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On solar zenith angle dependence of annual component quiet-day range in *H* at Alibag

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ABSTRACT. The annual component of monthly mean diurnal range in the quiet-day H at Alibag, isolated by digital filtering and averaged for the years 1909 to 1963, is found to have a dependence on monthly solar zenith angle at noon according to $(\cos X)^{0.85}$. Relevant features of the residual annual variation of the diurnal range, obtained after normalization for the solar-zenigh angle modulation are discussed and attributed to similar variations in the prevailing winds of the lower ionosphere at middle and high latitudes. The indicated easterly winds appear strongest in mid winter and mid summer and weakest around September.

1. Introduction

It is generally accepted that the quiet-day geomagnetic variations (*Sq*) are caused by electric currents generated in the lower E-region of the ionosphere by the dynamo mechanism. On the basis of observed variations average current systems have been derived (Chapman and Bartels 1940; Matsushita and Maeda 1965). Experimental detection of currents at E-layer heights by rocket-borne magnetometers (Singer, Maple and Bowen 1951 ; Cahill 1959; Davis, Stolarik and Heppner 1965; Maynard and Cahill 1965) have further conclusively established their existence.

Apart from the earth's permanent magnetic field, the two necessary requirements for generation of the currents are an electrically conducting layer and a motive force in the form of ionospheric winds. The former is brought about by ionization of atmospheric constituents by solar ultra-violet radiation and the latter is given rise to by gravitational and solar-heat-induced atmospheric tides. The ionospheric winds, moving the ionized air across the lines of force of the earth's main magnetic field, set up electromotive forces to drive electric currents. Since it is the vertical component of the main magnetic field that is of principal importance in the dynamo action and since this component field is considerable only in middle and high latitudes, the generation of electromotive forces, as indicated by Wulf (1965), is mainly due to wind at these latitudes. Completing their circuits *via* low-latitude conducting regions the electric currents establish large scale current vortices which move with the Sun, causing the observed ground-level daily variations in the geomagnetic field components.

Recent studies (Gupta 1967; and Brown and Williams 1969) have stressed on solar radiation energy as the principal agency contributing to both electrical conductivity and winds of the ionospheric current-layer. Energy absorbed is both a function of the radiation flux and of the solar zenith angle with respect to a particular region. When monthly mean *Sq* magnitudes are considered with solar radiation flux remaining about the same for all months (about the same degree of solar activity), the monthly values should have a dependence on cos X(X is solar zenith angle at noon for middle of a month). The purpose here is to ascertain this dependence using monthly mean magnitudes of *Sq* in the horizontal component of the geomagnetic field at Alibag (Lat. 18°·5 N, Long. 72°.9 E).

2. Data and Analysis

An appropriate measure of the magnitude of *Sq* is the diurnal range given by the difference between maximum and minimum hourly values on quiet days. Diurnal range formed this way represents *Sq* magnitude better than the diurnal range given by the difference between instantaneous maximum and minimum values of magnetic elements during a day, since the latter is likely to be affected by sporadic incidence of disturbance fluctuations even on quiet days, enhancing or diminishing the extreme values. The magnetic element selected for the study is the horizontal component field. Monthly mean diurnal range (rH) is obtained by averaging the daily 24 hourly values over the 5 International quiet days of each month, correcting these for the non-cyclic changes and then taking the difference between the maximum and minimum average hourly values, which for Alibag occur around noon and midnight respectively. Such rH values are formed for the years 1905-1967, to give a series of 756 values.

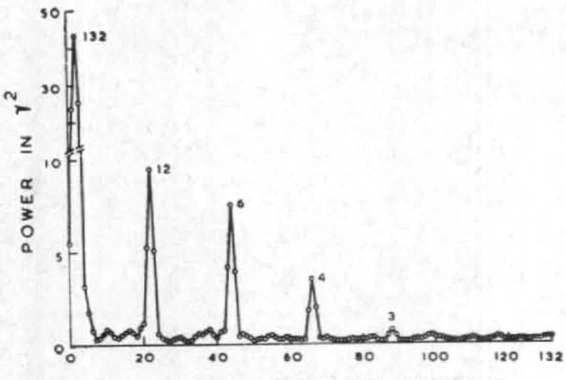

Fig. 1. Power spectrum of monthly mean quite-day range in H at Alibag for the years 1905-1967

Indicated periods for the prominent peaks are in months

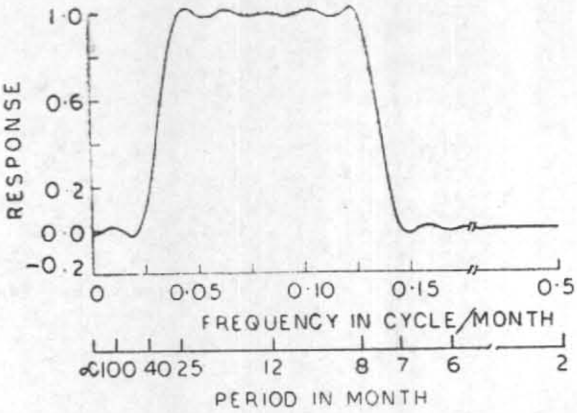

Fig. 2. Frequency response of the 97-weight bandpass symmetric filter

The scale shows periods in months

This series has prominent periodic components of 11 years 12, 6 and 4 months. The relative variances at these components obtained by the method of power spectrum analysis, as outlined by Blackman and Tukey (1959), with autocorrelations truncated at 132 lags, are depicted in Fig. 1. While maximum power is concentrated in the 11-year component the 12 and 6-month oscillations are also prominent. That rH or any other measure of Sq magnitude is highly correlated with solar activity is well known. The 11-year component in rH is, therefore, the result of solar-cycle variation of ionizing ultra-violet radiation flux. The precise origin of the 6-month oscillation in the quiet-day range is as yet not certain. Speculative suggestions have been put forward by Appleton (1964), Wagner (1968) and Maeda (1968). For the latitude of Alibag, where the variation of solar zenith angle at noon is largely a 12-month periodicity, the 6-month oscillation in the station's rH can have only negligible association with the solar zenith angle. The 12-month component in rH on the other hand, has an obvious close relation with the annual variation in solar zenith angle at noon.

For the purpose of this investigation periodic components other than the 12-month are eliminated from the rH series. This is done by numerical filteration. A band pass symmetrical filter of 97 weights is designed following Behanon and Ness (1966). Fig. 2 shows the frequency response characteristics of the filtering function. The filter has the effect of eliminating from the data series periods equal to and less than 7 months and also those equal to and greater than 45 months, while passing without attenuation periods from 8 to 25 months. Application of the filter to the rH series results in loss of 48 data-points both at the beginning and towards the end of the series, so that the length of series is now from January 1909 to December 1963. Also, according to the characteristic of the band pass filter, the filtered values are centred around the mean. Addition of the mean value of the original series restores the filtered values to a series equivalent to the original but with the unwanted frequencies eliminated. For each month of the year these values are then averaged over the 55-year period to give average monthly values ($\overline{rH}$) for the period 1909 to 1963, which covers five solar cycles. These 12 $\overline{rH}$ values are shown plotted in Fig. 3(A). A smooth 12-month oscillation is readily seen, with maximum and minimum in June and December respectively. It may be noticed that the amplitude of variation shown by the curve, as given by half the range, is $5\cdot8\gamma$. This is in close agreement with the amplitude of $6\cdot1\gamma$ given by power spectrum analysis of the data (Amplitude$=2\sqrt{\text{Power}}$).

The process of averaging over the 55-year period implies that the same average solar activity and therefore the same average flux of ionizing radiation is associated with each of the 12 values of $\overline{rH}$. The monthly inequalities in them are, therefore, attributable mainly to differences in solar zenith angle at noon from month to month. It is relevant to note that according to Appleton (1964) the magnitude of Sq in the Y component as well as the critical E-layer frequencies in South-east England are explicitly controlled by the solar zenith angle. Assuming $\overline{rH}$ to vary as $\cos^n X$,

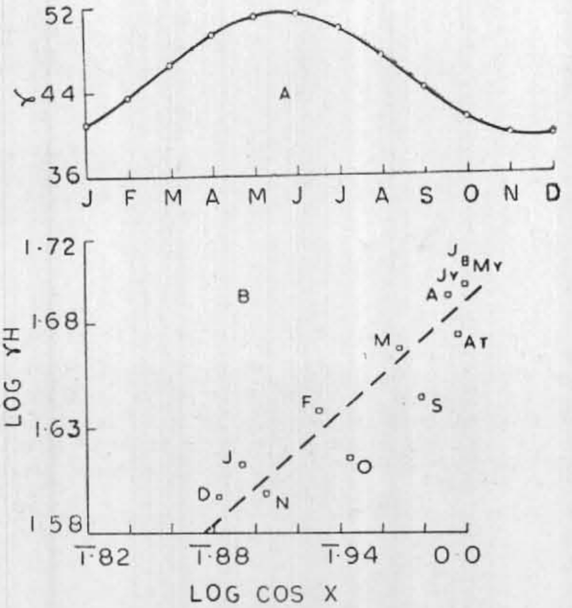

Fig. 3(A). Monthly mean quiet-day range ($\overline{rH}$) obtained after application of the band-pass filter and averaging over the years 1909–1963

Fig. 3(B). Logarithmic plot of monthly $\overline{rH}$ against cos X for Alibag

TABLE 1

Monthly values of $\overline{rH}$ and of solar zenith angle X for Alibag

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\overline{rH}$ γ	41·0	43·5	46·5	49·3	51·0	51·2	49·8	47·2	44·1	41·3	39·7	39·6
X (deg)	39·86	31·52	20·95	9·04	0·12	4·66	2·98	4·41	16·41	26·96	37·00	41·88
Annual comp. of X+mean X(deg)	38·47	31·64	21·60	11·04	2·80	0·91	0·89	7·72	17·76	28·32	36·56	40·27

where X is the solar zenith angle at noon for the middle of each month, the value of the index n may be estimated by a logarithmic plot of the 12 months' $\overline{rH}$ and cos X and determining the slope of the linear trend of the points. Fig. 3(B) shows this plot. The values of monthly X used are those of the annual component (derived by harmonic analysis of monthly values of X) added to the mean of the 12 original values of X so that they strictly correspond to the monthly $\overline{rH}$, which is purely annual. These values together with the original values of solar zenith angle and those of $\overline{rH}$ for the 12 months of year are listed in Table 1. The value of n indicated in Fig. 3(B) is 0·85.

The value of the index n may also be estimated indirectly. In Fig. 4 are shown the relation between annual mean values of rH at Alibag (rH') and those of monthly median critical frequency of E-layer at noon (fE) at Ahmedabad (Lat. 23°.0N, Long. 72°·6E), fE being raised to powers of 1, 2, 3 and 4. The data are for the years 1955-1964. For all cases linearity is clear. But the best linear relationship appears to be between rH' and $(fE)^3$, according to which one parameter is zero when the other is also zero.

Allen (1946) showed that the rate of change with solar activity, as reckoned by sunspot number (R), was about the same for Sq amplitude and $(fE)^3$, (78×10^{-4} and 72×10^{-4} respectively) the values of these parameters having been normalized with respect to those for R=0. For rH' at Alibag, similarly normalized, the rate of change with sunspot number for the period 1905-1960 was shown to be 70×10^{-4} (Yacob 1966). This rate is not only comparable with Allen's results but is also about the same as those for R and $(fE)^3$

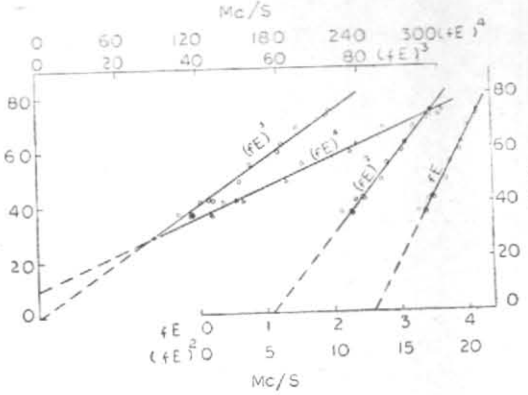

Fig. 4. Plots of annual mean quite-day range rH' at Alibag against annual mean of monthly median fE, fE^2, fE^3 and fE^4 at Ahmedabad

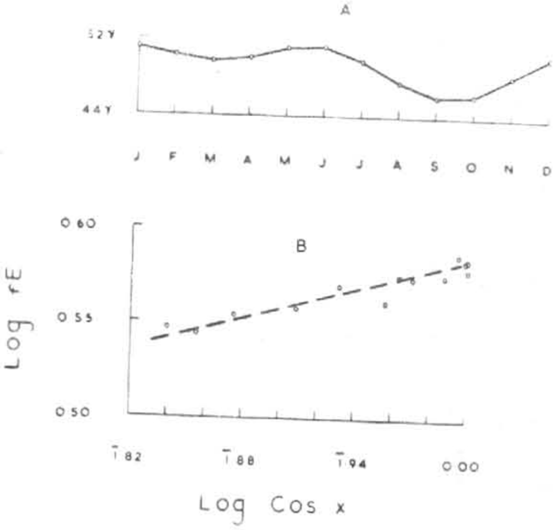

Fig. 5(A). Residual annual variation in $\overline{rH}$ after normalization for dependence on solar zenith angle

Fig. 5 (B). Logarithmic plot of monthly median fE averaged for the years 1955-1964 against monthly cos X for Ahmedabad

computed from the linear relationship between R and fE or $(fE)^2$ given by several other researchers, which are indicated below.

Investigator	Period	Station	Rate of change with R of normalized $(fE)^3$
Scott (1952)	1946-50	Ottawa and Prince Rupert	74×10^{-4}
Saha (1953)	1949-52	Calcutta	63×10^{-4}
Noonkester (1964)	1951-59	Washington	67×10^{-4}
Appleton (1964)	1934-53	Slough	73×10^{-4}

These results indicate a parallelism in the responses of rH' and $(fE)^3$ to solar activity and stress the significance of the linear trend between the two, as already seen for $(fE)^3$ of Ahmedabad and rH' of Alibag. The linear relationship may be expressed as $rH'=K_1\,(fE)^3$. With the known dependence of fE on solar zenith angle according to $fE=K_2$ (cos $X)^p$, the relationship between the monthly parameters averaged over a large number of years becomes—

$$\overline{rH}=K(\cos\ X)^{3p}=K\ (\cos X)^n$$

The index p, in respect of the E-layer ionization, according to Chapman equilibrium condition, has the value 0·25. Practical determinations for daily variation in solar zenith angle give the index a value of about 0·3. But for monthly mean solar zenith angles at noon the value is found to agree closely with the theoretical value (Ratcliffe 1960). This is confirmed in Fig. 5(B) showing a logarithmic plot of monthly median fE at noon averaged over the years 1955-64 against the monthly $\cos X$ for Ahmedabad. The linear trend of the 12 points has a slope (p), of 0·26, indicating the value of 0·78 for n, which agrees closely with the direct estimate of 0·85. This value compares favourably with 1·0 as the approximate index of $\cos X$ found by Appleton (1964) for the dependence of geomagnetic field component Y at Abinger-Hartland on the midday solar zenith angle. The dependence of monthly values, $\overline{rH}$, of the average annual component on solar zenith angle at noon may accordingly be taken as $(\cos X)^{0 \cdot 85}$. The implication of this dependence is discussed in the following section.

3. Discussion

The indicated dependence of $\overline{rH}$ at Alibag on monthly solar zenith angle as $(\cos X)^{0 \cdot 85}$ should arise from a similar dependence of either or both the factors contributing to Sq currents over the station, *viz.*, the electric field and the electrical conductivity of the current layer. Electrical conductivity being more a local phenomenon than the electric field, solar-zenith-angle modulation of $\overline{rH}$ should be through a greater influence on the former. If, therefore, the monthly $\overline{rH}$ values are normalized for dependence on solar zenith angle by dividing each month's value by the respective $(\cos X)^{0 \cdot 85}$, the monthly inequalities in electrical conductivity would be equalised and the resulting residual variation in $\overline{rH}$ should depict the trend of annual variation of the electric field and the ionospheric winds in the middle and high latitudes mainly responsible for its generation. This variation should be considered to reflect the annual trend mainly for winds originating from gravitational tides, since normalization for solar zenith angle variation would also partly annul the variation in the solar heating effect and, therefore, in the solar-heat-induced winds.

The residual annual variation of $\overline{rH}$ after such normalization is shown in Fig. 5(A). It depicts two maxima of about equal magnitude one in January and the other in June. The principal minimum occurs in September and a subsidiary one in March. Accordingly, it appears that winds at ionospheric current layer heights (about 100 km) in the northern hemisphere are intense in both midsummer and midwinter, becoming less intense around March and weakest around September. No direct results of annual variation of ionospheric wind parameters are available for comparison, except those by Greenhow and Neufeld (1961), which are for the years 1953 to 1958 at heights of 85-100 km above the earth's surface. The annual variation of the east-west component of the prevailing wind given by them (their Fig. 5) shows remarkable similarity with the residual annual variation of $\overline{rH}$. According to them every year there are strong eastward components present during the summer and winter months and the winds tend to be westward in spring and during the autumn. Prevailing easterly winds lead to currents flowing in the same sense as the Sq system and westerly winds tend to decrease the current intensity (Stenring 1969).

Wulf (1965) has highlighted the seasonal assymmetry with respect to solar declination in the daily variation of H at San Juan, Honolulu and Tucson, attributing the cause to variations in the prevailing winds in the lower ionosphere. For months of essentially the same solar declination on opposite sides of the year the form of the daily variation was shown to differ greatly. The same feature is observable in Fig. 3(B). For pairs of months with the solar zenith angle about equal, the values of $\overline{rH}$ differ appreciably, *e.g.*, between January and November, February and October, March and September and April and August. Always the former month (falling in the first half of the year) has greater diurnal range than the latter in each pair, giving rise to the type of annual variation in residual $\overline{rH}$ seen in Fig. 5(A).

The magnitude of the residual annual variation of $\overline{rH}$ shown in Fig. 5(A) is much smaller compared with the original annual variation of $\overline{rH}$ (Fig. 3A). The variance of the normalized $\overline{rH}$ variation is only 3·04 while that for the original annual variation is 18·19, indicating that the solar zenith angle variation, which controls solar radiation energy absorbed in the current layer, accounts for a large part (83 per cent) of the annual variation in $\overline{rH}$. This result substantiates the finding of Gupta (1967) that solar radiation is the main agent responsible for geomagnetic variations. He found that the contribution by solar radiation to the diurnal frequency in geomagnetic field component H was as large as 99 per cent and to the semidiurnal frequency about 90 per cent.

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