Longitudinal Morphology of the Morning Counter Equatorial Electrojet during Low solar activity

Abstract

The primary aim of this study is to investigate the longitudinal morphology of the Morning Counter-Equatorial Electrojet (MCEJ) during a period of low solar activity (specifically, the year 2008). The study employed a comparative longitudinal analysis of the Morning Counter-Equatorial Electrojet (MCEJ) during a period of low solar activity. Data from four equatorial stations were collected using the Magnetic Data Acquisition System (MAGDAS) during the year 2008. After data cleaning and processing, including hourly binning, baseline determination, and non-cyclic variation correction, MCEJ events were identified based on negative excursions in the H-component of the Earth's magnetic field. The frequency, intensity, and timing of these events were analyzed across different longitudes and seasons to investigate their longitudinal and seasonal variations. Additionally, the impact of MCEJ events on the noontime equatorial electrojet was assessed.The study identified two types of Morning Counter-Equatorial Electrojet (MCEJ) events. The first type, associated with late reversal of the nighttime westward electric field, decreases in frequency eastward. The second type, linked to late reversal of the abnormal eastward electric field, increases eastward. Both types can influence the noontime electrojet, with the first type showing stronger seasonal dependence.

Key words: Morning Counter-Equatorial Electrojet (MCEJ), equatorial electrojet (EEJ), westward electric field (WEF), eastward electric field (EEF), longitudinal variation, seasonal variation, solar activity, ionosphere, magnetosphere.

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1. Introduction

Magnetic field perturbations at the Earth's surface reflect electrodynamic changes of various current systems situated at the upper atmospheric region. During quiecence periods, the magnetic field exhibit a regular occurring pattern that changes with local time (LT) from one particular day to the other. At the magnetic equator, the field shows unique features due to a complex electrodynamic process within its confined region not exceeding ±3° dip latitude. One common noticeable feature is an abnormally enhanced eastward current situated in the E-region of the ionosphere during the daytime near the magnetic equator known as the equatorial electrojet (EEJ), Somayajulu *et al.*, (1993). The EEJ which is a consequence of the mutual orthogonality of electric and magnetic field at the equatorial dip latitude flows only during absence or minimal solar-terrestrial magnetic disturbance periods, Somayajulu *et al.*, (1993). The EEJ is sometimes known to reverse its direction from the normal eastward current flow to westward during certain normal quiet-days. This reversal was first identified by Gouin, (1962) and was later named Counter-equatorial electrojet (CEJ) by Gouin and Mayaud, (1967). The visible manifestation of the reversal current is the obvious suppression or decrease of the northward (X) or

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horizontal (H) component of the Earth magnetic field as a negative excursion below the baseline level [Somayajulu *et al.*, 1993; Abbas *et al.*, 2019 etc.].

Ever since the discovery of the CEJ phenomenon more than 6 decades ago, it has continued to gained attention of several notable research workers due to its global dynamic influence not only within but also beyond its confined region, hence several impressive studies have emerged on the morphological characteristics, longitudinal variations and its causative mechanism [e.g., Rastogi, 1974; Marriott *et al.*, 1979]. Studies have generally shown that large-scale tidal winds generate substantial polarization electric field at low latitude that is directed eastward (westward) during daytime (night-time) hours. The switch in the direction occurs in the morning (0700 LT) and evening (2000 LT) hrs eg., Fejer *et al.*, 2008. This background field is the main driver of the eastward current known as EEJ during the daytime hours and invariably responsible for the westward field of the horizontal magnetic field at night-time.

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The westward current which manifest during the normal eastward electrojet has been explained in terms of several factors by notable research workers. For example, Somayajulu et al., (1993), Sridharan et al., (2002) explained the occurrence of the daytime westward current in terms of atmospheric tidal effects. Earlier studies by Stening (1977), Raghavarao & Anandarao, (1980) revealed that appropriate combinations of atmospheric tidal modes are capable of generating the dayside westward current at the magnetic equator.

Several studies have also been extensively conducted to unravel the characteristics features of the CEJ mechanism such as solar cycle, seasonal, longitudinal, day-to-day variability and their dependence on lunar phase using ground-based and satellite observations. These studies revealed that the phenomena are more frequent or dominant in the morning and late afternoon hours [e.g., Rastogi, 1974, Fambitakoye & Mayaud, 1976, Venkateswaran *et al.*, 2017, Abbas *et al.*, 2019]. An independent study by Mayaud (1967) revealed that the morning CEJ occurrences are more frequent at the equinoxes and dominant afternoon CEJ events occur during local summer solstice.

Earlier effort by Rastogi (1974) gave us some insight of the morphological features as well as the longitudinal dependence of the CEJ phenomenon. Later, Rastogi (1981) identified two categories of CEJ events; one that shows a systematic changes in its diurnal pattern which seems to be controlled by the lunar tide and the other that changes abruptly instantaneously associated to South-North changes in the interplanetary magnetic field (IMF). He further explained that the CEJ events associated to lunar tide seems to persist for several days over a wider longitudinal width. All these studies to a large extent gave us a clearer understanding of the causative mechanism and other features of the CEJ events such as it day-to-day variability. To the best our knowledge, no study has been conducted on the morphological characteristics of the morning counter electrojet (MCEJ) apart from it widely reported dominance over other local time (LT) events in some regions and occur more frequently especially during high solar activity but the detail feature of the MCEJ is not elusive. Hence, this present study seeks to explore for the first time detail longitudinal morphology of the MCEJ during low solar activity. In view of this, the data and method of analysis are describes in section 2, the results are presented in section 3 and discussion of the findings are given in section 4.

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2. Data and Analysis

The horizontal component of the Earth's magnetic field measured over Four (4) equatorial stations across the globe acquired using Magnetic Data Acquisition system (MAGDAS) are used to study the longitudinal morphology of morning counter equatorial electrojet (MCEJ) during quiet days of the year 2008. Table 1 provide the list of the stations and their coordinate systems used in the study. The diurnal variations of the MCEJ were generated from the International quiet days (IQDs) published at the World Data Centre catalogue. The days used were carefully selected based on the magnetic activity index $A = \leq 6$ and the concept of local time (LT) was employed throughout the analysis.

Each day, the MAGDAS records minute average values of the H-component of the Earth magnetic field. The 1440 minutes average values were binned to hourly values and this reduced the data to 24 hourly values. The baseline was further defined as the average of the two hours flanking the local midnight (0000 LT and 0100 LT). The daily baseline values for the element used in the study given as;

$$H_{\circ} = \frac{H_{0000} + H_{0100}}{2} \qquad (1)$$

Where H_{0100} and H_{0000} are the hourly values of H at 0100 and 0000 LT respectively. The hourly departure that is approximately equal to the hourly solar quiet of H-component was estimated by simply subtracting the baseline values of a particular day from each hourly value of that same day. The hourly departure is further corrected for non-cyclic variation so as to eliminate the difference between the value of a field at the 24th LT and 1st LT hour as earlier established by Vestine (1947 and Matsushita and Campbell (1967). Hence, the corrected non-cyclic hourly departures give the solar daily variation of H-component of the Earth's magnetic field during magnetically quiet days.

3. Results and Discussion

Figure 1 (panels a and b) depicts the longitudinal profile of the quiet time H-field at some selected stations across the globe on January 30, 2008 and January 31, 2008 respectively. It is eminent that a conspicuously daytime depression known as counter-electrojet of the H-field are readily observed during the morning hours (MCEJ) on January 30, 2008 (panel a). The MCEJ appeared exceptionally strong (38 nT) in tha American sector (ANC), very feeble in the West Africa (ILR) and East Asian sector (LKW) and surprisingly absent at YAP that is just separated by about 2 hours from the eastern side of LKW. Similar MCEJ events were also observed on January 31, 2008 (panel b) at LKW and YAP separated by a narrow longitude with no traces of the MCEJ at ILR and ANC separated by more than 6 hours. These results are in agreement with earlier findings of Rangarajan and Rastogi (1993) and Kane and Trivedi (1981) that independently observed in their respective studies that CEJ events may not necessary occur on the same day at two stations even if they are separated by about 30° longitude or less, suggesting that the variability in occurrence pattern at observatories may be due to the neutral wind patterns which are confirmed at longitudinal zone. The MCEJ appeared weak (25 nT) at LKW and stronger (45 nT) progressively with longitude seen at YAP.

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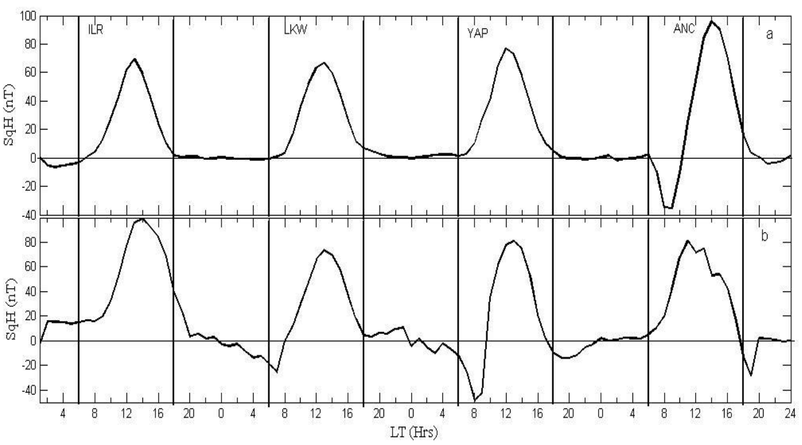

Figure 1. Longitudinal variation of Sq H at some selected stations across the globe on (a) 30 January, 2008, (b) 31 January, 2008

These results established the fact that the occurrence of MCEJ events is thus not entirely longitude dependence or due to some driving events occurring at the same time across all the longitudes, but rely on some other mechanisms for its occurrence. The absence of MCEJ at some of these longitude sectors may likely to be due stronger local mechanism over the global phenomena. The prominent MCEJ that extended to about 1000 LT hrs at ANC shift the noontime peak to later hours (1400 LT) seen in Figure 1 (panel a) and other sectors with feeble MCEJ had their noontime EEJ intensity around 1200 LT hrs. In a different study and different local time Rastogi, (1973) observed cases whereby the daytime CEJ events in the H-field is quite different or differed greatly between two longitude stations (AAB and KOD). He observed that afternoon CEJ (ACEJ) is fairly localized in longitude. We assert that the MCEJ events in this study also follow suite fairly localized in longitude which in some occasions may not occur on the same day even if they are separated by a narrow longitude of 2 hours as the case between LKW and YAP in Figure 1 (panel a).

Moreover, careful observation of the MCEJ on these days clearly revealed some outstanding features and thus indicates that the events exhibit varying characteristics. For instance, the MCEJ events that occurred across all the longitudes were found to be associated to late reversal of night-time westward electric field (WEF) exception of ANC which is unconnected to the late reversal of the WEF. The MCEJ associated to late reversal of nighttime WEF signal the superposition of highly westward normal night-time current that extended to early morning hours over the equatorial region. Another interesting aspect of these exceptionally or pertinent MCEJ associated with the late reversal of WEF seen in YAP in Figure 1 (panel b) and the one not connected to late reversal of night-time WEF obvious at ANC in Figure 1 (panel a) that extended well beyond 0900 LT shift the noontime EEJ peak to latter hour (1400 LT hrs) of the day. This thus, indicates that both forms of MCEJ events possess the characteristics to shift the EEJ intensity to latter hours. This result is in sharp agreement with earlier effort by Kane and Rastogi, (1974) that examined various causes of CEJ events at different longitude sector and observed that the events exhibit varying nature even if

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they are separated by limited longitudinal extent. The diurnal variations of ΔH (YAP) with no traces of MCEJ and ΔH (LKW) with feeble MCEJ associated to late reversal of night-time WEF seems not to have any significant influence on the diurnal trend at these longitudes strictly following the strong electrojet characteristics. The incredible enhancement on the daytime EEJ in the West African sector (ILR) and the systematic reduction in the EEJ as it flows eastward (see Figure 1, panel b) is a clear evidence of the modification of the entire current system associated with the Sq field and the electrojet. The mechanism is more conspicuous with step-like decrease in the American sector (ANC). We assert that the modification of the EEJ is a characteristic of counter electrojet (CEJ) not strong enough to cause the EEJ to go beyond the night-time baseline.

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Figure 2 shows the diurnal variations of the EEJ at ILR, LKW, YAP and ANC on May 10, 2008. It is obvious that this day is characterized by MCEJ conspicuously seen at all the stations exception of LKW with evening CEJ (ECEJ) which is not the concerned of this study. The absence of MCEJ at LKW on this day may likely be attributed to prevalence of local effect over the global mechanisms. For example, the MCEJ at ILR that extended to 08:00 LT hrs is associated to late reversal of night-time WEF and this shifted the noon peak to about 13:00 LT hrs.

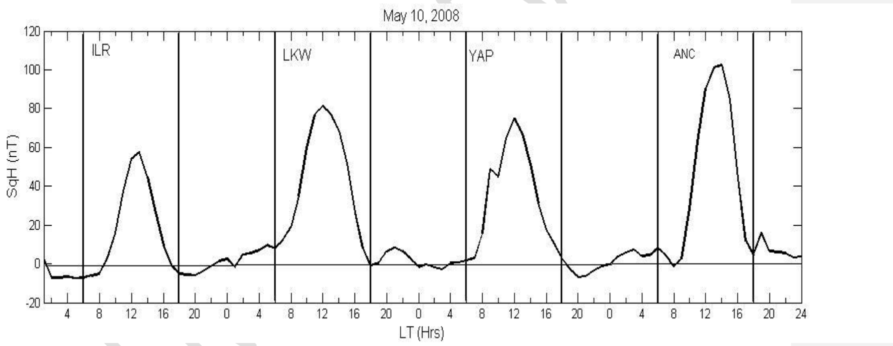

Figure 2. Diurnal variation of the EEJ on May 10, 2008

Also from Figure 2, the MCEJ that occurred around 08:00 LT hrs at ANC that is not associated to late reversal of night-time WEF In fact, the MCEJ at this longitude sector (ANC) is associated to late reversal of abnormal night-time eastward electric field (EEF). The effect of this MCEJ event shifted the noontime EEJ peak to latter hours (1400 LT). This further clearly indicate that the MCEJ associated to late reversal of normal night-time WEF and those connected to late reversal of abnormal nigh-time eastward electric field have the tendency to shift the noontime EEJ peak to latter hours under some certain ionospheric conditions.

The variation of EEJ index at YAP in Figure 2 does not show negative values during the morning hours but exhibit some form of depression around 1000 LT hrs which is different than the normal EEJ variation. This anomaly becomes more obvious when compared with the expected normal electrojet current pattern. This may likely indicate the presence of the westward current in addition to the normal eastward current system. This event takes place when the normal eastward current is strong; hence the superposed westward current was not sufficiently strong enough to cause a net negative excursion hence we observed only a slight depression in the EEJ index around 1000 LT hrs and reduced the noontime EEJ peak instead of a proper MCEJ with negative values. Even this situation can be considered a characteristics of CEJ phenomenon and thus indicator of weak MCEJ event.

Extending this description further, we thus suggest that the reversal of the equatorial electrojet seems to be due to some mechanism which when stronger than the normal eastward current caused an overlapping of westward current or complete reversal of the eastward current at the vicinity of the magnetic equator. The overall results seems to indicate that the extended local time of daytime WEF of MCEJ associated with late reversal and those not related to late reversal of WEF play significant role in determining the noontime peak and magnitude of the EEJ depending on the strength of the EEJ.

Figure 3 show the diurnal variations of H-field on a series of days in September 2008. Interestingly, MCEJ associated to late reversal of night-time WEF could be seen in all the days in the West African sector (ILR), this feature is completely absent at any longitude sector exception of ANC seen on September 24, 2008. On each of these days, the magnetic activity index Ap≤ 6 and this thus makes these days to be considered magnetically quiet. The MCEJ seen in the American sector (ANC) is not associated to late reversal of night-time WEF indication that the MCEJ on this day at this longitude sector exhibit different feature to the West African sector (ILR) that is associated to late reversal of normal night-time WEF.

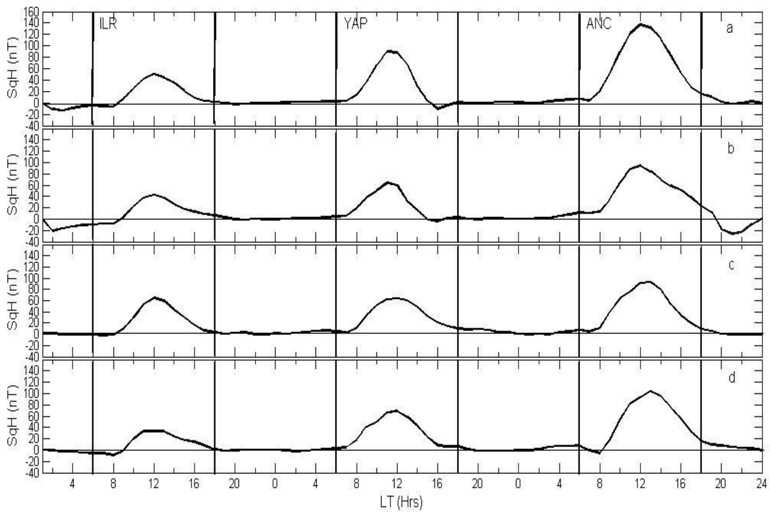

Figure 3. Diurnal variation of H-field on series of days (a) September 20, 2008 (b) September 22, 2008, (c) September 23, 2008 and (d) September 24, 2008 respectively

The frequent or dominant occurrence of MCEJ associated to late reversal of night-time WEF in the West African sector (ILR) could signal the presence of weak EEJ or eastward current strength to overcome the normal night-time westward current that extended beyond 0600 LT hrs at this longitude sector. To determine the local time effect of the MCEJ associated/not associated to late reversal of night-time WEF, Figure 4 is plotted. These MCEJ events were found during 0700-0800 LT hrs. Two categories of MCEJ can be identified on this day. The MCEJ not associated to late reversal of WEF that occurred in the West African sector (ILR) and the one associated to late reversal of WEF are seen in American sector (ANC). These MCEJ were observed to extend to around 0800 LT but having strong influence on the EEJ having its peak at 1100-1200 LT hrs respectively. These noontime EEJ peak in spite the MCEJ is a normal phenomenon and expected owing to the weak MCEJ that does not go beyond 0700 LT to cause any significant influence on the EEJ intensity. On the other hand, the diurnal variation of the H-field in the Asian sector with complete absence of MCEJ, in fact an abnormal enhancement of ΔH that started building up from midnight (0100 LT) hrs and progressively enhanced with local time (LT) result in early peak of EEJ around 1100 LT hrs. This is in agreement with earlier effort of Rastogi (1974) that opined that EEJ reaches its peak intensity around 1100 (1200) LT hrs during low (high) solar activity periods.

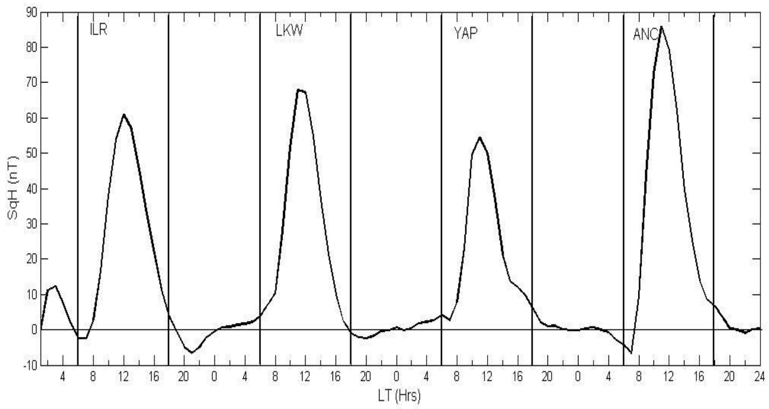

Figure 4. Diurnal variation of H-field on November 4, 2008

Generally, the MCEJ events were found to decrease as the electrojet current flows from the West African sector (ILR) to East American sector (ANC). The higher occurrence of MCEJ events 122 days occurred in the West African sector (ILR) and progressively dropped with longitude to about 59 days seen in the American sector (ANC) as shown in table 2.0. This seems to point to the fact that as the jet flows eastward, there seems to be extra input energy that tends to reduce or minimize the occurrence of MCEJ.

Table 2.0: Total occurrence of morning CEJ events in the year 2008

ILR	LKW	YAP	ANC
122	81	74	59

In some days, the MCEJ events were reliably observed to be associated to late reversal of the normal night-time westward electric field (WEF). These MCEJ events associated to late reversal of WEF were found to decrease progressively as the EEJ flow eastward with higher occurrence of 105 days observed in the West African sector ILR and dropped to about 22 days at American sector (ANC) as shown in table 3.0. This indicates the progressive increase in the intensity of the eastward current with longitudes which tend to reduce the effect of the late reversal of the night-time WEF during the morning hours. We assert that the occurrence of MCEJ associated to late reversal of normal night-time WEF signal weaker morning EEJ strength, hence, MCEJ associated to late reversal of night-time WEF seems to thrive in a region or longitude with weaker build-up EEJ current intensity. Extending this description further, it is expected that the background E-field is still pointing westward before 0600 LT hrs dominating the current direction (westward). During the subsequent hours (0700 LT), the large-scale electric field should switch direction and drift eastward gaining more momentum to overcome the night-time westward electric field thereby establishing eastward current responsible for the positive magnetic field variations. The dominance of MCEJ events associated to late night-time WEF at the West African sector (ILR) could signal the prevalence or extension of the night-time WEF beyond 0600 LT hrs at this longitude sector. On average, MCEJ associated to late reversal of WEF were observed to occur at all longitudes but predominantly in the West African sector (ILR). This is consistent with the earlier report of Cohen and Achache (1990) that found CEJ events at all the longitude considered in their study. During the subsequent hours (after 0700 LT hrs), the large-scale eastward field gained more momentum and overcome the westward field, hence resulting in the enhanced noontime peak of the EEJ intensity reliably observed in Figures 1-4

Table 3.0: MCEJ events associated to late reversal of WEF in the year 2008

ILR	LKW	YAP	ANC
105	59	33	22

Apart from the MCEJ associated to late reversal of night-time WEF, there are other MCEJ that are not associated to late reversal of WEF, in fact these MCEJ are associated to unusual night-time eastward electric field (EEF). These MCEJ increases linearly with longitude in the eastward direction as the electrojet flow, except at ANC where it slightly dropped to about 37 days as shown in table 3.0. the West African sector (ILR) with the highest number of MCEJ associated to late reversal of night-time WEF recorded the least number of days (18) with MCEJ associated to reversal of abnormal EEF and this progressively increase in the eastward direction as the electrojet gained momentum. This established the fact that as the electrojet flow eastward during the daytime it gained more momentum that increases the frequency of the occurrence of MCEJ events that are associated to late reversal of unusual night-time eastward electric field at the same time enhances the occurrences of MCEJ that are associated to night-time reversal of normal WEF. Hence, this study for the first time established the categories MCEJ events that decreases or increases with longitude in the eastward direction depending on the night-time electrical conductivity of E-region.

Table 4.0: MCEJ events associated to late reversal of EEF in the year 2008

ILR	LKW	YAP	ANC
18	22	41	37

From Figure 5, it is obvious that MCEJ events were generally observed to be most frequent in August with highest 15, and 12 days in Africa (ILR) and Asian (LKW) sectors respectively. In te American sector (ANC), the highest frequency (13 days) occurred in December. These are solstice months identified with weak electrojet current intensity and widely reported CEJ occurrences.

This result is consistent with Vichare and Rajaram (2011) that observed that the occurrence of CEJ events maximizes during the solstice months. This result established that the MCEJ exhibit longitudinal variability just like the afternoon and noon CEJ events earlier reported by research workers e.g., Rastogi (1974). The frequent occurrence of MCEJ phenomena at ILR could be explained in terms of the fact that at low solar magnetic activity period, the lower solar flux level cause

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significant decrease in the build-up level of atmospheric ionization rate and this lower the ionospheric conductivity hence reduce the build-up of EEJ during the morning hours. The reduced EEJ intensity create a conducive condition for MCEJ to prevail during the early morning hours as observed in the West African sector (ILR).

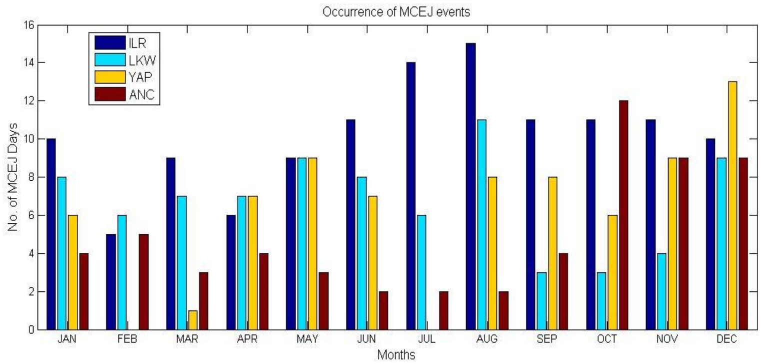

Figure 5. Monthly occurrence of morning counter-equatorial electrojet (MCEJ) in year 2008

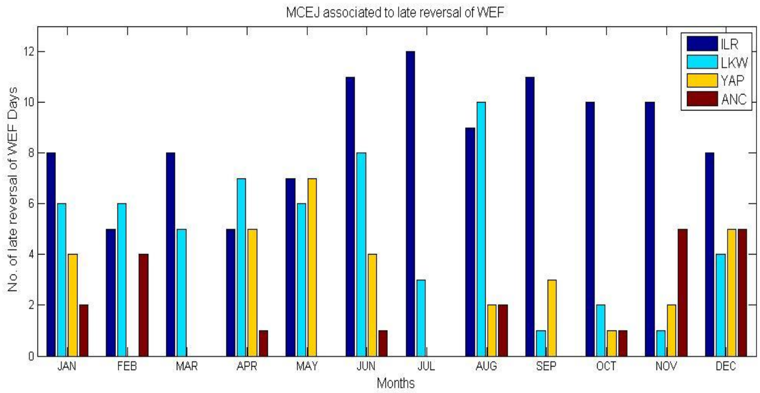

Figure 6 Monthly occurrence of late reversal of morning westward electric field (WEF)

Figure 6 shows the occurrence frequency of MCEJ associated to late reversal of night-time WEF observed in each month during the solar quiet year 2008. These MCEJ events exhibit higher magnitudes in all the months through the year in the West African sector (ILR) exception of February, April and August respectively. During these periods, the highest occurrence frequency of 12, 9 and 5 days were recorded in July at the African sector (ILR), August at the Asian sector (LKW) and November and December with equal number of days in the American sector (ANC). On average, least occurrence frequency of MCEJ associated to late reversal of night-time WEF were observed in each month through the year at the American sector (ANC) exception of November and December.

Figure 7 shows the monthly occurrence of MCEJ associated to late reversal of the unusual night-time eastward electric field (EEF). On average, the occurrence of the CEJ phenomenon is less frequent in the West African sector (ILR) and occurrence more frequent in the American sector (ANC) with its peak amplitude in October. In the Asian sector, it appeared more frequent in YAP over the East Asian sector (LKW). This higher occurrence of late reversal of the abnormal night-time eastward electric field could be attributed to local longitudinal gradient effect over the global mechanism. This result further earlier confirms earlier report that night-time sometimes exhibit positive magnetic field variations indication of eastward electric field that extended to early morning hours of this study. Amazingly these night-time positive variations were observed during solar minimum activity in contrast to earlier studies that reported the phenomenon mostly in the American sector during maximum solar activity. This further implies that at night-time when solar activity ceased to exist and electrical conductivity of the E-region is minimal or shut-down, some fundamental mechanisms either of ionospheric or non-ionospheric origin may play significant role in generating and sustaining the electrical conductivity of the E-region ionosphere.

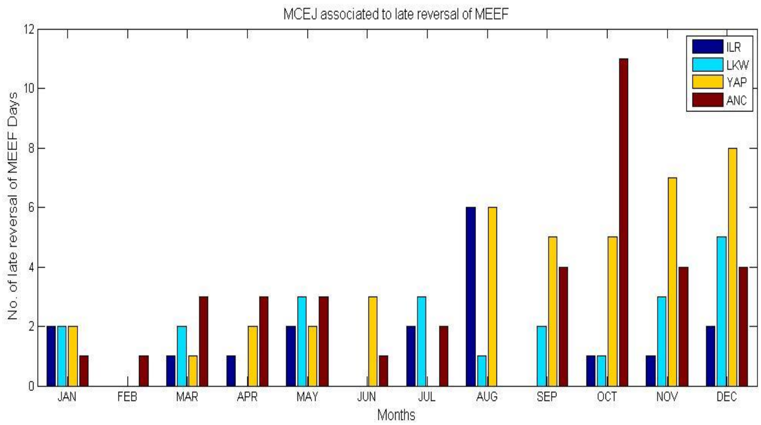

Figure 7. Occurrence of late reversal of morning eastward electric field (MEEF)

Figure 8a shows the seasonal variations of MCEJ events that are associated to late reversal of WEF during the equinox, summer and December solstices. It is consistently seen that even the MCEJ associated to late reversal of WEF consistently appeared higher at the West Africa sector (ILR) throughout the seasons and lowest in the American sector (ANC) seen in equinox season. The higher (lower) occurrence of the seasonal MCEJ associated to late reversal of WEF at the West African sector (American sector) is a strong reflection of weaker (stronger) morning equatorial electrojet current intensity at these longitude sectors as earlier mentioned.

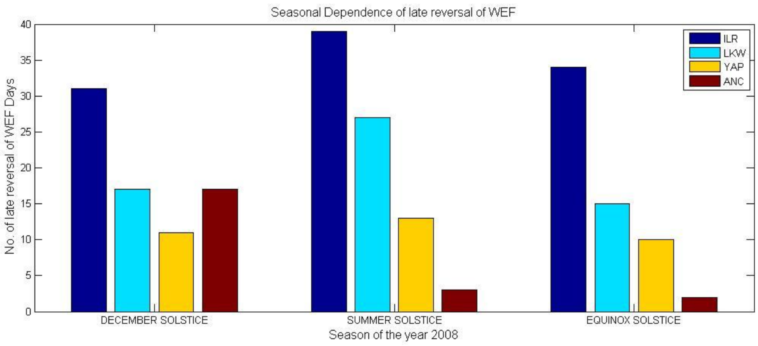

Figure 8a. Seasonal variation of late reversal of WEF in year 2008

The highest number of days (39) of the seasonal MCEJ occurred in the West African sector (ILR) in summer solstice and shifted to December solstice seen in the American sector (ANC). It is noteworthy to note that these are solstice seasons where the strength of the eastward current intensity is weak and thus suggest the occurrence of more CEJ events which are likely to take place at region and periods of weak normal electrojet current, hence could attribute to the observed higher MCEJ events on these seasons. Figure 8b that depict the seasonal variability of late reversal of MEEF showed maximum occurrence (21) in the American sector seen in equinox season. On average, the seasonal MEEF does not show any clear distinct variations but however, their magnitudes were observed to appear lower than their corresponding MCEJ magnitudes associated to late reversal of WEF. This further clarifies or substantiates the fact that seasonal MEEJ does not show any longitudinal seasonal variation.

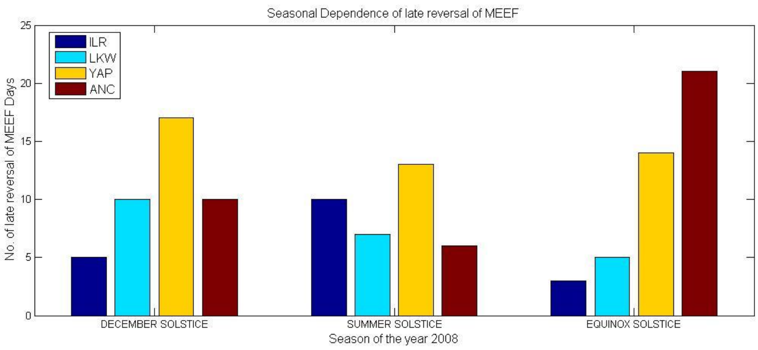

Figure 8b. Seasonal variation of late reversal of MEEF in year 2008.

4. Conclusion

The study which examined for the first time the longitudinal characteristics of the MCEJ events identified two forms of CEJ:

i. MCEJ events that are associated to late reversal of night-time westward electric field (WEF) that decreases progressively in the eastward direction from the West Africa (ILR) to South America (ANC) sector.

ii. MCEJ phenomenon that is associated late reversal of abnormal night-time eastward electric field (EEF). These CEJ events were found to decrease in the eastward direction in contrast to these associated to late reversal of the normal night-time WEF.
iii. The higher (lower) occurrence of the seasonal MCEJ associated to late reversal of WEF at the West African sector (American sector) is a strong reflection of weaker (stronger) morning equatorial electrojet current intensity at these longitude sectors
iv. On average, the seasonal MEEF does not show any clear distinct variations but however, their magnitudes were observed to appear lower than their corresponding MCEJ magnitudes associated to late reversal of WEF.

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Authors' Contributions to Knowledge

This study for the first time identify two categories of morning Counter-Equatorial Electrojet (MCEJ) phenomenon and significantly advances the understanding of those Mornings Counter-Equatorial Electrojet (MCEJ) by exploring there longitudinal seasonal behaviour and assessing their impact on the noontime equatorial electrojet. The findings provide valuable insights into the complex interplay of factors influencing MCEJ behavior and their role in shaping ionospheric dynamics and space weather phenomena.

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