AGU PUBLICATIONS

JGR

Journal of Geophysical Research: Space Physics

RESEARCH ARTICLE

10.1002/2014JA020728

**Key Points:**
- Abnormal intensification of electric currents
- Latitudinal sections of the African stations
- Highest and positive magnitude in February

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**Citation:**
Bolaji, O. S., A. B. Rabiu, O. R. Bello, A. Yoshikawa, K. Yumoto, O. O. Odeyemi, and O. Ogunmodimu (2015), Spatial variability of solar quiet fields along 96° magnetic meridian in Africa: Results from MAGDAS, *J. Geophys. Res. Space Physics*, *120*, 3883–3898, doi:10.1002/2014JA020728.

Received 19 OCT 2014
Accepted 23 MAR 2015
Accepted article online 26 MAR 2015
Published online 12 MAY 2015



# Spatial variability of solar quiet fields along 96° magnetic meridian in Africa: Results from MAGDAS

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**Abstract** We have used chains of Magnetic Data Acquisition System (MAGDAS) magnetometer records of the horizontal (*H*) and vertical (*Z*) magnetic field intensities during September 2008 to August 2009 (year of deep minimum) across Africa to study their variability during the quietest international days, which coincidently associated with the sudden stratospheric warming (SSW) event in January 2009. This selection of the most international quiet days is indicative of 80% that are strongly associated with days when unusually strong and prolonged sudden SSW event occurs in January 2009. Interestingly, in January, a significant magnitude depletion of solar quiet ($S_q$) equivalent current was observed near noon hours around the magnetic equator (Addis Ababa, ABB) compared to any other months along with a consistent significantly reduced value across the Northern Hemisphere and moderate decrease at the Southern Hemisphere. Also, we found that Nairobi and Dar es Salaam at the Southern Hemisphere, which are close to ABB (dip equator), are strongly prone to westward electric field compared to the magnetic equator and Khartoum at the Northern Hemisphere. Significant negative values of $MS_q(Z)$ magnitudes observed near noon hours at Hermanus indicate the presence of induced currents that suggest ocean effects along with reversal to significant positive values in the afternoon, which subsided before 1800 LT in almost all the months, indicate stronger influence of ionospheric currents. On seasonal variability of $S_q(H)$, a slight depression at ABB during September equinox is one of the evidences of seasonal $S_q$ focus shift. Latitudinal variability of $S_q$ near-noon hours was also investigated.

## 1. Introduction

The geomagnetic field components *H* and *Z* are the scalar values of the horizontal and vertical components. The estimates of these define the electric current parts that were induced inside the solid Earth and extended to the ionosphere [*Olsen*, 2007]. The overhead electric currents estimated from these components, which are regular, are related to ionospheric currents whose position and shape are roughly constant in a reference system fixed with respect to the Sun. This system is referred to as solar quiet ($S_q$) variation and is primarily related to the ionospheric dynamo processes described by *Mazaudier and Blanc* [1982] and *Vassal et al*. [1998]. Irregular solar quiet ($S_d$) variation, which could result from the prompt injection of energies into the ionosphere from magnetospheric sources, storms, or substorms has been discussed extensively by *Akasofu* [1977] and *Fairfield* [1979] to mention a few. The $S_d$ observations are not frequent compared to the $S_q$ daily occurrences because the $S_d$ observations rely on the records from geomagnetic storm events. In this paper, our focus is on the regular overhead electric currents flowing during quiet condition in the *E* region of the ionosphere. These observations during quiet days are in the neighborhood of the 96° magnetic meridian (MM) that stretch over geomagnetic latitudes 42.29°S to 25.76°N in Africa. This similar data set has been used by *El Hawary et al*. [2012]; they found annual variation in the $S_q$ of *H* and declination (*D*) along with two vortices on the dayside of the Southern Hemisphere during spring period.

Previous research on $S_q$ currents in Africa including the works of *Rastogi* [2004], *Vassal et al*. [1998], *Chapman and Raja Rao* [1965], *Doumouya et al*. [1998], *Onwumechili* [1959], and *Fambitakoye and Mayaud* [1976] have examined Δ*H* and Δ*Z* components mainly on the longitudinal sections and fairly on the latitudinal sections of the African stations. Their findings have revealed many outstanding results that have improved our understanding regarding the morphology of the $S_q$ currents. For example, recent observational studies by *El Hawary et al*. [2012] confirmed abnormal intensification on the daily range of *H* field over the dip equator that was found by *Egedal* [1947] and named equatorial electrojet (EEJ) currents by *Chapman*

[1951]. *Chapman* [1951] referred to this abnormal intensification as an enhanced eastward band of electric currents within the equatorial ionosphere. He devised model equations of current ribbon of constant intensity to examine the latitudinal variations of $\Delta H$ and $\Delta Z$ as follows:

$$\Delta H = \frac{j}{w}\tan^{-1}\frac{Zwh}{h^2 + x^2 - w^2} \tag{1}$$

$$\Delta Z = \frac{j}{zw}\log\frac{(x+w)^2 + h^2}{(x-w)^2 + h^2} \tag{2}$$

These latitudinal variations are due to an extended sheet current of zero thickness, which is a function of height ($h$), the semiwidth ($w$), and the distance ($x$) from the magnetic equator. $J$ is the strength of the uniform electrojet sheet current. From these equations, Chapman suggested that the $S_q$ variation of the $\Delta Z$ component is the spatial gradient of the horizontal current intensity. He assumed that $\Delta H$ is totally northward so that the electric field and the current are entirely eastward. This indicates that $\Delta Z$ is zero at the electrojet belt. Chapman further stated that $\Delta Z$ will have minimum and maximum values near noon hours over the Northern and Southern Hemispheres outside the equatorial electrojet belts. *Chapman* [1919] had earlier confirmed these equations using geomagnetic data from 21 observatories over the American sector. He found that $\Delta H$ variability outside the equator around 40°N and 40°S was reversed from the near-noon peak seen at the equator, but $\Delta Z$ was of opposite signs at stations north and south of the equator. Similar variability on $\Delta H$ and $\Delta Z$ has been detected by *Pramanik and Yegna* [1952] in India and *Onwumechili* [1959] in Nigeria. Equations (1) and (2) have also been established by *Chapman and Raja Rao* [1965], *Fambitakoye and Mayaud* [1976], *Rastogi* [2004], and *Doumouya et al.* [1998]. A further effort worth mentioning is the occasional reversal of $\Delta H$ field during daytime hours at Addis Ababa, which was reported by *Gouin and Mayaud* [1967]. They ascribed this phenomenon to the reversal of the EEJ current and named it counter equatorial electrojet (CEJ) current. This CEJ current was later found by *Hutton and Oyinloye* [1970] over Nigeria. It was also reported by *Rastogi* [1974], *Yizengaw et al.* [2011], and *Ngwira et al.* [2012] using geomagnetic data from the African, American, and Asian stations. *Rastogi* [1974] observed CEJ events during the morning, noon, and evening hours. He found that CEJ events during evening hours are highest with the lowest during noon. He suggested that the occurrence of CEJ events occurred most frequently during evening hours with the lowest occurrence during noon period. He suggested that this scarcity of CEJ events occurs mostly when the solar activity is increasing. He noted that $\Delta Z$ field at equatorial stations could reverse its direction during CEJ events and this might sometimes be due to induced currents. Also, recent works of *Yizengaw et al.* [2011] and *Ngwira et al.* [2012] over the African and American sectors have shown intense and consistent CEJ during the main phases of geomagnetic storm. They attributed the CEJ events during stormy period to intense westward electric field initiated by higher-energy deposition from the solar wind-magnetosphere-ionosphere interactions into the high latitude that mapped into middle-low latitudes.

The literature on African sectors cited above described $S_q$ currents on $H$ and $Z$ components mostly on single stations along longitudinal sectors. Observations of latitudinal variations in America and Asia sectors further established that the $S_q$ currents strongly vary with latitudes. To the best of our knowledge and from the results of *El Hawary et al.* [2012] that used coordinated MAGDAS data set over Africa that is similar to the one that will be employed in this study, no detailed report on $S_q$ variability regarding its coincident with occurrence of sudden stratospheric warming (SSW) during a year of deep minimum (2008–2009) has been made across the latitude of Africa. The use of similar coordinated MAGDAS networks by *El Hawary et al.* [2012] to investigate observational $S_q$ currents over Africa for the first time makes the coincident SSW that occurs during a year of deep minimum unimportant. Since little is known about the relationship between tropospheric forcing and $S_q$ currents across Africa, this paper will investigate the $S_q$ currents of $H$ and $Z$ components from south to the north of Africa through the equator (96° MM) during a year of deep minimum.

## 2. Materials and Methods

Records of the horizontal ($H$) and vertical ($Z$) components of the geomagnetic field obtained using Magnetic Data Acquisition System (MAGDAS) network from September 2008 to August 2009 were analyzed. The stations involved are located between South Africa and Egypt on geomagnetic latitude between 42.29°S and 25.76°N, which is along 96° magnetic meridian (MM) in Africa. Details of MAGDAS system are reported

**Table 1.** Coordinates of Stations Along 96° MM

| | | Geographic | Coordinates | Geomagnetic | Coordinates |
|---|---|---|---|---|---|
| Station Names | Station Codes | Latitude (deg) | Longitude (deg) | Latitude (deg) | Longitude (deg) |
| Fayum | FYM | 29.18 | 35.50 | 25.76 | 112.65 |
| Aswan | ASW | 23.59 | 32.51 | 15.20 | 104.24 |
| Khartoum | KRT | 15.33 | 32.32 | 5.69 | 103.80 |
| Addis Ababa | ABB | 9.04 | 38.77 | 0.18 | 110.47 |
| Nairobi | NAB | −1.16 | 36.48 | −10.65 | 108.18 |
| Dar es Salaam | DES | −6.47 | 39.12 | −16.26 | 110.59 |
| Lusaka | LSK | −15.23 | 28.20 | −26.06 | 98.32 |
| Maputo | MPT | −25.57 | 32.36 | −35.98 | 99.57 |
| Durban | DRB | −29.49 | 30.56 | −39.21 | 96.1 |
| Hermanus | HER | −34.34 | 19.24 | −42.29 | 82.20 |

in *Yumoto and CPMN Group* [2001], *Yumoto and the 210° MM Magnetic Observation Group* [1995], *Yumoto and the 210° MM Magnetic Observation Group* [1996], and *Rabiu et al.* [2009]. The coordinates of stations along 96° MM are shown in Table 1, while Figure 1 displays the location of the stations.

The baseline value of the geomagnetic field intensity of the *H* and *Z* components, Base*H* and Base*Z*, was deduced from MAGDAS records of 1 min value and converted to 1 h local time bins for each day of every month. The Base*H* and Base*Z* on each day were defined as the average values of *H* and *Z* components near local midnight (i.e., between 2400 LT and 0100 LT). This is expressed mathematically as follows:

$$\text{Base}H = \frac{BH_1 + BH_{24}}{2} \quad (3)$$

$$\text{Base}Z = \frac{BZ_1 + BZ_{24}}{2} \quad (4)$$

$BH_1$ and $BZ_1$ are the hourly values of *H* and *Z* components, respectively, at 0100 h, and $BH_{24}$ and $BZ_{24}$ are the hourly values of *H* and *Z* components, in that order at 2400 h. The hourly departures ($\Delta H$ and $\Delta Z$), which are approximately equal to solar quiet (ionospheric current) of *H* and *Z* components ($S_q(QH)$ and $S_q(QZ)$), are the residual values after subtracting the Base*H* and Base*Z* values from the five quietest days average of *H* and *Z* component values on each hour of each of the five quietest days. Therefore,

$$\Delta H_t = BH_t - \text{Base}H \quad (5)$$

$$\Delta Z_t = BZ_t - \text{Base}Z \quad (6)$$

where $t = 1$ to 24 h. These analyses are carried out on every day of each month under investigation. These hourly departures $\Delta H_t$ and $\Delta Z_t$ (from equations (5) and (6)) are further corrected for noncyclic variations, which makes the values of $\Delta H_t$ and $\Delta Z_t$ at 0100 h their values at 2400 h [*Vestine*, 1947; *Rabiu*, 2000]. These hourly departures corrected values are the solar quiet daily variations of *H* and *Z* components ($S_q(QH)$ and $S_q(QZ)$), respectively, which are the mean hourly values from a selected group of days. These selected groups of days are obtained from the Geoscience Australia catalogue at http://www.ga.gov.au/oracle/geomag/iqd_form.jsp. These are the five international quietest days, and they depict

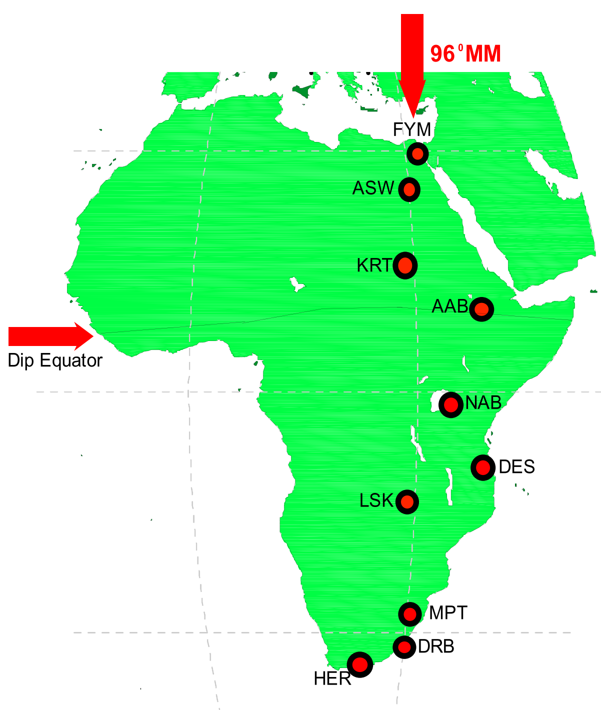


**Figure 1.** African stations along 96° MM.

when the geomagnetic variations are minima in each month. The year 2008 is a year of the solar radiation minimum and 2009 is a year of the geomagnetic minimum since one century (1901) and have average sunspot numbers of 2.8 and 3.1, respectively. During these years, the geomagnetic conditions reveal that there are few geomagnetic storms that are moderate. The highest one observed from the archives of World Data Center catalogue at http://wdc.kugi.kyoto-u.ac.jp/ was on 22 July 2009 with disturbance storm time ($D_{st}$) value of −78 nT and planetary magnetic ($K_p$) value of 4.3. The time convention for the data is in universal time (UT), but local time (LT) is used in the analysis. Therefore, all the stations are converted to LT in reference to Greenwich mean time.

The diurnal variations of $S_q(H)$ and $S_q(Z)$ for the five quietest days over a month are used to estimate their monthly mean values: ($MS_q(H)$) and ($MS_q(Z)$) over all the stations from September 2008 to August 2009. Their seasonal variations were estimated by averaging their monthly mean values for each season. These months are grouped into four seasons: December solstice or D season (November–February), March equinox or March E season (March and April), June solstice or J season (May–August), and September equinox or September E season (September and October). The latitudinal variability over all the stations at 1100 LT (near-noon) hours was also investigated. This is achieved by plotting all monthly values of $S_q(H)$ and $S_q(Z)$ across all stations at 1100 LT.

## 3. Results

### 3.1. Monthly Mean Variations of $S_q(H)$

Figures 2a and 3 are contour plots with grid lines on the *x* and *y* axes that depict the latitudinal profile of monthly mean variations of $S_q(H)$ and $S_q(Z)$, respectively, along the African 96° MM. On the *y* axes, geomagnetic (GM) latitudes (LAT) of stations under investigation were arranged in increasing order from the Southern to Northern Hemisphere. The *x* axes show varying local time (LT) of each station in every month in hours (HRS). The color bar codes beside each contour plot (Figures 2a and 3) represent the intensity of $S_q$ magnitudes with respect to *H* and *Z* components. In all the months from the Northern to the Southern Hemisphere, positive peak magnitudes of $MS_q(H)$ were observed during daytime hours around noon. During these near-noon hours, elliptical loop signatures of $MS_q(H)$ in the range of ~20–77 nT were observed from the dip equator and stretched northward and southward. These showed a highest and positive magnitude in February at Addis Ababa (ABB), within dip equator, a station at 0.18°S GM latitude with a value of ~77 nT. The lowest magnitude of $MS_q(H)$ was observed near noon hours at Hermanus (HER) in March with a value of ~−15 nT. Higher magnitudes of $MS_q(H)$ were observed at ABB in all months near noon hours, but they were not as strong as that in February. However, in May, June, and August, these higher magnitudes of $MS_q(H)$ were observed to have shifted to Khartoum (KRT) significantly, about 6° north of the dip equator, leaving moderate magnitudes of $MS_q(H)$ at the dip equator (ABB) and weak magnitudes at Nairobi (NAB), the southern edge of ABB. In July and September–December, moderate magnitudes of $MS_q(H)$ in the range of ~42 nT (December) to ~49 nT (October) were observed at ABB with an exception in January having significant reduction. The $MS_q(H)$ magnitudes observed in January near noon hour at ABB are significantly depleted compared to any months at ABB, which is unusual. The $MS_q(H)$ magnitude near noon hour at ABB in January is ~30 nT with a significant decrease to ~15 nT at about 11°N around NAB and a moderate decrease to ~20 nT around 6°S (KRT). The significant decrease in $MS_q(H)$ magnitude at the Southern Hemisphere was higher compared to that at the Northern Hemisphere in January across the hemispheres. Also, the moderate magnitude of $MS_q(H)$ in September near noon hour is ~47 nT at ABB and was observed to have shifted to around 11°S (NAB) with slight increment in $MS_q(H)$ magnitude to ~48 nT. However, a reduced $MS_q(H)$ magnitude of ~32 nT was observed at the northern neighborhood of ABB (KRT) in September. The observed highest $MS_q(H)$ magnitude around the dip equator (ABB) near noon hours decreases as one moves either southward or northward from ABB. These decreases in magnitudes were more significant when the elliptical loops disappear. This shows that signature patterns of $MS_q(H)$ spreads appear decreasing near noon hours on either side of the equator as one moves southward and northward.

However, $MS_q(H)$ signatures beyond FYM could not be observed because MAGDAS facilities were unavailable. However, around Lusaka (LSK), significant negative $MS_q(H)$ values were observed in all months immediately after prenoon peaks of $MS_q(H)$ magnitudes. The intensity of this negative $MS_q(H)$ value during afternoon

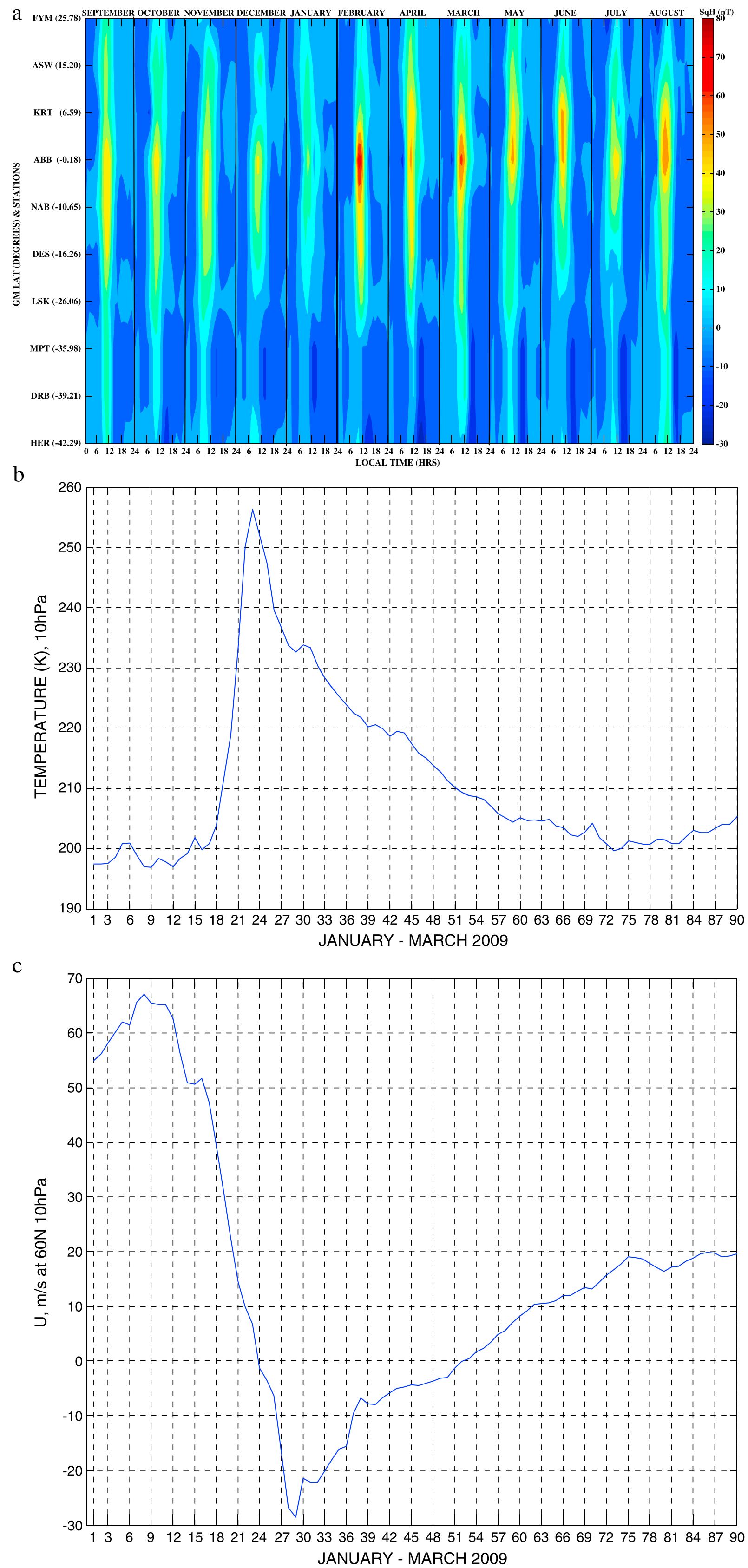
a
SEPTEMBER OCTOBER NOVEMBER DECEMBER JANUARY FEBRUARY APRIL MARCH MAY JUNE JULY AUGUST
SqH (nT)
FYM (25.78)
ASW (15.20)
KRT (6.59)
ABB (-0.18)
NAB (-10.65)
DES (-16.26)
LSK (-26.06)
MPT (-35.98)
DRB (-39.21)
HER (-42.29)
GM LAT (DEGREES) & STATIONS
LOCAL TIME (HRS)
b
TEMPERATURE (K), 10hPa
JANUARY - MARCH 2009
c
U, m/s at 60N 10hPa
JANUARY - MARCH 2009

**Figure 2**

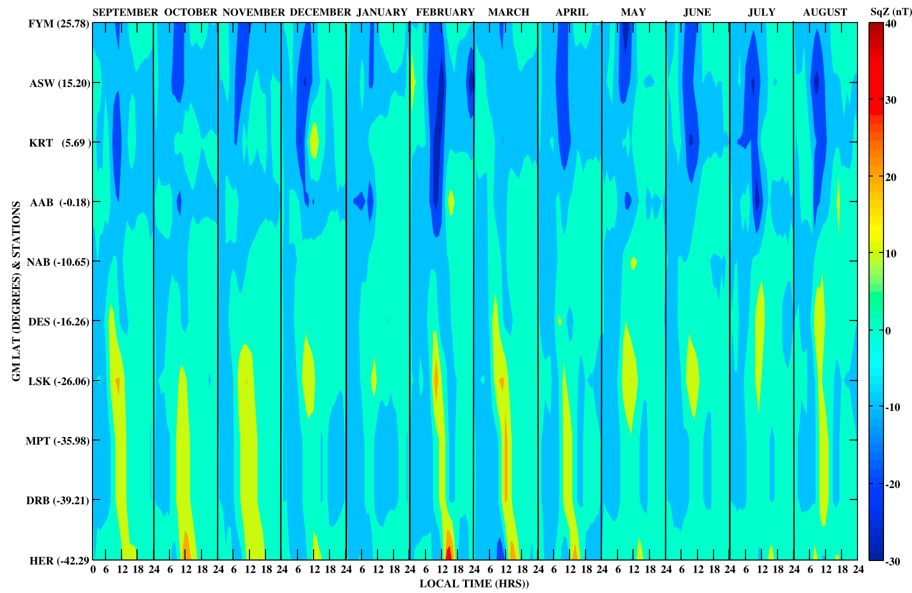


**Figure 3.** Latitudinal profiles of monthly mean variation of $S_qZ$ along 96° MM from September 2008 to August 2009.

hours (1600 LT) was highest at HER in March and has a value of ~−26 nT. Interestingly, these highest intensities of negative $MS_q(H)$ values in all the months at the Southern Hemisphere stations: LSK, MPT, DRB, and HER were observed around 1600 LT and 1800 LT with corresponding counter electrojet (CEJ) events around 1700 LT and 1800 LT at ABB, a station at 0.18°S of GM latitude and on either side of the hemispheres. At about 11°S (NAB) around 1700 LT and 1800 LT, westward currents were observed in all months. At the Northern Hemisphere of ABB (KRT) around the same period, westward currents were found in January, June, August, and November. However, CEJ event was absent at the dip equator (ABB) in January, March, April, September, and October. This indicates that minimal CEJ events were observed at the dip equator along with minimal westward currents at the Northern Hemisphere close to ABB compared to its Southern Hemisphere counterparts.

### 3.2. Monthly Mean Variations of $S_q(Z)$

Along the African 96° MM from north to the south (Figure 3), $MS_q(Z)$ magnitudes from 0100 to 0600 LT were observed to fluctuate between the intensities of ~−12 nT and ~22 nT. The lowest value of ~−12 nT was observed at ABB in January around 0600 LT, and the highest value of ~22 nT was observed at ASW in February. Between 1800 LT and 2400 LT, $MS_q(Z)$ intensities are in the range of ~0.1 nT and ~−26 nT. The least positive intensity was observed in February at Nairobi (NAB) around 1900 LT, and the weakest negative intensity was seen in February at Aswan (ASW) around 2300 LT. From sunrise through to noon and to the dusk hours, $MS_q(Z)$ magnitudes were observed to decrease significantly from the equator (ABB) toward the Northern hemisphere (KRT-FYM). These reductions in the $MS_q(Z)$ magnitudes were observed in all months with highest negative peaks mostly around prenoon hours. This highest negative peak value of ~−29 nT was observed at ASW in February at noon.

At ABB, from 0700 LT till noon hours, $MS_q(Z)$ magnitudes ranged between ~2 nT and ~−24 nT in all months. Between 1000 LT and 1200 LT, magnitudes of ~2 nT and ~−24 nT were observed in January and July, respectively. Immediately after these scenarios, between afternoon and the dusk sectors, the variability patterns of $MS_q(Z)$ in all months were observed maintaining their magnitudes in the range of ~0.1–~18 nT, on all hours. The highest (~18 nT) was observed in August around 1700 LT, and the lowest (~0.1 nT) was in December around 1800 LT.

**Figure 2.** (a) Latitudinal profiles of monthly mean variation of $S_qH$ along 96° MM from September 2008 to August 2009. (b) Stratospheric temperature at 10 hPa in January–March 2009. (c) The mean zonal wind at 60°N and 10 hPa during January–March 2009.

Just after ABB toward the Southern Hemisphere, $MS_q(Z)$ was observed to increase in magnitude positively. This was visible in the morning sector at NAB, a station at geomagnetic latitude of ~10°S and increased with time toward near-noon hours at Dar es Salaam (DES). These significant increases were later observed to have shifted to noon hours between LSK and Maputo (MPT) with January, May–July, and December as exceptions. This trend indicates that apart from the buildup in the morning in NAB toward DES, increments of $MS_q(Z)$ magnitudes were observed to have shifted from the morning to between forenoon and afternoon periods as the geomagnetic latitude decreased. This is obvious between DRB and HER where increases in magnitudes were further shifted, became highest at afternoon toward the dusk period, and subsided before 1800 LT. This trend was observed in February–May and September–November with highest magnitude of ~39 nT in February around 1500 LT. The trend was partial in January, June–August, and December such that positive magnitudes of $MS_q(Z)$ subsided before getting to HER and fluctuated between ~0.1 nT and ~0.4 nT. In January, May–July, and December, $MS_q(Z)$ subsided at LSK, and in August, it subsided at DRB. At DRB closer to HER, slight $MS_q(Z)$ positive magnitudes were observed to regenerate during afternoon hours and further stretched to HER. These regenerated $MS_q(Z)$ magnitudes that were slightly significant were observed in May, July, and August. After $MS_q(Z)$ magnitude subsided at LSK and DRB, no stronger positive regeneration of $MS_q(Z)$ magnitude was observed from the noon to dusk hours in January, June, and December as the latitudes decrease toward HER. At the Southern Hemisphere and away from the electrojet belt, our results show positive increments of $MS_q(Z)$ in the morning, which were continuous and progressively shift to near-noon hours at DES, on GM latitude of ~17°S. They were observed to further shift between near noon and the dusk period between LSK and HER, on GM latitude of 26.06°S and 42.29°S, respectively. These shifted between near noon, and the dusk period had higher intensity in February–April and September–November.

### 3.3. Latitudinal Variations of $MS_q(H)$ and $MS_q(Z)$ Near Noon Hours

Plots of monthly mean of $S_qH$ against the geomagnetic latitude of stations along the African 96° MM near-noon hours are shown in Figure 4. These monthly mean variations of $S_q(H)$ near-noon hours were observed to gradually increase from the Southern Hemisphere toward equator stations. This was observed from LSK in December–March and May. Similar gradual increase was observed earlier at MPT in September–November, April, and August. At the Southern Hemisphere in June and July, there was no increase in magnitude from HER to LSK. However, a sharp increase was observed at DES and NAB in June and July, in that order. Highest magnitudes of $MS_q(H)$ near-noon hours were observed between ABB and KRT. The highest value of ~70 nT was observed near noon hours in February. However, there were depressions from $MS_q(H)$ magnitudes near noon hours at ABB in July and September–December with immediate sharp increased values at their northern strips (KRT). These depressions were slight in July and September–November but highest in December.

Figure 5 shows the latitudinal variations of $MS_q(Z)$ near noon hours over the African stations along 96° MM. The signature of the latitudinal variability of $MS_q(Z)$ (Figure 5) over the African stations is opposite that of $MS_q(H)$ in Figure 4. From Figure 4, the magnitude of $MS_q(H)$ variability increases toward stations in the Northern Hemisphere, while the magnitude of $MS_q(Z)$ is decreasing toward the Northern Hemisphere (Figure 5). The increase in $MS_q(Z)$ magnitude toward the Southern Hemisphere was highest at LSK in September, November, January–March, May, and June. The highest value (~22 nT) at LSK was observed in March, near noon hours. Exceptions to these highest increases over LSK were observed in fourfolds. One of the observations is a sharp increase from LSK in October, which increases steadily through DRB and was highest in HER. Surprisingly, in December, a high value (~18 nT) of $MS_q(Z)$ was observed at ABB near noon hours, subsided between NAB and DES and increased to an even higher value (~20 nT) at LSK. Higher magnitudes of $MS_q(Z)$ near-noon hours were also observed at MPT in April and August. Finally, higher magnitude of $MS_q(Z)$ was observed at DES in July. After these high values at LSK, MPT, and DES, they were observed to subside through the Southern Hemisphere with minimal values at HER with exceptions in October and January.

### 3.4. Seasonal Variations of $S_q(H)$ and $S_q(Z)$ Along the African 96° MM Latitudes

Figure 6 shows the seasonal variations of $S_q(H)$ in contour plots with grid lines on *x* and *y* axes. The color bar code beside the contour plot represents the intensity of seasonal $S_q(H)$ magnitudes.

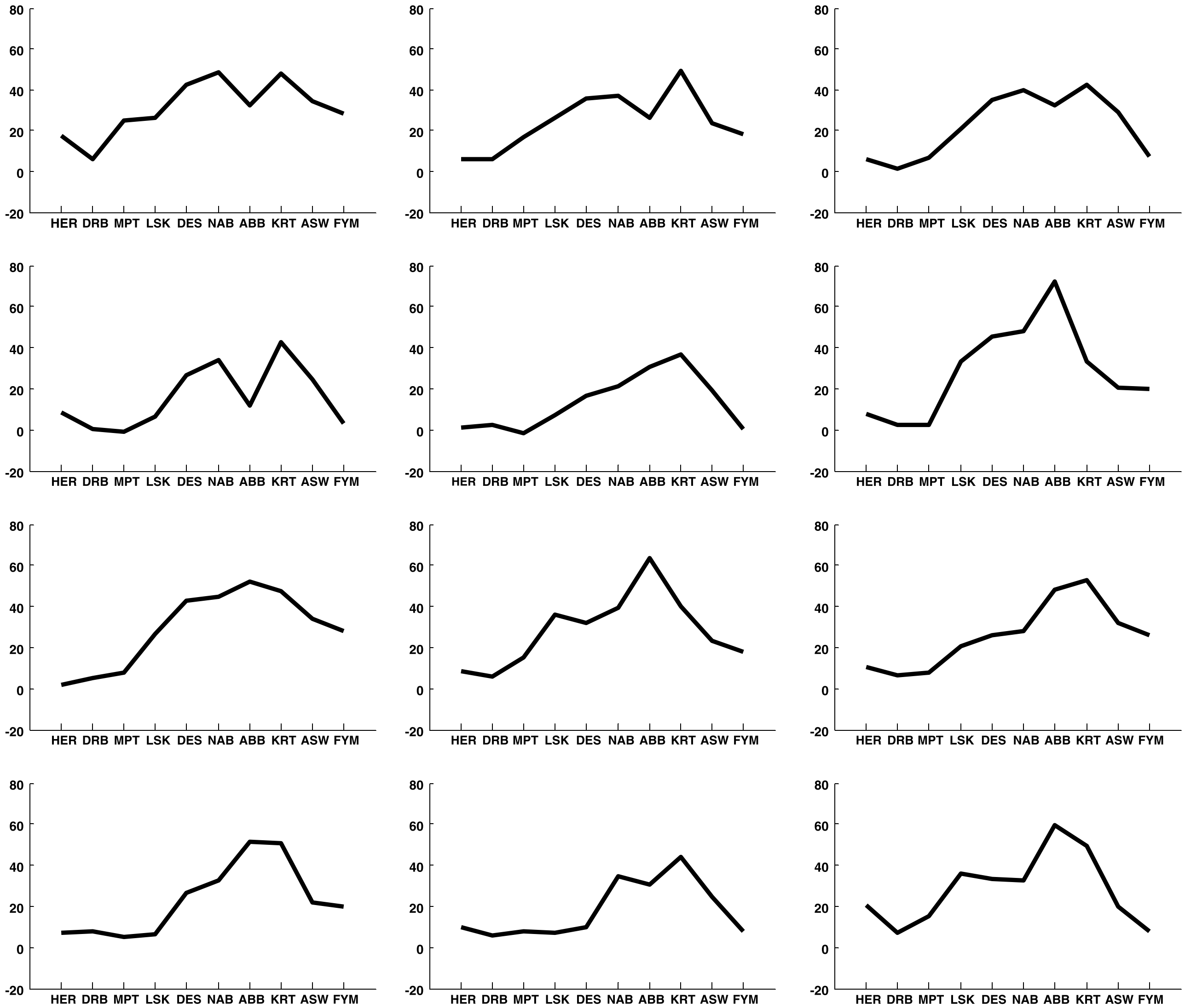


**Figure 4.** Latitudinal profiles of monthly mean values of $S_qH$ near noon hours along 96° MM.

In all the seasons from the Northern to Southern Hemisphere through the equator, $S_q(H)$ positive peak magnitudes were observed near noon hours (1000–1200 LT). These magnitudes are highest at the dip equator (ABB), its north and south fringes, KRT and NAB, irrespective of the season. The highest intensity of $S_q(H)$ was seen at ABB around 1100 LT with a value of ~50 nT during the March equinox. A gradual reduction in magnitudes of $S_q(H)$ was observed as one moves toward the north and south edges of the EEJ zone: KRT and NAB. This highest magnitude near noon hours in March equinox at ABB was observed to have reduced to ~40 nT in June season at KRT. During this reduction, gradual shifting of the reduced intensity of $S_q(H)$ from ABB to KRT was observed. The higher magnitude that was gradually shifted to KRT in June season was observed to have separated into two parts and further shifted to northern and southern edges of ABB, KRT, and NAB in the September equinox. This separation in September equinox results from depletion of $S_q(H)$ intensities at ABB. The result, shifts in $S_q(H)$ intensity to the immediate northern (KRT) and southern (NAB) edges of ABB, is very weak. Very weak magnitudes of 22 nT were still visible over ABB at 1100 LT. The most depleted $S_q(H)$ intensities were seen at ABB in December season, where magnitudes of $S_q(H)$ intensities in comparison to that observed in September equinox over ABB were not high. However, high magnitude of $S_q(H)$ during December season was observed at KRT with a value of 27 nT. Apart from March equinox, the aforementioned shifting and separation of $S_q(H)$ magnitudes away from ABB indicate that the $S_q(H)$ magnitudes at Northern Hemisphere edge of the EEJ

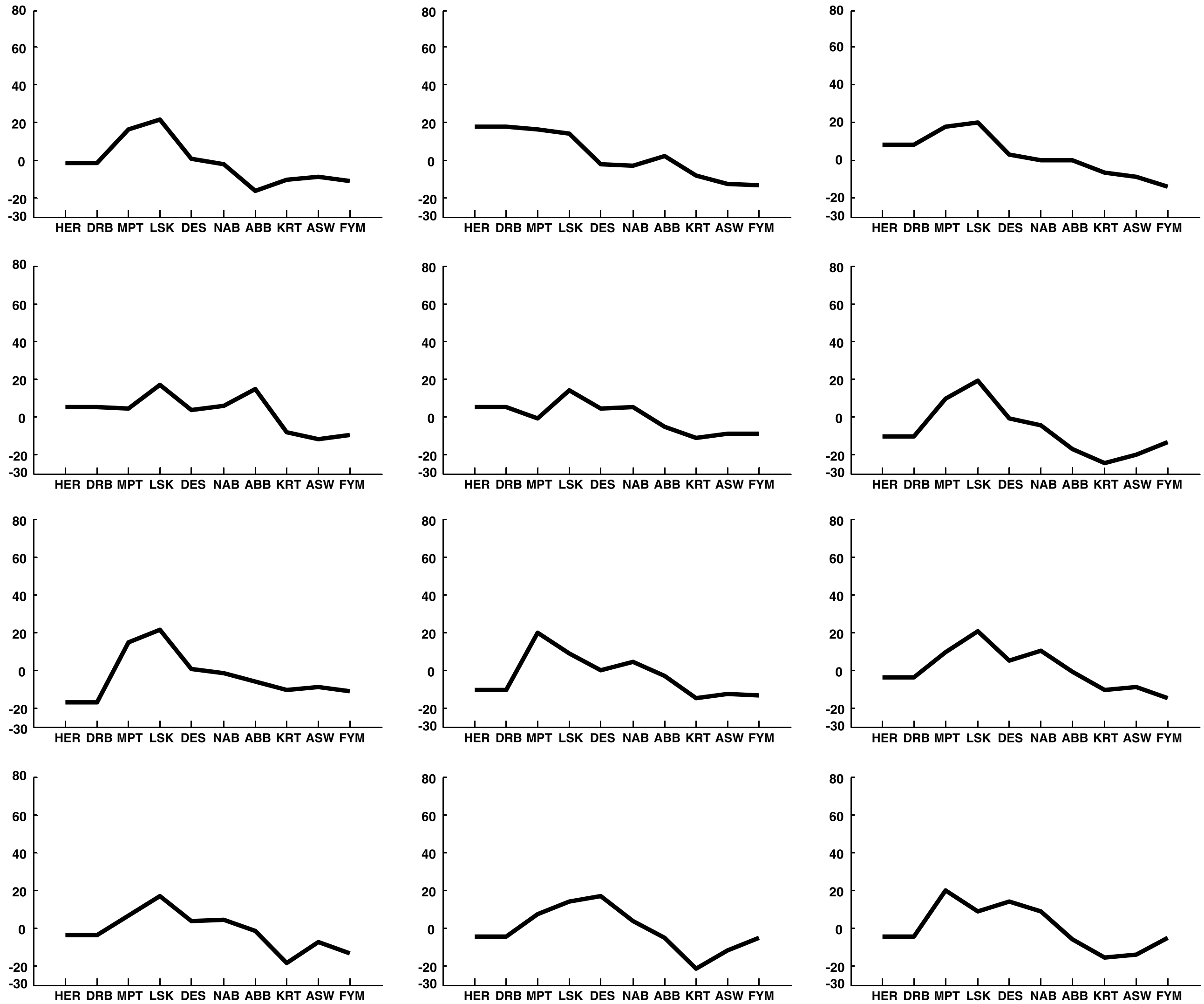


**Figure 5.** Latitudinal profiles of monthly mean values of $S_qZ$ near noon hours along 96° MM.

zone are always greater than that of its Southern Hemisphere edge. Around 0100–0700 LT from Northern Hemisphere (FYM) through ABB toward Southern Hemisphere, $S_q(H)$ values were observed to range between 0 and ~−10 nT.

The positive peak values near noon hours from north to south show that the daytime $S_q(H)$ magnitude is always greater than the nighttime magnitude; these observations indicate that the ionospheric current is very active during daytime [*Rastogi*, 2004; *Bolaji et al.*, 2013]. As earlier mentioned, an observation that was beyond the baseline value (zero) has been reported by *Gouin and Mayaud* [1967], *Hutton and Oyinloye* [1970], and *Bolaji et al.* [2013]. They attribute these observations to the dominancy of westward currents over the normal prevailing $S_q$ currents during daytime hours. These westward currents were observed to decrease in magnitude around 0100–0700 LT as one moves away from the Northern Hemisphere and approaches the Southern Hemisphere. The maximum, negative peak value of ~−10 nT was observed during morning hours at the Northern Hemisphere during June season. At the Southern Hemisphere, from MPT to HER, our results show that westward currents supersede normal prevailing $S_q$ currents around 1400–1800 LT. These westward currents were also observed during the dusk period to presunrise hours between MPT and HER but not as strong as that around 1400–1800 LT. These stronger westward currents during daytime hours have highest magnitude and the most frequent occurrence during afternoon than the morning hours. The highest westward current has a value of ~−20 nT around 1500 LT at HER during

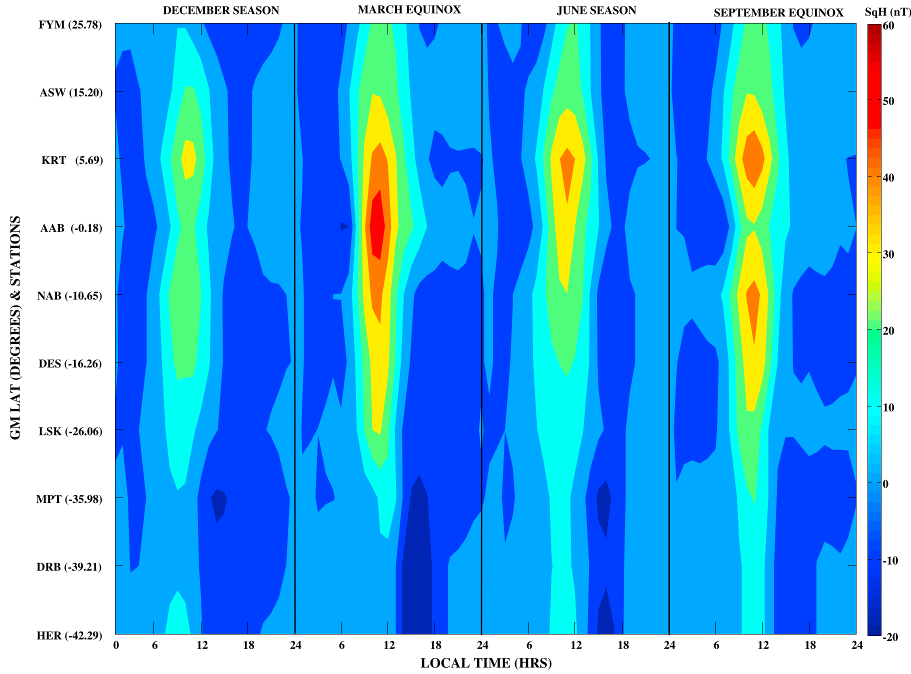


**Figure 6.** Seasonal variations of $S_qH$ along 96° MM from September 2008 to August 2009.

the March equinox. However, the least value (~−8 nT) of westward current magnitude around 1500 LT was observed in December season.

Figure 7 shows the seasonal variations of $S_q(Z)$ along the African 96° MM latitudes. From 0100–1200 LT, weak magnitudes of $S_q(Z)$ having negative values were observed from the Northern to Southern Hemisphere. At ABB, slight increments in $S_q(Z)$ magnitudes were observed around afternoon hours in all seasons and the highest value of ~13 nT was observed around 1500 LT in December season. These $S_q(Z)$ magnitudes

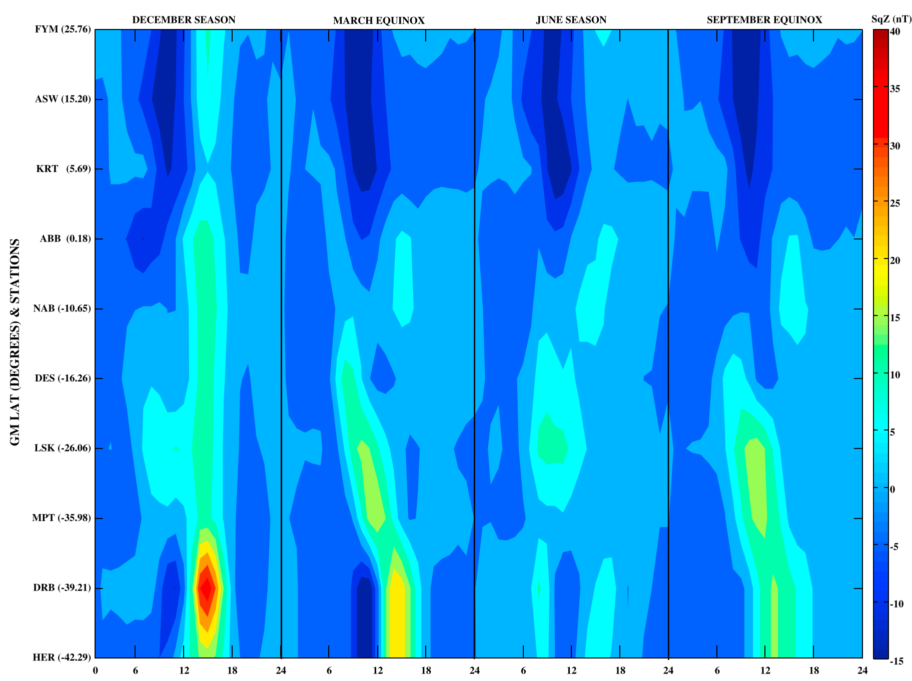


**Figure 7.** Seasonal variations of $S_qZ$ along 96° MM from September 2008 to August 2009.

become weakest near noon hours at the Northern Hemisphere immediately after ABB. The weakest magnitude of $S_q(Z)$ near noon hours was observed in March equinox at FYM and has a value of ~−14 nT. Exceptions to these weak magnitudes of $S_q(Z)$ near noon hours in all the stations were observed between DES and MPT. During all seasons, at NAB in the morning, gradual increments in $S_q(Z)$ magnitudes were observed. These gradual increments in $S_q(Z)$ were observed shifted further from morning to near-noon hours, where they became intensified between DES and LSK, with June season as an exception. The range of increase between DES and LSK near-noon hours is from ~0.5 nT to ~15 nT across all seasons. The increase was more significant at LSK during the equinoctial months: March and September equinoxes. However, slight increases in $S_q(Z)$ magnitudes (about ~10 nT) were observed from 1200 LT to around 1800 LT in December season between NAB and LSK. In all seasons and beyond LSK, that is, between MPT and HER, these intensified $S_q(Z)$ magnitudes were further observed to have shifted from near-noon to afternoon hours, with greater intensities. From MPT to HER, higher increase in magnitude of $S_q(Z)$ was observed in all seasons from noon to afternoon hours decreasing gradually toward the dusk period. These increments at noon hours were observed between MPT and HER in all seasons with June season as an exception. Possible mechanisms that could be responsible for this are induced currents. At DRB, highest value of $S_q(Z)$ (~35 nT) was observed around 1400 LT and the least value of ~7 nT was observed around 1600 LT during December and June seasons, respectively. However, at HER in all seasons, $S_q(Z)$ magnitudes were observed to reduce compared to DRB during afternoon hours. During all seasons between dusk and nighttime hours (1800–2400 LT), weaker magnitudes of $S_q(Z)$ were observed.

## 4. Discussion

Previous studies by *Campbell and Schiffmacher* [1985, 1988], *Takeda* [2002], *Chen et al.* [2008], *Rastogi and Trivedi* [2009], *Yamazaki et al.* [2012], and *El Hawary et al.* [2012] have shown that magnitude of $MS_q(H)$ near noon hour around the magnetic equator is enhanced relative to those at low latitudes (Figure 1). The enhancement in magnitude of $MS_qH$ at the dip equator around noon hour is in accordance with equations (1) and (2) above (under section 1) put forward by *Chapman* [1951]. These observations have also been reported in the earlier works of *James et al.* [1996], *Onwumechili* [1959], and *Rastogi et al.* [2008] and attributed to the addition of superposition of worldwide $S_qH$ field and the EEJ field at low latitude of the ionosphere around the magnetic dip equator, where ABB is located. We therefore suggested that this enhancement is due to an increased effective ionospheric conductivity along the magnetic equator. However, the reduction on the magnitudes of $MS_q(H)$ as one moves away from ABB to the north and south could be due to the significant presence of the normal prevailing $S_q$ field while the EEJ current is reducing. Also, as a result of higher magnitude observed in the Northern compare to Southern Hemisphere, it indicates that the $S_q$ current focus was more shifted to Northern compare to Southern Hemisphere across the 96° MM. Our result regarding the asymmetry signature of $S_qH$ current is consistent with the work of *Pedatella et al.* [2011] that used space- and ground-based magnetometers during solar minimum conditions that include equatorial sector of Africa and its neighborhood.

The significant negative magnitude of $MS_q(H)$ observed during afternoon hours around LSK with highest magnitude at HER indicates that highest ionospheric currents at ABB become insignificant at HER. As expected, our results have shown that $MS_q(H)$ magnitudes at the extreme Southern Hemisphere (HER) are extremely low near noon hours and dominated by westward currents during afternoon hours. We therefore attributed this scenario from LSK to HER during daytime hours to the dominancy of stronger westward currents over global and normal eastward $S_qH$ currents. Similar results regarding inconsistent distributions of $S_qH$ magnitudes due to its focus shifting between the Northern and Southern Hemispheres of Africa that resulted to asymmetry in the shape of the $S_qH$ currents pattern have been reported by *Campbell and Schiffmacher* [1985, 1988], *Takeda* [2002], *Chen et al.* [2008], *Trivedi* [2009], *Yamazaki et al.* [2012], and *El Hawary et al.* [2012]. They found that at the south of the $S_q$ focus in the Southern Hemisphere of the African, American, and Asian sectors, $S_q$ currents are usually westward, which causes the negative $MS_qH$ current observed between LSK and HER.

The westward $MS_qH$ currents during daytime hours between LSK and HER that occur simultaneously with the CEJ around the magnetic equator between 1700 LT and 1800 LT signify that the vertical electric field (positive $E_Z$) reported by *Fejer et al.* [1985], *Fejer* [1991], and *Fejer et al.* [1991] has turned downward (negative $E_Z$)

around 1600 LT and was strongest at 1700 LT and 1800 LT. The effect of negative $E_Z$ was minimal and relaxes at ABB around 1600 LT due to the presence of the superimposed EEJ currents, which later maximize around 1700 LT and 1800 LT. This westward $MS_qH$ current could play a significant role regarding plasma uplift along the crest ($\pm 15° - \pm 17°$) of Africa in the *F* region of the ionosphere. Previous work by *Bolaji et al*. [2013] that involved simultaneous variability of the horizontal geomagnetic field intensity and total electron content at an equatorial trough station (Ilorin on geographical coordinates: 8.47°N, 4.68°E and geomagnetic coordinates: 1.84°S, 76.80°E), Nigeria, has shown that westward currents development during daytime over the trough could inhibit plasma uplift to the crest. Therefore, westward $S_qH$ current development along the crest, coupled with the simultaneous inhibition of plasma uplift to the crest, could trigger another scenario: further suppression of fountain effect along the crest in the *F* region during daytime hours. It is suggested that this needs more investigation and could be a subject for future research.

In January, the significant depletion in the magnitude of $MS_q(H)$ near noon time at the magnetic equator, a slight increment at about 6°N around KRT, and significant reduction across the latitude coincide with the occurrence of sudden stratospheric warming (SSW). The SSW is a meteorological phenomenon, when the polar temperature in the stratosphere suddenly increases during the northern winter. Our observations from the Geoscience Australia catalogue at http://www.ga.gov.au/oracle/geomag/iqd_form.jsp, Figures 2b and 2c, show that 80% of quietest international days are days when SSW event is in progress. From Geoscience Australia catalogue, the 10 international quietest days in January 2009 are on the 12, 22, 23, 11, 24, 28, 7, 18, 25, and 17. Figure 2b is a stratospheric average air temperature at 90°N and 10 hPa (*T*) from January to March. It shows that SSW event begins on 12 January, peaks on 23 January, and subsides from 24 January. Also, Figure 2c is the zonal wind zonal mean (*U*) at 60°N and 10 hPa, which signifies that reduction in the value of *U* begins on 12 January, significant reduction was observed from 21 January, and a marked reversal from the eastward to westward was obvious from 24 January. The reductions from 12 to 20 January indicate a minor SSW, and from 21 January until when *U* reverses, the conditions for the occurrence of a major SSW event were met. Now comparing Geoscience Australia catalogue with Figures 2b and 2c, days 7 and 8 are non-SSW days and the remaining days are SSW days, which confirms that 80% of quietest international days are days when SSW event is in progress. This is obvious from our results that a significant depletion of $MS_q(H)$ magnitude near noon hours in January is observed across the latitude compared to other months. This is because variable atmospheric waves from the lower atmosphere drive electric fields and currents in the ionosphere, which in turn affects the ionospheric and EEJ current intensity across the hemisphere. Recently, *Vineeth et al*. [2009], *Sridharan et al*. [2009], *Fejer et al*. [2010], *Stening* [2011], *Park et al*. [2012], and *Yamazaki et al*. [2012] found that the EEJ current is significantly disturbed during SSW events. They reported that this significantly disturbed EEJ current during SSW events is characterized mostly by increase and decrease during local morning and afternoon hours, in that order. Interestingly, the observation of the $S_qH$ currents excluding the quietest days over Africa is imperative; that is, the period before, during, and after the SSW will be considered as a topic of the future. This should be able to give detailed morphology of ionospheric currents over Africa during SSW.

Our results regarding $MS_q(Z)$ in Figure 3 are not fully inconsistent with the findings of *Chapman* [1919, 1951], *Chapman and Raja Rao* [1965], *Fambikatoye* [1976], *Fambitakoye and Mayaud* [1976], *Doumouya et al*. [1998], and *Rastogi* [2004]. They suggested that $S_qZ$ magnitude will be zero at the dip equator near noon hours. *Fambikatoye* [1976] made the first investigation and used a network of geomagnetic stations at the dip equator and outside both sides of the magnetic equator over the central Africa region to study simultaneous regular variability of $S_q(H)$ and $S_q(Z)$. Our results clearly support the findings of *Fambikatoye* [1976] that around 07:30 to 10:30 LT, $S_q(Z)$ variability exhibits maxima and minima values of $S_q(Z)$ over the Southern and Northern Hemispheres outside the electrojet belt fringe, respectively. However, in contrast to these aforementioned findings, $MS_q(Z)$ magnitudes are not completely zero at ABB but fluctuate between ~0.1 nT and ~−23 nT near-noon hours. It should, however, be noted that ABB is not exactly at 0° GM latitude but close (0.18°N), which could be responsible for its magnitudes fluctuation between ~0.1 nT and ~−23 nT near-noon hours and not zero magnitude. At the Southern Hemisphere and outside the electrojet belt, $MS_q(Z)$ magnitudes at NAB and DES are slightly maxima in the morning and fluctuate between zero and negative values zero near noon hours. These indicate that there is a reduction in the value of $MS_q(Z)$ outside the electrojet belt and could be due to the influence of a slight induced current. As expected, the reduced values of $MS_q(Z)$ at NAB and DES near-noon hours are consequence of their location at coastal stations. The induction in the oceans strongly affect $S_qZ$ field in coastal regions; therefore, the interactions of the resistive mantles and conductive oceans play significant roles on these reduced values of $MS_q(Z)$. Similar results have been reported by *Carlo et al*. [1982] using 17 networks of geomagnetic stations around the Ethiopia sector suggesting that the induced eddy current reduces the value of $S_qZ$ near-noon hours at the Southern Hemisphere stations outside the electrojet belt. Also, *Kuvshinov et al*. [2007] used experimental data, one- and three-dimensional (3-D) conductivity model to further investigate the controversial anomalous daily variations of the vertical *Z* component reported by *Rastogi* [2004] at the south Indian electrojet stations. As earlier mentioned, *Rastogi* [2004] invoked that a deep-seated conductor channels currents between India and Sri Lanka, which initiated the anomaly. However, *Kuvshinov et al*. [2007] have shown that the EEJ plays no part in the observed large positive prenoon peak and concluded that the anomaly is due to the ocean effect on the *Sq* variations and not from a conductor either in the lower crust or upper mantle.

The increased magnitude of $MS_q(Z)$ between LSK and DRB near-noon hours corresponded well with signatures of $MS_q(H)$ near-noon hours at ABB and its northern stations (KRT and FYM). This is in conformity with the proposed *Chapman* [1951] model highlighted in section 1, which signifies that the ionospheric electrojet current was dominant from north through ABB to DRB. This reveals that there is insignificant contribution from induced eddy currents to the observed $MS_q(Z)$ variations. Greater negative magnitudes of $MS_q(Z)$ in the range of ~10 to ~20 nT observed between DRB and HER near-noon hours in all the months with exceptions in October and November indicate that induced eddy current is dominant. This signifies that variability at DRB and HER was significantly influenced by induction in the oceans associated with the $S_qZ$ field. The stations DRB and HER are located on the coast near a deep ocean trench, so as expected, they are strongly affected by the ocean effect. This is evident from their varying local time and latitude characteristics; since HER is closer to the deep ocean trench than DRB, it is more affected. Another suspected mechanism that could influence $S_qZ$ variability is a deep-seated conductor found by *Huttl and Schwartze* [2013] over one of the oldest preserved collision zones between continents (South Africa). Their investigation using magnetotelluric depth sounding probes confirmed deposits of graphite shear traces, an unusually good electrical conductor, within the interior of the Earth over South Africa.

The greater positive magnitudes of $MS_q(Z)$ (~9–~39 nT) during afternoon hours, which is significant in February–May, July, and September–November with reduced values in January, June, August, and December, are due to ionospheric currents influence [*Rastogi et al*., 2004]. At the Northern Hemisphere stations (KRT and FYM) near noon hours, where the magnitudes of $MS_q(Z)$ are continuously decreasing toward FYM, it is clearer that the normal ionospheric current is dominant. This signature pattern shares similar characteristics with respect to the *Chapman* [1951] model.

As can be observed from Figure 4, the gradual increase in magnitude of $MS_q(H)$ from the Southern Hemisphere toward the equator stations is due to the gradual superposition of EEJ currents to the normal prevailing $S_q$ currents as one moves toward the equatorial region. The EEJ currents, which are intense at the equator, result in larger magnitude of $MS_q(H)$. The shift of the highest $MS_q(H)$ magnitude between KRT and ABB could result from the inconsistent $S_q$ focus movement between the dip of the equator and its edge. The position of the $S_q$ focus has tendencies to determine where greater intensity of $MS_q(H)$ magnitude could be found.

As earlier reported under section 3.1, *Chen et al*. [2008] and *Rastogi and Trivedi* [2009] suggested that unequal focus position shifts could be due to the EEJ axis, which does not always coincide with the dip equator. *Rabiu et al*. [2013] also suggested that on average, EEJ axis is at dip latitude of 0.19°N. This inconsistent shift in the position of $S_q$ focus could result to inconsistent plasma distribution from the trough to the north and south of the equator. This could further result to inconsistent distribution of equatorial ionization anomaly in the *F* region and its top side as proposed by *Appleton* [1946]. Similar results that show continuous shifting in the position of $S_q$ focus have been reported by *Hasegawa* [1960] and *Stening et al*. [2005]. At 2 h interval in a day, Hasegawa observed that the position of the $S_q$ focus varied by as much as 15° on consecutive days when tracked across the latitudes investigated. *Hasegawa* [1960], *Onwumechili et al*. [1996], and *Butcher and Brown* [1981] attributed the day-to-day shift in the position of the $S_q$ focus to the ionospheric dynamo variability, which result in redistribution and skewing of the $S_q$ current system. On the reduction of the equatorial electrojet amplitude at ABB, *Stening et al*. [2005] suggested that some of these changes, but not all, may be attributed to the influence of high-latitude current systems such as magnetically quiet system.

Therefore, we suggest that ionospheric $S_q$ currents could maximize at the Northern or Southern Hemisphere outside the dip equator and not always at the dip equator.

Our results from Figure 5 further validate *Chapman* [1951] model. As expected, minimal values of $MS_q(Z)$ were observed over the equatorial electrojet zone near-noon hours. However, an exception observed in December near-noon hours, when $MS_q(Z)$ magnitude at ABB surprisingly increase to ~18 nT, has been reported by *Rastogi* [2004] over Trivandrum, India, an equatorial station. *Rastogi* [2004] suggested that such an abnormal peak of $MS_q(Z)$ in December at ABB near-noon period is not a direct effect of the ionospheric currents but could be due to the induction current, which is highest when the basic electrojet current is reducing most rapidly.

On seasonal variability of $S_q(H)$ (Figure 6), separating the equinoctial season into two parts (March and September equinoxes) distinguishes our observations from older results. We observed that our results do not correspond well with the seasonal equinoctial maximum observed by *Chapman and Raja Rao* [1965] and *Bolaji et al*. [2013] at equatorial zones. At ABB, March equinox was highest, and in September equinox, it depleted, maximizing at the immediate southern (NAB) and northern (KRT) edges of ABB. Research on seasonal variability by *Butcher and Brown* [1981] and *Stening et al*. [2007] to determine the exact position of the seasonal $S_q$ focus on quiet days, which could possibly determine where greater intensity of $S_q$ magnitudes could be, shows that the latitude of the $S_q$ focus is most poleward in the summer and equatorward in the winter. The results of *Hasegawa* [1960] and *Onwumechili et al*. [1996] did not support the suggestions of *Butcher and Brown* [1981] and *Stening et al*. [2007]. Our results share similar characteristics with the works of *Butcher and Brown* [1981] and *Stening et al*. [2007], hence the separation and slight depression of seasonal $S_q(H)$ during September equinox and the poleward and equatorward shifts during June and December seasons, respectively. Our results further support the results of *Hasegawa* [1960], *Onwumechili et al*. [1996], and *Stening et al*. [2005, 2007] that the seasonal $S_q$ focus is inconsistent, because it changes hour by hour and day by day across latitudes.

Our results (Figure 7) regarding seasonal variation of $S_q(Z)$ are not in conformity with observations of *Rastogi* [2004]. *Rastogi* [2004] reported forenoon peaks of $S_q(Z)$ magnitudes in March and September equinoctial seasons at Trivandrium, an equatorial station in India. From all seasons during forenoon periods, our results show that $S_q(Z)$ magnitudes fluctuate between 0 and ~−5 nT at equator (ABB), southern edge of ABB (NAB), and northern edge of ABB (KRT). Although, $S_q(Z)$ magnitudes are negative with gradual increments near noon hours between DRB and HER, the electromagnetic induction currents are controlled by the season. This is obvious from our results near noon hours in all seasons with the highest value of ~−8 nT in June season. Also, highest magnitude of $S_q(Z)$ was observed in December season around 1400 LT between DRB and HER. This observation differs from *Chapman and Raja Rao* [1965] and *Rastogi* [2004] works on equinoctial maxima, which could be a reflection of similar seasonal variability in $S_q(H)$.

## 5. Conclusion

Experimental data from the Magnetic Data Acquisition System (MAGDAS) facility have provided us clearer morphology about the horizontal and vertical solar quiet ($S_q$) currents over Africa. The investigated spatial and latitudinal variability of the horizontal and vertical geomagnetic field intensities over Africa follows most expectations of *Chapman* [1951] model equations of current ribbon of constant intensity. However, at the equatorial zone (ABB), $S_q(Z)$ magnitudes are not completely zero but varying and indicate absence of induced eddy currents. The coincident association of SSW with the quietest international days that result to reduction on the ionospheric currents across the Africa latitudes in January needs further investigation. The depletion of seasonal $S_qH$ during December season coupled with increments across its hemispheres confirms significant influence of $S_q$ focus shifts that have been reported by *Butcher and Brown* [1981] and *Stening et al*. [2007]. Hence, further clarification on its quantitative analysis of $S_q$ focus shift will be the topic of the future.

**Acknowledgments**
The Magnetic Data Acquisition System (MAGDAS) data used for this paper are available at International Center for Space Weather Science and Education (ICSWSE) website www.serc.kyushu-u.ac.jp/data/ upon request from the Project Leader (PL) of MAGDAS/CPMN observations, A. Yoshikawa. The authors acknowledge support of the Japan Society for the Promotion of Science (JSPS) Core-to-Core Program, B. Asia-Africa Science Platforms. The MAGDAS/CPMN group at International Center for Space Weather Science and Education (ICSWSE), Kyushu University, Japan, and all hosts of MAGDAS facilities across Africa are acknowledged for keeping records of magnetic data and making them available for this study. The anonymous JGR reviewers were acknowledged for their constructive suggestions and comments that improved this work.

Larry Kepko thanks the reviewers for their assistance in evaluating this paper.

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