EQUATORIAL IONOSPHERE :
-MAGNETIC VARIATIONS
- THE DYNAMO THEORY

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- Currents in ionosphere were first discovered through the daily regular variations of the geomagnetic field.

- interpretation of these variations resulted in the concept of equivalent current.

- before dynamo theories were developed.

- In the first part of my lecture, I give an overview of the geomagnetic field daily regular variations and equivalent current systems at low and mid latitudes.

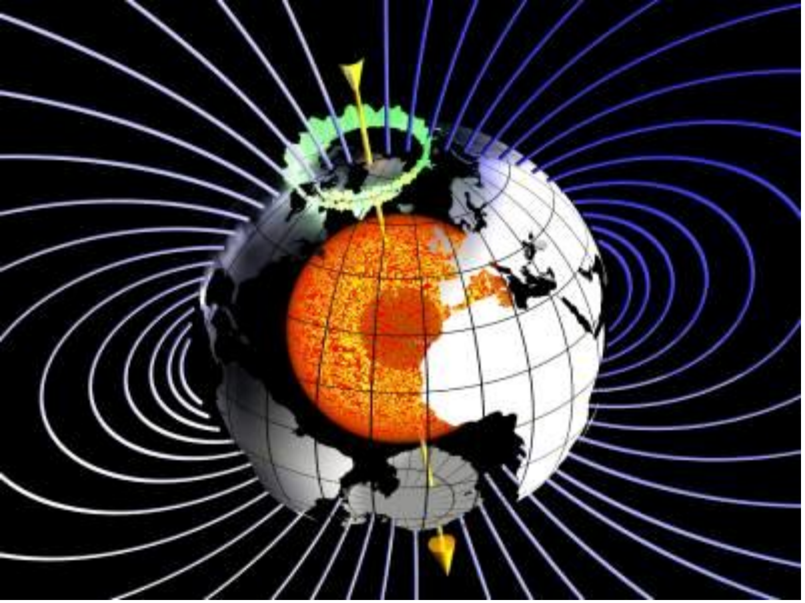
-The second part will focus on the ionospheric dynamo in general, and on the mechanism of the equatorial electrojet and associated currents.

- VARIATIONS OF THE GEOMAGNETIC FIELD

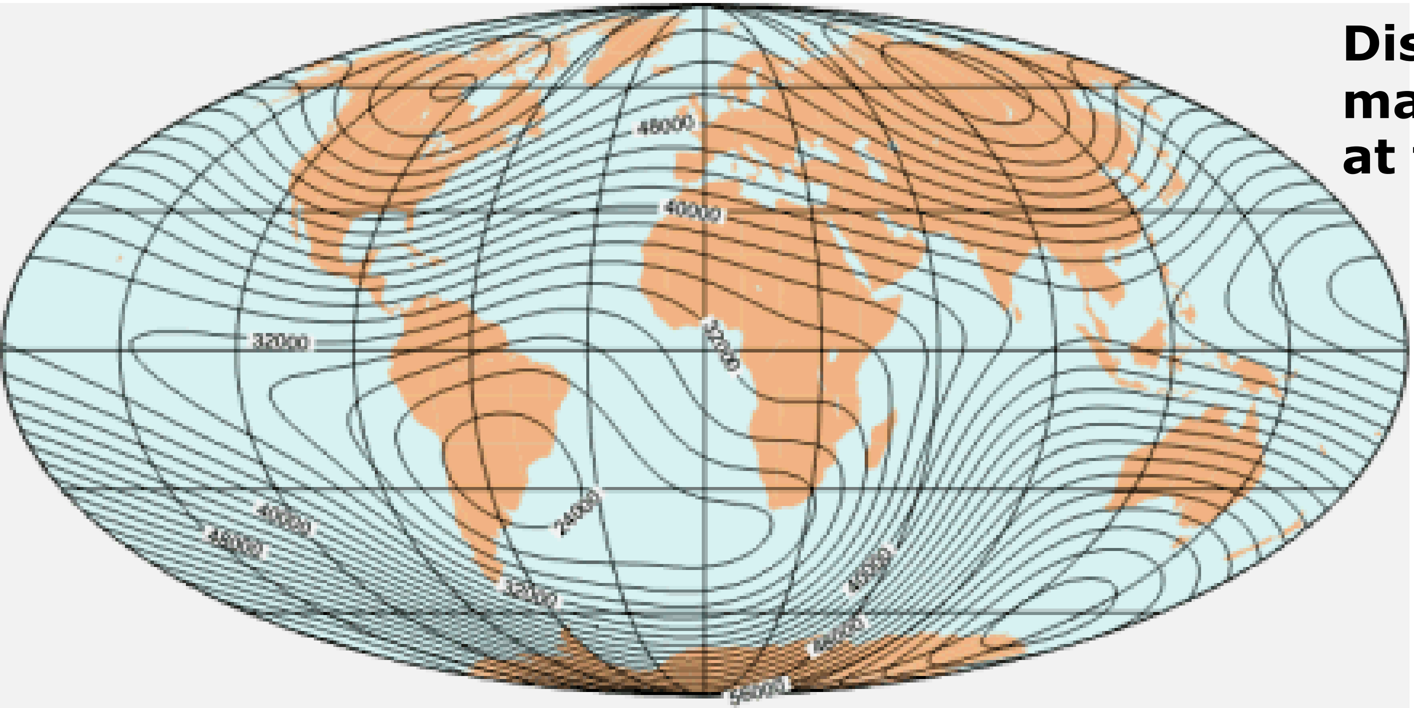
- Composition of observed geomagnetic field:

$$Bt = Bp + Ba + Be + Bi$$

Bp = geomagnetic main field
Ba = lithospheric anomaly fields
Be = magnetic field variations due to currents in ionosphere and magnetosphere
Bi = induced fields in the solid Earth



- The main field Bp has a quasi dipole structure, roughly similar to that of a magnet, tilted by 11,4° from the Earth rotation axis.
  - Bp~99% of to field at the Earth surface
  - Bp ~30.000nT at dip-equator
  - Bp ~60.000nT at the poles
  - Bp is created by motions of liquid core
- its ”secular variation” is about 1% per year.



Distribution of the main field intensity at the Earth surface.

- Time variations of the geomagnetic field

$$dB/dt = dBp/dt + dBa/dt + dBe/dt + dBi/dt,$$

Ba varies at geological time scale > 100 yrs: $dBa/dt \simeq 0$

Finaly

$$dB/dt = dBp/dt + dBe/dt + dBi/dt$$

with

-dBp/dt = secular variation $\simeq$ 1%/year

- $dBe/dt + dBi/dt$ = transient variations

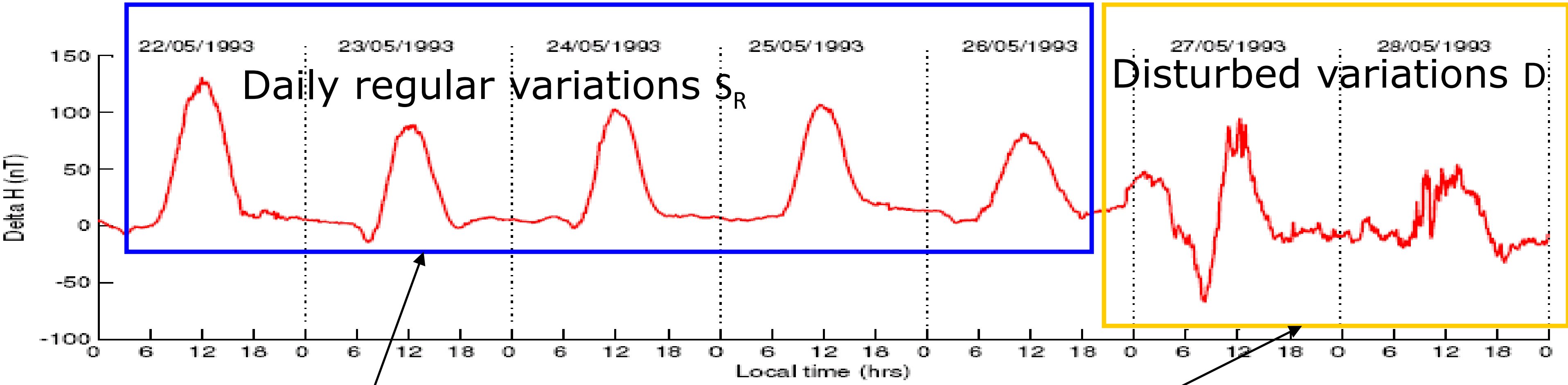
Remark: The transient variations are considered as disturbances with regard to internal components ***Bp*** and ***Ba***.

The transient variations of geomagnetic field.

The transient variations of geomagnetic field can be divided into two main categories:

- **Daily regular variations**

- **Irregular or disturbed variations**.

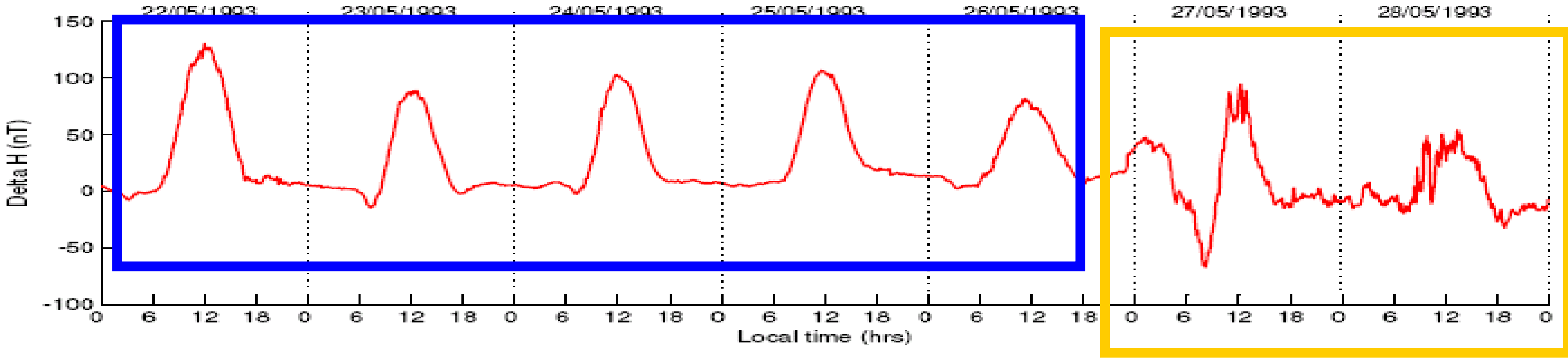


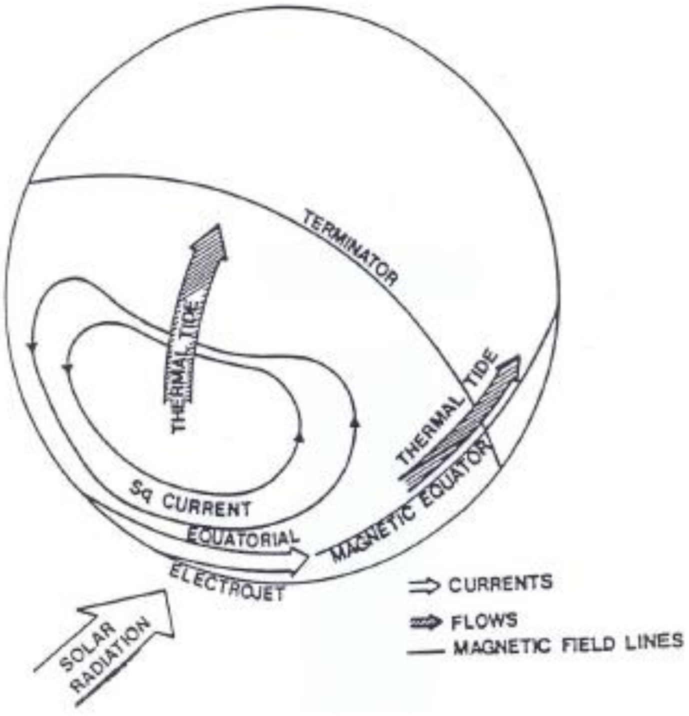
Daily regular variations S_R

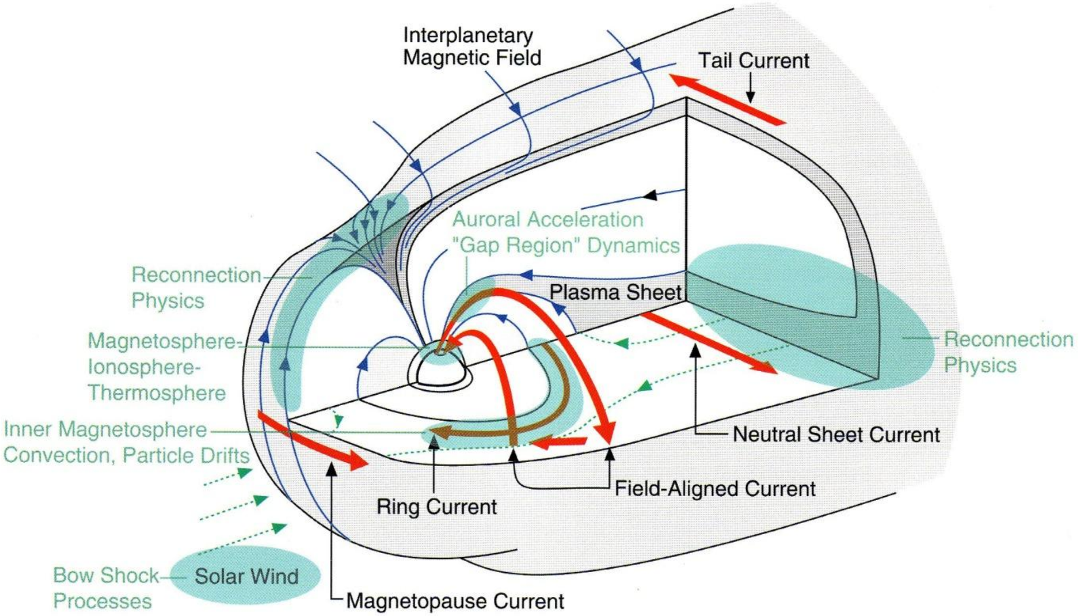
Disturbed variations D

Geomagnetically quiet conditions

Geomagnetically disturbed conditions


22/05/1993
23/05/1993
24/05/1993
25/05/1993
26/05/1993
27/05/1993
28/05/1993
Delta H (nT)
150
100
50
0
-50
-100
0
6
12
18
Local time (hrs)


TERMINATOR
THERMAL TIDE
THERMAL TIDE
Sq CURRENT
EQUATORIAL
ELECTROJET
MAGNETIC EQUATOR
SOLAR RADIATION
CURRENTS
FLOWS
MAGNETIC FIELD LINES


Interplanetary Magnetic Field
Tail Current
Auroral Acceleration
"Gap Region" Dynamics
Reconnection Physics
Plasma Sheet
Magnetosphere-Ionosphere-Thermosphere
Reconnection Physics
Inner Magnetosphere Convection, Particle Drifts
Neutral Sheet Current
Field-Aligned Current
Ring Current
Bow Shock Processes
Solar Wind
Magnetopause Current

Study of the daily regular variation

Study of the daily regular variation requires that we take into account the geographic locations because the nature of the sources may change according to dominant processes in the area of study:

- near the dip-equateur about +/-15° dip-latitude (Low latitudes), the EEJ effect is dominant

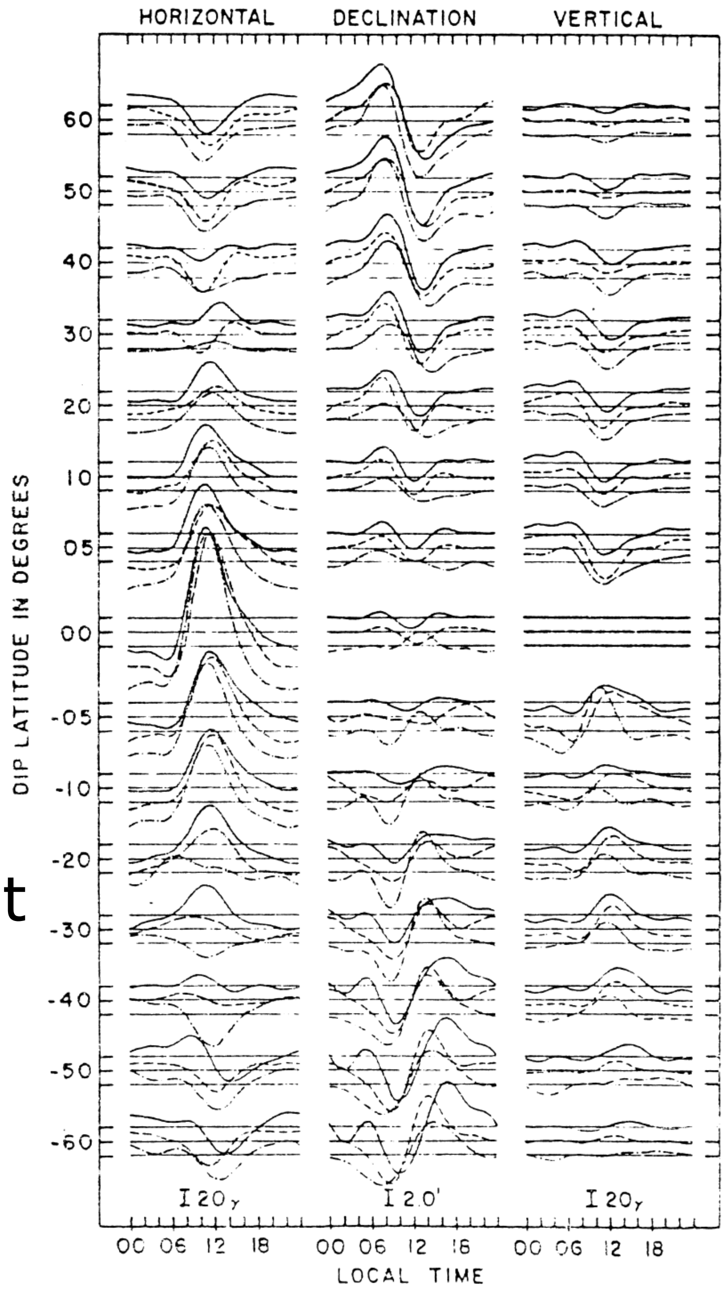
- between +/-15° et +/-70° (mid latitudes), the daily regular variations are produced by the planetary Sq current that are generated by the regular ionospheric dynamo.

- Above +/-70° (high latitudes), magnetic variations (S_R^P) are produced by currents that are associated with coupling processes between magnetosphere and high latitude ionosphere through magnetic lines of force.

This lecture is focus on the daily regular variations in mid and low latitudes.

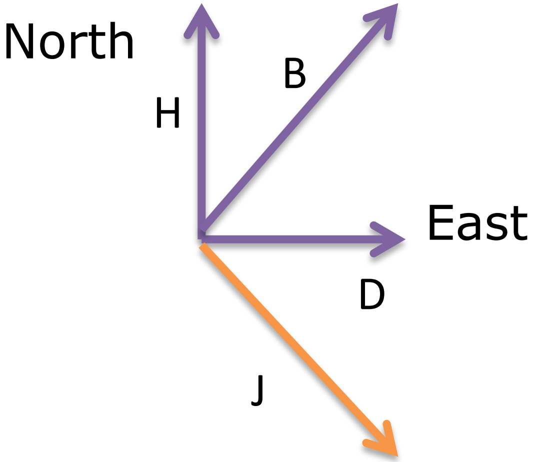
The diurnal variations of H, D and Z components have typical morphologies that change as function of geographic position.

These magnetic variations are interpreted in term of equivalent current according to their different shapes.



For this interpretation variations of H and D components are used to represent the field vector in horizontal plane, based on Chapman (1919)'s assumption. In this assumption ionosphere is considered an plane layer above a plane surface.

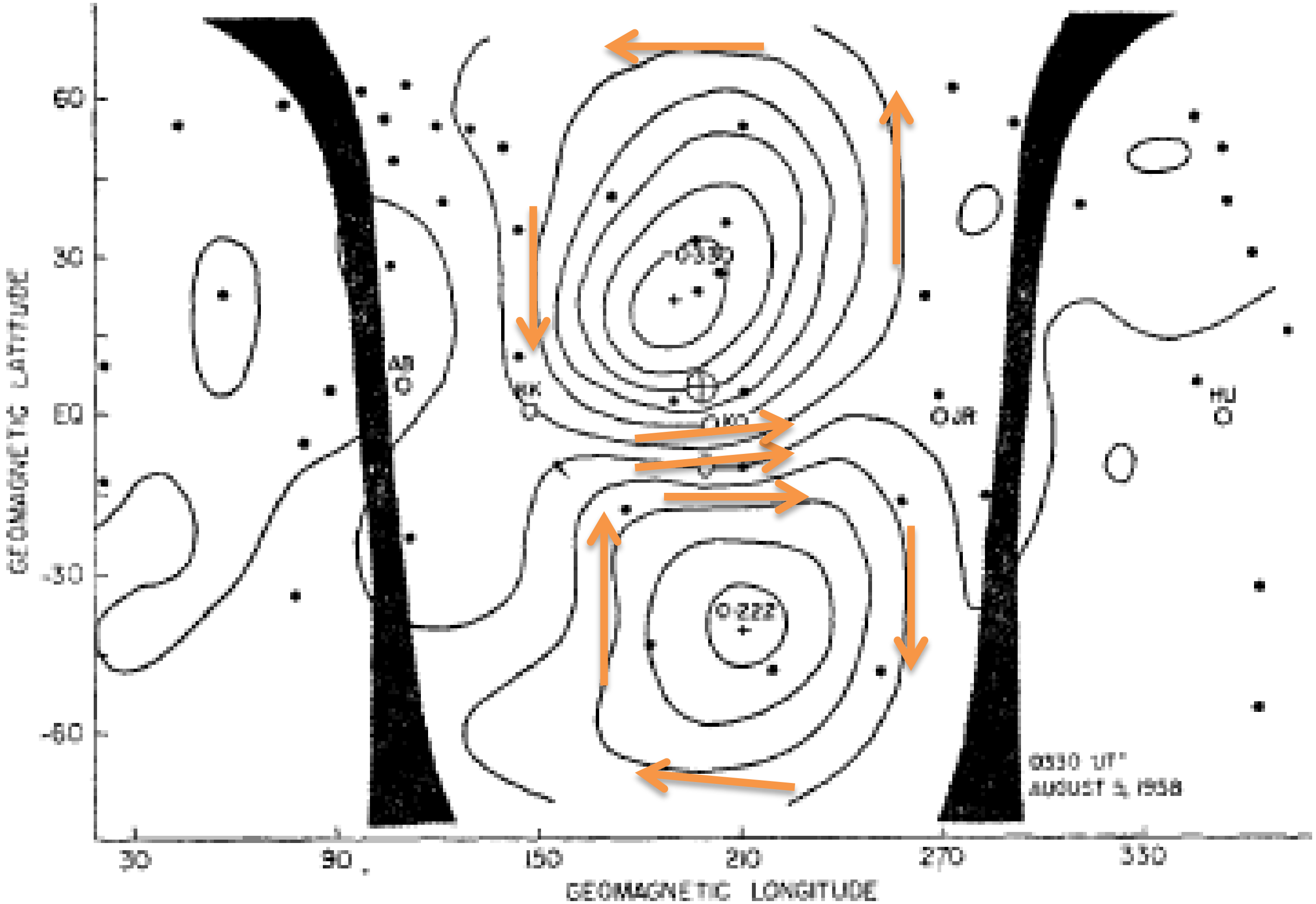
The geometry of mid latitude Sq equivalent current is determined by representing at every location the resulting vector from H and D components and turn 90° clockwise.



$$\vec{B} = \vec{H} + \vec{D}$$

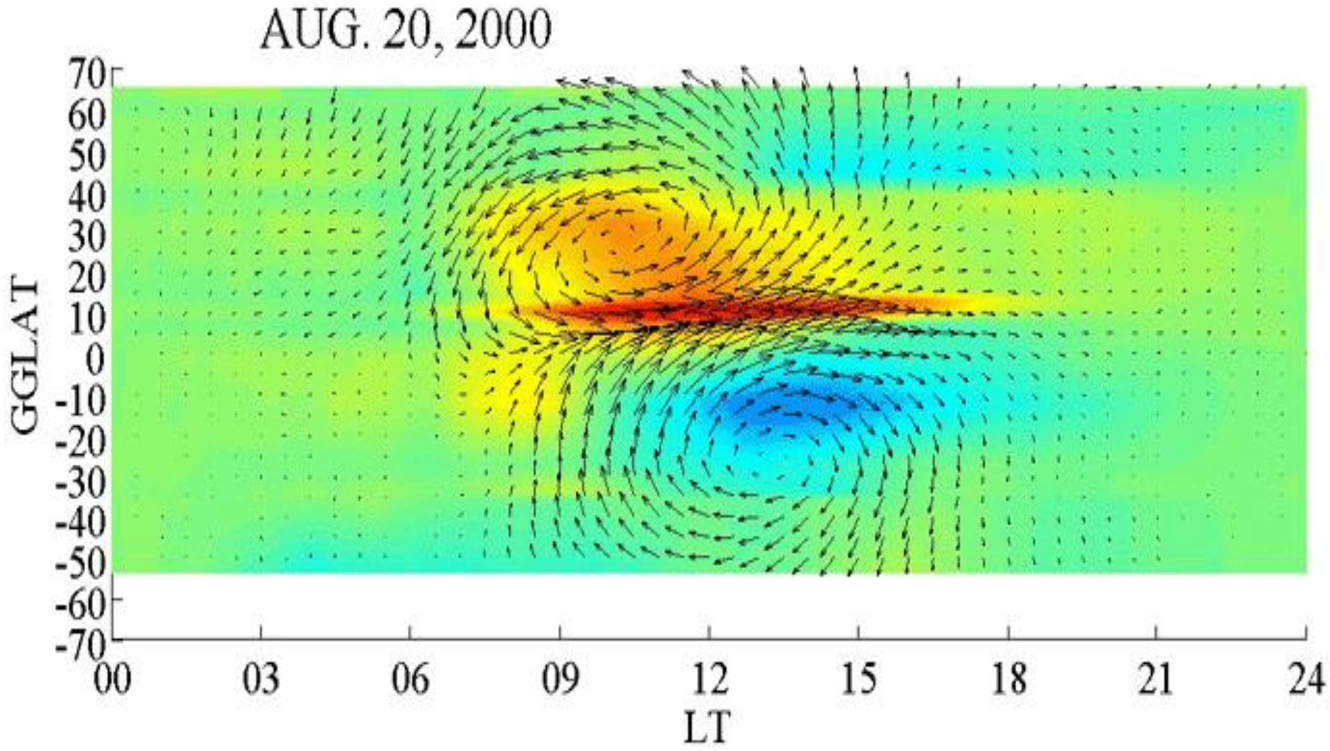
$$\vec{J} \rightarrow \vec{B}(-90^\circ)$$

The first Sq equivalent current map was established by Chapman (1919).



The t Sq equivalent current is organized in two vortices in which current flow clockwise in the south and counter-clockwise in the North.

Here is an example of Sq current map obtained from MAGDAS data in the Asian longitude Sector.



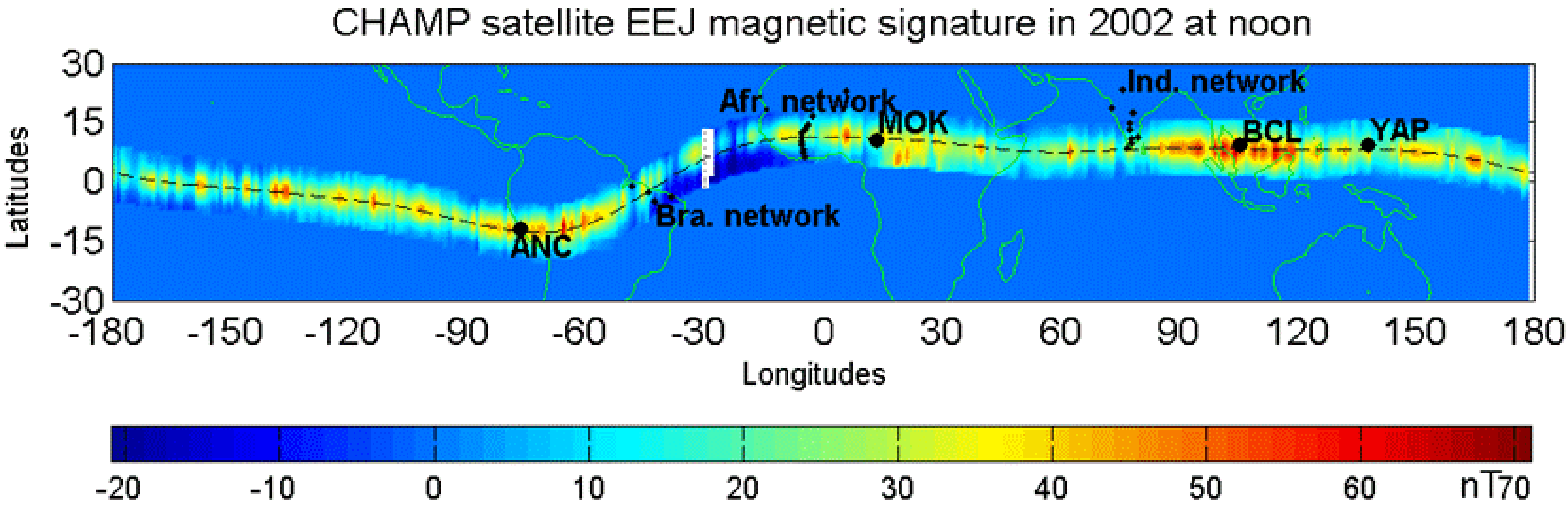
In a symetric system, the vortices are focused at about +/-30° to +/-40° dip-latitude.

Daily regular variation (S_R) near the geomagnetic dip equator.

-The daily regular variation was first observed S_R in mid latitudes observatories in Europe. Graham (1724) discovered magnetic transient variations from observations at London in 1722.

- The first observation of S_R at the dip-equator was made at Huancayo (Peru) in 1922. Bartels and Johnston (1939) noticed “abnormally” enhanced daily regular variation in the H component of the geomagnetic field at Huancayo.

- Egedal (1947) demonstrated that phenomenon was also observed at other equatorial observatories, which was lately prooved by the POGO series of satellites observations(Cain et Sweeney, 1972).



CHAMP satellite EEJ magnetic signature in 2002 at noon

Magnetic signature of the EEJ extrated from the CHAMP satellite observations around local noon in 2001.

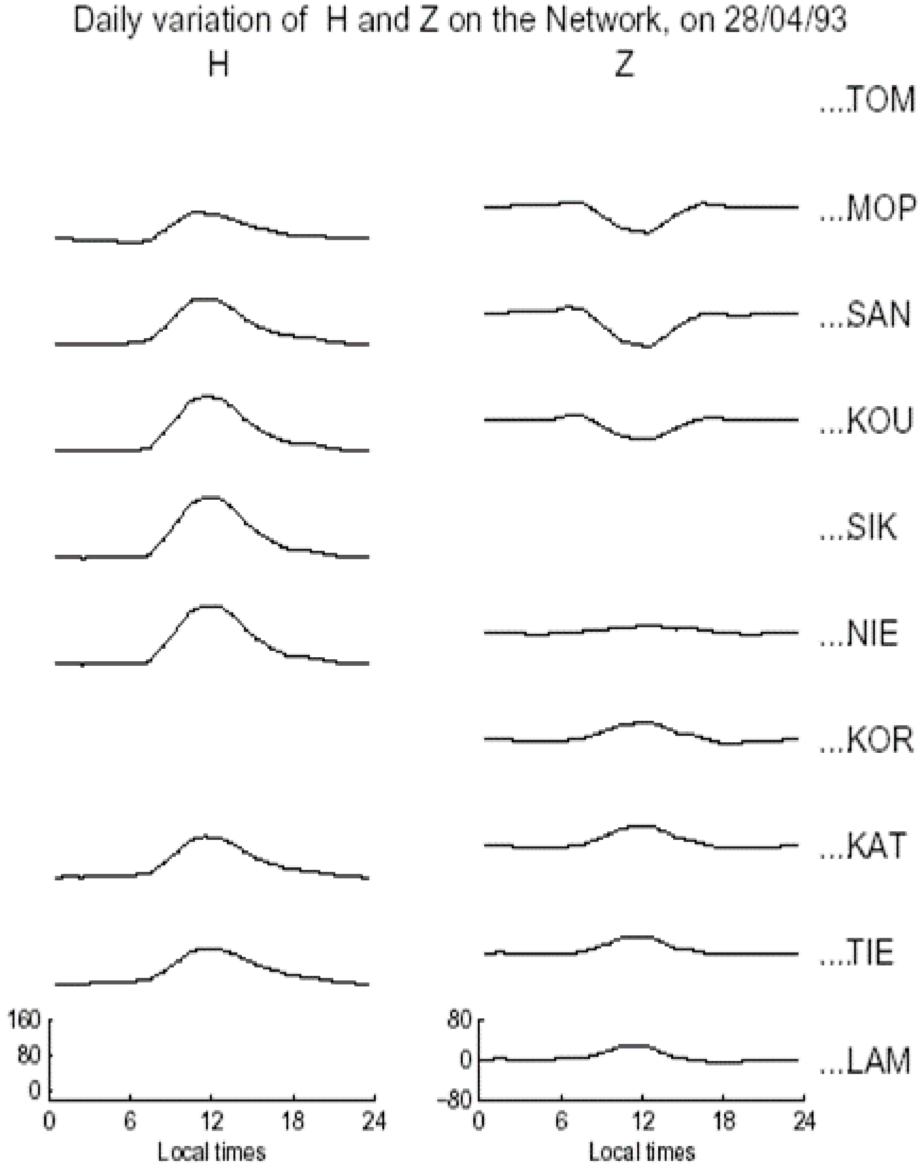
- The enhancement in the ***H*** component was interpreted as due to an intense current that flows from West to East along the geomagnetic dip-quateur, at about 105km altitude.

-The existance and mechanism of this current were demonstrated by Martyn (1948).

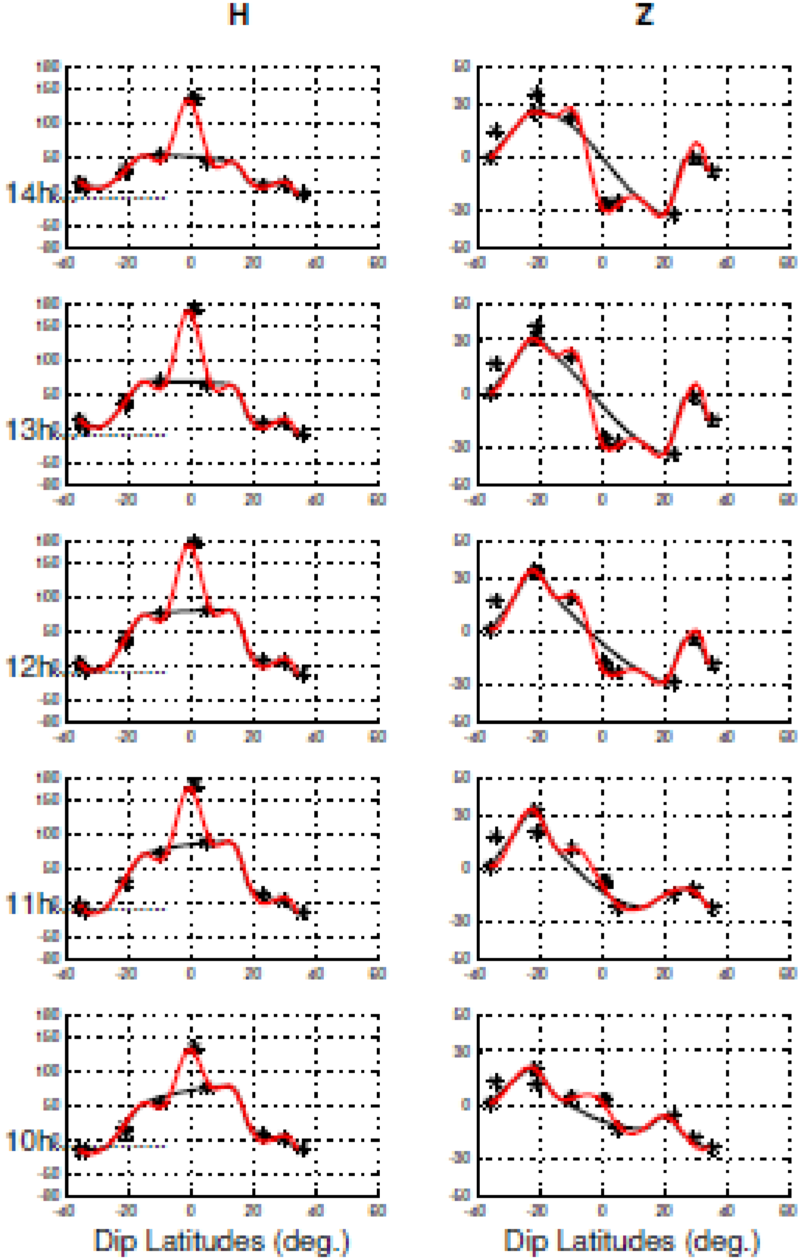
-Chapman gave the name « Electrojet Equatorial » in 1951.

- The equatorial electrojet is considered as a supplement current that overlaps the mid latitude Sq current system near the dip-equator in a latitude band of about +/-3°.

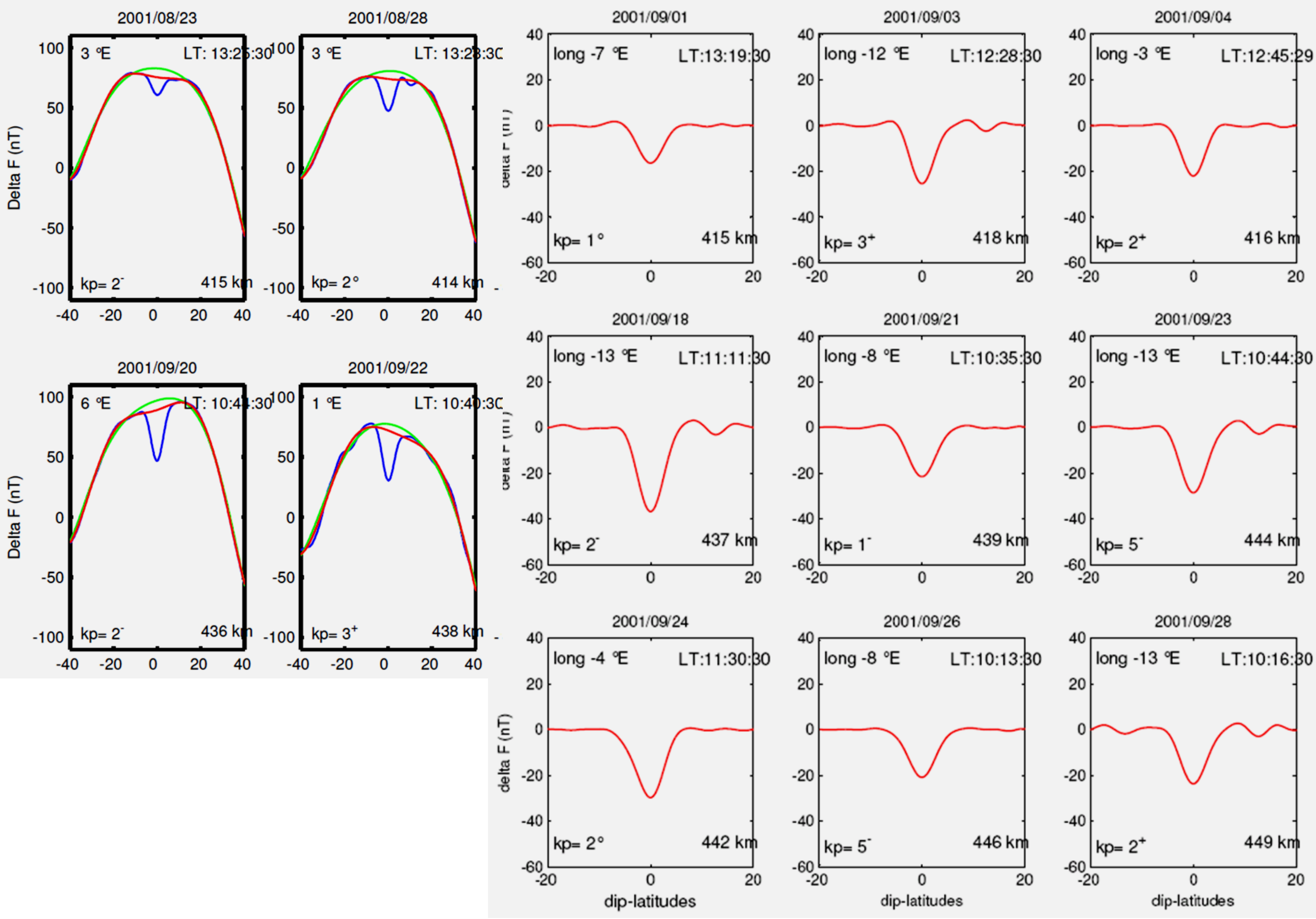
- Defined as flowing from West to East, equatorial electrojet is primarily characterised through its effects in the ***H*** and ***Z.*** It is therefore considered to have no effect in the ***D*** component.



Variations of ***H*** and ***Z*** as function of local time on ground.



Variations of ***H*** and ***Z*** as function of latitude on ground.

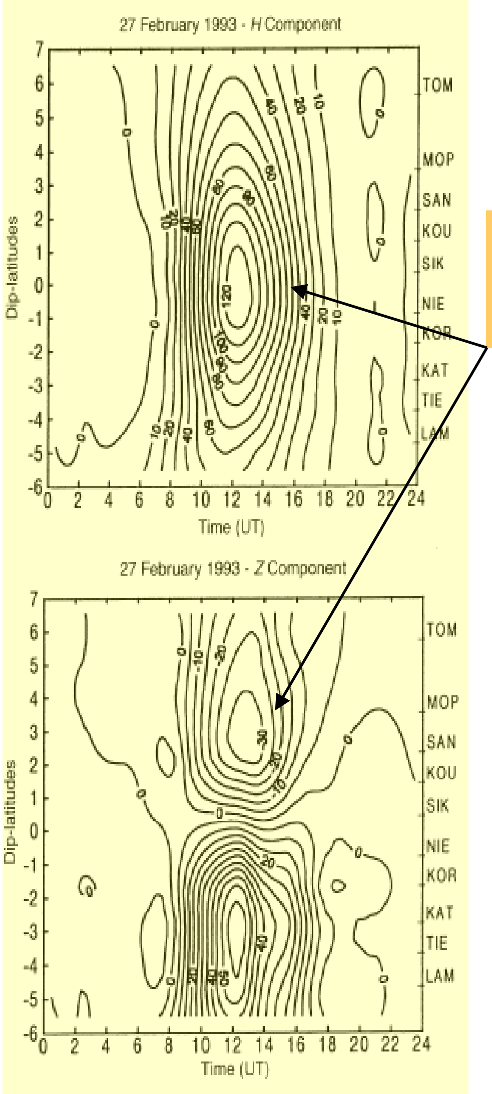


CHAMP satellite Observations

- The counter-electrojet

During certain quiet days, at certain hours (mostly in the morning and afternoon) the latitude profiles of H and Z are reversed accross the dip-equateur. This reversal was interpreted by Gouin and Mayaud in 1967 as the effect of a current ribbon that flow westward, which they named « Counter-electrojet ».

-Contours maps of H and Z as functions of latitude and local hours.

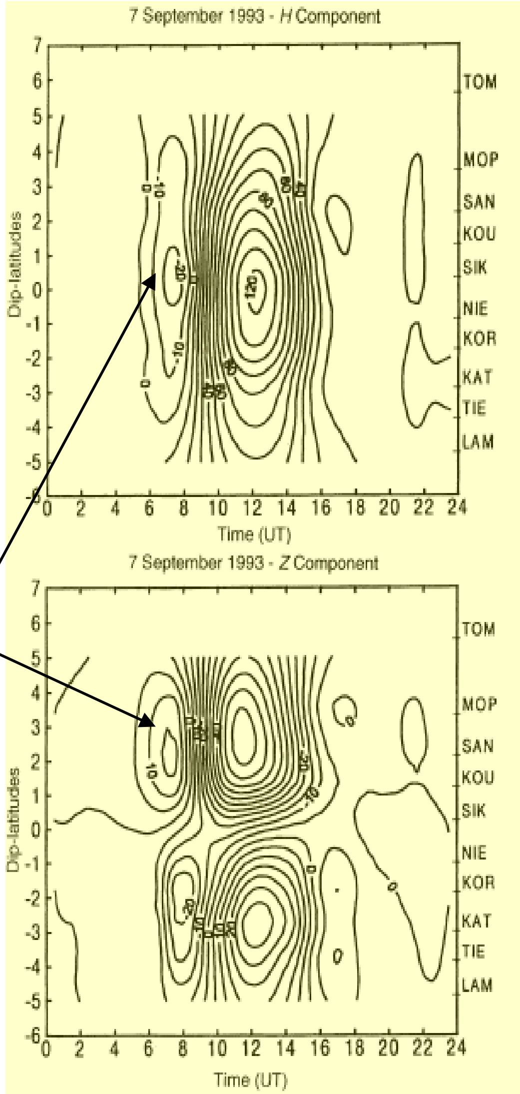


27 February 1993 - *H* Component

27 February 1993 - *Z* Component

Effects of eastward current ribbon : EEJ

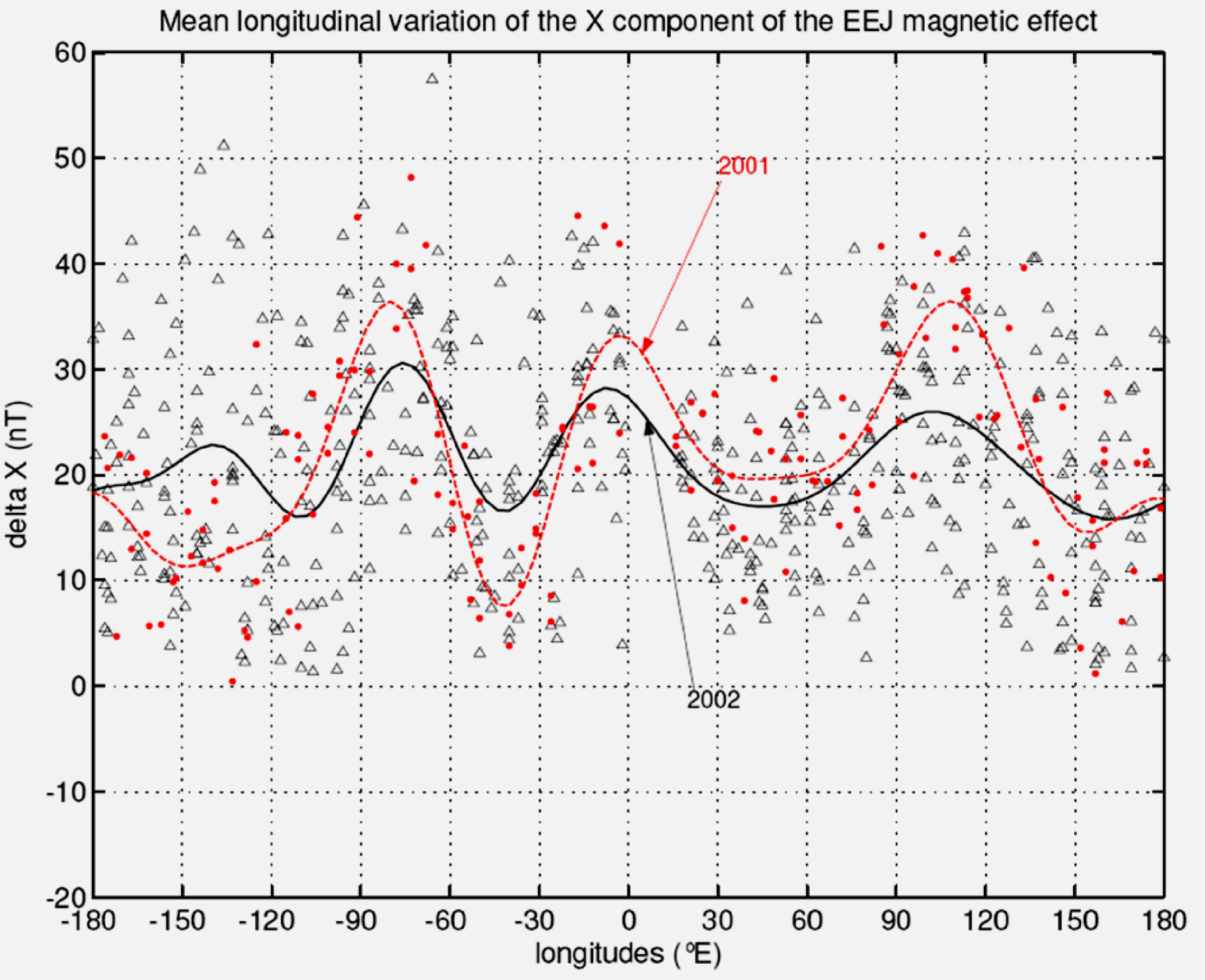
Effects of westward current ribbon : Counter-électrojet



7 September 1993 - *H* Component

7 September 1993 - *Z* Component

longitudinal Variation of the EEJ magnetic effect at 12LT, from CHAMP satellite observations



-Based on the effects in ***H*** and ***Z***, equatorial electrojet has been assimilated some times to a line current *I (A)*, some times to a thin ribbon (Chapman, 1951; Fabitakoye et Mayaud, 1976) or to a thick ribbon (Onwumechili, 1967).

1 – Thin ribbon: $I(x) = I_0 \left(1 - \frac{(x-c)^2}{a^2} \right)^m$ current density in A/km. I_0 current density at the center of the ribbon, ***c*** position of the center and ***a*** the half width of the ribbon.

m=0, uniform distribution (Chapman, 1951)
m=1, parabolic distribution (Chapman, 1951)
m=2, quadratic distribution (Fambitakoye and Mayaud, 1976).

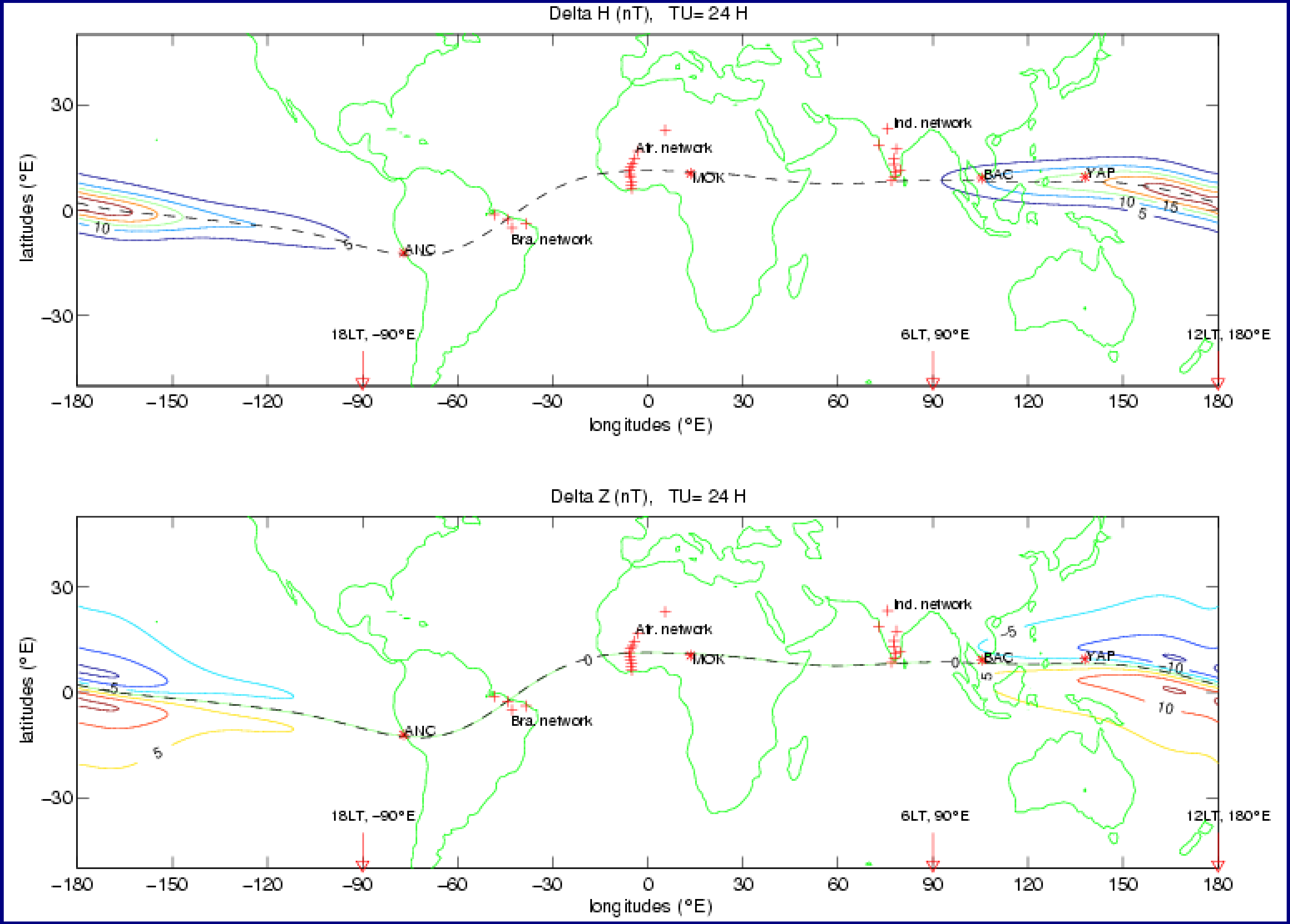
I_0, ***c*** and ***a*** are the EEJ parameters, seen as a thin current ribbon.

2– thick ribbon (Onwumechili, 1967):

$$J(x,z) = J_0 \frac{a^2(a^2+\alpha x^2)}{(a^2+x^2)^2}\frac{b^2(b^2+\beta z^2)}{(b^2+z^2)^2}$$

$J(x,z)$ is current density (A/km^2), J_0 current density at the center. a, b, α and β are the EEJ parameters for thick ribbon.

Simulation of the Equatorial electrojet effects (Doumouya et al., 2003)



Snapshots (fixed UT) of the EEJ magnetic signature at 450km

Interpretation of the daily regular variations of the geomagnetic field has resulted in concept of equivalent current systems in mid (Sq) and low (EEJ) latitude ionosphere. The question that arises from this is:

What are the origins of these currents?

The response of this question is given through **ionospheric dynamo theories**.

The second part of my lecture will now address this aspect, with a special accent on low latitude currents that are the equatorial electrojet and associated currents.

IONOSPHRIC DYNAMO

- Equivalent currents determined from daily regaular variations of the geomagnetic field, clearly demonstrate the existance of current flow in ionosphere.

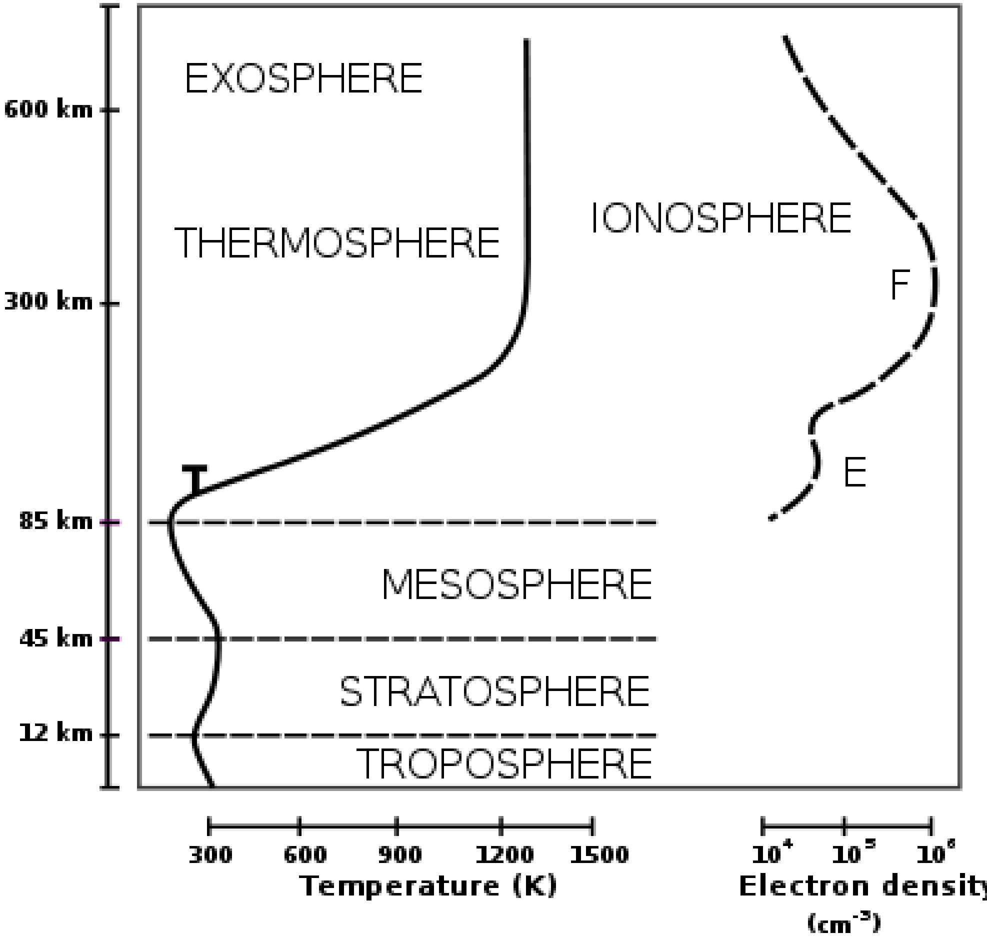
- Which physical processes govern the generation of these currents in low and mid latitude ionosphere?

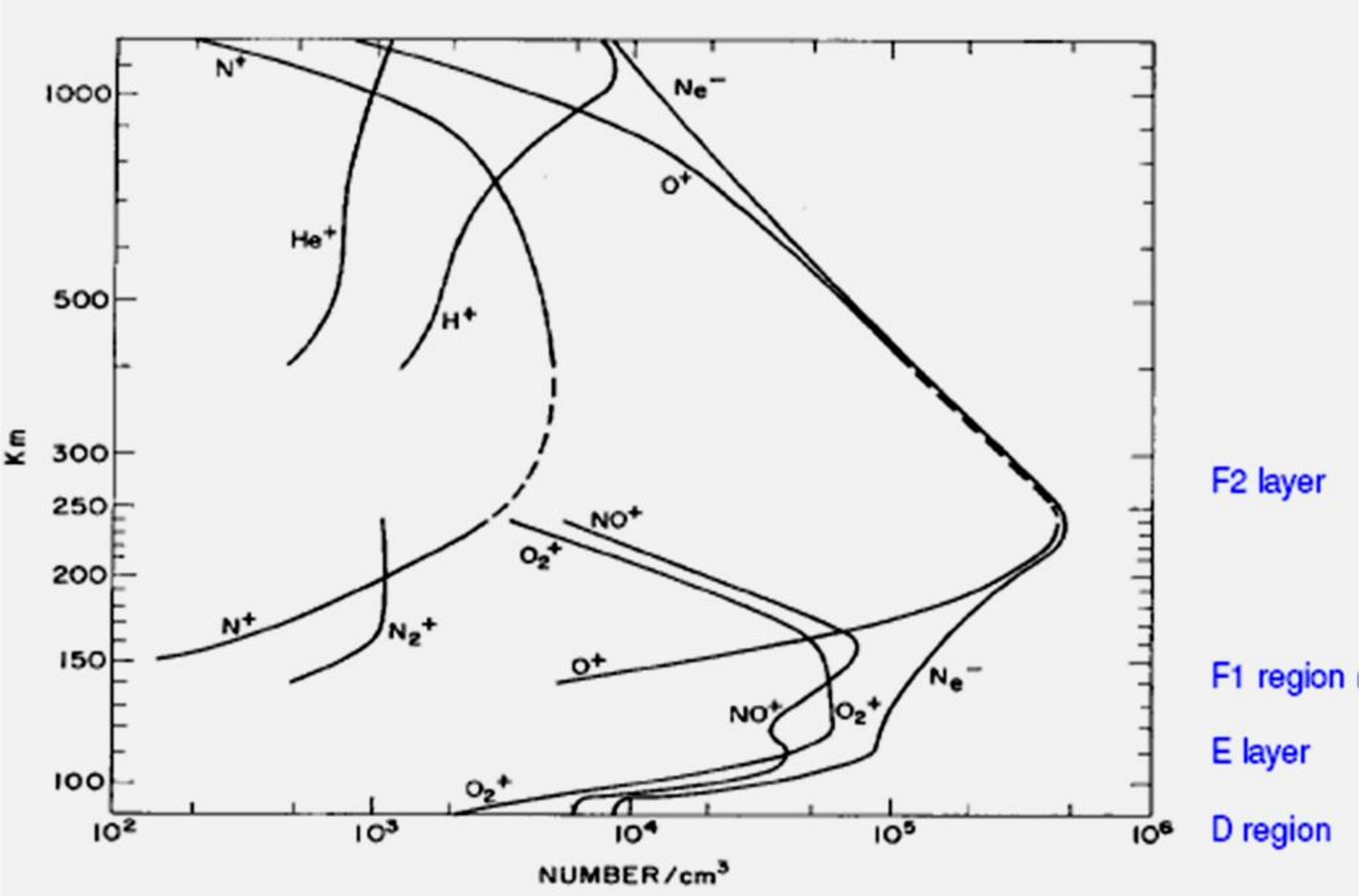
-To respond this question it is important to have a clear idea of the ionosphere through its composition, structure, conductivity, interactions between particles that compose ionospheric plasma, and with Earth’s magnetic field.

Ionosphere

Ionosphere is the partially ionised layer of the atmosphere.

It is located above 50 km altitude and coupled with the mesosphere and the thermosphere.





Vertical profiles of electrons and different positive ions concentration in ionosphere. Ionospheric layers are displayed.

In the ionosphere negative charges carried by electrons whose density equals that of positive ions together. Ionosphere is a weak density plasma, which is mostly composed by NO^+, O_2^+ and O^+ and electrons in the presence of densest neutral gas.

Electron and ion densities is the balance of processes of production (P), loss (L) by recombination and transport (T) of charges. The density N_r of a given specie r of charged particle can be determined from continuity equation:

$$\frac{\partial N_r}{\partial t} = P(N_r) - L(N_r) - \vec{\nabla} \cdot (N_r \vec{V}_r)$$

$P(N_r)$ is the production rate of the particle r,

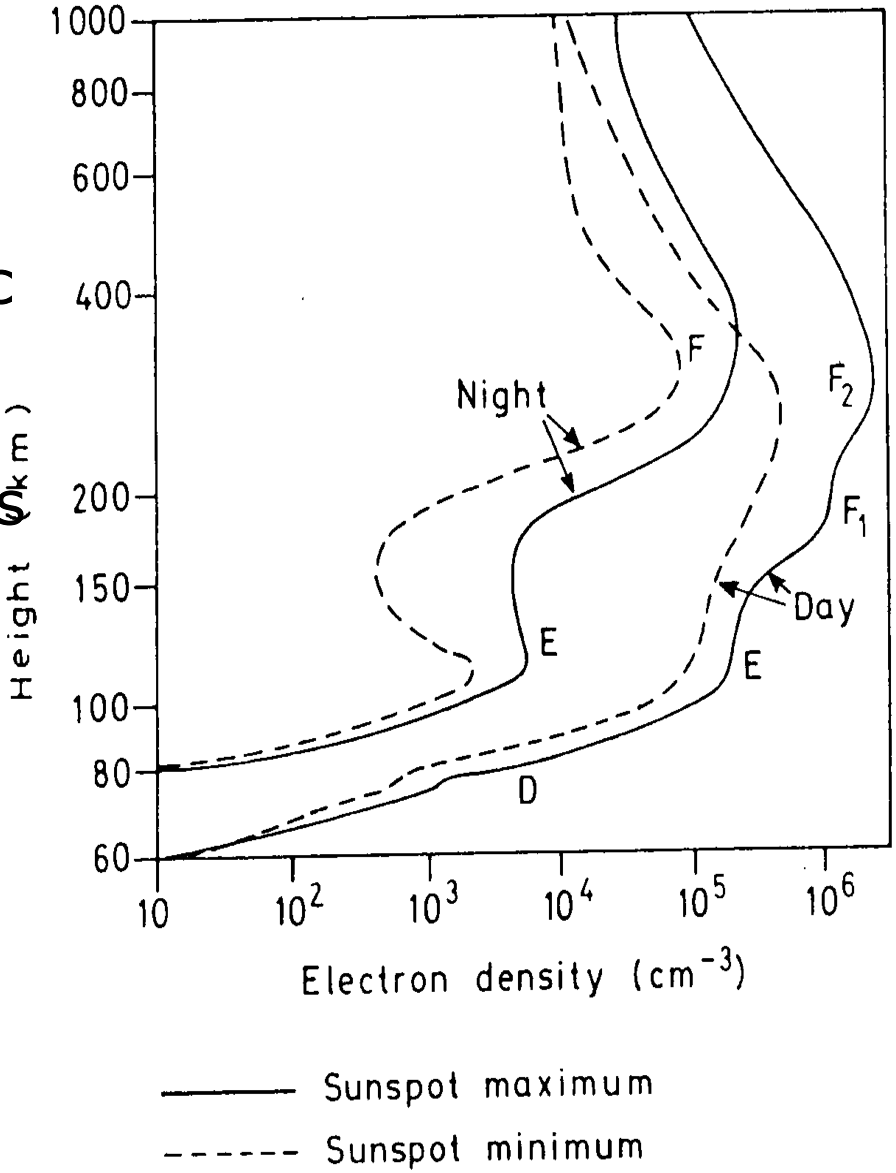
$L(N_r)$ the rate of loss recombination and

$\vec{\nabla} \cdot (N_r \vec{V}_r)$ the rate of transfert of r toward external regions

$\vec{V}_r$ the average velocity of r

Structure of ionosphere

According to the atmospheric composition and dominant processes, ionosphere is divided into D, E et F regions (F is divide into F1 et F2 layers during daytime).



- The D-Region

-The D region, located from 50km to 80km is strongly **collisional**: collision frequencies (ν_{en}) of electrons-neutrals and (ν_{in}) ions-neutrals are very strong. Which causes strong absorption of HF radioelectric waves lower than 1 MHz.

- Recombination is very quick, which causes its disappearance during night time, when photoionisation is stopped.

- The E-Region

The E-region is located between 90 and 150km. In this region, positive ions (NO^+ and O_2^+) density is approximatly equal to electron density *Ne*.

- Strong collision of ions,
- Weak collision for electrons.

-The F-region

The F-region is between 150 et 600km or more. It is divided into two layer (F1 and F2) during daytime.

-The layer F1 (150-200km) is mostly composed NO+ et O2+ positive ions .

-The layer F2 (200-600km) the only one that last during the night, is composed ion O+.

- Weak collisions of both ions and electrons.

-In the F-region the dominant process is diffusion of charges. Plasma is drifted

- upward from E to F-region during the daytime

- downward from magnetosphere during the night, which maintain relative high density in the nighttime F-region.

Ionospheric dynamo

The ionosphere is plasma of weak energy (0.1-1eV). Thus current circulations is caused by the motions of charged particles that are carried by neutral winds across the geomagnetic field. This process gives rise to a dynamo action, known as ionospheric wind dynamo, which produces electric fields and currents in the ionosphere.

Electric fields ion the ionosphere

Through collisions between ions and neutrals, electrons and neutres, and between ions and electrons, charged particles are carried at neutral wind velocity $\vec{V}_n$. A particle of charge q moving in the geomagnetic field ($\vec{B}$), experiences the magnetic force

$$\vec{F} = q(\vec{V}_n \times \vec{B})$$

Which induces the primary electromotive field :

$$\vec{E}_0 = \vec{V}_n \times \vec{B}$$

The magnetic force $\vec{F}$ causes charge separation and results in the polarization field $\vec{E}_p$ between dawn and dusk.

The total electric field in the ionosphere is:

$$\vec{E} = \vec{E}_p + \vec{V}_n \times \vec{B}$$

The current density in the ionosphere is given by the Ohm's law :

$$\vec{j} = \overline{\sigma}(\vec{E}_p + \vec{V}_n \times \vec{B})$$

Where $\overline{\sigma}$ representes the conductivit tensor in the ionosphere.

The ionospheric conductivity and currents

Currents in low and mid latitude ionosphere are generated through dynamo processes that rely on charged particles motions across the geomagnetic field lines. These motions are caused by combined force effects. The most effective forces are:

$$\vec{F}_{em} = \pm e(\vec{E} + \vec{V}_n \times \vec{B})$$

- Lorentz’s force

$$\vec{F}_c = m\nu(\vec{V} - \vec{V}_n)$$

- frictional forces

$$\vec{P} = m\vec{g}$$

- gravitation force

$$\vec{F}_p = \frac{1}{N}\vec{\nabla}(NkT)$$

- pressure gradient force

e is elementary charge;

m and $\vec{V}$ are masse and velocity of charged particle;

ν is its collision frequency;

$\vec{V}_n$ is velocity of neutrals;

$\vec{g}$ is acceleration of gravitation;

N and T are respectively the concentration and temperature of charged particle.

k is the constant of Boltzmann.

The collision frequencies of electrons and ions with neutrals are respectively ν_{en} and ν_{in}, and between electrons and ions are ν_{ei} and ν_{ie}.

In the E and F-regions, concentration of electrons (N_e) equals that positive ions (N_i).

Currents in the dynamo region are due to differential velocity between elctrons and ions $(\vec{V}_i - \vec{V}_e)$, according to

$$\vec{j} = N_e . e(\vec{V}_i - \vec{V}_e)$$

This differential velocity is obtained by solving the equations of motions of the particles based on forces balance.

$$N_e e(\vec{E} + \vec{V}_i \times \vec{B}) - N_e m_i \nu_{in}(\vec{V}_i - \vec{V}_n) - N_e m_i \nu_{ie}(\vec{V}_i - \vec{V}_e) + N_e m_i \vec{g}$$
$$- \vec{\nabla}(N_e k T_i) = 0$$

$$- N_e e(\vec{E} + \vec{V}_e \times \vec{B}) - N_e m_e \nu_{en}(\vec{V}_e - \vec{V}_n) - N_e m_e \nu_{ei}(\vec{V}_e - \vec{V}_i) + N_e m_e \vec{g}$$
$$- \vec{\nabla}(N_e k T_e) = 0$$

In these equations, dominant forces are electromagnetiques ($\vec{F}_{em}$) and frictional forces ($\vec{F}_c$).

For simplification, gravitational and pressure gradient forces are neglected. The equations become:

$$N_e e(\vec{E}+\vec{V}_i\times\vec{B}) - N_e m_i \nu_{in}(\vec{V}_i-\vec{V}_n) - N_e m_i \nu_{ie}(\vec{V}_i-\vec{V}_e) = 0$$

$$-N_e e(\vec{E}+\vec{V}_e\times\vec{B}) - N_e m_e \nu_{en}(\vec{V}_e-\vec{V}_n) - N_e m_e \nu_{ei}(\vec{V}_e-\vec{V}_i) = 0$$

The equations are solved in the geomagnetic field referential system.

After solving the equations, the total current in ionosphere is given by:

$$\vec{j} = \sigma_0 \vec{E}_{//} + \sigma_P (\vec{E}_\perp + \vec{V}_n \times \vec{B}) + \sigma_H \frac{\vec{B}}{B} \times (\vec{E}_\perp + \vec{V}_n \times \vec{B})$$

$\vec{E}_{//}$ and $\vec{E}_\perp$ are projections of electric field $\vec{E}$ in the directions parallele and perpendicular to $\vec{B}$; B is the intensity of $\vec{B}$.

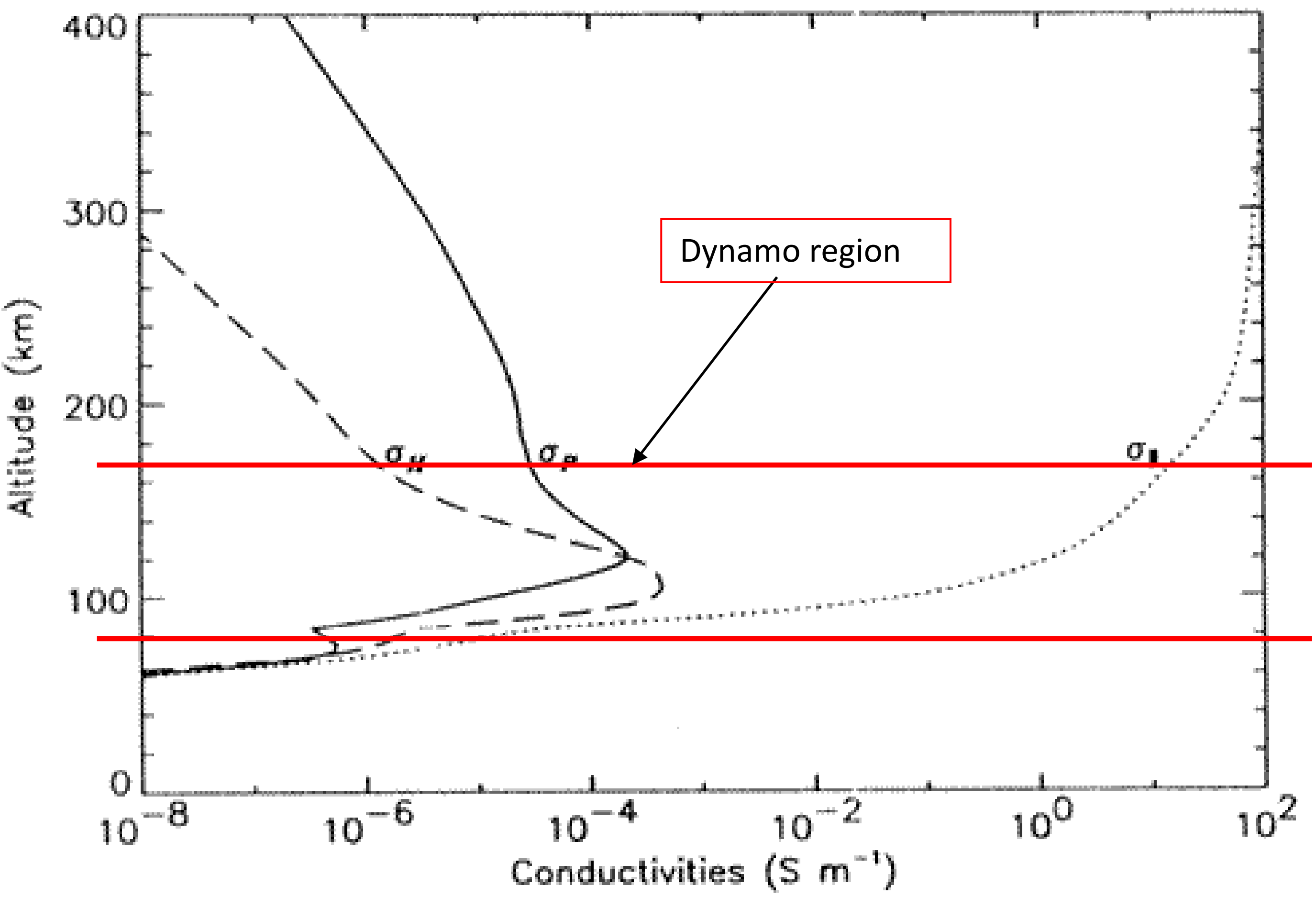
$$\sigma_0 = N_e e^2 \left(\frac{1}{m_e \nu_e} + \frac{1}{m_i \nu_i}\right)$$: parallele conductivity

$$\sigma_P = \frac{N_e e}{B}\left(\frac{\nu_e \Omega_e}{\nu_e^2 + \Omega_e^2} + \frac{\nu_i \Omega_i}{{}_i\nu_i^2 + \Omega_i^2}\right)$$: conductivité de Pedersen

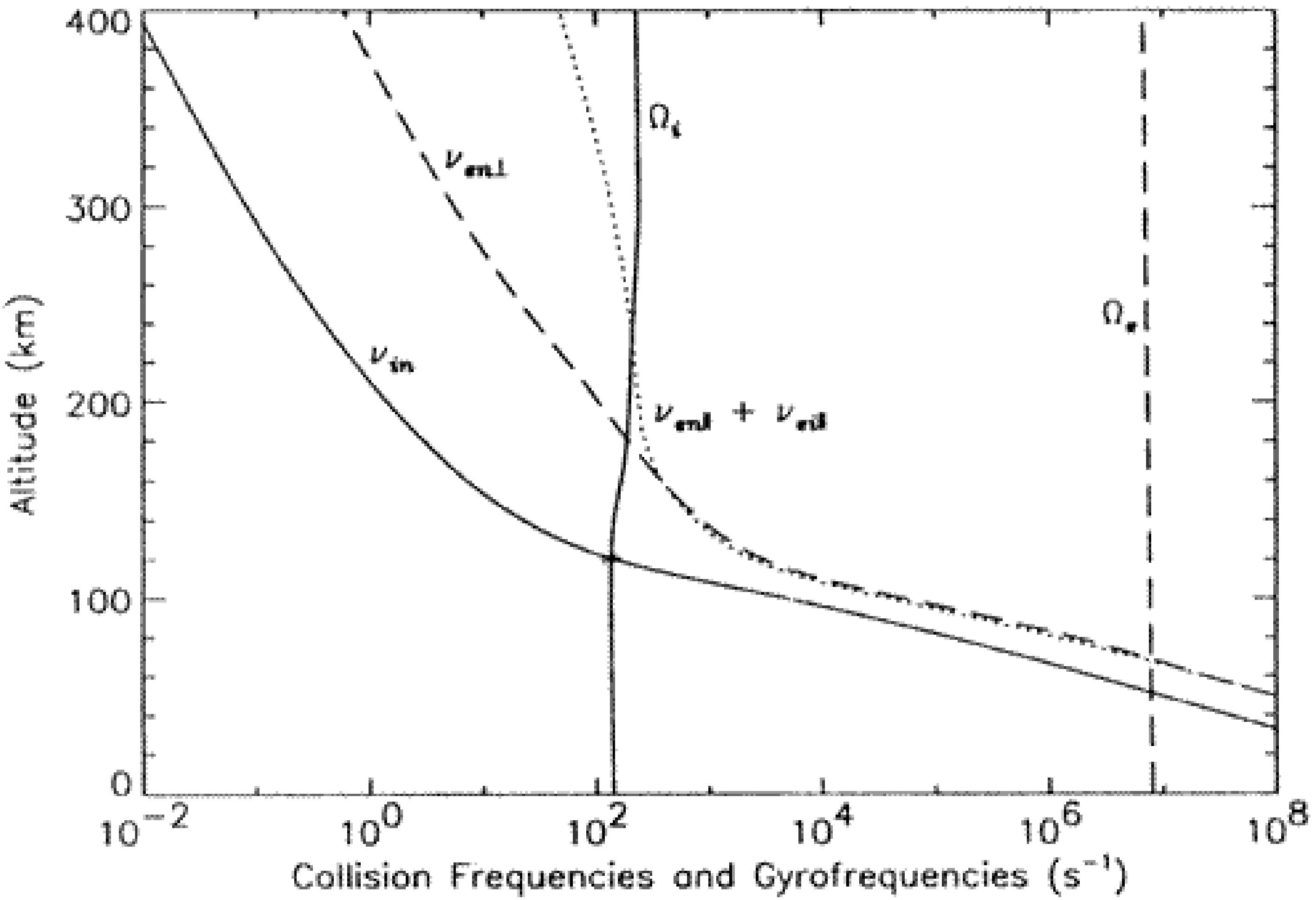
$$\sigma_H = \frac{N_e e^2}{B}\left(\frac{\Omega_e^2}{\nu_e^2 + \Omega_e^2} - \frac{\Omega_i^2}{\nu_i^2 + \Omega_i^2}\right)$$: conductivité de Hall

$\Omega_e = \frac{eB}{m_e}$ and $\Omega_i = \frac{eB}{m_i}$ gyrofréquencies;

$\nu_e = \nu_{en} + \nu_{ei}$ and $\nu_i = \nu_{in} + \nu_{ie}$ effective collision frequencies



Profils verticaux de conductivité parallèle ($\sigma_{//}$), de Pedersen (σ_P) et de Hall (σ_H), en moyenne latitude, en équinoxe dans les conditions de minimum solaire. (Richmond, 1995).


400
300
200
100
0
Altitude (km)
Ω_i
$\nu_{en\perp}$
ν_{in}
Ω_e
$\nu_{en\parallel} + \nu_{ei}$
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{8}
Collision Frequencies and Gyrofrequencies (s^{-1})

Ionospheric current

The general ionospheric current density

$$\vec{j} = \sigma_0 \vec{E}_{//} + \sigma_P (\vec{E}_{\perp} + \vec{V}_n \times \vec{B}) + \sigma_H \frac{\vec{B}}{B} \times (\vec{E}_{\perp} + \vec{V}_n \times \vec{B})$$

Comprises 3 components

$$\vec{j}_{//} = \sigma_0 \vec{E}_{//}$$ Parallele current

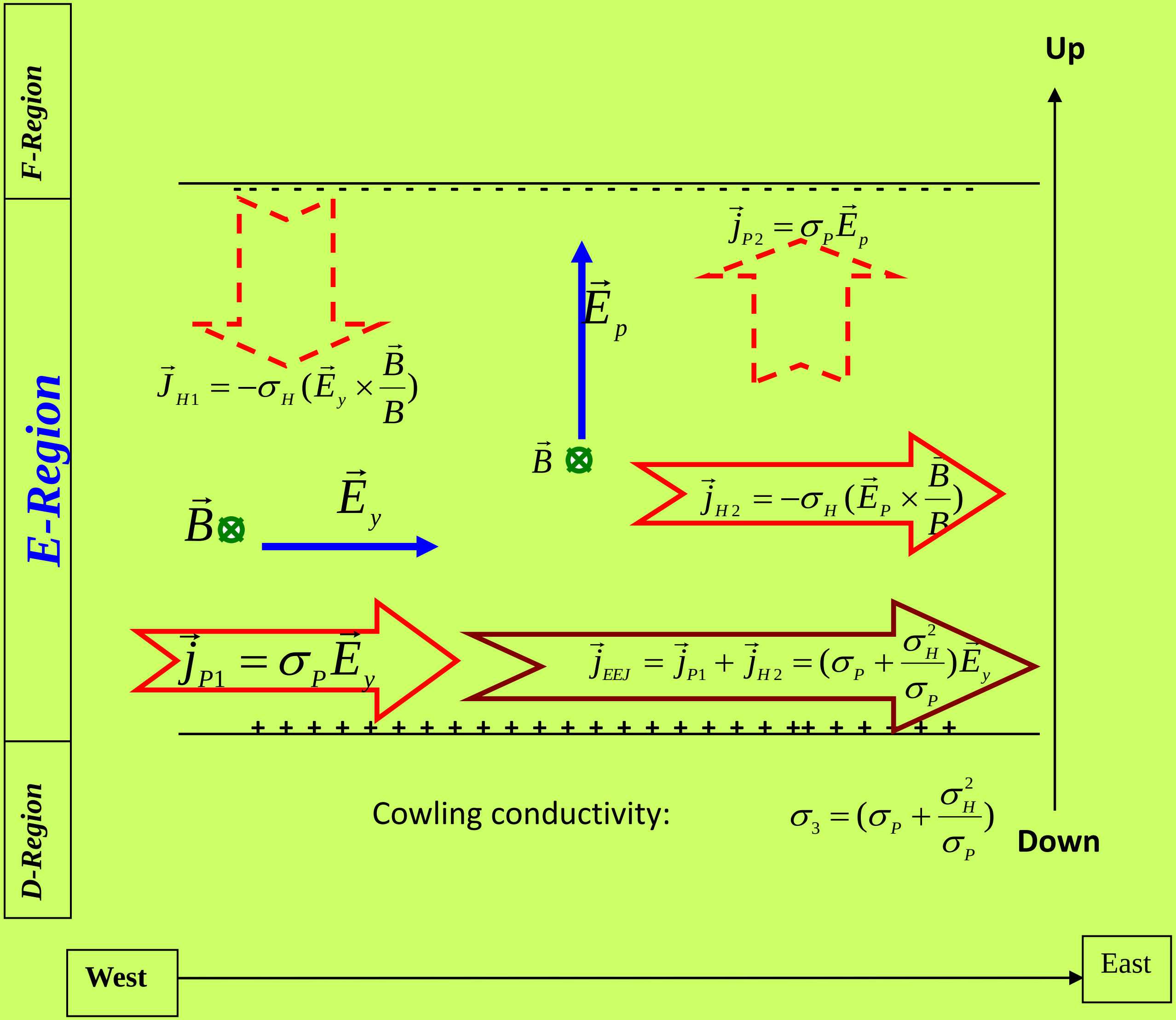
$$\vec{j}_P = \sigma_P (\vec{E}_{\perp} + \vec{V}_n \times \vec{B})$$ Pedersen current

$$\vec{j}_H = \sigma_H \frac{\vec{B}}{B} \times (\vec{E}_{\perp} + \vec{V}_n \times \vec{B})$$ Hall current

Equatorial Electrojet and associated currents

In low latitude electrique field of the global dynamo is horizontal and eastward during daytime . This zonal electric field $\vec{E}_y$, is perpendicular to the geomagnétic field $\vec{B}$ which is northward.

Mechanisme de l’EEJ



$$\vec{J}_{H1} = -\sigma_H (\vec{E}_y \times \frac{\vec{B}}{B})$$

$$\vec{j}_{P2} = \sigma_P \vec{E}_p$$

$$\vec{E}_p$$

$$\vec{B} \otimes$$

$$\vec{j}_{H2} = -\sigma_H (\vec{E}_P \times \frac{\vec{B}}{B})$$

$$\vec{B} \otimes \quad \vec{E}_y$$

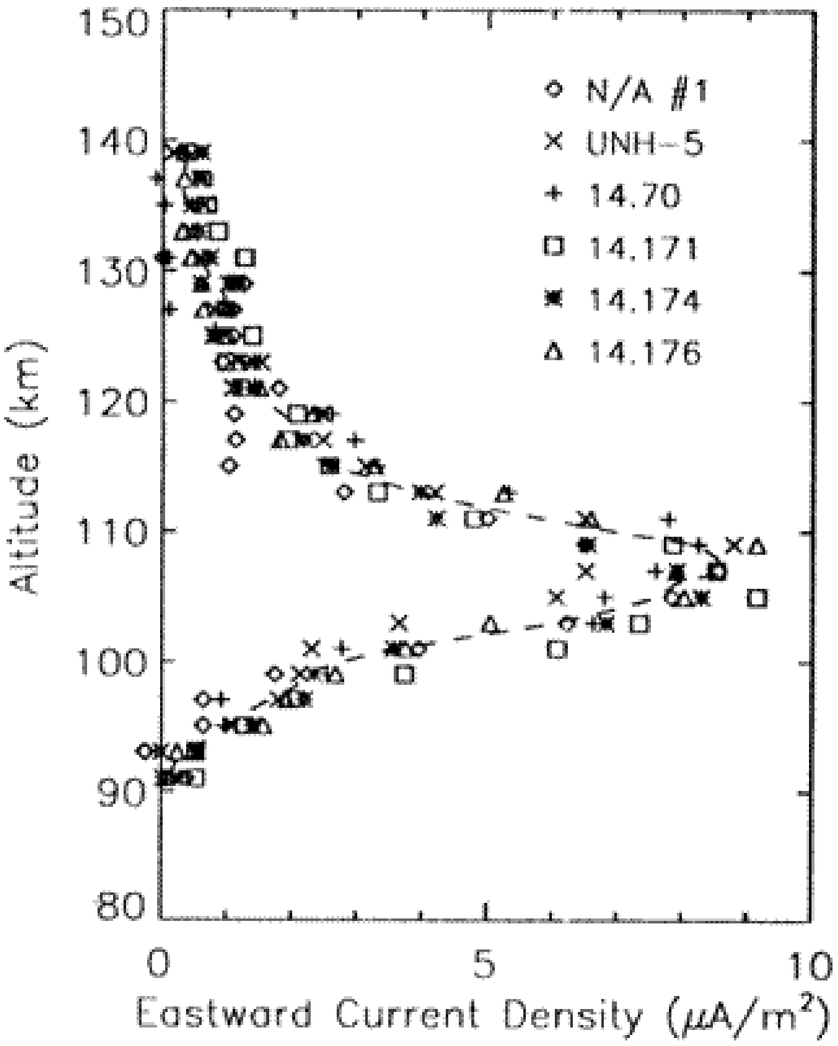
$$\vec{j}_{P1} = \sigma_P \vec{E}_y$$

$$\vec{j}_{EEJ} = \vec{j}_{P1} + \vec{j}_{H2} = (\sigma_P + \frac{\sigma_H^2}{\sigma_P})\vec{E}_y$$

Cowling conductivity: $\sigma_3 = (\sigma_P + \frac{\sigma_H^2}{\sigma_P})$

$$\vec{j}_{H2} = -\sigma_H (\vec{E}_P \times \frac{\vec{B}}{B})$$

Supplement current due to horizontal configuration of $\vec{E}_y$ and $\vec{B}$ at the dip-equator.

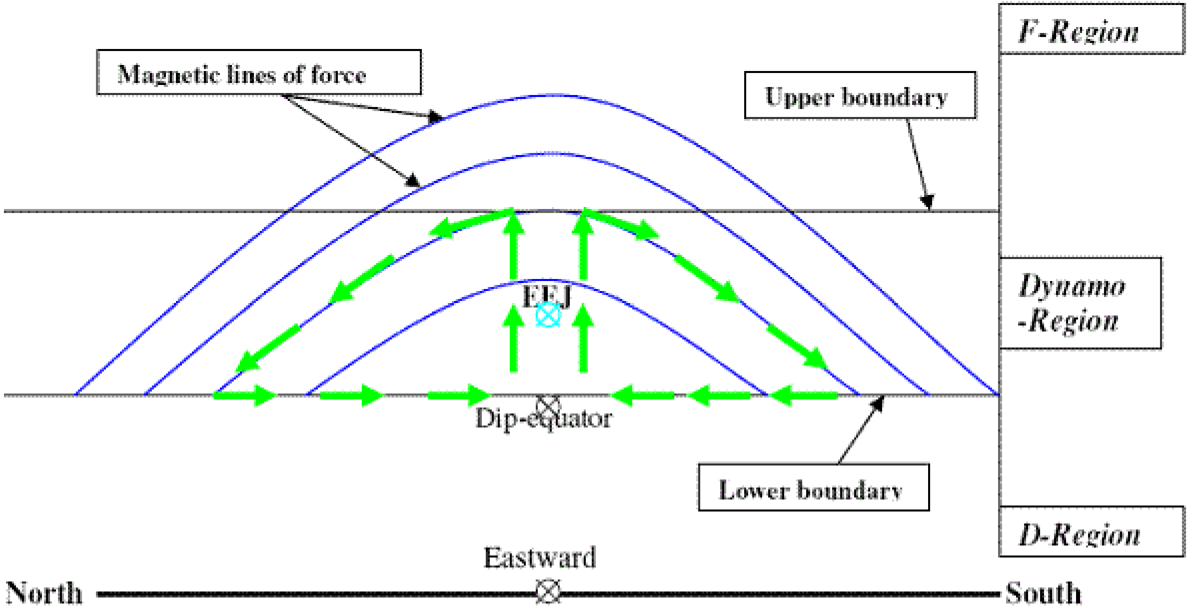


Profil vertical de la densité de courant à l'équateur magnétique au Pérou, à partir des mesures de fusées.

- Meridional current of the equatorial electrojet

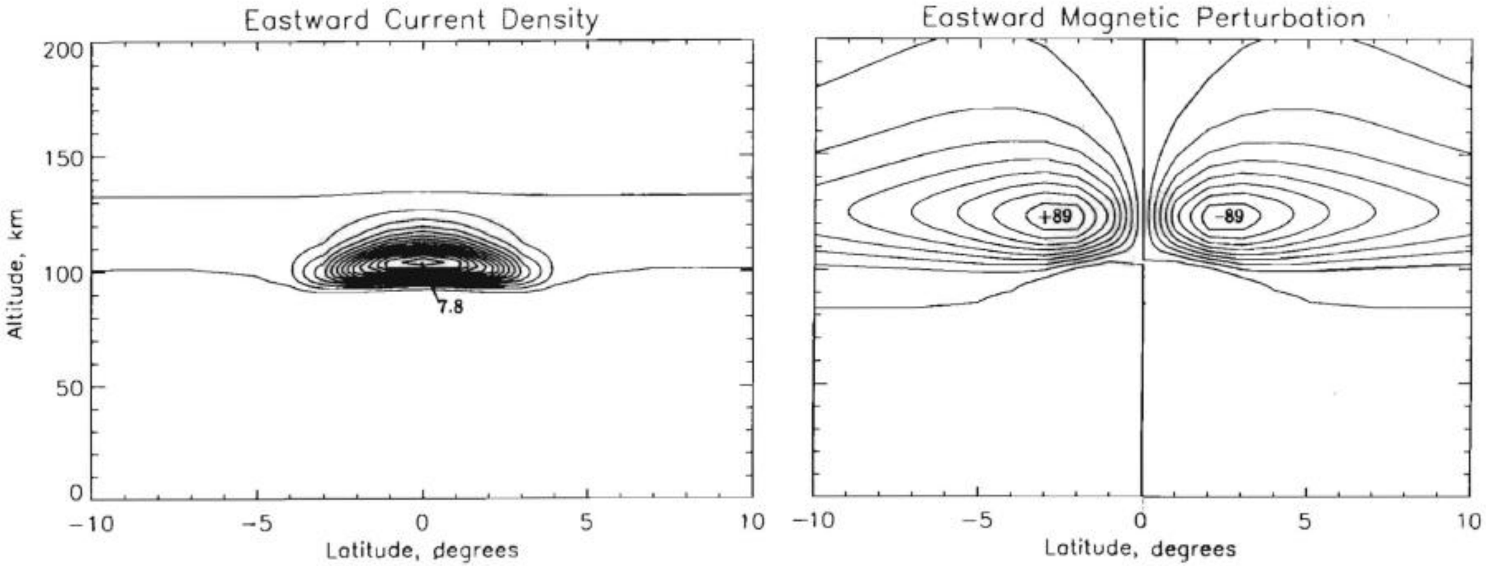
$$\frac{E_p}{E_y} > \frac{\sigma_H}{\sigma_P}$$

$$\frac{E_p}{E_y} = \frac{\int \sigma_H ds}{\int \sigma_P ds}$$



$$\vec{j}_z = \sigma_P \vec{E}_p - \sigma_H (\vec{E}_y \times \frac{\vec{B}}{B}) > 0$$

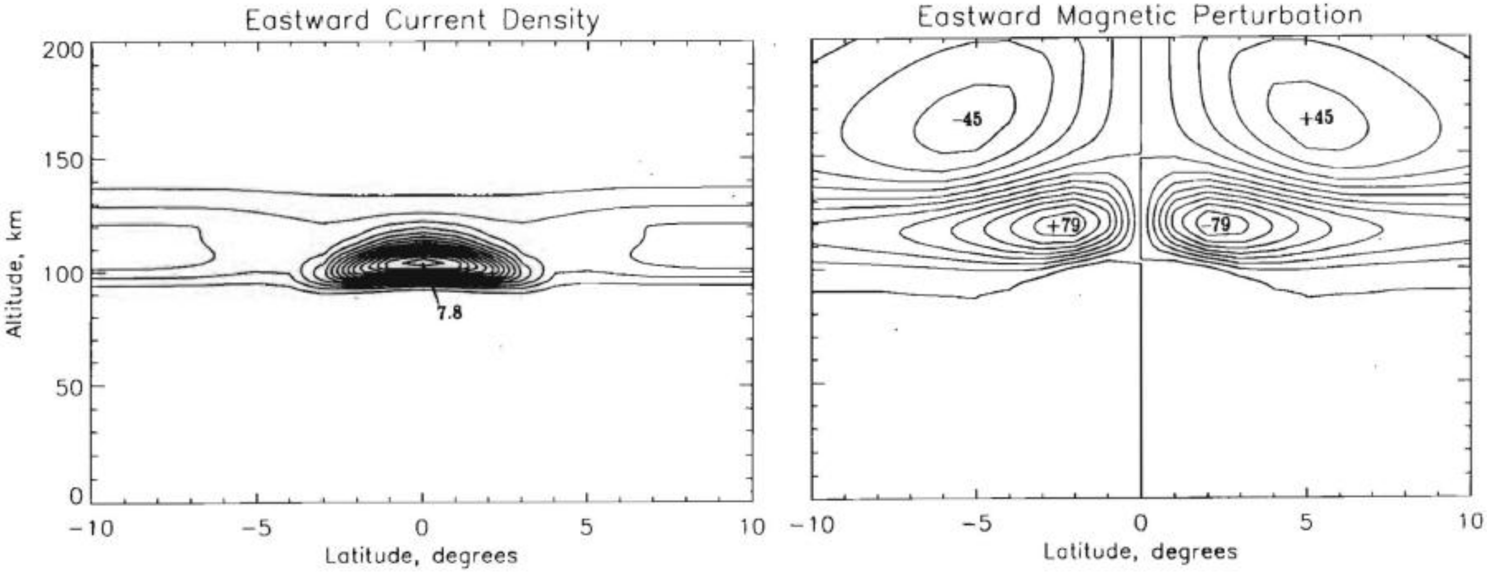
Eastward Electric Field = 0.5 mV/m, No Wind



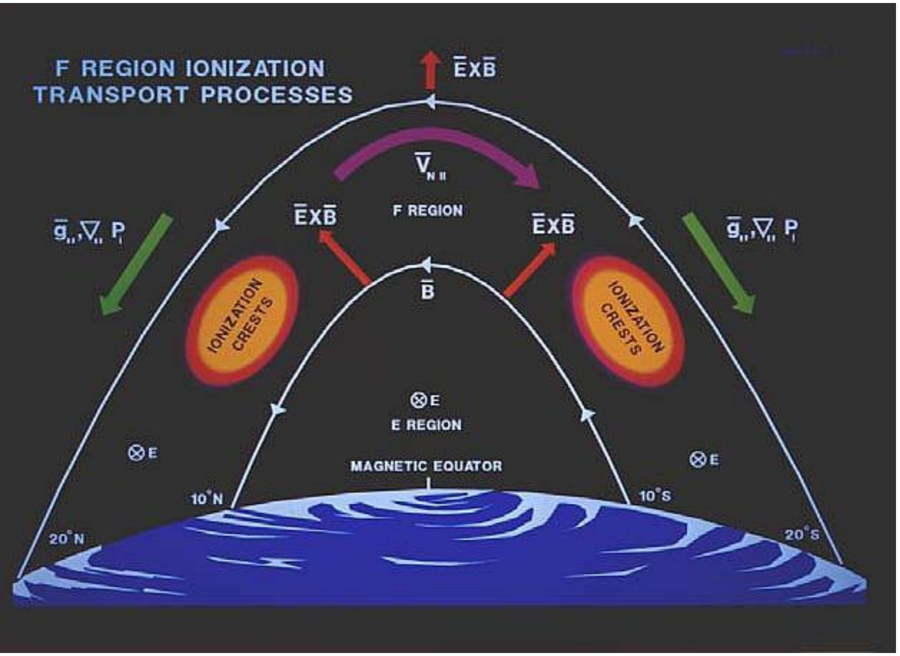
Contour Interval 0.5 $\mu A/m^2$

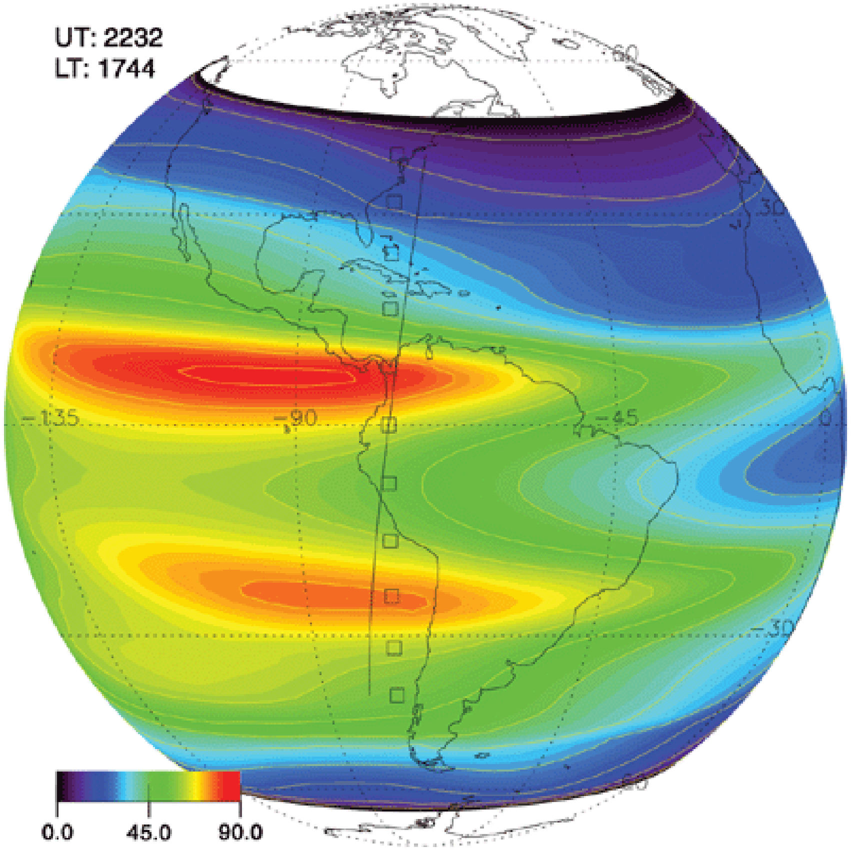
Contour Interval 10 nT

Adding High-altitude Eastward Wind



- Anomalie équatoriale





- At higher altitude, in F- region, the proces that originates meridional currents in the E region, cause equatorial anomaly.

Conclusion

Particular configuration of the geomagnetic field and electric field generates

- An intense current : EEJ

- A strong conductivity : Cowling Conductivity

- Equatorial fontaine and ionisation anomaly

- Plasma irregularities and bubbles.