Some Aspects of Sq at Sanae

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A preliminary analysis of the Sq variation in H, Z and D as observed at Sanae during 1960 to 1970, is presented. Aspects that are discussed include the solar cycle variation, seasonal variation, semi-annual variation, and day-to-day variability of the Sq variation.

'n Voorlopige analise van die Sq-variasie in H, Z, en D, soos gedurende 1960 tot 1970 te Sanae waargeneem, word aangebied. Aspekte wat bespreek word, is die sonsiklusvariasie, seisoenvariasie, halfjaarvariasie en dag-tot-dag-veranderlikheid van die Sq-variasie.

Introduction

During geomagnetically quiet periods all components in geomagnetic records show smooth patterns of daily variation in solar local time. This pattern is called the "solar quiet daily variation" and is commonly denoted by Sq. It is known, however, that trapped particles in the magnetosphere may cause long-lasting effects on apparently quiet magnetic variation (*Maeda et al.*, 1964) and therefore, absolutely quiet variation is an idealized concept which cannot readily be estimated from observed data. Certain criteria described in the next section were thus used to select quiet days for the present study.

Previous analyses of the Sq variation pattern led to the conclusion that it is caused by currents flowing in the dynamo region of the ionosphere at an altitude of 90-150 km, together with induced currents in the earth and sea. (See *Matsushita*, 1967, for a review.) The ionospheric currents will therefore depend in intensity on the number of free electrons (that is, primarily on the degree of solar-produced ionization) and in shape on the driving mechanism (that is, on ionospheric winds and electric fields). *Olson* (1970a, 1970b) investigated the possibility of a magnetopause current system, caused by solar wind flow, as an explanation of the Sq variation, and also considered a possible contribution by ring currents and currents in the neutral sheet. His magnetopause current system could produce all the major features of the Sq variation, but only at one-fifth of the observed magnitude. The ring currents and neutral sheet currents showed effects of very small magnitude (of the order of 4γ in the magnetic X and Y components).

The Sq variation has been studied quite extensively at low and middle latitudes, and the trend was to assume that the variation at high latitudes could be considered as an extrapolation of the middle-latitude pattern. Analysis of IGY geomagnetic data showed, however, that in addition to the well-established Sq field in temperate latitudes, a polar Sq field exists on the polar cap (*Nagata & Kokubun*, 1962). This field was denoted by S_q^p.

The quiet day magnetic variation over the polar cap has resulted in some controversy in recent years, an important question being whether this variation is restricted to the polar cap, or whether it also extends towards lower latitudes. *Nishida & Kokubun* (1971) mention the point that S_q^p is derived from the data of the polar cap area alone, and that this does not exclude the possibility of an extension of the S_q^p variation to lower latitudes by the existence of two current vortices in the low-latitude region, associated with the two polar S_q^p current vortices. They propose that the DP2 variation, which extends from the polar cap to low latitudes, may be the principle constituent of S_q^p, especially in view of the close similarity between the characteristics of S_q^p and DP2. *Oguti* (1968) found that the geomagnetic variation in the polar region during periods of extreme quiet is an extension of the lower-latitude Sq field only. The S_q^p field therefore seems to be a feature of slightly disturbed conditions.

Kawasaki & Akasofu (1967), on the other hand, considered two exceptionally quiet days ($\Sigma Kp = O_+$ and $\Sigma Kp = 1_+$). They found a certain degree of disagreement between their S_q^p currents and the system proposed by *Nagata & Kokubun* (1962), which they ascribed to possible contamination by the auroral electrojet of the latter two authors' results. They concluded, however, that the S_q^p field is confined to the region within the auroral oval. In a later report *Kawasaki & Akasofu* (1972) discussed the relation between S_q^p and DP2. They found S_q^p both on extremely quiet days, and, significantly enhanced, also on moderately disturbed days.

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They also showed that DP2 is not a new mode but one of the manifestations of magnetospheric substorms. *Nishida* (1973) queried this last result on the ground that the argument of Kawasaki and Akasofu for the non-existence of DP2 is based on a premise that requires the non-existence of DP2 for its validity. *Feldstein & Zaytzev* (1967) separated the DP current system from the observed total current system to obtain S_q^p and found the resultant S_q^p system to consist of only one current vortex, completely contained in the polar cap and located between 12h00 and 18h00. In a study of DP2 at middle and low latitudes *Matsushita & Balsley* (1972) concluded that the whole concept of DP2 needs to be reconsidered, and they also drew attention to the effect on the determination of DP2 of the choice of a base level for the measurement of magnetic variations.

Sanae, situated at 60° S corrected magnetic latitude, is in a position between the mid-latitude Sq field and the polar S_q^p field. Magnetic observations from Sanae may therefore be useful in establishing the possible existence of a quiet day variation in addition to the well known Sq variation (i.e. a possible extension of a polar quiet day variation to lower latitudes).

This paper presents the results of an analysis of the Sq variation as observed at Sanae in the geomagnetic horizontal intensity (H), vertical intensity (Z), and declination (D) during the years 1960 to 1970.

Data Analysis

The criterion for the selection of quiet days was the Kp indices of the day under consideration. All days with all eight Kp indices of less than 2_- were included, as well as days with not more than one Kp index of 2_-, 2_o or 2_+. This often excluded one or more of the international quiet days of a particular month. As a result of loss of data and the rather stringent selection procedure, no data were available for the equinox period of 1962.

The data for the selected quiet days were then analysed in the following way.

After elimination of the non-cyclic change, the daily geomagnetic variations were expressed as a periodic function by a finite series of trigonometric functions:

$$f(t) = s_o + \sum_{n=1}^{k} s_n \operatorname{Sin}(nt + \alpha_n)$$

where s_o = mean of the 24 hourly mean values
s_n = amplitudes of the trigonometric functions
α_n = phase angles

It was found that the synthesis of the daily mean value (s_o) and the first four harmonics (that is k=4) obtained from such a harmonic analysis of the Sanae data reproduced the observed Sq variation with sufficient exactness.

In order to determine whether the data exhibit any dependence on magnetic activity, the data for the individual selected days of three months, representative of summer, winter, and equinox, were used in a harmonic analysis. The months used, and the ranges of ΣKp associated with them, were:

January 1963 (summer): ΣKp = 0_+ to 5_+
August 1964 (winter): ΣKp = 1_+ to 9_+
October 1965 (equinox): ΣKp = 1_+ to 6_-

None of the magnetic elements showed any discernable dependence on ΣKp for any of the amplitudes or phase angles of the four harmonic components. The data for the winter month exhibited a high degree of fluctuation, especially in phase angle. This may be a result of the day-to-day variability of Sq which is discussed in a later section.

In the following sections, the following notation is used:

Sq(H) denotes the Sq variation in H.
$Sq(H)_R$ denotes the synthesized range of the Sq variation in H.
$Sq(H)_{sn}$ and $Sq(H)_{\alpha n}$ denote the amplitudes and phase angles of the harmonic components (n = 1 to 4) of the Sq variation in H. Similar notation is used for Z and D.

Experimental Results

Solar Cycle Variation

In later sections magnetic data are averaged over all the years analysed in this paper (1960 to 1970). It is therefore necessary to determine whether the solar cycle variation of Sq has any effect on the interpretation of such averaged results. For this purpose the data for each year were sub-divided according to the three Lloyd seasons j, e, and d, where at Sanae

j denotes the winter solstice months (May to August)
e denotes the equinoctial months (March, April, September, October)
d denotes the summer solstice months at Sanae (November to February).

A harmonic analysis was performed on each of the data groups thus obtained, and the results were used to obtain "synthesized ranges" of hourly mean values.

The synthesized ranges and the amplitudes of the first two harmonic components of the three magnetic elements showed the expected solar cycle variation for each of the three seasons. The solar cycle dependence was investigated further by comparing the synthesized ranges and harmonic amplitudes with the average sunspot number, R_z, for each Lloyd season of each year in a regression analysis. As a matter of interest the Wolf ratio, M, was also determined for each regression analysis, where M is defined as follows (*Chapman & Bartels*, 1940) - The regression line

$S = A + BR$

with S the ranges or amplitudes of the Sq variation and R the sunspot numbers, may be written as

$S = A(1 + MR)$

where M (= B/A) is the Wolf ratio.

Table 1

Solar cycle variations in Wolf ratios (M) and correlation coefficients (r)

	Synthesized Ranges		1st Order Harmonic		2nd Order Harmonic	
	10^4M	r	10^4M	r	10^4M	r
Horizontal						
Summer	74,5	,893	72,2	,915	53,4	,564
Winter	233,6	,869	844,2	,788	189,2	,904
Equinox	85,7	,886	101,0	,915	152,4	,902
Declination						
Summer	53,0	,805	48,8	,775	66,8	,739
Winter	143,3	,833	223,8	,775	125,6	,767
Equinox	67,0	,879	68,4	,848	72,3	,857
Vertical						
Summer	74,4	,797	71,6	,863	68,5	,672
Winter	129,0	,839	332,2	,853	166,8	,774
Equinox	93,4	,787	123,8	,857	90,4	,624

Table 1 gives the Wolf ratios and correlation coefficients (r) obtained in the regression analysis of the synthesized ranges and the first two harmonic component amplitudes. The fourth order, and sometimes also the third order, harmonic components did not show a significant solar cycle variation. A reason for this may be the small amplitudes of these components, which may result in a solar cycle variation which is smaller than the scatter of the data. On a graph a solar cycle variation was generally evident in the third order harmonic amplitude in spite of the small magnitude and relatively large scatter.

Table 1 shows an annual variation of the Wolf ratio for all components. M is always smallest in summer and largest in winter. The observed seasonal variation of M is in agreement with results reported earlier (*Chapman, Gupta & Malin,* 1971; *Scheepers,* 1973), but it is not possible to compare the present results with those reported earlier because of the somewhat erratic behaviour of the seasonal variation of M with latitude.

The correlation coefficients in Table 1 are all fairly high, but it seems reasonable to assume that they could be improved by a more accurate determination of R_z. Instead of using the average R_z for a particular Lloyd season, as was done here, only the sunspot number associated with the selected quiet day could be used.

No solar cycle variation of the phase angles was evident, except for a small variation ($\sim$ 20°) in $Sq(H)\alpha_2$ and $Sq(Z)\alpha_2$ for the summer months.

From these results it can be concluded that the Sq variation for a particular month averaged over a solar cycle may be used, as long as care is exercised in drawing conclusions from the ranges or amplitudes thus obtained because they show a significant solar cycle variation. The shape of the daily variation curves should not be affected to any marked extent by such an averaging process, as they show no significant solar cycle variation.

Annual Variation

The annual variation of the shape and amplitude of the Sq variation of H, Z, and D was determined by dividing the year into 24 half-month periods. The magnetic data for each half-month period were then averaged over the eleven years 1960-1970. The resultant 24 Sq curves for each magnetic element may be influenced by the solar quiet years, 1964 and 1965, because the selection criterion resulted in more days being selected from these years than from the more active years. From the 24 curves, the mean curve for periods 1 and 24 (mid-December to mid-January) was determined to represent the typical summer Sq variation. Similarly periods 6 and 18 were used to represent the equinoctial Sq variation, and periods 12 and 13 to represent the winter variation. These results for each of the magnetic elements are presented in Fig. 1.

The curves in Fig. 1 may now be compared with the average Sq variation curves for the different longitudinal zones given by *Matsushita* (1967) in his Fig. 7. As Sanae at 2° W (geographic) lies midway between the Africa-Europe zone (zone 1) and the North and South American zone (zone 3), it can be expected that such a comparison will be rather difficult. It is in fact found that some of the curves in Fig. 1 compare better with the zone 1 variation while others can be associated with zone 3 variations. In general it may be concluded that the curves in Fig. 1 agree in all major features with the average Sq curves given by Matsushita in his Fig. 8.

Fig. 1 may also be compared with the known equivalent current systems associated with quiet magnetic variations. These current systems are:

- the mid-latitude Sq system (*Matsushita,* 1967, Fig. 9);
- the polar S_q^p system (*Nagata & Kokubun,* 1962, Figs. 7 and 8, and other reports quoted above);

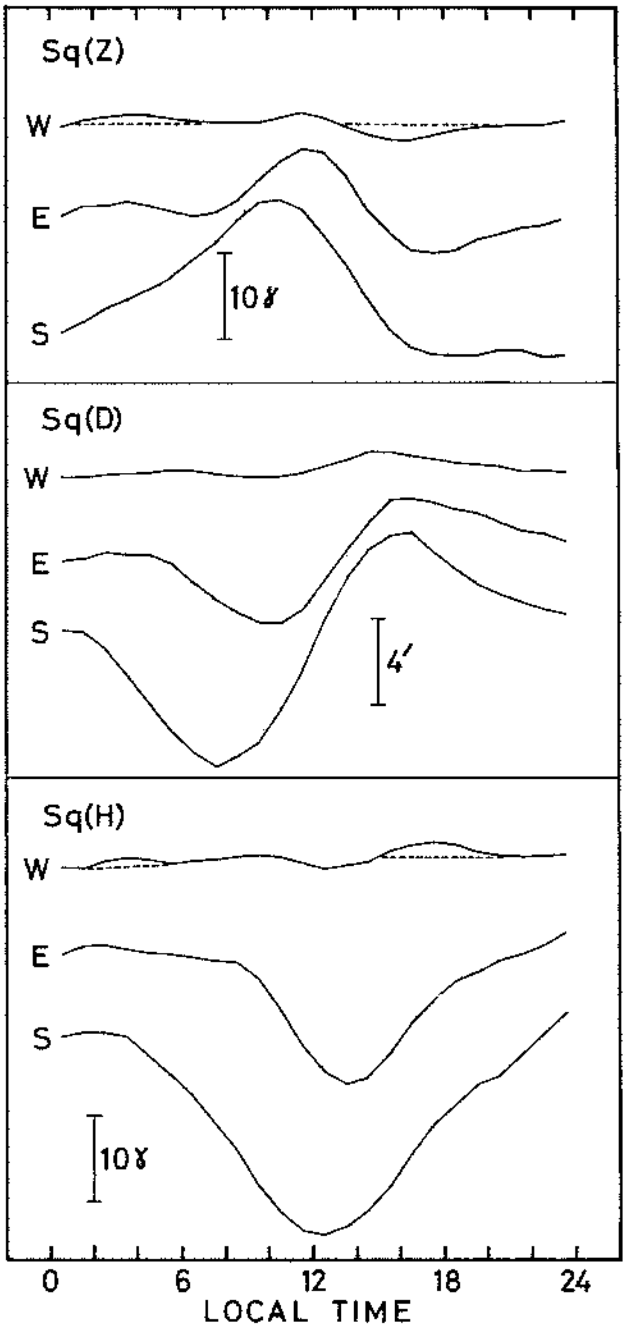

Fig. 1. The Sq variation in the three magnetic elements for the summer (S), winter (W), and equinox (E) at Sanae. The irregularities discussed in the text are indicated by broken lines on the winter Sq(H) and Sq(Z) curves.

the polar and mid-latitude DP2 system (*Nishida* 1968, Fig. 1); and
the auroral electrojet (*Rostoker*, 1972, Fig. 11b).

The Sq system can qualitatively describe all the major features of the curves in Fig. 1. The seasonal decrease in range of the Sq variation at Sanae agrees with the decrease in current intensity from summer to winter. The phase changes of the variation at Sanae also agree with the longitudinal shift of the Sq current system with season.

The auroral electrojet, if it existed at all on the selected days, is not expected to have a significant effect at Sanae during quiet days, as this station then lies some distance equatorward of the auroral oval (at least 10° in latitude during the daytime).

Comparing the Sq variation at Sanae with S_q^p or DP2 is rather difficult because these systems will be superimposed on the much more intense mid-latitude Sq current system. During winter, however, the mid-latitude Sq current has such a small effect at Sanae that one would expect the presence of other current systems to show up better then. Some irregularities can in fact be observed in the Sq(H) and Sq(Z) variation during the winter. Sq(H) shows a small maximum at 17h00 and possibly also between 00h00 and 06h00. Sq(Z) on the other hand shows, in both winter and the equinoctial period, a small minimum at 16h00 and a maximum at 04h00. It should be noted that because Z is negative at Sanae, a minimum means a larger negative value, that is a numeric increase. The statistical significance of this additional daily variation needs some consideration, as the range of the variation is of the same order as, or even smaller than, the standard deviation of the data. The diurnal variation of Sq(H) and Sq(Z) of the 5 monthly international quiet days of the Lloyd winter seasons taken separately for each of the years 1960 to 1970, show this additional variation clearly for each year, although not as smoothed as in Fig. 1. It is therefore reasonable to accept that this variation exists as a distinct variation in addition to the normal mid-latitude Sq variation.

If it is assumed that Sanae lies on the outer boundary of the S_q^p current system, then the minimum and maximum in Sq(Z) agree with the current system proposed by *Nagata & Kokubun* (1962). For Sq(H), however, it is only the afternoon maximum which may be ascribed to this current system. In the morning one would have expected a minimum. The single-vortex S_q^p current proposed by *Feldstein & Zaytzev* (1967) also explains the afternoon irregularities in Sq(H) and Sq(Z) at Sanae, but cannot explain the morning irregularities.

If, on the other hand, one considers the DP2 current, which extends to sub-auroral latitudes, all the irregularities of the Sq variation at Sanae may be explained. The maximum and minimum in Sq(Z) and the afternoon maximum in Sq(H) can be directly accounted for by the current system. In the morning, however, Sanae at 60° S (geomagnetic) lies close to the focus of the DP2 current. A positive or negative peak in Sq(H) would therefore depend on whether the focus is equatorward or poleward of Sanae. As it is reasonable to assume that the DP2 focus may shift in latitude from day to day, it may be concluded from the morning positive peak in Sq(H) in Fig. 1 that this focus generally lies equatorward of Sanae during winter.

The above explanation thus seems to favour the existence of the more extended DP2 current, rather than the S_q^p current. Considering, however, the conclusion of *Kawasaki & Akasofu* (1972) that DP2 is just one of the manifestations of magnetospheric substorms, it may also be concluded that the irregularities in Fig. 1 are a result of polar substorms rather than a feature of Sq at Sanae.

(The median value of ΣK_p for the winter period discussed above was 6_+).

It should also be kept in mind that an eastward evening auroral electrojet and a westward morning electrojet could also explain the maximum and minimum in Sq(Z) and the evening maximum in Sq(H). It should therefore not be assumed too readily that the auroral electrojet has no effect at Sanae during the selected days.

It is difficult to include the winter Sq(D) at Sanae in the above discussion because the normal Sq(D) maximum at 16h00 coincides with the irregularity observed at 16h00 in Sq(H) and Sq(Z).

Day-to-Day Variability

The day-to-day variability of the Sq variation has already been reported by a number of workers, amongst them *Brown & Williams* (1969) and *Schlapp* (1968), for middle latitude stations. Brown and Williams determined this variability for Sq(H) and illustrated the concept by considering the local time of occurrence of minima in Sq(H) (that is, phase changes). Schlapp on the other hand considered day-to-day changes in the range of Sq(H) over a world-wide network of stations. The general conclusions were that this variability occurs more often in winter than in summer (*Brown & Williams,* 1969) and that the correlation between stations falls off rapidly with distance (*Schlapp,* 1968).

To determine whether this feature is also found at Sanae, a harmonic analysis was performed on each of the selected quiet days and the means of the harmonic components for the 24 half-month groups of data used in calculating the Annual Variations determined. The first-order harmonic amplitudes and phase angles found for the three magnetic elements are given in Fig. 2, together with the standard deviation of each point.

The great variability of the phase angles during the winter, as shown by the standard deviation, is immediately evident. These results, which agree with those reported by *Brown & Williams* (1969), seem to suggest that an irregular variation may exist superimposed on the normal Sq variation. During summer the much more intense normal Sq variation dominates, but as the range of this variation decreases towards winter, the irregular effect begins to dominate. Figs. 10, 11 and 12 of Brown and Williams also show that the abnormal minima exist together with the normal minimum in the Sq(H) variation, rather than as a phase shift of the normal Sq(H) minimum.

The semi-annual variation

When the annual variation of $Sq(H)_{s1}$ shown in Fig. 2 is considered, small maxima in the amplitude close to the equinoxes are evident. These maxima appear in data groups 4 (last half of February) and 21 (first half of November). This observation may be compared with similar results reported by *Wagner* (1968, 1969). He found maxima in the summed ranges of the magnetic X and Y components during April and September. The observation that the maxima at Sanae do not coincide with the equinoxes, or with the maxima at Niemegk

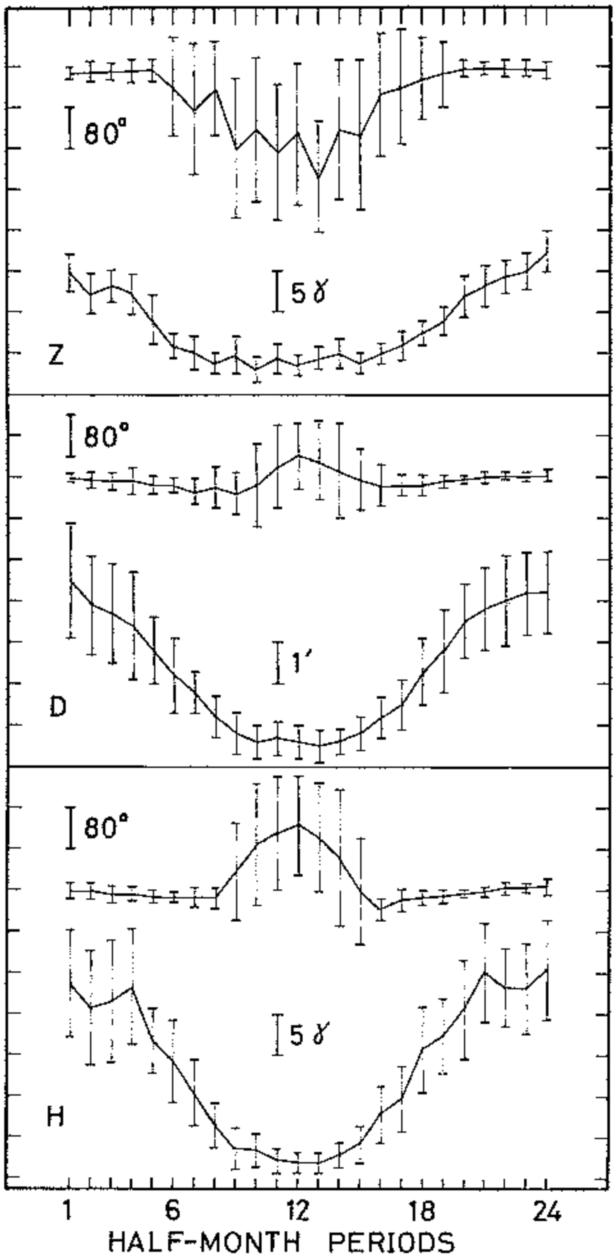

Fig. 2. The annual variation of the first-order harmonic amplitudes and phases of the three magnetic elements for the 24 half-month periods. The amplitude and phase are given by the lower and upper curve respectively for each magnetic element, and the error bars give the standard deviations from the mean.

(the station used by Wagner), may be explained by the fact that when a small semi-annual variation is superimposed on a much larger annual variation, the resultant semi-annual maxima shift away from the equinoxes. As an example of this, the function Sin $(2\theta + 285°)$, which is a semi-annual variation with maxima at the equinoxes, may be superimposed on the function 5 Cos χ (χ = solar zenith angle) which is representative of the E-layer electron density (*Muggleton,* 1972). Calculation of the resultant function:

$$5 \cos\chi + \sin(2\theta + 285°)$$

for a latitude of 70° S (Sanae) gives semi-annual maxima in periods 4 and 20, in good agreement with

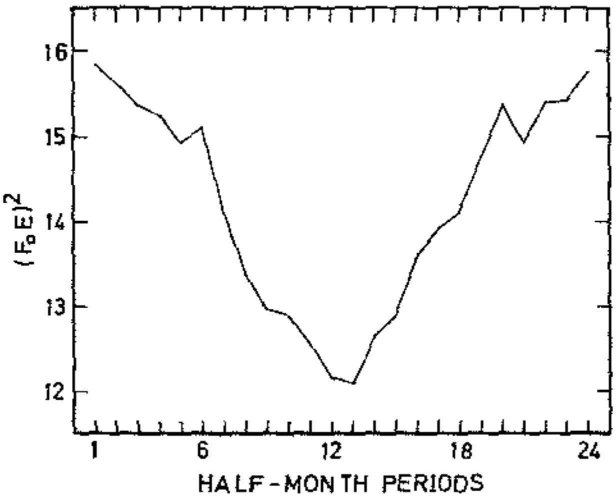

Fig. 3. The annual variation of the ionospheric noon $(FoE)^2$ *values at Johannesburg for the 24 half-month periods.*

the Sanae results. Using the same function for a latitude of 52° N (Niemegk) the maxima are found in September and April, in complete agreement with Wagner's (1969) results.

The problem now remains to explain the existence of the semi-annual variation with maxima at the equinoxes. The Sq currents may vary either because of changing electron densities or because of changes in the ionospheric driving mechanisms. *Wagner* (1968) mentioned that a semi-annual variation in the ionospheric prevailing wind vector had been observed at 92 km altitude. However, E-layer electron densities may also be considered as a possible cause. A semi-annual variation in magnetospheric particle precipitation phenomena (*Kühn*, 1969) and ionospheric particle densities (*Titheridge,* 1973) is known to exist, and it was shown by *Boller & Stolov* (1969) that by using the Kelvin-Helmholtz instability, the semi-annual variation in magnetic activity could be explained by the effect of the tilt-angle of the earth's dipole axis on solar wind interaction with the magnetosphere. *Ivanov-Kholodny & Kazatchevskaya* (1971) also observed that ionization of the E-region by precipitating electrons may occur.

In order to test the possibility of larger electron densities during the equinoxes accounting for the observed semi-annual variation in Sq(H) amplitude, the annual variation of $(f_oE)^2$ was determined from ionosonde data obtained at Johannesburg. As mentioned by *Muggleton* (1972) the E-region maximum electron density, $N_m(E)$, is related to the critical frequency by the expression

$$N_m(E) \propto (f_oE)^2$$

The average noon values of $(f_oE)^2$ for Johannesburg for the years 1967 to 1970, also divided into 24 half-month groups, are shown in Fig. 3, and small maxima in the electron density are evident near the equinoxes.

It therefore seems that increased electron densities in the E-region should also be considered as a possible explanation of the semi-annual variation in Sq(H) amplitude.

Conclusion

The solar cycle variation of Sq at Sanae agrees with similar results from other observatories. The seasonal variation of the Wolf ratio, M, does not compare too well with results reported by *Chapman, Gupta & Malin* (1971) and by *Scheepers* (1973). Both these reports, however, show a somewhat irregular variation of M with latitude and season, and one must therefore agree with their conclusion that the properties of the Wolf ratio should be investigated in more detail.

The Sq(H) and Sq(Z) variation observed in the winter at Sanae seems to agree with the DP2 current system, and its sub-auroral extension, as proposed by *Nishida* (1968) and *Nishida & Kokubun* (1971). The present data, however, are not conclusive enough to support either the possibility that DP2 is the major constituent of S_q^p as proposed by *Nishida & Kokubun* (1971), or that DP2 is one of the manifestations of polar magnetospheric substorms as proposed by *Kawasaki & Akasofu* (1972). The possibility of substorm activity affecting the present analysis is not excluded, especially because the median ΣK_P was relatively high (6_+) during the period considered in the analysis. More conclusive results may be obtained by considering Sq for individual quiet days, but the effect of the day-to-day variability of Sq should then be taken into account.

The day-to-day variability observed in the phase angles of all three of the magnetic elements also needs further study to arrive at an explanation. An analysis of individual days may in this case also provide more insight into thi sfeature of the Sq variation.

The observed semi-annual variation in the amplitude of Sq(H) agrees well with results reported for other stations (*Wagner*, 1968, 1969). It is evident from the present results that electron precipitation and increases in E-layer ionization should also be considered as possible mechanisms to explain this phenomenon. An accurate description of the semi-annual variation will be difficult unless an accurate description of the solar ionization of the E-layer is available.

The semi-annual variation cannot be determined unambiguously by the simple process of performing a harmonic analysis on the annual variation curve of the amplitude or range of Sq(H), because the $\text{Cos}\,\chi$ dependence of electron densities also contains a second-order harmonic. As an example, a harmonic analysis performed on the function

$$5\,\text{Cos}\,\chi + \text{Sin}\,(2\theta + 285°)$$

gave the amplitude and phase angle of the "semi-annual variation" as 1,05 and 300° respectively at a latitude of 70° S, and 1,18 and 300° at 30° S, instead of the values 1,00 and 285° in the term Sin $(2\theta + 285°)$, which is the "semi-annual" part of the above function. The variation of electron density with χ as actually observed in the E-layer is much more complicated than the simple relation used here (*Muggleton,* 1972), and so it can be expected that a harmonic analysis will give even more unreliable values for the semi-annual variation amplitude and phase angle than are illustrated here.

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