Solar-cycle periodicity in secular variation of H at Alibag

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ABSTRACT. Quiet-day monthly mean values of H at midday and midnight of Alibag for the period 1906 to 1967 are examined for cyclic variations of sunspot cycle periodicity after elimination of the secular variation by the method of polynomial regression and the technique of numerical filteration. The cyclic component is observed both in the midday and midnight series, with prominent amplitudes from about 1930 to 1955. For most of the solar-cycles during the period of data the component variation is nearly in phase with the sunspot cycle and its amplitude for the midday series is almost twice that for the midnight series. Since the two data series differed only in respect of the magnitude of Sq (H) in them, it is construed that in addition to other causes Sq (H) also contributes to the solar-cycle variation in H.

1. Introduction

Solar-cycle variation of geomagnetic force components and declination, superposed on their secular change, has been the subject of a number of investigations. Till recently the method of isolating the solar-cycle variation was to eliminate the secular change by smoothing the annual mean values of the magnetic elements and then subtracting them from the corresponding original values. Alternately a polynomial curve, usually of the second degree was fitted to the original data series and the departures of the observed values from the fitted curve were examined for correspondence with the sunspot cycle. A summary of earlier work done has been given by Pramanik and Ganguli (1954). Moos (1910) and Schmidt (1916) found correspondence between the variation of annual mean sunspot numbers and the differences (residuals) between observed annual mean values of magnetic elements and those calculated from second degree polynomial curves fitted to observed data. By smoothing annual mean data of Oslo for the years 1820 to 1948 and subtracting them from observed values Wasserfall (1950) extracted the solar-cycle component in almost all magnetic elements. Beagley and Bullen (1949) fitted a third degree polynomial to annual mean declination of Christchurch and Apia and found a tendency for periodicity of 22 years in the data instead of the 11-year cycle. Pramanik and Ganguli (1954) fitted quadratic curves to annual mean values of H and D of Alibag and several other stations. They found no clear parallelism between sunspot cycle and the differences between observed and calculated values.

Application of numerical filters to long data series for extraction of anticipated periodicities in the data has been attempted in recent years. Degaonkar (1963) computed overlapping 11-year means of annual mean values of a few stations and by subtraction from the original series obtained clear periodic variation with sunspot cycle in H, Z and F of Tucson. The method was in effect a simple numerical filteration with the 11 weights of the filtering function identical and equal to 1/11. Yukutake (1965) applied the technique of filteration to annual mean values of X, Y and Z of a number of stations and showed the presence of 11-year component in the data. His procedure consisted of numerical differentiation of the time series followed by the application of a high pass numerical filter for eliminating the secular trend and long periodicities in the data. Bhargava and Yacob (1968) used a 25-weight numerical band pass filter with maximum response at frequency of 1/11 cycle/year to obtain the solar-cycle variation in annual mean values of H at Alibag for the period 1848 to 1967, and at seven other observatories for different periods. The annual mean values were based on data for all days and all hours. The amplitude of solar-cycle variation obtained was 11 to 21γ, which was slightly larger than that of Yukutake (1965) in X of 2 to 17γ.

The solar-cycle variation in H has always been found to be in phase opposition to the sunspot cycle. This result has been interpreted by early investigators as a consequence of greater incidence of geomagnetic disturbance during the sunspot maximum epoch, since disturbances on the average lower the value of H. It is, however, well known

TABLE 1

Orthogonal polynomials P_n and their coefficients b_n fitted to midday and midnight series

Values of t for Student's test of significance of b_n and variation accounted for by each term P_n b_n are also given

	Midday Series					Midnight Series				
	Degree n =					Degree n =				
	0	1	2	3	4	0	1	2	3	4
Orthogonal polynomial (P_n)	1·0	$X - 30\cdot5$	$X^2 - 61\cdot0X + 610\cdot0$	$X^3 - 91\cdot5X^2 + 2214\cdot5X - 10797\cdot0$	$X^4 - 122\cdot0X^3 + 4758\cdot7X^2 - 63300\cdot6X + 178921\cdot7$	1·0	$X - 30\cdot5$	$X^2 - 61\cdot0X + 610\cdot0$	$X^3 - 91\cdot5X^2 + 2214\cdot5X - 10797\cdot0$	$X^4 - 122\cdot0X^3 + 4758\cdot7X^2 - 63300\cdot6X + 178921\cdot7$
Coefficient (b_n)	37750·03	39·9443	0·24053	—0·028786	$9\cdot518\times10^{-8}$	37712·23	39·8604	0·242172	—0·028397	$9\cdot003\times10^{-8}$
t for significance of b_n	—	36·7	3·9	32·7	0·09	—	36·9	4·0	32·2	0·08
Variance accounted by P_n b_n	—	$3\cdot16804082\times10^7$	$2\cdot940651\times10^5$	$1\cdot0384216\times10^6$	—7·6	—	$3\cdot15475034\times10^7$	$2\cdot981037\times10^5$	$1\cdot0105304\times10^6$	—6·8
Original variance of series		$3\cdot30682697\times10^7$					$3\cdot29115257\times10^7$			

that the Sq currents causing the diurnal changes in H are much stronger during sunspot maximum years than during minimum years. This has the effect of increasing the daily mean value of H in low latitudes, during sunspot maximum years. Thus, while geomagnetic disturbance tends to reduce H during years of high solar activity, the Sq effect tends to increase it. It is likely that the disturbance effect predominates over the Sq effect, so that the solar-cycle variations in H is in phase opposition to the sunspot cycle. However, if quiet days only are considered, probably the solar-cycle variation, attributable largely to the Sq effect, may be in phase with the sunspot cycle. This aspect has in fact been examined by Yukutake (1965). He found for Tucson the solar-cycle variation in X to be in phase opposition to the sunspot cycle whether the annual mean values taken for analysis were for all days or for ten quiet days of each month. This finding does appear to show that Sq has no contribution to the solar-cycle variation in geomagnetic field. But Tucson is not an appropriate station to give a decisive answer to the question, since it is too close to the latitude of the focus of Sq current system. At Tucson the magnitude of Sq is rather small and does not vary appreciably from sunspot minimum to sunspot maximum years. At Alibag the solar-cycle variation in H for all days tended to be in phase with the sunspot cycle during solar-cycles 17 and 18, though during earlier cycles the variation was observed to be in phase opposition to the sunspot variation (Bhargava and Yacob 1968). The phase change in solar-cycle variation of H during solar-cycles 17 and 18 could be the effect of other periodicities in the data series or a result of relatively large contribution by the Sq effect. The present investigation is aimed at resolving the contribution by Sq to the solar-cycle variation in H.

2. Analysis and Results

The data used were from the horizontal component of the geomagnetic field at Alibag for the period 1906 to 1967. The period was restricted to these years since the Colaba (Bombay) data for international quiet days were not available for earlier years. Two series of data were taken for analysis. One series was for local noon and the other for local midnight. The series consisted of monthly mean values obtained by averaging (except for the years 1921-23) three-hourly values centred around local noon and local midnight respectively, the hourly values being those for the five international quiet days only. In the case of the years 1921-23 only bi-hourly values were available and so the values for 12^h and 0^h local time were averaged over the five international quiet days to give the monthly mean values for midday and midnight respectively. The number of data points in each series was 744. The two series were similar in that they were for the most quiet days of each month. They differed in respect of the magnitude of Sq (H) in the respective series. Magnitude of Sq (H) was large in the data for the local noon and comparatively negligible in those for local midnight. Successful extraction of the solar-cycle component from the two series should contribute to an understanding of the causes of the component variation.

The method of polynomial regression and the technique of applying numerical filters to the two data series were both attempted. To each series of 744 monthly values a polynomial of third degree was fitted by the use of orthogonal polynomials as outlined by Kendall (1948). The polynomial was of the form,

$$Y = b_0P_0 + b_1P_1 + b_2P_2 + b_3P_3$$

where Y is the dependent variable representing the mean values of H; P_n, with coefficient b_n, is the orthogonal polynomial in X of degree n, X being the independent variable representing months. The number of data points as well as the magnitude of each (of the order of 38000 γ) involved in the computations proved too large for the limit of accuracy of number storage in the CDC 3600 Computer of the Tata Institute of Fundamental Research, which was used for all computations. Only about 97 per cent of the original variance of the series could be accounted for by the fitted curve. To obviate this difficulty groups of 12 monthly values were averaged to give annual mean values, so that the number of data points could be substantially reduced to 62. Further, to make the dependent variable also small, 38000 γ was subtracted from each annual mean value. Orthogonal polynomials and their coefficients up to the fourth degree were computed for each series. These are shown in Table 1. In the same table are also shown the values of t for Student's test of significance of the coefficients and the variation accounted for by each orthogonal polynomial.

It is immediately seen that all the coefficients except that of the fourth degree polynomial are significant. Besides, the variance accounted for by the fourth degree orthogonal polynomial is seen to be negative, indicating that this polynomial was redundant. The curve best fitting each series had, therefore, to be restricted to the third degree. The variance accounted for by the curve fitted to each series was as much as 99·84 per cent of the original variance.

Using the third degree polynomial fitted to annual mean values of H at local noon and local midnight from 1906 to 1967 (the independent variate taking values of X=0 to 61) monthly mean values were calculated giving X the values $\frac{-11}{24}, \frac{-9}{24}, \ldots\ldots, \frac{-3}{24}, \frac{-1}{24}, \frac{1}{24}, \frac{3}{24} \ldots\ldots \frac{9}{24}, \frac{11}{24}$, corresponding to January to December of 1906; $\frac{13}{24}, \frac{15}{24} \ldots\ldots \frac{25}{24}, \frac{27}{24}, \ldots\ldots \frac{33}{24}, \frac{35}{24}$. corresponding to January to December of 1907 and so on with final values $\frac{1453}{24}, \frac{1455}{24}, \ldots\ldots, \frac{1465}{24}, \frac{1467}{24}, \ldots\ldots\ldots, \frac{1473}{24}, \frac{1475}{24}$ corresponding to January to December of 1967. The 744 computed values for local noon and midnight are shown as continuous curves in Fig. 1. The monthly observed values are also plotted to indicate the scatter (values for January and July only of each year are shown, to reduce conjestion). The polynomial curves do fit the observed values quite well and give a fairly accurate trend of secular variation in H from 1906 to 1967. Two clear turning points are observed. One is in the year 1914 from when H increased rapidly and the other in 1965 marking a decreasing trend in the element.

The monthly differences obtained by subtracting the computed values from observed values are shown plotted in Fig. 2, together with variations of annual mean Zurich sunspot numbers. These show the presence of periodicities of about 35 and 11 years. The 35-year component has its maxima around 1915 and 1950 and a minimum around 1932. The 11-year component appears irregular with respect to the sunspot cycle. During some epochs the two are in phase and in others they are in phase opposition. At the solar minimum epochs of 1914 and 1965 the 11-year variation in H show maxima, while at those of 1924, 1934, 1944 and 1954 this component has minima. Similarly, at the solar maximum epochs of 1907 and 1928 the 11-year variation in H tends to have minima while at those of 1918, 1937, 1948 and 1958 maxima are observed. The indications are that the solar-cycle response in H appears in phase opposition to the sunspot cycle in the solar-cycle 15 and again in 20. During the cycles 17 to 19 the response tends to be in phase with the sunspot cycle. The important feature is

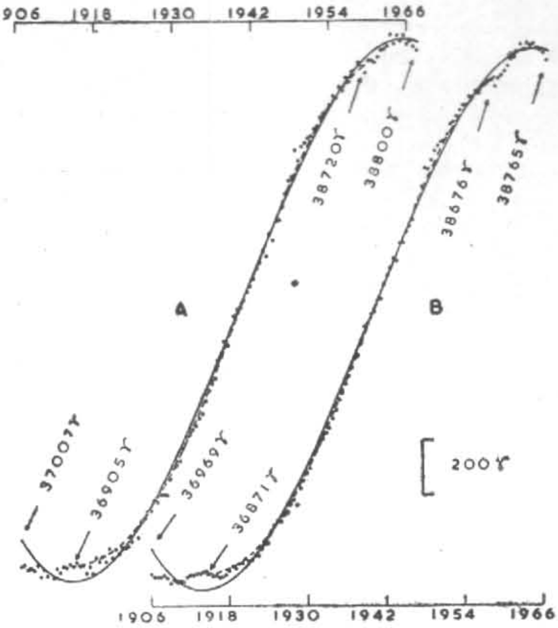

Fig.1. Secular trend in quiet-day H at Alibag for the period 1906 to 1967 for the midday (A) and midnight (B) data series

Continuous line curve is from polysnomial regression method and dashed line curve is the result of application of ultra low pass filters. Plots of observed monthly mean values (for January and July only of each year) show the closeness of fit

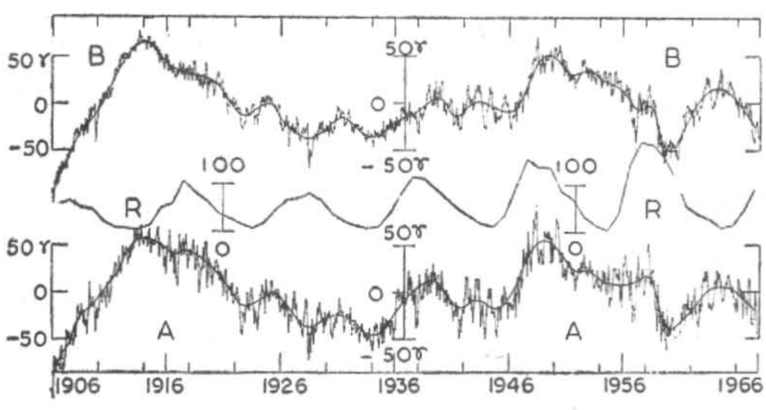

Fig. 2. Departures of observed monthly mean values of quiet-day H from polynomial curves of the third degree fitted to data series centred at midday (A) and midnight (B)

Aunual mean Zurich Sunspot Numbers are shown by R

the similarity of the response at noon and midnight.

With 744 monthly departures from the computed curve it should be possible to have an estimate of the average amplitude of the solar-cycle variation from power spectrum analysis, This was attempted following Blackman and Tukey (1959), with 180 (somewhat larger than the ideal 150 for the number of data points) as the maximum lag for each series. The results obtained did not give sufficient resolution of power near the solar-cycle period of about 130 months on account of the maximum lag being rather small and due to excessive power of larger periodicities like that of 35 years. Moreover, the series of departures were not ideally stationary, since, as seen earlier the solar-cycle variation at different epochs of the period of data were not identical in phase. The results of power spectrum analysis have therefore not been presented.

Next, the technique of numerical filteration was applied to the two data series. The filters used were computed following Behanon and Ness (1966). The filter weights were symmetrical about the central weight and the transfer functions of the filters had very small overshoot near the cut-off frequencies. In all four filters were designed. The first was an ultra low pass filter with 201 weights (N=100), designed to eliminate completely all frequencies $\geqslant$ 1/100 cpm (cycle per month). Its frequency responses were 1·0, 0·94, 0·49 and 0·12 at 0, 1/600, 1/200 and 1/130 cpm respectively. Such a filter would isolate the secular trend in the data series. The second was a high pass filter with again 201 weights. Its frequency responses were equal to 1 minus those for the ultra low pass filter at corresponding frequencies. All frequencies 1/100 cpm would be passed without attenuation of amplitudes by this filter. The third filter had only 31 weights (N=15) and it was a low pass filter designed to eliminate high frequencies in the data series. The fourth one was a band pass filter with 301 weights (N=150) and peak response near the solar-cycle frequency. The number of weights in the filter had to be large so that only a narrow band of frequencies close to that of the solar-cycle was passed without much attenuation of amplitudes. The frequency responses were 1·0 at 1/110 cpm, 0·9 and 0·2 at 1/130 and 1/260 cpm and again 0·9, 0·44 and 0·07 at 1/100, 1/80 and 1/70 cpm respectively. The responses were practically zero for frequencies $\leqslant$ 1/500 and $\geqslant$ 1/60 cpm. The application of this filter would isolate from the original data series the cyclic component close to the solar-cycle frequency ($\approx$1/130 cpm). The frequency response characteristics of the filters computed are shown in Fig. 3.

A linear transformation of the data series is effected by application of the numerical filters according to the following scheme—

$$Y_t = \sum_{k=-N}^{N} W_k \; X_{t+k}, \quad t=0,\, 1,\, \ldots,\, n-1$$

where Y_t is the output of the filter corresponding to X_t of the original series and W_k the filter weights ($2N+1$ weights in all). The number of data points in the original series in ($n + 2N$), (X_{-N} to X_{n+N-1}) and that in the filtered series becomes n (Y_0 to Y_{n-1}), the filtering process reducing the length by $2N$.

The secular trends of the data series for local noon and midnight, obtained by the application of the ultra low pass filter are shown in Fig. 1 (broken line curves) together with those obtained by the polynomial regression method. The trends obtained by the two methods are similar, but those given by numerical filteration show a better fit with the original data. Since 100 data points were lost at each end of the series in the filtering process the clear turning points indicated by the polynomial curves are not seen in the secular trends given by the filter.

Application of the high filter to the data series eliminated the secular trend completely and attenuated amplitudes of low frequencies. The solar-cycle frequency was passed with about 90 per cent response and higher frequencies with almost no attenuation. The output of the filter is shown in A(1) and B(1) of Fig. 4, for the midday and midnight series respectively. These are similar to the plots of residuals obtained by the polynomial regression method. In the same figure are also shown for comparison variations of annual mean Zurich sunspot numbers. Solar-cycle periodicity is discernible in both A(1) and B(1). The large period oscillation of about 35 years is not observed, having been suppressed by the high pass filter. Application of the low pass filter with 31 weights to the output of the high pass filter smoothed the variations by eliminating high frequency oscillations. These results are shown in A(2) and B(2) of Fig. 4. A clear solar-cycle periodicity is seen, but a mixing of periods of a few years is still there.

A smoother version of the solar-cycle variation is obtained by application of the band pass filter to the original data series. The output of the filter for the midday and midnight series are shown in A(3) and B(3) of Fig. 4 respectively. Since the filter had 301 weights, 150 data points were lost at each end of the series. Nevertheless, the remaining lengths of the two series (from May 1915 to August 1959) still comprised four solar-cycles and were sufficient to depict the 11-year variation.

Comparison with variations of sunspot numbers shows the presence of solar-cycle periodicity in the two series of filtered data. This is particularly prominent during the period 1930 to

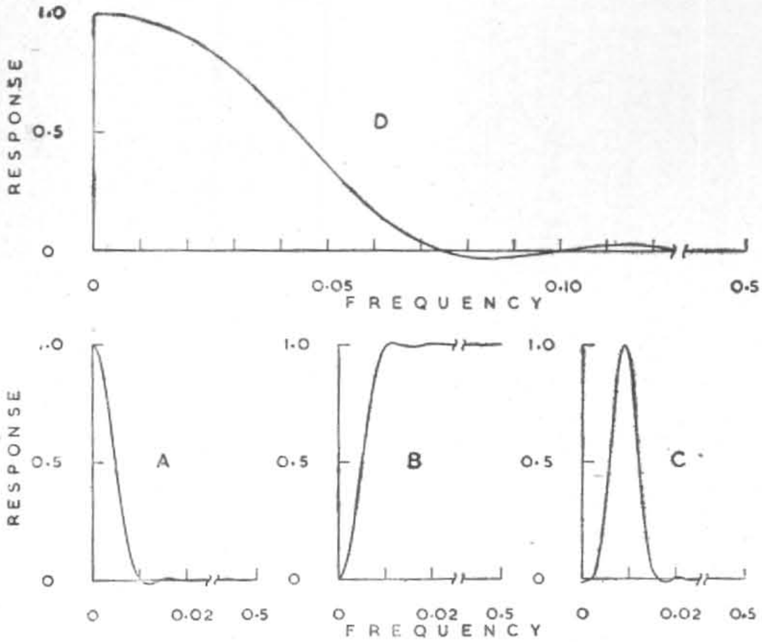

Fig. 3. Frequencies responses of the 201-weight ultra low pass filter (A), 2011-weight high pass filter (B), 301-weight band pass filter (C) and 31-weight low pass filter (D)

Frequencies is in cycle per month

1955 when the amplitude of the cycle variation attains large magnitude. The amplitude is small and variation somewhat irregular during earlier years and again tend to diminish after 1955. The solar-cycle response in both the series is almost in phase with the sunspot cycle, the variation in H leading sunspots variation by nearly a year. The phase lead is more for the midnight series than for the midday series. Another difference noticed is that the solar cycle response in the midday series is almost double that in the midnight series. The average response (peak to trough and trough to peak range) during the period 1930 to 1955 as measured from curves A(3) and B(3) is 38γ and 20γ for the midday and midnight series respectively. In terms of average amplitude it will be approximately 19γ and 10γ. These figures are comparable with 2 to 17γ in X of Yukutake (1965) and 11 to 21γ in H given by Bhargava and Yacob (1968). No attempt was made to subject the filtered series to power spectrum analysis. The number of data points having been reduced substantially by the filters, resolution of power near the solar-cycle period would be much worse than what was possible in the case of the 744 departures from the fitted curves.

3. Discussion

Both methods of analysis have brought out the solar-cycle periodicity in the data series for local noon as well as for local midnight. The technique of numerical filteration appears to be a better method, since a clear version of the periodicity could be derived by its application. The results show that solar-cycle variation in quiet-day H at noon as well as at midnight tended to be in phase with the variation of sunspot numbers during quite a number of solar-cycles in the period chosen for study. This finding is opposed to those of earlier investigators, who found the variations in sunspot numbers and in the geomagnetic field components to be in phase opposition. The results were not different even for quiet-day data of Tucson (Yukutake 1965). Bhargava and Yacob (1968), however found that for annual mean values of H at Alibag, based on all-days data, the solar-cycle response was largely in phase with variation of sunspot numbers from about 1930 to 1955, though the periodicity was in phase opposition to the sunspot cycle during earlier years from 1860 to about 1920. This difference in behaviour of relative phase from one period to another was attributed to influences by larger periodicities still present in the filtered data.

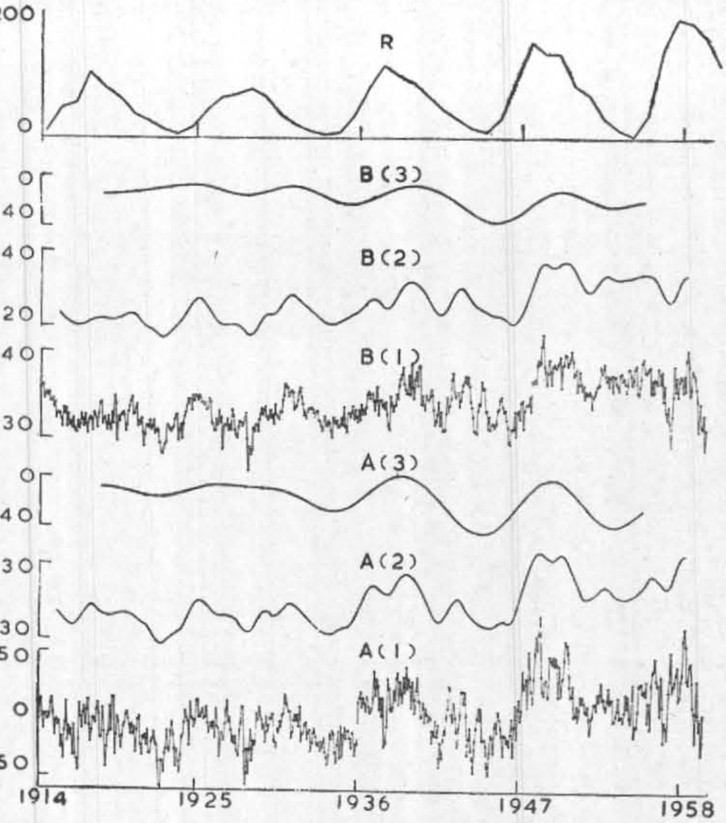

Fig. 4. Plots of data series for midday (A) and midnight (B) after application to original series of high pass filter (1), followed by 31-weight low pass filter (2) and of band pass filter (3)
R is annual mean Zurich Sunspot Number

The present investigation has shown that solar-cycle periodicity is present even in the data centred around local midnight. At this time of the night there is practically no $Sq(H)$ superposed in H. The effect of magnetic disturbance too is largely eliminated by confining the data to the 5 quietest days of each month, though some effect of depression of the field produced by intense magnetic storms may still be present even on quiet days. In any case geomagnetic disturbance gets eliminated as a major cause since the solar-cycle variation happens to be more in phase with the sunspot cycle. Geomagnetic disturbance is known to depress the field during epochs of solar maxima and any solar-cycle variation arising from its cause should therefore be in phase opposition to the sunspot cycle.

The amplitude of solar-cycle periodicity detected in the data centred around local noon is found to be nearly twice that from midnight data. The two series of data differed only in respect of the magnitude of $Sq(H)$ superposed in them. The larger amplitude must be construed to have been contributed by the greater magnitude of $Sq(H)$ in the noon-time data. The results from the noon-time series therefore indicate that $Sq(H)$ is also a cause of the solar-cycle periodicity, additional to whatever causes it in the night-time series.

In all probability the solar-cycle component variation in geomagnetic field may be the result of several effects, of which one is definitely Sq, as revealed by this investigation. Another is the effect of geomagnetic storms with associated modulation of the ring currents in respect of particle density and distance of location, coupled with the compressional effects of the solar wind on the magnetosphere (Yukutake 1965). The observed cyclic variation could also have contributions from periodic fluctuations of the relative motion between the earth's core and mantle and of the westward drift of the eccentric dipole (Vestine and Kahle 1968). According to Zolotov (1967) the westward drift fluctuates with a period of 10—15 years and has a negative correlation with 11-year solar activity. The different component causes may not be simultaneous but may differ in phase as well as in their effective cyclic periods, so that during one period of years the net effect appears with phase opposed to and during another practically in phase with the sunspot cycle.

It is not certain whether the periodicity of about 35 years observed by the method of polynomial regression is a real phenomenon or merely a result given by the particular fitted curve. Detection of a 30-year cyclic variation in the geomagnetic field components X and Z of Alibag, Sverdlovsk and Pavlovsk has, however, been indicated by Kuliyeva (1967). The author also refers to a 30-year periodicity in moderate geomagnetic storms found by V. I. Afanas'yeva and Yu. D. Kalinin.

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