Space Weather and Upper Atmospheric data analysis training workshop for East African Community

The study of Equatorial Electrojets

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September 26, 2023

MAGNETIC LATITUDE REGIONS

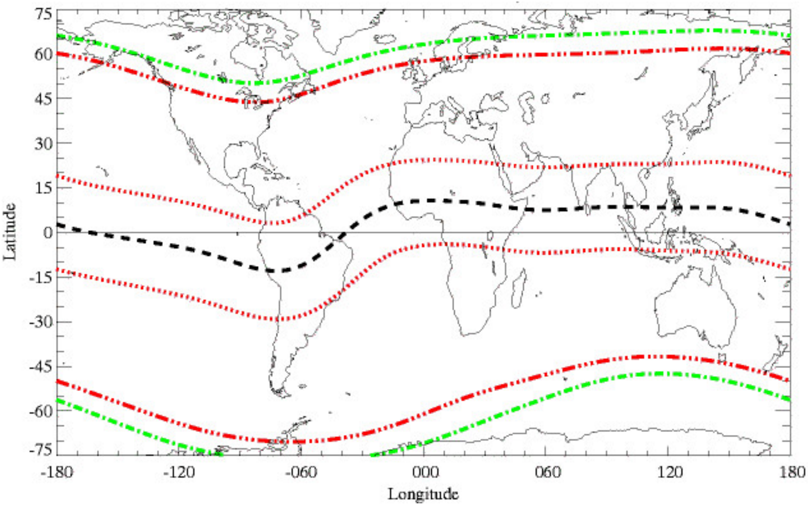

Figure 1: Geomagnetic Boundaries, Source Northwest Research Associates Inc, 2000.

CURRENTS IN EQUATORIAL IONOSPHERE

- The E region of the equatorial ionosphere consists of two layers of currents responsible for the solar daily variation in the Earth's magnetic field:

  1. Worldwide solar quiet daily variation, Sq (altitude 118$\pm$ 7 km), responsible for the global quiet daily variation observed in the Earth's magnetic field.

  2. Equatorial electrojet (EEJ): a narrow ribbon of current flowing eastward in the day time equatorial region of the Earth's ionosphere (altitude 106$\pm$ 2 km).

- The flowing currents in the ionosphere induce magnetic perturbations on the ground.

EEJ and Sq currents

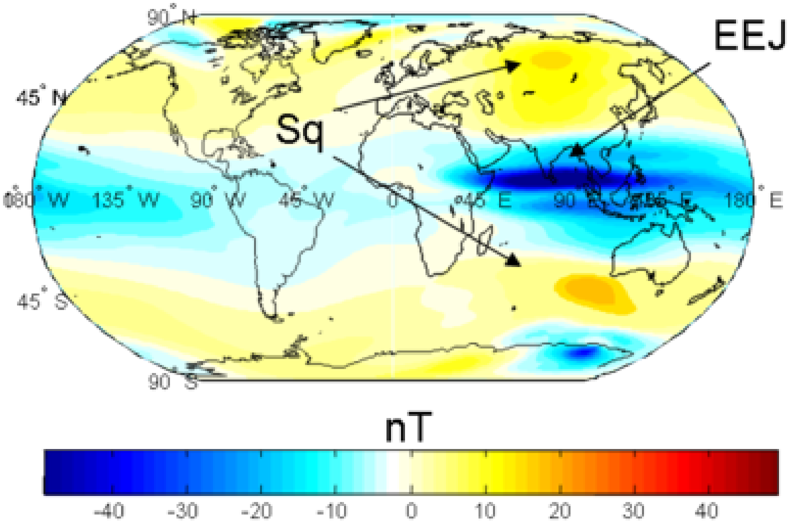

Figure 2: EEJ and Sq currents.

HISTORICAL PERSPECTIVE

- The abnormally large amplitude of variations in the horizontal components measured at equatorial geomagnetic observatories, as a result of EEJ, was noticed as early as 1920 from Huancayo geomagnetic observatory in Peru.
- Currently, observations by radar, rockets, satellites, and geomagnetic observatories are used to study EEJ.
- The EEJ is attributed to the action of tidal winds, which moving the ionosphere across the magnetic field, provoke the appearance of a current flowing along it (Forbes, 1981).

- EEJ exists due to anisotropic nature of ionospheric electrical conductivity.
- In the ionospheric E-region, tidal winds drive currents during the daytime which, together with the magnetic field, cause the accumulation of positive and negative charges at the dawn and dusk terminators respectively, resulting in a strong eastward electric field along the magnetic equator.
- This gives rise to the Hall and Pedersen currents, and Cowling (1933) showed that when a Hall current is restricted by the presence of boundaries, the effective (Cowling) conductivity parallel to the boundaries is significantly enhanced beyond the normal Pedersen conductivity.
- It was later realised that the presence of low conducting layers above and below the E-region are sufficient to drive this Cowling conductivity near the magnetic equator, giving rise to the equatorial electrojet (EEJ) (Heelis, 2004; Forbes, 1981).

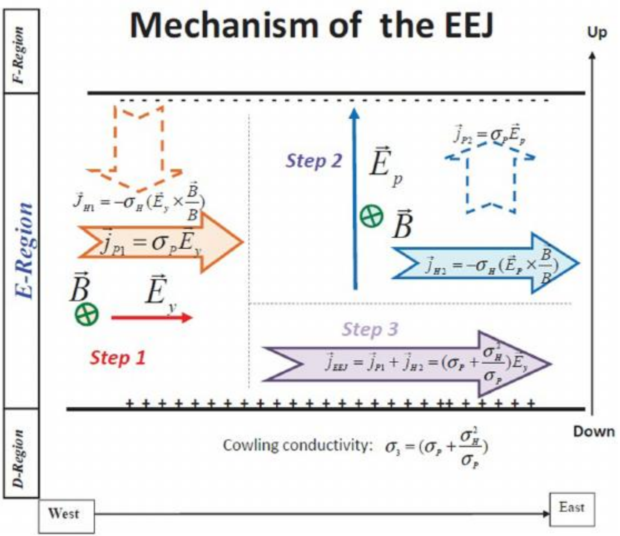

Figure 3: Enhancement of the effective conductivity at the magnetic equator (Grodji et al., 2017)

COWLING CONDUCTIVITY

- At the geomagnetic equator, the Sq current systems of the southern and northern hemispheres touch each other and form an extended nearly jet-like current in the ionosphere, the equatorial electrojet (EEJ).
- However, the electrojet would not be so strong as it is if it were formed only by the concentration of the Sq current.
- The special geometry of the magnetic field at the equator together with the nearly perpendicular incidence of the solar radiation cause an equatorial enhancement in the effective conductivity which leads to an amplification of the jet current.
- To see this combined action, consider a situation where the magnetic field is about horizontal to the Earth's surface as is the case at the equator.

- The direction of the magnetic field is from south to north, along the x-axis.

- The primary Sq Pedersen current flows eastward in the y direction, parallel to the primary ionospheric electric field, E_y.

- As sketched in Figure 3, this primary electric field drives a Hall current which flows vertically downward in the z-direction, causing a charge separation in the equatorial ionosphere with negative charges accumulating on the top boundary and positive charges accumulating at the bottom of the highly conducting layer.

- This space charge distribution creates a secondary polarisation electric effect, E_p, vertically directed from the bottom to the top of the conducting ionosphere.

- The polarisation electric field drives a vertical Pedersen current opposing the Hall current.

- The resulting equilibrium condition in which no vertical current flows is

$$j_z = \sigma_H E_y + \sigma_P E_p = 0, \tag{1}$$

which yields for the secondary vertical electric field

$$E_p = -\frac{\sigma_H}{\sigma_P} E_y. \tag{2}$$

- In addition, the secondary polarisation electric field component generates a secondary Hall current component flowing into the y direction

$$j_{H2} = -\sigma_H E_p = \frac{\sigma_H^2}{\sigma_p} E_y. \tag{3}$$

- The total current into the eastward direction consists of the sum of the primary Pedersen and the secondary Hall current

$$j_{EEJ} = j_{p1} + j_{H2} = \left(\sigma_p + \frac{\sigma_H^2}{\sigma_p}\right) E_y. \tag{4}$$

- The conductivity term appearing on the right-hand side is called Cowling conductivity

$$\sigma_3 = \sigma_p + \frac{\sigma_H^2}{\sigma_p}. \tag{5}$$

- For typical Hall-to-Pedersen conductivity ratios of 3–4 the Cowling conductivity is an order of magnitude higher than the Pedersen conductivity, explaining the amplification and concentration of the EEJ current above the equator.

- The strong horizontal jet current causes a magnetic field disturbance which weakens the horizontal terrestrial magnetic field at the Earth's surface over a distance of about 600 km across the equator (similar to the effect of the ring current field).

- Typical disturbance fields near the noon magnetic equator are of the order of 50–100 nT.

GEOMAGNETIC FIELD COMPONENTS

- These are declination (D), inclination (I), horizontal intensity (H), vertical intensity (Z), total intensity (F) and the north (X) and east (Y) components of the horizontal intensity.

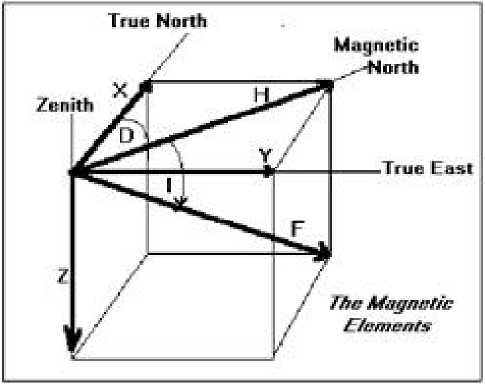

Figure 4: Geomagnetic field components.

COMPONENT EQUATIONS

- $H = F \cos I$.
- $F = H \sec I$.
- $Z = H \tan I = F \sin I$.
- $X = H \cos D$.
- $Y = H \sin D$.
- $H^2 = X^2 + Y^2$.
- $F^2 = X^2 + Y^2 + Z^2$.
- $\tan I = Z/H$.
- The field is either specified by (X,Y,Z) or (H,D,Z).

TEMPORAL AND SPATIAL VARIATIONS OF EEJ

- The EEJ is a prominent indicator of magnetosphere-ionosphere-thermosphere coupling.
- The EEJ is largely affected by solar extreme ultraviolet radiation during quiet times, with the result that its intensity is higher at noon than in the morning and evening, with an average peak of approximately 0.15–0.2 A/m.
- At noon, the position of the peak value of EEJ is located at the dip equator and is virtually independent of the season and longitude (Lühr et al., 2004).
- During quiet times, charged particles in the ionosphere accumulate at the dawn (dusk) terminator to form an eastward electric field, which is believed to be the cause of EEJ.

TEMPORAL AND SPATIAL VARIATIONS OF EEJ

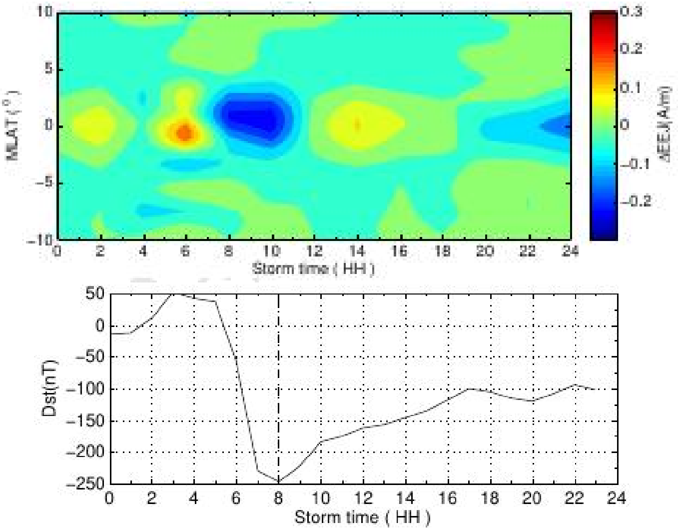

Figure 5: EEJ perturbation versus universal time and MLAT during the magnetic storm on 15 May 2005 (Zheng et al., 2018).

Conclusions from Zheng et al., 2018:

- The EEJ underwent an eastward enhancement and a subsequent westward enhancement during the magnetic storm.
- The eastward and westward peaks of the EEJ occurred in the main phase and the recovery phase, respectively.
- An eastward enhancement of the EEJ on the dayside mainly results from the penetration of the dawn to dusk convection electric field at high latitudes.
- During storm times, the region 1 FACs are markedly stronger than those in region 2, and hence the FACs move to low latitudes.
- There is thus a high and possibility that the dawn to dusk electric field might penetrate to middle and low latitudes.

- During a period of a westward enhancement of the EEJ, a westward zonal wind weakens or even turns eastward, while the arrival of the westward peak of the EEJ coincides with the propagation of a travelling atmosphere disturbance to the region of the dip equator, which indicates that the enhanced equatorward wind might be the main reason for the westward enhancement of the EEJ.

EXPERIMENTAL ASPECTS

- There are essentially two equipments which provide useful data to study the equatorial electrojet: magnetometer and radar.

MAGNETOMETERS

- Magnetometers are probably the oldest type of equipment to study the equatorial electrojet. They are even related to the history of this phenomenon.
- Fluxgate sensors are typically ring cores of a highly magnetically permeable alloy around which are wrapped two coil windings: the drive winding and the sense winding.
- The triaxial fluxgate magnetometers presently used are essentially composed of a primary coil which, under the influence of the earth's magnetic field, transfer to a secondary coil its induction that is transformed into an electric signal.
- The system operates with saturated nucleus and provides information about the variations of the earth's magnetic field, necessary to compute the current flowing in the electrojet region.

- Unfortunately the current derived from these measurements is a height integrated value and besides contains a component from the current flowing within the Earth.
- The height integrated value includes not only the electrojet current but also another component due to currents flowing in the magnetosphere (Kamide et al. 1981).
- At equatorial latitudes this last component may be neglected and the separation of the space and ground components can be made using a meridional chain of magnetometers (Forbes, 1981).
- However, as commented on by Rastogi (1992) the space and the ground components of the current may be due to magnetospheric currents. This increases considerably the complexity of the interpretation of magnetometer data.
- Among the advantages of this equipment we mention its low cost and widespread use.
- The disadvantage is that it provides only height integrated values of the current of difficult interpretation.

RADARS

- A radar constitutes a very important ground equipment to be used in the study of upper atmosphere phenomena.
- It operates in the HF, VHF or UHF ranges and the prices, quality and complexity are intimately connected.
- These characteristics are basically determined by two factors:

  a) The required altitude resolution.
  b) The nature of the target particle response.

- As far as altitude resolution is concerned, one wishes an altitude resolution better than 5 km which is about half the thickness of the electrojet width.
- Regarding the nature of the target particle response radars may observe coherent or incoherent scatter echoes.
- Echoes from the equatorial electrojet region are essentially coherent (Fejer and Kelley, 1980) and are stronger when compared to incoherent scatter echoes.

- Coherent scatter transmitters and receivers are much less expensive than those used in incoherent scatter since their operational system is similar to those of the usual reflection type radars.
- They are designed to operate in CW mode for bistatic measurements or else in pulsed mode for monostatic measurements.
- The description of these techniques is found in Evans (1969).
- The bistatic radars have the transmitter and receiving antennas at different sites and so the scattering volume is determined by the intersection of the two antenna beams.
- The monostatic radar use the same antenna for transmission and reception having its scattering volume controlled by the pulse width.
- Satisfactory antenna beams for electrojet measurements cannot be wider than 1° (pencil beams) and pulse widths no larger than 15 μ sec.

- Radars provide measurements of the Doppler shift, Δf, between the transmitted and received frequencies, produced by the target motion.
- The line-of-sight phase velocity is expressed by:

$$v_r = \frac{c\Delta f}{2f}, \tag{6}$$

where c is the velocity of light (in vacuo) and f is the transmitted frequency (Balsley, 1969).

- When this velocity is computed for the electrojet it refers to the electron velocity and may be used to derive the electric field (Viswanathan, 1990).
- However, since the electrojet is dominated by irregularities one observes a frequency spectrum instead of a single frequency shift (Fejer and Kelley 1980).
- This spectrum gives information on the two-stream instability and the gradient drift instability, from which it is possible to determine the electrojet drift velocity (Balsley, 1969, 1973).

EQUATORIAL ELECTROJET CLIMATOLOGICAL MODEL (EEJM1)

- This model uses six years of satellite magnetic measurements from the CHAMP, Ørsted and SAC-C satellites.
- It provides an unprecedented longitudinal coverage of the EEJ magnetic signature.
- This model is a result of inverting the magnetic signature for the current density and then fitting the observed currents.
- The model provides the climatological mean and variance of the EEJ as a function of longitude, local-time, season, solar flux, and lunar local-time.
- The model coefficients and software can be downloaded from the website: `http://models.geomag.us/EEJ.html`.

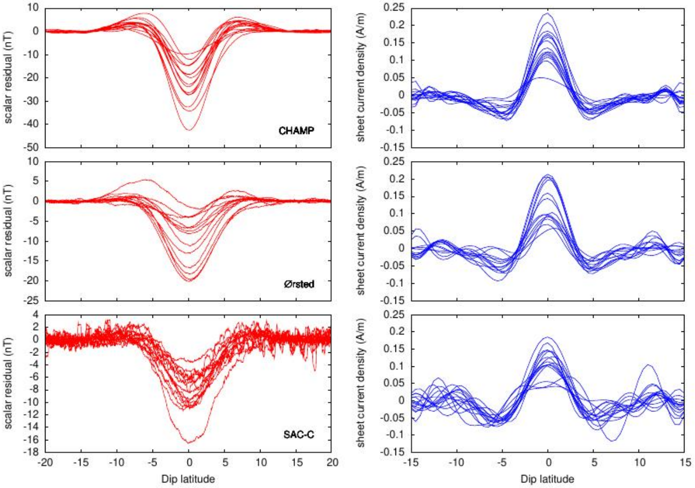

Figure 6: Left: Magnetic field residuals; Right:EEJ signal after inverting magnetic data (Alken & Mauss, 2007)

EEJM1

- Download the model software and coefficients from `http://geomag.org/models/EEJ.html`.
- Download the latest version of generator-scripting-language (gsl) using the link: `https://mirrors.gethosted.online/gnu/gsl/`.
- Extract the files inside the gsl folder and cd to the files with

  `configure`
- Type "./configure && make && make install" in terminal and press enter.
- cd to the unzipped folder of the model.
- Type "wine eej_plot.exe -h" for options such that you remove the default values.
- Specify what you want as the out put file in the form "plot_<var>_data.txt".

EEJM1 WAVE NUMBER 4

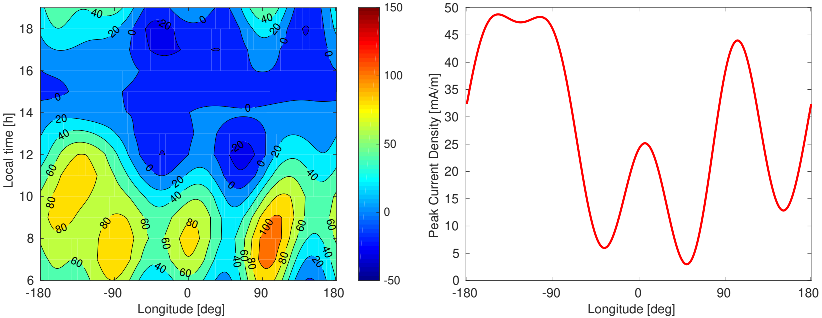

Figure 7: EEJ current density as a function of longitude and local-time from the CHAMP satellite data.

EXERCISE

Use the default values in the EEJ model to obtain th EEJ map for DOY 172 between 06–19 LT.

THANK YOU