnetic elements H and D at Eskdalemuir on international 'quiet' days, in winter and summer. (*b*) Comparison of diurnal variation form of actual 'December minus June' percentage frequency of occurrence of Potsdam K indices 0 and 1, ΔF, with the 'contamination risk' curve ΔS_q (arbitrary vertical scale) deducted from figure 6(*a*).

The general similarity between the two curves of figure 1 (*b*) implies a strong possibility that S_q contamination plays an important part in the annual component of Potsdam K index. Since, however, a physically real summer maximum of disturbance, implying as it does a strong solar zenith angle dependence, would very probably be accompanied by a midday maximum and midnight minimum of such disturbance, the contamination hypothesis can hardly be held proved. A clearer answer to the question is sought later by intercomparison of various observatories.

5. K VARIATION AT WIDELY DISTRIBUTED OBSERVATORIES

Investigation of the annual variation of the K disturbance index is here pursued at selected observatories extending over as wide a range of latitude as possible. Discrimination is again made between the conditions obtaining at various disturbance levels.

5·1. *Equatorward of auroral zone*

The Kp daily sum, with which daily K sums at individual observatories correlate very highly, was used to distinguish five distinct levels of activity. In each of the four equinox-solstice months, March, June, September, December, of the 11 year period 1945–55 a selection, based on Kp daily sum, was made of 10 days in each of the five disturbance classes: minimum, lower quartile, median, upper quartile, maximum, denoted classes I to V, respectively. Thus, for example, of the $11 \times 30 = 330$ days available for June, the 10 'upper quartile' group (IV) days selected were such that 80 days were of greater Kp sum and three times as many, i.e. 240 days, were of smaller Kp sum. Equality of numbers in each month was obtained by omitting 31 March and 31 December.

In each of the $5 \times 4 = 20$ groups of 10 days thus selected, mean daily K sums were computed at eleven observatories ranging very widely in both latitude and longitude. The results for each station are shown graphically in figure 7 in the form of departures (ΔK) from the mean daily March and September K sum for the corresponding station and level of activity: this method of display was chosen because it shows the result for each month in relation to those for the remaining months while omitting the actual K levels, which are of no intrinsic interest. Finally, in figure 7, the average results for the seven northern hemisphere and four southern hemisphere stations are separately shown for each level of disturbance.

The following conclusions are drawn from figure 7.

(*a*) The main feature is that maximum disturbance occurs at all stations at the equinoxes relative to the solstices, from level II or III upwards. This semi-annual component increases markedly in terms of K index from levels I to V and therefore, in view of the logarithmic nature of K, increases to a still greater extent in absolute force units.

(*b*) There is no marked latitudinal variation of amplitude of the semi-annual component of K. Since the K scale contracts from high to low latitudes, a latitudinal variation of amplitude of the semi-annual component, in force units, very similar to that of the disturbance phenomenon itself is implied.

(*c*) An annual component of opposite sign in the two hemispheres, i.e. a summer–winter effect, is apparent at nearly every station and disturbance level up to IV. The effect is less certain at level *V* though it still emerges in the mean hemispherical curves. The K amplitude of the component changes little up to level IV, implying some increase in terms of force units with increase in disturbance level. Increase in amplitude of this component with increase in latitude may also be observed in accordance with expectations of such a seasonal component.

(*d*) Appreciable admixture of S_q in the K values can be ruled out, except perhaps at level I where intercomparison of the various results suggests that part at least of the annual component is spurious and is such as would be expected to be produced by S_q contamination. There is, however, no possibility that the presence of S_q or, at higher disturbance levels, of S_D (disturbance daily variation) can account for the demonstrated magnitudes of the annual component.

The results of figure 7 are supported and amplified by results obtained by quite a different approach, as follows.

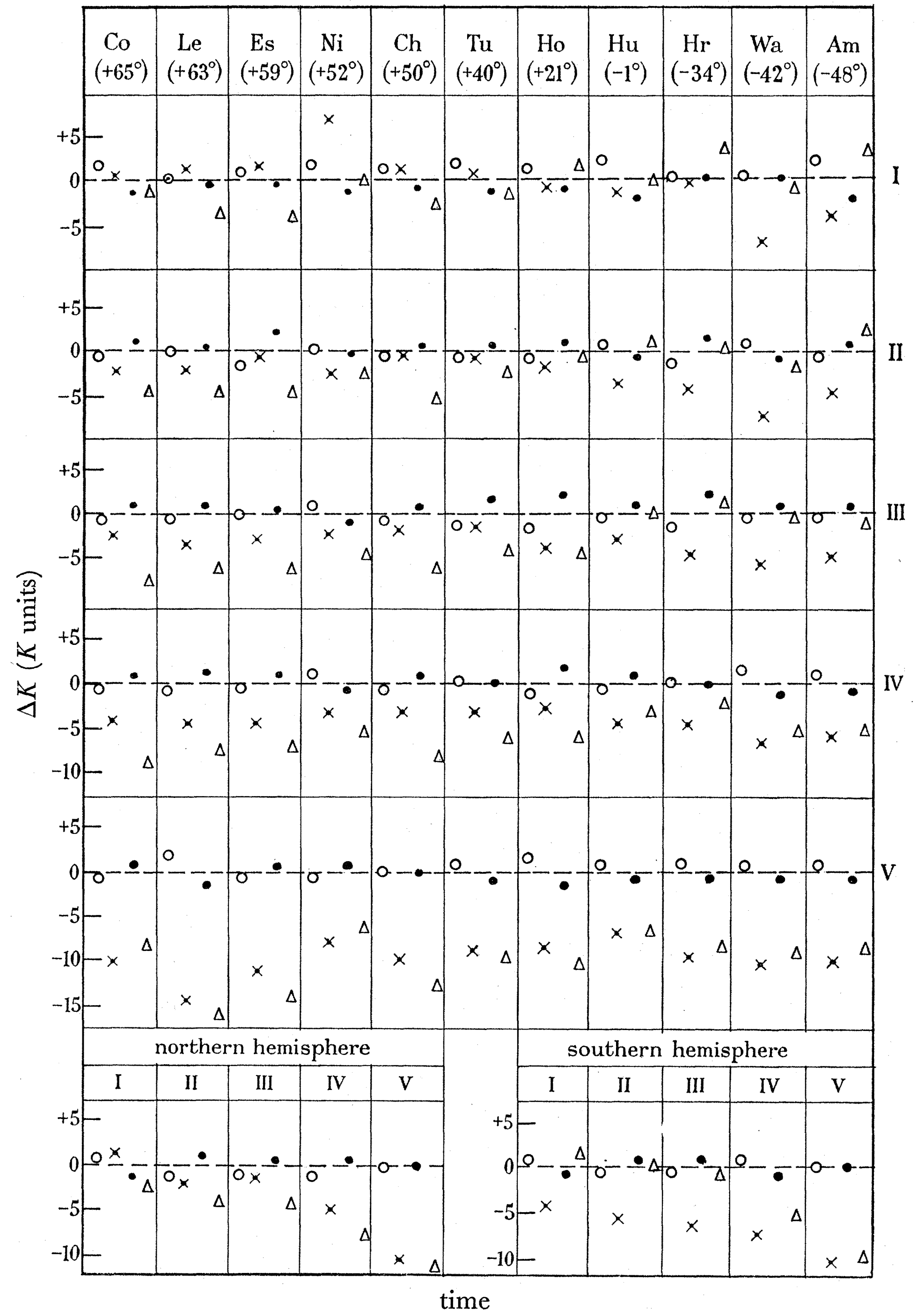

FIGURE 7. Relative values of mean daily K sums in March (○), June (×), September (●), December (△), 1945–55 at each of 11 observatories and five levels of disturbance. Mean hemispherical values are also shown. The selected observatories are indicated by the accepted two-letter abbreviation and the geomagnetic latitude (+ and – for northern and southern hemispheres, respectively). See, for example, *I A G A Bulletins*, K series.

Use was made of the known statistical maxima of *Kp* in order to reduce the amount of labour required to reach reliable conclusions. Such equinoxial maxima may not emerge too clearly in individual years, or even in the average of a few years. Individual *K* values are subject to the same 'casual' influences which are, however, effectively removed by considering the annual variation of the ratio *K*:*Kp*.

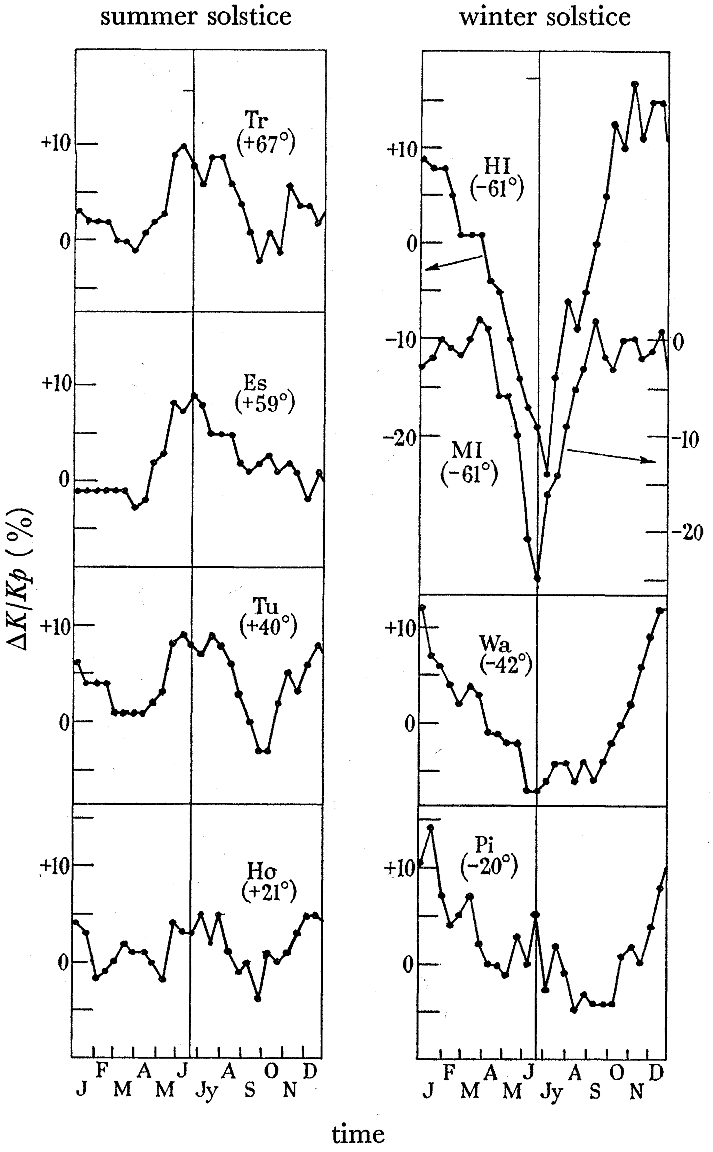

FIGURE 8. Annual variation of average percentage ratio $\Delta K/Kp$ at selected stations in either hemisphere. Plotted values refer to alternate calendar weeks.

Attention was diverted from low disturbance by selecting in each calendar week (extra days being rounded off as previously described) the day of maximum *Kp* sum, and expressing the corresponding daily *K* sum at each selected station as a percentage ratio of *Kp*. This procedure was continued year by year until it became apparent, from the degree of agreement found for *K*:*Kp* for corresponding weeks in different years, that a reliable mean annual variation of the ratio had been obtained. A period of 6 years (1949–54) was found sufficient to achieve this: only 2 years' data were available for the high latitude southern hemisphere stations Heard Island (−61°) and Maquarie Island (−61°), but the amplitudes of annual variation of the ratio found in these two cases were so large that there is no doubt as to their reality. The selected stations, four in each hemisphere and selected so as to accord reasonably in geomagnetic latitude, range from 67° north to 61° south. For each station the mean annual variation of $K:Kp$ was obtained as 52 weekly percentage ratios, each the mean of six values (apart from Heard and Maquarie Islands). The values are shown in figure 8, arbitrarily plotted as departures (Δ) from the average percentage ratio for the 5-week periods centred on each equinox.

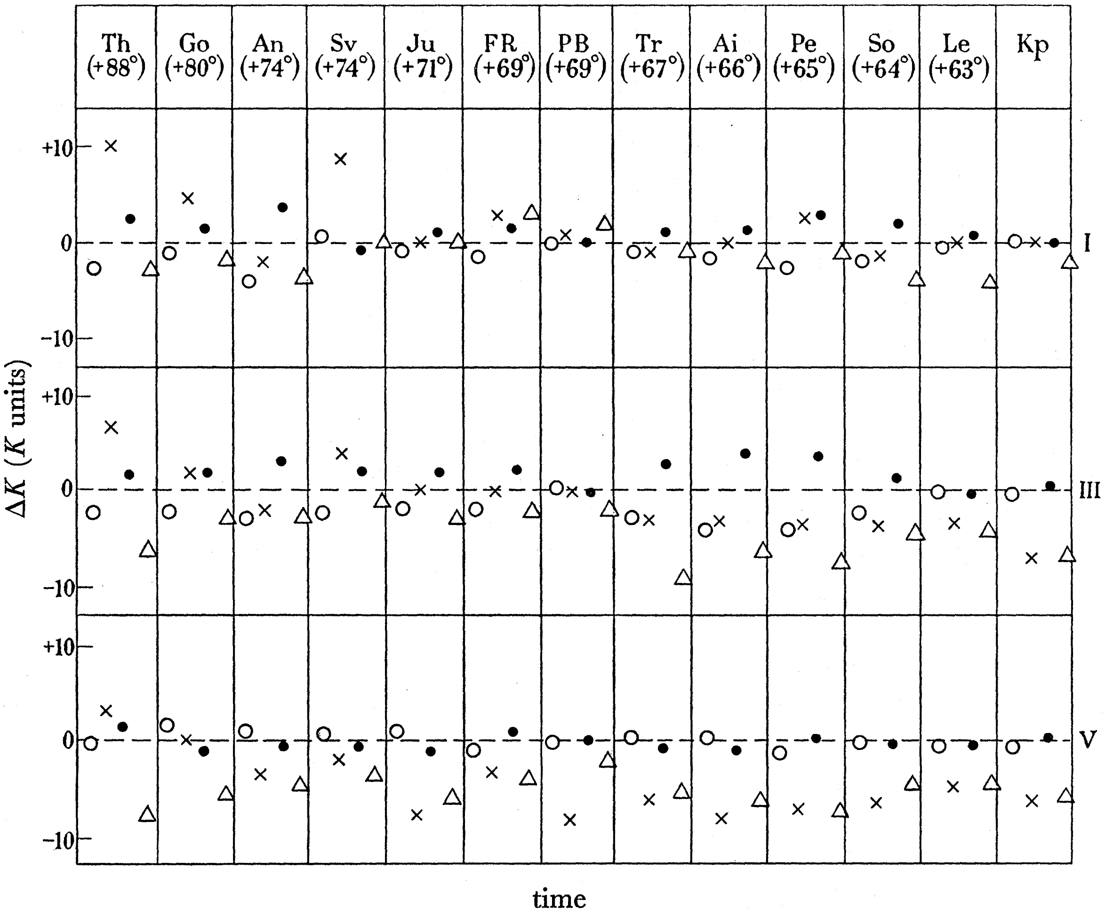

FIGURE 9. Relative values of mean daily K sums in March ○, June, ×, September ●, December △, 1932–33 at each of 12 polar observatories and three levels of disturbance. The corresponding Kp values are also shown.

Each of the plotted curves departs significantly from a straight line, indicating marked regional variations in the form of the annual variation relative to the simple equinoxial maxima of Kp. The presence of an annual component centred on or near the solstices is the most interesting feature revealed. The amplitude of the winter–summer component increases with latitude and in a given latitude appears to be appreciably bigger in the southern than in the northern hemisphere. The results apply to a level of disturbance corresponding to about level IV (though less homogeneous than level IV) and can be little influenced by either S_q or S_D.

5·2. *Poleward of auroral zone*

The main *K* data available for discussion in this zone is that for the Second Polar Year (1932–33), all of it for the north polar regions. The known complexity of events within and poleward of the auroral zone makes it unlikely that such data are adequate for full discussion of the annual variation there. An attempt is, however, made to determine the main features of the variation, using a modification of the first of the two methods employed for the equatorward region.

In each of the 4 months September and December (1932), March and June (1933), four minimum, median and maximum (levels I, III, V) days were identified on the basis of daily *Kp* sums. Average *K* sums were computed in each of these twelve groups of 4 days at each of the stations situated from Lerwick polewards. In so short a period there is a risk of serious 'curvature', 'end' and sample effects. The corresponding mean *Kp* values, shown in figure 9 with the plotted ΔK values for the twelve stations, suggest, however, that in this particular case the influence of such effects is probably not serious.

Two distinct effects may be discerned in the plotted data of figure 9.

(*a*) A semi-annual component with March and September maxima, so small as to be of doubtful reality at level I, but growing in importance at all stations as disturbance increases and becoming by far the main feature at disturbance level V, except at the two stations nearest the pole.

(*b*) An annual component with June maximum, largest near the pole, where it is at all levels the main feature. This component is visible at most of the other nine stations in the quietest conditions and at all of them on average days: it is, however, of doubtful reality on the most disturbed days when some large differences in behaviour appear at stations differing little in latitude.

6. UNIVERSAL TIME AND SEMI-ANNUAL COMPONENTS OF DISTURBANCE

In the statistical experiment designed to identify a possible u.t. diurnal component in disturbance (Lewis & McIntosh 1953), consideration was given to the diurnal and seasonal features of variation of each of three angles in the sun-earth system. These angles, considered to be possible parameters in the disturbance phenomenon, were those between the earth's magnetic axis and

(i) the plane of the ecliptic (ϕ_1),
(ii) the plane of the sun's equator (ϕ_2),
(iii) the line joining sun and earth (ϕ_3).

The u.t. component revealed in the investigation was interpreted as depending mainly on ϕ_3 but probably also, to a much smaller degree, on ϕ_1 or ϕ_2.

Since the directions of the earth's rotational axis and of the planes of the ecliptic and solar equator are all fixed in space, ϕ_1 and ϕ_2 vary diurnally between limits which remain constant throughout the year. Variations of these two angles cannot therefore contribute to the annual variation of disturbance. The situation, is however, different with respect to ϕ_3 which undergoes important seasonal changes, as shown in figure 10. At the equinoxes ϕ_3 has a mean daily value closest to 90°, attaining this value of 90° at 'geomagnetic sunrise' and 'geomagnetic sunset' and varying diurnally with a departure ($\Delta\phi_3$) from 90° which averages about 6° over the day and reaches a maximum value of 11° at 'geomagnetic midnight' and 'geomagnetic noon'. At the solstices ϕ_3 has a maximum average daily departure from 90°, this average departure being 23°, with daily extreme values of 12 and 34°.

If the u.t. component is genuine and its interpretation mainly in terms of ϕ_3 correct, a semi-annual component of disturbance is implied by the semi-annual variation of ϕ_3. Whether interpretation in terms of ϕ_3 is in fact a satisfactory explanation of the actual semi-annual component of disturbance will then depend on the degree of similarity between the phases and magnitudes of the u.t. and semi-annual components. Comparison of relative magnitude is best achieved by selection of data on a basis other than that employed in the previous u.t. investigation. A reassessment is therefore first made of the u.t. component and the opportunity taken to examine whether its amplitude varies with level of disturbance in a manner similar to that of the semi-annual component.

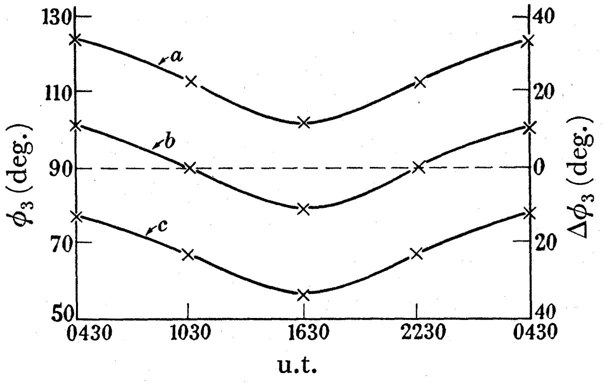

FIGURE 10. Daily variation of the angle ϕ_3 (or $\Delta\phi_3$). *a*, December; *b*, equinoxes; *c*, June.

6·1. *Data*

Seven northern and five southern hemisphere observatories with available *K* data for 1950–55 were selected such that they were well distributed in latitude and longitude ($\Sigma \sin \lambda = 0$, λ being geomagnetic longitude). Attention was confined to periods lying within about 1 week of equinox or solstice (16 to 30 June and September, 16 to 31 March and December). All such 'solstice days' of daily *Kp* sum greater than 20 in 1950–55 were selected and in each calendar year an equal number of the most disturbed 'equinox days', as judged by the daily *Kp* sum.

For comparison of results at two distinct disturbance levels the above material was divided into two sections:

(*a*) all days of *Kp* sum not less than 30 from the selected solstice days (actually 10 such days in each of the June and December periods) and the same total number of days of highest daily *Kp* sum from the selected equinox days (8 in March, 12 in September);

(*b*) the remaining days from the original selection (21 in June, 19 in December, 20 in March, 20 in September).

On the basis of the results obtained with the above data, a further selection of material at six of the twelve stations and at a still higher level of disturbance was made in the period 1940–49, in a manner to be described later in more detail.

6·2. *Procedure*

(*a*) *u.t. variation*

In each of the four groups of days the diurnal variation of K, arranged according to u.t., was averaged for each of the twelve observatories over all the selected days (about 30 in each group) and the mean K variation was also calculated in each group. In addition, similar calculations were made at the two separate disturbance levels (a) and (b).

The attempted elimination of the predominant local time (l.t.) component in the daily variation of disturbance by the combination in u.t. of stations of carefully selected longitudes is inevitably less than perfect. No direct method is therefore available of revealing a u.t. component which is uncontaminated by l.t. effects. The main method of attack was, therefore, as in the previous u.t. paper, to subtract daily variations arranged in u.t., averaged in longitude and separated by 6 months. This device has the advantage of permitting of ready interpretation of the results in terms of the possible operative angles ϕ_1, ϕ_2, ϕ_3 and of eliminating any residual l.t. variation on the assumption that such a variation has the same form in the two periods, separated by 6 months, which are subtracted. Such an assumption appears very reasonable for the two equinoxial periods but perhaps less so for the two solstice periods. In the event, as will be shown, the amplitude of the u.t. component increases so rapidly with disturbance level that a residual l.t. effect in the 'remainder' is of very minor importance at high levels of disturbance, even when solstice months are subtracted.

A difficulty with the 6 months subtraction process is that, when applied at the equinoxes, it effectively eliminates any ϕ_3 component (in addition to any l.t. effect) since such a component would have identical phases at the two equinoxes. On the other hand, addition of these variations leaves the u.t. component masked by a l.t. effect which is then far from negligible. Since the subtraction process applied at the solstices strongly suggested a ϕ_3 component of disturbance, an attempt was made to measure the ϕ_3 component at the equinoxes by estimating and allowing for residual l.t. effects in the average variations added for the two equinoxial months.

In final assessment of the ϕ_3 u.t. component amplitudes, allowance was required for the fact that subtraction of out-of-phase components, or addition of in-phase components, effectively doubles the true amplitude.

(*b*) *Semi-annual variation*

For comparison with the amplitudes of the u.t. component attributed to ϕ_3 in the various groups of stations and levels of disturbance, corresponding measures of the equinox-solstice disturbance variation were obtained by subtracting the average daily K sums for the two periods. The method of selection of data—the same total number of equinox and solstice days at the top end of the disturbance scale— implies that such subtraction yields a reasonable measure of the amplitude of the semi-annual component.

6·3. *Results*

(*a*) ϕ_1 *or* ϕ_2 *dependence of u.t. component*

A u.t. component depending on ϕ_1 or ϕ_2 would be expected to produce in the equinoxial difference curve 'March minus September' a first harmonic with maximum occurring at either geomagnetic sunrise or sunset, i.e. at 10.30 or 22.30 u.t. Any such component would not be admixed, in the equinox difference curve, with a component depending on ϕ_3.

The average March, September and 'March minus September' K daily variation curves, arranged in u.t., for all selected stations and days are shown in figure 11. It is apparent that, in terms of the standard errors involved, no significant variation, either of the phase required by a ϕ_1 or ϕ_2 effect, or of any other phase, emerges in the data used. Subdivision of the equinox data into disturbance levels (*a*) and (*b*) gave a negative result (not reproduced graphically) in either case.

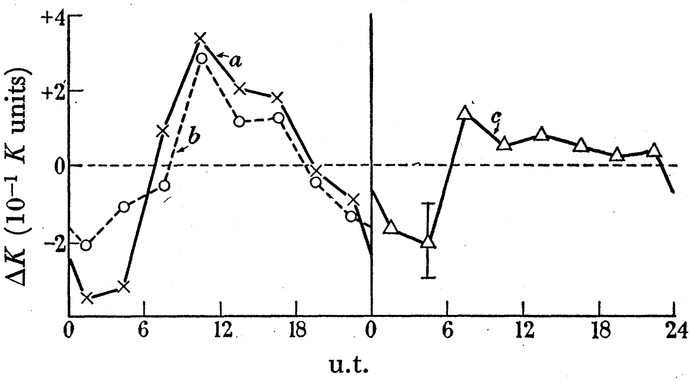

FIGURE 11. Average daily variation (u.t.) of K index at twelve observatories on selected days of Kp sum >20, 1950–55. *a*, March; *b*, September; *c*, 'March minus September'.

In the previous u.t. investigation (Lewis & McIntosh 1953) in which the same procedure was used with other data, a different result was obtained in that a component of small but probably significant amplitude and with about the 'correct' phase angle then emerged. Reservations were, however, then made about the reality of the component. It now appears that magnetic disturbance dependence on the angles ϕ_1, or ϕ_2 is very doubtful and, if it exists at all, very small. No appreciable error will therefore result from neglect of this component. As is explained later, the matter is of some significance in the problem of the annual variation, despite the fact that ϕ_1 or ϕ_2 variations play no direct part in the latter.

(*b*) ϕ_3 *dependence of u.t. component*

(i) *Solstices.* The average K daily variations for June, December and 'June minus December' for all selected days and observatories are shown in figure 12. The difference variation is statistically significant and the times of maximum and minimum are in close agreement with those previously obtained with very largely independent data. Comparison with figure 10 suggests very strongly that magnetic disturbance is at a maximum when ϕ_3 is closest to 90° and at a minimum when ϕ_3 is furthest removed from 90°.

The composite result of figure 12 is shown separately in figure 13 for the two levels of disturbance (*a*) and (*b*), for individual and for averaged observatories. At the lower level (*a*) the difference variation does not show at all reliably a morning maximum and afternoon minimum at individual observatories but the average curve is of this type. At the higher level (*b*) the u.t. difference variation for each station is very markedly close to the average form. Two facts may be inferred: first, the 'June minus December' result does not arise from S_q contamination of K; secondly, the amplitude of the disturbance component measured by the 'June minus December' method increases with the disturbance level.

Time of June maximum and corresponding amplitude of inferred ϕ_3 diurnal component, computed by harmonic analysis, are shown on a harmonic dial in figure 14 (*a*) for each of the twelve stations at disturbance level (*b*). The phase resolution obtainable by analysis of only eight daily K values is small. At six of the original twelve stations showing a wide scatter of computed time of maximum in figure 14 (*a*), the 'June minus December' calculation was therefore repeated for fresh selected data (1940–49) at a still higher level of disturbance (*c*), namely, all days of Kp sum not less than 35. The corresponding harmonically analysed results are shown in figure 14 (*b*).

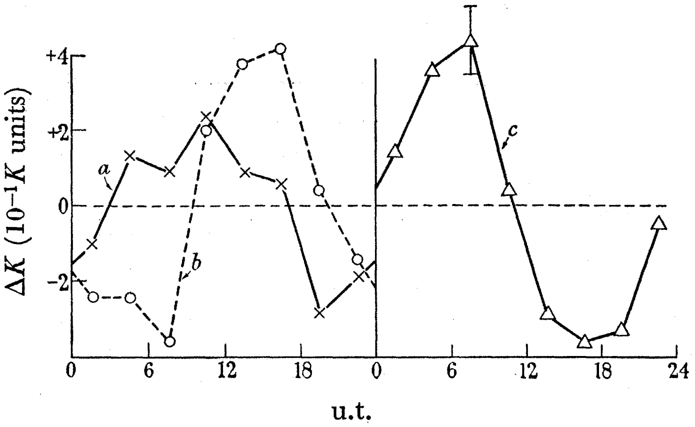

FIGURE 12. Average daily variation (u.t.) of K index at twelve observatories on selected days of Kp sum > 20, 1950–55. *a*, June; *b*, December; *c*, 'June minus December'.

Any real ϕ_1 or ϕ_2 diurnal component would be expected to contribute with unchanged amplitude but changed phase, to a 6 months' difference K variation computed for various times of the year. In the 'June minus December' difference variation a ϕ_1 or ϕ_2 contribution would be exactly in-phase or out-of-phase with the ϕ_3 contribution. Since, however, the equinox difference curve did not support the existence of a ϕ_1 or ϕ_2 component, no correction for such a component was applied in the harmonic analysis of the solstice difference variations which were therefore attributed entirely to ϕ_3.

(ii) *Equinoxes.* For all the originally selected days and observatories the average daily K variations are shown in figure 15, corresponding to 'June plus December' (*a*), 'March plus September' (*b*), 'March plus September' minus 'June plus December' (*c*). Finally, for comparison with curve *c*, the curve *d* of the diurnal variation of $\Delta\phi_3$ at the equinoxes is shown.

The interpretation placed on the 'June plus December' curve *a* is that it represents entirely a residual l.t. effect, since any u.t. contributions made by ϕ_1, ϕ_2, ϕ_3 are exactly out-of-phase at the two solstices and thus disappear on addition of the two solstice variations. The case is, however, different at the two equinoxes when contributions from a u.t. component dependent on ϕ_3 are exactly in phase: possible ϕ_1 or ϕ_2 components, on the other hand, remain out of phase and disappear on addition. The equinox variation curve *b* may therefore be an admixture of a residual l.t. effect and a ϕ_3 component in u.t.

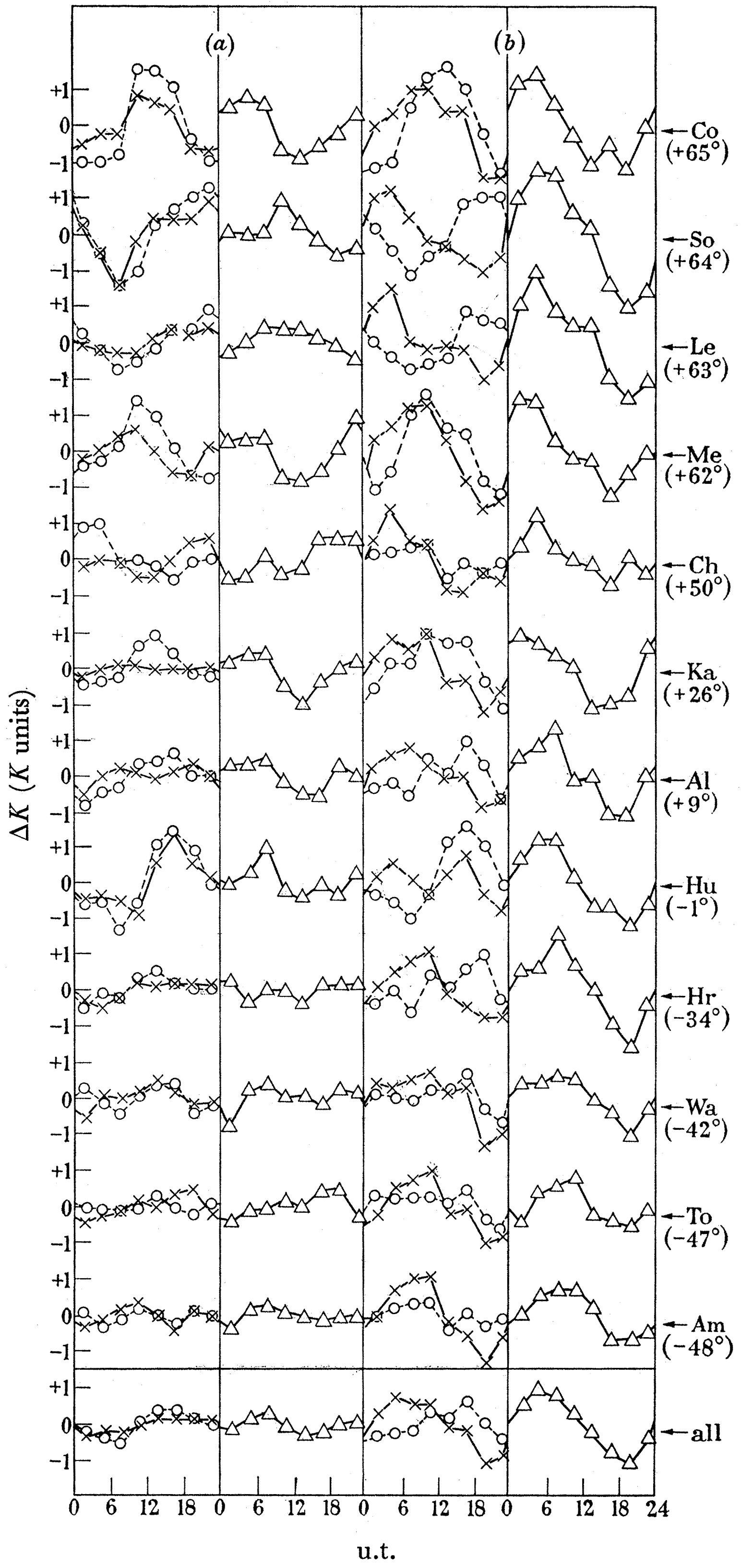

FIGURE 13. Average June, December, 'June minus December' daily variation (u.t.) of K index at each of twelve observatories on selected days (1950–55) corresponding to disturbance levels (a) and (b); also mean daily variation for all the observatories. ×—×, June; ○---○, December △—△, 'June minus December'.

variation. Reasonable approximation may be made to the mean equinox residual l.t. effect in curve *b* by assuming it to be the same as that found at the solstices (curve *a*). Curve *c*, obtained by subtraction of *a* from *b*, should thus correspond to a measure of the ϕ_3 component of disturbance at the equinoxes.

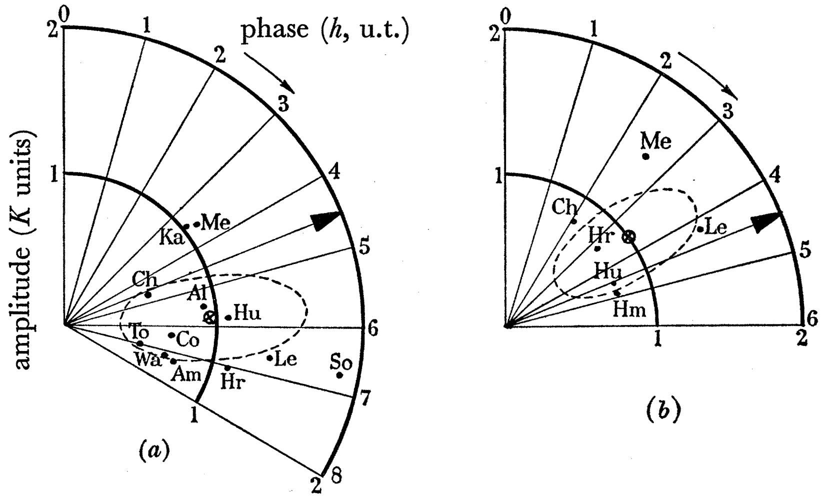

Figure 14. Harmonic dials showing amplitudes and times of summer solstice maximum of inferred ϕ_3 diurnal components of disturbance. Dial (*a*) refers to twelve stations at disturbance level (*b*), dial (*b*) to six stations at disturbance level (*c*). The probable error ellipse of the average component is shown in each case.

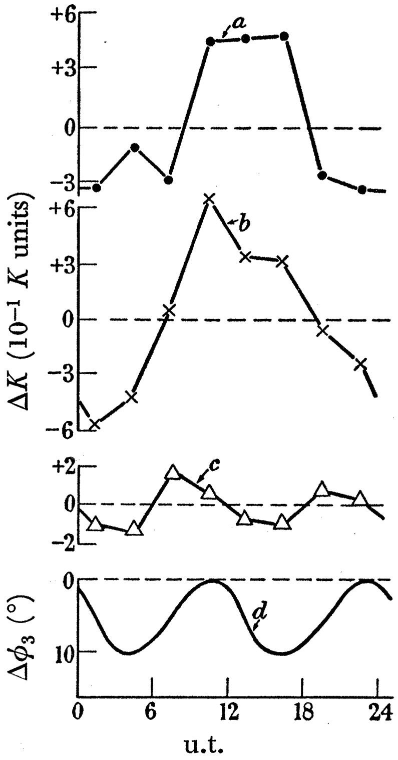

Figure 15. Average daily variation (u.t.) of *K* index at twelve observatories on selected days of *Kp* sum > 20, 1950–55 *a*, 'June plus December'; *b*, 'March plus September', *c*, 'March plus September' minus 'June plus December'. Curve *d* shows daily variation (u.t.) of angle $\Delta\phi_3$ at equinoxes.

Curve *c* of figure 15, consisting as it does of a reasonable approximation to a *semi*-diurnal wave with maxima near geomagnetic sunrise and sunset (10.30 and 22.30 u.t.) and minima near geomagnetic noon and midnight (16.30 and 04.30 u.t.) is of the form required of a ϕ_3 component: curve *d* shows that ϕ_3 is 90° near the times of daily maxima, and is furthest removed from 90° near the times of daily minima, of equinoxial disturbance. Corroboration is thus obtained of the existence of a ϕ_3 dependence in disturbance, together with a measure of the daily range of this disturbance variation—necessarily rougher than is obtained by the more direct solstice approach—corresponding to a daily departure from 90° of ϕ_3 ranging from 0° to 11°.

(*c*) *Range of semi-annual variation*

Strictly comparable results for the three distinct disturbance levels (*a*), (*b*), (*c*) were obtained by confining attention to the six stations shown in figure 14(*b*).

The mean value of the *K* sums for the six stations in each of the equinox and solstice periods, and the difference between these means (i.e. the range of the semi-annual variation), was calculated at each disturbance level. The means and difference, with computed probable errors, are shown in table 5, together with corresponding measures (mean daily *K* sums) of the daily range in u.t. disturbance attributed in the solstice-difference method to ϕ_3: the u.t. amplitude found at each level by harmonic analysis refers to a single *K* index and was increased by a factor of 8 in order to represent the magnitude of the effect in mean daily *K* sums; the factor of 2 required for conversion of harmonic amplitude to range and the same factor involved in subtracting out-of-phase components (June and December) cancel out.

TABLE 5. COMPARISON OF SEMI-ANNUAL AND U.T. (ϕ_3) DISTURBANCE COMPONENTS

disturbance level	mean daily *K* sums (*K* units) equinox	solstice	difference	equivalent mean daily range (*K* sums) of ϕ_3 component in u.t. disturbance (*K* units)
(*a*)	22·6	21·4	1·2 ± 0·4	1·5
(*b*)	35·7	30·3	5·4 ± 1·5	7·8
(*c*)	48·2	34·6	13·6 ± 2·4	8·6

6·4. *Discussion*

The investigation of the u.t. disturbance component described above has confirmed its reality and has demonstrated that, when the disturbance level is high, the u.t. component may be clearly recognized even at individual stations.

The computed time of June maximum—December minimum of daily disturbance is, in each of two independent samples, 04.30 u.t. (within the limits of the probable error ellipse; figure 14): the mean time from the combined samples is, in fact, within a few minutes of 04.30 u.t. This implies that daily disturbance is at a maximum when ϕ_3 is closest to 90°. Corroboration is given by the semi-diurnal nature of the daily disturbance component at the equinoxes.

The verified existence of a ϕ_3 component in daily disturbance necessitates the existence of systematic disturbance effects, on a different time scale, associated with ϕ_3 annual variation. Since ϕ_3 has a daily mean value closest to 90° at the equinoxes and furthest removed from 90° at the solstices, it is apparent that the phase of the ϕ_3 component identified in daily disturbance is precisely that required in order that this same component should be capable of explaining entirely the semi-annual wave of disturbance.

Apart from inevitable sampling uncertainties, identical amplitudes of the semi-annual component and the ϕ_3 component determined at the solstices are not to be expected, since they correspond to different ϕ_3 ranges about different mean values. Thus the daily variation of ϕ_3 at the solstices is from 12 to 34° (both departures from 90°), while the semi-annual swing of ϕ_3 is from about 6 to 23°. The comparison made in table 5 serves, however, to show that the K amplitudes of both components increase with disturbance level and that corresponding amplitudes are in reasonable accord.

The conclusion reached from these detailed phase and amplitude comparisons is that the semi-annual variation of angle ϕ_3 provides a satisfactory explanation of the corresponding variation of magnetic disturbance.

7. CONCLUSIONS

The main results and conclusions so far reached may be summarized as follows.

(*a*) 'Planetary' K variation—applying strictly to conditions equatorward of the auroral zone—is a twice-yearly wave with maxima occurring, within the limits of probable standard error, at the equinoxial dates. The absence of an annual component is a necessary result of the procedure involved in computing the planetary index.

(*b*) The planetary semi-annual wave operates at all levels of disturbance down at least to the limit at which the K index can be expected to operate efficiently. The 'missing' storms near the solstices are at the top end of the disturbance scale.

(*c*) The latter fact eliminates the possibility of acceptance of an axial theory limited to an annual variation of simple hit-or-miss of particle streams. An aiming hypothesis cannot, however, on this account be discounted, since systematic variations of particle density may possibly occur within the solid angles of particle streams, on their arrival at the earth.

(*d*) It is considered that the axial hypothesis concerning the cause of March-September maxima must, nevertheless, be abandoned because of the wide departure of the statistical dates of maxima from those required. In particular, the closeness of these dates to the equinoxes is considered to demand an explanation based on the geocentric position of the sun.

(*e*) At low disturbance levels only an annual component centred on the solstices is evident in the Potsdam K index, at high levels only an equinoxial semi-annual wave. At medium activity levels both components can be discerned. K indices 3 and under are mainly involved in the annual wave. Consideration of the diurnal variation of frequency of such low K indices suggests that this annual wave may arise from admixture of S_q and K in quiet conditions but that the possibility that this component is a real physical part of disturbance cannot be ruled out.

(*f*) Investigation of the K index variation at selected stations over a wide range of latitude and on both sides of the northern auroral zone reveals that the equinoxial wave is a feature that affects all stations. It is barely evident on the quietest days, apparently because of contamination of K by S_q, but increases in amplitude with rise of activity and is of overwhelming importance at high levels, except quite close to the pole. The K amplitude of this wave varies little with latitude, implying a latitudinal variation in absolute measure similar to that of the disturbance phenomenon itself.

(*g*) An annual wave with summer maximum is an undoubted statistical feature of the K index at all latitudes. The nature and magnitude of this wave are such that S_q and S_D are considered to contribute very little to it except in very quiet conditions, when some admixture of S_q and K at most stations equatorward of the auroral zone is strongly indicated. The annual wave must therefore be considered of real physical significance in the disturbance phenomenon.

(*h*) The amplitude of the annual wave increases very markedly with latitude. Close to the pole it remains the predominant feature of annual variation at high disturbance levels in spite of an appreciable equinoxial wave there.

(*i*) There is no indication, within the auroral zone, of a region of sudden discontinuity across which different laws of annual variation operate—equinoxial maxima as opposed to a summer maximum and winter minimum. Change of emphasis between the two types of variation appears to progress relatively smoothly in terms partly of geographic, and partly of geomagnetic, latitude.

(*j*) The amplitude of the annual component appears to be larger, in a given latitude, in the southern than in the northern hemisphere.

(*k*) The equinoxial wave and u.t. daily component of disturbance have a common cause in the obliquity of the earth's magnetic axis.

7·1. *Explanation of annual component*

Attempts have been made in recent years to explain magnetic storms, either in whole or in major part, on the basis of an atmospheric dynamo theory. The direct supporting evidence up to the present time consists mainly of low latitude effects, confined to the sunlit hemisphere, in the earliest stages of magnetic storms. In addition, however, evidence has been accumulating of the existence of ionospheric winds, partly systematic and partly 'random', superimposed on the large daily tidal components that provide the e.m.f. for the S_q variations. Such winds, blowing in a conducting layer of the atmosphere, would be expected to play some part in producing magnetogram effects which would be interpreted as 'disturbance' and would, for instance, contribute to the K index. Also Vestine (1954) has been able to show that certain features of the magnetic disturbance field have a reasonable interpretation in terms of a general circulation of the earth's atmosphere (Kellogg & Schilling 1951). The latter circulation, though based on observational evidence, is, however, still largely hypothetical so far as are concerned the inferred meridional components which play an important part in Vestine's theory.

The large height gradients of observed winds in the ionsphere, coupled with the uncertainty as to the ionospheric region mainly responsible for dynamo currents, makes it difficult to discuss in detail the possibility that the annual component of magnetic range disturbance has its origin in a corresponding variation of an atmospheric dynamo effect. General considerations strongly suggest, however, that this is the likely explanation. The best evidence now available (e.g. Murgatroyd 1957) is to the effect that throughout the lower ionosphere, where true winds are thought to blow, definite patterns of strong zonal air movement exist in winter and in summer, while spring and autumn winds are lighter and transitional in character: meridional and 'random' wind components are often strong in all seasons but show no systematic features. The important factor in the dynamo effect, other than wind strength, is the atmospheric conductivity which in the lower ionsophere is largely controlled by the solar zenith angle and thus has a summer maximum and winter minimum, with amplitude of seasonal variation increasing with (mainly) geographic latitude. The combination of strong variable winds and high conductivity in the ionosphere in summer affords a ready explanation of the observed features of the annual component.

Asymmetry about the equator of ionospheric wind circulation appears a likely result of the 6% additional heat radiation received by the earth at perihelion (early January) relative to aphelion (early July). Ionospheric conductivity is almost certainly also subject to geographical asymmetry from this cause. These facts offer a likely explanation of the differences in amplitude of annual disturbance component observed in corresponding north and south latitudes, since perihelion increase of dynamo effect in disturbance is almost exactly in phase with the southern hemisphere summer increase of disturbance.

7·2. *Explanation of semi-annual component*

Three possible explanations of the equinoxial component, which has been shown to be world-wide in character and of major importance in other than very quiet conditions, are here discussed.

(*a*) *Obliquity of solar axis to pole of ecliptic*

The analysis has, on statistical grounds, rejected this (axial) feature as providing even a partial explanation of the semi-annual disturbance wave. This result, negative though it is, is of interest because of its implications in the properties of the solar particle streams which cause disturbance.

Among the important factors in the solar-magnetic storm relationships are these:

(i) *Direction of solar particle emission.* The established existence of a recurrence tendency in multiples of about 27 days—the solar rotation period—effectively dispels uncertainty as to the existence of a preferred direction of solar particle emission, since no recurrence tendency of any interval would occur in the absence of some such preferred direction, while preference for a direction other than radial would produce two recurrence intervals within the solar rotation period.

(ii) *Solar latitude of emitting regions.* The lag of average magnetic disturbance behind relative sunspot number in the solar cycle carries two implications: first, the existence of a strong tendency towards radial emission of streams is supported; secondly, the solar emitting regions have a solar cycle latitude variation closely in phase with that of visible sunspots. It is therefore a reasonable assumption that, averaged over a sunspot cycle, there is a solar latitude of maximal frequency of emission of potential storm-producing particles. This latitude may be in the range 10 to 15°, as it is for sunspots, but conclusive evidence on this point is not so far available.

(iii) *Frequency distribution of particle stream width.*

(iv) *Possible departures of stream form from spherical symmetry.*

(v) *Possible systematic variation of particle density within solar particle streams, on arrival at the earth.*

On the reasonable assumptions of preferred radial emission and of maximum frequency of emission from solar latitude, then an effect in the annual incidence of disturbance would necessarily be associated with the annual variation of aiming conditions arising from the obliquity of the solar equator to the earth's ecliptic. Such an effect would appear independently of the frequency distribution of particle stream width. The form of such an annual variation of disturbance would depend on the preferred mean latitude of emission: early March and September maxima would be expected if the latitude is greater than 7·2°; while four annual maxima, symmetrically disposed in pairs with respect to early March and early September would be expected for mean latitudes less than 7·2°, degenerating to two solstice maxima for a preferred solar latitude of 0°.

Since no such maxima, primary or secondary, were obtained by statistical analysis of *Ap*, or of Potsdam *K* indices at any one of four sunspot-cycle epochs, it may be concluded that the stated condition of a systematic variation of particle stream density across a section of the solar stream does not obtain, at least on arrival of the stream near the earth. It may further be assumed that the frequency distribution of particle stream width, shown by Chapman (1929) to be required for the operation of an axial effect in the annual variation of disturbance, or rather the corresponding distribution calculated on the basis of the actual preferred mean solar latitude of emission, is not in fact fulfilled by the particle streams.

(*b*) *Atmospheric dynamo*

Since the dynamo effect has already been accepted as offering a reasonable explanation of the annual component it is apparent that it cannot also serve to explain the semi-annual component. The main reason for rejection of this cause may be briefly stated: the worldwide similarity of characteristics displayed by the semi-annual component cannot be satisfied by a dynamo explanation which must involve large hemispherical, latitudinal and possibly even regional variability of effect.

(*c*) *Obliquity of earth's magnetic axis to sun-earth line*

A suggestion was made by Bartels (1928) that the annual variation of disturbance may arise from a seasonal variation of the angle between the earth's magnetic axis and the line joining sun and earth, along which the solar particles are presumed to travel. This suggestion is one that has received no support and strangely little comment in later discussion of the problem.

In § 6 it was verified that there exists in the diurnal variation of disturbance a component which can be definitely ascribed to the obliquity of the earth's magnetic axis. It was inferred that a component, arising from the same cause, must exist in the annual variation of disturbance. Finally, comparison of the phase, magnitude and other properties of the two components left no doubt that the obliquity of the earth's magnetic axis relative to the sun-earth line offers a reasonable total explanation of the equinoxial maxima of disturbance.

REFERENCES

Bartels, J. 1928 *Handb. Experimental physik*, **25**, 166.
Bartels, J. 1932 *Terr. Magn. Atmos. Elect.* **37**, 1.
Bartels, J., Heck, N. H. & Johnston, H. F. 1939 *Terr. Magn. Atmos. Elect.* **44**, 411.
Bartels, J. & Veldkamp, J. 1949 *J. Geophys. Res.* **54**, 295.
Bartels, J. & Veldkamp, J. 1954 *J. Geophys. Res.* **59**, 423.
Bell, B. & Glazer, H. 1956 *J. Geophys. Res.* **61**, 179.
Bell, B. & Glazer, H. 1957 *Smiths Contr. Astrophys*, **2**, no. 5, 51.
Bell, B. & Glazer, H. 1958 *Smiths Contr. Astrophys*, **2**, no. 8, 161.
Chapman, S. 1929 *Mon. Not. R. Astr. Soc.* **89**, 465.
Chapman, S. & Stagg, J. M. 1929 *Proc. Roy. Soc.* A, **123**, 27.
Chapman, S. & Stagg, J. M. 1931 *Proc. Roy. Soc.* A, **130**, 668.
Chree, C. 1915 *Proc. phys. Soc. Lond.* **27**, 193.
Chree, C. 1927 *Proc. phys. Soc. Lond.* **39**, 389.
Cortie, A. L. 1913 *Mon. Not. R. Astr. Soc.* **73**, 52.
Gnevishev, M. N. & Ol, A. I. 1946 *Terr. Magn. Atmos. Elect.* **51**, 163.
Kellogg, W. M. & Schilling, G. F. 1951 *J. Met.* **8**, 222.
Lewis, R. P. W. & McIntosh, D. H. 1953 *J. Atmos. Terr. Phys.* **4**, 78.
Mayaud, P. N. 1956 *Exp. Polaires Francaises, Resultats Scient.* S.IV, 2.
Murgatroyd, R. J. 1957 *Quart. J. R. Met. Soc.* **83**, 417.
Naqvi, A. M. & Bhargava, B. N. 1954 *Indian J. Met. Geophys.* 5, 195.
Naqvi, A. M. & Tandon, J. N. 1955 *Indian J. Met. Geophys.* **5**, 251.
Nikolsky, A. P. 1947 *Terr. Magn. Atmos. Elect.* **52**, 147.
Stagg, J. M. 1935 *Proc. Roy. Soc.* A, **149**, 298.
Tandon, J. N. 1956 *J. Geophys. Res.* **61**, 211.
Vestine, E. H. 1954 *J. Geophys. Res.* **59**, 93.