550·38·538·6

Annual variation of amplitude and phase of *Sq* (*H*)

A. YACOB and D. RADHAKRISHNA RAO

Colaba Observatory, Bombay

(*Received 29 August 1968*)

ABSTRACT. Persistence of both the 12-month and 6-month oscillations in the annual variation of amplitudes of the first two harmonics monthly mean *Sq* (*H*) for Alibag and of a large change during the later half of the year in the phase angles are observed during different solar cycles. The same features are found for a few other stations. The semi-annual components variation in amplitudes is found to be the predominant feature for stations close to the geomagnetic equator. Possible causes of the features observed are discussed.

1. Introduction

Annual variations of amplitude and phase of the first two harmonics of monthly mean *Sq* (*H*) at Alibag averaged for the period 1905–60 were examined by Yacob and Rao (1966). The variations of the amplitudes were predominantly 12-monthly with maximum in summer and minimum in winter. A semi-annual component with equinoctial maxima was also present. For both the harmonics the variations of the phase angles were rather small from January to June but large during the later half of the year with a sharp minimum in September and equally sharp maximum in November. The same features were seen for years of sunspot maximum and sunspot minimum (Figs. 1, 2 and 5 of Yacob and Rao 1966). With a view to examine if similar features are observed at other stations also, quiet-day hourly values of H of a number of stations have been analysed. The stations are given in Table 1, with their geographic and geomagnetic co-ordinates. Alibag data are also re-examined for different solar-cycle years to see if the features observed for 1905-60 as a whole are persistent.

2. Data and results

The treatment of data of the different observatories for the derivation of the amplitudes C_1 and C_2 and phases ϕ_1 and ϕ_2 of the first two harmonics of monthly mean *Sq* (*H*) is exactly the same as outlined earlier (Yacob and Rao 1966). The data of all the observatories considered are, however, not for the same period. This is not a major drawback since seasonal variations are not expected to change from one period of years to another. The actual period of years over which the monthly quiet-day data have been averaged is indicated in respect of each station in Table 1.

The results of annual variations of C_1, C_2, ϕ_1 and ϕ_2 have been shown graphically and these will now be examined for each station.

Alibag

The average annual variations of the *Sq* (*H*) parameters for the solar-cycles 15, 16, 17, 18 and 19 are found to be essentially the same as observed for the period 1905–60 as a whole and, therefore, they have not been shown here. For purposes of comparison, however, Fig. 1 of Yacob and Rao (1966) has been reproduced in Fig. 1. The 12-month component with summer maximum and the semi-annual one with equinoctial maxima in C_1 and C_2 are observed for each solar-cycle group of years. The phases ϕ_1 and ϕ_2 are seen to depict some random variations, during the first half of the year. But the large oscillation during the later half of the year with minimum around September and maximum around November is prominent during all the solar-cycles.

Trivandrum, Kodaikanal and Annamalainagar

These stations are close to the geomagnetic equator with geopgraphic latitudes around 10°N and geographic longitudes comparable with that of Alibag. The annual variations of the *Sq* (*H*) parameters for these stations are shown in Figs. 2(a), 2(b) and 3(a). A striking similarity in the annual trends of each of the parameters is noticed for the three stations. Unlike those for Alibag, variations of C_1 and C_2 depict a very predominant semi-annual feature with equinoctial maxima. In fact the annual component has been almost completely masked by the semi-annual component. The annual variations of ϕ_1 and ϕ_2 for these stations are also quite different from those for Alibag. Predominance of semi-annual variation with equinoctial maxima is clearly apparent. The minima occur in July-August and December, with a third minimum in February in the case of Trivandrum and Annamalainagar.

TABLE 1

Geographic and Geomagnetic co-ordinates of the stations along with the period of data

Station	Geographic		Geomagnetic		Period
	Lat.	Long	Lat.	Long	
Hurbanovo	47° 52′N	18° 12′E	47·1°	99·8°	1949-60
Honolulu	21° 18′N	158° 06′W	21·0°	266·5°	1948-59
Alibag	18° 38′N	72° 52′E	9·5°	143·6°	1905-60
San Juan	18° 23′N	66° 07′W	29·9°	3·2°	1948-59
Annamalainagar	11° 24′N	79° 41′E	1·8°	149·4°	1958-65
Kodaikanal	10° 14′N	77° 29′E	0·7°	147·5°	1950-60
Trivandrum	8° 29′N	76° 57′E	−0·9°	146·3°	1958·65
Huancayo	12° 03′S	75° 20′W	−0·6°	353·8°	1923-44
Apia	13° 48′S	171° 46′W	−16·0°	260·2°	1938-58
Hermanus	34° 25′S	19° 14°E	−33·7°	81·7°	1938-59

Huancayo

This station is also close to the geomagnetic equator but about 13°S of the geographic equator. The annual variations of C_1 and C_2 (Fig. 3b) are essentially similar to those for Trivandrum, Kodaikanal and Annamalainagar, with prominent equinoctial maxima and minima in June and January (for C_2 this minimum is in November). There is, however, one difference. The equinoctial maximum is larger during the vernal equinox for the northern latitude stations, Trivandrum, Kodaikanal and Annamalainagar while the maximum during the autumnal equinox is larger for the southern latitude station, Huancayo. The magnitude of the variations for all the geomagnetic equatorial stations is almost two-fold that for Alibag. This is evidently the effect of the equatorial electrojet. The annual variations of ϕ_1 and ϕ_2, at Huancayo, however, bear no resemblance at all to those for Trivandrum, Kodaikanal or Annamalainagar. There is no evidence of semi-annual oscillation of any significance. The sharp positive change from August to November, especially in ϕ_2, is, on the other hand, similar to the change observed for Alibag.

Honolulu and San Juan

These stations are in geographic latitudes comparable with that of Alibag. Their geomagnetic latitudes increase in steps of about 10° from Alibag to Honolulu and then to San Juan. Figs. 4(a) and 4(b) show the annual variations of *Sq* (*H*) parameters for Honolulu and San Juan respectively. Some similarity in the variations of C_1 is observed for these stations and Alibag. But a clear semi-annual component is absent, though peak amplitude occurs in March. A clearer semi-annual component is present in C_2 for Honolulu and its variations are similar to those for Alibag. The magnitudes of variations in C_1 and C_2 at the two stations are small compared with those for Alibag and they do not appear higher in summer than in winter. A large measure of similarity in the annual variations of the phase angles for Honolulu with those for Alibag is seen. The sharp minimum in September is conspicuous in both ϕ_1 and ϕ_2 while the sharp maximum occurs one or two months later than for Alibag. In fact the annual variations of all *Sq* (*H*) parameters for Honolulu appear similar to those for Alibag. The phase variations for San Juan at first sight appear different from those for Honolulu or for Alibag, with broad minimum during the summer months. But a closer examination reveals some common features. The decrease during the earlier part of the year and the rapid positive change during the later part of the year are features similar to the other two stations. The range of variations is, however, very much larger at San Juan.

Hurbanovo

This station has fairly high geographic as well as geomagnetic latitude. The annual variations of all the parameters (Fig. 5) are distinctly different

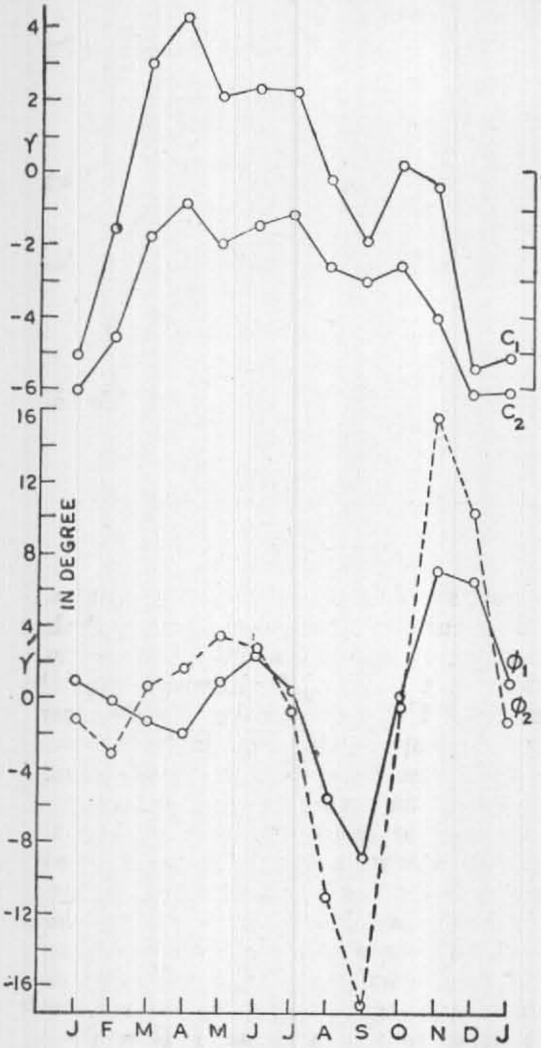

Fig. 1. Alibag (1905-1960)

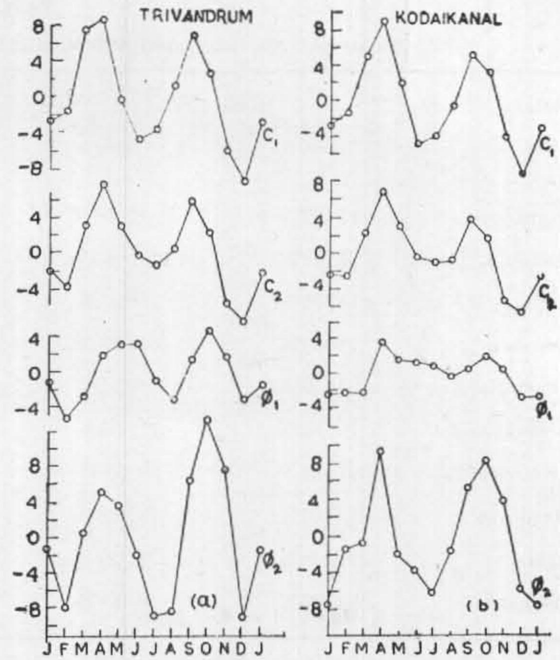

Fig. 2. Trivandrum & Kodaikanal

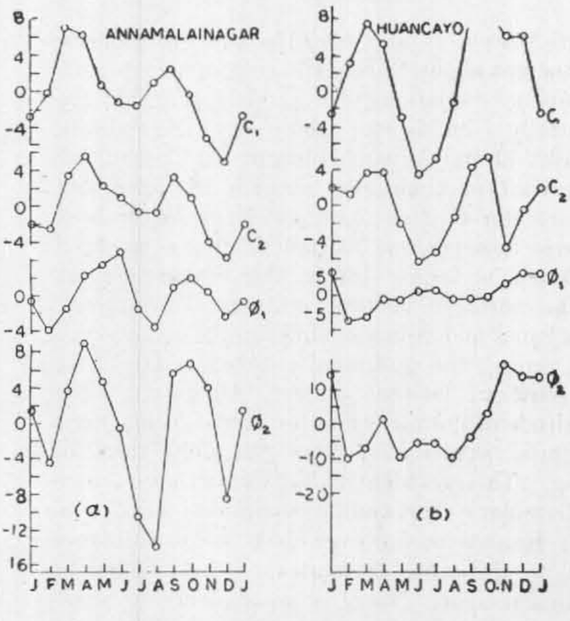

Fig. 3. Annamalainagar & Huancayo

Annual variations of mean monthly amplitudes C_1, C_2 and phaes ϕ_1, ϕ_2

from those for stations in lower latitudes. The variations of C_1 and C_2 are predominantly annual with maxima in July-August (local summer) and minimum in December-January (local winter). Equinoctial maxima are not clearly discernible, except for a faint indication in March for C_1 and C_2. The variations of ϕ_1 and ϕ_2 are again different from those seen for low latitudes. The annul trends are exactly opposite of those for San Juana. Both ϕ_1 and ϕ_2 have broad maximum during the summer months and minimum in winter. The ranges of variation are large, particularly for ϕ_1 and they are comparable with those for San Juan.

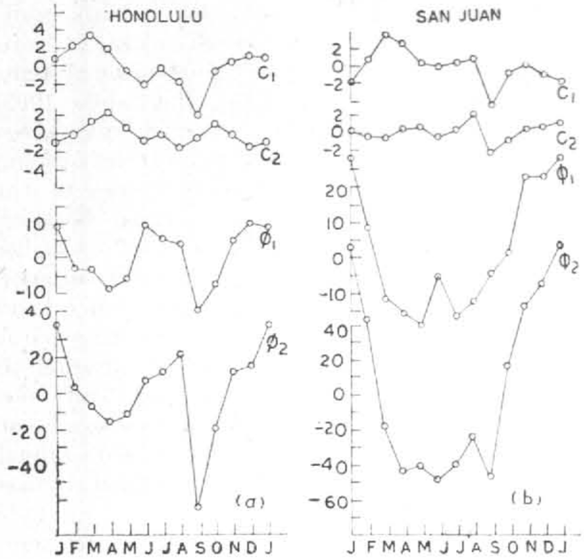

Fig. 4. Honolulu & San Juan

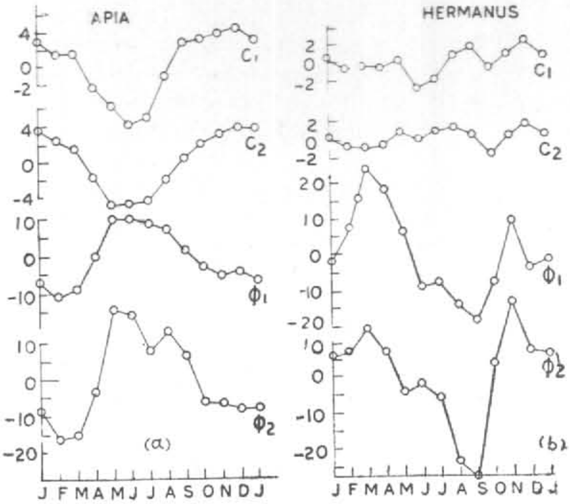

Fig. 6. Apia & Hermanus

Apia and Hermanus

These are southern latitude stations. The geographic latitude of Apia is comparable with that of Huancayo. Hermanus is at 35°S. The annual variations of C_1 and C_2 for Hermanus (Fig. 6b) are small and appear irregular. No significant semi-annual component is present in the variations of the amplitudes. A surprising feature of the variations of the amplitudes is their similarity to those observed for San Juan. Both stations are close to the average latitude of *Sq* current focus. But one is in the northern hemisphere and the other in the southern hemisphere. ϕ_1 and ϕ_2 show regular annual trends. with prominent maximum in March and November and minimum in September. There is a large swing from the minimum in September to the maximum in November in both ϕ_1 and ϕ_2. This feature is very much similar to that seen for Alibag.

In the case of Apia regular annual trends are seen in all the parameters (Fig. 6a). Both C_1 and C_2 are maximum during local summer and minimum during local winter. ϕ_1 and ϕ_2 are maximum in local summer and minimum in February. The phase variations tend to be similar to thóse of Hurbanovo, northern mid-latitude station. There is no clear evidence of equinoctial maxima in any of the parameters.

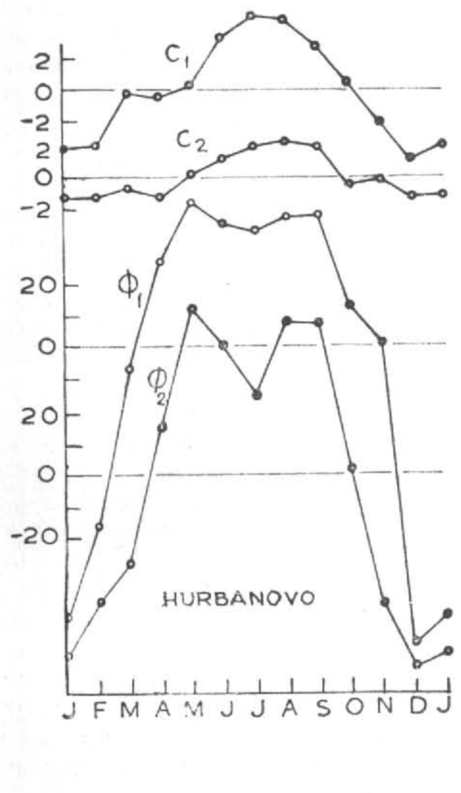

Fig. 5. Hurbanovo

Annual variations of mean monthly amplitudes C_1, C_1 and phases Φ_1, Φ_2

3. Discussions

The characteristics of annual variations of the parameters C_1, C_2, ϕ_1 and ϕ_2 of mean monthly *Sq* (*H*) observed earlier for Alibag for the period 1905–60 as a whole and for the sunspot maximum and minimum years of the period are found to be persistent, since they appear in the annual variations for a number of groups of years corresponding to separate solar-cycle. The amplitude variations have a predominantly annual component with maximum in summer. A semannual component of lesser magnitude with equinoctial maxima is also present. The phases vary little during the first half of the year but undergo a large oscillation during the later half, registering a sharp mimimum around September and an equally sharp maximum around November. The results for other stations show a good deal of variability in the annual variations of the *Sq* (*H*) parameters. Nevertheless, some common features are observed.

The annual feature of the amplitudes attaining maximum values during local summer is also observed at Apia and Hurbanovo. The evidence is strong that this annual feature is a global phenomenon. Clear manifestation of this feature is, however, not observed for Honolulu, San Juan and Hermanus. This could be attributed to the proximity of these stations to the average latitude of *Sq* current focus. The variability in latitude of the *Sq* current focus could disturb the normal annual variations of the amplitudes.

The semi-annual feature of amplitudes attaining maximum values during the equinoxes is observed at a number of stations with varying degrees of clarity. This feature predominates at the low-latitude stations close to the geomagnetic equator.

The type of annual variation in phase angles seen for Alibag is observed for several stations widely separated in latitude, for example, Honolulu and Hermanus. The large positive change from about September to about November is seen also for San Juan and even for the geomagnetic equatorial station, Huancayo. A large semi-annual component tends to obscure the type of variations seen for Alibag in the annual variations of phase angles at Trivandrum, Kodaikanal and Annamalainagar. Nevertheless, the large positive change during the later part of the year may still be identified especially for Trivandrum and Annamalainagar.

Annual variations of *Sq* (*H*) parameters depend on the monthly mean pattern and strength of *Sq* electric current systems. Solar ionization of the ionospheric *Sq*-current layer largely controls the conductivity of the layer. The intensity of ionization, varying with solar zenith angle, contributes to an annual variation in the conductivity of the layer. The conductivity variation will have a large annual component for regions distant from the geographic equator and a large semi-annual component for regions close to this equator. The *Sq* currents being extensive systems (Chapman and Bartels 1940, Matsushita 1965) changes in conductivity in one region can affect the current strength in the entire current system, with maximum effects being felt close to the region of conductivity change. Annual variation in conductivity close to the tropics and at higher latitudes will impart a largely 12-monthly variation to the *Sq*-current strength. On the other hand annual variation in conductivity near the equator will impart a largely semi-annual variation to the current strength. From this point of view the predominance of the annual component at Hurbanovo and Apia and of the semi-annual component at Trivandrum, Kodaikanal, Annamalainagar and Huancayo in the amplitude variations are accountable as largely solar ionization effects. The striking predominance of the semi-annual component at the geomagnetic equatorial stations may have a dependence on the proximity of these stations to the geomagnetic equator. The exact mechanism is not clear.

The semi-annual variation of geomagnetic field, particularly of the component *H*, has been explained on the basis of the axial theory of Cortie (1912) and of the equinoctial hypothesis of Bartels (1932, 1963). These explanations, however, apply only with reference to incidence of geomagnetic disturbance, so that semi-annual variations of field are characterized by minima during the equinoxes. The *Sq* (*H*) variations (in low latitudes) do not have minimum magnitudes during the equinoxes; on the contrary they are maximum. Nor can the 'quiet-time ring current' (Currie 1966) account for the semi-annual variations in *Sq* (*H*) amplitudes, since, again the effect of the ring current will be to produce equinoctial minima.

The hypothesis of semi-annual change of *Sq*-current strength arising from a similar semi-annual change in ionization in high latitudes has been discussed at length by Wagner (1968), with a measure of scepticism. The greater predominance of the semi-annual feature of *Sp* (*H*) amplitudes at the geomagnetic equatorial stations as compared with those at higher latitude stations observed here definitely casts further doubt on the hypothesis. Wagner (1968) has sought for additional cause of the observed seasonal variations from atmospheric winds at current-layer heights. He has drawn attention to sudden phase jump in autumn and amplitude jump in Sepember/October of winds close to the current layer observed by other investigators. These

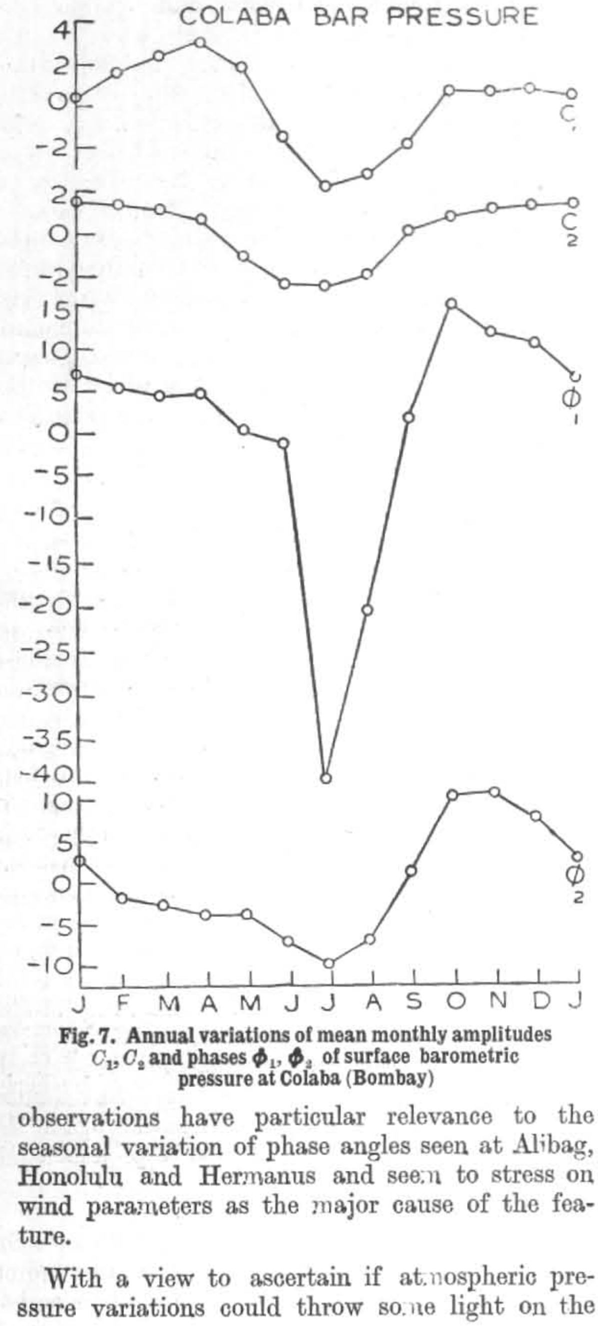

Fig. 7. Annual variations of mean monthly amplitudes C_1, C_2 and phases ϕ_1, ϕ_2 of surface barometric pressure at Colaba (Bombay)

observations have particular relevance to the seasonal variation of phase angles seen at Alibag, Honolulu and Hermanus and seem to stress on wind parameters as the major cause of the feature.

With a view to ascertain if atmospheric pressure variations could throw some light on the influence of atmospheric tides on $Sq(H)$ parameters, the monthly mean hourly surface atmospheric pressure at Bombay (very close to Alibag) averaged for the period 1941-60 were harmonically analysed to examine the annual trends of the amplitudes and phases of the first and second harmonics of the monthly mean diurnal variation. The results are shown in Fig. 7.

It is interesting to note that though the monthly values of amplitude C_2 of diurnal variation of atmospheric pressure is of larger magnitude than those of C_1 (more than double), C_1 has a very much larger annual range of variation. While C_2 has a purely annual oscillation with minimum in summer and maximum in winter C_1 has a discernible semi-annual component also, with maximum around the equinoxes. Both ϕ_1 and ϕ_2 of atmospheric pressure show large oscillations during the second half of the year, somewhat similar to those observed for $Sq\,(H)$ at Alibag. The oscillation in pressure is, however in advance of that in $Sq\,(H)$ by about two months. The similarity tends to stress on the influence by atmospheric wind parameters on $Sq(H)$. In this connection it is relevant to draw attention to observations by Wulf (1967). He found an asymmetry in geomagnetic Sq with respect to the solstices and suggested the seasonally changing large scale air circulation in the ionospheric Sq current layer as a probable cause.

In concluding it has to be stressed that precise causes of annual trends of $Sq\ (H)$ parameters observed in this investigation remain vague. The vagueness is apparently due to a number of factors like solar ionization varying with solar zenith angle, Sq-current layer conductivity changing with varying particle ionization in high latitudes, changes in atmospheric wind parameters and large scale air circulation in the ionospheric Sq-current layer and possibly several more, all playing their parts simultaneously.

4. Acknowledgement

We thank Shri B. N. Bhargava for some suggestive comments.

REFERENCES

Bartels, J.	1932	*Terr. Magn.*, **37**, 1.
	1963	*Ann. Geophys.*, **19**, 1.
Chapman, S. and Bartels, J.	1940	*Geomagnetism*, Vol. 1, Oxford Univ. Press.
Cortie, A. L.	1912	*Mon. Not. R. astr. Soc.*, **73**, 52.
Currie, R. G.	1966	*J. geophys Res.*, **71**, 4-79.
Matsushita, S.	1965	*J. atmos. terr. Phys.*, **27**, 1317
Wagner, C. U.	1968	*Ibid.*, **30**, 579
Wulf, U. R.	1967	*Mon. Weath. Rev.*, **93**, 660.
Yacob A. and Rao, D. R. K.	1966	*J. atoms. Terr. Phys.*, **28**, 351.