赤道ジェット電流の変化と$S\sigma$電流系との関係

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VARIABILITY OF EEJ AND
ITS RELATION TO Sq

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(赤道ジェット電流の変化とSq電流系との関係)

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平成 26 年
VARIABILITY OF EEJ AND
ITS RELATION TO Sq

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SUBMITTED
BY
NURUL SHAZANA BINTI ABDUL HAMID
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Abstract

The equatorial electrojet (EEJ) is a strong eastward ionospheric current flowing in a narrow band along dip equator. This study discusses the variability of EEJ as well as its relation to the global Sq current at dip equator. Both current components are calculated from EUEL index which is constructed from northward component of ground based magnetometer data. Study of EEJ dependence on solar activity shows an approximate 24-day and 28-day periodicities in the EEJ component, which are in phase with the F10.7 variations. As for the seasonal dependence, the EEJ component shows prominent semiannual variation, with maxima around equinoxes and minima around June solstice. Longitudinal variation of EEJ is discussed as well, where EEJ is shown to be strongest in South America and weakest in Indian sector. The relation between EEJ and Sq at dip equator is examined using latitude normalized data. A low positive correlation between EEJ and Sq is obtained in Southeast Asian sector, while a low negative correlation is revealed in South American and Indian sectors. Furthermore, their relationship is found to be independent of hemispheric configuration of stations used to calculate their magnetic perturbation, and also change little during low and moderate solar activity level. Additionally, an empirical model of EEJ is developed based on simultaneous data from 6 stations pairs in South American, East and West African, Indian and East and West Southeast Asian sectors. Two main functions being considered are local time and longitudinal dependence of EEJ. Patterns of measured and modeled EEJ variations are found to be quiet similar with difference in magnitudes within 15 nT. Misfits are observed in East African and Indian sectors and high day to day variation of EEJ could be the cause.
Dedication

I dedicate this dissertation to my family, especially to…

Muhammad Nazuan Zulkifli
Aqeela Muhammad Nazuan
Hjh. Hazizah Aripin
Hj. Abdul Hamid Abdullah
Hjh. Noorhayati Ahmad
Hj. Zulkifli Abdul Rahman

and to my late grandmother,

Hjh. Fatimah Kantan

who passed away in 1999 at age 68.
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Nurul Shazana Abdul Hamid
Kyushu University
2014
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Chapter 1

Introduction

1.1 Equatorial Electrojet and Sq Current

The equatorial electrojet (EEJ) current has always been conceived as a phenomenon confined to narrow area around ±3° of dip equator. This current, which is often described as "a ribbon of intense electric current", is flowing eastward in the dayside of equatorial $E$ region of about 600 km wide and within 90 to 130 km altitude. The primary reason for this intense current density is the geomagnetic field geometry, which exhibits exactly horizontal lines of force at these latitudes. Solar-quiet (Sq) on the other hand is a global current system consists of two large vortices of electric currents in the dayside ionosphere, one in each hemisphere, counter-clockwise in the Northern hemisphere, and clockwise in the Southern hemisphere. This current is driven by solar EUV radiation, which not only produces the ionization in the $E$ region but also heats the atmosphere and causes the wind. Both current overlap at
dip equator to give total current and greatly affect the geomagnetic data measured around there.

The effects of EEJ was first discovery in 1922 at the Huancayo equatorial geomagnetic observatory established by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington in Peru. Its effect is noticed from the variations with abnormally large amplitudes in the horizontal components of the magnetic field. Study by Chapman [1951] has suggested that the intense current flowing eastward in a narrow band along dip equator is responsible for this anomaly and named it as “electrojet”. Since then, there have been many studies investigating the EEJ from ground based geomagnetic observations [Forbes, 1981], from rockets [Onwumechili, 1992a], and as well as from low-Earth orbiting satellites [Le Mouel et al., 2006]. Among these, ground-based observations track very closely the temporal variations of the EEJ intensity while rocket measurements provide means of in-situ observations of important EEJ parameters like the current density distribution. Low-Earth orbit satellites on the other hand pass very rapidly over the current system. Their measurements thus can be regarded as a snapshot of the spatial structures.

1.2 Classical Theory

Figure 1.1 illustrates the formation of EEJ and Sq at dip equator. An eastward Pedersen current and downward Hall current are produced from the combination of the eastward electric field, $\vec{E}_y$, generated by the global dynamo with the northward magnetic field, $\vec{B}$. Here, the Hall current is less than 25% of the Pedersen current density. This Hall current leads to an accumulation of charges at the edges of dynamo layer. An upward directed polarization electric field, $\vec{E}_H$, is created and
continues to increase in strength until its own Pedersen current compensates the downward Hall current. The magnitude of $\vec{E}_H$ is about 20 times that of $\vec{E}_y$. The field also produces its own Hall current that flows in the eastward direction. The primary Pedersen current, $\vec{j}_P = \sigma_P \vec{E}_y$, is in response to the peak Pedersen conductivity at about 130 km altitude, whereas the secondary Hall current, $\vec{j}_H = \sigma_H \vec{B} \times \vec{E}_H / \vec{B}$, is in response to the peak Hall conductivity near 110 km altitude [Onwumechili, 1997; Prölss, 2004]. This is consistent with rocket observations which showed that the lower current layer peaks at an altitude of 107±2 km and the upper current layer peaks at 136±8 km [Onwumechili, 1992a]. The intense lower current layer, flowing eastward near the equator, is defined as the equatorial electrojet (EEJ), whereas the weak upper current layer is suggested to be part of the global Sq current which flows eastward of the Sq forci (about 35° dip latitude), but westward poleward of the current forci [Onwumechili, 1992b]. Because the lower layer current consists of mainly the secondary Hall current and the upper layer current consists of mainly the primary Pedersen current, the EEJ practically corresponds to $\vec{j}_H$ while Sq at the equator corresponds to $\vec{j}_P$. Both currents overlap at dip equator to give total current

$$\vec{j}_T = \vec{j}_P + \vec{j}_H = \left( \sigma_P + \frac{\sigma_H^2}{\sigma_P} \right) \vec{E}_y = \sigma_C \vec{E}_y$$

where $\sigma_C$ is known as Cowling conductivity [Hirono, 1950; 1952]. The ground magnetometer observations at the station near dip equator are directly influence by $\vec{j}_T$.

There are two schools of thought on the definition of EEJ: one defines the EEJ as the enhanced part ($\vec{j}_H$) of the current at the equator, and the other defines the EEJ as the total current ($\vec{j}_T$) that includes the Sq contribution at dip equator. On the basis of the physics of the equatorial current formation described above, the first
definition is adopted in this study. Details studies of EEJ current have been reported by Forbes [1981], Reddy [1989] and Stening [1995].

As an independent current system, the EEJ has its own return current that differs from those of the global Sq system as illustrates in Figure 1.2. Beyond the flanks of the dip equator at about 3° dip latitude, a downward electric field, \( \vec{E}_L \), dominates and consequently the EEJ current, \( \sigma_H \vec{E}_L \), reverses into westward and grows with increasing dip latitude to peak at about 5.2±0.8°; this is the return current of the EEJ [Onwumechili, 1992b]. The EEJ return current is weak and covers a much greater latitudinal range than the forward current. Beyond 5° dip latitude, the return current gradually decreases until all eastward currents have returned at about 10±3° dip latitude but sometime extending to about 17° or the Sq focus. In all ground based and satellite profiles, the EEJ current is fully returned below the 30° dip latitude. Therefore, the observed ground magnetic field at low latitude is not a result due purely to the Sq current, but is a result due to the combination of the Sq current and the EEJ return current. However, the EEJ return current is much less intense than the global Sq current and therefore the effect of this current on magnetic measurement in low latitude regions is small compared to that of the Sq current.
Figure 1.1 Formation of currents in the equatorial ionosphere.

\[ \vec{j}_p = \sigma_p \vec{E}_y \]

\[ \vec{B} \times \vec{E}_y \]

\[ \vec{j}_H = \sigma_H \vec{B} \times \vec{E}_H / B \]

\[ \vec{j}_T = \vec{j}_p + \vec{j}_H = \left( \sigma_p + \frac{\sigma_H}{\sigma_p} \right) \vec{E}_y \]

Figure 1.2 Illustration of the EEJ and global Sq current system.
1.3 Research Background

Since its discovery, EEJ current has been the subject of many studies. Over the last several decades, extensive experimental and theoretical research has been carried out to study the EEJ in many ways such as its variability including solar activity, seasonal, and longitudinal dependence. Solar activity is known to have a direct solar impact on EEJ and has been widely discussed [Onwumechili, 1997; Rastogi et al., 1994] with most of former studies limiting their analyses to quiet day periods. The existence of seasonal variation in EEJ intensities has also been widely reported in several longitude sectors using both ground based [Doumouya et al., 1998] and satellite measurement [Le Mouel et al., 2006]. On the other hand, previous studies on longitudinal dependence of EEJ tend to focus their analysis in certain sector or area such as Shume et al. [2010] which compared east and west of coast South American sector. A comprehensive study, however, still appears to be lacking in most of these subjects. Another topic that has been pending for several decades is the relation between EEJ and Sq. Several attempts have been made to quantify this relation including early study by Osborne [1964; 1966], but a conclusive result is still not achieved as some study reports a significant correlation [Ogbuehi et al., 1967] while other none [Okeke et al., 1998; Okeke and Hamano, 2000b]. In all studies, some common problems exist such as the lack of long, continuous and simultaneous data from different longitude sectors, difficulty in isolating EEJ from Sq and uncertainties due to latitudinal variation of both current components. Despite previous researches, some characteristics of the EEJ still remain to be investigated as the above problems have led to an open and pending questions such as What is the relation between EEJ and Sq at the dip equator? How does EEJ vary with longitude? All these motivate the current study. The objective of this study is
to provide answers to these questions by using long and continuous data from several longitude sectors with the support of appropriate analysis method.

In Chapter 2, the data used in this study and how the analysis was done are presented. The variability of EEJ and its relation with Sq are presented and discussed in Chapter 3 and 4 respectively. Moreover, an empirical model of EEJ is presents in Chapter 5. Lastly, Chapter 6 presents the summary of findings and the recommended future works.
2.1 Data

2.1.1 Magnetic and Solar Flux Data

The magnetic data used in this study were mainly provided by MAGDAS (MAGnetic Data Acquisition System)/ CPMN (Circum-pan Pacific Magnetometer Network) [Yumoto and Group, 2001]. This network was constructed under MAGDAS project led by the principal investigator (PI), Prof. Kiyohumi Yumoto (1996-2012) of Kyushu University before recently lead by Dr. Akimasa Yoshikawa (2013-present) from the same university. Data from stations in Indian sector were mainly obtained from Indian Institute of Geomagnetism (IIG) while data from Fuqene (FUQ) station in South America were directly requested from the observatory. Other than that, data from Tamanrasset (TAM) in African region were downloaded from International Real-time Magnetic Observatory Network (INTERMAGNET) [Kerridge, 2001] website. Details of all stations that provided data in this study are listed in Table 2.1. The EEJ and Sq currents components used
were calculated from *EUEL* index which is derived from northward *H* component of the magnetic data. The construction of this index will be explain in the next section.

For the analysis of solar activity dependence, the data of 10.7 cm solar radio flux (F10.7) were downloaded from the OMNI database of GSFC/SPDF Web interface at http://omniweb.gsfc.nasa.gov/. This index is a general indicator of solar activity and has often been used as a proxy for solar extreme ultraviolet (EUV) radiation [Huang *et al.*, 2009].
Table 2.1 Geomagnetic and geographic coordinates of stations used in this study.

<table>
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<th>Region</th>
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<th>Geographic</th>
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<tr>
<td></td>
<td>Name</td>
<td>Code</td>
<td>Lat. (°)</td>
</tr>
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<td>ANC</td>
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</tr>
<tr>
<td></td>
<td>Fuquene</td>
<td>FUQ</td>
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<td>ILR</td>
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<td>Tamanrasset</td>
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<td></td>
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<td>AAB</td>
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<td>Nairobi</td>
<td>NAB</td>
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<tr>
<td>India</td>
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<td></td>
<td>Alibag</td>
<td>ABG</td>
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<td>LKW</td>
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<td></td>
<td>Kototabang</td>
<td>KTB</td>
<td>-0.20</td>
</tr>
<tr>
<td></td>
<td>Davao</td>
<td>DAV</td>
<td>7.00</td>
</tr>
<tr>
<td></td>
<td>Muntinlupa</td>
<td>MUT</td>
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2.1.2 EUEL Index

The commonly used method of calculating the EEJ strength involves obtaining the EEJ from the horizontal intensity on quiet days as $\Delta H_{dip \ equator} - \Delta H_{off-dip \ equator}$, where $\Delta H$ is the variation in $H$ from the mean midnight level for that observatory [Manoj et al., 2006; Yacob, 1977]. For this study, we used the EUEL electrojet index proposed by International Center for Space Weather Science and Education (ICSWSE) of Kyushu University [Uozumi et al., 2008]. To construct the EUEL index, the median value of the geomagnetic northward, $H$, component data was first subtracted from the original magnetic data to obtain $ER_S$ for each available equatorial station, $S$. Next, the mean value of $ER_S$ observed at the nightside (LT=18-06) stations along the magnetic equatorial region, defined as $EDst$, is subtracted from the $ER_S$ data of each equatorial station to compute the EUEL index. The $EDst$ (equatorial disturbance in storm time) index has been found to show variations similar to the $Dst$ index. The $EDst$ index represents the global magnetic variation, including disturbances in the equatorial region due to sudden storm commencement, SSC, or Chapman-Ferraro and ring current, and part of disturbances of magnetospheric origin such as substorms and the DP2 effect. For the off-dip equator station, we consider the latitudinal disturbance variation by subtracting $EDst^* \cos(\phi)$, where $\phi$ is the geomagnetic latitude of the station. Thus, the disturbance effects of SSC and ring currents and some disturbances of magnetosphere origin are removed from the EUEL index. The 1-hour resolution of this index is then used to calculate EEJ and Sq currents components.
2.1.3 CM4 Model

This study uses CM4 global current model [Sabaka et al., 2004] to normalize all observations to exactly at dip equator. This model was derived from observatory data as well as data from POGO, Magsat, CHAMP and Orsted satellites missions. Latitudinal profiles of Sq fields were obtained by simulating the CM4 model with the actual solar flux, F10.7 as the controlling parameter. Figure 2.1 illustrates the example of this model output in India sector. The usage of this model will be explained in details in section 3.3.

2.2 Method of Analysis

The ideal way to isolate EEJ and Sq is to have a dense of latitudinal profile of geomagnetic station across the dip equator. In the lack of that, many studies applied the two-station method. This method utilizes two stations located along the same longitude, with one located near dip equator around ±3° dip latitude while the other one outside this region. The magnetic EEJ component was determined as follows. For each station, the hourly EEJ component is calculated as $\Delta EUEL = EUEL_{dip equator} - EUEL_{off-dip equator}$ with the assumption that Sq current component at both stations are the same. Occasionally, the normal EEJ current reverses in the westward direction, a phenomenon called the counter electrojet (CEJ). The CEJ is observed as a depression in the horizontal intensity measured in the equatorial regions. It occurs mainly a few hours after dawn and a few hours before dusk but is rarely observed around local noon. Rastogi and Iyer [1976] showed that the EEJ strength reached its maximum around 11 LT during solar minima and around 12 LT during solar maxima. Thus, by using data around noontime, we limit our analysis to the period in which the EEJ current is strongest and can ignore the morning and evening
effects. The daily EEJ component in this study is obtained by taking the maximum $\Delta EUEL$ value between 09 and 15 LT while Sq component is taken as the maximum $EUEL_{off-dip\ equator}$ during the same time interval. Figure 2.2 illustrates example using Indian data.
Figure 2.1 An example of the CM4 global current model along 77.8° longitude (Indian sector).

Figure 2.2 An example of two station method using the EUEL index data from Tirunelveli (TIR) and Alibag (ABG) stations in Indian sector. EEJ component is given by maximum $\Delta EUEL = EUEL_{TIR} - EUEL_{ABG}$ during 09-15 LT.
3.1 Solar Activity Dependence

3.1.1 Introduction

It is understandable that both Sq and EEJ intensities increase with increasing F10.7. As solar activity increases, the sun emits more UV, EUV, and other ionizing radiation that enhance the air motion through heating and electrical conductivity through ionization in the ionosphere. Consequently, this increases ionospheric currents which produce larger geomagnetic daily variation. This is a well-known feature of the solar activity effect on Sq and EEJ.

Some previous studies have briefly discussed the relation of both currents components to solar activity. Briggs [1984] proposed a clear 27-day periodicity for the Sq fields, which was in phase with the variations of F10.7. The influences of solar activity on the EEJ intensity were discussed by Rastogi et al. [1994] and Onwumechili [1997]. Uozumi et al. [2008] detected the same dominant peak in both the power spectrum of F10.7 and of the H component at a station near the dip equator using the EUEL index. Recently, using the second definition of EEJ (Sq
contribution is included), Yamazaki et al. [2010] demonstrated that EEJ intensity is correlated to F10.7 variations with a sensitivity of 77±12. They defined the EEJ sensitivity to F10.7 as \((b/a) \times 10^4\) using least-square regression in the form of \(EEJ = a + b \times F10.7\). Most former studies on the relation between the EEJ and solar activity have limited their analyses to quiet day periods. In this study, we use EUEL index and since the disturbances in the equatorial region have been removed in this index, we are able to analyze long and continuous data rather than data during selected quiet days. The aim is to clarify the dependence of EEJ components on the solar activity represented by the F10.7 index.

3.1.2 Data and Analysis

Figure 3.1 shows the map of stations at Southeast Asian sector that were used to calculate EEJ in this study. The pair consists of Davao (DAV) station which is located at the dip equator and Muntinlupa (MUT) station which is located outside the EEJ band (off-dip equator). Analysis is performed using data for 2011, a year in which the solar cycle was in an inclining phase.

Figure 3.2 shows the obtained daily EEJ component together with the daily F10.7 used in the analysis. In this figure, the EEJ plot was graphically shifted upward. The F10.7 flux values during the year 2011 are mostly in the range of 80–150 sfu \((1 \text{ sfu}=10^{-22} \text{ Wm}^{-2}\text{Hz}^{-1})\) unlike during high solar activity years which commonly have values between 150 and 200 sfu. The F10.7 values began to increase by the end of the year with a possible periodicity of 27-day solar rotation. This clearly demonstrates that during the study period the solar cycle was in the inclining phase. From these superimposed plots, we can also see that both the F10.7 and EEJ data follow a similar trend.
3.1.3 Result and Discussion

Figure 3.3 shows the power spectrums of daily F10.7 and daily EEJ obtained from the DAV-MUT station pair. Several dominant peaks appear in both spectrums. Two dominant 20- and 28-day peaks appear in the F10.7 power spectrum. On the other hand, peaks appear around 24 and 28 days in the EEJ spectrum and these may correspond to the peaks that appear in the F10.7 spectrum.

To confirm this relation, we conducted a cross-spectrum analysis between daily F10.7 and daily EEJ. Cross-spectrum analysis indicates the relationship between two time series at a certain frequency or period $\Gamma_{xy}(\omega) = Z_x(\omega)Z_y^*(\omega)$ where $Z_x(\omega)$ and $Z_y(\omega)$ denote the Fourier transform of time series $x$ and $y$. Such analysis yields both the coherence spectrum and phase spectrum. The coherence spectrum provides a measure of the stochastic coupling of the two signals within a certain frequency band, $\kappa_{xy}(\omega) = \frac{|\Gamma_{xy}(\omega)|^2}{\Gamma_{xx}(\omega)\Gamma_{yy}(\omega)}$ where $\Gamma_{xx}(\omega)$ and $\Gamma_{yy}(\omega)$ are the power spectrum of the respective signals. Coherence values range from 0 (uncorrelated) to 1 (perfectly correlated). This function can show the frequencies at which two sets of time-series data are coherent or incoherent. The phase spectrum measures the phase shift between the data sets at each frequency as $\Phi_{xy}(\omega) = \tan^{-1}\left(\frac{\text{Im}(\Gamma_{xy}(\omega))}{\text{Re}(\Gamma_{xy}(\omega))}\right)$. The result is shown in Figure 3.4. Similar to power spectrums, peaks appear at approximately 24 and 28 days in the cross spectrum between F10.7 and EEJ. At these peaks, the coherence reaches values of 0.9858 and 0.9993, respectively, with a phase difference of nearly zero.
Figure 3.1 Map of stations used in this study.

Figure 3.2 Daily F10.7 and daily EEJ during the year 2011.
Figure 3.3 Power spectrum of (a) F10.7 and (b) the EEJ component obtained from the DAV-MUT station pair during 2011.

Figure 3.4 (a) Cross-spectrum, (b) coherence, and (c) phase angle between the daily F10.7 and daily EEJ.
We then quantified this relationship by using correlation analysis. In contrast to the coherence function, the correlation coefficient describes both the direction (positive or negative) and degree (strength) of relationship between two signals over a certain time with values varying from -1 to 1. We present the results of both auto- and cross-correlation analyses in Figure 3.5. The temporal day-to-day variations of both auto-correlations of F10.7 (Figure 3.5(a)) and EEJ DAV (Figure 3.5(b)) have a similar pattern. The peak at 20 days at both sides of time lag is present in the F10.7 auto-correlation but not in the EEJ auto-correlation. These peaks correspond to the 20-day peak in the power spectrum of F10.7 that can be seen in Figure 3.3. The cross-correlation between F10.7 and the EEJ is displayed in Figure 3.5(c). The correlation coefficient between F10.7 and the EEJ at zero lag was found to be 0.45, which indicates that EEJ current does not fully correlate with the solar flux data, suggesting that the EEJ strength is influenced by other factors. A closer examination of the EEJ auto-correlation shows 5- to 7-day peaks, which may indicate variations driven by the lower atmosphere. Because the $EDst$ index contains only partial information on magnetosphere origin disturbance, its subtraction from the $EUEL$ index may not fully eliminate the effects of magnetosphere origin disturbance. This may be one of the factors that influences EEJ strength and consequently affects the correlation value obtained.

Our cross-correlation value is quite low compared to value of 0.53 obtained by Yamazaki et al. [2010] using the same dip equator station. One reason for this difference could be the different period used in their study. Yamazaki et al. [2010] used data during almost one solar cycle (1996–2005), whereas we used data only for 2011. Furthermore, they used the second definition of EEJ, which includes the Sq contribution, whereas we excluded the Sq contribution. Our correlation value
between EEJ and F10.7 is slightly higher than the value of 0.40 obtained by Sripathi [2012] using data from the Indian sector during the year 2008. In addition to using data from a different year, the difference could have resulted from the fact that the EEJ magnetic signature is weaker over India than in the Southeast Asian sector [Doumouya et al., 2003].

3.1.4 Conclusion

The solar F10.7 flux and the EEJ current represented by the EUEL index in the Southeast Asian sector during 2011 were found to have a similar trend. Our result confirms that F10.7 and the EEJ have higher coherency at periods of 24 and 28 days. This suggests that the solar flux has a significant impact on the EEJ strength at these time scales. Despite the higher coherence at these periods, the correlation between the two quantities is low, likely due to the low coherence at other periods. The low correlation coefficient between the EEJ and F10.7 variations might indicates the influences of the lower atmosphere on the EEJ strength as well as magnetospheric disturbances. Because the magnetic signature of the EEJ strength is known to have a longitudinal dependence that is strongest in South America, moderate in West Africa, and lowest in Asia, analysis using data from other longitude sectors may provide a different result.
Figure 3.5 Auto-correlation functions of the (a) daily F10.7 and (b) daily EEJ and (c) cross-correlation function between them.
3.2 Seasonal Dependence

3.2.1 Introduction

Onwumechili [1997] has shown the existence of seasonal variation in EEJ intensity, which is highest in equinoxes and lowest in solstice at 11 and 12 LT. The magnetic field component measured at magnetic dip equator station is expected to peak in the equinoxes like the current that gives rise to it. This is in accord with the early study by Chapman and Raja [1965] using ground based magnetic data at Pacific, African and Indian sectors. Similar conclusions have been drawn utilizing networks of ground based observations in the Indian [Rastogi et al., 1994], West African [Doumouya et al., 1998], and Japan [Okeke and Hamano, 2000a] longitude sectors. These seasonal variabilities have also been reported by recent satellite studies by Le Mouel et al. [2006] and Alken and Maus [2007]. Recently, Shume et al. [2010] have shown that EEJ has maximum strength during equinoxes in the west coast of South America but has a prominent maximum during solstice in the east coast, and suggested that the difference in the magnetic declination angle in the equatorial station at each coast could be the cause. In this study, we used EUEL index to examine the pattern of seasonal variation in east and west of Southeast Asian sector. It should be noted that the dip equator station at east part of Southeast Asia was established around early 2008 and a completed one year data are only available for 2011. It is imperative to consider the present study as a preliminary analysis because of the one full year data used.

3.2.2 Data and Analysis

Figure 3.6 shows the map of both east and west stations pairs at Southeast Asian sector that were used to calculate EEJ in this study. The east pair consists of DAV-
MUT stations while on the west side, Langkawi (LKW) is located near dip equator and Kototabang (KTB) is located outside the EEJ band. Analysis is performed using data in 2011. Figure 3.7 presents the *EUEL* index of each station. The *EUEL* index of dip equator station is found to have higher amplitude than *EUEL* index of off dip equator station. Besides, one can observe fairly clear semiannual variation of *EUEL* index of dip equator station.
Figure 3.6 Map of stations used in this study.

Figure 3.7 Hourly *EUEL* index of (a) LKW-KTB at west side and (b) DAV-MUT at east side of Southeast Asia.
3.2.3 Result and Discussion

Daily local EEJ and global Sq component obtained are shown in Figure 3.8(a) and 3.8(b) respectively for LKW-KTB and DAV-MUT pairs. In this figure, daily EEJ and Sq component plot from DAV-MUT pair were graphically shifted upward by 50 nT. A closer scrutiny of these plots shows semiannual variation, prominent in EEJ compared to Sq component. We then applied data smoothing in order to emphasize the low frequency components (longer trends). This is done by calculating the 27 days running mean represented by the thick line behind each daily plot.

One can observe that seasonal variations of the EEJ components are highest in equinoxes and lowest in June solstice (Figure 3.8(a)). This semiannual variation is also found in the global Sq components (Figure 3.8(b)). The mechanisms of this seasonal variation are still not fully understood though it is expected as geometric effect causes semiannual changes of solar ionization and heating of the ionosphere at equatorial latitudes. Alken and Maus [2007] related the strengthening and weakening of EEJ during equinox and solstice respectively to the seasonal shifts of Sq foci demonstrated by Tarpley [1973] in which both northern and southern Sq foci shift equatorward during equinox and poleward during solstice. On the other hand, Onwumechili [1997] suggested the effect of the noontime eastward dynamo electric field, $E_y$, to be the cause as it is shown to be larger in equinox than in summer and winter. Another factor to be considered is the solar heating. Since this depends on the solar zenith angle like the ionization, there is the possibility of semiannual variation in the thermospheric winds. In fact, semiannual variation of the diurnal tidal wind field in the middle atmosphere has been observed from satellite measurements by Burrage et al. [1995].
Closer scrutiny of Figure 3.8(a) will reveal an asymmetry in EEJ semiannual variation with peak at September-October equinox is slightly higher than peak at March-April equinox. Same feature is observed for both east and west stations. Yamazaki et al. [2010] also reported the similar spring-fall asymmetry in the east of Southeast Asia and claim this is as a common feature. The EEJ intensities at both dip equator stations are also found to be slightly higher in the December solstice than June solstice. Since both stations are located in the northern hemisphere, the ionospheric conductivity there should be higher during June solstice (local summer) than December solstice (local winter) and therefore this winter-summer asymmetry should not be due to conductivity. A similar feature has been reported in Indian [Yacob, 1975] and American [Hutton, 1967] sectors. The physical mechanism for both asymmetry however are still not clear.

Additionally, we compared the daily variation of local EEJ and global Sq components. Figure 3.9 presents the plot of ratios of daily EEJ to daily Sq measured from DAV-MUT pair. For most of the available days, result shows that the amplitude of local EEJ component is higher than that of the global Sq component. This is due to the fact that the EEJ current is much more intense than the global part of Sq current along the magnetic equator. Exception on several days is probably a sign that some disturbance of magnetosphere origin effects are left in the EUEL index and affect the EEJ strength. The mean values of the use ratio is shown in Table 3.1.
Figure 3.8 Daily variations of (a) EEJ and (b) Sq components measured from LKW-KTB and DAV-MUT pairs. Thick lines represent 27 days running average.

Figure 3.9 Ratio of EEJ to Sq measured from DAV-MUT pair.
Table 3.1 Ratio of mean EEJ to mean Sq from LKW-KTB and DAV-MUT pairs in 2011.

<table>
<thead>
<tr>
<th>Station pair</th>
<th>LKW-KTB</th>
<th>DAV-MUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio (EEJ/Sq)</td>
<td>1.04</td>
<td>1.26</td>
</tr>
</tbody>
</table>

3.2.4 Conclusion

The continuous data of local EEJ and global Sq magnetic component calculated from EUEL index of two stations pairs at Southeast Asian region during a year of 2011 are found to have semiannual variations. Both EEJ and Sq components show prominent seasonal variation at both east and west Southeast Asia as they are maxima in equinoxes and minima in solstice with spring-fall and winter-summer asymmetry in the EEJ variation.

3.3 Longitudinal Dependence

3.3.1 Introduction

Satellite [Alken and Maus, 2007; Le Mouel et al., 2006] and ground based [Doumouya et al., 2003; Rastogi, 1962; Shume et al., 2010] magnetic field studies have shown that the magnitude of the EEJ varies longitudinally. The shape of EEJ longitudinal profile is one of the outstanding issue in EEJ studies. To date, global maps of EEJ show that this current is stronger in South America and weakest in the Indian sector. The electrojet also varies longitudinally within the South American continent. It is stronger on the west coast compared to the east coast of South America. One also needs to keep in mind that EEJ current varies dramatically with
latitude, within ±6° across the dip equator. This fact gives some uncertainty in the EEJ estimation from ground based data as it is often impossible to locate the station exactly at the dip latitude. So far, this problem was faced by all previous studies using ground observation on this topic. Furthermore, the Sq current at dip equator also differs from that outside this region as Sq current is also known to vary with latitude. Most previous studies directly used Sq measured at off dip-equator station and this will certainly affect the calculated EEJ at dip equator. To overcome these uncertainties, we normalized the observation data to the dip equator using the CM4 model \cite{Sabaka et al., 2004} by estimating peak EEJ and Sq values at dip equator to yield more accurate results.

3.3.2 Data and Analysis

We use long term ground based magnetometer measurements from 6 stations and Figure 3.10 shows the geographic distribution of these stations. The stations are grouped into three pairs, one in the South American sector, one in Indian sector and one in Southeast Asian sector. Analysis is carried out using the maximum \textit{EUEL} index during noontime for days with \textit{Kp}\leq3 during the years of 2005-2011 (see Figure 3.12).

As mentioned above, we normalize the observation at these stations to the dip equator using the CM4 model. The method is similar to the one used in \textit{Manoj et al.} [2006]. Figure 3.11 details an example from TIR-ABG pair in Indian sector. The latitudinal profile of Sq is obtained by fitting polynomial of degree 2 to the CM4 model after the region of ±3° at dip equator was masked. The 6° region across dip equator was masked to avoid the influence of the EEJ. Using this latitudinal profile,
we normalize the observed $EUEL$ at off-dip equator station ($\theta$ dip latitude) to dip equator (0° dip latitude) using the following formula:

$$EUEL(0^\circ) = \frac{CM_4(0^\circ)}{CM_4(\theta^\circ)} EUEL(\theta^\circ).$$

This gives normalized Sq at dip equator. On the other hand, $EUEL$ observed at station near dip equator ($\theta^\circ$ dip latitude) is normalized to dip equator (0° dip latitude) directly using CM4 model profile and the same formula. This gives normalized total current at dip equator. In Figure 3.11, the normalized data at the dip equator are indicated by the diamond symbol. EEJ current is calculated as the difference between the normalized total current at dip equator with normalized Sq at dip equator:

$$EEJ = EUEL_{total}(0^\circ) - EUEL_{Sq}(0^\circ).$$

The same procedure is applied to all stations pairs.
Figure 3.10 Map of stations used in this study.

Figure 3.11 An example of latitudinal profile of Sq field simulated by CM4 model at Indian sector. The black dots indicate $EUEL$ at TIR and ABG. Sq at dip equator is estimated by normalizing $EUEL$ at ABG to the dip equator, while total current at dip equator is estimated by normalizing $EUEL$ at TIR to the dip equator. Normalized data are indicated by open diamonds. EEJ is calculated by subtracting normalized Sq from normalized total current.
Figure 3.12 shows the normalized EEJ and Sq at dip equator calculated from all three stations pairs from 2005 to 2011. Continuous data are obtained from South American (ANC-FUQ pair) and Indian (TIR-ABG pair) sectors with data gap around the end of April to early September 2009 in South America and from January to end of April 2011 in Indian sector. On the other hand, plot of EEJ and normalized Sq from Southeast Asian sector (DAV-MUT pair) shows a lot of data gaps including end of 2005, end of 2006, big gap from May 2008 to middle September 2009, and first six months in 2010. Additionally, we plot the monthly average of both EEJ and Sq for each year as presented in Figure 3.13. Apparently, EEJ is significantly larger than Sq in South American sector but both are comparable in Indian and Southeast Asian sectors. In this section, we compared the intensity of normalized EEJ in these three sectors. The relation between the normalized EEJ and Sq are discussed in section 4.
Figure 3.12 EEJ and Sq calculated from three stations pairs that are (a) ANC and FUQ at South America, (b) TIR and ABG at India, and (c) DAV and MUT at Southeast Asia. Sq is given by the normalized EUEL from off-dip equator station while EEJ is calculated as the difference between normalized total current and Sq at dip equator. The gray lines indicate 27-day centered moving average of the data.
Figure 3.13 Monthly average of EEJ and Sq calculated from three stations pairs that are ANC and FUQ at South America, TIR and ABG at India, and DAV and MUT at Southeast Asia.
3.3.3 Result and Discussion

Figure 3.14 shows the ratio of EEJ in those three longitude sectors. It is evident that EEJ strength at ANC in South America is stronger than the others two sectors as the mean ratio of this station over the others two stations are more than 1 (see Figure 3.14(a) and (b)). Meanwhile EEJ at DAV in Southeast Asia is found to be stronger than EEJ at TIR in Indian sector as shown by the ratio plot and mean value in Figure 3.14(c). We further confirmed this by calculating EEJ yearly and seasonal averages as shown in Figure 3.15. Thus, mean values of EEJ seem to be indeed strongest in South America and weakest in Indian sector.

The longitudinal variation of EEJ found in this study is in agreement with the one reported by Doumouya et al. [2003] which used data from at 4 different longitude sectors. Study by Shume et al. [2010]which isolates EEJ and Sq at the dip equator also agrees with Doumouya et al. [2003] in South American sector, in that EEJ is found to be stronger on the west coast than on the east coast irrespective of solar activity condition. However, it should be noted that Doumouya et al. [2003] did not subtract the contributions of the global Sq from their EEJ magnetic effect due to the absence of dip equator station at certain longitude sectors, and therefore dissimilarity could happen in other longitude sectors. We will compare this result with the one in section 5 where longitudinal variability of EEJ is calculated from simultaneous data from 4 different sectors in order to calculate parameter for EEJ empirical model.
Figure 3.14 Ratio of (a) EEJ at ANC in South America to EEJ at TIR in India, (b) EEJ at ANC in South America to EEJ at DAV in Southeast Asia and (c) EEJ at DAV in Southeast Asia to EEJ at TIR in India.

Figure 3.15 (a) Yearly and (b) seasonally average of EEJ at ANC in South American, TIR in Indian and DAV in Southeast Asian sectors.
So far, the origin of the EEJ longitudinal variation is left unexplained. Among the first study on this topic, Rastogi [1962] has conclude that the strength of EEJ current over the magnetic equator is greater in regions having weaker magnetic field. The inverse correlation between EEJ (with Sq contribution) and the main field (B) has also been pointed out by Doumouya et al. [2003]. Other than that, Onwumechili [1997] has discussed the possible contribution of Joule heating proposed by Deminov et al. [1988] in which they believe that the joule heating increases the drift velocity and therefore the current.

3.3.4 Conclusion

The normalization technique is applied to calculate EEJ from three longitude sectors which are South America, India and Southeast Asia using data with $Kp \leq 3$ from 2005-2011. Normalized EEJ currents calculated in this current study are found to have longitudinal variation similar with the one reported by previous study, that is EEJ is maximum in South America and minimum in India sector. Future investigations are needed to understand the cause of these longitudinal variation.
Chapter 4

EEJ-Sq Relationship

4.1 Introduction

The relationship between EEJ and Sq current has been studied for many years, but until now, an agreement still appears to be lacking on this topic. Some previous studies found a good correlation between them, while others showed none. This conflict results likely from the lack of good continuous data and the difficulty in isolating global Sq and EEJ at dip equator stations. Most studies used two-station method to calculate EEJ as a difference between measurements at dip equator station and that at off-dip equator station, and directly used data from off-dip equator station to represent global Sq contribution at dip equator. In many cases, no significant correlation is obtained [Ogbuehi et al., 1967; Okeke et al., 1998; Okeke and Hamano, 2000b]. On the other hand, studies by Kane [1971] and Yamazaki et al. [2010] which used the total H component at dip equator to represent EEJ (which we refer as total current afterwards) revealed a good correlation with Sq at off-dip equator stations. This controversy might be understood as the correlation coefficient
between two time series $x_1$ and $x_1 + x_2$ will usually be different from that between $x_1$ and $x_2$ [Mann and Schlapp, 1988]. In the present study, we reexamine the EEJ-Sq relationship by using long term ground based magnetometer data from station pairs in three longitude sectors, which is limited in previous studies in this topic. Additionally, we compared the EEJ-Sq relationship with total current-Sq relationship. Possible mechanisms are discussed to explain the results obtained.

4.2 Data and Analysis

As mentioned earlier, data used in this study of EEJ-Sq relationship is the same as the one use in section 3.3. Normalized $EUEL$ from dip equator station and off-dip equator represent normalized total current and normalized Sq at dip equator respectively. EEJ is defined as the difference between these two (see Figure 3.11).

4.3 Result and Discussion

Top panels in Figure 4.1 show scatter plot of EEJ against normalized Sq intensities measured at 3 stations pairs for the whole period study. Box-fitting Least Squares (BLS) is applied and the corresponding linear regression and correlation coefficients are shown in this figure. The slope for the linear fitting is negative in South American and Indian sectors but positive in Southeast Asian sector. However, the scattering is quite large as seen in Figure 4.1. We therefore performed a t-test analysis to examine the significance (with confidence of 95%; $\alpha=0.05$) of both the slope, $\beta$, and the correlation coefficient, $R$. The null hypothesis is $H_0:A=0$ (there are no significant relation and correlation) while the alternative hypothesis is $H_1:A\neq0$ (there are significant relation and correlation) where A in both hypotheses
are $\beta$ and $R$. The $t$- and $p$-value are calculated using the formulas listed in Table 4.1 in order to reject ($|t| > t_{\text{crit}}; p < \alpha$) or accept ($|t| < t_{\text{crit}}; p > \alpha$) the null hypothesis. Figure 4.2 illustrates these rejection and acceptance regions in the $t$-distribution of two-tailed $t$-test. Additionally, we also calculate the confidence interval for each slope. The statistic values obtained are shown in Table 4.2. The $|t|$ values are $> t_{\text{crit}}$ and the $p$ values are $<0.05$ for all $\beta$ and $R$ tested; thus we reject the null hypothesis and conclude that for 95% confidence level, both $\beta$ and $R$ values obtained are significant. Note that all slopes are also proven to be within the 95% confidence interval. We therefore conclude that the EEJ and the $Sq$ at the dip equator are weakly correlated. The weak correlation is positive in Southeast Asian sector, but negative in South American and Indian sectors. The negative relation between EEJ and $Sq$ in those two sectors is unforeseen and could not be explained by the classical theory discussed in Figure 1.1. More detailed studies are required to explain the negative relationship obtained, including study of conductivity and wind at those sectors.

We also examine relation between total current and $Sq$ as illustrate in the bottom panels of Figure 4.1. As expected from the definition of total current itself, this current shows a positive linear relation (slope) with $Sq$ for all longitude sectors. The correlation between total current and $Sq$ is found to be higher than correlation between EEJ and $Sq$ in both Indian and Southeast Asian sectors with $R$ value for total current and $Sq$ is more than 0.5 in Southeast Asian sector. The $t$-test showed that both slopes $\beta$ and correlation coefficients $R$ values obtained are significant and the results are included in Table 4.2. These correlation coefficients are consistent with the fact that $Sq$ component is more significant in the total current for both Southeast Asian and Indian sectors compared to South American sector (see Figure
3.13). Figure 4.1 thus demonstrates how the definition of EEJ affects the conclusion on the EEJ-Sq relationship. In the rest of this section, we use the EEJ defined by the two-station method for further investigation.

The top row of Figure 4.1 shows positive slope and correlation in Southeast Asian sector, which is opposite to other sectors. We notice that stations pairs we use in South American and Indian sectors are located in the north of the dip equator while in Southeast Asia, DAV (dip equator station) is located in the south. We performed analysis using different stations pairs in Southeast Asian sector along 210° chain to investigate whether this northern(N)–southern(S) hemisphere (by referring to dip equator) configuration affects the results obtained. Location of these stations is illustrate in map at the left panel of Figure 4.3. Similar regression analysis is performed by using S–N, N–N, S–S and N–S stations pairs and the results are shown in the same figure. We can see that although there is some difference in the $\beta$ and $R$, the sign remains to be positive in all cases and is independent of the hemispheric configuration. We therefore conclude that the EEJ-Sq relationship in the Southeast Asian sector is indeed different from South American and Indian sectors.
Figure 4.1 Scatter plot of the EEJ versus normalized Sq (top panels) and normalized total current versus normalized Sq (bottom panels) obtained from three station pairs that are ANC and FUQ in South America, TIR and ABG in India, and DAV and MUT in Southeast Asia.
Table 4.1 Formula to calculate confidence interval of slope, \( t \)-value and \( p \)-value.

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<thead>
<tr>
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<th>Confidence Interval</th>
<th>( t )-value</th>
<th>( p )-value</th>
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<tr>
<td><strong>Slope (( \beta ))</strong></td>
<td>( \beta \pm t_{crit} \times SE )</td>
<td>( t = \frac{\beta}{SE} )</td>
<td>( p = 2 \times tcdf(-abs(t), n - 2) ), where ( p &lt; \alpha ) = reject, or ( p &gt; \alpha ) = accept the null hypothesis.</td>
</tr>
<tr>
<td><strong>Correlation Coefficient (( R ))</strong></td>
<td>( t = R \frac{\sqrt{n - 2}}{\sqrt{1 - R^2}} )</td>
<td></td>
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* \( t_{crit} \) is critical \( t \)-value, and SE is standard error of the slope.
* See Appendix A for description of \( tcdf \) function.

Figure 4.2 T-distribution for two-tailed t-test. Rejection regions (with \( \alpha = 0.05 \)) are shown in red.
Table 4.2 Slope, $\beta$ (lower-, upper-confident interval), and correlation coefficient, $R$ and their t-test analysis results including $t$-value, critical $t$-value, $t_{crit}$, and $p$-value.

<table>
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<tr>
<th></th>
<th>South America</th>
<th>India</th>
<th>Southeast Asia</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EEJ-Sq</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$ (lower, upper)</td>
<td>-2.0131 (-2.0162, -2.0101)</td>
<td>-1.4104 (-1.4125, -1.4083)</td>
<td>1.5910 (1.5875, 1.5945)</td>
</tr>
<tr>
<td>$R$</td>
<td>-0.3247</td>
<td>-0.1843</td>
<td>0.1581</td>
</tr>
<tr>
<td><strong>Total current-Sq</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\beta$ (lower, upper)</td>
<td>1.9193 (1.9161, 1.9226)</td>
<td>1.6123 (1.6103, 1.6142)</td>
<td>2.0423 (2.0393, 2.0453)</td>
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<tr>
<td>$R$</td>
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<td>0.4129</td>
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<table>
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<th>South America</th>
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<th>Southeast Asia</th>
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<td><strong>EEJ-Sq</strong></td>
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<tr>
<td>$\beta$</td>
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<td>0.8900×10^3</td>
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<tr>
<td>$t_{crit}$</td>
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<td>1.9614</td>
<td>1.9620</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$R$</td>
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<td>-7.6737</td>
<td>5.4390</td>
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<tr>
<td>$t$</td>
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<tr>
<td>$p$</td>
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<tr>
<td><strong>Total current-Sq</strong></td>
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<td></td>
</tr>
<tr>
<td>$\beta$</td>
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</tr>
<tr>
<td>$R$</td>
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</tr>
<tr>
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<tr>
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<td>2.2637×10^{-5}</td>
<td>0</td>
<td>0</td>
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Figure 4.3 Scatter plot of the EEJ versus normalized Sq obtained from four stations pairs that are DAV-MUT, CEB-MUT, DAV-MND and CEB-MND in Southeast Asia. Left panel illustrates the geographic location of all stations.
We further check EEJ-Sq relationship dependence on solar activity level by analyzing each year data from 2005 to 2011 as presented in Figure 4.4, Figure 4.5 and Figure 4.6 for South American, Indian and Southeast Asian sectors, respectively. In each figure, we present scatter plot of EEJ versus Sq for each year followed by the plot of \( \bar{P}_{10.7} \) parameter, \( R \) and slope values. The value of yearly average \( \bar{P}_{10.7} = 0.5(F10.7 + <F10.7>) \) parameter represents the solar activity level [Richards et al., 1994]. The period used in this study is dominated by low solar activity with the lowest \( \bar{P}_{10.7} \) value is 68.82 (in 2008) and the highest \( \bar{P}_{10.7} \) is 113.84 (in 2011, inclining phase of solar cycle). Note that we also include the scatter plot for the whole data period in the last panel in each figure which is the same as the one appears in Figure 4.1. Results show that \( R \) values are small for all years hence confirms that EEJ and Sq at dip equator are only weakly correlated to each other regardless of the solar activity level. Again, one can see that \( R \) and slope in South American and Indian sectors are negative in contrast to positive values in Southeast Asia. However, we are not sure about the exception in year of 2010 in Southeast Asian sector as the result could not be significant due to the big data gap for the first six months.
Figure 4.4 Scatter plot of the EEJ versus normalized Sq obtained from station pair ANC and FUQ in South American sector for each year from 2005 to 2011. The second last panel shows the plot of slope and correlation coefficient values for each year while the last panel is the scatter plot for the whole 2005-2011 years.
Figure 4.5 Same as Figure 4.4 but for station pair TIR and ABG in Indian sector.
Figure 4.6 Same as Figure 4.4 but for station pair DAV and MUT in Southeast Asian sector.
Some previous studies have also reported a weak correlation between EEJ and Sq. Okeke and Hamano [2000b] have performed analysis using data from three dip equator stations located at South America (-75.2°) and Pacific sectors (-157.5° and 158.33°). They found small correlation coefficient values between EEJ and Sq calculated from 5 quiet days of each month in 1998. Their results are in agreement with work of Okeke et al. [1998] which used data in Indian sector during quiet year of 1986. On the other hand, study by Ogbuehi et al. [1967] showed that correlation coefficient between EEJ and Sq reached -0.6 in December solstice during 1958. By using the different northern-southern stations configuration with dip equator station located at western Pacific Ocean, they concluded that the EEJ tends to be negatively correlated with Sq currents measured from stations equatorward of global Sq current focus. The different results obtained is due to the large longitude separation of the station pairs used in their study, which was quite significant, about 30°, as the north and south off-dip equator stations are located at Vietnam and Papua New Guinea respectively. Furthermore, the latitude separations of off-equator stations are remarkable, 15° and 17° for north and south stations respectively and these certainly affect the calculated EEJ current. In general, the longitude and latitude separations of ground stations used in all previous studies were quite big and therefore their results could not be conclusive. The new technique applied in this study allowed us to overcome these uncertainties and therefore provides more precise results.

Other previous studies which reported high correlation between EEJ and Sq are Kane [1971] and Yamazaki et al. [2010]. However, it should be noted that both studies used the total current instead of the EEJ defined by the two-station method, thus their conclusion is essentially about the total current-Sq relationship. Kane
[1971] has reported a high positive correlation between total current and Sq in equinoxes and winter using Indian data during quiet days in 1964. Yamazaki et al. [2010] also reported a high positive correlation in Southeast Asian sector using quiet days data from 1996 to 2005. The results from these two studies are consistent with our results on the total current-Sq relationship shown in the lower row of Figure 4.1. On the other hand, we have also shown how different the EEJ-Sq relationship is from the total current-Sq relationship, with the later having a generally much higher correlation. The fact that the correlation value between two time series, \( x_1 \) and \( x_2 \), is usually different from that between \( x_1 \) and \( x_1 + x_2 \) can be used to explain the conflict faced by the previous researchers in this area. Therefore, it is apparent that the definition of the EEJ significantly affects the conclusion on the "EEJ-Sq" relation. We have adopted the EEJ obtained using the two-station method for our study.

There are several factors that might contribute to the weak correlation between EEJ and Sq. Rocket measurement by Onwumechili [1992a] showed that EEJ and Sq at dip equator flow at different altitude where the effective conductivities, electric fields and winds are different. This suggests that Sq and EEJ are driven by different drivers, which could naturally result in a weak correlation between the two. Fang et al. [2008] has demonstrated using the TIME-GCM simulation that local wind could significantly affect the EEJ. On the other hand, we know Sq is driven by global wind structure. Thus, we may say that the stronger the local wind, the less correlation between the EEJ and Sq. In addition, some studies have suggested that EEJ has its own circuit whose return paths and intensity variations are different from the global Sq current [Ogbuehi et al., 1967; Onwumechili,
This study has shown the EEJ-Sq relationship varies with longitude. In particular, the Southeast Asian sector shows a positive weak correlation, which is opposite to that in the South American and Indian sectors. Since the declination angle in Southeast Asian sector is similar to that in Indian sector, it cannot be the cause for the difference. Thus, the difference is likely caused by the wind. The archipelagic state of Southeast Asia causes a warm pool there, which drives intense deep convection activity. This consequently generates excessively strong atmospheric waves [Tsuda and Hocke [2004]], some of which can propagate upward to the dynamo regions to disturb the neutral wind there hence the electric field and currents. This meteorological aspect may significantly contribute to the unique EEJ-Sq relationship in this sector. Model simulations should be carried out to confirm it. At the same time, details study is needed to explain the negative relationship obtained in South American and Indian sectors.

4.4 Conclusion

In this section, we have examined the EEJ-Sq relationship at dip equator in three longitude sectors that are South America, India and Southeast Asia for geomagnetically quiet days (Kp≤3) from year 2005 until 2011. The noontime EEJ and Sq currents intensities were derived for each day with consideration of latitudinal variation of both currents. The main results of this study are summarized as following;
1. A weak correlation between the EEJ and the Sq at the dip equator is obtained with a positive value in Southeast Asian and negative values in South American and Indian sectors. The negative relations obtained should be investigated in future studies.

2. These relations are independent of hemispheric configuration of stations used to calculate them and also to change little during low and moderate solar activity levels.

3. These results demonstrate that Southeast Asian sector is indeed different from the Indian and South American sector, indicating unique physical processes particularly related to the electro-dynamo. This aspect should be explored in future studies.

4. Finally, we suggest that in studying their relationship, one needs to isolate the global Sq contribution from the total current at dip equator to obtain the EEJ, as we have shown how different the result could be when using the total current.
Chapter 5

EEJ Empirical Model

5.1 Introduction

There have been previous attempts in constructing EEJ models, both theoretically and empirically. Most theoretical approaches have assumed various current distributions and analyzed the resulting magnetic effects [Chapman, 1951; Fambitakoye and Mayaud, 1976]. On the other hand, the empirical model of Onwumechili and Ezema [1992] is based on POGO satellite data and provide measurement of several important parameters of EEJ such as mean peak current intensity. But it does not offer longitudinal profile of EEJ. This aspect is then considered by Doumouya et al. [2003] in their empirical model based on ground magnetic data recorded at six longitude sectors. They however did not eliminate the Sq contribution to geomagnetic data at dip equator station due to the absence of off-dip equator station. In this study, we used the same method proposed by Doumouya et al. [2003] with some modifications. First, we eliminate Sq contribution at dip
equator by using two-station method. Second, we consider latitudinal variation of Sq and EEJ by normalizing the observation data to the dip equator.

5.2 Data and Analysis

In this study, a simple empirical model is developed using simultaneous normalized data from 12 stations as shown in Figure 5.1. The stations are grouped into six pairs, one in the South American sector, two in African sector (east and west), one in Indian sector and two in Southeast Asian sector (east and west). Details of each station are available in Table 2.1. The simultaneous data are obtained from September 16 to 30, 2009.

The empirical model used in this study is given by:

\[ I(t, \lambda) = I_{11}(\lambda) \exp \left( -\frac{(t - T)^2}{t_m^2} \right) \]

where \( I(t) \) and \( I(\lambda) \) express local time and longitudinal function of EEJ respectively. In this model, \( t_m \) is a fitting parameter that controls the time window of the Gaussian-like shape with the average value is 4 h [Doumouya et al., 2003]. On the other hand, \( T \) is the local hour of maximum EEJ determined from the observation data. Figure 5.2 shows the plot of mean EEJ for each noontime from 09 LT to 15 LT calculated from normalized data of all station pairs. On average, \( T \) is equal to 11 LT as shown in Table 5.1.

In this model, longitudinal function of EEJ, \( I_{11}(\lambda) \), is expressed by a numerical spline function estimated from the peak value of EEJ amplitude. Figure 5.3 shows the mean values of EEJ along the dip equator at six different longitude sectors for local time 09 LT to 15 LT. Solid and dash lines represent linear and spline
interpolations respectively. The EEJ current component is found to be always strongest in South American sector regardless of local time. However the current is weakest in Indian sector during 09 and 10 LT but shifted to African sector during 11 to 14 LT. Based on the local time dependence discussed earlier, the longitudinal profile of EEJ is chosen to be expressed by the numerical spline function fitting the mean EEJ at 11 LT, $EEJ_{11}(\lambda)$, with interval $i$ (about 30°) between 13 control points along the dip equator,

$$EEJ_{11}(\lambda) = a_i(\lambda - \lambda_i)^3 + b_i(\lambda - \lambda_i)^2 + c_i(\lambda - \lambda_i) + d_i$$

The spline coefficient, $a_i$, $b_i$, $c_i$ and $d_i$ and the control points are listed in Appendix B. Figure 5.4 shows this spline function. Also shown is the inverse main intensity field ($1/F$) at dip equator, multiplied by an arbitrary factor $5 \times 10^6$ in order to reach the same amplitude range as EEJ. The longitudinal function of EEJ, $I_{11}(\lambda)$, is then obtained using the following formula:

$$I_{11}(\lambda) = \frac{EEJ_{11}(\lambda)}{0.4\arctan \left(\frac{a}{h}\right)}$$

where $a$ and $h$ are the half width and height of EEJ, adopted as 330km and 105km respectively [Doumouya et al., 1998].
Figure 5.1 Map of stations used in this study.

Figure 5.2 Mean EEJ from 09 LT to 15 LT calculated from all station pairs. Circle symbols indicate the maximum mean EEJ of each pair.
Table 5.1 Maximum local time (LT) where mean EEJ amplitude is the highest (see Figure 5.2).

<table>
<thead>
<tr>
<th>Pair (region)</th>
<th>Local time (LT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANC-FUQ (South America)</td>
<td>11</td>
</tr>
<tr>
<td>ILR-TAM (west African)</td>
<td>10</td>
</tr>
<tr>
<td>AAB-NAB (east African)</td>
<td>10</td>
</tr>
<tr>
<td>TIR-ABG (India)</td>
<td>11</td>
</tr>
<tr>
<td>LKW-KTB (west Southeast Asia)</td>
<td>11</td>
</tr>
<tr>
<td>DAV-MUT (east Southeast Asia)</td>
<td>11</td>
</tr>
</tbody>
</table>
Figure 5.3 Longitude dependence of the magnetic effects of EEJ from 09 LT to 15 LT. Circle symbols represent mean EEJ calculated from normalized observation data. Solid and dash lines represent linear and spline interpolations respectively.

Figure 5.4 The mean longitude dependence of the magnetic component of EEJ at 11 LT and the inverse of the main field (1/F).
The following expression, corresponding to the fourth degree current distribution, is used to compute EEJ magnetic signature in nT:

\[
EEJ(t, \lambda) = 0.2 \frac{I_0}{a^4} [(a^2 - X_s^2)^2 + (2a^2 - 6X_s^2)h^2 + h^4](\arctan R_B - \arctan R_A)
\]

\[
+ 0.2 \frac{I_0}{a^4} [2(a^2 - X_s^2)X_s h + 2X_s^3 h^3][\ln(1 + R_B^2) - \ln(1 + R_A^2)]
\]

\[
+ 0.2 \frac{I_0}{a^4} \frac{h^4}{3} (R_B^3 - R_A^3) - 0.4 \frac{I_0}{a^4} X_s h^3 (R_B^2 - R_A^2)
\]

\[
- 0.2 \frac{I_0}{a^4} [(2a^2 - 6X_s^2)h^2 + h^4](R_B - R_A)
\]

where \(X_s = x_s - c = 0\); \(R_A = \frac{x_s-a}{h}\); \(R_B = \frac{x_s+a}{h}\)

when \(X_s\) is the distance between station located at position \(x_s\) and \(c\) (position of EEJ center) and equal to 0 due to the normalization technique applied. \(I_0\) (current intensity at the EEJ center) is in A/m while \(EEJ\) is in nT. In the empirical model developed, \(I_0\) is represented by the time and longitude varying current intensity, \(I(t, \lambda)\), discussed earlier. The simplified expression is as below;

\[
EEJ(t, \lambda) = 0.4 \frac{I(t, \lambda)}{a^4} \left[ (a^2 + h^2)^2 \arctan \left( \frac{a}{h} \right) + \frac{a^3 h}{3} - 2a^3 h - ah^3 \right]
\]

\[
= 34.8713 \times \frac{EEJ_{11}(\lambda)}{28.94} \exp \left( - \frac{(t - 11)^2}{16} \right)
\]

\[
= 1.205 (\lambda) \exp \left( - \frac{(t - 11)^2}{16} \right)
\]
5.3 Result and Discussion

The comparison between measured and modeled EEJ components between 09 LT to 15 LT for available dip equator stations are presented in Figure 5.5. It can be seen that the patterns of measured and modeled noontime EEJ are quite similar with difference in magnitudes are within 15 nT. There are however case of quite large misfit in Adis Ababa at east African sector and Tirunelveli at Indian sector. We further examine the longitudinal profile of EEJ derived from the model as in Figure 5.6. It can be seen that for each local time from 09 to 15, longitudinal profile of EEJ shows that this current is strongest in South American sector and smallest in African sector, unlike the observation data where EEJ is smallest in Indian sector during 09 and 10 LT but shifted to east African sector during 11 to 14 LT (see Figure 5.3). High day to day variation of EEJ could be the cause of these misfits.

This model is made to improve the empirical model proposed by Doumouya et al. [2003]. Two novel features of this current model are the normalization of observation data to dip equator and the elimination of Sq contribution at dip equator which are limited in most of previous studies. It can be summarized that the empirical model successfully reproduces the EEJ components on a global scale around noontime. More detailed future work is necessary to enhance this model.
Figure 5.5 Comparison between observed (blue dots) and computed (green dots) EEJ during noontime.
Figure 5.6 Longitudinal profile of EEJ derived from the model from 09 to 15 LT.
5.4 Conclusion

An empirical model of EEJ, including local time and longitudinal dependence, has been constructed based on the simultaneous observations recorded from 12 magnetometer stations located in six different longitude sectors. It shows that the EEJ is strongest in South American sector regardless of local time and weakest in Indian sector during 09 and 10 LT but shifted to African sector during 11 to 14 LT. These longitude variations of EEJ roughly follow variations of the inverted main field strength along the dip equator except for in Indian and Southeast Asian sectors. The result showed that the EEJ component derived from the model presented similar pattern with measured EEJ from ground data during noontime with larger discrepancies in east African and India longitudes sectors.
In this study, we presented the variability of equatorial electrojet, EEJ based on ground magnetometer data and checked its relation to the global Sq current at dip equator. Additionally, we constructed an empirical model which includes local time and longitude dependence of EEJ. We summarize the results of this study as the following:

- The normalization technique applied yield more accurate results since it can overcome the uncertainties due to latitudinal variation of EEJ and Sq.
- A weak correlation between the EEJ and the Sq at the dip equator is obtained with a positive value in Southeast Asian and negative values in South American and Indian sectors.
- EEJ-Sq relationship are independent of hemispheric configuration of stations used to calculate them and also to change little during low and moderate solar activity levels.
• EEJ-Sq relationship in Southeast Asian sector is indeed different from the Indian and South American sector, indicating unique physical processes particularly related to the electro-dynamo.

• EEJ varies with longitude, strongest in South America and weakest in India sector during 09 and 10 LT but shifted to African sector during 11 to 14 LT.

• The empirical model successfully reproduces the EEJ components on a global scale during noontime with significant discrepancies in east African and India longitudes sectors.

Finally, we list remaining issues that need further and deeper investigation:

• Analysis of data from other longitude sectors and other type of data is required to explain the physical relationship between EEJ and Sq in more details.

• Usage of average of available data (yearly) to calculate parameter used in the EEJ empirical model instead of limited to simultaneous data from several stations.

• Usage of higher resolution data (example 1- or 5-min) to confirm the local time dependence in the EEJ empirical model.

• Include other terms in the EEJ empirical model such as seasonal dependence.
List of References


Hutton, R. (1967), Sq currents in the American equatorial zone during the IGY—I Seasonal effects, Journal of Atmospheric and Terrestrial Physics, 29, 1411–1427.


Mann, R. J., and D. M. Schlapp (1988), The equatorial electrojet and the day-to-day variability of Sq, Journal of Atmospheric and Terrestrial Physics, 50(1), 57-62.


Appendix A

Student's $t$ cumulative distribution function (cdf)

The MATLAB function of $p = t\text{cdf}(x,\nu)$ returns Student's $t$ cdf at each value in $x$ using the corresponding degrees of freedom in $\nu$

The $t\text{cdf}$ is:

$$p = F(x|\nu) = \int_{-\infty}^{x} \frac{\Gamma\left(\frac{\nu + 1}{2}\right)}{\sqrt{\nu\pi}} \frac{1}{\sqrt{\nu}} \frac{1}{\left(1 + \frac{t^2}{\nu}\right)^{\frac{\nu+1}{2}}} dt$$

where $\Gamma(\cdot)$ is the Gamma function.

The result, $p$, is the probability that a single observation from the $t$ distribution with $\nu$ degrees of freedom will fall in the interval $[\infty, x)$. 

Appendix B

Spline coefficients and control points

Spline Coefficients

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<th>$b_i$</th>
<th>$c_i$</th>
<th>$d_i$</th>
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</table>

Control points

-355.32
-321.23
-282.2
-260.22
-234.6
-77.15
4.68
38.77
77.8
99.78
125.4
282.85
364.68