Seasonal and Annual Variations of Equatorial Electrojet and Counter Elecrojet Strength during the Ascending Phase of Solar Cycle 24

Abstract

The seasonal and annual variation of the equatorial electrojet strength at Addis Ababa and Mbour during the ascending phase of solar cycle 24 has been investigated. We used magnetic field measurements obtained from International Real-time Magnetic Observatory Network (INTERMAGNET) stations in Ethiopia, Addis Ababa (AAE) and in Senegal, Mbour (MBO) for the duration from January 2009 to December 2014. The results showed that both seasonal and annual peaks for Equatorial Electrojet (EEJ) at AAE occurred at around local noon and the amplitudes were greater than those at MBO, which peaked much later. The late peaks at MBO were attributed to the effect of tidal winds and the variations in the geomagnetic field. However, the Counter Electrojet (CEJ) at MBO peaked in the late morning and presented larger amplitudes than AAE which peaked much earlier. This implied that EEJ occurring around noon had greater amplitudes which were attributed to higher ionization rates during this period; hence EEJ and CEJ were to found to be local time dependent phenomena. The Addis Ababa station displayed large peaks of EEJ with very small peaks of CEJ while Mbour station displayed large CEJ peaks and small EEJ peaks. The EEJ strength annual variations showed a longitudinal dependence with the peak value at Addis Ababa being higher at 40nT, than the value at Mbour which was about 20nT in the same year 2012. This was attributed to the fact that AAE was much nearer to the dip equator than MBO, hence a greater enhancement of the EEJ current at AAE. For the seasonal variation, the CEJ amplitude at MBO was larger than the amplitudes at AAE, with the largest peak at MBO being -40nT observed in the year 2011 during the September E-season while the largest for AAE was -20nT in the year 2013 for both March and September E-seasons. EEJ exhibited a longitudinal variation.

Key words: Equatorial electrojet, counter electrojet, seasonal variation, annual variation, solar cycle 24

1.0 Introduction

The equatorial ionosphere plays an important role in the satellite-Earth communication and applications in the space weather studies. Due to these important roles and its complexities, the equatorial ionosphere and its current systems has continued to gain much interest [1]. The equatorial ionosphere over the dip (magnetic) equator is characterized by a number of noticeable electrodynamic processes. One of these processes includes a flow of a non-uniform intense eastward ionospheric current within latitude of within ± 3^o on either side of the dip equator at a lower altitude E-region centred at around 106 ± 2 km [2-4]. This eastward current is known as the equatorial electrojet (EEJ) [5]. Around the magnetic equator, there is an unusual orientation of the field with relation to the Earth. The magnetic field lines of force which are associated with EEJ are horizontal around the dip equator. Hence large vertical electrical polarization field responsible for enhanced eastward currents are likely to be set up [3]. During some quiet periods, the daytime EEJ strength is weakened especially early in the morning and evening and reverses direction and flows westward for some short period before returning to its normal afternoon value, and disappearing around sunset [6, 7]. This reversal in direction of current during magnetically quiet period is known as counter equatorial electrojet (CEJ). Scientists have carried out various studies on the features and morphology of

EEJ and CEJ along various longitudinal sectors. Idowu et al [8] used estimation method and the Fambitakoye simulation model to concurrently study the electrojet current in order to establish the correlation between the these two methods. The hourly magnetic field horizontal component Data from MAGDAS stations along the 2100 magnetic meridian for the year 2007 were used in the study. The Fambitakoye model gave higher values than the estimation method even though the performance of the two methods was observed to be similar. The stations nearer to the dip equator showed higher amplitudes of the EEJ current than stations away from the dip equator. Tuo et al [9] studied longitudinal EEJ profiles using satellite magnetic measurements of full CHAMP in the period 2001 to 2010. A longitudinal pattern of wave four was observed on EEJ averagely. A detailed analysis of the Monthly averages when analyzed into detail, gave two categories of longitudinal profiles: a main phase which had three maxima and a secondary phase which had one maximum forming the EEJ wave four pattern of variation. Mungufeni et al [10] carried out a correlation analysis between the EEJ and the equatorial ionization anomaly (EIA) occurrence at the East African sector. This was done using statistical analysis by use of differential technique to determine the EEJ for quiet geomagnetic conditions and to derive Total Electron content by finding the TEC ratio across the trough as the CT: TEC ratio, in order to get the EIA strength for the region. The trough was found to lie rather to the South of the dip equator possibly as a result of the slight shift of the EEJ centre to the South of dip equator at the East African region, The study highlighted a positive correlation between the EEJ and EIA Strengths during the day, with the strongest positive correlation being witnessed from 13:00 to 15:00LT. Rabiu et al [11] examined the longitudinal variability of the EEJs and the occurrence of its CEJs using magnetometers in the year 2009 along the magnetic equator in the South American, African and Philippines sectors. The results showed that EEJ underwent variability from one longitude representative station to another with the strongest EEJ of about 192.5nT at South American axis at Huancayo and minimum peak of 40.7nT at Ilorin in Western Africa. The African stations of Ilorin and Addis Ababa registered the greatest percentage of CEJ occurrence. The percentage occurrence of CEJ varied with seasons across the longitude. Akpaneno & Adimula [12] studied the Horizontal component variability of the Earth’s magnetic field from ten MAGDAS magnetometers along the magnetic equator. The H variation with Sq(H) enhancement in all ten stations peaked around local noon with a steady similar pattern of variation in all EEJ, linked to the intensified dynamo action in the regions. The changing Sq(H) ranged between 20nT and 170nT with peaks around 1200- 1300hours LT. They also observed that the magnitude of variation on disturbed days were generally higher due to the disturbances within the ionosphere emanating from the sources from outside it external like effects of space weather and storms. Their results confirmed the presence of CEJ occurring in the morning and evening hours with maximum amplitude of -25nT recorded during pre-sunset as well as a longitudinal variability in the EEJ. They recorded a pronounced equinoctial maximum which was attributed to the enhanced electron density at equinox. Yizengav et al [13]carried out a study of longitudinal variability of dayside EEJ for all local times using ground based observations (magnetometers) situated at different longitudes between 2010 and 2013 . Their results showed EEJ being stronger in the West African sector and decreased from West to East longitudinal sectors. They also confirmed the presence of significant longitudinal difference in the dusk sector pre-reversal drift using the ion velocity meter (IVM) instrument on-board the C/NOFS satellite with strong pre-reversal drift in the West American sector compared to African sector. Okeke & Hamano [14] investigated the variations of the geomagnetic field at low latitudes within the equatorial zone using the Japanese new designed Ocean Hemisphere Network Project to carry out long term observations on the pacific remote places. The components of the geomagnetic field were analyzed and the results showed that the magnitude of depicted diurnal variation whose peaks were observed during the day around 1200LT in the three EEJ regions that were investigated. According to this research, the H component showed a diurnal variation with the enhancement in these regions because of the enhanced equatorial dynamo action. On the other hand, the D component diurnal variation indicated that the EEJ current system comprised of an East-West component as well as a North –South component. Despite recent studies on characterization EEJs and occurrence of CEJs having been carried out in the equatorial regions, more research needs to be done on the EEJs and CEJs in order to understand their features and morphology along various longitudinal sectors [11, 17]. EEJ and CEJ display significant diurnal, seasonal longitudinal and solar cycle variability [13, 16].

In this paper, we used the AMBER and INTERMAGNET array of magnetometers situated within the African equatorial region to establish this link between EEJ and CEJ strength over Addis Ababa (AAE) and Mbour (MBO) during the ascending phase of solar cycle 24.

2.0 Methodology

2.1 Data sources

2.1.1Geomagnetic indices data

Geomagnetic activity indices: planetary magnetic index, Kp and Disturbance storm time (Dst) index that were used to identify the most quiet and highest disturbed days of every month for the whole period of study were obtained from the website: http://wdc.kugi.kyoto-u.ac.jp/ of world data centre for geomagnetism located at Kyoto, Japan.

2.1.2 Magnetic field data

Magnetic field measurements from International Real-time Magnetic Observatory Network (INTERMAGNET) stations in Ethiopia, Addis Ababa and Mbour in Senegal for the duration from January 2009 to December the year 2014 were used.

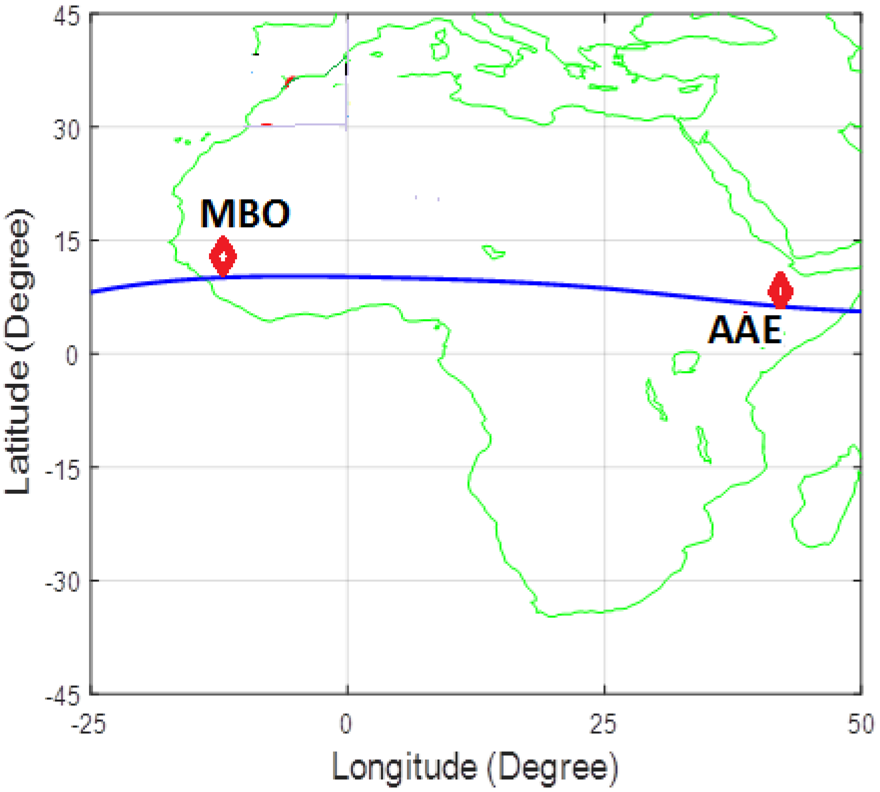

Figure 1: Geomagnetic locations map of magnetometer network for AAE and MBO

Geographic and geomagnetic location information of Magnetometer network for: ETHI and MBO were used in this study is given in Table 1:

Table 1: Geographic and geomagnetic locations of AAE and MBO

STATION ID	**STATION NAME**	**Geographic Latitude**	**Geographic Longitude**	**Geomagnetic Latitude**	**Geographic Longitude**
AAE	Addis Ababa	9.0°N	38.8°E	0.9°N	110.5°E
MBO	Mbour	14.43°N	16..97°W	2.06°N	58.24°W

2.2 Methods

The strength of Equatorial Electrojet was estimated by taking the difference in the amplitudes of the SqH of the geomagnetic field at a station within the dip equator, whose dip latitude range is within ±3° and a station within the low latitude but off the dip equator within ±6-9° of almost equal longitude sector. This is because the station within the EEJ strip has Sq current enhanced with Equatorial Electrojet current while the one outside only has Sq current [1].

$$EEJ = Sq\,at\,the\,EEJ\,strip - Sq\,Outside\,the\,EEJ\,stri \qquad (1)$$

The universal time presentation of the data was converted to local time convention for analysis, according to the relation in equation 2,

$$LT = UT + \left\lfloor \frac{\theta}{15} \right\rfloor \qquad (2)$$

Where θ is the geomagnetic longitude of the stations studied.

The reason for this is because during the 24 hour rotation of the Earth, it covers a longitudinal difference of one degree which gives a difference of 4 minutes in time.

The Lloyd seasons were used to group months in order to study the seasonal variation with each season being approximated through finding the monthly average for all months making up a given season. The Lloyd seasons were obtained by grouping the months into seasons as: December solstice (or D season) covering the months of November, December January and February; March equinox (or March E season) covering March and April; June solstice (or J season) covering the months of May, June, July and August and September equinox (or September E season) which took care of September and October in accordance to the works of [1]. Each year was approximated by finding monthly averages of H for the particular months making a year. The EEJ seasonal and annual variations were studied and results plotted in Figures 2 and 3.

3.0 Results and discussions

3.1 Annual variations of EEJ strength at AAE and MBO.

Figure 2 shows the annual variations of EEJ strength at AAE and MBO from 2009 to 2014

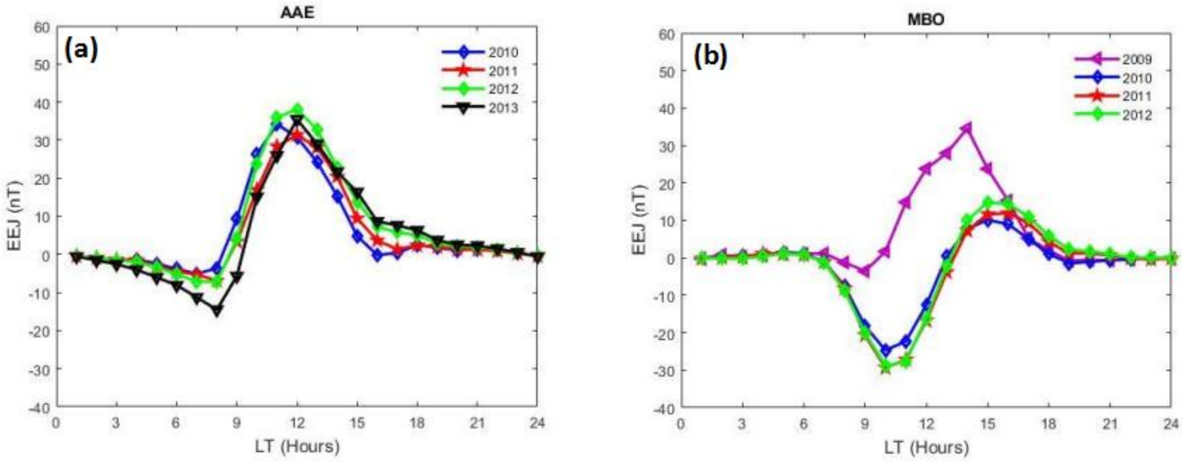

Figure 2: Annual variation in the EEJ strength from 2009 to 2014 for: (a) Addis Ababa (AAE), (b) Mbour (MBO)

The annual variation of EEJ strength had the highest peak of 40nT at local noon in Addis Ababa which occurred in the year 2012 as indicated in Figure 2(a). The largest magnitude of EEJ strength was recorded in the 2012 which is a high solar activity year. This shows that annual EEJ strength is local time and solar activity dependent. The night (1800LT-0600LT) EEJ strength at Addis Ababa is around 0nT. The station also recorded a morning CEJ with a recorded maximum peak of about -15nT for the year 2013. The peak occurred at around 0800LT.

In Mbour, the maximum annual EEJ strength magnitude was recorded in 2009 with a peak of about 35nT as indicated in Figure 2(b). This year in Mbour showed a different trend as compared to the remaining years under study. This calls for further research. The daytime peaks of about 15 nT occurred in the afternoon at around 1500LT. The rest of the years recorded daytime peaks of less than 20nT and the night time values were between 0-5nT. This also shows that EEJ annual variation is a function of solar activity and local time. However, Mbour station recorded high magnitudes of a morning CEJ at around 1000LT with maximum peak of -30nT recorded in the 2012.

The annual variation of EEJ indicates that the peaks at low solar activity years occurred slightly earlier than the peaks during high solar activity years. This may imply that when the solar activity is low, the ionization peak is attained earlier increasing the conductivity of the ionosphere.

In summary, the EEJ strength annual variations showed a longitudinal dependence with the peak value at Addis Ababa being higher at 40nT, than the values at Mbour which was about 20nT in the same year 2012. This was attributed to the fact that AAE (geomagnetic latitude 0.9^{o}) was much nearer to the dip equator than MBO (geomagnetic latitude 2.06^{o}) hence a greater enhancement of the EEJ current at AAE. At Addis Ababa, the magnetic variation was only 1.5^{o}E and the dip equator was aligned almost to the East. Since the H component was also directed daily almost to the north, then the direction of flow of the EEJ current was perpendicular to the magnetic variation. The EEJ at MBO peaked much later in the day at around 1500LT as compared to AAE where the peak occurred at around local noon. This was associated with the longitudinal variations of the Earth’s magnetic field which influences the non-migratory tides. This longitudinal variation in the mean annual strength of EEJ agrees with the findings of [13, 16], that, the strength EEJ is greater as one moves to the eastern African sector than to the west. They attributed this to a process of reinjection of energy to the electrojet as it flows eastwards

3.2 Seasonal variations of EEJ and CEJ strength at Addis Ababa (AAE) and Mbour (MBO)

Figure 3 represents the results of the EEJ strength seasonal variation at Addis Ababa (AAE) and (Mbour) MBO for the period starting from the year 2009 to 2014.

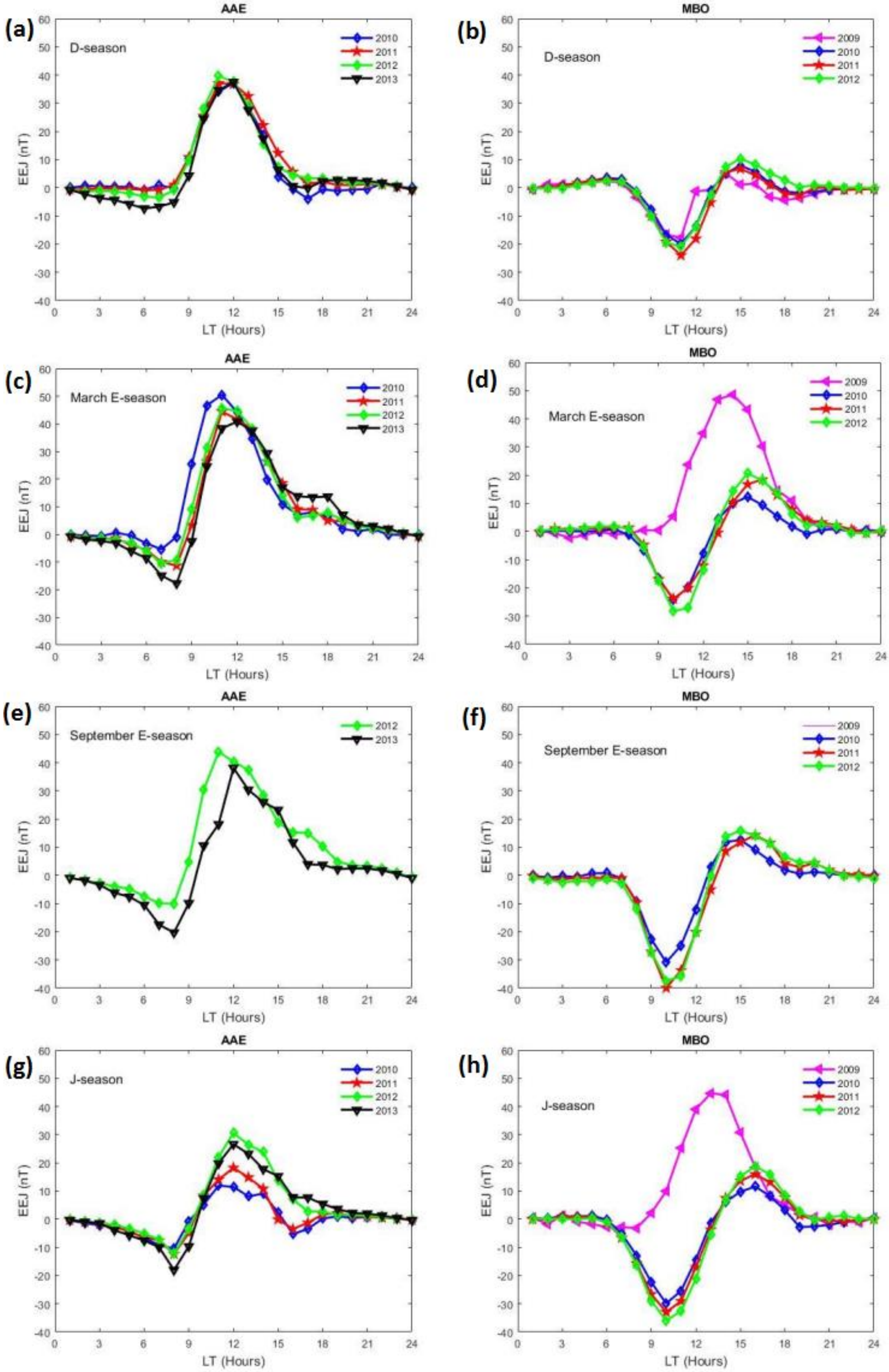

Figure 3: Seasonal variations of EEJ strength and CEJ at AAE and MBO from 2009 to 2014.

Seasonal EEJ strength at Addis Ababa (AAE) for December solstice, March Equinox, September Equinox and June solstice had maximum peak values of 42nT, 50nT,48nT and

35nT respectively, all occurring between 1000LT -1200LT as indicated by Figure 3(a), 3(b), 3(c) and 3(d). A morning CEJ ranging between -15nT and -20nT was also recorded for J season and the equinoxes while the D season showed a CEJ magnitude of less than -10nT. The CEJs were observed between 0800LT and 0900LT.The night time amplitudes were quite low averaging between 0-5nT. At Mbour (MBO), the EEJ magnitude peaks mainly in the afternoon between 1300LT and 1500LT with a maximum of 20nT for D and September Equinox. March Equinox and J season recoded maximum peaks of 50nT in the year 2009. This station also recorded morning CEJ occurring between 0900-1100LT. The maximum peaks for D, March E, September E and J seasons were 25nT in 2011, 30nT in 2012, 40nT in 2011 and 35nT in 2012 respectively. The night time magnitudes were about 0nT.

Generally, from the results it was noted that EEJ was recorded in both AAE and MBO stations, with AAE recording higher magnitudes as compared to MBO. AAE had morning EEJ while MBO had an afternoon EEJ with slightly lower magnitudes. This is an indication that EEJ exhibits a longitudinal variation attributed to the migratory tides fluctuations, diurnal tide propagations, local wind effects, and meridional winds effect as discussed by [11] in their study of the longitudinal variability of the EEJ from one representative station up to another.

From Figure 3, it was also observed that both stations recorded a CEJ with AAE recording an early morning CEJ between 0600LT and 0900LTwhile MBO recorded CEJ in the late morning between 1000LT- 1100LT.The CEJ amplitude at MBO was larger than the amplitudes at AAE with the largest peak at MBO being -40nT observed in the year 2011 during the September E-season while the largest for AAE was -20nT in the year 2013 for both March and September E-seasons. This indicates that CEJ also exhibits a longitudinal variation. While the magnitude of EEJ is greater in Addis Ababa than Mbour, the magnitude of CEJ is however greater in Mbour than in Addis Ababa implying that there could be an increased westward electric conductivity and high gradients in ionospheric conductivity during late morning hours in Mbour than in Addis Ababa. These factors that favor the occurrence of CEJ however oppose the occurrence of its EEJ. This is consistent with the findings of [11].

Conclusions

This study has identified that both seasonal and annual peaks for EEJ at AAE occurred at around local noon and the amplitudes were greater than the amplitudes at MBO which peaked much later. The late peak at MBO was attributed to the effect of tidal winds and the variations in the geomagnetic main field. However, the CEJ at MBO peaked in the late morning and presented larger amplitudes than AAE which peaked much earlier. It therefore implied that EEJ occurring around noon had greater amplitudes attributed to higher ionization rates during this period; hence EEJ and CEJ were to found to be local time dependent phenomena. The Addis Ababa showed a large peak of EEJ with a very small peak of CEJ while Mbour station displayed a large CEJ peak and a small EEJ peak. The EEJ strength annual variations showed a longitudinal dependence with the peak value at Addis Ababa being higher at 40nT, than the values at Mbour which was about 20nT in the same year 2012. This was attributed to the fact that AAE was much nearer to the dip equator than MBO, hence a greater enhancement of the EEJ current at AAE. For the seasonal variation, the CEJ amplitude at MBO was larger than the amplitudes at AAE with the largest peak at MBO being -40nT observed in the year 2011 during the September E-season while the largest for AAE was -20nT in the year 2013 for both March and September E-seasons. EEJ exhibited a longitudinal variation. The morning CEJ was recorded in the African equatorial region which did not show seasonal variation as the EEJ did. EEJ around local noon and CEJ occurring in the late morning had greater amplitudes as compared to those in the early morning and afternoon. This showed that EEJ depended on local time of the day and ionization rate. The findings in this study provide a new perspective in understanding the relationship between local ionization rates and EEJs and CEJs.

Author Contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

Acknowledgements

The authors thank the International Real-time Magnetic Observatory Network (INTERMAGNET) team for availing the magnetometer data resources that were used in this work. They also thank the world data centre for geomagnetism located at Kyoto, Japan: *http://wdc.kugi.kyoto-u.ac.jp/* for the Kp and Dst index values that were used to determine geomagnetic activity levels.

Disclaimer for Thesis:

This paper is an extended version of a Thesis document of the same author.
The Thesis document is available in this link: http://www.edocs.maseno.ac.ke/bitstream/handle/123456789/5606/LUCY%20THESIS.pdf?isAllowed=y&sequence=1

[As per journal policy, preprint /repository article can be published as a journal article, provided it is not published in any other journal]

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Option 2:

Author(s) hereby declare that generative AI technologies such as Large Language Models, etc. have been used during the writing or editing of manuscripts. This explanation will include the name, version, model, and source of the generative AI technology and as well as all input prompts provided to the generative AI technology

Details of the AI usage are given below:

1.

2.

3.

References

[1] Rabiu, B. A., Nagarajan, N., Okeke, F. N., & Ayiribi, A. E. (2007). Variability of equatorial ionosphere infered from geomagnetic field measurements. *A journal of science and technology vol. 8 No. 2*, 609.

[2] Richmond, A.D. (1973). Equatorial electrojet. Development of amodel including winds and instabilities, J. atmos. terr. Phys., 351083–1103.

[3] Onwumechili, C. A. (1997).The Equatorial Electrojet. *Gordon and Breach Science publisher*.

[4] Rabiu, A. B., Onwumechili, C. A., Nagarajan, N., and Yumoto, K. (2012) Characteristics of equatorial electrojet over India determined from a thick current shell model, J. Atmos. Sol.-Terr. Phy., 92, 105–115, doi:10.1016/j.jastp.2012.10.014, 2013.

[5] Chapman, S. (1951). Some phenomena of the upper Atmosphere, proceedings of the physical Society of London B, vol. 64, 833-843.

[6] Gouin, P. (1962). Reversal of the Magnetic Daily Variations at Addis Ababa, Nature, 139, 1145–1146, 1962.

[7] Gouin, P. & Mayaud, P. N. (1967). A propos de l'existence possible d'un "Counter Electrojet" aux latitudes, magnetiques equatoriales, Ann. Geophys., 23, 41–47, 1967.

[8] Idowu, A O, Adimula, A I, Ojerheghan G I (2020). Characterization of magnetic field horizontal component inselected stations along the 210 degree MM. *Nigeria Journal of Pure and Applied Physics, 10* (1), 16-19.

[9] Tuo, Z., Doumbia, V., Coisson, P., & etal. (2020). variations of the peak positions in the longitudinal profile of noontime equatorial electrojet. *Earth Planets Space , 72*, 174.

[10] Mungufeni, P., Habarulema, J. B., Orue, Y. M., & Jurua, E. (2018). Statistical Analysis of the correlation between the equatorial elecrojet and the occurrence of the equatorial ionization anomaly over the East African sector. *Annales Geophysicae , 36* (3), 841-853.

[11] Rabiu, A. B., Yumoto, K., Falayi, E. O., Bello, O. R., & MAGDAS/CPNGroup. (2011). Ionosphere over Africa: Results from geomagnetic field measurements during international Heliophysical Year IHY. *Journal of Sun and Geosphere , 6*, 61-64.

[12] Akpaneno, A. F. and Adimula, I. A. (2015). Variability of H component of the Geomagnetic Field from some equatorial electrojet stations. Sun and Geosphere 10: 65-77.

[13] Yizengaw, E., Moldwin, M. B., Zesta, E., Biouele, C. M., Damtie, B., Mebrahtu, A., et al. (2014). The longitudinal variability of equatorial electrojet and vertical drift velocity in the African and American sectors. *Annales Geophysicae , 32*, 231-238.

[14] Okeke, F. N., Onwumechili, C. A., & Rabiu, B. A. (1998). Day-to-day variability of geomagnetic hourly amplitudes at low latitudes. *Geophysicae Journal Internationale* , 484-500.

[15] Bolaji, O. S., Oyeyemi, E. O., Fagundes, P. R., deAbreu, A. J., deJesus, R., Rabiu, A. B., and Yoshikawa, A. (2014). Counter Electrojet Events using Ilorin Observations during a Low Solar Activity Period, The African Review of Physics, 9, 361–376, 2014.

[16] Rabiu, A. B., Folarin, O. O., Uozumi, N. S. A., Hamid, T. and Yoshikawa, A. (2017). Longitudinal variation of equatorial electrojet and the occurrence of its counter electrojet. Ann. Geophys., 35, 535–545, 2017. doi:10.5194/angeo-35-535-2017.