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Seasonal evolution of S_q current system at sub-auroral latitude

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The quiet-time ($\Sigma K_p \leq 3$) daily variations of the geomagnetic field at the Indian Antarctic station, Maitri (Geographic Coord.: 70.75°S, 11.73°E; Geomagnetic Coord.: 66.84°S, 56.29°E) during two consecutive years of a solar minimum are considered in order to investigate the characteristics of the solar quiet (S_q) current system. The present work reports the signatures of the south limb of the S_q current loop of the southern hemisphere over a sub-auroral station. It is observed that the seasonal variation of the S_q current strength over Maitri is strongest during the summer months and weakest during the winter months. In spite of the total darkness during the winter months, an S_q pattern is identified at Maitri. The range of the horizontal field variation in the daily S_q pattern during summer is one order higher than that during winter. An interesting feature regarding the phase of the local time variation in the seasonal pattern is found here. A sharp shift in the time of the peak S_q current to later local times (>1 hour per month) is observed during January–February and July–August, which may correspond to the transition from the complete presence, or absence, of sunlight to partial sunlight. The differences in the incoming solar UV radiation during such transitions can cause a sudden change in the local ionospheric conductivity pattern, and can also trigger some unusual thermo-tidal activity, that might be responsible for modifying the global S_q pattern.

Key words: S_q current system, seasonal variation, sub-auroral latitude.

1. Introduction

It is well-established that a regular diurnal variation in the geomagnetic field, also referred to as the solar quiet day (S_q) variation, is observed at mid- to low-latitudes on magnetically quiet days (Chapman and Bartels, 1940; Richmond *et al.*, 1976; Matsushita and Campbell, 1987; Campbell, 1997). The dynamo currents flowing in the E-region ionosphere due to atmospheric tidal motion across the geomagnetic field are essentially responsible for the S_q variations, comprising two oval-shaped current loops on the dayside in each hemisphere (Matsushita and Campbell, 1987). The latitudinal extent of this current system is very wide-ranging from low to high geomagnetic latitudes in both hemispheres.

A extensive study of the S_q current to investigate characteristics such as the solar activity dependence, the seasonal variation of its strength, movement of the S_q foci, tidal dependence, longitudinal variation, etc., have been carried out by many researchers (Yacob and Rao, 1966; Gupta, 1973; Tarpley, 1973; Hibberd, 1985; Patil *et al.*, 1985; Rastogi *et al.*, 1994; Miyahara and Ooishi, 1997; Stening *et al.*, 2007; Yamazaki *et al.*, 2010; Pham Thi Thu *et al.*, 2011). Campbell and Schiffmacher (1985, 1988) have analyzed quiet time geomagnetic field records in the Northern, as well as in the Southern, hemisphere. They showed that the seasonal variation of the S_q current is semiannual in the low to mid latitude region (up to around 50° geomagnetic latitude), and is annual at higher latitudes. The differences in the seasonal responses between mid- to low-, and high-, latitude S_q variations are intriguing. The annual variation at higher latitudes is obvious due to large ionospheric conductivity differences between the summer and winter seasons. At low- to mid-latitudes, the solar zenith angle is a minimum in equinoxes and a maximum in both the solstices, thereby resulting in larger ionospheric conductivities during equinoxes. However, the conductivity differences due to the seasonal movement of the Sun are not enough to account for the observed changes in the seasonal variation of the S_q amplitude at low- to mid-latitudes. In addition, it has been well established that the equatorial electrojet also exhibits a semiannual variation (Chapman and Rajarao, 1965; Campbell and Schiffmacher, 1985, 1988), which cannot be explained merely by ionospheric conductivity. Several justifications have been proposed for the semiannual response of the S_q strength at low latitudes (Tarpley, 1973; Stening, 1991). Tarpley (1973) suggested that the equatorward movement of either the northern or southern S_q focus at each equinox could cause an equinoctial enhancement of the electrojet. Whereas Stening (1991) explained the semiannual variation near the equator and the S_q focus, in terms of the superposition of a current system generated by various forms of semidiurnal tide.

A large day-to-day variability of S_q currents (strength and shape) has been observed (Mayaud, 1965; Butcher and Brown, 1981; Chen *et al.*, 2007), and is mainly attributed to

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changes in the tidal wind, solar radiation, geomagnetic activity, ionospheric conditions, etc. (Torta *et al.*, 1997). Using a method of natural orthogonal components, Chen *et al.* (2007) analyzed the day-to-day variability of the S_q variations. They found positive and negative correlations for the stations on the same north- or south-side of the S_q current system focus and for the stations on different sides of the S_q focus, respectively. In addition, they reported noticeably enhanced S_q values on some disturbed days, but on other disturbed days they found dramatically reduced S_q variations, suggesting the dominant effects of the disturbance dynamo process.

Thus, an essential understanding of the S_q current system has been acquired through an extensive analysis of low- to mid-latitude station data, covering both sides (equatorward and poleward) of the S_q current system focus in both hemispheres. Although very few studies have been carried out at the edge of the S_q current loop near higher magnetic latitudes (Campbell and Schiffmacher, 1985, 1988; Carafella *et al.*, 1998; Detrick and Lanzerotti, 2001; Sillanpaa *et al.*, 2004). At higher magnetic latitudes, the magnetic variations are affected by a wide range of different phenomena, and magnetospheric processes that may completely dominate the S_q current pattern. The electric fields and currents in the polar region are essentially driven by field-aligned currents caused by solar wind-magnetosphere-ionosphere interactions; resulting in two-cell convection patterns and enhanced ionospheric conductivity in both polar regions (Nagata and Kokubun, 1962). Sillanpaa *et al.* (2004) used an IMAGE magnetometer array to obtain the average signatures of the high-latitude quiet-time magnetic variations. Figure 7 from their paper shows that the observations for Corrected Geomagnetic (CGM) latitudes less than 65° exhibit the signatures of an S_q current system, while latitudes higher than 65° CGM latitude show different signatures. On the contrary, Detrick and Lanzerotti (2001) reported S_q current variations beyond an 80° geomagnetic latitude, which is well beyond this boundary. The boundary of the auroral oval is highly variable with respect to geomagnetic activity, and in the polar-cap region significant magnetic perturbations are always present even on geomagnetically quiet days (Nagata and Kokubun, 1962). This plays a crucial role in determining the higher latitude extent of the S_q current system and, hence, could account for the differences in the results.

The Indian Institute of Geomagnetism has been operating a digital fluxgate magnetometer at the Indian Antarctica station, Maitri (Geographic coordinates: 70.75°S, 11.73°E; Geomagnetic coordinates: 66.84°S, 56.29°E), since the year 2003. The CGM coordinates of this location are (63.11°S, 53.59°E). The analysis of geomagnetic data at Maitri has proved that the station occupies a sub-auroral position during quiet times and comes under the influence of Auroral Electrojet (AE) and Field Aligned Currents (FAC) with increasing geomagnetic disturbances (Hanchinal *et al.*, 1996). Thus, being a sub-auroral location, Maitri is very sensitive to electromagnetic changes in the geo-environment.

In this paper, we investigate the magnetic field recordings at Maitri and attempt to delineate the characteristics of quiet-time magnetic field variations at the sub-auroral location. The magnetic field variations in this paper are interpreted mainly in terms of the atmospheric current systems and not in terms of ground-induced currents. Section 2 describes the data selected for the present study. Results including the diurnal patterns and seasonal variations of its amplitudes and patterns are discussed in Section 3. Section 4 discusses the results, and Section 5 presents the conclusions of this study.

2. Data Acquisition and Analysis

For the present study, we use magnetic field variations in all three components recorded by the digital fluxgate magnetometer with a one-minute sampling interval. The accuracy of the magnetometer is 0.1 nT. As discussed in the previous section, the location of Maitri station is very sensitive to geomagnetic disturbances, and thus it is very important to select the quiet days with extra care. The variation of the equatorward edge of the auroral oval with the geomagnetic activity can also affect the shape and amplitude of the S_q variation over Maitri. Therefore, for the selection of days suitable for studying the S_q system, it is not sufficient to look for times of low K_p, but, in addition, the activity of the auroral electrojet (AE) index has to be low (Xu, 1989).

We have selected days with $\Sigma K_p \leq 3$ for the years 2009 and 2010. As mentioned above, the criteria of a low ΣK_p only is not sufficient, and, therefore, we inspected each day individually to confirm that at least the local daytime is free of disturbance. The AE indices on these days were verified to have lower values (daily average <60 nT). Since the solar minima of solar cycle 23 took place around 2009–10, it was possible to acquire a good number of quiet days with $\Sigma K_p \leq 3$. During the year 2009, we obtained 3 days in each month, except for the months of April and November, in which only 2 days in each month satisfied the $\Sigma K_p \leq 3$ condition. In the year 2010, seven months had 3 days in each month; three months had 2 days in each month and two months had only one day in each month. On average, we obtained more than 5 days per month in two years. The averages of the magnetic field variations on these days were used to obtain the typical patterns of quiet-time magnetic field variations at Maitri.

3. Observations

3.1 Diurnal pattern

The typical diurnal patterns of different components of the geomagnetic field variations at Maitri are obtained by averaging the respective components of magnetic field data over all quiet days (63 days) used in this study. Figure 1 shows a plot of the diurnal variations of the H-, D- and Z-components of the magnetic field variations at Maitri. It resembles the typical diurnal variation of H-, D- and Z-components of S_q type at mid-latitudes in the southern hemisphere (Matsushita and Campbell, 1967). The north component of the magnetic field (H) starts decreasing after sunrise (∼6 LT) and attains a minimum near local noon, then starts recovering back to pre-sunrise values. Variations in the D-component starts decreasing after sunrise, attaining a minimum during morning hours and then crosses zero around noon and attains a maximum in the afternoon hours. Variations in the Z-component are also more or less simi-

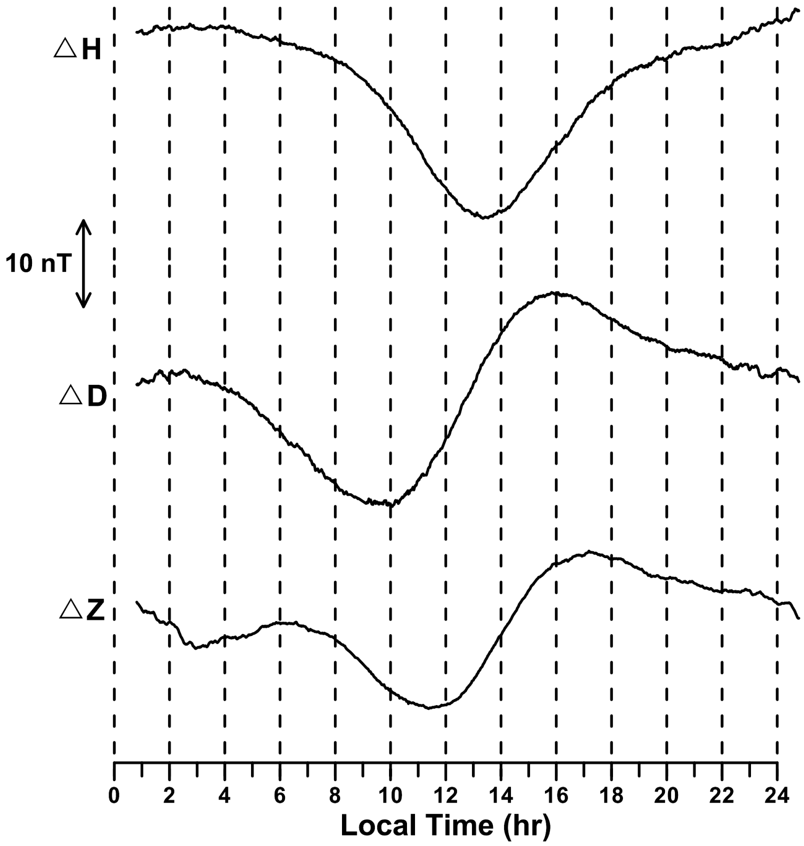

Fig. 1. Geomagnetic field variations in the H-, D-, and Z-components at Maitri, averaged over all the quiet days ($\Sigma K_p \leq 3$) used in this study.

lar to that of the D-variation. However, the magnitude of the Z-variation is small compared to those of the H- and D-components.

The signatures of the H- and D-variations shown in Fig. 1 are of a typical kind due to a clockwise horizontal current flowing in the southern hemisphere, which is a result of the global ionospheric dynamo. The latitudinal location of Maitri is well beyond the focus of the S_q current system, and, hence, experiences the westward limb of the S_q current loop during daytime, peaking near local noon; and negative-positive bipolar variations in the D-component are due to the meridional currents flowing in the morning and afternoon sectors. Normally, the ground magnetic field variations seen in the Z-component are contaminated by the induced subsurface currents. Since we do not intend to study the induced current effects here, we will not discuss this component.

3.2 Seasonal variation

3.2.1 Range of S_q variation Figure 2 shows the diurnal variation of the H- and D-components of the geomagnetic field at Maitri, during twelve months, which are averaged for selected quiet days of 2009 and 2010. It is obvious from the figure that the pattern remains the same in all months, depicting a typical S_q-type variation. However, the amplitude of variations has significant seasonal dependency. It is clearly observed that the variations are smaller in winter months and significantly larger in summer months. In order to quantify this, we show Fig. 3 depicting the diurnal ranges of the H- and D-components, which represents the strength of the S_q variations over Maitri, in various months. The error bars corresponding to the estimated standard error of the mean are also shown for all the months. Note that here the range of the D-variation represents the total range between pre-noon and post-noon extrema. It is observed from Figs. 2 and 3 that, at Maitri, the ΔD-variation is often larger than the ΔH-variation, which is in accordance with the typical characteristics of the S_q variation beyond the S_q focus (Patil *et al.*, 1983). The diurnal ranges of the H- and D-components show larger values during November, December, January and February, which are the summer months at Maitri. During the winter months (May, June, and July), the values are smaller. The lowest diurnal ranges are observed in the month of June for both the H- as well as D-components and it gradually increases from July to February. After attaining a maximum in February, it again starts decreasing. Thus, the annual variation in the strength of the S_q pattern is clearly observed. The range of H-variations during summer is ~40 nT, and that during winter is ~4–5 nT, indicating around an order of one difference between the summer and winter months. One can also notice a small depression in both the H- and D-components in the month of January. It is very difficult to find the reason for this depression, although the possible role of short-scale geomagnetic disturbances cannot be ruled out.

3.2.2 Local time of S_q peak In order to examine the seasonal evolution of the shape of the S_q currents flowing over Maitri station, we record the local time of dip in the H-variation, which corresponds to the time of the S_q peak

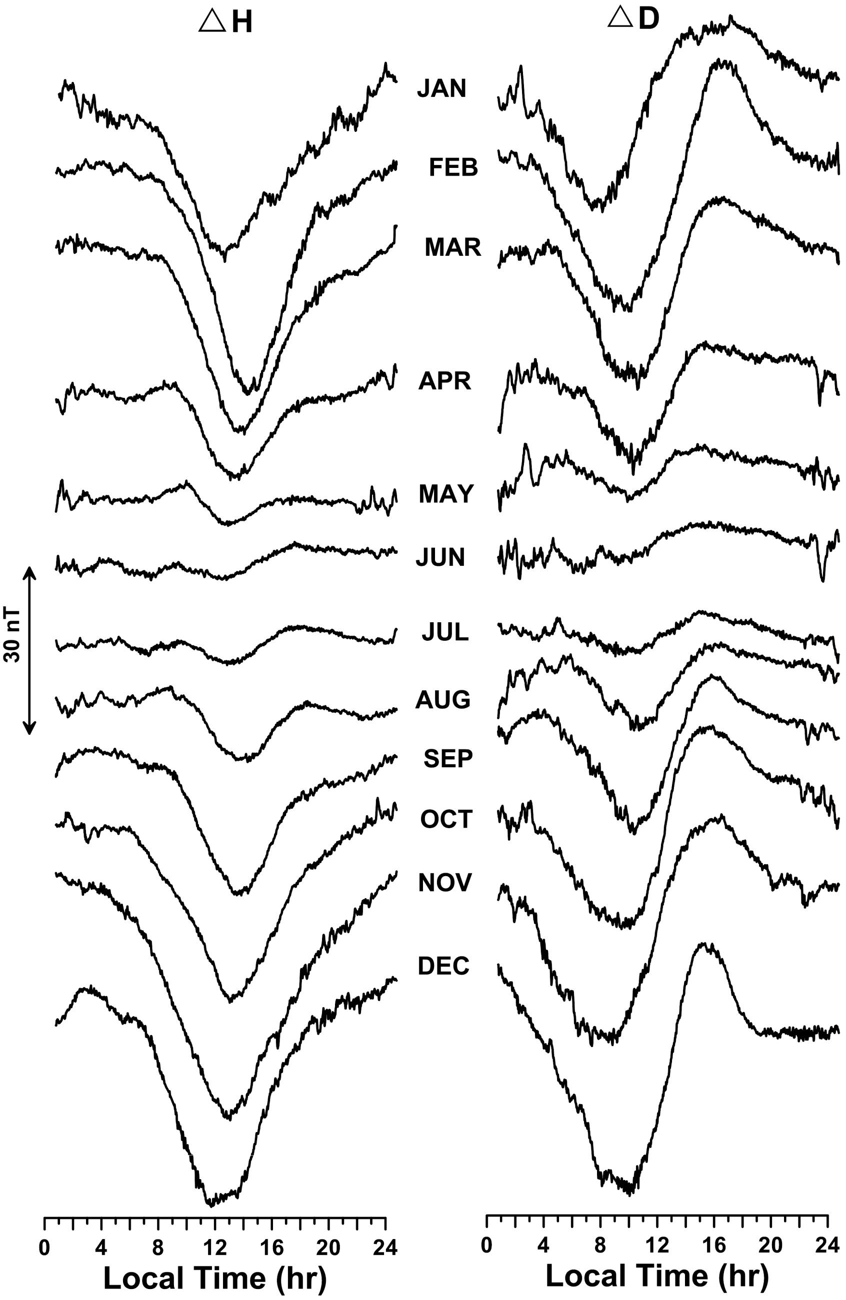

Fig. 2. H- and D-variations during various months averaged over quiet days ($\Sigma K_p \leq 3$) of years 2009 and 2010.

over Maitri, during various months, shown in Fig. 4(a). It can be observed that the time of minimum H changes abruptly from January to February almost by 1.5 hr (12.5 to 14 LT). Between February and May, the time of the minimum shifts relatively slowly towards an earlier local time, almost at the rate of 20 to 30 minutes per month. However, between July and August, again the time of the minimum changes abruptly by more than one hr (12.75 to 14 LT). Between July to November, the time shifts to an earlier local time approximately at the rate of 20 to 30 minutes per month. Also, it can be noticed that during May–June–July and November–December–January, the time shift is a minimum (<15 minutes per month).

Therefore, depending upon the rate of the time shift of the S_q peak, one can classify the months of the year into the following three categories: (1) Months of highest gradients, viz. January–February and July–August; (2) Months of moderate gradients, viz. February–May and August–November; and (3) Months of lowest gradients, viz. May–June–July and November–December–January.

Likewise, we also record the timings of maximum and minimum D, which are shown in Figs. 4(b) and 4(d). It can be assumed that the cross-over of D-variations from morning negative to afternoon positive variations takes place approximately at the midway between the two extrema occurring in the morning and afternoon hours. Therefore, for the sake of convenience, we refer to the midpoint of the local times of the minimum and maximum D-variation as the cross-over point, which indirectly represents the peak of the S_q variation (shown in Fig. 4(c)). Figure 4(e) shows the time

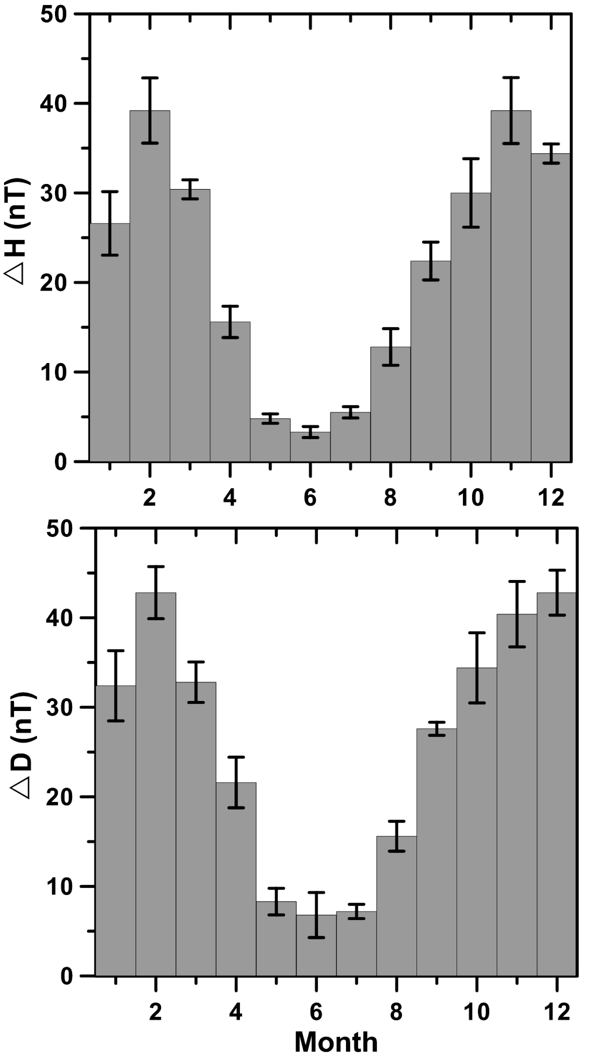

Fig. 3. Bar diagram showing diurnal ranges of H- and D-components during various months. Error bars are the estimated variance of the mean.

interval between the minimum and maximum D-deviation. One can observe from Fig. 4(b), that the time of maximum D sharply increases by more than one hour from January to February. Similarly, the time of minimum D (Fig. 4(d)), and the midpoint of the local times of the two extrema in the D-variations (Fig. 4(c)) also display sharp changes (>1 hr) between these two months. Then the LT of maximum D gradually moves towards lower local times (going nearer to noon) until the month of July. From July to August, once again a sudden shift (of ~1 hr) towards evening times (~16 LT) is observed (Fig. 4(b)). In Fig. 4(d), the LT of minimum D moves gradually towards local noon, but during July and August there is an abrupt change in the LT of minimum D; and again moves gradually towards earlier LT's. These movements of maximum and minimum D-variations towards noon between March to June could be attributed to the shrinking of the S_q current system due to a decreasing amount of daylight time with the gradual arrival of winter. The mid LT of minimum and maximum D-variation shown in Fig. 4(c) also shows the evidence of abrupt changes between January–February, and July–August.

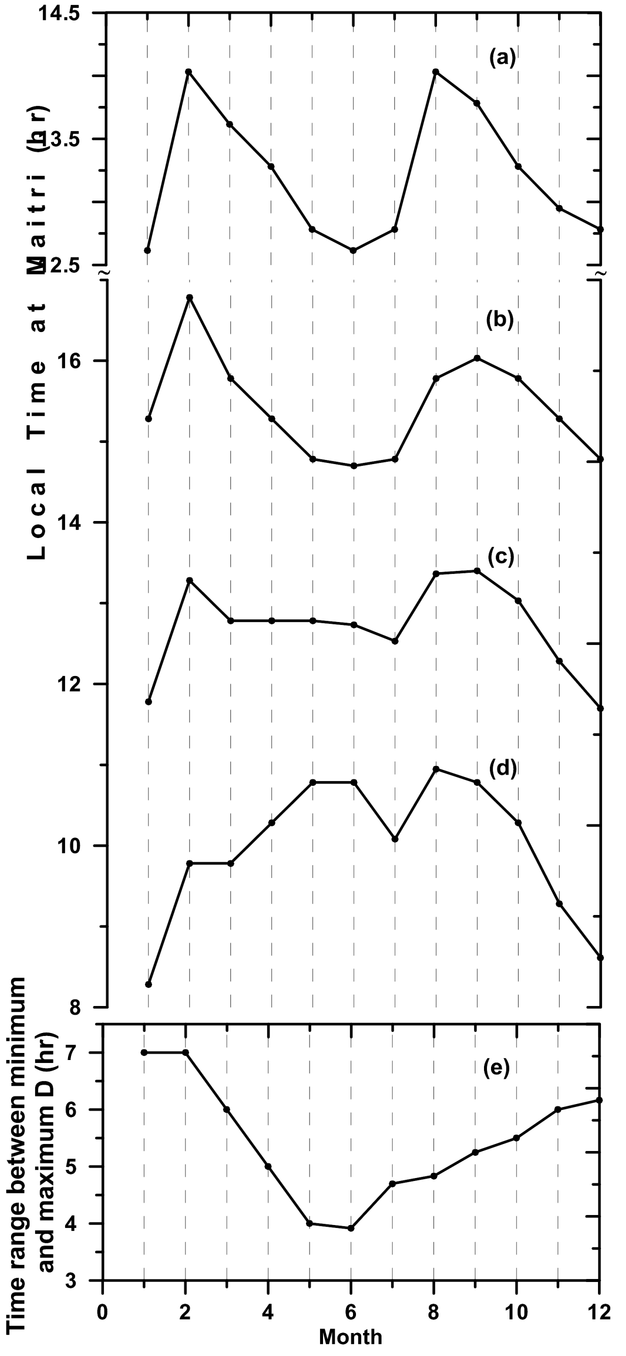

Fig. 4. Seasonal variation of (a) LT of minimum H, (b) LT of maximum D, (c) LT of midpoint of two extrema in D, (d) LT of minimum D, and (e) time interval between morning and afternoon extrema in D-variations. See the text for details.

In general, to some extent, variations in Figs. 4(b), (c) and (d), can be classified into similar categories of months during the year as listed above for the time of maximum depression in the H-variation.

Figure 4(e) shows the time range between minimum and maximum D-variation, that can provide a nearly proportionate estimate of the time duration of the S_q variations. It shows that the time interval does not change abruptly between January–February, or July–August, rather it is almost the same during these months. The time interval changes from a longer to a shorter duration from summer to winter, which is obvious due to the day-night differences during summer and winter.

4. Discussion

The seasonal variability of the range of the S_q variation over a sub-auroral station, described in this paper, indicates an annual variation-peaking during summer and a weakening during the winter months. Campbell (1997) has summarized the daily magnetic field variations due to the S_q current system at various latitudes for different months of the year in both hemispheres. His figure 2.24 indicates a summer peak and a winter minima at higher latitudes, while the variation is of a semiannual type at low to middle latitudes, peaking at equinoxes and a minimum during solstices. Thus, the present results are in agreement with earlier high-latitude observations.

The observation regarding the seasonal variation of the time of the S_q peak over Maitri (Fig. 4) is quite puzzling. Nevertheless, these observations are interesting and have not been reported earlier. The sudden shift of the daily local time of the strongest S_q current over Maitri, between Jan–Feb and July–August, has been checked carefully. This feature is found to be quite persistent in both years, and, hence, it is important to look for the cause of such a rapid phase shift.

Figure 5 plots the diurnal variation of the solar zenith angle (SZA) at the Maitri location on the 21st day of each month. The dashed horizontal line in each plot shows the solar zenith equal to 90°, which eventually represent the horizon on ground. An SZA less than 90° indicates that the sun is above the horizon and one greater than 90° indicates that the sun is below the horizon and the station will not observe sunlight on the ground. The portion with an SZA greater than 90°, indicating local darkness, is shown by the shaded area in the plots. Thus, Fig. 5 portrays the times of sunlight and darkness over Maitri during various months of the year. Consequently, crossings of the 90° level represent the local sunrise and sunset timings on the ground. However, in the ionosphere these timings differ approximately by one hour, as the ionosphere can experience sunlight for a longer time than on the ground.

One can see from these plots that during November, December and January, Maitri experiences 24-hour sunlight, whereas during May, June and July, it experiences darkness throughout the day. Thus, for a period of about three months centered at mid-December, Maitri is continuously in sunlight, indicating that the ionosphere over Maitri is illuminated by solar UV throughout the day. In contrast, during a period of about three months centered at mid-June, Maitri is in total darkness, indicating that the ionosphere over Maitri does not receive any solar UV radiation. The electrical conductivity due to the ionization of the upper atmosphere caused by solar UV rays is important in producing the ionospheric electric currents and, subsequently, the ground magnetic signatures. At Maitri, the differences in the ionospheric conductivity during summer and winter are large. Therefore, one would expect a maximum variation in the geomagnetic field during the Antarctic summer. Nevertheless, during winter, with a complete lack of solar radiation, it is still possible to have some ionospheric conductivity, although much lower than that during summer. Wang *et al.* (2005) found that the ionospheric conductivity in the auroral region strongly depends on the solar zenith angle (solar irradiance) during daytime, but during nighttime the effects of precipitating electrons play a dominant role in maintaining the ionospheric conductivity. Due to different types of energetic-particle ionization during geomagnetic activity and significantly different conditions of solar illumination over Maitri (polar type), the ionospheric conductivities at Maitri are much different from that at low to middle latitudes. The extreme conditions of sunlight during summer and winter over the polar to sub-auroral region cause concentrations of many chemically active species (that are crucial in determining the ozone dis-

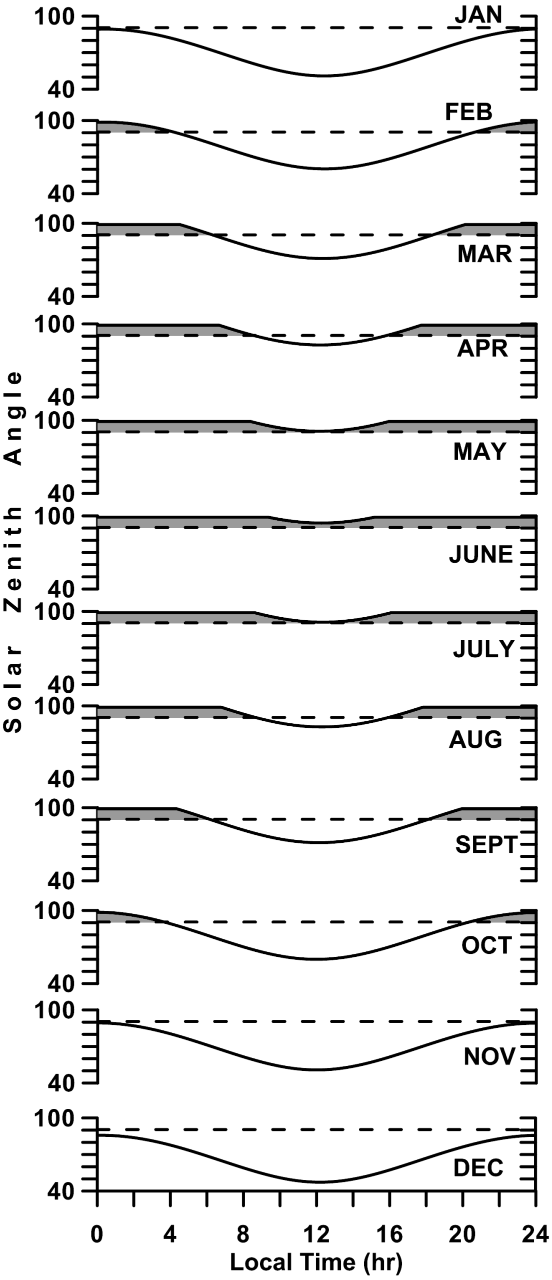

Fig. 5. Diurnal variation of solar zenith angle over Maitri, on 21st day of each month. Horizontal dashed lines indicate SZA of 90°. The hours of darkness are shown by the shaded area.

tribution) to be considerably different from those typical of mid latitudes. In addition, large latitudinal temperature gradients (due to differences in sunlight and ozone distribution) can cause large-scale dynamical circulation of the upper and middle atmosphere, which could be responsible for the ionospheric conductivities during a winter of total darkness (Roederer *et al.*, 1982). Also to some extent, the conductivity of the conjugate ionosphere of summer can be mapped to the winter ionosphere.

Although the S_q variations in the geomagnetic field are due to the global dynamo currents induced by neutral winds associated with the tides in the lower thermosphere, they can also be modulated by local conductivities. The abrupt changes in the local conductivity patterns can lead to abrupt modifications of the S_q current system as well. During January, the Sun is in the sky all the time (24 hours), and then the local sunrise and sunset start appearing in the month of February. In the same way, in the month of July, Maitri does not experience local sunrise and sunsets, but in the month of August it begins to emerge. This could be responsible for our observation of a sudden time shift in the S_q peak during January–February and July–August (Fig. 4). During January, there was continuous solar illumination causing no drastic day-night conductivity differences. Similarly, during July, there was no distinctive termination boundary of ionospheric conductivity. However, during the subsequent months, viz. February and August, sharp boundaries of day-night start appearing. Thus, this could lead to a transformation from a situation of continuous ionization, or total absence of ionization, due to the solar radiation, to some kind of generation (sunlight time) and termination (absence of sunlight) of the ionization. Since the S_q current system is of a global nature, somehow local variations have to be coupled with the global pattern. However, in doing so, this may result in a sudden shift in the pattern. Therefore, a sudden delay of about 1–1.5 hr in the local time (LT) of the S_q peak in the months of February and August (Fig. 4(a)), could appear with the emergence of the day-night terminator (DNT). If a maximum shift of the S_q peak is seen due to high gradients in the ionization and temperature across the terminator line when DNT appears (January–February and July–August), then the disappearance of DNT in the months of May and November should also result in a sudden morning-side shift of the S_q peak. But, we do not observe such a sharp change during April–May and October–November, although we do see a time shift of ∼30 minutes during these pairs of months. This may indicate that the maximum shift of the S_q peak in LT is seen only when the system departs from prolonged extreme local conditions of ionospheric conductivities. Migration from locally-modified ionospheric conductivities over a prolonged time to the appearance of DNT (which normally occurs at other locations under the S_q system) leads to a sudden shift of the S_q peak towards latter local times. Whereas migration from DNT occurrence to extreme local ionospheric conditions (disappearance of DNT) does not result in the rapid movement of the S_q peak. The quasi-steady state of the local S_q system (forming a part of the global S_q current system) in the southern hemisphere is established at a faster rate with the occurrence of DNT and is destroyed at a slower rate when the DNT disappears. While local ionospheric conditions, when DNT is absent, seem to achieve a quasi-steady state slowly. Therefore, when local conditions are overtaken by the appearance of DNT, Maitri experiences a sudden shift in the LT of the S_q peak, but does not observe a sharp change when DNT disappears and local conditions dominate. We envisage that the system remains in the quasi-steady state even after the DNT is withdrawn and, hence, there is no sudden change in the S_q pattern.

During February–March–April and August–September–October, Maitri station sees DNT, and behaves normally as any low- to mid-latitude station. In the presence of DNT, there is a steady gradual shift of the S_q peak to earlier local times by 30 minutes at Maitri as we move to the subsequent month during February–March–April and August–September–October (Fig. 4(a)). The magnitude of the shift may vary with the location of the station. In the months of absence of DNT (May–June–July and November–December–January), the S_q peak gradually shifts either towards morning or towards evening, from one month to another. However, this shift is small (∼10–15 min/month) as compared with that during the months when DNT is present (∼30 min/month). The disappearance of DNT marks the decrease in the local time shift of the S_q peak from 30 min to 15 min towards the earlier local times as seen from May–June and November–December. A prolonged absence of DNT marks the reversal in the trend of the LT shift of the S_q peak.

In the absence of DNT, the local ionospheric conditions can vary slowly (quasi-statically) and will cause a steady LT shift in the S_q peak. This is what we observe during November–December–January and May–June–July. The appearance of DNT causes an adiabatic (sudden) change in the local ionospheric conditions and leads to a sudden large LT shift of the S_q peak. That is why we observe the sudden change in LT of the S_q peak from January to February and July to August. Once the DNT appears, again the local ionospheric conditions change to quasi-statically. Therefore, during February–March–April and August–September–October, we observe steady changes in the LT of the S_q peak. Withdrawal of DNT after its continuous presence does not result in adiabatic changes in the local ionospheric conditions because the S_q system remains in the quasi-steady state even after the disappearance of DNT. This could be the reason that we do not see a sudden change in the S_q current pattern during April–May and October–November.

Furthermore, the differences in the intensity of the impinging solar UV radiation can activate different types of neutral wind patterns driving the ionospheric dynamo currents, thus triggering unusual thermotidal activity. The tidal motion activated by the sudden ‘switching on’ and ‘switching off’ of the solar irradiation could be a potential candidate for the modulation of the dynamo currents and a shifting of the S_q peak in the local time.

It is worth noting the observations by Stening *et al.* (2007), who investigated the seasonal variation of the S_q focus on quiet days. Their Figure 7 shows a sharp equatorward shift of the southern S_q focus from January to February and a similar equatorward movement of the southern focus was seen during July–August as well. Therefore, the question arises: "is there any association between this equatorward movement of the S_q focus and the observed shift of the S_q peak to later local times over Maitri?" If the answer is "yes", then a similar shift in the peak S_q time should be present at lower latitudes too. Therefore, it is important to examine the time of the S_q peak at lower latitudes. However, while carrying out such exercise, one should also keep in mind that a tilted S_q current loop is a commonly-observed feature of the S_q system (Mayaud, 1965), and, hence, a shift in the S_q peak will be less prominent at low- to mid-latitudes compared to that at higher latitudes. Also, Chen *et al.* (2007) found that the latitudinal shift of the S_q current focus is more important than current intensity variation to the day-to-day variability in the S_q daily range. It is possible that some antisymmetric tidal modes become activated, either due to the differences in the extreme conditions of incoming solar UV radiations at higher latitudes or due to a day-to-day variability in the overall atmospheric conditions, which could be responsible for the latitudinal movement of the S_q focus. This aspect of the diurnal S_q-pattern needs to be examined in future studies.

5. Conclusions

This paper investigates geomagnetic field variations due to a quiet S_q current system observed by a ground-based magnetometer located at a southern sub-auroral latitude. Although the study of the S_q current has a long history and its climatological features have already been well documented, the high-latitude part of S_q is relatively not well studied, partly because the effect of the magnetospheric current is usually intense there. Also, it is useful to know the quiet-time variation as a baseline at sub-auroral latitudes. We have extracted quiet geomagnetic field variations from the magnetic data, and examined the average local time and seasonal variations.

The following are the conclusions of the present study:

(1) The present study identifies the signatures of the south limb of the solar quiet current loop of the southern hemisphere over the Indian Antarctic station, Maitri (Corrected Geo. Mag. Lat. = 63.11°S), on all the magnetically quiet days ($\Sigma K_p \leq 3$) throughout the years 2009 and 2010.

(2) Marked seasonal changes are observed in the H-, and D-components. Because the amount of solar UV radiation received by the ionosphere is highest during summer, the amplitude of the S_q variations is large during summer (a few tens of nT), and weak during winter (a few nTs), exhibiting an annual variation. In spite of the total darkness during winter months, an S_q pattern is identified at Maitri.

(3) The obtained climatological variations are generally in agreement with previous studies, therefore confirming the annual variation of S_q at sub-auroral region.

(4) A discernible change in the phase of the local time variation through the change in time of the peak of the S_q current is evident during particular months. We believe that this may be due to a sudden change in the ionospheric conductivity pattern and/or trigger unusual thermo-tidal activity, due to the transitions from the complete presence, or absence, of sunlight to partial sunlight, and vice versa.

(5) Accordingly, the present paper highlights the role of the extreme conditions of impinging solar UV radiation in the sub-auroral region, which can trigger particular thermo-tidal activity, and can modify the global S_q current pattern. A better picture of the seasonal evolution of the S_q pattern could be obtained using a larger database. This will be a part of our future studies.

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