Variability of geomagnetic field at Langkawi, south-east asia during the ascending phase of solar cycle 24

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Abstract

The magnetic records obtained at low latitude geomagnetic observatory of Langkawi for the period of 3 years was used to study the diurnal and monthly-mean variation of the horizontal, H, and vertical, Z, geomagnetic field intensities during quiet and disturbed conditions. Results revealed that quiet SqH and SqZ with their corresponding disturbed variations (SdH and SdZ) shows minimum values at nighttime (19:00-05:00) LT hrs that are lower than the pre-sunrise (06:00-07:00) LT hrs. On quiet conditions, the SqH shows remarkable daytime linear increase from 155 nT in 2011 to 160 and 162 nT in 2012 and 2013. The disturbed period exhibit irregular variation trend with highest values 227, 215 and 237 nT in 2011, 2012 and 2013 respectively. The daytime maximum MSqH values increase from ∼125 nT in 2011 to 135 nT in October 2013, in contrast to MSdH that decrease progressively from 166 nT in September 2011 to 145 nT in March 2013. The reduced MSdH magnitude with increasing solar activity seems to indicate weakening effect of the disturbance dynamo dynamo mechanism. The daytime maximum SqZ and SdZ with their monthly-mean (MSqH and MSdH) readily conform to those amplitudes variation pattern with lesser magnitudes. The daytime SqH maximum with their MSqH were observe to occur around (10:00-12:00) LT hrs and shifted to 14:00 LT during disturbed period indication of possible modification of equatorial electrojet during disturbed period. The greater seasonal SSqH magnitude at the equinoctial season may likely be due to the fact that the sun is directly towards the equator around this season. The increase in AsqH and ASdH with solar activity can be likened to the effect of solar activity on the ionospheric conductivity.

Keywords: Ionosphere, Solar quiet current, magnetic field, magnetosphere.

Resumen

Los registros magnéticos obtenidos en el observatorio geomagnético de baja latitud de Langkawi durante un período de 3 años se utilizaron para estudiar la variación media diurna y mensual de las intensidades del campo geomagnético horizontal (H) y vertical (Z) en condiciones tranquilas y perturbadas. Los resultados revelaron que las SqH y SqZ en condiciones tranquilas, con sus correspondientes variaciones perturbadas (SdH y SdZ), muestran valores mínimos durante la noche (19:00-05:00) horas de luz solar, inferiores a los valores de la hora de luz solar antes del amanecer (06:00-07:00). En condiciones tranquilas, el SqH muestra un notable aumento lineal diurno de 155 nT en 2011 a 160 y 162 nT en 2012 y 2013. El período perturbado exhibe una tendencia de variación irregular con los valores más altos de 227, 215 y 237 nT en 2011, 2012 y 2013 respectivamente. Los valores máximos diurnos de MSqH aumentan de ~125 nT en 2011 a 135 nT en octubre de 2013, en contraste con MSdH que disminuye progresivamente de 166 nT en septiembre de 2011 a 145 nT en marzo de 2013. La magnitud reducida de MSdH con el aumento de la actividad solar parece indicar un efecto de debilitamiento del mecanismo dinamo-dinamo de perturbación. Los máximos diurnos de SqZ y SdZ, con sus medias mensuales (MSqH y MSdH), se ajustan fácilmente a estos patrones de variación de amplitud con magnitudes menores. Se observó que el máximo diurno de SqH con su MSqH se produjo alrededor de las 10:00-12:00 horas locales (LT) y se desplazó a las 14:00 horas locales (LT) durante el período de perturbación, lo que indica una posible modificación del electrochorro ecuatorial durante dicho período. La mayor magnitud estacional de SSqH en la estación equinoccial probablemente se deba a que el sol se encuentra directamente hacia el ecuador en esta estación. El aumento de AsqH y ASdH con la actividad solar puede compararse con el efecto de la actividad solar en la conductividad ionosférica.

Palabras clave: Ionosfera, Corriente Solar Quieta, Campo Magnético, Magnetosfera.

I. INTRODUCTION

The regional and global monitoring of the Earth's magnetic field reveal outstanding changes that are regular in some days and irregular at other times. These changes in geomagnetic field are linked to two different physical phenomena: the regular variations which are observed only during magnetically quiet days are sometimes referred to as geomagnetic daily variations or simply solar quiet (Sq) variations e.g., [1]. These variations generated by overhaed current flowing in the E-region of the ionosphere. The irregular variations are mostly related to the response of the magnetospheric activities and are mostly referred to as solar disturbed (Sd) variations. These variations are generated during ionospheric disturbance dynamo mechanism in combine effect with current of non-ionospheric origin [2].

Various current systems flow in the upper región of the atmosphere and thus extablish electric and magnetic fields at the gound surface of the Earth. The field at a specific point is dependent on location, latitude, local time, season and phase of the solar cycle. At the magnetic equator, there exist two current systems, The World Solar quiet (WSq) current that flows eastward at an altitude height of 113±7 Km and the EEJ current flowing either eastward or westward at low altitude layer of 107±8 Km [3, 4, 5].

The superposition of these currents at the magnetic equator generates the intensed solar daily geomagnetic field variations. Studie has shown that both the solar quiet Sq and solar disturbed Sd variations exhibit significant day-to-day variability that vary in their amplitudes, phase and focal latitudes from one day to another, e.g., [2, 5, 6, 7]. The variations in both strength and phase of the Sq and Sd is largely attributed to significant changes in ionospheric dynamo mechanism which in-turn is dependent on ionospheric conductivity and tidal winds [2, 8].

The enhanced solar disturbed H-field SdH during magnetic disturbances is caused by leakages of the high latituude to low latitudes. [9] observed that during disturbance periods, there are times Sd amplitudes are enhanced while at other times it is decreased. The SqZ and SdZ during quiet and disturbed periods have been widely reported to represent very closedly the temporal gradient of the SqH and SdH fields [3, 4, 8]. The characteristics of the regular and irregular variations of the H-field over India, Africa and American sectors have been carried out [3, 4, 6, 10]. The result revealed that during disturbed days, the daily variations of the H-field SdH shows lower values relative to the quiet-time SqH. This has been explined as due to the dominance of the westward disturbances current, e.g., [4].

The above literatures highlights some of the studies conducted on the variabilities of Sq and Sd from other regions of the world. To the best of our knowledge no detail report on the daily variations of Sq and Sd have been made over the Malaysian latitude knowing well that geomagnetic field changes with location, and time scale. Hence, this paper is set to investigate the solar daily variations of geomagnetic field H and Z component during quiet and disturbed conditions.

II. DATA AND METHOD OF ANALYSIS

The study was carried out using magnetic field records of the horizontal and vertical components of the Earth obtained from Magnetic Data Acquisition System (MAGDAS) network at Langkawi (geographic latitude: 6.3^0N, geographic longitude: 99.68^0N, geomagnetic latitude: -2.32^0S geomagnetic longitude: 171.29^0) for a period of 3 years (2011, 2012 and 2013). These years are during the ascending phase of the solar cycle 24. The magnetometer fluxgate records seconds and minute data and only the minute data waere engaged in this study. The data composed of 1mins averages were binned to hourly average and this reduced the data to 24 hourly values of each particular day considered in the study. This was carried out throughout the years under investigation. The baseline was defined as the average of four flanking local midnight (00:00 LT, 01:00 LT, 22:00 LT and 23:00 LT) respectively. This is represented by the equation:

$$\mathrm{H_b} = \frac{\mathrm{H_{00:00}} + \mathrm{H_{01:00}} + \mathrm{H_{22:00}} + \mathrm{H_{23:00}}}{4}, \tag{1}$$

$$Z_\mathrm{b} = \frac{Z_{00:00} + Z_{01:00} + Z_{22:00} + Z_{23:00}}{4}. \tag{2}$$

Where, $H_{00:00}$, $H_{01:00}$, H_{2200} and $H_{23:00}$ and $Z_{00:00}$, $Z_{01:00}$, $Z_{22:00}$ and $Z_{23:00}$ represent the hourly values of the H and Z component at 01:00, 02:00, 23:00 and 24:00 LT hours. The midnight baseline values were further subtracted from the hourly values to get the hourly departures from the midnight for same particular day, this relation is expressed as;

$$\Delta \mathrm{H} = H_t - H_b, \tag{3}$$

$$\Delta \mathrm{Z} = Z_t - Z_b. \tag{4}$$

Where t is the time in hours and ranged from 01:00 to 24:00 LT. H_t and Z_t are the hourly values of the two components H and Z. The hourly departure is further corrected for non-cyclic variation a phenomenon where the difference between the value of a field at the 24^{th} LT hour of a particular day and the 1^{st} LT hour of that same day is eliminated according to [11] This is achieved by making linear adjustment on the daily hourly values of the Sq using the following relation:

$$\Delta_\mathrm{k} = \frac{\mathrm{M_1} - \mathrm{M_{24}}}{23}. \tag{5}$$

Where M_1, $M_{2\ldots}$ M_{24} represent the hourly values of ΔH and ΔZ at 01:00 LT, 02:00 LT….24:00 LT. The linear adjusted value for each hour is given as:

$$\mathrm{M_1} + 0\Delta_\mathrm{k},\ \mathrm{M_2} + 1\Delta_\mathrm{k}, \ldots \mathrm{M_{24}} + 23\Delta_\mathrm{k}. \tag{6}$$

The linearly adjusted values are expressed in the relation below;

$$\Delta H_t\,(M) = M_t + (t-1)\Delta_t. \tag{7}$$

Hence, the corrected non-cyclic hourly departures gives the solar daily variation of H and Z components. This solar daily variation is approximately equal tosolar quiet daily H-field (SqH) and its corresponding vertical component as SqZ and the solar disturbed daily H-field is represented as SdH and its vertical component as SdZ. To thoroughly explore the geomagnetic field in terms of solar terrestrial activity, 3 years data are utilized. These data were selected from two categories of group from each month obtained from Geosciences Australia catalogue at http://www.ga.gov.au/oracle/geomag/iqd_form.jsp. The first category consist of 10 group of days which are called the 10 international quiet days that depict when the geomagnetic variations are minima in each month and the other category are 5 international disturbed days that shows the extent of magnetic disturbance in each month. The monthly mean are obtained by averaging all the quiet and disturbed days under a particular month for both elements. The seasonal variation is grouped into three seasons in accordance to Llyord with equinoctial season comprising of (March, April, September and October), June solstice (May, June, July and August), December solstice (November, December, January and February). Each season is deduced by taking average of all monthly mean values of each hour under a particular season for both elements (H and Z) during quiet and disturbed periods.

III. RESULTS AND DISCUSSION

A. Diurnal variations of solar quiet (Sq) and solar disturbed (Sd)

Figures. 1-4 illustrate the diurnal variations of solar quiet daily variation, Sq, and solar disturbance daily variation Sd of the horizontal, H, and vertical, Z, component during quiet and disturbed periods. It is obvious from Figure. 1a and 1b that SqH exhibit day-to-day variability which is large particularly during the equinoctial months (March, April, September and October). The Figure also demonstrates the presence of night-time (19:00-05:00) LT hrs magnitudes with highest value (~20 nT) around 19:00 LT hrs in April 2011. It maintained this maximum value (~20 nT) through 2012 but shifted to February. The night-time magnitudes dropped to 15 nT around 19:00 LT in June 2013. These night-time SqH magnitudes demonstrates ionospheric conductivity is not completely zero but exhibit some substantial amount of current do flow. Besides these night-time magnitudes SqH are possessed by consistent minimum pre-sunrise (06:00-07:00) LT hrs positives magnitudes with maximum value (~39 nT) in May 2011. In 2012, the magnitude had decreased to ~35 nT seen in June. With increase in solar activity, these magnitudes were observed to further drop to ~30 nT as depicted in June 2013. The day-time SqH magnitudes were observed to vary and reached their peak values differently from one day to another. For example, SqH daytime maximum amplitudes fluctuate between ~40 and 155 nT in May and April 2011. In 2012, it oscillates in the range between ~45 and 160 nT seen in November and September. In 2013, the amplitudes had not changed much it ranged between ~50 and 162 nT also seen in November and September.

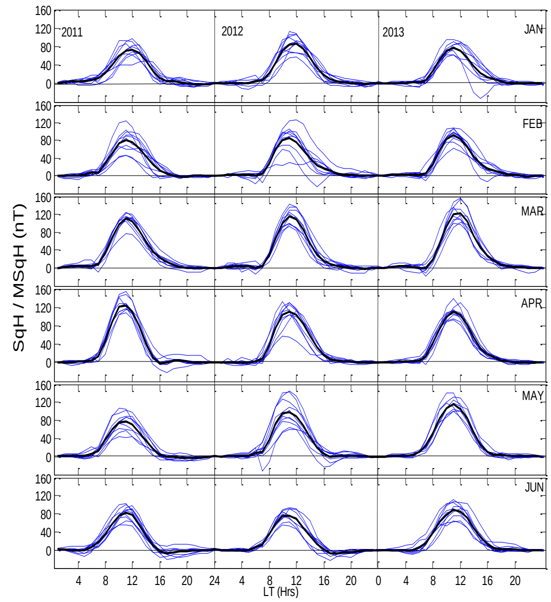

Figure 1a. Diurnal variations of SqH during quiet days from January to June.

From all the graphs, it can be seen that, SqH continue to rise steeply during the sunrise (06:00-07:00) LT to reach its peak values mostly around (11:00-12:00) LT. This feature is in accordance to the day-to-day variation pattern of Sq earlier reported by several researchers' e.g., [2, 8, 9, 12]. The decrease in SqH was rather gentle and reaches its base level mostly at sunset. Apart from these maxima, Sq*H* are characterized by minimum depression lasting for 2-3 LT hrs particularly during the pre-sunrise and the pre-sunset hours. The minimum depression occasionally have values below the night-time baseline values indicated by a horizontal black line and are known as counter equatorial electrojet (CEJ), [13]. These mínimum SqH below the baseline are consequences of the reversal of the eastward current during the daytime [3, 5, 6].

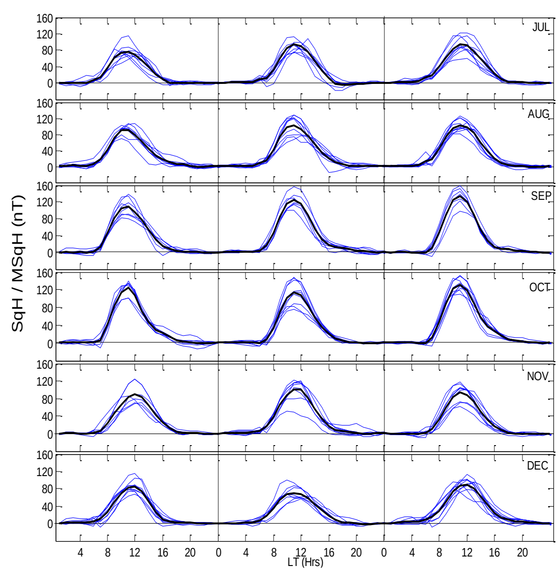

Figure 1b. As in Figure 1ª but for July to December.

During CEJ events, the magnitudes of the westward current in SqH were observed to be highest (∼-21 nT) around 17:00 hrs LT in June 2011. The negative amplitude increase to ∼ −32 nT around 07:00 hrs LT in May 2012 with further increase in 2013 to ∼-33 nT around 15:00 LT hrs seen in January. The CEJ events were observed to be more frequent during the summer months (May, June, July and August). Figure 2a and 2b shows the variations of the vertical Z-component during quiet days SqZ. The variability of SqZ also shows the presence of night-time (19:00-05:00) LT hrs magnitudes that are generally low with highest value (∼25 nT) seen in July 2011. The night-time magnitude is observed to decrease to ∼20 nT in August 2012. Year 2013 is not exception to these night-time magnitudes with maximum value (∼15 nT) recorded in July. The day-time variability of SqZ shows highest value (∼60 nT) in November 2011 and later dropped to ∼59 nT in March 2012. The highest day-time SqZ magnitudes (70 nT) was observed in September 2013.

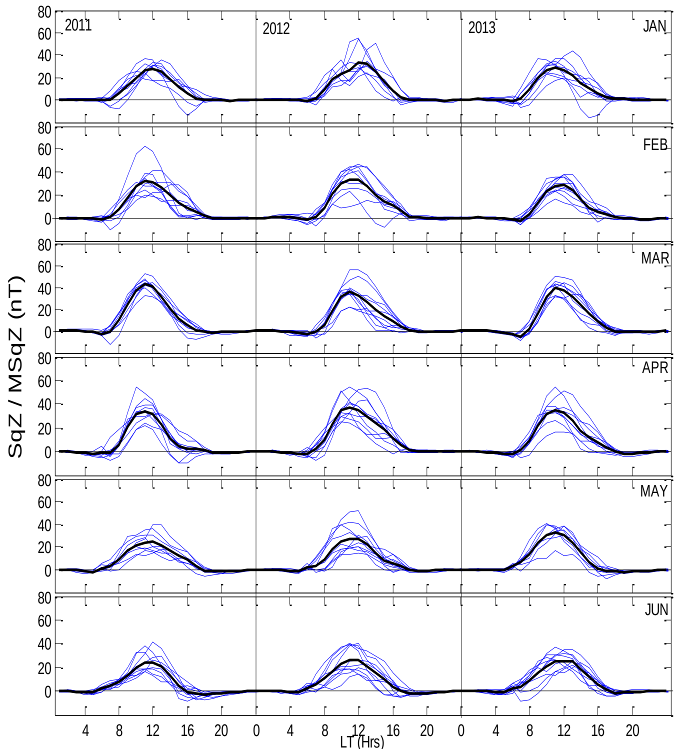

Figure 2a. Diurnal variations of SqZ during quiet days from January to June.

Generally, SqZ shows daytime variation pattern similar to SqH for it rises at sunrise (0:600-07:00) LT hrs, reached its peak mostly around noon (10:00-12:00) LT hrs and decrease afterwards. Similar variations have earlier been reported by [3, 4, 8]. These day-time positive magnitudes of SqZ are in accordance to chapman's model of a typical station on the southern edge of the magnetic equator. The enhanced positive variation of SqZ are seen to continuously reduced in the months of May, June, July, August and September 2011. Similar scenario are also seen in the months of May, June, July and August 2012 and 2013. These reduced SqZ amplitudes were observed to be in the negative range around (10:00-12:00) LT in the months of August and September 2011.

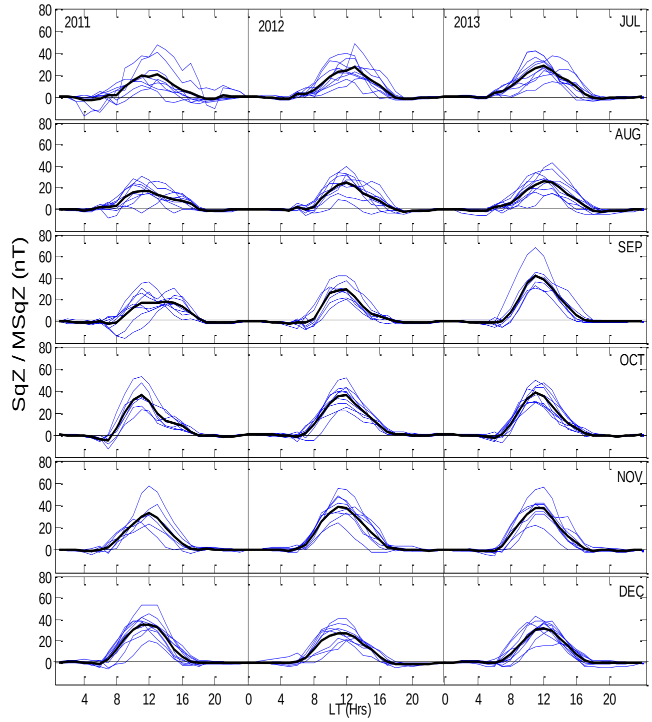

Figure 2b. Diurnal variations of SqZ during quiet days from July to December.

The continuous reduction of daytime SqZ magnitude is an evidence of gradual weakening of direct ionospheric sheet current due to low solar intensity and the slowly effect of induced current from the Earth surface which become stronger in August and September 2011 resulting to practical cancellation of the direct ionospheric sheet current [14]. Similar negative amplitude of SqZ has been earlier reported by [16] and attributed it to induced current from the solid Earth surface. Hence, we infer that the solar daily variation of SqZ over the Malaysia is not just the effect of direct ionospheric current but a combined effect of the eastward ionospheric current in the E-region of the ionosphere and the induced current from the solid Earth surface. Irrespective of the day, the variability of S_qH are generally seen to be larger than those of SqZ. Their greater magnitudes are direct effect of ionospheric current system.

Figure. 3a and 3b shows the behavior of H-fiel during disturbed period (SdH). As can be observed, SdH are possessed by night-time magnitudes with highest amplitude value ∼110 nT in September 2011 and decreased to ∼90 nT in February 2012 and ∼70 nT in December 2013. The SdH is also observed to increase sluggishly at sunrise to peak values around (10:00-14:00) LT and decreases slowly even after dusk, indication of likely modification of the normal eastward current during day-time hours over the Malaysian sector [8].

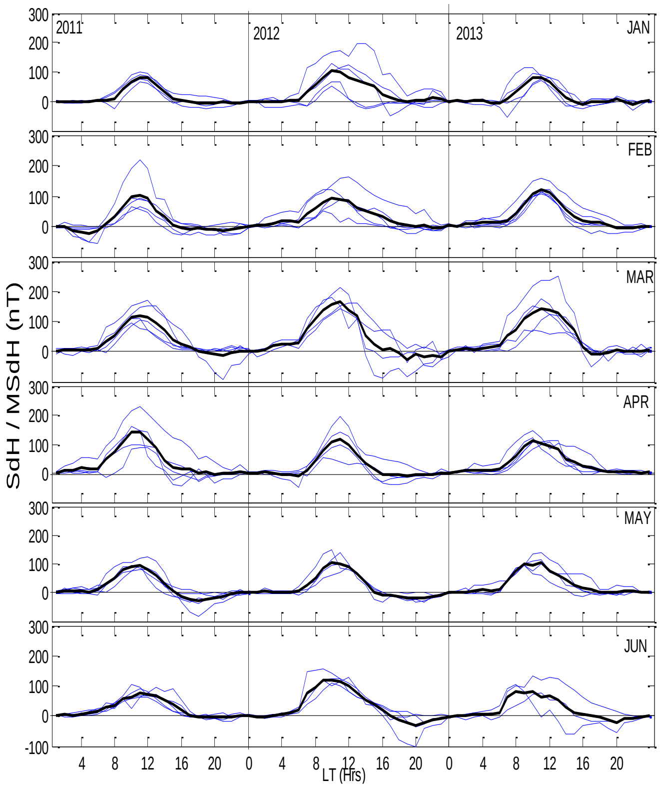

Figure 3a. Diurnal variations of SdH during disturbed days from January to June.

From Figure 3a and 3b, the daytime SdH magnitude attained highest value (259 nT) in September 2011 and dropped to 220 nT in November 2012. These amplitudes were observed to increase to 260 nT in March 2013. Some of the day-time diurnal amplitudes of SdH were observed to be very low which are more noticeable in the months of June and September 2011 with similar occurrence in January, February, March, April, September and November 2012. Year 2013 is not exception to these reduced magnitudes, seen in January, March, May, June August, October and December. These lower values of SdH with negative range during day-time arise from stronger influence of westward current over the EEJ zone.

Figure 3a and 3b shows prominent westward current during the pre-sunrise and (06:00-07:00) LT and pre-sunset to nighttime (14:00-18:00) LT hours. The magnitudes of the westward current in SdH reaches highest value -100 nT around 21:00 LT in March 2011 and decreased to -90 nT also in June 2012. In 2013, the amplitude had decreased to -80 nT still in June. These negative amplitudes of SdH are stronger evidences of the westward disturbance equatorial current effect [4, 6, 8]. Generally, the day-time magnitudes of SqH and SdH were observed to be greater than their night-time magnitudes in all the years.

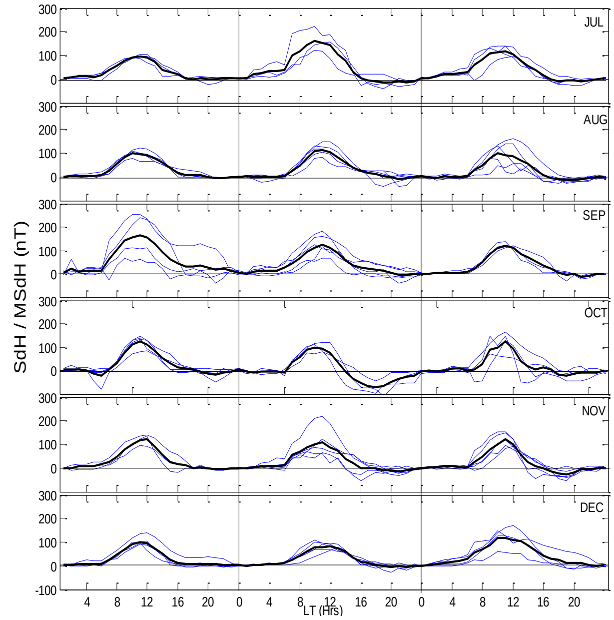

Figure 3b. Diurnal variations of SdH during disturbed days from July to December.

In Figure 4 (a and b), the SdZ also shows night-time variations with lower magnitudes compared to corresponding SqZ. The maximum amplitude (15 nT) is observed in September 2011 which decrease to ~10 nT seen in March 2012 and January 2013. In SdZ, the highest value (60 nT) occurred in February 2011 and dropped to 59 nT in April 2012 with a sharp increase to about 62 nT in January 2013. During disturbed period, SdZ shows weak amplitudes in the months of May, June, August and September across all the years. These weaker amplitudes were further observed to be negative particularly in the months of August 2011, June and July 2012 with similar occurrence in July 2013. We infer that these weaker amplitudes are direct consequences of induced current from the solid Earth in combine effect with the disturbed external currents.

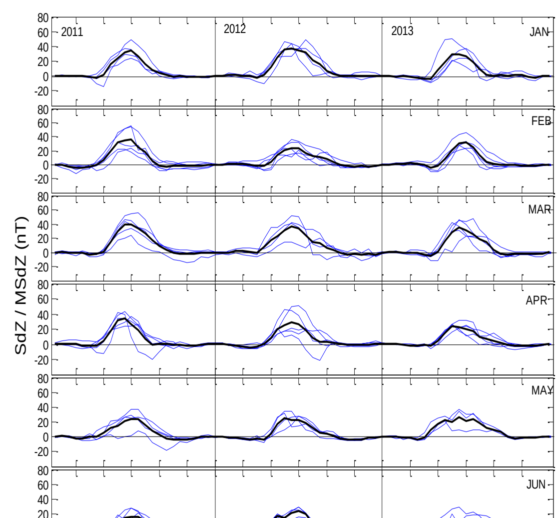

Figure 4a. Diurnal variation of SdZ during disturbed days from January to June.

IV. MONTHLY DIURNAL VARIATIONS

From Figure 1a and 1b, the monthly diurnal variations of MSqH which are represented by thick black curve shows a smooth appearance that start to build up during the sunrise (06:00-07:00) LT hrs with peak values mostly around noon (11:00-12:00) LT hrs and decay afterwards. The range in day-time MSqH magnitudes were observed to vary from one month to another. For example, the range in daytime MSqH Magnitudes in 2011 were found to be between 75 and 125 nT seen in July and October. In 2012, the amplitudes had increased to a range between 70 and 125 nT in December and September. In 2013, the amplitudes oscillate between 78 and 135 nT in January and October.

From Figure. 2a and 2b, the MSqZ denoted by thick black curve, shows positive variation that start to build-up around (06:00-07:00) LT hrs. Exception to these early ionizations are the months of July, August and September seen at 08:00 hrs LT. These months exhibit MSqZ variations with broad phase which extend towards the night-time. Similar features are observed for the months of May, June, July and August in 2012 and 2013 respectively. This characteristics is not common and may be due to combine effect of ionospheric current sheet and induced current from the Earth surface in the presence of weak thermal heating of the upper atmosphere around these periods [15]. The daytime MSqZ magnitudes fluctuate between the range 17 and 44 nT visible in August and March 2011. It oscillates between 25 and 39 nT seen in November and December 2012. It stayed on this minimum range through 2013 but shifted to July while it maximum value (42 nT) is recorded in September. In Figure 3 (a and b), MSdH amplitudes ranged between 76 and 166 nT in June and September 2011 and further fluctuate in the range between 81 and 164 nT seen in December and March 2012. In 2013, the amplitudes oscillate between 81 and 145 nT in June and March. The salient feature to note here is the linear decrease in the maximum range of MSdH with solar activity, indication of slowly build-up of westward current over the equatorial region. The day-time MSdH variability were observed to reach their peak values mostly around (10:00-11:00) LT hrs in 2011. These peak shifted to around (12:00-14:00) LT hrs in 2012 and 2013 suggesting changes in the electric field during disturbed period. From Figure 4a and 4b, MSdZ amplitudes ranged between 17 and 45 nT in June and November 2011. In 2012, the amplitudes are seen in the range between ~19 and 38 nT in July and November and decreases in 2013 to a range between ~11 and 37 nT obvious in June and November. They show maximum amplitudes mostly around (11:00-14:00) LT hrs. Our results show that MSdH and MSdZ exhibit weak amplitudes values in the winter months (May. June, July and August) with highest values in the other months. Generally, the variability of MS_qH and MSdH for any of the months through the years is greater than their corresponding MSqZ and MSdZ Variations. Their great magnitudes are attributed to stronger ionospheric current effect to which H-component is more susceptible.

V. SEASONAL VARIATIONS OF Sd AND Sq

Figure 5 shows that the day-to-day variability of Sq and Sd exhibit significant seasonal variations for both quiet and disturbed conditions. The black, red and blue curves represent December solstice, equinox season and June solstice during quiet periods while their corresponding dash line with asterisks depict their disturbed variations.

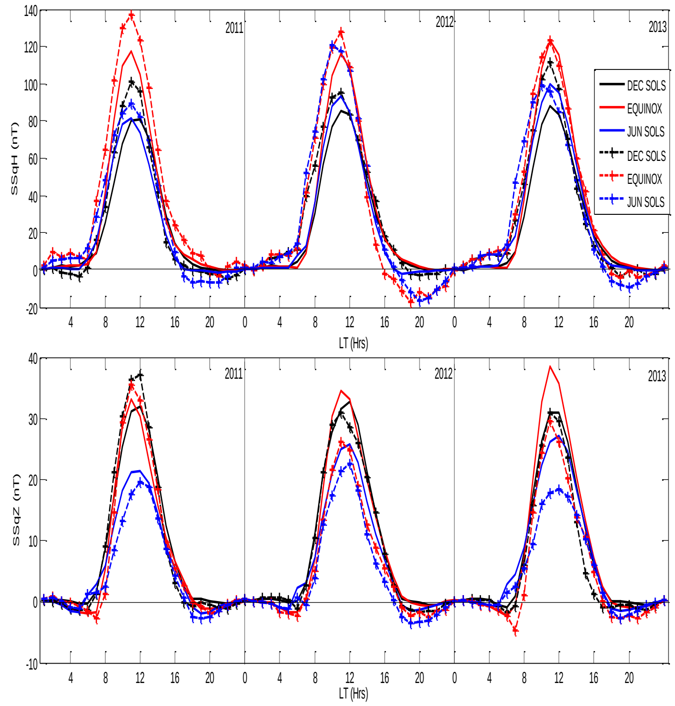

Figure 5. seasonal variations of SqH, SdH, SqZ and SqH.

It is readily seen that seasonal variations shows systematic increase for both elements (H and Z). For example, regardless of the year the seasonal variations of H-field, SSqH increased linearly from ~80, 80 and 120 nT In June solstice, December solstice and equinox season in 2011 to peak amplitudes values ~90, 100 and 130 nT seen in 2013, indication of possible influence of solar activity on the seasonal variations. Similar equinoctial maxima have earlier been reported by [3, 14, 16, 17]. Thus greater SSqH magnitude at the equinoctial season may likely be due to the fact that the sun is directly towards the equator around this season and thus increase the ionospheric conductivit that resulted to higher MSqH magnitudes around these periods. Similar behavior is observed in SSqZ with peak values ~20, 32 and 33 nT in June solstice, December solstice and equinoctial season in the year 2011. These magnitudes were observed to increase ~28, 33 and 37 nT in 2013.

Our seasonal variations show lower values in solstices and higher values in equinoctial season resulting to semi-annual variations pattern. [18] reported semi-annual variation in equatorial electrojet to be due to a decrease at the solstices rather than increase at the equinoxes. [5, 19], Suggested variability of equatorial electrojet current (EEJ) on the horizontal component of the Earth magnetic field could be responsible for the observed semi-annual variation of SqH. During disturbed period, SSdH does not show any linear increment with increase in solar activity but rather a decrease was observed particularly in the equinox season from 138 nT observed in 2011 to 133 and 128 nT in 2012 and 2013 respectively. This linear decrease in SSdH with solar activity at the equinoctial season is evidence of weakening of disturbance effect with solar activity. Similar decrease is also seen in SSdZ during December solstice from 38 nT in 2011 to 29 and 30 nT in 2012 and 2013. The June solstice for both SSdH and SSdZ shows peaks values that are lesser than those of equinox and December solstice. The overall seasonal variation shows peak values around (11:00-12:00) LT hrs, with greater magnitudes during magnetically disturbed period than their counterpart quiet periods. Their greater magnitudes may likely be that extra energy is imputed in the eastward direction mainly during daytime.

A. Yearly mean solar daily variations

Figure. 6 shows the average yearly mean daily variations for the two elements (H and Z) for both quiet and disturbed conditions. The annual mean (ASqH) of SqH is represented by red dash line and their disturbed variation (ASdH) is denoted in red dash line with asterisks. Similarly, the black curve represent the annual mean solar variation of SqZ (ASqZ) while their disturbed variation (ASdZ) are represented by black dash line with asterisks. For both conditions, the increase in ASqH and ASdH occurred before 05:00 LT hrs LT with pronounced magnitudes in ASdH particularly in the year 2012 and 2013. These magnitudes (few nT) in ASdH were observed to subside with incoming solar radiation around (05:00-06:00) LT and further increase immediately during the sunrise (06:00-07:00) LT hrs period, indication of different mechanism responsible for their source. The pronounced magnitudes in ASdH before pre-sunrise are evidences of current effect outside ionospheric influence.

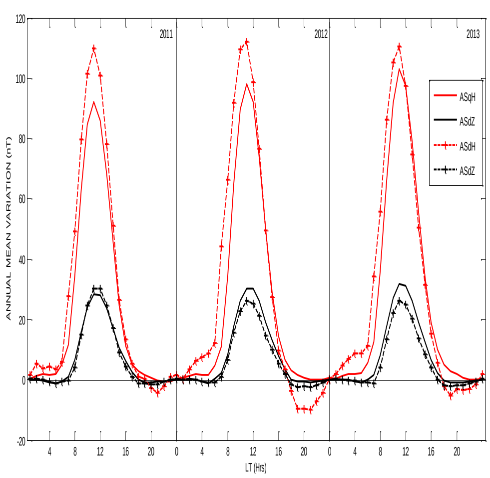

Figure 6. Yearly average solar daily variations of Sq and Sd.

The variations of ASqH were observed to increase linearly with solar activity to reach peak values 92, 98 and 103 nT in 2011, 2012 and 2013. ASdH shows similar increment with peak values 110,115 and 117 nT seen in 2011, 2012 and 2013 respectively. The decrease in ASqH and ASdH with increasing solar activity can be likend to the effect of solar activity on the ionospheric ductovity, [20]. The variability of ASqH and ASdH were observed to reach their peak values at 11:00 hrs LT. Another feature to note here is that the annual mean solar variation during disturbed period (ASdH) exhibit significantly larger values compared with the corresponding values for quiet periods over the Malaysian ionosphere. Our findings are in contrast to the Indian and American observation by [4] that found greater magnitudes of annual mean solar variation during quiet days relative to the disturbed period. The increase in ASdH in our result may likely be due to modification of the normal eastward current or arises from the increase in strength and width of the equatorial electrojet current intensity during magnetically disturbed period. Also from Figure 6, the ASqZ shows variation pattern similar to ASqH, it steeply increase to peak amplitude values 28, 30 and 32 nT in 2011, 2012 and 2013. During disturbed period, ASdZ attained maximum value 30, 26 and 27 nT in 2011, 2012 and 2013. This non-linear increment in ASdZ might likely result from the combined effect of the disturbed ionospheric current in the E-region of the ionosphere and induced current from the Earth surface. Beside these maxima, the ASdH are characterized by depression that fluctuate in the range between -1 and -5 nT in 2011 and 2012 around 18:00 hrs LT indication of westward current around these periods. The vertical component readily respond to these westward current with lesser magnitudes compared to the ones in ASdH.

VI. CONCLUSIONS

1. The daytime SqH magnitudes increases from 45 nT in September 2011 to 162 nT in september 2013 and the SdH sluggihsly increased from 259 nT in September 2011 to about 261 nT in March 2013. Irrespective if the day, the variability of SqH and SdH are generally obaserved to be larger than those of the SqZ and SdZ and the SdH are about twice or more greater than the SqH magnitudes.
2. Evidence of counter-equatorial electrojet (CEJ) and westward current are eminent in SqH and SdH magnitudes indication of the reversal of the eastward current and the dominant effect of the disturbance dynamo processes.
3. The SdH sluggisly increase at sunrise to reach their peaks values around (10:00-14:00) LT hrs and slowly deacreases even after dusk, indication of posible modification of the current system.
4. The negative SdH magnitudes are stronger evidence of the westward disturbed equatorial current effect.
5. Both the SqZ and SdZ depict night-time variations and their daytime magnitudes does not show any apreciable differences.
6. The SqH and SqZ demonstrate the presence of night-time to pre-sunrise magnitudes that decreases with solar activity

7. The sluggish increase in SdH at sunrise to peak values mostly around (10:00-14:00 LT) and the gradual decrease even after dusk are evidences of likely modification of the normal eastward current during perturbed conditions over the Malaysian sector
8. We infer that the solar daily variations of SqZ over the Malaysian región is not just the effect of direct ionospheric current but a combined effect of the eastward current from the E-region and the induced current from the solid Earth.
9. During disturbed period, the seasonal SSqH and SSdH dose not show any linear increment with increase in solar activity, rather a decrease was observed especially during the equinox season.
10. The anual increase of ASqH and AsdH with solar activity can be likened to the effect of solar activity on the ionospheric conductivity.

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REFERENCES

[1] Mazaudier, C., Blanc, M., *Electric currents above Saint-Santin, 2,* Model. J. Geophys Res. **87**, 2465 (1982).

[2] Chen, G. X., Xu, W. Y., Du, A. M., Wu, Y. Y., Chen, B., & Liu, X. C., *Statistical characteristics of the day-to-day variability in the geomagnetic Sq field,* Journal of Geophysical Research: Space Physics **112**(A6), (2007).

[3] Rastogi, R. G., *On the simultaneous existence of eastward and westward flowing equatorial elctrojet current,* Proc., Ind., Acad., Sci. **81A**, 80-92 (1975).

[4] Rastogi, R. G., *Disturbance daily variation of equatorial electrojet current*, Current Science **74**, 457-460 (1998).

[5] Bolaji, O. S., Adimula, I. A., Adeniyi, J. O, Yumoto, K., *Variability of horizontal magnetic field intensity over Nigeria during low solar activity,* Earth Moon Planet **110**, 91–103 (2013).

[6] Rabiu, A. B., Nagarajan, N., Okeke, F. N., Ariyibi, E. A., Olayanju, G. M., Joshua, E. O., & Chukwuma, V. U., *A. study of day to day variability in geomagnetic field variations at the electrojet zone of Addis Ababa, East Africa,* AJST **8**, 55 (2007).

[7] Abbas, M., Zaharadeen, Y. J., Joshua, B., Mohammed, S., *Geomagnetic field variations at low latitudes along* 96^0*magnetic meridian*, Int. J. Mar. Atmos. Earth Sci. **1**, 96–109 (2013).

[8] Okeke F., N., Onwumechili, C., A. and Babatunde, A. R., *Day-to-day variability of geomagnetic hourly amplitudes at low latitudes,* Geophys. J. Int. **134**, 484–500 (1998).

[9] Stening, R. J., Reztsova, T., Minh, L. H. *Day-to-day changes in the latitudes of the foci of the Sq current system and their relation to equatorial electrojet strength*, J. Geophys. Res. **110** (A10308), 1–6 (2005).

[11] Matsushita, S. and Campbell, W. H., *Physics of Geomagnetic Phenomena,* (Academic press, New York, vol. 1, 302, 1398p. 1967).

[12] Yamazaki, Y. & Maute, A., *Sq and EEJ—a review on the daily variation of the geomagnetic field caused by ionospheric dynamo currents,* Space Science Reviews **206**, 299-405 (2017).

[13] Gouin, P. and Mayaud, P. N., *A propos des existence possible d'un contre electrojet aux latitudes magnetiques equatoriales,* Ann. Geophys. **23**, 41–47 (1967).

[14] Chapman, S. and Raja Rao, K, S., *The H and Z variations along and near the equatorial electrjet in India, Africa and the Pacific,* J., Atmos., Terr., Phys. **27**, 559-581 (1965).

[15] Rastogi, R. G., *Disturbance daily variation of electrojet current at Indian longitude sector*, Journal of Atmospheric and Solar-Terrestrial Physics **62**, 695-700 (2000).

[16] Yamazaki, Y., KHäusler, K. and Wild, J. A., *Day-to-day variability of midlatitude ionospheric currents due to magnetospheric and lower atmospheric forcing*, J. Geophys. Res. Space Phys. **121**, 7067–7086 (2016).

[17] Obiekezie, T. N. and Obiadazie, S. C. *The variability of H component of geomagnetic field at the African sector,* Phys. Rev. Res. Int. **3**, 154– 160 (2013).

[18] Stening, R. J., *An investigation of solar activity effects in Australian radiosonde data*, Journal of atmospheric and terrestrial physics **56**, 545-553 (1994).

[19] Abbas, M., Abidin, Z. Z., Jusoh, M. H., Bolaji, O. S. & Yoshikawa, A., *Features of horizontal magnetic field intensity over northern island of Malaysia*, Indian Journal of Physics **93**, 1247-1257 (2019).

[20] Anad, F., Amory-Mazaudier, C., Hamoudi, M., Bourouis, S., Abtout, A. & Yizengaw, E., *Sq solar variation at Medea Observatory (Algeria), from 2008 to 2011*, Advances in Space Research **58**, 1682-1695 (2016).