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Variations of Focus Latitude and Intensity of Overhead Current System of Sq with the Solar Activity

Masanori SHIRAKI

Abstract

A simple method to estimate focus latitude of *Sq* is presented. Using this method latitude changes due to the solar activity are studied in the West Pacific and the North American regions. The changes are large in winter for both regions, and the center of focus is in higher latitude during solar quiet years than that during solar active years. The changes in equinox and summer are smaller than that in winter, and in summer the change shows rather opposite sense. Consequently, the seasonal changes of focus latitude are different between the active and quiet years of the sun.

A measure of intensity is obtained simultaneously and the relation between the measure and the sunspot number is also examined. The coefficient *m* of the relation shows seasonal and regional differences. The largest value of *m* in winter is consistent with the large change of focus latitude in winter.

1. Introduction

A magnetogram of a geomagnetically quiet day shows a regular daily variation of a few ten gammas in range. This variation is called solar quiet daily variation, *Sq*. There have been many studies on this variation up to the present. Its morphology has become clear as geomagnetic records come to be obtained in the extensive network all over the globe. From long period observations *Sq* was found to vary in intensity in unison with the annual mean sunspot numbers, by 50% or more. This fact led Stewart in 1882 to infer that *Sq* must have its origin in the upper atmosphere. His inference was extended by Schuster (1908) and Chapman (1919) in mathematical form. This idea is now known as the atmospheric dynamo theory. Their studies propose that *Sq* variation is caused by electric currents which flow in the electrically conductive dynamo layer. It may be at a height of 100–125 km. Recent rocket and satellite observations of the ionosphere have provided a certain result for our confidence in existence of an actual dynamo region (e.g. Davis et al 1967).

The important influence of solar activity on *Sq* during sunspot cycle has been studied by many research workers. Change of the solar activity, which is roughly indicated by sunspot numbers, affects state of dynamo layer and consequently *Sq* variation. The problem is to study how the state of dynamo layer and *Sq* variation are influenced by the solar activity, respectively. The conductivity of the dynamo layer is related to the critical frequency of *E* layer, where *Sq* current flows mainly. The ionosphere has been studied by the ground based sounding. And it is found that the critical frequency of E layer varies in the course of sunspot cycle in a manner consistent with the solar cycle variation of Sq (Ratcliffe and Weekes 1960, Maeda and Fukao 1972).

The solar cycle influence on Sq variation has been studied in connection with Sq intensity which is expressed mainly by ranges. As first reported by Wolf in 1859, the influence of annual mean sunspot number Rz on annual mean range of Sq, $r(Sq)$, is expressed by the formula

$$r(Sq) = A\,(1 + M \cdot Rz).$$

However, different values of the coefficient M have been given for different stations, different elements and different seasons (Chapman and Bartels 1940). This non-uniformity of M values may indicate that the distribution of Sq current changes in form as well as in intensity in the course of sunspot cycle.

Focus latitude of Sq current system is affected by the current form. Several studies of Sq indicate that focus latitude is likely to change with the activity of the sun. Matsushita (1960) and the present auther (Shiraki 1972) studied the seasonal change of focus latitude of Sq in the North American region and the West Pacific region, respectively. Their results show that focus latitudes in summer are higher than those in winter. Their studies are based on the IGY data (the mean sunspot number Rz was 187.5 for 1957–1958) and the IASY data (Rz = 66.6 for 1971), respectively. During these years the sun was comparatively active.

On the other hand, Ota (1949) and Hasegawa (1960) showed that the position of focus shifted towards the pole in winter and towards the equator in summer. They used the Second Polar Year data (Rz = 8.4 for 1932–1933). The same conclusion was obtained by Bartels (Chapman and Bartels 1940) from the spherical harmonic analysis of geomagnetic data obtained in the sunspot minimum year of 1902 (Rz = 5.0). These analyses indicate that the focus latitude of Sq current is situated in lower latitude in summer than in equinoxes and winter during rather quiet years of the sun. This opposite seasonal change may be caused by the difference in the solar activity rather than by the difference in the method of analysis. To make it clear the solar cycle influence on focus latitude of Sq current system is examined during one solar cycle or more in the present paper.

The overhead current system of Sq can be calculated from Sq variations observed on the earth's surface by potential theory. The location of focus of counterclockwise oval currents in the northern hemisphere or of clockwise ones in the southern hemisphere is determined. This method is the most desirable one to obtain the focus position. However this method requires a lot of data of Sq variation on the globe and the analysis is not easy. Up to this time some simpler methods have been used to determine the focus position of Sq current system (Ota 1949, Matsushita 1960, Osborne 1966, 1968, Yanagihara 1970). These methods utilize the nature of Sq variation near the focus. For example, Osborne (1966, 1968) estimated the focus position using ranges of horizontal intensity of two stations near the focus. To obtain a range at a station he adopted a mean value from 10 to 13 hour as daytime value. It may be influenced by phase differences in horizontal intensity variation between stations and seasons. *Sq* variation in the West Pacific region shows such phase change (Shiraki 1972). Yanagihara (1970) discussed the changes of focus latitude of *Sq* with special reference to a period from 10 to 30 days. He used a parameter which is calculated from the horizontal intensity variation of a station. He stated that this parameter shows roughly a relative variation of focus latitude. In his method the influence of phase differences between stations and seasons become small. And moreover the influence of disturbances become small. However this parameter includes the effect of intensity change. This effect must be excluded for the study of solar cycle variation of *Sq* because intensity of *Sq* changes very much in the course of solar cycle. In the present paper a modified method is presented and the variation of focus latitude of *Sq* current system due to the solar cycle is examined in the West Pacific and the North American regions.

2. Estimation of focus latitude of *Sq* current system

Sq variation has been studied in detail by Chapman and Bartels (1940), Vestine et al (1947), and Matsushita (1967). Variations of each element show different latitudinal dependency. Among them *Sq* variation of horizontal intensity gives us information about the focus latitude of current system. Fig. 1 shows latitudinal *Sq* variation of horizontal intensity obtained by Matsushita (1967) from the IGY data. His result is given by the dip latitude. From this figure it is evident that the variation at higher latitudes than thirty degrees shows a pronounced minimum around noon or a little earlier. This type of the variation indicates that the station is in the north side of focus latitude. And the variation of a pronounced maximum in daytime indicates that the station is in the south side of focus latitude. The type of the variation changes near a latitude of thirty degrees where the focus position of *Sq* current system is located. Range of the variation is very small at the location. In the present paper this character of horizontal intensity is used for the estimation of focus latitude.

At first a parameter γ_1 is calculated from daily variation of horizontal intensity H at middle latitude stations as follows

$$\gamma_1 = \sum H\,(\text{daytime}) - \sum H\,(\text{nighttime})$$

The first term in the right hand side of the equation indicates the summation of hourly values during daytime from 6 a.m. to 6 p.m. The second term sums up hourly values during nighttime from 6 p.m. to 6 a.m. Considering the latitudinal dependency of horizontal intensity variation as shown in Fig. 1, in the northern hemisphere, the value of γ_1 at a station in the north of focus latitude may be negative, and, on the contrary, in the south of focus latitude it may be positive. Near the focus latitude γ_1 may be almost zero. Therefore the focus latitude ϕ_f is defined here by the latitude where γ_1 is equal to zero.

If the relation between γ_1 value and latitude ϕ is known, the latitude ϕ_f can be determined by γ_1 values of some middle latitude stations. In this paper the relation

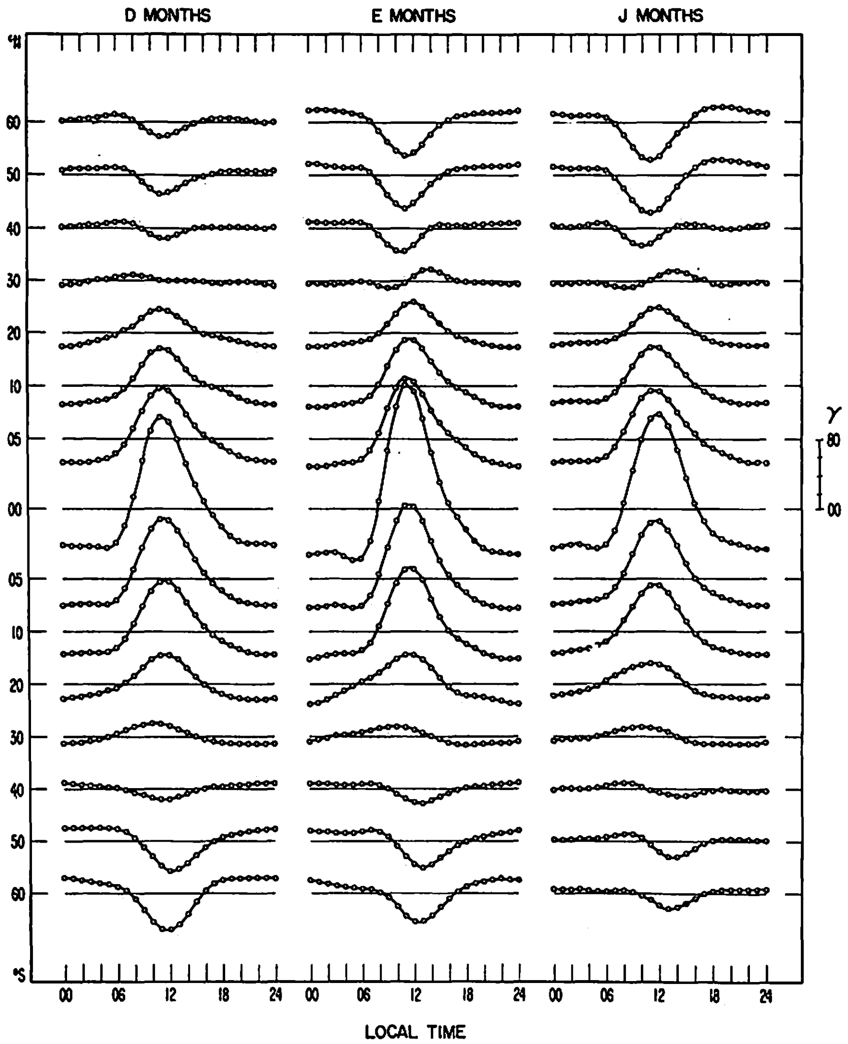

Fig. 1. World-wide averages of solar quiet daily variations of horizontal component at different latitudes for three seasons during the IGY. *D* month, *E* month and *J* month in the figure correspond to winter, equinox and summer seasons in this paper, respectively (after Matsushita 1967).

between γ_1 and ϕ is assumed to be linear near the focus latitude. And three stations are selected near the focus latitude to calculate γ_1. The focus latitude ϕ_f is determined by the least square method from these γ_1 values assuming linear relationship between γ_1 and ϕ.

From the definition of γ_1 it is understandable that γ_1 is related mainly to the amplitude of diurnal term. That is, the focus latitude defined here is a position where the coefficient a_1 of diurnal term of horizontal intensity changes its sign. By means of the graphical integration method Hasegawa (1960) deduced the potential distribution of *Sq* field every two hours in the universal time from the Second Polar Year data. His result is reproduced in Fig. 2. The focus position and the intensity of potential

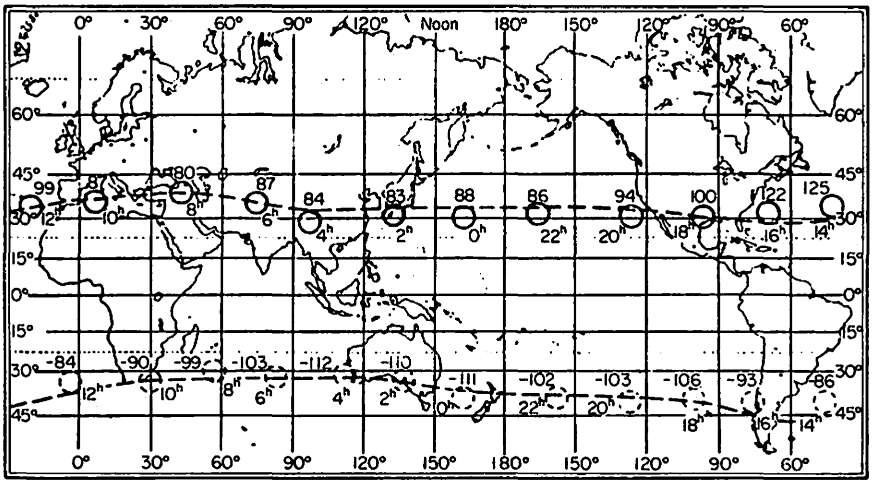

Fig. 2. Focus positions of Sq current system every two hours for the average of summer and winter during the Second Polar Year. Geographic coordinates. The number alongside each point indicates the potential (in units of 0.825×10^3 cgs) at each UT epoch. The broken curves in the two hemispheres show the boundaries at which the harmonic coefficient a_1 of diurnal component of the X variation changes its sign (after Hasegawa 1960).

are indicated in the figure. Simultaneously the broken curves in Fig. 2 show the position where the coefficient a_1 of diurnal term of the north component X changes its sign. The broken curves go nearly along the same course as focus position of current system which are deduced from the potential. This fact shows that the focus latitude ϕ_f here defined indicates approximately the actual focus latitude of *Sq* current system, neglecting the difference between horizontal intensity H and north component X.

A value of γ_1 contains both effects of intensity change of current system and of latitudinal change of focus. Besides the focus latitude ϕ_f, another quantity, inclination in the linear relation between γ_1 and ϕ, is calculated simultaneously. The inclination $|d\gamma_1/d\phi|$ does not express the intensity itself of *Sq* current, but gives a measure of the intensity. As γ_1 represents mainly characteristics of diurnal term, $|d\gamma_1/d\phi|$ is also related to intensity of diurnal term.

The above-stated method is a simpler way to estimate focus latitude. Consequently it includes some problems. As well known geomagnetic variations on the earth can be divided into two parts, external and internal. Approximately two-thirds of the varying magnetic field is directly due to overhead electric currents, and the remainder comes from the currents induced within the earth by the change of overhead currents. The focus positions of external and internal current systems may generally not coincide with each other. However, for an approximation, it is assumed that the internal current system does not have much effect on the focus position of the equivalent overhead current system (Hasegawa 1960). Another problem may arise from the approximation that the focus latitude is determined mainly by the position where the coefficient a_1 of diurnal term of horizontal intensity changes its sign. On account of these approximations the method may give only a rough focus position of current system. However these approximations may be accepted for the purpose to study relative changes of focus latitude under the condition that the analysis is confined to the same region and the same season. Even in such a case the relative change is fairly large as shown later, and this method may be useful to study the sunspot cycle influence on focus latitude and intensity of *Sq* current system.

3. Data and analysis

An observation during at least one solar cycle is desirable to study the relation between *Sq* variation and the solar activity. Moreover, to estimate focus latitude of current system by means of the method described in the previous section, observed values of horizontal intensity at two or more stations are necessary near focus latitude. From these reasons data in the West Pacific and the North American regions are analyzed in this paper.

Analyses carried out up to the present indicate that the focus of *Sq* current passes near thirty degrees of geographic latitude in the West Pacific region (Matsushita and Maeda 1965, Matsushita 1967, Shiraki 1972). Near this latitude three permanent stations at Memambetsu, Kakioka and Kanoya, are operated by the Kakioka Magnetic Observatory (belonging to the Japan Meteorological Agency). The locations of these stations are listed in Table 1 (a). Observation began in 1952 at Memambetsu, in 1913 at Kakioka, and in 1958 at Kanoya. These stations are convenient for the present study. Hourly mean values of horizontal intensity from 1958 to 1969 which have been given in the yearbooks of the Kakioka Magnetic Observatory are used. As it is seen in Table 1 (a) the local time at each station does not differ more than thirty minutes from the Japanese Standard Time (JST). So the difference is ignored and data are handled in reference to the JST. This ignorance gives little influence on γ_1 values.

On the other hand, in the North American region the following three stations are selected considering analyses carried out up to the present (Matsushita 1960, Matsushita and Maeda 1965). These stations are Cheltemham (moved to Fredericksburg in 1956), Tucson and San Juan. Their locations are listed in Table 1 (b). Analysis is made for the period of fifteen years from 1948 to 1962 for which data are at hand. At each station the value of γ_1 is calculated from horizontal intensity on the basis of its standard time. Focus position and intensity of *Sq* current is generally dependent

Table 1. Location of stations used in this study
(a) the West Pacific region

Station	Memambetsu	Kakioka	Kanoya
Geog. lat.	43°55′N	36°14′N	31°25′N
Geog. long.	144°12′E	140°11′E	130°53′E
Geom. lat.	34.0°N	26.0°N	20.5°N
Dip lat.	37.4°N	30.1°N	26.0°N

(b) the North American region

Station	Cheltemham Fredericksburg	Tucson	San Juan
Geog. lat.	38°44′N 38°12′N	32°15′N	18°23′N
Geog. long.	76°51′W 77°22′W	110°50′W	66°07′W
Geom. lat.	50.1°N 49.6°N	40.4°N	29.9°N
Dip lat.	54.9°N 54.4°N	40.3°N	32.1°N

on longitude as seen in Fig. 2. However, as differences in longitude in the North American region are not so large (Matsushita 1960), the influence of them on γ_1 is not taken into consideration. Neglecting the differences in longitude, ϕ_f and $|d\gamma_1/d\phi|$ are calculated similarly.

Solar quiet daily variation *Sq* is defined as a variation on a geomagnetically quiet day. Practically five international quiet days are selected per month to calculate *Sq* (Chapman and Bartels 1940), even though small disturbances are found usually on these days superposed upon the regular daily variation. Similarly derived *Sq* is used in the present study. Correctness of such *Sq* may depend somewhat upon the general disturbance level during the period in which *Sq* are derived, because selected quiet days during solar active years may include more disturbances than those during solar quiet years. So the effect of disturbances in *Sq* should be taken into consideration when the result of the analysis is discussed, particularly on solar cycle dependency (see section 5).

In the derivation of *Sq* the so-called noncyclic change (Price 1963) should be eliminated. The noncyclic change of *d* gammas per day gives an effect of $-3d$ gammas on γ_1 values when using hourly values from 00h to 24h in UT at stations in the West Pacific region. The mean noncyclic change of horizontal intensity on the international quiet days is 6.2 gammas at Kakioka for the period of twelve years of the present analysis. This amount cannot be ignored. Therefore in this study the noncyclic change is eliminated with a linear adjustment using the difference of mean values from 23h to 01h in UT.

After the adjustment for noncyclic change, Sq variation is calculated for every month and divided into three seasons for each year; winter (January, February, November, and December), equinox (March, April, September, and October), and summer (May, June, July, and August). And mean Sq variatoins of three seasons and the year are used for analyses on year-to-year change of focus latitude and intensity measure of Sq current system.

4. Results of analyses

The values of parameter γ_1, latitude ϕ, focus latitude ϕ_f and intensity measure $|d\gamma_1/d\phi|$ are calculated for mean Sq. Examples of the relation between γ_1 and ϕ in the West Pacific region are shown in Fig. 3 for sunspot maximum year 1958 (Rz =

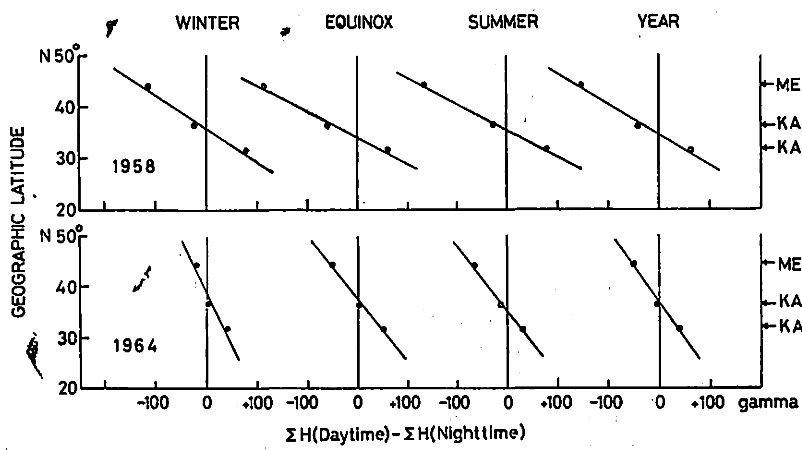

Fig. 3. Examples of the relation between parameter γ_1 and geographic latitude ϕ in the West Pacific region for the sunspot maximum year 1958 (Rz=184.8) and the sunspot minimum year 1964 (Rz=10.2).

184.8) and for sunspot minimum year 1964 (Rz = 10.2). Scale for ϕ is the geographic latitude. In the West Pacific region the geographic latitude differs about ten degrees from the geomagnetic latitude and six degrees from the dip latitude (see Table 1). These differences are nearly constant among three selected stations. Straight lines in the figure are the best fit ones determined by the least square method. It is clear that the linear relation holds approximately among stations used in this analysis. In detail γ_1 value at Kakioka is always smaller than the value of the straight line. It may be more precise to assume a curve of the second degree between γ_1 and ϕ.

Focus latitude ϕ_f and intensity measure $|d\gamma_1/d\phi|$ are determined from the best fit linear relation such as the straight lines in Fig. 3. Year-to-year changes of ϕ_f and $|d\gamma_1/d\phi|$ for mean Sq in each season and the year are shown in Fig. 4 for the West

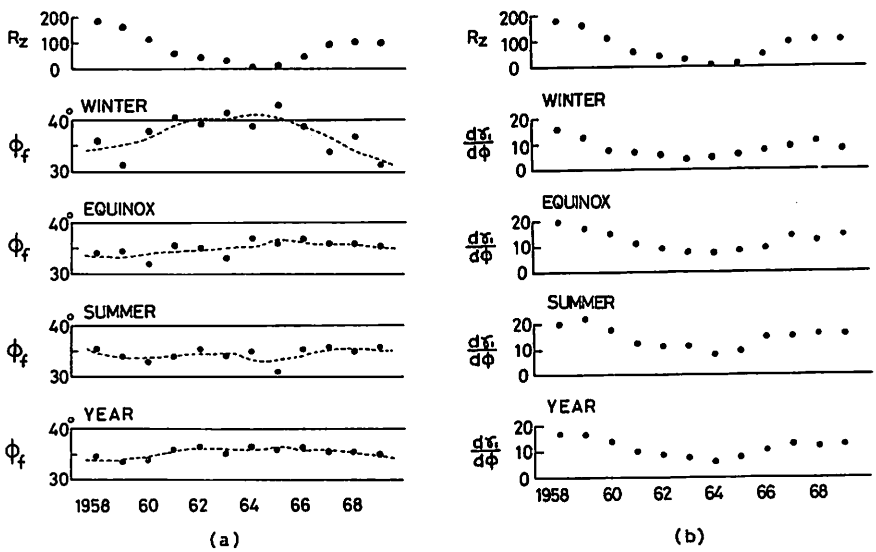

Fig. 4. Year-to-year changes of focus latitude ϕ_f (Fig. 4a) and intensity measure $|d\gamma_1/d\phi|$ (Fig. 4b) in the West Pacific region for three seasons and the year. The annual mean sunspot number Rz is also shown. The broken curves in Fig. 4a show the running averages of three years.

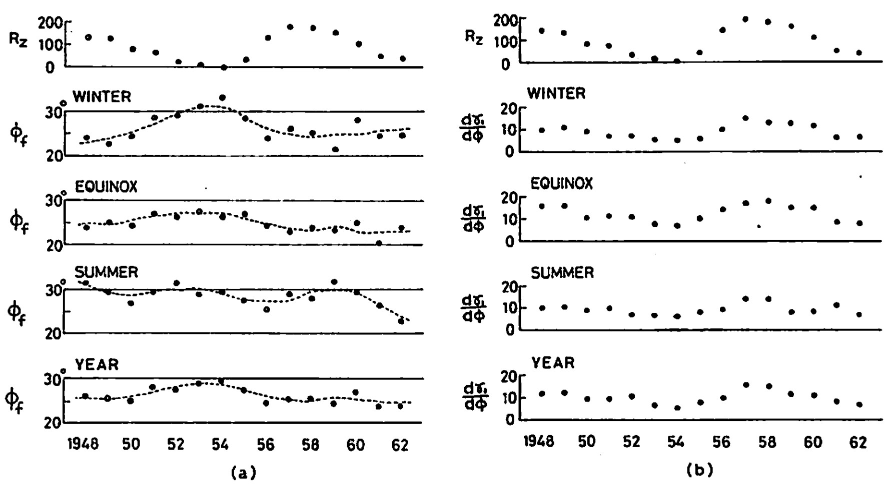

Fig. 5. Year-to-year changes of focus latitude ϕ_f (Fig. 5a) and intensity measure $|d\gamma_1/d\phi|$ (Fig. 5b) in the North American region for three seasons and the year. The annual mean sunspot number Rz is also shown. The broken curves in Fig. 5a show the running averages of three years.

Pacific region and in Fig. 5 for the North American region. Scale for ϕ_f is again the geographic latitude. In North American region the difference between geographic latitude and geomagnetic or dip one changes among three selected stations. Therefore the analyses are made separately using three latitude systems. However, they show nearly similar results for the present use. Annual mean sunspot numbers Rz are also shown in these figures.

In Figs. 4 and 5 it is clear that $|d\gamma_1/d\phi|$ changes largely in unison with Rz. This fact shows that intensity of Sq current system varies largely with the solar activity as $|d\gamma_1/d\phi|$ represents a measure of intensity, and this is consistent with the well known relation between ranges of *Sq* variation and sunspot numbers (Chapman and Bartels 1940).

On the other hand, the relation between ϕ_f and Rz is not so clear except winter season as seen in the figures, though it changes fairly in the course of the solar cycle. In winter the variation of ϕ_f shows a tendency that the focus of current system is located in lower latitude when the sunspot number is large and located in higher latitude when the number is small. The amount of ϕ_f variation is about ten degrees between high and low activities in both regions.

It is an interesting result that the focus latitude of current system as well as its intensity varies in the course of the solar cycle. There remains a little doubt that the variation of ϕ_f is an apparent one because *Sq* is contaminated by disturbances which are proportional to the solar activity. This point will be discussed in the next section.

5. Variation of focus latitude of *Sq* current system with the solar activity

Focus latitude ϕ_f for three seasons in Figs. 4 and 5 is obtained from mean *Sq* variation calculated from twenty international quiet days in each year. Examining daily variation in quiet days one by one in a season of a year, the variability is fairly large in both focus latitude and intensity (Matsushita 1960, Shiraki 1972). This variability may give a shift in the estimate of focus latitude of mean *Sq* current system if number of selected days is small, and may give a scattering in year-to-year variation of ϕ_f. To eliminate it more or less, running averages of three years are calculated for ϕ_f, and they are shown by smooth dashed curves in the figures. From these it has become clearer that the variation of ϕ_f in winter may have a relation with variation of the sunspot numbers. The relation of another seasons and the year is not so clear as that of winter.

In order to examine solar activity dependency with rather sufficient days for derivation of *Sq*, the whole years of analysis are divided into three groups according to sunspot numbers. Years and mean sunspot numbers for these groups are listed in Table 2. This division will be convenient also for later discussion done with respect to *K* index. For each group mean *Sq* variation of horizontal intensity is calculated for three seasons and the year, and then the focus latitude ϕ_f and the intensity measure $|d\gamma_1/d\phi|$ are similarly obtained. Results in both regions are shown in Table 3. Each value of ϕ_f and $|d\gamma_1/d\phi|$ listed in the table for a season is based on mean Sq for 80 days in the West Pacific region and for 100 days in the North American region. These numbers of quiet days may be sufficient to reduce the effect of day-to-day variability of daily variation on the estimate of mean ϕ_f and $|d\gamma_1/d\phi|$ in each season.

Table 2. Three groups of years divided by the solar activity and their mean sunsport numbers

(a) the West Pacific region

Group	Years	Mean sunspot numbers
Active	1958, 59, 68, 69	138.8
Medium	1960, 61, 66, 67	76.8
Quiet	1962, 63, 64, 65	22.7

(b) the North American region

Group	Years	Mean sunspot numbers
Active	1948, 56, 57, 58, 59	162.4
Medium	1949, 50, 51, 60, 61	90.8
Quiet	1952, 53, 54, 55, 62	25.1

Table 3. The changes of focus latitude ϕ_f and intensity measure $|d\gamma_1/d\phi|$

(a) the West Pacific region

	Active		Medium		Quiet	
	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$
Winter	34.5°	11.8 γ/°	37.6°	7.7 γ/°	40.9°	5.5 γ/°
Equinox	34.8	15.9	34.9	12.2	35.4	8.1
Summer	35.1	18.2	34.6	14.8	33.9	9.6
Year	34.6	14.7	35.5	11.8	36.0	7.7

(b) the North American region

	Active		Medium		Quiet	
	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$	ϕ_f	$\left\|\frac{d\gamma_1}{d\phi}\right\|$
Winter	24.2°	11.8 γ/°	25.5°	8.9 γ/°	28.9°	5.9 γ/°
Equinox	23.7	16.1	24.7	12.2	26.4	8.7
Summer	28.9	10.9	28.3	9.7	28.0	6.6
Year	25.5	13.0	26.1	10.2	27.3	7.4

Table 4. Differences of focus latitude among groups of solar activity
(a) the West Pacific region

	Active – Quiet	Active – Medium	Medium – Quiet
Winter	−6.4°	−3.1°	−3.3°
Equinox	−0.6	−0.1	−0.5
Summer	+1.2	+0.5	+0.7
Year	−1.4	−0.9	−0.5

(b) the North American region

	Active – Quiet	Active – Medium	Medium – Quiet
Winter	−4.7°	−1.3°	−3.4°
Equinox	−2.7	−1.0	−1.7
Summer	+0.9	+0.6	+0.3
Year	−1.8	−0.6	−1.2

As it is seen in Table 3, the focus latitude changes with the solar activity in both regions. Differences of focus latitude among different groups of the solar activity are given in Table 4. The difference is largest in winter season as it is mentioned already. In this season the focus is in higher latitude when the sun is quiet and it is in lower latitude when the sun is active in both regions. During equinox in the North American region the focus latitude changes in the similar way with a half amount of winter change, but in the West Pacific region it scarcely changes. In summer the latitude change is very small in both regions, and its sense is opposite to that in winter.

Change of the focus latitude during a solar cycle is a clear fact particulary for winter. However, for further discussions on the change of focus latitude of *Sq* current system, it is necessary to examine whether the change expresses the real change or apparent one due to minor disturbances superposed on *Sq* variation. For example, if a disturbance of increase in horizontal intensity, such as geomagnetic bays, appears in the nighttime of a selected quiet day, it makes the value of γ_1 slightly smaller. Considering that the disturbance is not so different among all stations in the middle latitude (Nagata and Fukushima 1967), values of γ_1 at all the selected stations near focus latitude will decrease similarly. Consequently the focus latitude estimated by the present method comes to lower one than the real one of *Sq*. A single disturbance may not affect so much the estimation of the focus latitude of mean *Sq*. And if disturbances vanish by the average of many days, they have little influence on *Sq* variation deduced from each group of sunspot numbers. However, if γ_1 is affected even in the average, the estimated latitude is not real but apparent.

It is difficult to estimate the actual amount of disturbance contamination in mean *Sq*. Therefore, first the required amount of disturbance to cause the observed change in the focus latitude is estimated. If the latitude change in Table 4 be apparent and be caused by superposed disturbances, the portion of γ_1 which is due to disturbances (hereafter denoted by $\Delta\gamma_1$) must change -75 gammas or more in the West Pacific region and -55 gammas or more in the North American region between active and quiet years for winter. Supposing the disturbance is larger in the active years, type of suitable disturbances for the change should be increase of horizontal intensity in nighttime or decrease in daytime. Bay type disturbance is a provable one of such disturbances. The required change of $\Delta\gamma_1$, -75 gammas here obtained for winter in the West Pacific region, will be compared with the change of K index in the next.

Fig. 6 shows three-hourly frequency distribution of K index at Kakioka for 80 international quiet days used to obtain mean Sq for winter season. K index cannot give the estimate of $\Delta\gamma_1$ directly because it represents only range without distinguishing direction of disturbance vector. Here upper limit of $\Delta\gamma_1$ deduced from K index will be calculated. Most favourable variation for increase of $|\Delta\gamma_1|$, such as increase of horizontal intensity in nighttime and decrease in daytime, is imagined to occur always for the actual K variation. Each K value is supposed to express a constant deviation of a half of the upper limit of the corresponding K scale in horizontal intensity with the said polarity. Under this rather unnatural supposition, upper limit of $|\Delta\gamma_1|$ is estimated at 83 gammas for active years and 61 gammas for quiet years from the frequency distribution of K index at Kakioka shown in Fig. 6. $\Delta\gamma_1$ is negative for increase in nighttime and decrease in daytime, that is -83 gammas for active

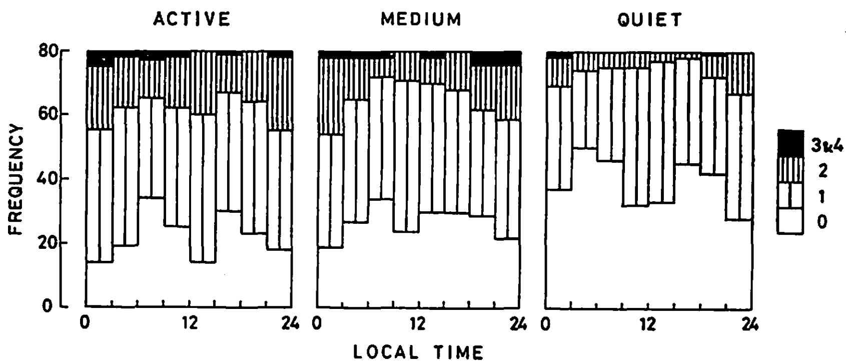

Fig. 6. Frequency distributions of K index at Kakioka for 80 international quiet days in winter for three groups of the solar activity given in Table 2.

years and -61 gammas for quiet years. Simple arithmetical difference gives a change of -22 gammas in $\Delta\gamma_1$. This value should be compared with the required change of -75 gammas. Clearly the upper limit cannot explain the observed change.

There will be some objections in the estimate of the difference in $\Delta\gamma_1$ between active and quiet years. If the local time dependency of the sense in horizontal intensity of disturbance is just reversed in quiet years, the difference should be -144 $(=-83-61)$ gammas which well satisfy the required change of -75 gammas. However this argument is too imaginative to take into consideration for the actual case, because there is no sign of such a reverse in the nature of geomagnetic disturbance.

Changes of ϕ_f can be caused also by a change of the magnitude of $|d\gamma_1/d\phi|$ under the condition that $\Delta\gamma_1$ exists, even though the difference of $\Delta\gamma_1$ between active and quiet years is small. To explain the observed change of ϕ_f in winter by this cause, disturbances in horizontal intensity should be negative in the nighttime and positive in the daytime for the observed change of $|d\gamma_1/d\phi|$. The local time dependency of the disturbance is the reverse of that in the previous case. Required magnitudes of $\Delta\gamma_1$, if they are constant throughout the active and quiet years, are +66 gammas in the West Pacific region and +55 gammas in the North American region, respectively. If change of $\Delta\gamma_1$ is taken into consideration, the required magnitudes of $\Delta\gamma_1$ should be larger than the above mentioned magnitudes, supposing that the magnitude of $\Delta\gamma_1$ in quiet years is smaller than that in active years. Upper limit of $\Delta\gamma_1$ calculated from the frequency distribution of K index is +83 gammas for active years and +61 gammas for quiet years, respectively in the West Pacific region, as it is described already. These magnitudes are rather comparable with required ones. However it is unnatural to accept these as the real cause, considering that the estimated $\Delta\gamma_1$ value is the upper limit under unnatural supposition.

Above discussions are made about result for winter season which shows the most predominant change of ϕ_f. If the observed latitude change in winter is apparent one due to disturbances, similar change must be expected in the other seasons. The frequency distributions of K index in summer, not shown in this paper, are not so different from that in winter. Nevertheless the results in Table 4 show that the latitude change in summer is opposite to that in winter for both regions. This leads us to conclude that the disturbance superposed on quiet days does not explain the observed latitude change. There might remain slight doubt on the nature of minor disturbances which occurred in rather quiet days, because studies of geomagnetic disturbances hitherto carried out are based mainly on large disturbances. If the nature of such minor disturbances is reversed, particularly in its direction between winter and summer, the seasonal difference in the solar cycle dependency of ϕ_f may be accounted for by the disturbance hypothesis. However, such a reverse is not expected as far as the present knowledge is concerned. From these considerations, results in Table 4 cannot be attributed to disturbances represented by K index as shown in Fig. 6.

Another approach to the estimation of disturbance contribution in the change of ϕ_f is tried by using disturbance daily variation, S_D. As days used here to calculate Sq variation are not absolutely quiet, mean daily variation calculated from these days is mainly due to Sq, but also include a fraction due to disturbances. The additional variation is a disturbance daily variation, S_D. As one of the nature of S_D a seasonal change is found (Yanagihara, private communication). S_D of horizontal intensity in summer is positive in forenoon and negative in afternoon, and the phase is a little lagging in winter. In consequence $\Delta\gamma_1$ for S_D shows a seasonal difference between winter and summer. It is positive in winter and nearly zero in summer. This is consistent with the seasonal difference in the solar cycle depepndency of latitude change. However, the magnitude of $\Delta\gamma_1$ for S_D cannot explain the latitude change to be apparent one due to S_D. For example, S_D variation of horizontal intensity at Kakioka calculated from international disturbed days minus quiet days from 1949 to 1967 shows variations of 17 gammas in range in winter and of 20 gammas in range in summer. From these S_D variations $\Delta\gamma_1$ is $+58$ gammas in winter and $+8$ gammas in summer. As $\Delta\gamma_1$ for S_D is positive in winter, it should be compared with the required amount of $\Delta\gamma_1$, $+65$ gammas, which is estimated before supposing that the observed latitude change is caused by disturbances. Though these values of $\Delta\gamma_1$ are comparable each other, it must be noted that S_D variation used here is calculated from international disturbed days. If the latitude change is supposed to be caused by disturbances, S_D variation as large as one which is deduced from very disturbed days must be superposed as additional variation on *Sq*. This may be hardly considerable. As $\Delta\gamma_1$ calculated from very disturbed days is to the extent of 58 gammas in winter and 8 gammas in summer, the actual amount of $\Delta\gamma_1$ in the mean *Sq* variation calculated here may be very small. And it may hardly explain the focus latitude changes shown in Table 4 as apparent ones.

From foregoing discussions it becomes clear that the latitude changes shown in Table 4 are not apparent but real. Focus latitude of *Sq* current system itself changes with the solar activity. The change is large in winter and is different between winter and summer.

Hitherto the discussion was mainly fixed to the change due to the solar activity in each season, though the problem was introduced by different seasonal changes of focus latitude for different solar activities. Looking at Table 3 from a viewpoint of seasonal change, the focus latitude is higher in winter than in summer in the solar quiet years, and on the contrary, it is lower in winter than in summer in the solar solar active years. Different seasonal changes for different solar activities are noticable in both regions and are very similar to the previous results introduced in the section one. The contradiction between previous two results is well explained by the difference of solar activities.

6. Variation of the measure of current intensity with the solar activity

As mentioned in the section 2 a quantity of $|d\gamma_1/d\phi|$ is a measure of current intensity. It is clear in Figs. 4 and 5 that $|d\gamma_1/d\phi|$ changes in unison with annual mean sunspot numbers. This fact may be consistent with the solar cycle dependency of ranges of *Sq* variation of magnetic elements.

The form and range of horizontal intensity of diurnal variation at a station in the middle latitude depend on the focus position of current system. In the previous section it was ascertained that the focus latitude changes fairly in the course of solar cycle, especially in winter. Therefore the solar cycle change of the range is much affected by the latitude change. On the otherhand, the effect of latitude change is eliminated in the measure of intensity $|d\gamma_1/d\phi|$. Moreover $|d\gamma_1/d\phi|$ is less affected by disturbances than the range because the former's amount is changed only by the

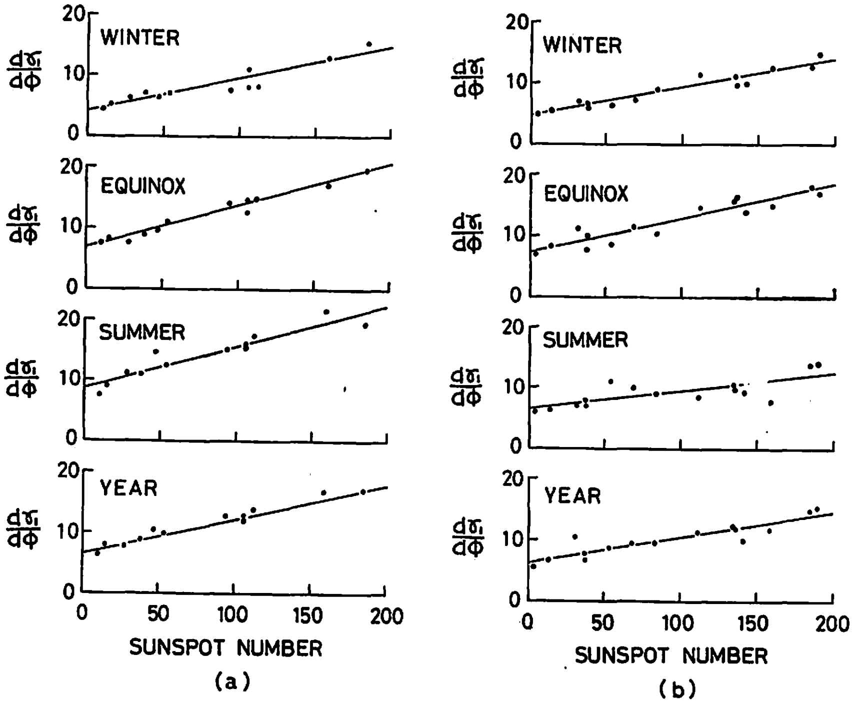

Fig. 7. Correlation between intensity measure $|d\gamma_1/d\phi|$ and sunspot number Rz for three seasons and the year in the West Pacific region (Fig. 7a) and in the North American region (Fig. 7b).

mean difference of disturbances among stations even if disturbances occur whereas the latter is clearly influenced by disturbance itself at the time of maximum or minimum. Though $|d\gamma_1/d\phi|$ may be better than the range, it is uncertain whether it represents a whole intensity of Sq current system as $|d\gamma_1/d\phi|$ is obtained mainly from the diurnal term of middle latitude stations.

Correlation between $|d\gamma_1/d\phi|$ and annual mean sunspot number Rz is shown in Fig. 7. It is clear that $|d\gamma_1/d\phi|$ is approximately related to Rz by a linear relation as

$$|d\gamma_1/d\phi| = |d\gamma_1/d\phi|_0 \ (1 + m \cdot 10^{-4} \cdot Rz).$$

Values of $|d\gamma_1/d\phi|_0$ and m are calculated by the least square method for both regions in each season and the year and are given in Table 5. Straight lines calculated from these values are presented in the figure.

$|d\gamma_1/d\phi|_0$ represents the intensity for the absolutely quiet sun, and changes among seasons. This seasonal change is different between the West Pacific and the North American regions. In the West Pacific region the value is greater in summer. On the other hand it is greater in equinox than in summer in the North American region. Similar difference is seen also in Table 3 for each activity level. It is ascertained that

Table 5. The coefficient $|d\gamma_1/d\phi|_0$ and the value m in the linear relation between $|d\gamma_1/d\phi|$ and sunspot number Rz.

(a) the West Pacific region

	$\left\|\frac{d\gamma_1}{d\phi}\right\|_0$	m
Winter	$4.06^{\gamma/\circ}$	136
Equinox	6.66	103
Summer	8.56	80
Year	6.54	92

(b) the North American region

	$\left\|\frac{d\gamma_1}{d\phi}\right\|_0$	m
Winter	$4.63^{\gamma/\circ}$	101
Equinox	7.18	78
Summer	6.42	46
Year	6.27	67

the difference is not due to the difference of the period used in the analyses examining it for the common period from 1958 to 1962 for two regions.

The coefficient m also shows a seasonal change. It is large in winter and small in summer in both regions. Influence of the solar activity on intensity is different between seasons and it is most effective in winter. This is consistent with the fact that the change of focus latitude is largest in winter. That is, Sq current system is most severely affected in winter by the solar activity.

Comparing values of m between two regions, those of the West Pacific region are larger than those of the North American region for all seasons and the year. This means that the West Pacific region is more influenced by the change of sunspot numbers than the North American region.

7. Conclusions

A simple method to estimate focus latitude and intensity of Sq was presented. Using this method they were studied with respect to the solar activity and seasonal change using data in the West Pacific and the North American regions.

According to the derivation of Sq in this paper, which is the same as usual one based on five international quiet days, there remaines a slight doubt that latitude change may be an apparent one due to disturbances. However, it has been ascertained in the section 5 that the change is too large to be caused by disturbances in quiet days. Therefore the observed change expresses the change in Sq current system itself. Solar cycle dependency of focus latitude ϕ_f of Sq current system is large in winter for both regions. The center of focus in winter is in higher latitude during the solar quiet years than that during the solar active years. Changes in equinox and summer are smaller than those in winter, and in summer changes show rather opposite sense. Consequently, seasonal changes differ each other between active and quiet years as stated in the introduction.

Intensity measure $|d\gamma_1/d\phi|$ is linearly related to the sunspot number. The coefficient m in the linear relation shows seasonal and regional differences. Considering the seasonal change of m, Sq in winter season is most severely influenced by the solar activity. This is consistent with the fact that the latitude change is severest in winter.

In the most of studies carried out up to the present, influence of the solar activity on Sq has been considered with respect to the intensity of Sq current system. Increase of the solar activity bring increase of solar fluxes, and consequently increase of ionization in the ionosphere. And the conductivity of dynamo layer becomes higher and the intensity of Sq becomes larger. Solar cycle dependency of the conductivity of dynamo layer may be infered from that of electron density at E layer, and the latter has been well studied (Ratcliffe and Weekes 1960, Maeda and Fukao 1972). According to results by Maeda and Fukao (1972), electron density at E layer increases by about 1.4 times as the sunspot number increases from 0 to 100, and its seasonal and regional differences are small. These results are different from the solar cycle dependency of the intensity of Sq current. Values of the coefficient m for $|d\gamma_1/d\phi|$ in Table 5 are larger than that of electron density at E layer and show remarkable seasonal and regional differences. So the magnitude itself and the differences among seasons and regions in the coefficient m obtained here cannot be explained only by the change of conductivity. Moreover the change of focus latitude in the course of solar cycle indicates that Sq current system changes in form as well as in intensity. This fact is hardly explainable by the change of conductivity. According to the dynamo theory wind as well as conductivity has an important role for Sq current system. The relation between wind in the upper atmosphere and the solar activity is little known as yet. Considering that the wind contributing to Sq is mainly of thermal origin (Tarpley 1970), it may be influenced by the change of solar activity. The difference in solar cycle dependency between intensity of Sq and conductivity of dynamo layer may be due to increase of wind speed caused by increase of solar activity. And the different values of m among seasons and regions shown in Table 5 may be due to the different influences of solar activity on wind speed. The change of wind speed causes intensity change of Sq current but does not cause change of its form. However, as the form of current system changes depending upon the solar activity shown by the change of focus latitude, direction of the wind as well as its speed may be influenced by the solar activity.

Regarding wind in the upper atmosphere, the prevailing wind which is not periodic has been observed (Greenhow and Neufeld 1961). By theoretical calculations it is shown that the prevailing wind in the dynamo layer causes a Sq-like current system (van Sabben 1962, Maeda and Murata 1968). Intensity and focus latitude of the Sq-like current system depend upon intensity and direction of the prevailing wind. As it is hardly possible to separate the above *Sq*-like current system from the true *Sq* current system, the change of *Sq*-like current system is apparently regarded as the change of true *Sq* current system. So if intensity and direction of the privailing wind change depending upon the solar activity, it may cause changes of intensity and from of *Sq* current here obtained.

Another *Sq*-like equivalent current system may be caused by non-ionospheric currents, such as magnetopause current (Mead 1964, Olson 1970) and field aligned current (Fukushima and Kamide 1972). They may be influenced by the solar activity and may cause apparent changes of intensity and focus latitude of *Sq* current.

Some origines of solar cycle dependency in *Sq* considered here are not conclusive. Observational facts are not enough and discussions are given only for simple cases. It is necessary to study whether the above-mentioned origins can explain the magnitude and sense of changes of intensity and focus latitude depending upon the solar activity obtained here.

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太陽活動による地磁気日変化等価電流系の変動

白 木 正 規

概 要

最初に，地磁気日変化等価電流の中心緯度を簡単に推定する方法について述べた。そして，この方法を用いて電流系の中心緯度が太陽活動に依存して変動するかどうか，太平洋西岸地域と北アメリカ地域の二つの地域について調べた。どちらの地域でも，電流系の中心緯度は冬に大きな変化がみられ，太陽活動の静かな期間には中心は高緯度にあり，太陽活動の活発な期間には中心は低緯度にある。春秋と夏の中心緯度の変化は小さく，夏には冬とはむしろ逆の変化を示す。この結果，電流系の中心緯度の季節変化は太陽活動の静かな期間と活発な期間では異った変化を示す。

電流系の中心緯度と同時に，電流系の強さを示す量が得られる。この量と太陽黒点数との関係についても調べた。これらの関係を示す係数 m は，季節によっても，地域によっても異なっている。m の値が冬に最も大きいことは，電流系の中心緯度が冬に大きな変化を示すことと矛盾のない結果である。