Overview of the Equatorial Electrojet and Related Ionospheric Current Systems

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References

1) Onwumechi, C. A (1997)
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1 Introduction

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Introduction

Astronomy  Astrophysics  Space Physics
Introduction

Astronomy

Observation and scientific study of celestial objects such as stars, planets, comets, and galaxies and phenomena such as moon phases, eclipses, meteor showers.

- Instruments:
  - Optical telescope
  - Radio telescope
  - Star charts

Space Physics

SUPER BLUE BLOOD MOON
JANUARY 31

The lunar eclipse phenomenon will last for
5 Hours 17 Minutes
6.51 P.M - 12.08 A.M (February 1)

152 years

Mar 31, 1866
Jan 31, 2018

was last observed

Supermoon
The moon is at the nearest position to the earth in its orbit

Bloodmoon
The sun, earth & moon in the same line

Bluemoon
Two full moon phases that take place in the same month

Gerhana bulan
Gerhana bulan terjadi ketika matahari, bumi, dan bulan berada pada garis sejajar. Bulan purnama akan menjadi merah karena tertutupi oleh bayangan bumi.

Supermoon
Supermoon terjadi ketika bulan purnama berada dalam jarak terdekatnya dengan bumi.

Blue moon
Blue moon adalah bulan purnama yang terjadi dua kali dalam satu bulan kalender.
Introduction

Astrophysics

A branch of astronomy that applies the law and principles of physics to explain and interpret astronomical phenomena.

Important discoveries:
- The Theory of Relativity
- Black Holes
- The Big Bang and Inflationary Theory
- The Age of the Universe
- Dark Energy
Study of the phenomena that occur in our solar system (e.g. solar wind, space weather). Focuses closely everything above Earth's atmosphere until the edge of the solar system which includes the Earth's ionosphere, the magnetosphere and magnetotail, the Sun's corona and solar wind.

Begin in the early 1950s when Van Allen launched the first rockets to a height around 110 km.

Space physics utilizes in situ measurements such as rocket, space craft, satellite.
Introduction

Atmospheric layers

- For understanding the ionospheric electrodynamics and its coupling to the magnetosphere and lower atmosphere.
- For determining a base level for geomagnetic indices.
- For monitoring solar radiation activity.
- For estimating electrical conductivity within the Earth.

NASA/Goddard
Introduction

Brief History Remarks of EEJ

1922
“The magnetometer recording of the daily variation of the earth’s magnetic field at Huancayo, Peru, started…”

1947
Edegal, J.
“ The great augmentation of the range of H in a narrow zone near the magnetic equator seems to indicate that the variation is caused by a varying electric current flowing in a very narrow zone of the atmosphere above magnetic equator... the current is flowing in a height of about 100km.”

1951
Chapman, S.
“The abnormally large range of the daily variation of the horizontal component of magnetic force over Huancayo, Peru indicates the daily rise and decline of a concentrated eastward electric current... The name electrojet is suggested for this concentrated current.”

Sydney Chapman [1888-1970]
Introduction

Geomagnetic Field

rapid rotation + liquid conducting interior—electric charges move about → Main part of geomagnetic field
Introduction

Geomagnetic Field

Boreal (north)
Austral (south)

(Onwumechili, 1997)
Earth's magnetic field can be represented by a **three-dimensional vector**.

According to the National Geophysical Data Center (NGDC), Earth's magnetic field is described by **seven components**:

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>the total intensity of the magnetic field vector</td>
</tr>
<tr>
<td>H</td>
<td>the horizontal intensity of the magnetic field vector</td>
</tr>
<tr>
<td>Z</td>
<td>the vertical component of the magnetic field vector; by convention Z is positive downward</td>
</tr>
<tr>
<td>X</td>
<td>the north component of the magnetic field; X is positive northward</td>
</tr>
<tr>
<td>Y</td>
<td>the east component of the magnetic field; Y is positive eastward</td>
</tr>
<tr>
<td>D</td>
<td>magnetic declination, defined as the angle between true north (geographic north) and the magnetic north (the horizontal component of the field). D is positive eastward of true North.</td>
</tr>
<tr>
<td>I</td>
<td>magnetic inclination, defined as the angle measured from the horizontal plane to the magnetic field vector; downward is positive</td>
</tr>
</tbody>
</table>

\[
\begin{align*}
\text{Declination (D)} & \quad D = \tan^{-1} \left( \frac{Y}{X} \right) \\
\text{Inclination (I)} & \quad I = \tan^{-1} \left( \frac{Z}{H} \right) \\
\text{Horizontal (H)} & \quad H = \sqrt{X^2 + Y^2} \\
\text{North (X)} & \quad X = H \cos(D) \\
\text{East (Y)} & \quad Y = H \sin(D) \\
\text{Intensity (F)} & \quad F = \sqrt{X^2 + Y^2 + Z^2}
\end{align*}
\]

\[
F = (X^2 + Y^2 + Z^2)^{1/2} = (H^2 + Z^2)^{1/2}
\]

\[
H = F \cdot \cos(I), \quad Z = F \cdot \sin(I), \quad X = H \cdot \cos(D), \quad Y = H \cdot \sin(D)
\]
Introduction

Geomagnetic Field

Example of Geomagnetic Component Data
Introduction

Geomagnetic Field

• The EEJ is centered about the magnetic dip equator defined by $I=0$. 

INCLINATION (DEGREES)
Introduction 

Variations of the Geomagnetic Field

Solid Earth internal sources
- The main field is due to the Earth’s liquid outer core motions
- The crustal fields are due to magnetized rocks in the Earth’s crust

External sources
- Ionospheric currents
- Magnetospheric currents
Introduction

Variations of the Geomagnetic Field

-Nighttime value is used as a reference to determine the variation of external sources (ionospheric currents do not normally flow in nighttime).
Introduction

Variations of the Geomagnetic Field

Langkawi (UT+8)
Variations of Geomagnetic External components

The external fields are the most time variable parts of the geomagnetic field. They can be divided into:

1. Geomagnetic solar quiet daily variation, $S_q$ (major) + Geomagnetic Lunar quiet daily variation, $L$ (minor)

2. Irregular variations, $D$

Variations of the Geomagnetic Field

Introduction
Introduction

Variations of the Geomagnetic Field

Origins of the irregular variations of the geomagnetic field

- The irregular geomagnetic variations are associated with interaction between the solar winds and the magnetosphere, and with coupling processes between the magnetosphere and high latitude ionosphere through geomagnetic field lines.
- They are commonly estimated by the indexes like Dst, and Kp.
Introduction

Variations of the Geomagnetic Field

Origins of the regular daily variations of the geomagnetic field

Steward (1882) proposed the hypothesis that geomagnetic variations are caused by the current flowing in electrically conducting region of the upper atmosphere.

Atmospheric Dynamo Theory

- The sun and the moon produce tidal forces in the atmosphere, which result in air motion that is primarily horizontal.
- The motion of electrically conducting air (\(U\)) across the Earth’s magnetic field (\(B\)) gives rise to electromotive forces (\(U \times B\)).
- This process generates electric fields and currents in the dynamo region (altitude range of 90-150km) that cause daily variation in the geomagnetic field.

Current density in ionosphere is given by the Ohm’s law as:

\[ J = \sigma (E + U \times B) \]

- The current density is required to be divergence-free,
  \[ \nabla \cdot J = 0 \]
  and the static electric field can be expressed by an electric potential \(\Phi\):
  \[ E = -\nabla \Phi \]
Introduction

Ionospheric conductivity

- In the ionosphere, the conductivity tensor is highly anisotropic.
- The ionospheric current density is given as

\[
J = \sigma_{//} E_{//} + \sigma_p (E_\perp + U \times B) + \sigma_H \frac{B}{|B|} \times (E_\perp + U \times B)
\]

\[
\sigma_0 = N_e e^2 \left( \frac{1}{m_e \nu_e} + \frac{1}{m_i \nu_i} \right)
\]

parallel Conductivity

\[
\sigma_p = \frac{N_e e}{B} \left( \frac{\nu_e \Omega_e}{\nu_e^2 + \Omega_e^2} + \frac{\nu_i \Omega_i}{\nu_i^2 + \Omega_i^2} \right)
\]

Pedersen Conductivity \perp \vec{B}, // \vec{E}

\[
\sigma_H = \frac{N_e e^2}{B} \left( \frac{\Omega_e^2}{\nu_e^2 + \Omega_e^2} - \frac{\Omega_i^2}{\nu_i^2 + \Omega_i^2} \right)
\]

Hall Conductivity \perp \vec{B}, \perp \vec{E}

\[
\Omega_e = \frac{eB}{m_e}
\]

Gyrofrequency of electrons

\[
\Omega_i = \frac{eB}{m_i}
\]

Gyrofrequency of ions

\[
\nu_e = \nu_{en} + \nu_{ei}
\]

Collision Frequency of electrons

\[
\nu_i = \nu_{in} + \nu_{ie}
\]

Collision Frequency of ions
Conductivities as function of altitudes under equatorial, equinox and average solar conditions computed by Forbes and Lindzen (1976).
Introduction

Ionospheric conductivity

- Rocket measurements at India by Subbaraya et al. (1972)

Conductivities plot suggests that a large Hall current drives the EEJ.
2 Ionospheric Currents

2.1 EEJ and Sq
2.2 Counter Electrojet (CEJ)
2.3 Global Sq
2.4 Polar-region current
2.5 Inter-Hemisphere Field Aligned Currents
Horizontal ionospheric currents, such as the auroral electrojets, the equatorial electrojet and the Sq (solar quiet) current systems are largely confined to the E region.
Electrojet current densities inferred from 2600 passes of the CHAMP satellite over the magnetic equator between 11:00 and 13:00 local time.

- **EEJ current** is an eastward current flow around the dip equator (±3°) in E-region of the ionosphere within the range of 90 to 120 km altitude.
Ionospheric currents

EEJ and Sq

- Sq current is a global current formed by 2 large vortices of electric currents in the dayside ionosphere.
Ionospheric currents

EEJ and Sq

Dip latitude

IEEE J

Sq
Ionospheric currents

EEJ and Sq

- $\mathbf{E}_H$ is more than 20 times greater in magnitude than $\mathbf{E}_y$ at altitude near 110 km.
- At the dip equator, the total current is given by
  \[
  \sigma_{P1} \mathbf{E}_y + \sigma_{H2} \mathbf{E}_H = \left( \sigma_p + \frac{\sigma_H^2}{\sigma_p} \right) \mathbf{E}_y
  \]
Ionospheric currents

EEJ and Sq

- $\sigma_H$ is maximum at ~110 km, the current in this altitude (lower layer) range is predominantly Hall current that drives the EEJ.
- $\sigma_P$ is maximum at ~130 km, the current in this altitude (upper layer) range is predominantly Pedersen current that drives the worldwide part of Sq current system.

Conductivities profiles computed using

Ionospheric conductivity model of WDC Kyoto (Yamazaki & Maute, 2016)

Rocket measurements at India by Subbaraya et al. (1972)
**Ionospheric currents**

**EEJ and Sq**

- At the dip equator, the **total current** is given by
  \[ \sigma_{P1} E_y + \sigma_{H2} E_H = \left( \sigma_P + \frac{\sigma_H^2}{\sigma_P} \right) E_y \]
- \( E_H \) is more than 20 times greater in magnitude than \( E_y \) at altitude near 110 km.

*Latitudinal profile of the quiet daily variation of the horizontal geomagnetic component (Onwumechili, 1967).*
Ionospheric currents

Calculation of EEJ - Two Station Method

EEJ = Total current – Sq current

Traditional two-station method

Off-equator station

Dip equator station

EEJ (a)

TIR (θ=0.21°) - ABG (θ=10.36°)
EEJ-Sq relationship

The estimated EEJ intensities at DAV (Southeast Asia) against eastward Sq current intensities. (Yamazaki et al., 2010)

Scatter plot of the EEJ versus normalized Sq (top panels) and normalized total current versus normalized Sq (bottom panels) obtained from: ANC and FUQ in South America, TIR and ABG in India, and DAV and MUT in Southeast Asia. (Hamid et al., 2014)

- EEJ-Sq relationship is influenced by the Sq contribution in the dip-equator region.
Ionospheric currents

Counter Electrojet (CEJ)

- The equatorial counter electrojet (CEJ) current is EEJ reversal during magnetically quiet periods (Gouin and Mayaud, 1967).
- CEJ is a westward electric current flowing within a narrow band centred on the dip equator.
- CEJ is different with the westward EEJ return current that observed outside the EEJ zone.
- This is indicated by negative geomagnetic H data typically lasting for a few hours.
- This event was first observed during the study of the magnetic records at Addis Ababa, Ethiopia, in 1962 by Gouin (1962).
- Type of CEJ based on Alex & Mukherjee (2001):
  - Morning Counter Electrojet (MCEJ), 0700–0800 LT.
  - Noon Counter Electrojet (NCEJ) - a rare phenomena, at 1100–1200 LT.
  - Afternoon Counter Electrojet (ACEJ), 1300–1400 LT.
  - Evening Counter Electrojet (ECEJ), 1500–1800 LT.

Diurnal variation of geomagnetic field H at Trivandum (India) during the counter electrojet days of 25 and 26 June 1987. The control day is on 23 June 1987. (From Somayajulu et al. 1994).
Various mechanisms have been suggested to explain CEJ such as:


- An **upward wind with a sufficiently large magnitude** (15–20 m/s) (Raghavarao and Anandarao 1980).

- Occurrence of CEJ is dependent on the **phase of the moon, suggesting that lunar tides play a role** (Bartels and Johnston 1940; Rastogi 1974; Sastri and Arora 1981).

- CEJ event during winter is often observed during a **stratospheric sudden warming** event, (Stening et al. 1996; Sridharan et al. 2009; Fejer et al. 2010).

- **Penetration of the polar-region electric field** to equatorial latitudes (Rastogi and Patel 1975; Rastogi 1977, 1997; Kikuchi et al. 2003, 2008).

- Storm-time thermospheric winds tend to drive a westward electric field in the dayside equatorial region through the mechanism known as **disturbance dynamo** (Blanc and Richmond 1980; Fuller-Rowell et al. 2002).

- Recently, Vineeth et al. (2016) reported a remarkable correlation between the monthly mean meteor counts and the number of afternoon CEJ events during 2006–2007. Their observations are consistent with the numerical results by Muralikrishna and Kulkarni (2008), which predicted that a **dust-particle layer of meteoric origin** could cause a reversal of the vertical polarization electric field in the equatorial electrojet.
Ionospheric currents  

Global Sq

Schematic drawings of global Sq current system (Ogbuehi et al. 1967)

Schematic illustrating the dayside view of the equivalent Sq current system (Yamazaki, 2011)
The basic pattern of the equivalent Sq current system is consistent throughout the year; counterclockwise on Northern hemisphere, clockwise in the Southern hemisphere.
Ionospheric currents

A two-cell current pattern is visible within the polar cap; the current cell on the morning side is negative, evening side is positive; driven by high latitude electric fields generated by the solar wind-magnetospheric dynamo.

During disturbed periods, the current intensity is enhanced and the current system expands to lower latitude, the magnetic effect is called DP2 (quasi-periodic fluctuations period of 30-40 min).
Ionospheric currents

Inter-Hemisphere Field Aligned Currents

- This current was first suggested by van Sabben (1966) in an attempt to explain the north-south asymmetry of the equivalent Sq current system.
- This current would cause “apparent” cross-equatorial currents in the equivalent Sq current system.
- Figure 9b showing the inter-hemispheric field-aligned currents.
- Fukushima (1994)
- Lühr et al. (2015)

(Figure 9 from Yamazaki & Maute, 2016)
3 EEJ Variability

3.1 Instruments in measuring EEJ
3.2 Diurnal variation
3.3 Latitudinal variation
3.4 Longitudinal variation
3.5 Seasonal variation
**EEJ variability**

**Instruments in measuring EEJ**

- **Rocket:**
  - Determine ionospheric current density through the measurement of its magnetic field gradient.
  - Onwumechili (1997) lists 76 rocket measurements that were made between 1948 and 1973.
  - Provide the most direct measurement because their measurement are made *in situ*.
  - Very costly and provides only a transitory sampling above a very limited space.

- **Ground magnetometer:**
  - Global network such as MAGDAS and INTERMAGNET
  - Provide continuous and long term equivalent current distribution.

- **Satellite:**
  - Polar Orbiting Geophysical Observatory (POGO) satellites (1965 – 1971)
  - Ørsted satellite (1999 – present)
  - Swarm satellite (2013 – present)
EEJ variability

Diurnal variation

- EEJ-related magnetic effects in the daily variations of the horizontal (H) and vertical (Z) components appear at about 6 LT, reach a maximum near local noon and vanish after 18 LT.

- Doumouya et al (2003) use Gaussian-like function to fit the H component:

\[ G(t) = \exp\left(\frac{(t - T)^2}{t_m^2}\right). \]

The local time dependence of the horizontal (H) and vertical (Z) components of the equatorial electrojet associated magnetic effects in West Africa. (Doumouya et al, 2003).

Gaussian (solid lines) fit to the normalized \( \Delta H \) daily variation of the EEJ magnetic effects (dotted line) in Brazil. (Doumouya et al, 2003).
Diurnal variation

- The time for the peak EEJ is around local noon during solar maximum (1958) and shifts to earlier local times during solar minimum (1965).

Yearly average daily variations of $H$-field as well as the rate of change of $H$-field ($\frac{\delta H}{\delta t}$) at Huancayo, Addis Ababa and Trivandrum for low solar activity (1964) and high solar activity (1958). (Rastogi and Iyer 1976).
• The resultant vertical electric field is given by 
\[ E_z = E_H + E_L \]
• At dip equator, \( E_H \) dominates and \( E_z \) is upwards. Thus, EEJ is relatively intense at dip equator.
• \( E_z \) and EEJ decrease with latitude and at about ±3° dip latitude, \( E_z = 0 \). This is latitude of EEJ current focus.

• Beyond current focus, \( E_L \) dominates and \( E_z \) is downward, resulting in a westward flow of the EEJ. This is the return current of EEJ.
• EEJ return current peaks around 5° before gradually decrease and terminate about 10±3° dip latitude or beyond.

Latitudinal profile of EEJ current intensity derived from POGO satellites. (Onwumechili, 1997)
EEJ variability

Latitudinal variation

Latitude dependence of the horizontal (H) and vertical (Z) components of the equatorial electrojet associated magnetic effects in West Africa. (Doumouya et al, 2003).

Average geomagnetic daily variations in the magnetic-northward (N), magnetic-eastward (E), and vertically downward (Z) components during May–August of 1996–2007. (From Yamazaki, 2011)
The latitudinal profiles of $S_q$ and total currents in Southeast Asian sector during (a) solar minimum (2008) and (b) solar maximum (2014). The striped lines indicate the latitudinal variation of EEJ current. (Hamid et al, 2017).
EEJ variability Longitudinal variation

The mean longitude dependence of the magnetic effects of the equatorial electrojet at 12 LT (solid curve) and the inverse of the main field $5 \times 10^6/B$ (dashed line). (Doumouya et al, 2003).

- Comparison of the EEJ intensities at various longitude sector have revealed a strong dependence on the main field $B$ such as study by Rastogi (1962) and Doumouya et al. (2003).
**EEJ variability**

**Longitudinal variation**

- Comparison of the EEJ intensities at various longitude sector have revealed a strong dependence on the main field $B$ such as study by Rastogi (1962) and Doumouya et al. (2003).

- However, recent studies such as Rastogi (2006) and Hamid et al. (2015) pointed out that EEJ in Southeast Asia is significantly stronger than Indian sector.

- There should be other mechanism that also play role in modulating EEJ.

![Longitude dependence of the magnetic component of EEJ at 1100 LT and the inverse of the main field (1/F).](image)

(Hamid et al, 2015)
EEJ variability
Longitudinal variation

- Recent studies shown that EEJ is often dominated by the so-called “wave-4” pattern which is most prominent during June-October.

- Numerical studies have shown that the eastward-propagating diurnal tide with wave number 3, the so-called DE3, is the main cause of the wave-4 longitudinal pattern (Hagan et al., 2007; Jin et al., 2008).

The satellite-based empirical model of Alken and Maus (2007)
EEJ variability

- The TIE-GCM simulation is consistent with the satellite measurements.

The satellite-based empirical model of Alken and Maus (2007)

TIE-GCM with $F_{10.7} = 120$ sfu. (Yamazaki & Maute, 2016)
EEJ variability  

Seasonal variation

- The semiannual variation of EEJ is evident only during morning hours and it practically disappears in the afternoon.

Seasonal variations in the H-component geomagnetic field at India (8.5° N, 77.0° E) at different local times for high solar activity periods (1979–1981) and low solar activity periods (1984–1986). (Rastogi et al., 1994)
EEJ variability

Seasonal variation

- Simulation shows that the semiannual variation in N is mainly due to upward-propagating tides from the lower atmosphere.

Contour plots for seasonal and local-time variations in the magnetic-northward (N) component of the geomagnetic daily variation at Tirunelveli (8.7° N, 77.8° E) for 2008. (a) Observations. (b) NCAR TIE-GCM simulation results. (c) NCAR TIE-GCM simulation results; the contribution of upward-propagating tides from the lower atmosphere. (d) NCAR TIE-GCM simulation results; the contribution of tides locally generated in the thermosphere by in-situ solar heating. (Yamazaki et al., 2014b)
THE END

THANK YOU.