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Solar cycle and annual variations of $Sq(H)$ at Alibag

A. YACOB and D. RADHAKRISHNA RAO
Colaba Observatory, Bombay-5, India

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Abstract—A study of the amplitudes and phase angles of the first two harmonics of the monthly $Sq(H)$ at Alibag with respect to solar activity (sunspot number, R), for the period 1905–1960, shows that (1) the amplitudes of both the harmonics have high positive correlations with R, (2) the phase angle of the first harmonic is negatively correlated with R, but with rather low correlation coefficients and (3) the phase angle of the second harmonic is uncorrelated with R. These findings confirm the earlier results obtained with annual mean values. Monthly linear regression equations are given for R and the amplitudes and phase angles.

Annual variations of the amplitudes and phase angles, as well as those of the coefficients in the monthly linear regression equations, are shown for the entire period of the investigation and also for the solar maximum and minimum epochs.

The annual variations of the phase angles show large changes for the latter half of the year with sharp minimum in September and maximum in November. These changes are similar for both the harmonics and the magnitudes as well as the character are the same for the solar maximum and minimum epochs, suggesting atmospheric tidal origin for the phenomenon.

1. INTRODUCTION

IN AN earlier paper YACOB and PRABHAVALKAR (1965) (hereafter referred to as Paper 1) have examined the first and second harmonics of the yearly mean $Sq(H)$ at Alibag in relation to solar activity for the period 1905–1960. A highly significant positive relationship was found between solar activity, as measured by the yearly mean relative sunspot number, and the amplitudes of the first and second harmonics of the yearly mean $Sq(H)$. The phase of the first harmonic was found to be related with sunspot number in such a manner as to delay the local time of maximum of the harmonic with increasing sunspot number. No significant relationship was, however, seen between solar activity and the phase of the second harmonic. In the present contribution the investigation is extended to the monthly mean parameters, to ascertain, (1) the extent of dependence on solar activity of the amplitude and phase of the first two harmonics of the monthly mean $Sq(H)$ and (2) the annual variation of the average monthly amplitudes and phase angles of the two harmonics.

2. DATA AND RESULTS

The hourly values of the element H at Alibag are averaged for the five international quiet days of each month of the period 1905–1960. After correcting the average hourly values for the non-cyclic change the hourly inequalities are derived and subjected to harmonic analysis to obtain the amplitude and phase (C_1, C_2 and ϕ_1, ϕ_2) of the first two harmonics of the monthly mean quiet-day diurnal variation, $Sq(H)$. The phase angles are reckoned from 0000 hr. G.M.T. The monthly mean relative sunspot number (R) for the period 1905–1957 have been taken from the

Table 1. Correlation coefficients between the monthly mean relative sunspot number, R, and the amplitudes, C_1 and C_2 and phase angles, ϕ_1 and ϕ_2, of the monthly mean $Sq(H)$ at Alibag for the period 1905–1960

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	For annual mean parameters
C_1 & R	+0·78	+0·86	+0·85	+0·87	+0·82	+0·85	+0·80	+0·91	+0·87	+0·79	+0·81	+0·76	+0·98
C_2 & R	+0·70	+0·66	+0·80	+0·80	+0·88	+0·83	+0·74	+0·86	+0·80	+0·71	+0·70	+0·65	+0·96
ϕ_1 & R	−0·36	−0·53	−0·53	−0·56	−0·67	−0·56	−0·46	−0·39	−0·47	−0·54	−0·62	−0·48	−0·93
ϕ_2 & R	+0·06	+0·06	+0·21	+0·17	+0·08	−0·05	+0·17	+0·06	−0·01	+0·10	−0·20	+0·06	+0·04

Table 2. Coefficients a, b and their product ab, in the linear relation $P = a(1 + bR)$ (P representing C_1, C_2 or ϕ_1) for each month of the year

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
C_1	a in γ	9·3	11·8	16·3	17·2	15·0	15·4	15·7	12·4	10·4	14·2	14·1	10·3
and	$b \times 10^4$	86	82	62	60	68	63	55	81	102	59	55	55
R	$ab \times 10^3$ in γ	80	97	101	103	101	97	86	100	107	85	77	57
C_2	a in γ	4·3	5·8	8·2	8·8	7·3	8·0	8·9	7·2	7·1	7·9	6·7	4·9
and	$b \times 10^4$	79	59	52	52	71	60	42	55	52	41	43	50
R	$ab \times 10^3$ in γ	34	34	43	46	52	48	37	40	37	32	29	25
ϕ_1	a in degrees	352·2	352·3	350·1	349·2	352·7	353·5	351·2	345·6	343·2	352·5	360·2	358·7
and	$b \times 10^5$	−17	−23	−18	−16	−18	−15	−13	−14	−19	−21	−24	−20
R	$ab \times 10^3$ in degrees	−59	−81	−63	−56	−63	−53	−46	−48	−65	−74	−86	−72

Table 3. Average monthly values of C_1, C_2, ϕ_1 and ϕ_2 (1) for the period 1905–1960 (2) for sunspot maximum years and (3) for sunspot minimum years

		Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Mean for the years 1905–1960	C_1 in γ	13·9	17·4	22·0	23·3	21·1	21·3	21·2	18·8	17·1	19·2	18·6	13·6
	C_2 in γ	6·3	7·8	10·6	11·5	10·4	10·9	11·2	9·8	9·4	9·8	8·4	6·3
	ϕ_1 in degrees	348·8	347·6	346·6	345·8	348·8	350·3	348·3	342·4	339·0	348·1	355·1	354·4
	ϕ_2 in degrees	245·1	243·2	246·9	247·9	249·7	249·0	245·5	235·3	229·3	245·8	261·9	256·6
	R	57	57	57	59	60	61	62	64	62	59	59	59
Sunspot maximum years	C_1 in γ	16·7	22·6	27·6	29·7	27·6	26·9	26·2	27·4	23·2	25·0	22·8	16·8
	C_2 in γ	7·6	9·9	13·0	14·4	13·6	13·5	13·6	12·5	11·8	11·9	9·9	7·2
	ϕ_1 in degrees	344·5	343·1	343·8	343·0	345·0	346·6	346·7	339·5	334·3	344·8	350·2	350·8
	ϕ_2 in degrees	243·1	242·7	248·3	249·2	251·2	248·3	249·9	236·0	228·4	247·9	258·8	255·2
Sunspot minimum years	C_1 in γ	10·9	12·3	16·5	16·5	14·8	17·0	16·5	12·9	11·2	14·9	15·1	11·4
	C_2 in γ	4·6	6·3	8·3	8·2	7·6	9·0	9·1	6·9	6·9	7·9	7·0	5·4
	ϕ_1 in degrees	349·3	351·3	349·9	349·1	353·0	352·9	349·8	345·3	343·2	351·1	357·9	357·7
	ϕ_2 in degrees	244·9	239·0	245·3	246·4	253·5	251·9	244·9	234·1	227·5	243·9	261·5	261·4

compilation by CHERNOSKY and HAGAN (1958) and for the years 1958–1960 from Zurich reports.

Correlation coefficients (C.C.s) between R and each of the parameters, C_1, C_2, ϕ_1, ϕ_2 are worked out for each month of the year based on the 56 pairs of monthly values. The results are shown in Table 1, together with those for the annual mean parameters given in Paper 1. Monthly linear regression equation of the form $P = a(1 + bR)$ is derived between R and P, where P is one of the parameters C_1, C_2 and ϕ_1. In Table 2 are given the monthly values of a, b and the products, ab, corresponding to the pairs of parameters R and C_1, R and C_2 and R and ϕ_1. In Table 3 are given the average values of C_1, C_2, ϕ_1 and ϕ_2 as well as the average relative sunspot number for each month of the year (averaged over the 56-year period). In the same table are also shown the average monthly values of C_1, C_2, ϕ_1 and ϕ_2 for the solar maximum and minimum epochs. For each solar cycle 3 years centred at the maximum as well as the minimum years have been considered, so that for the period 1905–1960 the number of years forming the maximum-epoch group and the minimum-epoch group is 15 each. The annual variations (monthly inequalities) of the average monthly values of C_1, C_2, ϕ_1 and ϕ_2 for the entire period 1905–1960 are shown in Fig. 1, and those for the solar maximum and minimum epochs in Figs. 2 and 5. The annual variations of the coefficients a and b and their product, ab, are shown in Figs. 3, 4 and 6.

3. DISCUSSION

1. *Solar-cycle variations*

The monthly C.C.s between R and each of the amplitudes C_1 and C_2 are positive and highly significant. They are, however, lower than the C.C.s for the yearly mean parameters (Paper 1). The monthly C.C.s for R and C_1 range from 0·76 to 0·91 while those for R and C_2 range from 0·65 to 0·88. The corresponding C.C.s for the annual parameters in Paper 1 are 0·98 and 0·96 respectively.

The monthly C.C.s between R and ϕ_1 are negative and range from 0·36 to 0·67. They are very much lower than the C.C. of 0·93 for the annual mean parameters, but are still statistically significant. The lower monthly C.C.s only indicate that the negative relationship between ϕ_1 and R does not manifest itself in clear terms unless average of large number of days are considered as in annual values, so that masking factors of random nature are averaged out. The negative C.C.s, though small, do indicate a systematic retardation (occurring later in the day) of the time of maximum of the first harmonic of $Sq(H)$ with increasing solar activity even in the case of the monthly parameter. There is no significant correlation between R and ϕ_2.

The coefficients a and b as well as their product, ab, show considerable monthly inequalities, which will be discussed later. It is, however, interesting to compare the average of the monthly values with those obtained with annual mean parameters in Paper 1. The average of the monthly values of a, b, and their product, ab, in the linear regression equations between R and C_1, work out to $13{\cdot}5\gamma$, 69×10^{-4} and $91 \times 10^{-3}\gamma$ which are comparable respectively with $13{\cdot}1\gamma$, 74×10^{-4} and $96 \times 10^{-3}\gamma$ obtained earlier for the annual parameters. The corresponding average figures in the case of R and C_2 are $7{\cdot}1\gamma$, 55×10^{-4} and $38 \times 10^{-3}\gamma$ which again

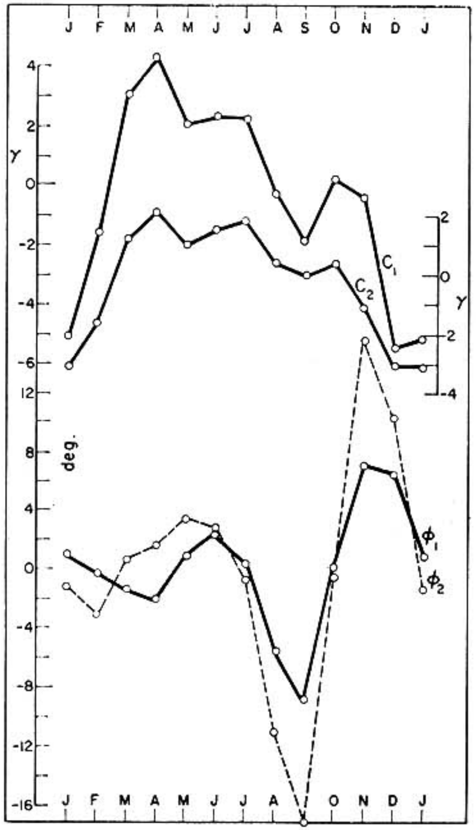

Fig. 1. Annual variations of the mean monthly amplitudes, C_1, C_2 and phases ϕ_1, ϕ_2 for the period 1905–1960.

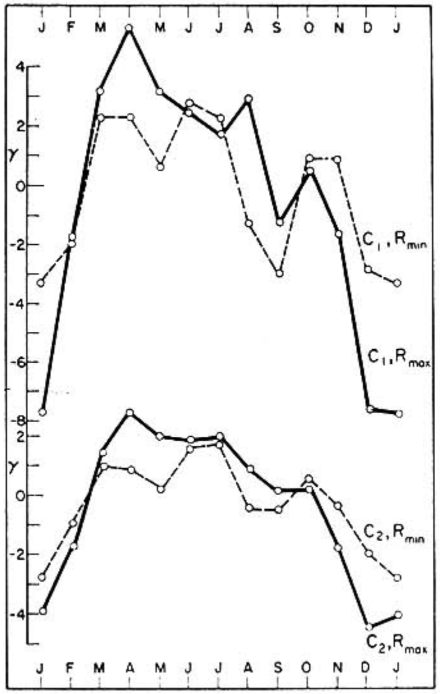

Fig. 2. Annual variations of the mean monthly amplitudes, C_1 and C_2, for the solar maximum and minimum epochs.

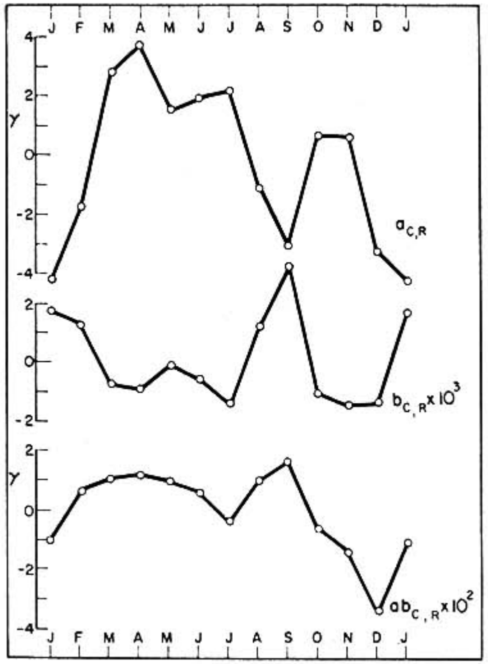

Fig. 3. Annual variations of the monthly coefficients, a and b, and their product, ab, in the linear regression equation between R and C_1.

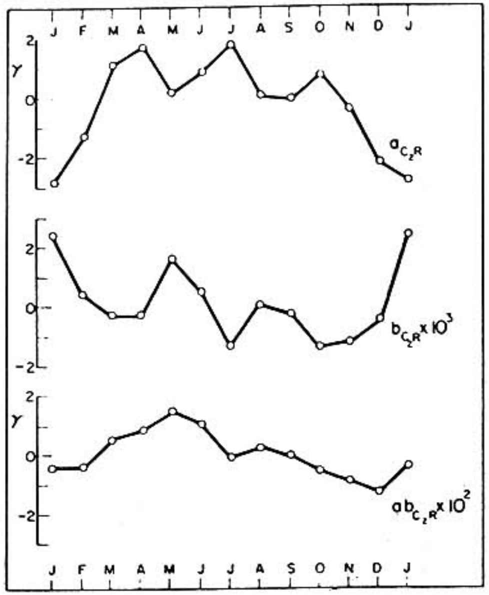

Fig. 4. Annual variations of the monthly coefficients, a and b and their product, ab, in the linear regression equation between R and C_2.

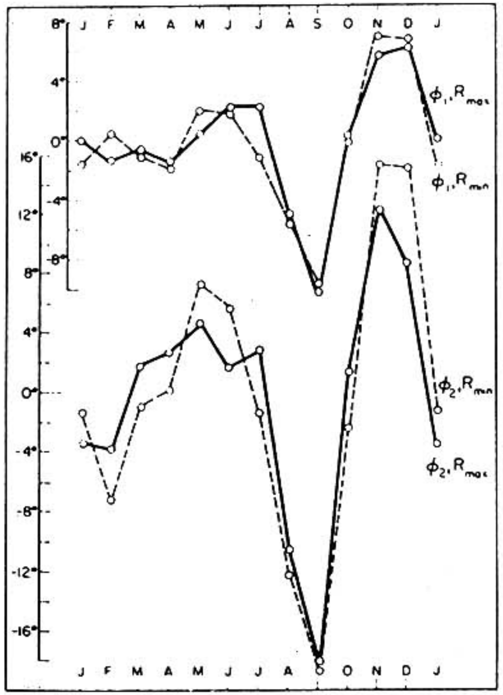

Fig. 5. Annual variations of the mean monthly phases, ϕ_1, and ϕ_2 for the solar maximum and minimum epochs.

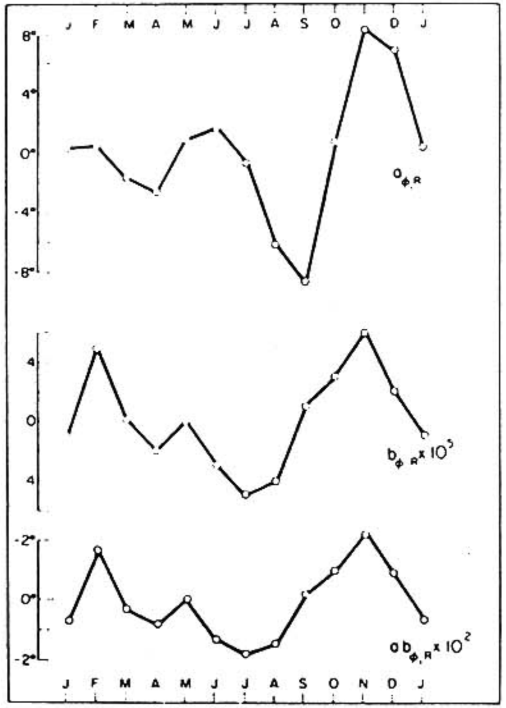

Fig. 6. Annual variations of the monthly coefficients a and b, and their product, ab, in the linear regression equation between R and ϕ_1.

compare well with the respective values of $6{\cdot}8\gamma$, 58×10^{-4} and $40 \times 10^{-3}\gamma$ for annual parameters reported earlier. These agreements tend to confirm the earlier results. The linear relationship between R and C_1, and C_2 are such that for an ideal average month of zero sunspot number the amplitude of the first harmonic is 13γ and that of the second harmonic is 7γ and the two amplitudes increase at the rate of about $0{\cdot}9\gamma$ and $0{\cdot}4\gamma$ respectively for an increase of 10 in the relative sunspot number.

In the case of linear relationship obtained between R and ϕ_1 the average retardation of the epoch of maximum for an average month is 2·6 min for an increase of 10 in the relative sunspot number. This is about the same as 3·0 min obtained earlier with annual values.

2. *Cause of solar-cycle variations*

The cause of the direct correspondence between sunspot number and amplitudes C_1 and C_2 of $Sq(H)$ is well known and need not be repeated here. But the cause of the negative relation between ϕ_1 and R continues to be intriguing and can only be speculated upon. As suggested earlier in Paper 1, the cause may be associated with the relaxation time of the particular ionospheric layer, where Sq electric currents flow.

Another plausible cause that suggests itself is the residual geomagnetic disturbance that is supposed to contaminate $Sq(H)$ even on very quiet days. The magnitude of disturbance is known to have direct correspondence with solar activity. It may be that the increase in contamination of $Sq(H)$ by disturbance also affects ϕ_1. This is examined by harmonically analysing the mean SD(H), for the solar maximum epoch (1946, 47, 48, 57, 58 and 59) and for the solar minimum epoch (1943, 44, 45, 53, 54 and 55), obtained from the difference of the yearly mean hourly values of H at Alibag for the international disturbed days and for the international quiet days (SD $-$ Sq). The results are given below for the first two harmonics.

	Solar maximum epoch		Solar minimum epoch	
	Amplitude (γ)	Phase in degrees (from 0000 hr G.M.T.)	Amplitude (γ)	Phase in degrees (from 0000 hr G.M.T.)
1st harmonic	16·5	70·3	11·1	89·6
2nd harmonic	1·2	152·6	0·9	242·0

It may be seen that SD(H) at Alibag is predominantly diurnal and if ϕ_1 of $Sq(H)$ is affected by SD(H) it should be through the diurnal component. The phase angle of the diurnal component of SD(H) decreases by about 20° from solar minimum ($R = 19$) to solar maximum ($R = 153$) epochs. In other words the maximum of the first harmonic of SD(H) occurs later in the day with increasing solar activity, and the order of lag is an hour for an increase of 100 in the relative sunspot number. The direction of change of the maximum epoch of the 1st harmonic of SD(H) with solar activity is the same as that for the first harmonic of $Sq(H)$. It thus appears likely that the decrease in ϕ_1 with increasing solar activity is the result of contamination of $Sq(H)$ by disturbance, unless the similar phase changes with solar activity noticed in the first harmonic of both SD(H) and $Sq(H)$ are caused by some common unknown agent.

The absence of any correlation between R and ϕ_2 indicates, as suggested in Paper 1, that ϕ_2 is controlled more by the ionospheric tides rather than by ionization of the Sq current layer.

3. *Annual variations in amplitudes*

Annual variations (curves of monthly inequalities in Fig. 1) of C_1 and C_2 are predominantly annual oscillations with maximum in summer and minimum in winter. Semi-annual waves with equinoctial maxima are prominent in the variation of C_1 and quite discernable in that of C_2. It is interesting to note that the summer maximum becomes more conspicuous than both the equinoctial maxima for the solar minimum epoch in the annual variations of C_1 and C_2 (Fig. 2). Otherwise the annual variations for the solar maximum and minimum epochs are essentially similar. The more prominent equinoctial maxima for the solar maximum epoch may be the result of greater contamination by geomagnetic disturbance of $Sq(H)$ during the maximum epoch than the minimum epoch. Even the very quiet days are considered to be not entirely free from geomagnetic disturbance. With the known increase in the magnitude of disturbance with increasing solar activity and tendency to have equinoctial maxima it is reasonable to expect a greater degree of contamination of $Sq(H)$ and a greater prominence of the equinoctial maxima for the solar maximum epoch. From this point of view the equinoctial maxima in the annual variation of C_1 or C_2 does appear to be the result of contamination of $Sq(H)$ by geomagnetic disturbance.

The annual variations of the coefficients, a, corresponding to the pairs R and C_1, and R and C_2 (Figs. 3 and 4) are similar to those of C_1 and C_2. In fact the similarity has only to be expected since they represent practically the same parameter. C_1 and C_2 represent the average amplitudes for the period 1905–1960, for solar activity corresponding to mean monthly sunspots of about 60, while the coefficients, a, represent the same amplitudes for a level of solar activity appropriate to zero sunspot number.

The annual variations of coefficients, b, corresponding to the pairs R and C_1, and R and C_2 (Figs. 3 and 4) are the reverse of those of a. Those of ab in the same two figures do not depict clear equinoctial maxima. The term ab gives the specific increment in the respective amplitudes with increasing sunspot number and the coefficients b, give the relative increase with sunspot number in the amplitudes of the first and second harmonics, i.e. the increase in the amplitudes when the coefficients a are unity. It is surprising that the annual variations of the terms intimately associated with solar activity do not show clear equinoctial maxima as the amplitudes C_1 and C_2 or the coefficients, a, do. This signifies that the equinoctial maxima depicted by the amplitudes C_1 and C_2 may not after all be entirely due to contamination of $Sq(H)$ by disturbance. Partly at least the phenomenon may be inherent in the pure Sq itself. As suggested by APPLETON (1964) the phenomenon may arise from the two contributing factors, namely ionization of the conducting layer and atmospheric tidal oscillations, becoming more in phase at the equinoxes than at the solstices.

4. *Annual variations in phase angles*

Annual variations shown by ϕ_1 and ϕ_2 (Fig. 1) are very interesting. There is not much of a monthly inequality from January to July. But from July to January the variations are strikingly prominent. For both ϕ_1 and ϕ_2 there is a very sharp minimum in September and a similar sharp maximum in November. The change from September to November is about 16° for ϕ_1 and about 33° for ϕ_2, which gives the same order of change (about 1 hr) in the time of maximum of the two harmonics. In fact from June to December the variations of ϕ_1 and ϕ_2 are such that the times of maxima of the harmonics change in the same sense and by the same amount from one month to another. The type and range of annual variation are about the same for the solar minimum and maximum epochs (Fig. 5), even for ϕ_1 which shows considerable dependence on solar activity. This is a clear indication that the annual variations seen have nothing to do with the ionization of the ionospheric Sq current layer and that they are caused entirely by the atmospheric tides in the layer.

In this connection it may be of interest to point out that according to CHAPMAN (1951) the phase angle of the solar semidiurnal barometric variation, S_2, is greatest in November or December for Washington, D.C., Coimbra, Lisbon, San Fernando and Kumamoto. However S_2 does not appear to have minimum phase angle in September as shown by both ϕ_1 and ϕ_2 here. No precise information regarding tides in the lower ionosphere is as yet available, nor are similar investigations for other stations have been published (as far as the authors are aware) for comparing the type and magnitude of annual variations of the phase angles ϕ_1 and ϕ_2 obtained here. It is however, significant to note that the annual variation of the northern Sq focal latitude for the west Pacific region during the Second Polar Year as determined by Ota and as shown by HASEGAWA (1960) in Fig. 11 of his paper, has a large measure of similarity with the monthly inequalities of ϕ_1 and ϕ_2 determined here. The Sq focus is shown to have a minimum latitude of about 30° in September and a maximum latitude of about 39° in November and December. Though Ota's results are limited to just a year's data and the region for which the results have been obtained is quite away from the longitude of Alibag, the variations shown by the two parameters (Sq focal latitude and the phase angles ϕ_1 and ϕ_2) are so strikingly similar, that possibly the two phenomena have the same cause. It has been indicated that, since ϕ_1, which shows considerable dependence on solar activity, also has the same type of annual variation as ϕ_2 the cause of the annual variations should be associated with the atmospheric tidal forces rather than with the ionization of the Sq current layer. A further indication may be had from the fact that during the months July–December, when the noon solar zenith angle for Alibag is steadily increasing, a large oscillation from minimum to maximum in ϕ_1 or ϕ_2 occurs. The intensity of ionization in the Sq current layer over and around Alibag should be expected to steadily decrease from July to December. The observed annual variations of ϕ_1 and ϕ_2 cannot therefore be associated with ionization of the Sq current layer. It thus appears that the variations of ϕ_1 and ϕ_2 in the course of the year and, presumably, the latitudinal variations of Sq focus shown by Ota, may both arise from changes in the atmospheric tidal forces or the changes in the wind systems of the Sq current layer. These changes obviously have the effect of varying the local time of maximum Sq current intensity in the horizontal west–east direction in the course of the year in the manner indicated by the variations of ϕ_1 and ϕ_2.

The annual variation of the coefficient a, corresponding to ϕ_1 and R (Fig. 6) is similar, to that of ϕ_1, as it should be and the range of variation is also the same for both. The annual variation of the numerical value of the coefficient b and that of the product ab are strikingly similar, unlike what has been seen in the case of the amplitudes. Since b is negative the indications are such that the rate of decrease in ϕ_1 with increasing solar activity is maximum in February and November and minimum in July. The cause of this feature is again not clear.

4. CONCLUSIONS

1. The correlation between solar activity and the amplitudes of the first and second harmonics is positive, and significantly high even for the monthly parameters.

2. The correlation between solar activity and the phase angles of the first harmonic of the monthly mean $Sq(H)$ is negative and comparatively low. But the C.C.s are found to be statistically significant.

3. There is no correlation between solar activity and the phase angle of the second harmonic of $Sq(H)$.

4. The annual variations of the amplitudes of the first and second harmonics show equinoctial maxima superposed on 12-monthly variation with summer maximum and winter minimum.

5. The annual variations of the phase angles of the first and second harmonics of $Sq(H)$ are strikingly prominent for the later half of the year. The variations are very similar for both the parameters with a sharp minimum in September and a sharp maximum in November. The range between September and November is such that the epoch of maximum is retarded by about 1 hr for both the parameters.

6. The origin of the cause of the particular annual variation of the phase angles is definitely seen to be associated with atmospheric tides, though the precise mechanism is not apparent.

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REFERENCES

APPLETON E. V.	1964	*J. Atmosph. Terr. Phys.* **26**, 633.
CHAPMAN S.	1951	*Compendium of Meteorology* (Edited by T. F. Malone) p. 510. American meteorological Society, Boston, Massachusetts.
CHERNOSKY E. J. and HAGAN M. P.	1958	*J. Geophys. Res.* **63**, 775.
HASEGAWA M.	1960	*J. Geophys. Res.* **65**, 1437.
YACOB A. and PRABHAVALKAR A. S.	1965	*J. Atmosph. Terr. Phys.* **27**, 73.