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Long-term behavior of annual and semi-annual S_q variations

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We have examined the long-term behavior (solar-cycle time scale) of annual and semi-annual S_q variations. We analyzed geomagnetic data observed at locations that were roughly geographically conjugate in the west Pacific region (Kakioka and Gnangara) during the last five solar cycles (1953–2006). Three-year compound data were constructed for each station for each year. The stationary component $\{\overline{S_q}\}_0$, annual component $\{\overline{S_q}\}_1$, and the semi-annual component $\{\overline{S_q}\}_2$, of the S_q variations were derived from the compound data. The solar-activity dependence of the derived three components was evaluated in comparison with the sunspot number ($\overline{R}$). It was found that the amplitudes of all three components ($\{\overline{S_q}\}_0$, $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$) have a positive linear correlation with the sunspot number. The most remarkable result is that the linear regression coefficient for $\{\overline{S_q}\}_0$ is much bigger than those of $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$. The physical mechanisms involved are yet to be understood.

Key words: S_q, ionosphere, ionospheric current, ionospheric conductivity, solar activity, sunspot number, geomagnetism, geomagnetic field.

1. Introduction

Since Wolf's discovery, in 1859, of the dependence of S_q amplitudes on the sunspot number, this relation has been extensively studied. It is known that there exists an almost linear relationship between the sunspot number and S_q amplitudes. The early work on this subject was summarized by Chapman and Bartels (1940). Yacob and Prabhavalkar (1965) and, in the following year, Yacob and Radhakrishna Rao (1966) examined $S_q(H)$, as observed at Alibag (18.6° north in geographic coordinates) from 1905 to 1960, and concluded that the increase of daily $S_q(H)$ amplitudes with increasing solar activity is due to the effect of solar activity on the ionization intensity. They also pointed out that solar activity controls not only the amplitudes but also controls the phase of the diurnal $S_q(H)$ component, that is, the maximum of the $S_q(H)$ tends to occur at a later time of the day in greater-sunspot years. Rastogi and Iyer (1976) explained this as a combination effect of ionospheric conductivity and electric field. Later, Vikramkumar *et al.* (1984) supported their idea after examining VHF back-scatter radar data. Briggs (1984) pointed out that S_q amplitudes correlate with the solar radio emission at 10.7 cm ($F_{10.7}$). He also showed evidence for the effect of 27-day solar rotation on the S_q amplitude. Takeda (1999, 2002a) found that the intensity of the equivalent S_q current system at a solar maximum is about twice as large as that at a solar minimum. Takeda (2002b) showed that the solar-activity dependence of the S_q variation is explained as an effect of the local ionospheric conductivity.

It has been known for many decades that the S_q field shows annual and semi-annual variations. The annual and semi-annual S_q variations have been observed worldwide (e.g., Wagner, 1969; Campbell, 1982; Rastogi *et al.*, 1994; Yamazaki *et al.*, 2009). Rastogi and Iyer (1976), and Rastogi *et al.* (1994) demonstrated a linear relationship between the yearly-averaged $S_q(H)$ range and the amplitude of semi-annual S_q variations at the dip-equatorial latitudes, which indicates a significant influence of solar activity on the semi-annual S_q variations. They did not produce any evidence for a dependence on solar activity for the amplitudes of the annual S_q variations at these latitudes. Briggs (1984) and Hibberd (1985) analyzed the difference value of the H component of the geomagnetic field, as observed at two observatories having in the same longitude but different latitudes. This method enabled them to estimate ionospheric current intensities even for magnetically-disturbed days. They could also find evidence of a dependence on solar activity for the semi-annual S_q variation. Vertlib and Wagner (1977) examined the latitudinal distributions of annual and semi-annual S_q variations. They pointed out that an increase of solar activity causes an increase in the amplitude for both annual and semi-annual components, but almost no change in their latitudinal distributions. Campbell and Matsushita (1982) showed that the semi-annual S_q variations are distinct only during solar maximum periods by comparing external equivalent currents during maximum and minimum solar activity. Later, Stening (1995) showed that semi-annual variations exist in the strength of the S_q current system even during solar minimum periods. Stening (1991) found that the semi-annual S_q variation near the dip equator is clear in the morning hours, but practically disap-

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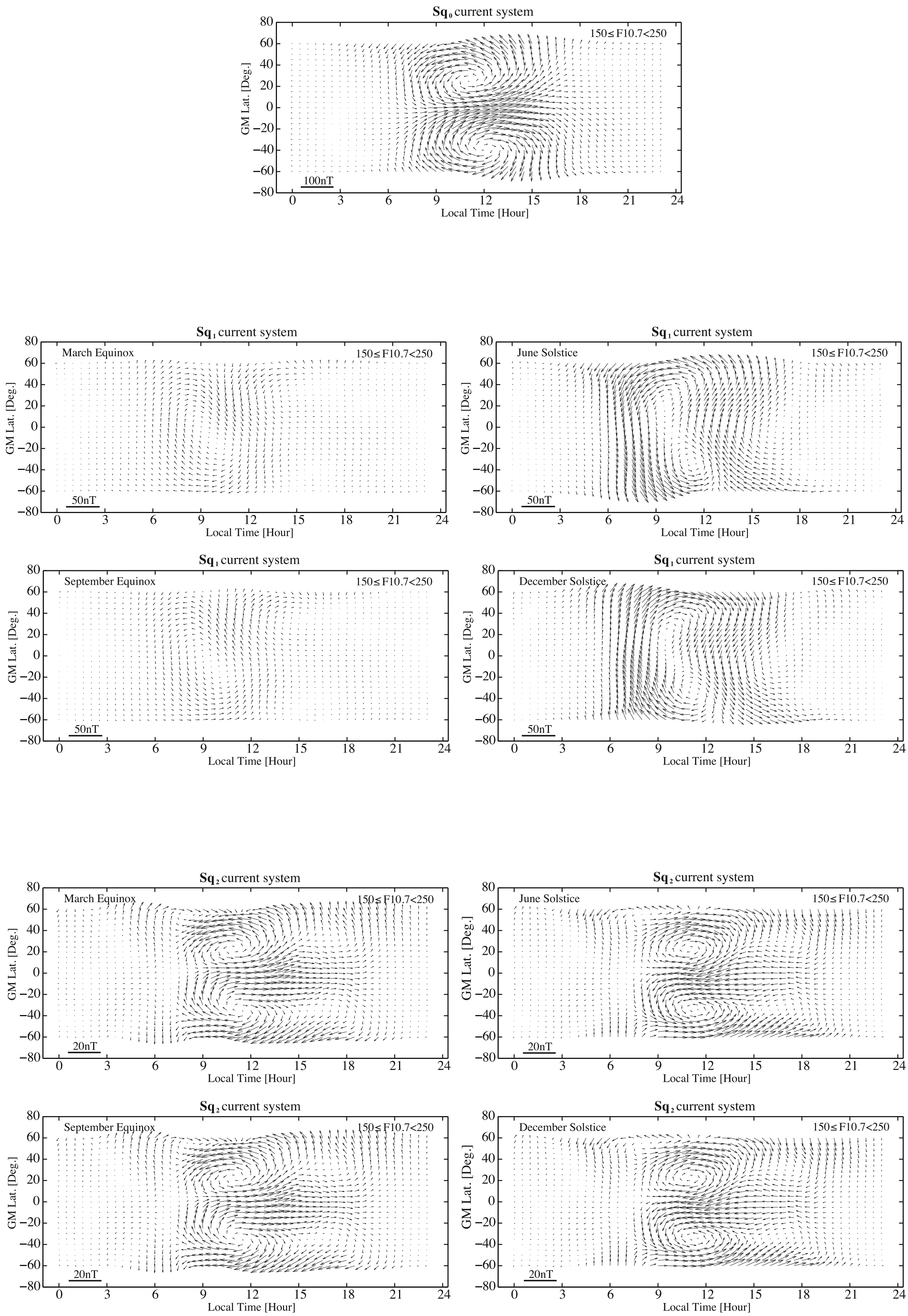

Fig. 1. The LAT-LT diagram of the equivalent current systems for the stationary, annual and semi-annual component of the S_q variations for a high solar-activity period ($150 \leq F_{10.7} < 250$), as originally derived by Yamazaki *et al.* (2009). The top panel shows the equivalent current system for the stationary component. The middle four panels show the equivalent current systems for the annual component for the March equinox (DOY = 80, upper left), the June solstice (DOY = 172, upper right), the Spring equinox (DOY = 264, lower left) and the December solstice (DOY = 355, lower right), while the bottom four panels show the equivalent current systems for the semi-annual component.

Table 1. A list of the magnetic observatories used in this study, with geographic and geomagnetic coordinates and the period for which data are available.

Station name	Code	GGLat. (N°)	GGLon. (E°)	GMLat. (N°)	GMLon. (E°)	Period
Kakioka	KAK	36.2	140.2	27.4	208.8	1952–2007
Gnangara	GNA	−31.8	116.0	−42.0	188.9	1958–2006

pears in the afternoon.

Yamazaki *et al.* (2009) pointed out that, on a seasonal time scale, S_q variations can be regarded as the superposition of the stationary, annual and semi-annual components. They analyzed ground-magnetometer data of 19 stations covering both the northern and southern hemispheres along the 210° magnetic meridian of the Circum-pan Pacific Magnetometer Network (CPMN; Yumoto and the CPMN Group, 2001) for the time span of 1996–2007. They derived equivalent current systems for the stationary, annual and semi-annual components of the S_q variation and found evidence for a fundamental difference in their spatial distributions. That is, equivalent current systems for the stationary and semi-annual components have a dayside vortex in each hemisphere, while the equivalent current system for the annual component has a single vortex centered at the equatorial region in the morning sector. Figure 1 shows the equivalent current systems for the stationary (the top panel), annual (the middle four panels) and semi-annual (the bottom four panels), components originally given by Yamazaki *et al.* (2009). Since their analysis was based on data from only one solar cycle, it was difficult to investigate the solar-cycle variation of the stationary, annual and semi-annual components. In this paper, the geomagnetic data covering five-solar-cycle spans were analyzed. This kind of analysis can reveal the long-term behavior of the three components.

2. Data Set and Analysis

We used geomagnetic data observed at Kakioka (Japan) and Gnangara (Australia). The data of Kakioka were provided by the Kakioka Magnetic Observatory in Japan and the data of Gnangara were downloaded from the website of the World Data Center for Geomagnetism, Kyoto. The two stations were selected for their location and data coverage (see Table 1). They are located at similar geographic latitudes and longitudes to each other, but in opposite hemispheres. The data set covers almost five solar cycles, which is long enough to examine the solar-activity dependence of both the annual and semi-annual components of the S_q field.

Hourly mean values of the geomagnetic field, the X and Y components, were analyzed. Here, the X and Y components are in the geographic north and east direction, respectively. Takeda (2002b) used only the Y component to examine the dependence of S_q variation on solar activity. However, as shown in Fig. 1, the distribution of northward and eastward equivalent currents is different in different seasonal components. Therefore, using only one component (either the X, or the Y component) is not sufficient to evaluate the dependence of the stationary, annual and semi-annual S_q components on solar activity. For this reason, we use both the X and Y components. The days on which $K_p \leq 2+$ during 00–24 LT were selected to avoid geomagnetic disturbance effects on the daily variation. The local time was calculated from universal time and the geographical coordinate of the observatories. We defined the daily amplitude of the S_q variation (here termed S_Q) as:

$$S_Q(\text{YEAR, DOY}) = \sum_{k=0}^{23} \frac{\sqrt{[\Delta X_k(\text{YEAR, DOY})]^2 + [\Delta Y_k(\text{YEAR, DOY})]^2}}{24} \quad (1)$$

where DOY and YEAR are the day number and year, respectively, and the subscript k indicates local time. The Δ symbol indicates the deviation from the night-time level, which is defined as the mean value at the five hours of either side of local midnight (i.e., 00, 01, 02, 22, 23 LT).

Values that departed more than 2σ from the 30-day centered moving average were considered to be outliers and were removed from the data set, where σ is a standard deviation of the data set. Note that for either station, the detected outliers accounted for only about 1% of the entire data. Figure 2 shows S_Q(YEAR, DOY) for the selected days during 1952–2007.

The data for plus-minus one year was compounded for each YEAR. This treatment of the data is made because there are some years for which we cannot obtain a sufficient number of quiet days from only one-year data to extract seasonal components. The compounded data is defined as $\overline{S_Q}$(YEAR, DOY), which is given in terms of the following: the stationary component $\{\overline{S_q}\}_0$, the annual component $\{\overline{S_q}\}_1$ and the semi-annual component $\{\overline{S_q}\}_2$. That is,

$$\overline{S_Q}(\text{YEAR, DOY}) \sim \{\overline{S_q}\}_0 + \{\overline{S_q}\}_1 + \{\overline{S_q}\}_2 \quad (2)$$

$$= \overline{A_0} + \overline{A_1} \cos\left(\frac{2\pi}{T}(\text{DOY} - P_1)\right) + \overline{A_2} \cos\left(\frac{4\pi}{T}(\text{DOY} - P_2)\right), \quad (3)$$

where T ($T = 365$) is the total number of days of the year, $\overline{A_0}$, $\overline{A_1}$ and $\overline{A_2}$ are the amplitudes of $\{\overline{S_q}\}_0$, $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$, respectively, and P_1 and P_2 are the phases of $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$, respectively, and denote the day number in which the first maximum appears. The amplitude and phase of the seasonal components (i.e., the values of $\overline{A_0}$, $\overline{A_1}$, $\overline{A_2}$, P_1 and P_2) are determined for each YEAR so as to minimize the root-mean-square error of the observed values.

3. Results of Data Analysis

Figure 3 compares the sunspot number $\overline{R}$ (three-year centered moving average) during the period 1953–2006 (the top panel) with the amplitudes of $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$. The sunspot number $\overline{R}$ is an indicator of solar activity. In the bottom panel, the solid lines show the results from the

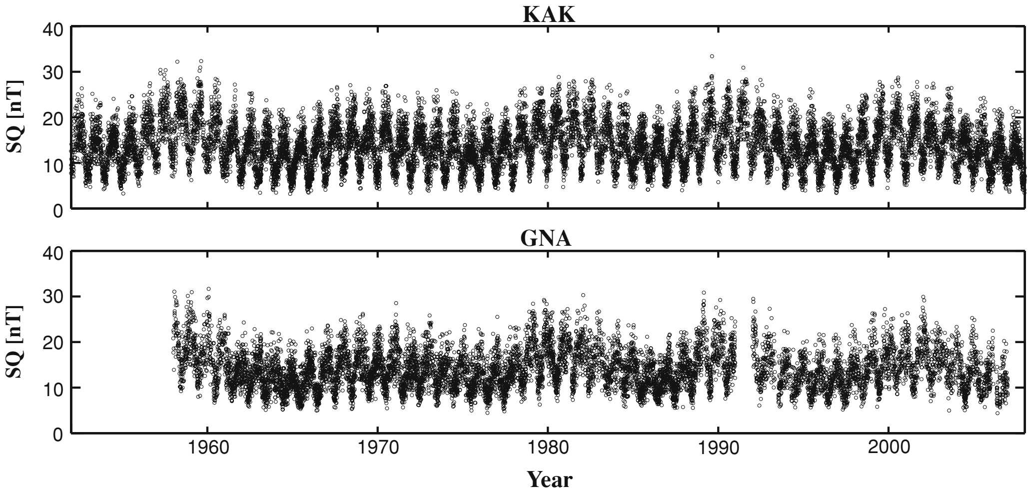

Fig. 2. S_Q(YEAR, DOY) for the selected days during 1952–2007. See Section 2 for data selection.

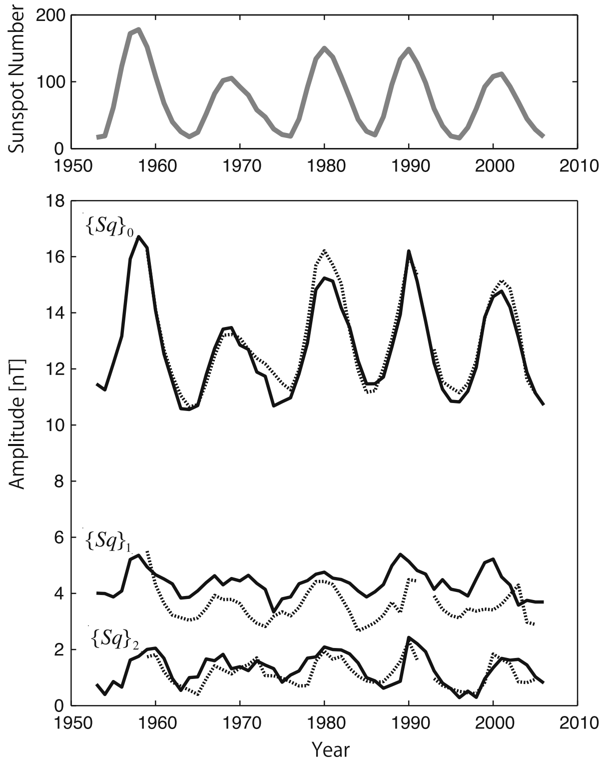

Fig. 3. Comparison between the sunspot number $\overline{R}$ (three-year centered moving average) during the period 1953–2006 (the top panel), with the amplitudes of $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$. In the bottom panel, the solid lines indicate the Kakioka data, while the broken lines indicate the Gnangara data.

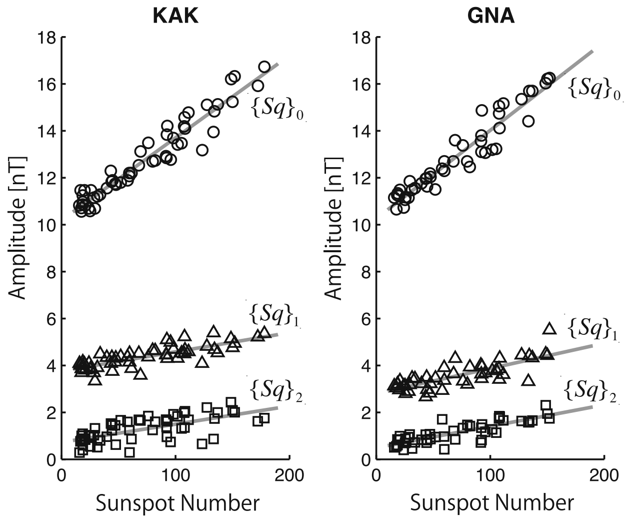

Fig. 4. Mass plots of the amplitudes of $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ against the sunspot number $\overline{R}$ (three-year centered moving average).

Kakioka data, while the broken lines show the results from the Gnangara data. It may be noticed that not only the stationary component ($\overline{\{S_q\}_0}$), but also the annual and semiannual components ($\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$, respectively) of the S_q field, are controlled by the solar activity.

We illustrate in Fig. 4 mass plots of the amplitudes of $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ against the sunspot number $\overline{R}$. It is now clear that all $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ amplitudes are linearly correlated with the sunspot number. The slope $\boldsymbol{a}$ and the intercept $\boldsymbol{b}$ of the best-fit linear regression line (in the least square sense) is summarized in Table 2. The slope $\boldsymbol{a}$ is a parameter quantifying the solar activity dependence of the $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ amplitudes, while the intercept $\boldsymbol{b}$ provides the normalized magnitude of the $\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ amplitudes at $\overline{R} = 0$. In the table, the interval from $\boldsymbol{a}_{\mathrm{low}}$ ($\boldsymbol{b}_{\mathrm{low}}$) to $\boldsymbol{a}_{\mathrm{up}}$ ($\boldsymbol{b}_{\mathrm{up}}$) indicates the 95% confidence interval for $\boldsymbol{a}$ ($\boldsymbol{b}$), which is estimated by 2000 times bootstrap resampling. From Fig. 4 and Table 2, it should be noted that the slopes of the linear regression line for $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ are similar to one another, but are much smaller than the value for $\overline{\{S_q\}_0}$ (about 20–30%).

When we compare the slope $\boldsymbol{a}$ at Kakioka with that at Gnangara, it can be seen that the slope $\boldsymbol{a}$ at Kakioka is a little smaller than that at Gnangara for all three components ($\overline{\{S_q\}_0}$, $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$). This is expected, as Kakioka is located at a slightly higher geographic latitude than Gnangara. The lower-latitude ionosphere can receive more EUV flux in a year. Earlier, Rastogi *et al.* (1994) pointed out greater

Table 2. The slope ***a*** and intercept ***b*** of the best-fit linear regression line with their 95% confidence interval.

	Component		$\boldsymbol{a}$ ($\boldsymbol{a}_{up} - \boldsymbol{a}_{low}$) $\times 10^4$	$\boldsymbol{b}$ ($\boldsymbol{b}_{up} - \boldsymbol{b}_{low}$)
Kakioka (KAK)	$\overline{\{S_q\}_0}$	Stationary	351 (319–351)	10.2 (10.0–10.4)
	$\overline{\{S_q\}_1}$	Annual	82.1 (67.1–96.4)	3.76 (3.64–3.88)
	$\overline{\{S_q\}_2}$	Semiannual	76.9 (54.0–101)	0.72 (0.567–0.907)
Gnangara (GNA)	$\overline{\{S_q\}_0}$	Stationary	377 (342–403)	10.3 (10.1–10.4)
	$\overline{\{S_q\}_1}$	Annual	107 (78.6–136)	2.80 (2.60–2.97)
	$\overline{\{S_q\}_2}$	Semiannual	91.2 (75.7–107)	0.49 (0.37–0.62)

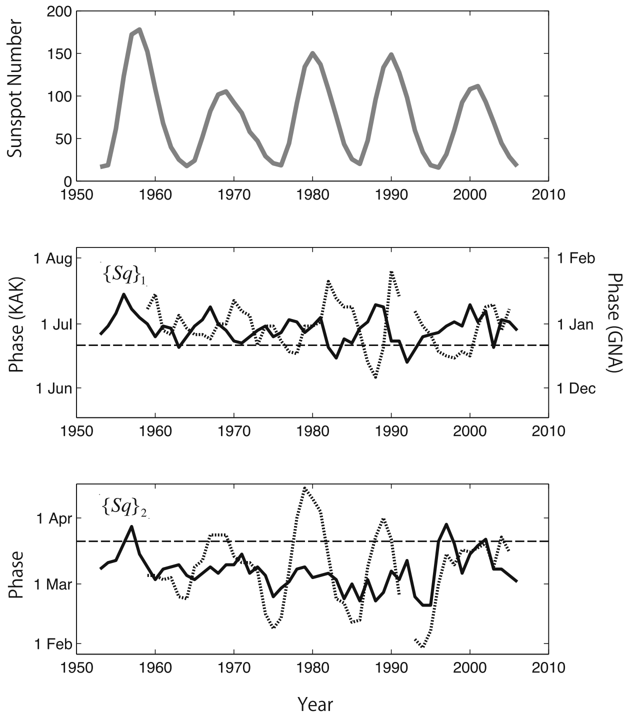

Fig. 5. Comparison between the sunspot number $\overline{R}$ (three-year centered moving average) during the period 1953–2006 (the top panel) with the phases of $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$. Note that, in the middle and bottom panels, the solid lines indicate the Kakioka data while the broken lines indicate the Gnangara data. Also, note that, in the middle panel, the horizontal broken line indicates the day of the June solstice for the Kakioka data (the left vertical axis) and the day of the December solstice for the Gnangara data (the right vertical axis).

solar cycle effects with decreasing latitude. We found this feature holds true for the annual and semi-annual S_q components as well as the stationary component.

Figure 5 shows $\overline{R}$ (the top panel) and the corresponding phases of $\overline{\{S_q\}_1}$ and $\overline{\{S_q\}_2}$ (the middle and bottom panels, respectively). In the middle panel, the horizontal broken line indicates the day of the June solstice for the Kakioka data (the left vertical axis) and the day of the December solstice for the Gnangara data (the right vertical axis). It can be seen that the day of the maximum amplitude of $\overline{\{S_q\}_1}$ tends to appear 7 days after the local summer solstice (i.e., June 21 for Kakioka and December 21 for Gnangara). The phases of $\overline{\{S_q\}_1}$ at Kakioka and Gnangara seem to be in an anti-phase relationship and neither of them seems to be correlated with the variation of $\overline{R}$. In the bottom panel, however, the horizontal broken lines indicate the day of the March equinox (March 21). It can be seen that the phases of $\overline{\{S_q\}_2}$ tend to appear 10 days before the equinox at both stations. Moreover, the phase of $\overline{\{S_q\}_2}$ at Gnangara was observed to be correlated with the variation of $\overline{R}$, but such a trend is barely apparent in the Kakioka data. This may be related to the north-south asymmetry of the ionospheric dynamo, but it is difficult to interpret with only our present data set. Data sets from a greater spatial coverage will be required to settle this problem (future work).

4. Discussion

The principal source of the quiet daily variation of the geomagnetic field (S_q variation) is the electric current flowing in the ionospheric E region (90–150 km), which is generated by the movement of conducting air across the Earth's main field (Richmond, 1979, 1989, 1998). Although the ionospheric current can induce secondary currents in the conducting earth, the secondary current does not make any difference to the solar-activity dependence of the S_q field because the intensity of the secondary current proportionally increases with increasing ionospheric current intensity (Malin *et al.*, 1975).

It is also known that the daily geomagnetic field variation is modulated, depending on the position of the Moon. This effect is probably due to the modulation of the ionospheric dynamo by the Moon's gravitational forces. The equivalent current derived from this geomagnetic effect is called the L current and its magnitude is about one tenth of the S_q current (Campbell, 1980). The solar-activity dependence of the L current is still controversial (Chapman *et al.*, 1971; Malin *et al.*, 1975). Since our analysis is based on three-year compound data, the L effect should be averaged out.

Residual effects of geomagnetic disturbances might affect our result. It is known that semi-annual variations exist in the geomagnetic activity. These variations are a result of a semi-annual variation of the southward component of the solar-wind magnetic field and is known as the Russell-McPherron effect (Russell and McPherron, 1973). It does not seem, however, that the semi-annual variation due to the Russell-McPherron effect is correlated with solar activity, and the expected phase, as predicted by this mechanism (5 April), is different from the observed phase (before March 21). Le Mouël *et al.* (2004) examined the long-term behavior of the semi-annual component of the geomagnetic activity index (*aa*-index). They reported that the phase of the semi-annual component of the *aa*-index is likely to occur between 21 March and 5 April, which is obviously different from ours. Therefore, the contribution of the residual geomagnetic disturbance to our results is expected to be small.

It has been known for a long time that the diurnal tidal wind field plays a primary role in the formation of the two-vortex pattern of the equivalent S_q current system (Maeda, 1955; Kato, 1956). Yamazaki *et al*. (2009) found that the equivalent S_q current system undergoes semi-annual variations keeping its two-vortex pattern. Thus, they naturally concluded that the diurnal tidal wind field causes the semi-annual S_q variations. For the annual S_q variations, Yamazaki *et al*. (2009) pointed out that the equivalent S_q current system for the annual S_q variations is characterized by a single-vortex pattern (see Fig. 1 of this paper). The single-vortex pattern for the annual component is consistent with the result by Winch (1981). Probably, the single vortex pattern for the annual component results from the greater intensity of S_q currents in the summer hemisphere than the winter hemisphere: During the June solstice, the higher-latitude annual currents are westward in the Northern Hemisphere and eastward in the Southern Hemisphere, and thus the northern S_q current vortex is strengthened and the southern S_q current vortex is weakened. During the December solstice, the higher-latitude annual currents are eastward in the Northern Hemisphere and westward in the Southern Hemisphere, and thus the northern S_q current vortex is weakened and the southern S_q current vortex is strengthened. Seasonal variations of the ionospheric conductivity and winds contribute to the annual variation of S_q currents. Although it seems that the neutral wind plays a very important role in the seasonal change of the equivalent S_q current system, the solar-cycle variations of neutral winds and electric fields in the dynamo region have not, unfortunately, been observationally established. Such information is required in order to separate their contributions from the local ionospheric conductivity effect.

What is established in this study is that the solar activity controls not only the stationary component of the S_q fields, but also their annual and semi-annual components. All three components ($\{\overline{S_q}\}_0$, $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$) have a positive linear correlation with the sunspot number. It is remarkable that the linear-regression coefficient for $\{\overline{S_q}\}_0$ is much bigger than those of $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$. This difference in the solar-activity dependence of the stationary and seasonal S_q components may be directly related to physical mechanisms causing them. In addition, the linear-regression coefficients for $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$ are similar in magnitude, which suggests that there is a common physical mechanism behind the dependences of $\{\overline{S_q}\}_1$ and $\{\overline{S_q}\}_2$ on solar activity. The physical mechanisms behind the solar-activity dependence of the seasonal S_q components are yet to be understood.

The present study has greatly enhanced our knowledge of the dependence of S_q fields on solar activity. Currently, the sunspot number is widely used for monitoring solar activity. However, as the sunspot number is based on a visual count of the number of individual spots, S_q field components may be able to monitor solar activity more accurately than current methods using the sunspot number. Such a practical use of S_q fields for space weather monitoring is worthy of further development.

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