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Article in *Advances in Space Research* · December 2022

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Validation of equatorial electrojet derived from Swarm observations using ground based magnetometers

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Received 4 August 2022; received in revised form 26 November 2022; accepted 1 December 2022

Abstract

This paper presents the analysis of the Equatorial electrojet (EEJ_S) and Counter equatorial electrojet (CEJ_S) at quiet times ($K_p \leq 3$) deduced from the absolute scalar magnetometers (ASM) of the Swarm satellites. The EEJ_S and CEJ_S were compared with their corresponding values, EEJ_G and CEJ_G respectively, from ground magnetometers in the South American, West African, and Asian sectors during the years 2014–2018. The results show that EEJ_S highly correlated with EEJ_G, over South American, West African and Asian sectors with correlation coefficients of 0.91, 0.77 and 0.92 respectively. CEJ_S with CEJ_G also showed a reasonably good correlation of 0.78, 0.98 and 0.83 over South American, West African and Asian sectors respectively. For the first time, the Swarm observations of CEJ and EEJ are validated against CEJ and EEJ from ground magnetometers, over South America, West Africa and Asia. Both the occurrence rates of CEJ_S and CEJ_G show similar diurnal and seasonal trends, with the highest occurrence rates in the morning (7:00–9:00 LT) and evening (15:00–19:00 LT) times and the lowest occurrence rates around noon (11:00 to 12:00 LT) time. The seasonal occurrence rates of CEJ_S and CEJ_G were high in the solstice months and the lowest rates were during equinox months for all the sectors. The longitudinal variability of CEJ_S and CEJ_G show highest occurrence rates in the West African sector and the lowest occurrence rates in the Asian sector. This longitudinal variability of CEJ_S and CEJ_G occurrence rates were attributed to the effect of the non-migrating tides, migrating tides and stationary planetary waves. The annual occurrence rates of CEJ_S and CEJ_G seemed anti-correlated with F10.7. © 2022 COSPAR. Published by Elsevier B.V. All rights reserved.

Keywords: Low latitude ionosphere; Equatorial electrojet; Counter electrojet

1. Introduction

The low latitude ionosphere is the region between $\pm 30^\circ$ of the geomagnetic equator where geomagnetic field lines are nearly horizontal to the Earth's surface (Beer, 1973). In this region, an intense eastward current flows. Chapman (1951) named this current the Equatorial electrojet (EEJ). The EEJ is a band of non-uniform intense current flowing in the ionospheric E region at an altitude of

about 106–110 km. This current is within a latitude strip of about $\pm 3^\circ$ from the geomagnetic equator and is usually eastward during daytime (Reddy, 1981; Rabiou et al., 2013). The primary driver of EEJ is the zonal eastward electric field. This electric field is created by the dynamo action in the ionospheric E region, where the thermospheric neutral winds cause the charged particles to move across the magnetic field lines, resulting in an eastward electric field. This zonal eastward electric field is mutually perpendicular to the northward geomagnetic field lines, leading to an upward movement of plasma, called the $E \times B$ drift (Anderson et al., 2004). Less conducting layers

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are set up below and above the E-region and the upward drift polarizes the ionospheric E-region, producing a vertical polarization electric field (Onwumechili, 1997). The result of this polarization electric field is a large flow of an eastward Hall current, which combines with the primary Pedersen current to give an enhanced effective Cowling conductivity (Cowling, 1932). This enhanced Cowling conductivity near the magnetic equator leads to EEJ. The EEJ manifests as strong enhancements of the measured daily variation of the horizontal component (H) of the geomagnetic field (Anderson et al., 2002).

The EEJ current sometimes reverses direction to westward during the day. This westward flowing current is referred to as the counter electrojet (CEJ)(Gouin, 1967; Gouin, 1962). Different physical mechanisms have been proposed to explain the occurrence of CEJ. The quiet time CEJ is explained in terms of the westward zonal winds, atmospheric gravity waves, lunar tides amplification during stratospheric sudden warming (SSW), vertical upward winds, and quasi-biennial oscillation (Somayajulu et al., 1993; Vineeth et al., 2012b; Sastri and Arora, 1981; Raghavarao and Anandarao, 1980; Chen et al., 1995). However, the CEJ that occur during storm periods are attributed to the westward prompt penetrating electric fields (Kikuchi et al., 2008).

The characteristics of EEJ and CEJ have been studied using ground based magnetometers (e.g. Hutton, 1970; Rastogi, 1974; Marriott et al., 1979; Alex and Mukherjee, 2001; Rabiou et al., 2017). With the launch of the low Earth orbiting (LEO) satellites, there came new opportunities for investigating CEJ and EEJ on a global scale. This started with the scalar magnetic field observations from Polar Orbiting Geophysical Observatory (POGO) (Cain and Sweeney, 1973; Onwumechili and Agu, 1980; Kim and King, 1999) and then later missions of Ørsted (Ivers et al., 2003; Vichare and Rajaram, 2011) and Challenging Mini-satellite Payload (CHAMP). The general observation from all these studies is that both EEJ and CEJ depend on local time, season, longitude, moon phase, geomagnetic activity, and solar activity. Lühr et al. (2004) presented a first statistical analysis of EEJ based on CHAMP magnetic field data, which offered a global aspect of several characteristics of EEJ e.g the noon-time EEJ current density profiles exhibited a sharp peak at the dip equator. To obtain a more detailed global representation of EEJ, Alken and Maus (2007) developed a climatological EEJM-2 model of EEJ using the scalar magnetic field measurements from Ørsted, CHAMP, and SAC-C satellites, which estimated the local time, longitudinal and seasonal variation of EEJ. They found that EEJ peak is weaker during solstice than equinox months, and peaks closer to noon time. The same model was later used by Lühr et al. (2008) to estimate the influence of non-migrating DE3 tide on the longitudinal variation of EEJ. A recent detailed overview of the climatological characteristics and tidal features of EEJ and CEJ from

previous studies using CHAMP observations is given in Lühr et al. (2021).

The longitudinal and seasonal variations of EEJ and CEJ have been known to be modulated by both the migrating and non-migrating tides. The EEJ and CEJ tidal characteristics have been studied using observations of CHAMP and Swarm (Lühr et al., 2008; Lühr and Manoj, 2013; Zhou et al., 2016; Zhou et al., 2018; Soares et al., 2018). They revealed that the eastward non-migrating tide with zonal wave-number 3 called the DE3 tide, has the strongest influence on the longitudinal and seasonal variation of EEJ and CEJ.

Manoj et al. (2006) estimated the longitudinal and latitudinal correlation lengths of EEJ from CHAMP and ground based observations. They showed that the concurrent observations of the EEJ from ground and CHAMP observations are consistent when the satellite is passing over the station and the correlation coefficient drops when measurements are compared from sites further than 15° longitude. Recently, Habarulema et al. (2019) analysed the statistics of CEJ occurrences using both C/NOFS observations and ground-based magnetometer over the American and African sectors. The study reported that, C/NOFS observed more CEJ events than the ground magnetometers by average of about 20% and 40% over the American and African sectors, respectively. They attributed this observation to the altitude differences at which these observations were made. The CEJ derived from the ground magnetometers represents a current in the ionospheric E region (90–110 km), while the vertical $E \times B$ drifts from the C/NOFS satellite was estimated within an altitude range of 400–550 km. The study utilized the negative $E \times B$ vertical drifts measured as the ion plasma drifts from the Ion Velocity Meter (IVM), as a proxy for the C/NOFS observed CEJ. The Swarm satellites contain the absolute scalar magnetometer (ASM), from which EEJ and CEJ can be directly obtained. Additionally, the C/NOFS satellite had an elliptical low orbit, in contrast to the Swarm satellites which have a circular polar orbit (Friis-Christensen et al., 2006). The Swarm satellites can therefore be used to capture more longitudinal features of EEJ and CEJ.

The purpose of this paper is to validate EEJ and CEJ derived from the ASM on board the Swarm satellites against the corresponding values of EEJ and CEJ, from the ground based magnetometer measurements. This study also characterized EEJ and CEJ according to local time, longitude, seasons, and solar flux levels. Such analysis will promote the usage of EEJ derived from the ASM and aid the understanding of the electrodynamics phenomena especially in regions such as the African sector with scarce instruments to monitor these phenomena.

The rest of this paper is organized as follows: the data and methods used in this study are described in Section 2, the results are presented and discussed in Section 3; and Section 4 summarise the findings of this study.

2. Data and methods

2.1. Data

2.1.1. The ground based magnetometer data

Quiet time ($K_p \leq 3$) magnetic data from ground based magnetometers in the West African, Asian and South American sectors were used in this study. The study covers the years 2014–2018, when the ground based magnetometers in all the selected sectors had data available. The two ground based magnetometers used over West Africa and Asia are operated by the African Meridian and B-Field Education Research (AMBER) network (Yizengaw and Moldwin, 2009). For the South American sector, the two magnetometers used form part of the Low-Latitude Ionospheric Sensor Network (LISN) project (Valladares and Chau, 2012). The data from both the AMBER and LISN networks are readily available at <http://magnetometers.bc.edu> and <http://lisn.igp.gob.pe/data/>, respectively. Table 1 shows the locations of the magnetometers from which data used in this study were obtained.

2.1.2. The Swarm satellites observations of EEJ and CEJ

The Swarm satellites were deployed by the European Space Agency (ESA) as a multi-satellite mission, consisting of three identical satellites, Alpha (Swarm-A), Bravo (Swarm-B) and Charlie (Swarm-C) (Friis-Christensen et al., 2006). Each space craft carries two magnetometers (ASM and Vector Field magnetometer (VFM)) on board. The ASM measures the strength of the magnetic field, while the VFM measures both the strength and direction of the magnetic field. In this study, the magnetic data set utilized is the Level 2 daily magnetic data products for all the three Swarm satellites. The magnetic data of the Swarm satellites can be obtained from <ftp://swarm-diso.esa.int/>.

2.2. Methods

2.2.1. Ground based magnetometer EEJ and CEJ identification

This study focused on geomagnetically quiet days. A day was considered to be quiet when for all the 3 h K_p values were ≤ 3 . The two ground based magnetometers in each sector were used to compute the EEJ using a standard method of differencing by Anderson et al. (2002, 2004), and has also been used in other studies (e.g. Yizengaw et al., 2014; Mungufeni et al., 2018; Habarulema et al., 2019). The difference in the horizontal component of the geomagnetic field ΔH was obtained by subtracting the magnitude of the H component of the geomagnetic field measured by the ground based magnetometer that is $6-9^\circ$ away from the geomagnetic equator ($H_{\text{offequator}}$), from that recorded by the magnetometer at the geomagnetic equator (H_{equator}), expressed as;

$$\Delta H = H_{\text{equator}} - H_{\text{off equator}} \quad (1)$$

Table 1

The coordinates of the ground based magnetometer used in this study.

Station name/ Country	Code	Coordinates		
		Geog Lat (°)	Geog Long (°)	Mag Lat (°)
Abuja, Nigeria	ABJA	10.5	7.6	−0.6
Yaounde, Cameroon	CRMN	3.9	11.5	−5.3
Phuket, Thailand	PUKT	7.9	98.4	−0.6
Bangkok, Thailand	BANG	14.1	100.6	6.2
Jicamarca, Peru	JICA	−11.8	−77.2	0.8
Piura, Peru	PIUR	−5.2	−80.6	6.8

The subtraction was to filter out contributions from the mid-latitude Solar quiet (Sq) currents (Anderson et al., 2004). Before differencing, to cater for the different offset of the different magnetometers, the nighttime baseline value were first removed from the H component. The baseline value for each day was obtained by averaging the H component of the geomagnetic field at a particular station from 23:00–3:00 LT. Contributions from the ring currents were considered to be insignificant since only data for quiet time was used in this analysis. The difference ΔH of the geomagnetic field was used as a measure of EEJ_G when positive and CEJ_G when negative. Subscript G is to distinguish the ground based measurements of EEJ and CEJ from the space based observations. Therefore, the Swarm measurements of EEJ and CEJ will be denoted as EEJ_S and CEJ_S , respectively.

2.2.2. Swarm satellites EEJ_S and CEJ_S identification

The Swarm satellites Level 2 daily magnetic data products utilized in this study that contains the Swarm satellite derived EEJ_S , were extracted from the Level 1b scalar magnetic data measured by the ASM at a frequency of 1 Hz. The procedure of extracting EEJ_S from the Level 1b magnetic data is discussed in Alken et al. (2015). The magnetic signal obtained is usually inverted to a height integrated current density, for an estimate of the current density producing it. This is done based on a current model of line currents. This model represents the geomagnetically eastward flowing EEJ current which peaks in the E-region at about 110 km altitude (Heelis, 2004). The linear currents flow along lines of constant quasi dipole latitude spaced 0.5° apart. Each of the linear currents are divided into 360 segments, where each segment is a straight line current spanning 1° of geographic longitude, and the endpoints of each segment are located at 110 km altitude.

The strength of the current profile in the vicinity of the geomagnetic equator was taken to be the estimate of EEJ_S , and this is the primary output of the Level 2 product. The negative value of the derived EEJ_S profile at the geomagnetic equator was taken to be CEJ_S . To filter out other contributions from the ring current, the Swarm satellites' derived EEJ_S and CEJ_S profiles for geomagnetically quiet days were considered. For direct comparison of the Swarm

satellites' derived EEJ_S and CEJ_S with EEJ_G and CEJ_G respectively from ground based magnetometers, it was necessary to limit the latitudinal coverage of the Swarm satellites data to remain within the EEJ band. Therefore a latitude range from -4° to 4° of the geomagnetic latitude and a longitude range from -5° to 5° centered at the geographic longitude of each pair of ground based magnetometer stations used, in each sector. Manoj et al. (2006) showed that the EEJ strength can be detected on the ground only within a latitudinal range of -4° to 4° from the dip equator. The same study also revealed that the correlation coefficient between EEJ derived from ground based magnetometers and CHAMP observations deteriorated beyond 20° longitude bin. Habarulema et al. (2018, 2019) used a similar geomagnetic latitude range. Since EEJ is a daytime phenomena, the Swarm satellites' passes were limited from 7:00 to 19:00 LT.

3. Results and discussion

3.1. EEJ_S and CEJ_S events from the Swarm satellites and EEJ_G and CEJ_G from ground based magnetometers

The LEO satellites provide a good opportunity for studying the spatial variation of EEJ and CEJ since they provide a global spatial coverage. However from an observational point of view, magnetic field measurements are done at some distance from the EEJ current. Therefore it is useful to compare ground and satellite based observations of EEJ. Fig. 1 shows EEJ_S and CEJ_S events from the Swarm satellites and EEJ_G and CEJ_G from the ground based magnetometers for a sample of selected days over the West African, South American and Asian sectors. In Fig. 1 (a) and (e) the Swarm satellites' derived EEJ_S as expected, peaks at the geomagnetic equator. The EEJ_S and EEJ_G are both positive, signifying an eastward EEJ current over West Africa (Fig. 1)) and Asia (Fig. 1(e) and (f)). The CEJ_G and CEJ_S are both negative, implying a westward CEJ event over West Africa (Fig. 1(c) and (d)). From Fig. 1 we observe that, these CEJ and EEJ events from the Swarm observations and ground magnetometers agree reasonably well over the South American, West African and Asian regions. This is because during the inversion of EEJ_S to the height integrated current density, the endpoints of each line segment was estimated to an altitude of 110 km. EEJ_G also flows within the ionospheric E dynamo region (90–110 km). Habarulema et al. (2019) observed some periods when both the C/NOFS satellite and ground magnetometer data agreed in identifying either upward or downward vertical drifts, which is similar to our observation.

3.2. Correlation of EEJ_S and CEJ_S with EEJ_G and CEJ_G

For a more statistical comparison between the Swarm observations and ground based magnetometer measurements, an analysis of the Pearson correlation of the average EEJ_S and CEJ_S within a range of $\pm 4^\circ$ from the dip equator,

with EEJ_G and CEJ_G respectively, was performed over South American, West African and Asian sectors. The correlation analysis was done at times when the Swarm satellites crossed within a geographic longitude range of $\pm 5^\circ$ centered at the geographic longitude of each pair of ground based magnetometer stations used, in each sector. The comparisons of EEJ_S with EEJ_G were done at around noon time (10:00–12:00 LT) while for CEJ_S with CEJ_G were at morning (7:00–9:00 LT) and evening (15:00–19:00 LT) times. Fig. 2 presents scatter plots of the coincident EEJ_S with EEJ_G (red) and CEJ_S with CEJ_G (blue), for the years 2014–2018 over South American, West African and Asian sectors. The red and blue lines show the linear least square fits for EEJ_S with EEJ_G and CEJ_S with CEJ_G , respectively. On each of the panel, the number of the coincidental EEJ and CEJ values, N , are presented together with their correlation coefficients, r . EEJ_S against EEJ_G shows a reasonably good correlation over the South American, West African and Asian regions, with r value of 0.91, 0.77 and 0.92 respectively Fig. 2. CEJ_S against CEJ_G also shows a good correlation over the South American, West African and Asian regions, with r value of 0.78, 0.98 and 0.83 respectively, (Fig. 2(a),(b), and (c)). The high correlation for EEJ_S with EEJ_G and CEJ_S with CEJ_G , signifies that these quantities are related. The coincidental data points of both EEJ_S with EEJ_G and CEJ_S with CEJ_G , that were correlated for each sector, are within the same ionospheric dynamo region, hence resulting into a high r . This high correlation implies that CEJ_S and EEJ_S can be used as a proxy for CEJ_G and EEJ_G respectively, at ground locations which lack magnetometer stations, and which ever ground or space observation data set that is used, gives a similar result, hence justifying the Swarm estimates of CEJ and EEJ.

Manoj et al. (2006) reported a short correlation length in longitude between the CHAMP estimates of EEJ with those from ground based magnetometers and attributed it to the local plasma instabilities in the Cowling channel. The good correlation values of EEJ_S with EEJ_G and CEJ_S with CEJ_G , over South America, West Africa and Asia in Fig. 2, were obtained within a longitude range of $\pm 5^\circ$ centered at the geographic longitude of each pair of ground based magnetometer stations used, in each sector. This therefore suggests that the longitude separation of $\pm 5^\circ$ between the Swarm satellites' passes and geographic longitude of the ground based magnetometers stations is a feasible longitudinal bin for comparison between the Swarm satellites' estimates of CEJ and EEJ with those from ground based magnetometers.

3.3. Longitudinal and Local time variation of CEJ_S , CEJ_G , EEJ_S and EEJ_G

The local time variation of CEJ_S occurrence rates were determined by expressing the number of CEJ_S events in hourly bins as a percentage of the total number of EEJ_S and CEJ_S events in that hour. This same procedure was fol-

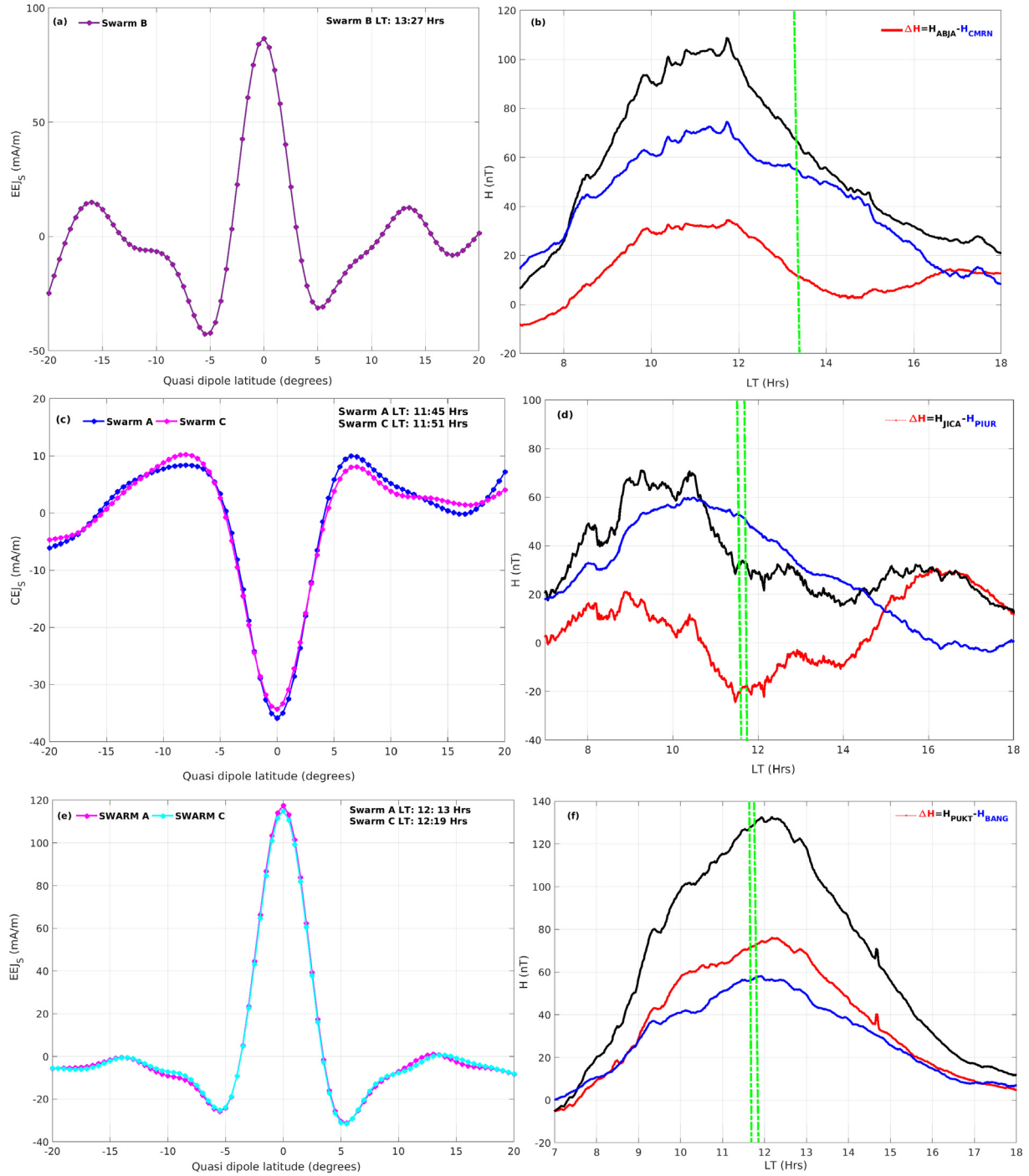


Fig. 1. The panels show (a) EEJ_S event as observed by Swarm B near Abuja pass (7°E) on 9 September 2014, (b) ΔH (red curve) (EEJ_G) from the ground based magnetometers at Abuja (ABJA) and Cameroon (CMRN). (c) Swarm A and C derived CEJ_S event near Jicamarca pass (80°W, 78°W) on 27 November 2016, (d) ΔH (red curve) representing a CEJ_G event from the ground based magnetometers at Jicamarca (JICA) and Piura (PIUR). (e) EEJ_S from Swarm A and C crossings near Phuket (97°E, 98°E) on 25 January 2015. (f) ΔH (red curve) showing EEJ_G from the ground based magnetometers at Phuket (PUKT) and Bangkok (BANG). (b), (d) and (f) daytime variation of H (black and blue curves) for the equator and off equator ground based magnetometer stations respectively. The dashed green vertical lines in panels (b), (d) and (f) represent the times when the Swarm satellites passed near the Abuja, Jicamarca and Phuket magnetometer stations respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

lowed to obtain the local time variation of CEJ_G. The occurrence rates of CEJ_G were the daily counts of CEJ from the ground based magnetometers in each sector. Fig. 3 shows the local time percentage occurrence rates of

CEJ_S and CEJ_G for the years 2014–2018, over the South American, West African and Asian regions. Generally in all the regions, both the Swarm satellites and ground based magnetometer data sets show the highest CEJ_S and CEJ_G

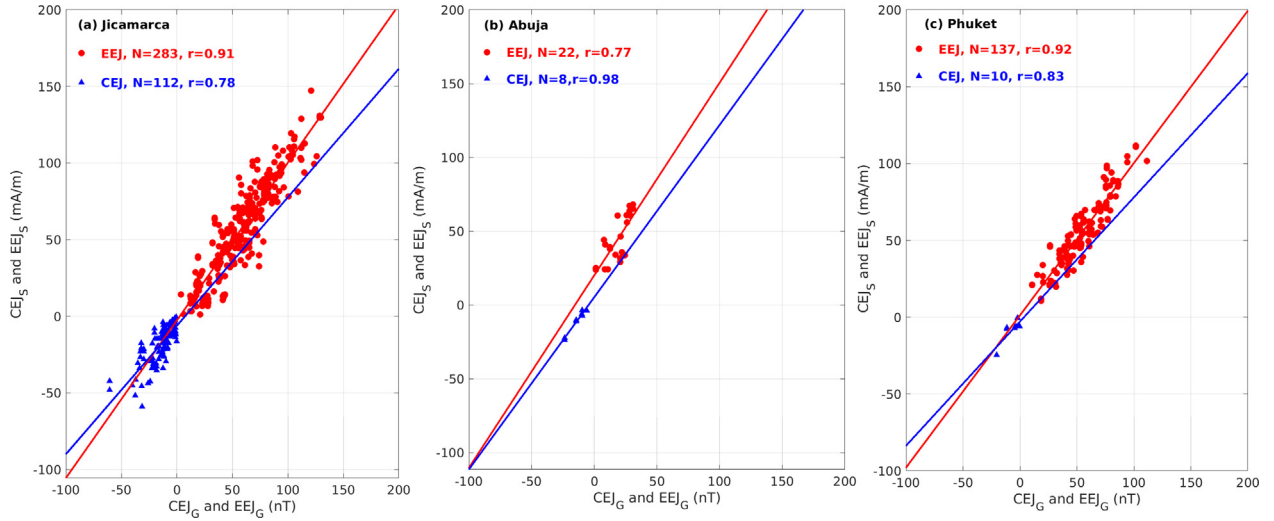


Fig. 2. Scatter plots of Swarm satellites' derived EEJ_S against EEJ_G (red) and CEJ_S against CEJ_G (blue) over (a) South American, (b) West African and (c) Asian sectors, respectively. r is the Pearson correlation coefficient and N is the total number of data points.

occurrence rates in the morning (7:00–9:00 LT) times. The occurrence rates of CEJ_S and CEJ_G in the morning times are more than 38%, 20% and 3% over the West African, South American and Asian sectors, respectively. The second maximum of CEJ_S and CEJ_G occurrence rates are in the evening (15:00–19:00 LT) times. As already mentioned, CEJ occurs when the equatorial dynamo electric fields are reversed to westward. It has been hypothesised that this reversal is possibly caused by the dynamo action of the semi-diurnal tidal wind fields (Alex and Mukherjee, 2001). The predominant contribution of semi-diurnal tidal modes having different magnitudes to the equatorial electric field plays a role in producing the CEJ occurrence patterns in the morning and evening local times over the equator (Marriott et al., 1979; Hanuise et al., 1983; Alex and Mukherjee, 2001). This result is similar to previous finding by Habarulema et al. (2019). They reported that the rate of CEJ occurrence over the American and African regions dominates during morning and evening hours. Zhou et al. (2018) also reported highest CEJ rates from

CHAMP observations with values exceeding 38% from 06:00 to 08:00 LT, and a shallow secondary maximum at 16:00 LT.

There are low CEJ_S and CEJ_G occurrence rates in all the sectors around noon time hours (11:00–1300 LT). The noon time occurrence rates of CEJ_S and CEJ_G are less than 19%, 9% and 2% over Abuja, Jicamarca and Phuket, respectively. Alex and Mukherjee (2001) also reported lowest CEJ occurrence rates at noon time over the Indian and African sectors, and attributed it to the increased eastward electric field and large gradients in ionospheric conductivity at these local times. A similar finding by Zhou et al. (2018) reported CEJ rates of less than 4% at around noon time (11:00 to 12:00 LT) from CHAMP observations.

The West African region exhibits the highest CEJ_S and CEJ_G occurrence rates and the lowest rates are observed in the Asian region. This longitudinal variability of CEJ occurrence rates are caused by non-migrating tides, migrating tides and stationary planetary waves from the stratosphere and troposphere (Vineeth et al., 2012a; Hagan and

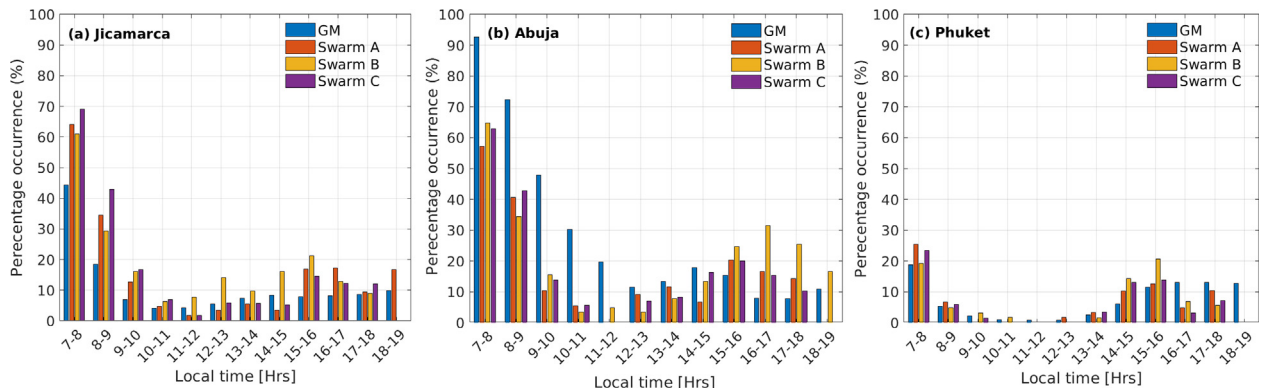


Fig. 3. Percentage occurrence of CEJ_S from the Swarm satellites and CEJ_G from the ground based magnetometers as a function of local time for the years from 2014 to 2018 over the (a) South American, (b) West African and (c) Asian regions, respectively. GM is ground magnetometer.

Forbes, 2002; Rabiou et al., 2017; Zhou et al., 2018). Similar CEJ longitudinal variations have been reported by Rabiou et al. (2017). Additionally, Habarulema et al. (2019) revealed high CEJ occurrence rates (equivalent to downward $E \times B$ drifts) derived from the C/NOFS satellite in the African sector than in the American sector. To understand more about the longitudinal variation of EEJ and CEJ with local time, the EEJ_S and CEJ_S were calculated in bins of $1\text{ hr} \times 5^\circ$ resolution in local time and geographic longitude (Fig. 4). The CEJ amplitudes are greatest in the morning times at about 7:00–8:00 LT, while the EEJ amplitudes are maximum around 10:00–12:00 LT, but can extend to 15:00 LT at 90° W longitude. The four peak structure of EEJ from the Swarm observations at around noontime in Fig. 4, represent the longitudinal wave-4 (WN4) pattern. This WN4 pattern has been observed in the EEJ from the CHAMP observations by Lühr et al. (2008) and in the E-region Electric field measurements by England et al. (2006). The dominant non-migrating DE3 tide combined with other non-migrating tides lead to this WN4 structure (Lühr and Manoj, 2013). The DE3 tide is primarily caused by the deep convection in the tropical troposphere (Lühr et al., 2008), and propagates vertically upwards from its source, transferring its energy and momentum into the E-region ionosphere before being dissipated (Hagan and Forbes, 2002; Hagan et al., 2007).

3.3.1. Seasonal variation of CEJ_S , CEJ_G , EEJ_S and EEJ_G

To examine the seasonal dependence of CEJ_S and CEJ_G over the South American, West African, and Asian sectors, the CEJ_S and CEJ_G data was categorized into seasons representing March Equinox (March-May), June Solstice (June-August), September Equinox (September-November), and December Solstice (December-February). The results of the CEJ_S and CEJ_G seasonal occurrence rates are shown in Fig. 5(i),(ii), and (iii) over the South American, West African and Asian sectors respectively.

The CEJ_S and CEJ_G occurrence rates are highest in the West African sector (Fig. 5(ii)), however during December

solstices CEJ_S and CEJ_G occurrence rates dominate over South America (Fig. 5(i)(d)). The lowest occurrence rates of CEJ_S and CEJ_G in all the seasons are observed in the Asian sector (Fig. 5(iii)). It is also seen in Fig. 5(i) (a) and (d) over the South American region that CEJ_S and CEJ_G occurrence rates are high near the December solstice and low near the March equinox. The occurrence rates of CEJ_S and CEJ_G are highest in June and December solstices over West Africa and Asia in Fig. 5(ii) (b) and (d) and Fig. 5(iii) (b) and (d), respectively. The lowest CEJ_S and CEJ_G occurrence rates are in March and September equinoxes over the West African and Asian sectors (Fig. 5(ii) (a) and (c) and Fig. 5(iii) (a) and (c)), respectively. Generally in all the sectors, CEJ_S and CEJ_G occurrence rates are highest during solstices months. This result agrees with that of other authors (e.g. Soares et al., 2018; Zhou et al., 2018; Habarulema et al., 2019). For instance Soares et al. (2018) showed that the maximum CEJ occurrence rate peaks around July-August and attributed it to the dominance of the DE3 tides during these months. Habarulema et al. (2019) also reported highest CEJ occurrences from the C/NOFS observations and ground based magnetometers during the winter and summer seasons which agrees with our December and June solstices season analysis.

To have a global picture of the seasonal variation of EEJ_S and CEJ_S amplitudes from the Swarm satellites, the EEJ_S and CEJ_S were calculated in 5° longitude bins for each month. The seasonal and longitudinal variation of the EEJ and CEJ amplitudes are quite evident in Fig. 6(a)-(c). Fig. 6(d) presents EEJ_G and CEJ_G amplitudes from the ground magnetometer at Jicamarca in South America. The greatest EEJ_S and EEJ_G amplitudes are both observed around March-May and August-October months (Fig. 6(a)-(d)). Moreover, the EEJ from the Swarm observations (Fig. 6(a)-(c)) exhibits the longitudinal WN4 pattern during these same months. This pattern is related to DE3 non-migrating tide. Zhou et al. (2016) revealed that there is a mixture of both the WN4 and WN3 patterns during March equinox months and the WN4 pattern maximizes around August months.

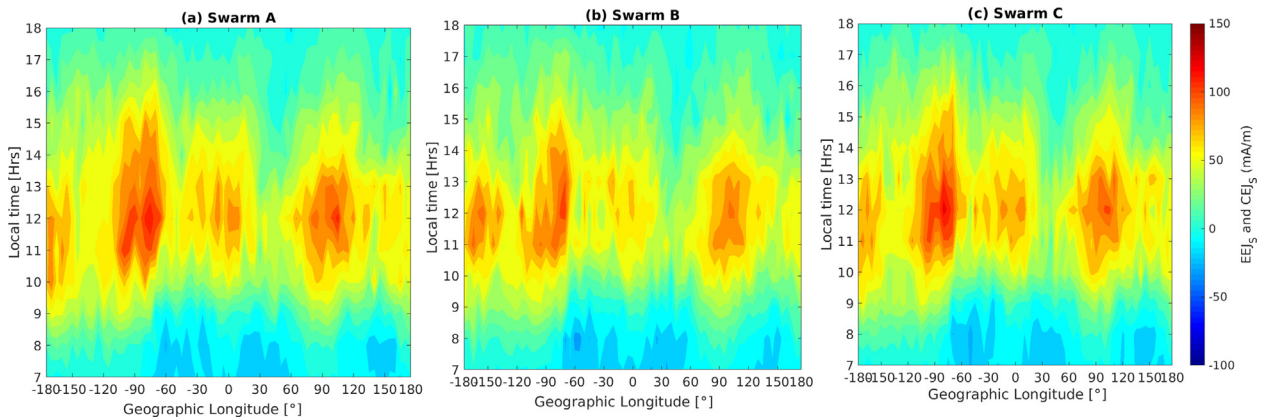
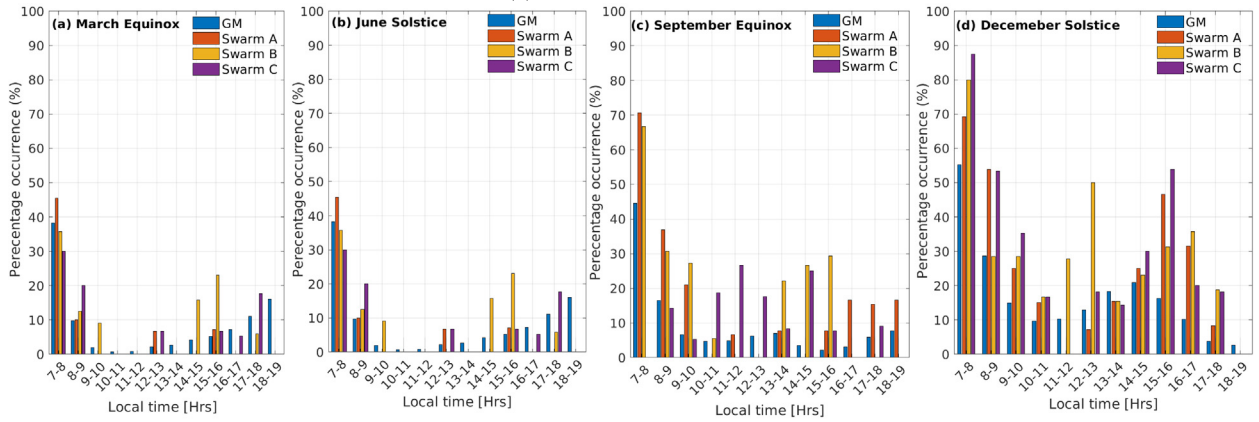
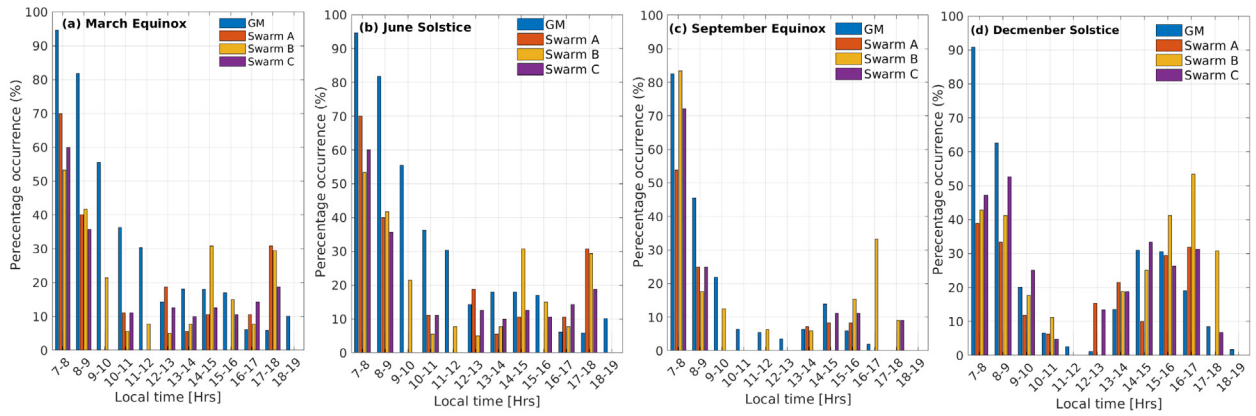


Fig. 4. Local time and longitude variation of EEJ_S and CEJ_S as observed by Swarm A, B and C for the years from 2014 to 2018.

(i) South America



(ii) West Africa



(iii) Asia

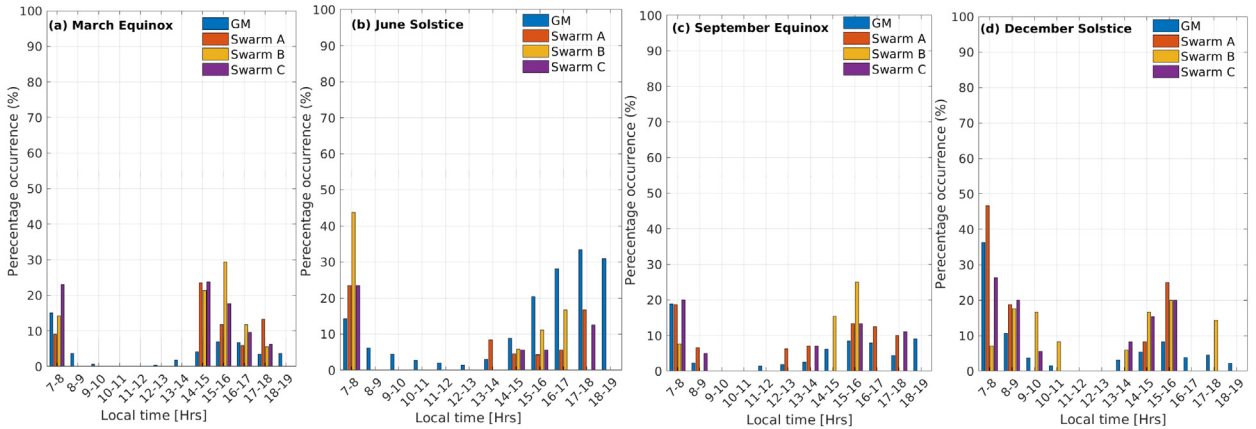


Fig. 5. Percentage occurrence of CEJ_S from the Swarm satellites and CEJ_G ground based magnetometers as a function of local time from 2014 to 2018 over (i) South America, (ii) West Africa, and (iii) Asia. Panels (a)-(d) are for the March equinox, June solstice, September equinox and December solstice, respectively. GM is ground magnetometer.

On the other hand, the CEJ_S amplitudes from the Swarm observations (Fig. 6(a)-(c)) are greatest around June-July months and exhibit the longitudinal WN3 pattern related the diurnal DE2 non-migrating tide. Zhou et al., (2018) reported the prevalence of the WN3 pattern in June. Similar seasonal variations of EEJ and CEJ are

reported by Yizengaw et al. (2014), Yizengaw and Groves (2018), Soares et al. (2018), Vichare and Rajaram (2011). From Fig. 6, we conclude that both the Swarm observations and ground based magnetometer at Jicamarca reveal that months with strong EEJ have weak CEJ.

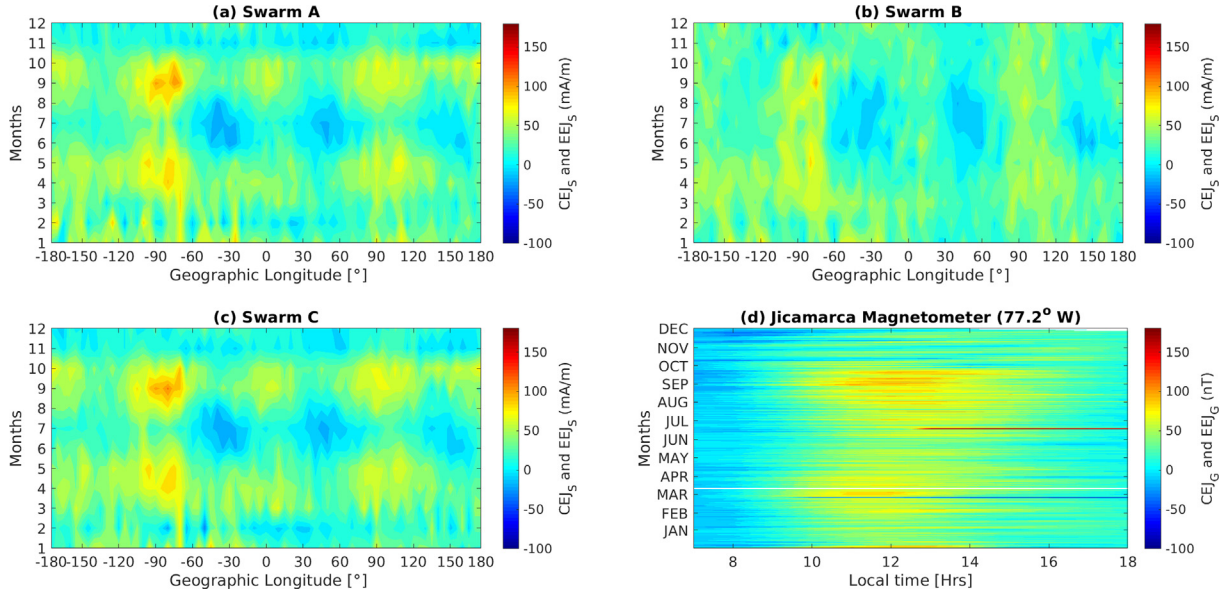


Fig. 6. The panels show: (a)-(c) Months and longitude variations of EEJ_S and CEJ_S amplitudes from the Swarm satellites. (d) Months and local time variation of EEJ_G and CEJ_G from the ground Jicamarca magnetometer.

3.4. Solar activity variation of CEJ_S and CEJ_G

Many of the ionospheric parameters for instance, ionospheric irregularities, and total electron content (TEC), depend on the solar activity. Fig. 7 presents the dependence of the annual occurrence rates of CEJ_S and CEJ_G on solar activity over South America, West Africa and Asia for the years 2014–2018. The annual occurrence rates of CEJ_S were obtained by taking the number of CEJ_S within yearly bins, expressed as percentage of the total number of CEJ_S and EEJ_S events within a year. The determination of the annual occurrence rates of CEJ_G followed the same steps. These annual occurrence rates were then compared with the annual mean

of solar activity measured by F10.7. The annual occurrence rates of CEJ_S and CEJ_G presented are the values for the months of June, July and August during 7:00–11:00 LT. It is easily seen from Fig. 7, that the annual occurrence rates of CEJ_S and CEJ_G increase for the years 2014–2018, while the F10.7 annual mean decreases during those same years. This result could be attributed to the unclear dependence of the winds that drive the quiet time CEJ with solar activity (Zhou et al., 2018). We therefore conclude from this observation that the annual occurrence rates of CEJ_S and CEJ_G are negatively correlated with the F10.7 annual mean. Soares et al. (2018) reported a similar result over the South American region.

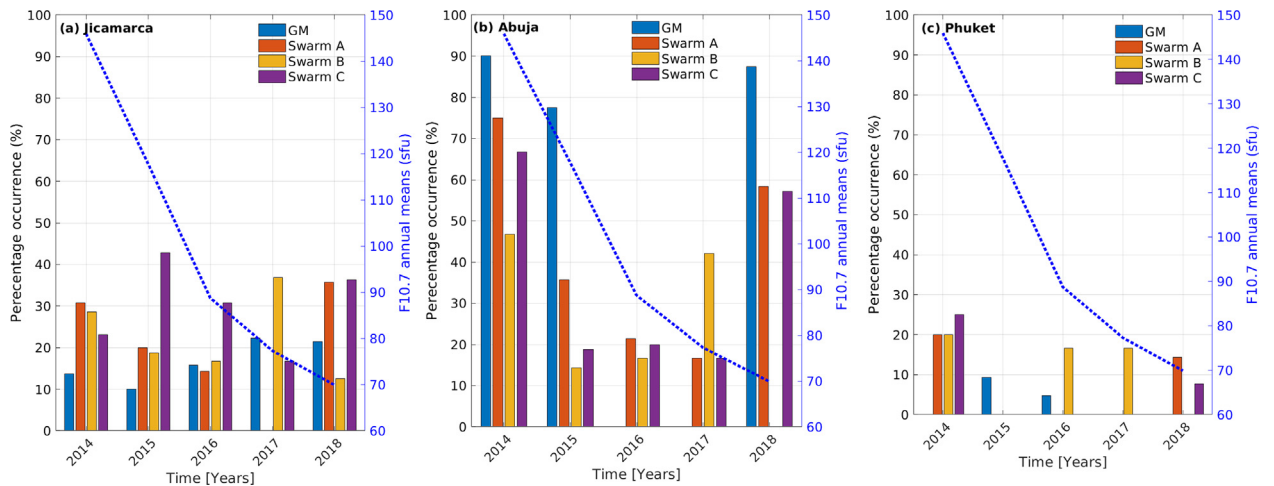


Fig. 7. Annual occurrence rates of CEJ_S from the Swarm satellites and CEJ_G from the ground based magnetometers over (a) Jicamarca, (b) Abuja and (c) Phuket. The dashed blue line shows the F10.7 annual means. GM is ground magnetometer. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Conclusion

In this study, we have compared EEJ_S and CEJ_S from the Swarm observations with CEJ_G and EEJ_G from ground based magnetometers over South American, West African and Asian sectors over a period of 5 years (2014–2018). Satellite observed CEJ_S and EEJ_S were correlated with ground magnetometer CEJ_G and EEJ_G , respectively over South American, West African and Asian sectors. The correlation of EEJ_S with EEJ_G showed a good positive coefficient of 0.91, 0.77 and 0.92, over South American, West African and Asian sectors respectively. CEJ_S against CEJ_G also showed reasonably good correlation with r value of 0.78, 0.98 and 0.83 over South American, West African and Asian sectors respectively. EEJ_S , EEJ_G , CEJ_G and CEJ_S were characterized depending on local time, season and solar activity. We found that both the occurrence rates of CEJ_S and CEJ_G show similar diurnal and seasonal trends, with the highest occurrence rates in the morning (7:00–9:00 LT) and evening (15:00–19:00 LT) times. The lowest CEJ occurrence rates were observed around noon (11:00 to 12:00 LT) time for all the sectors. The highest CEJ_S and CEJ_G occurrence rates were in the West African sector and the lowest rates in the Asian sector. The seasonal occurrence rates of CEJ_S and CEJ_G were high in the solstice months and the lowest rates during equinox months. The greatest amplitudes of the EEJ_S and EEJ_G were observed in the equinox months and least amplitudes in the solstice months. Both the annual CEJ_S and CEJ_G occurrence rates were negatively correlated with solar activity.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the Swedish International Development Agency (SIDA) through the International Science Program (ISP) of the Uppsala University, Sweden. We are thankful to ESA for providing the Swarm data, which is available at <ftp://swarm-diso.esa.int/>. The ground magnetometer data from AMBER and LISN networks were downloaded from <http://magnetometers.bc.edu> and <http://lisn.igp.gob.pe/data/>, respectively. The K_p index and F10.7 data used in this study were obtained from <https://omniweb.gsfc.nasa.gov/>.

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