Equatorial Ionospheric Electrodynamics

Outline

- Basic Principles

  Assume knowledge of altitude, latitude, and local time distribution of ion and neutral number density.

- Phenomenology and Explanations
  - E-region Dynamo
    - Basic diurnal drift patterns
  - F-region Dynamo
    - Day-night asymmetry in zonal drifts
    - Pre-reversal enhancement
  - Gravity driven currents
    - Spread-F
  - External Drivers (maybe)
- Challenges

Basic Principles

In a partially ionized plasma in a magnetic field the charged particle motion is anisotropic. It is determined by the distribution of charged and neutral particles.

THUS
Forces may drive ions and electrons at different speeds producing a current that may have a divergence

BUT
Polarization electric fields are produced to make the total current divergence free everywhere.

THEN
Modified electric fields redistribute the ionization and change the anisotropic motions.

Basic Principles

Forces that drive currents

- **Collisions with neutral particles.**
  - **Assume that neutral atmosphere and winds are given.**
  - **Tidal oscillations that propagate up from below.**
  - **In-situ circulation due to high-latitude energetic particles, Joule heating, and local heating from the sun.**

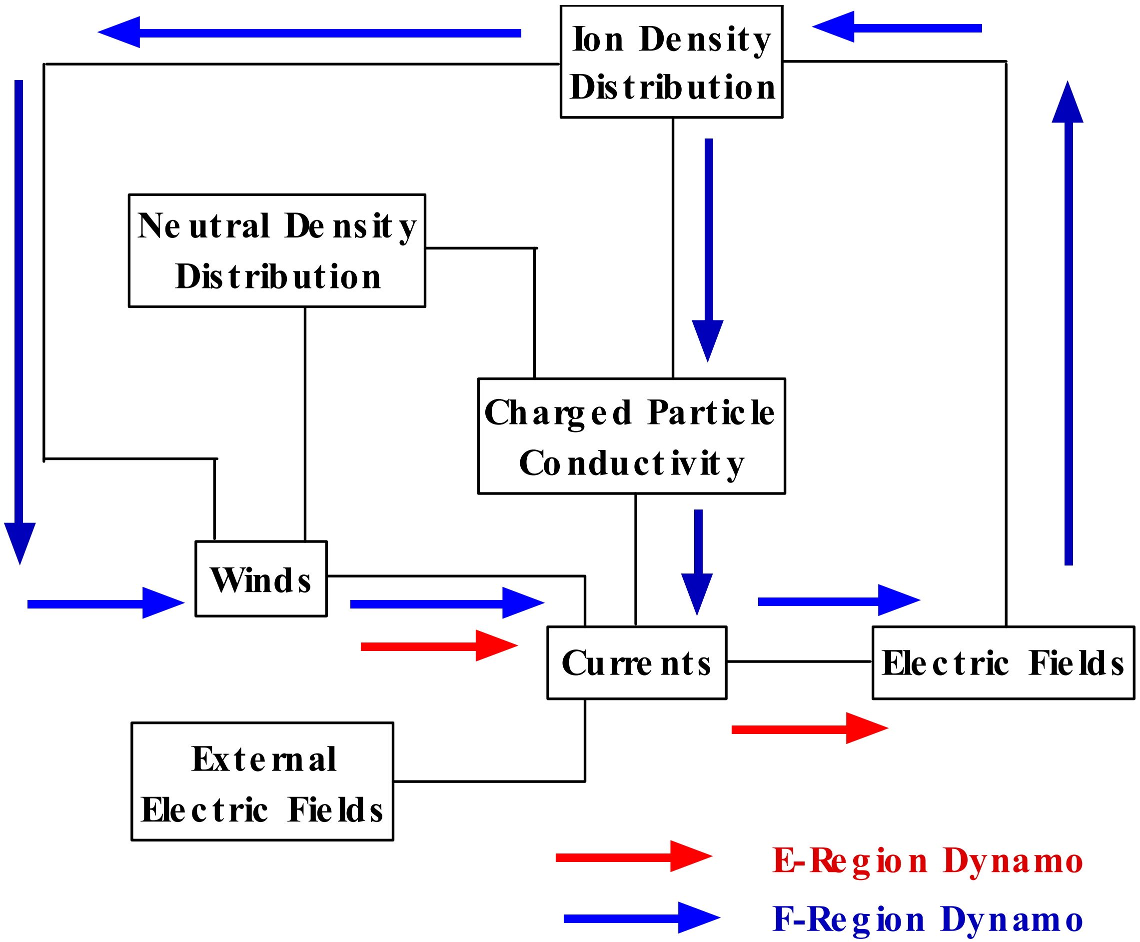
- **Electric Fields**
  - **Externally applied from magnetospheric sources.**
    - **Assume that they apply a potential difference across the region.**
  - **Internally produced to make total current divergence free.**

- **Lorentz Force**
  - **A charged particle in motion feels a force** $q\left(\vec{V} \times \vec{B}\right)$

- **Gravity**
  - **Most important for ions.**

- **Pressure Gradient**
  - **Perpendicular to the magnetic field this current is divergence free.**
  - **Parallel to the magnetic field is produces an ambipolar electric field to make ions and electrons move together.**

Basic Principles



Ion Density Distribution

Neutral Density Distribution

Charged Particle Conductivity

Winds

Currents

Electric Fields

External Electric Fields

→ E-Region Dynamo

→ F-Region Dynamo

Basic Principles

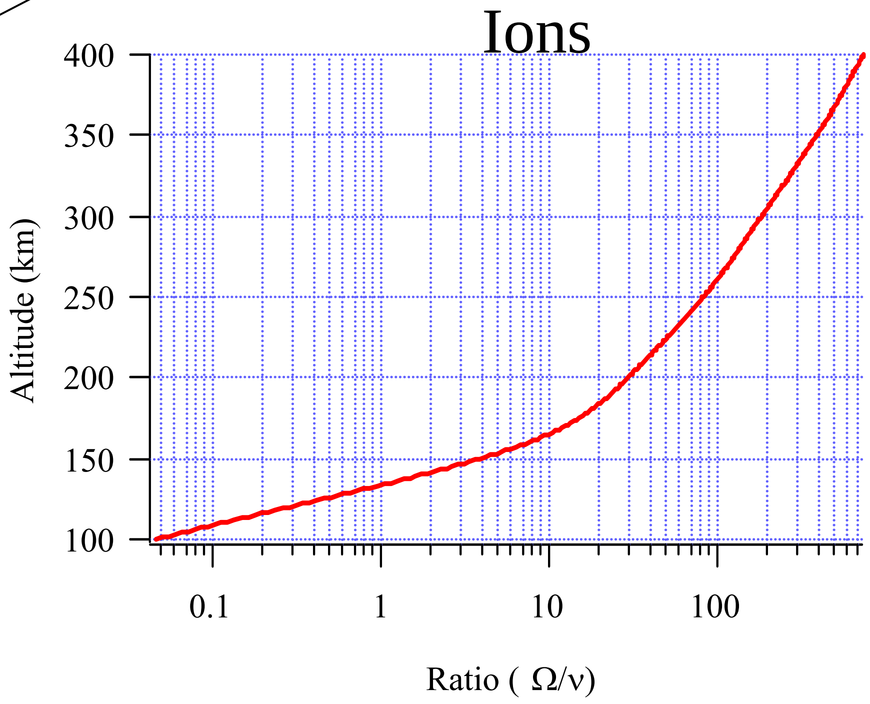
$$0 = -\frac{1}{N_i}\nabla N_i k T_i \quad + \quad m_i\vec{g} \quad + \quad e\left(\vec{E} \; + \; \vec{V}_i \times \vec{B}\right) \quad - \quad m_i \upsilon_{in}\left(\vec{V}_i - \vec{U}\right)$$

Pressure Gradient	**Gravity**	**Electric Field**	**Lorentz**	**Collisions with Neutrals**

$$0 = \underbrace{-\frac{1}{N_i m_i \upsilon_{in}}\nabla N_i k T_i \quad + \quad \frac{1}{\upsilon_{in}}\vec{g} \quad + \quad \frac{e}{m_i \upsilon_{in}}\vec{E} \; + \; \vec{U}}_{\textbf{Velocity Independent Forces } \vec{F}} \; + \; \frac{\Omega_i}{\upsilon_{in}}\vec{V}_i \times \hat{b} \quad - \quad \vec{V}_i$$

$$V_i^{\|} = F_i^{\|}$$

$$\vec{V}_i^{\perp} = \frac{1}{1 + \left(\Omega / \upsilon_{in}\right)^2}\left[\vec{F} + \Omega / \upsilon_{in} \, \vec{F} \times \hat{b}\right]$$



Basic Principles

Polarization fields are created by differences in ion and electron numbers of 1 in 10^8
Polarization fields are created on time scales of 10^{-6} seconds

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) \qquad \nabla \bullet \mathrm{J} = 0$$

The current is often expressed in terms of the direct, Pedersen, and Hall conductivity.

These are scalar quantities.

The use of Pedersen and Hall to denote currents can be quite dangerous since now a direction is implied with respect to the electric field.

Since the medium can polarize the electric field is generally not known a priori.

$$\sigma_0 = \frac{Ne^2}{m_e\upsilon_e} + \frac{Ne^2}{m_i\upsilon_i} \approx \frac{Ne^2}{m_e\upsilon_e}$$

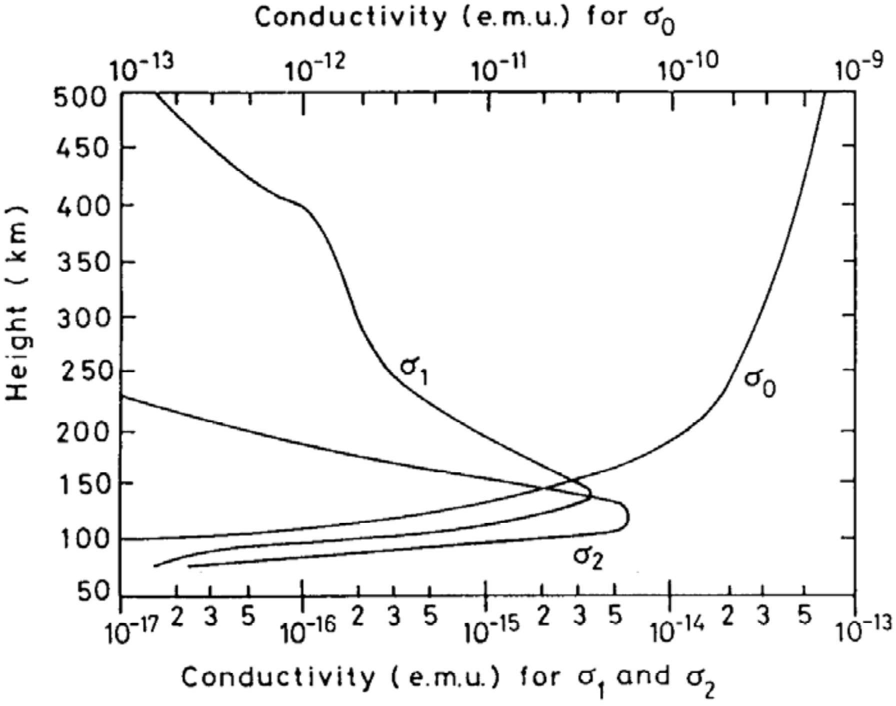
$$\sigma_p = Ne^2\left\lfloor \frac{1}{m_e}\frac{\upsilon_e}{\left(\upsilon_e{}^2 + \Omega_e{}^2\right)} + \frac{1}{m_i}\frac{\upsilon_i}{\left(\upsilon_i{}^2 + \Omega_i{}^2\right)} \right\rfloor$$

$$\approx \frac{Ne^2}{m_i}\frac{\upsilon_i}{\left(\upsilon_i{}^2 + \Omega_i{}^2\right)}$$

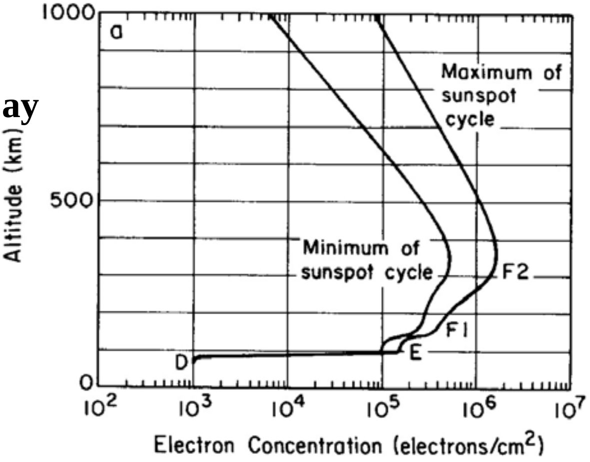
$$\sigma_H = Ne^2\left\lfloor \frac{1}{m_i}\frac{\Omega_i}{\left(\upsilon_i{}^2 + \Omega_i{}^2\right)} - \frac{1}{m_e}\frac{\Omega_e}{\left(\upsilon_e{}^2 + \Omega_e{}^2\right)} \right\rfloor$$

*** Ion and Electron Terms Cancel at high altitudes**

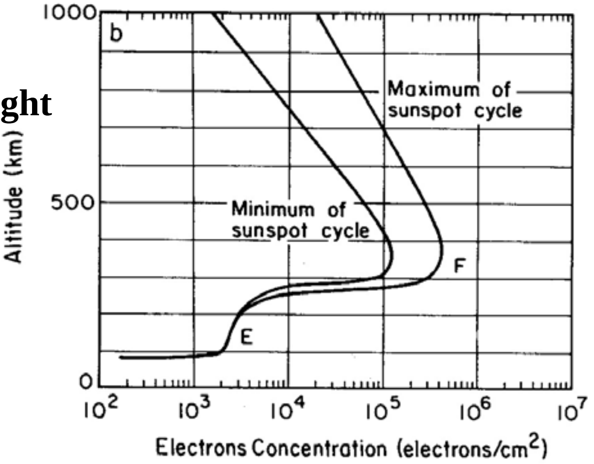
Ion Concentration and Conductivity



Day



Night



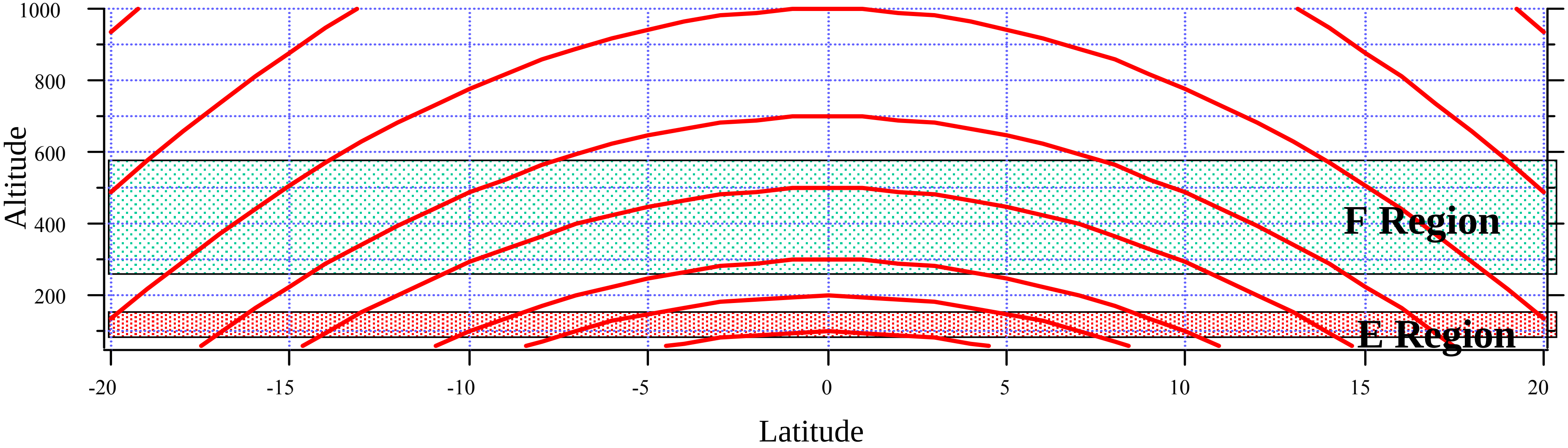
- **Hall conductivity in a layer near 120 km**
  Essentially removed at night

- **Pedersen conductivity distributed in two regions**
  E-region much greater than F-region during the daytime
  F region much greater than E region at night.

- **Direct conductivity much greater than transverse conductivities everywhere above 90 km.**
  For spatial scales larger than 10 km magnetic field lines are almost electric equipotentials even though field-aligned currents flow.

Basic Principles

$$\vec{J} = Ne\left(\vec{V}_i - \vec{V}_e\right) \qquad \nabla \bullet \mathrm{J} = 0 \qquad \frac{\partial \vec{J}^{\perp}}{\partial \perp} + \frac{\partial \vec{J}^{\parallel}}{\partial \parallel} = 0$$



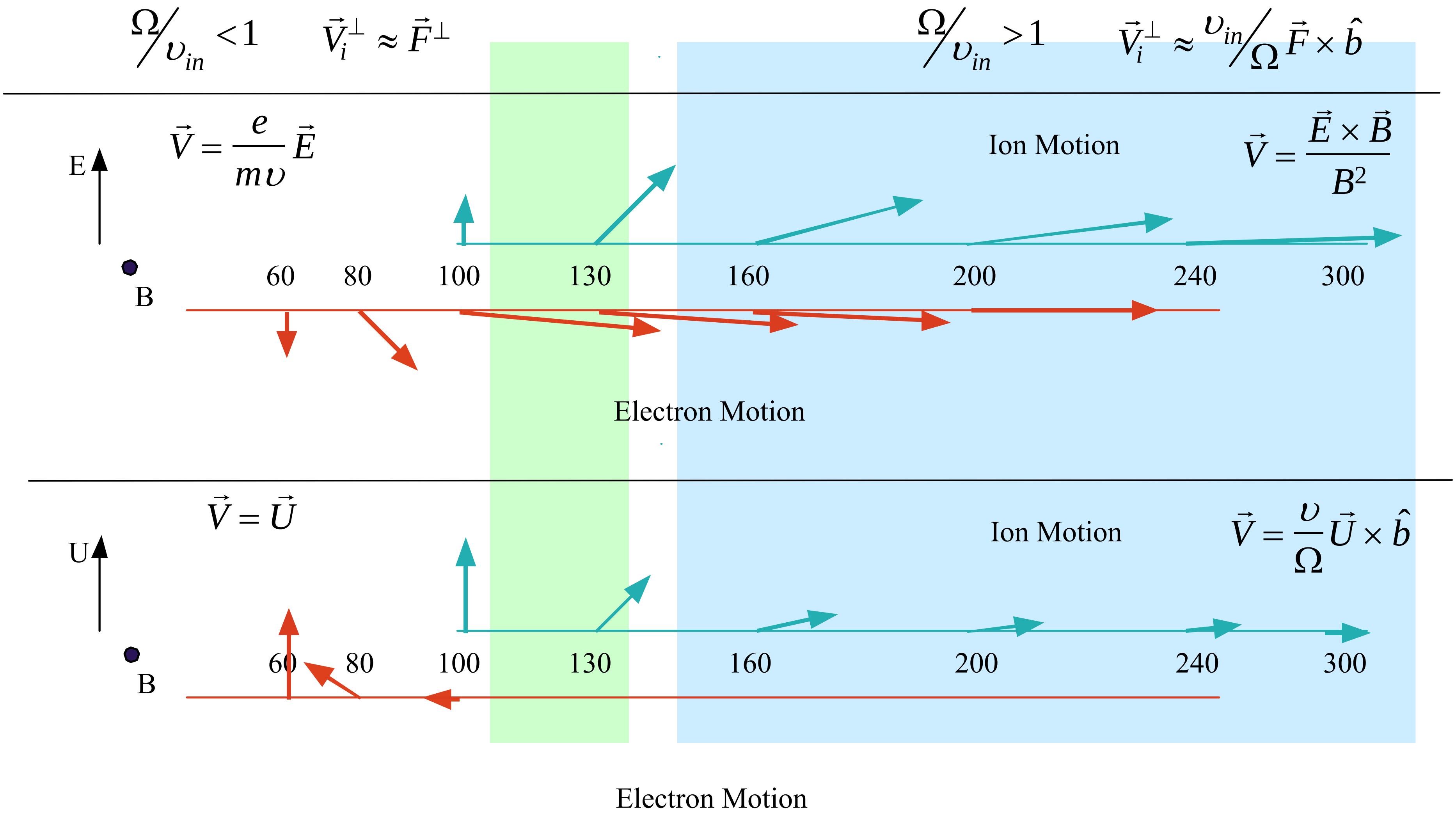
We assume that no current flows out of the bottom of the region and that above some altitude say 1000 km, the perpendicular current is negligible.

$$\int_{\substack{other\\end}}^{\substack{one\\end}} \frac{\partial \vec{J}^{\perp}}{\partial \perp} ds = 0 \qquad \int_{\substack{other\\end}}^{\substack{one\\end}} \left.\frac{\partial \vec{J}^{\perp}}{\partial \perp}\right|_{driver} ds + \int_{\substack{other\\end}}^{\substack{one\\end}} \left.\frac{\partial \overline{\sigma} \vec{E}^{\perp}}{\partial \perp}\right| ds = 0$$

Electric field depends on flux-tube integrated drivers and conductivity.

Basic Principles

Charged particle Motions Perpendicular to B



$\Omega/\upsilon_{in} < 1$ $\quad \vec{V}_i^{\perp} \approx \vec{F}^{\perp}$

$\Omega/\upsilon_{in} > 1$ $\quad \vec{V}_i^{\perp} \approx \upsilon_{in}/\Omega\, \vec{F} \times \hat{b}$

$\vec{V} = \frac{e}{m\upsilon}\vec{E}$

Ion Motion

$\vec{V} = \frac{\vec{E} \times \vec{B}}{B^2}$

Electron Motion

$\vec{V} = \vec{U}$

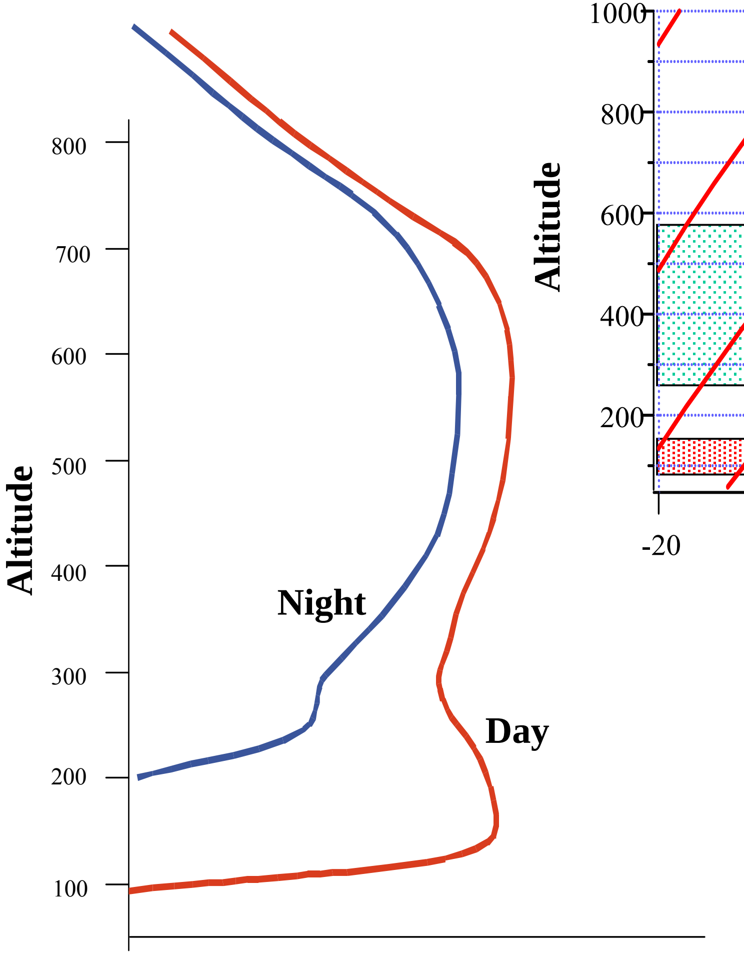
Ion Motion

$\vec{V} = \frac{\upsilon}{\Omega}\vec{U} \times \hat{b}$

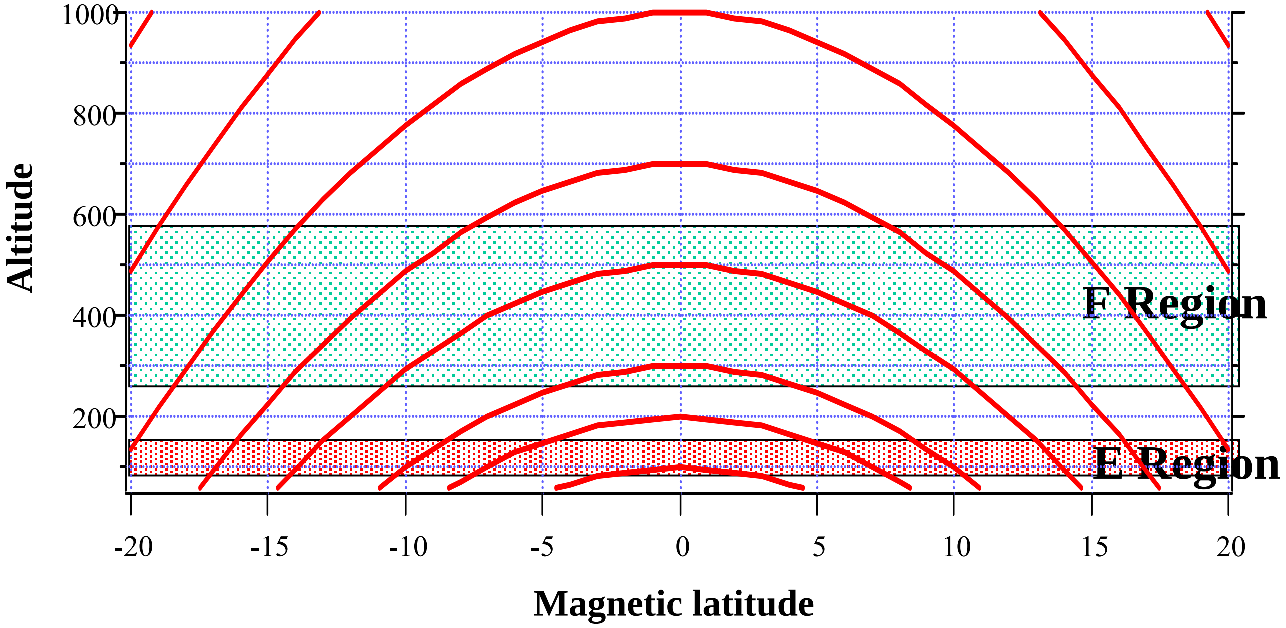
Electron Motion

Basic Principles

Electric field depends on flux-tube integrated drivers and conductivity.



Flux-tube-integrated Pedersen Conductivity

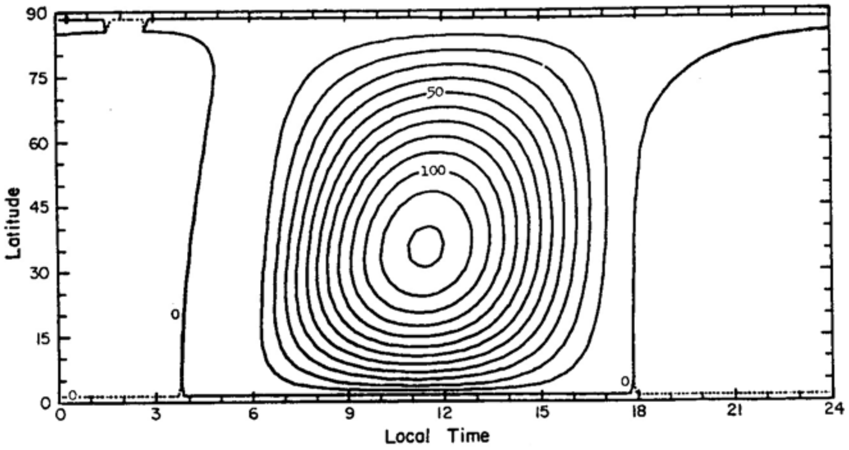


Polarization charges produced in one region within latitudes/apex heights of 10-15 deg/250-800 km can be removed by high conductivity in another.

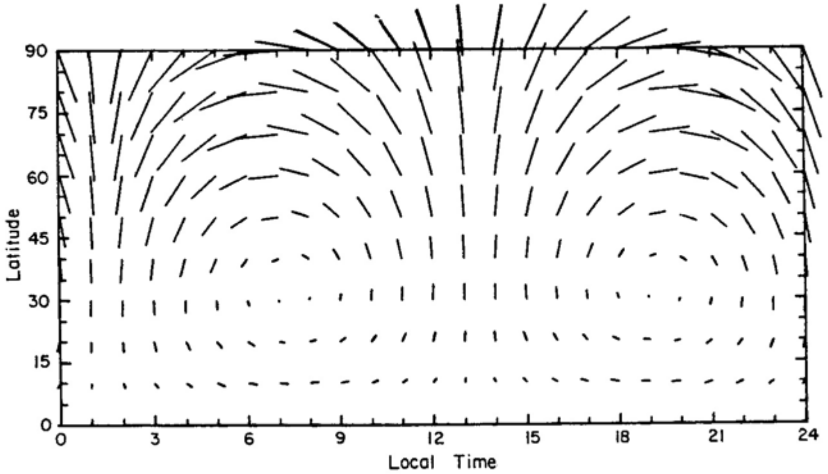
E-Region Winds and Currents

- Treat E region as a layer with wind independent of altitude.
- E-region density has peak near local noon and large gradients near sunrise and sunset.
- E-region density decreases with increasing latitude.
- Winds below 120 km result from propagating tidal oscillations generated below.
- Diurnal (one period in 24-hours) mode dominates at low latitudes.
- Wind driven currents most important during the daytime when E-region conductivity is highest.

Current circulates anticlockwise



Winds transport ions away from equator



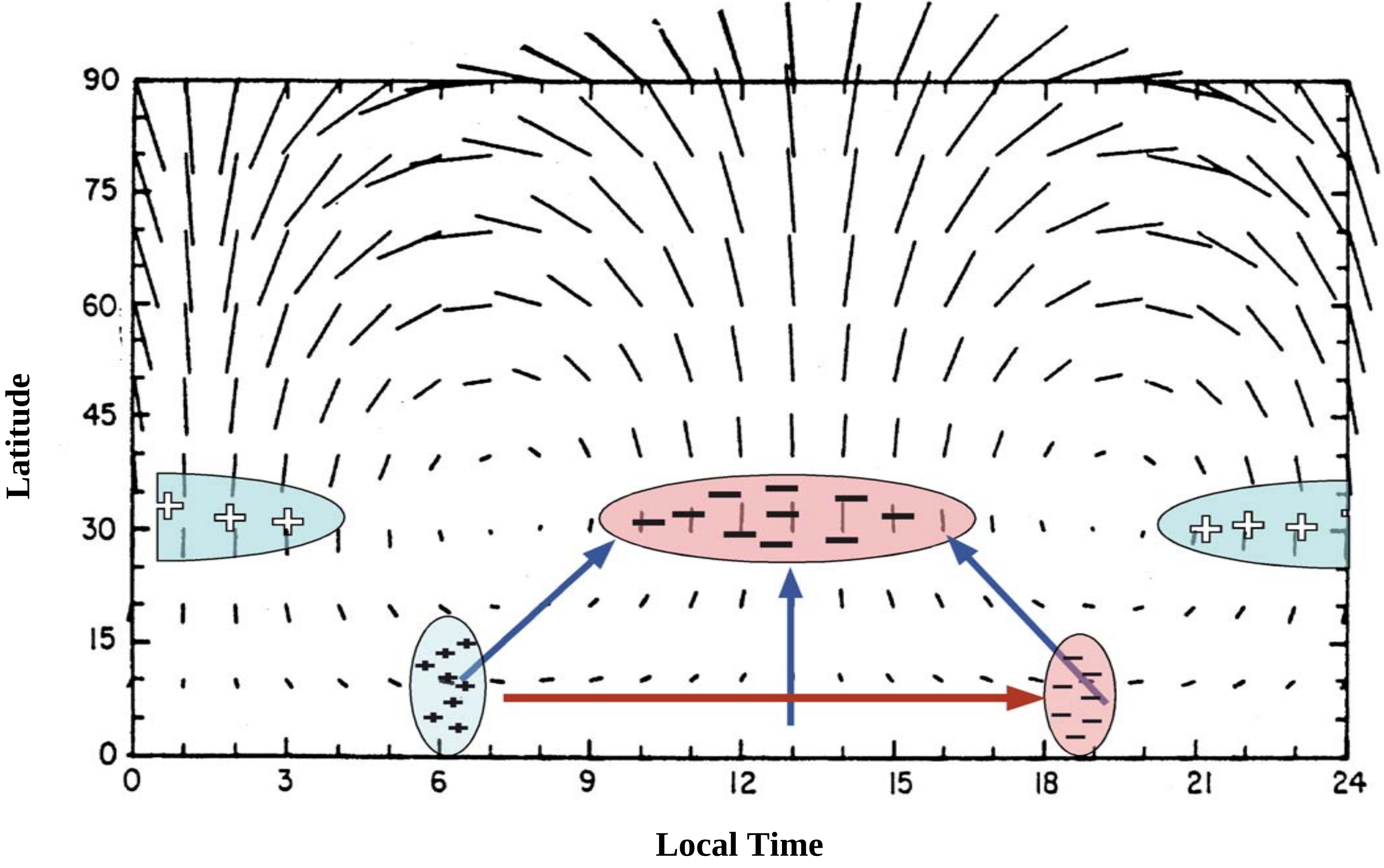
Tarpley, Planet. Space Sci., *18*, 1091, 1970

E-Region Dynamo

Neutral circulation transports ions away from local noon at mid latitudes.

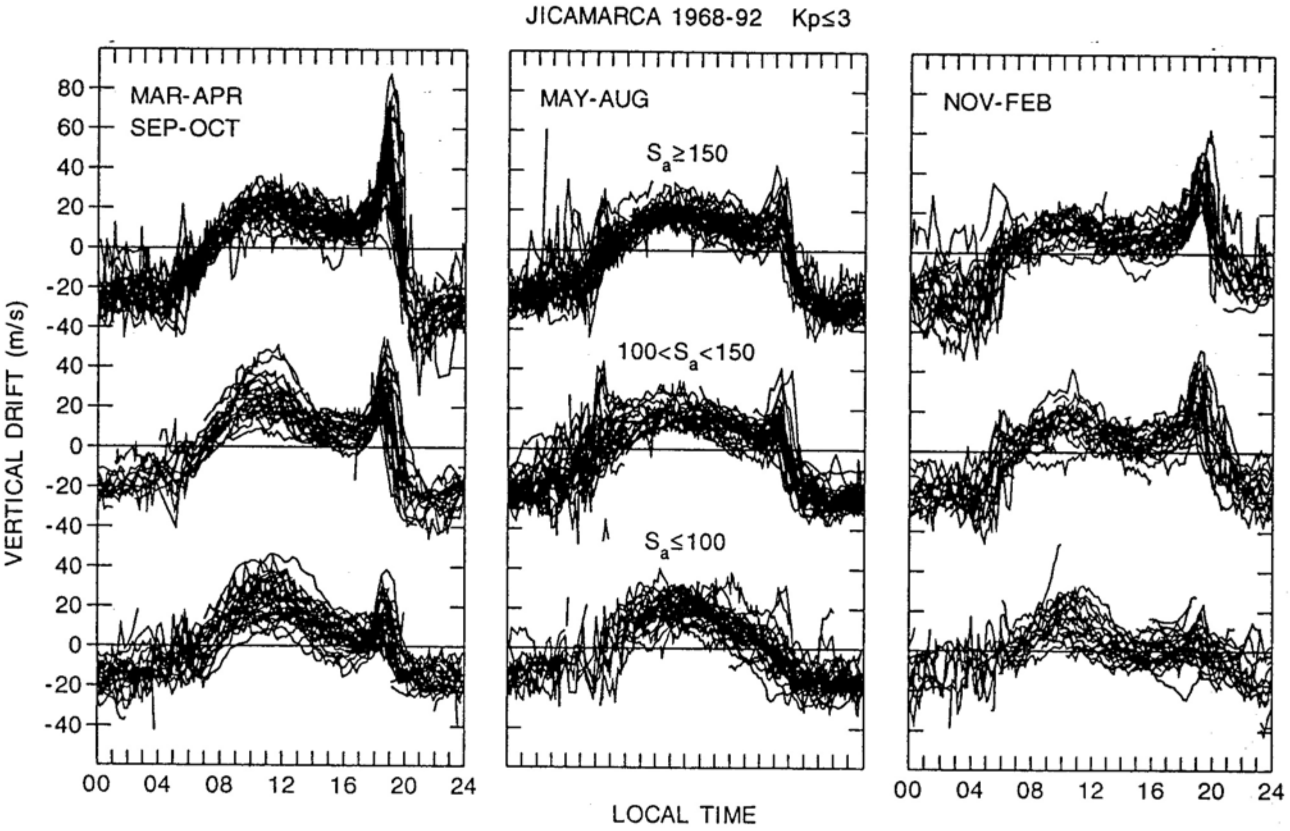
UxB drift of ions produces charge accumulation at the terminators.

Zonal and Meridional electric fields map to F-region.



Observed ExB Drifts

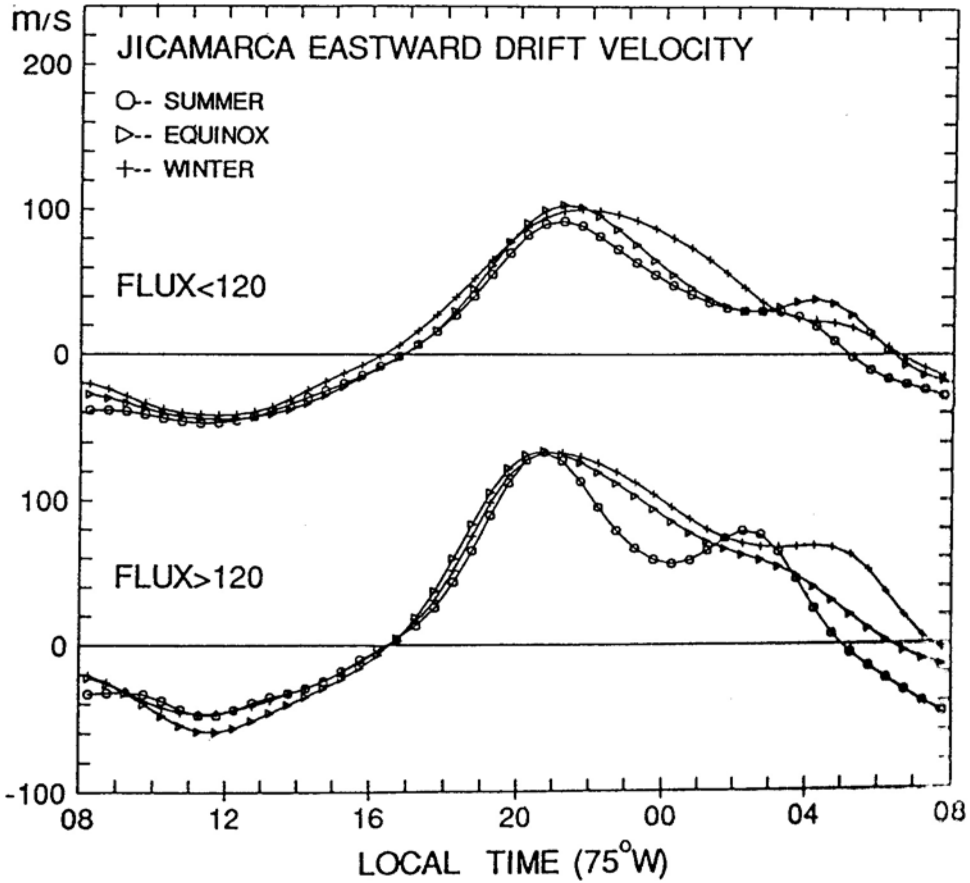
- **Mapped to the F-region zonal field produces vertical drifts up during day and down at night.**
- **Pre-reversal enhancement in vertical drift is not explained by E-region dynamo.**



Scherliess and Fejer, J. Geophys. Res., *104*, 6829, 1999

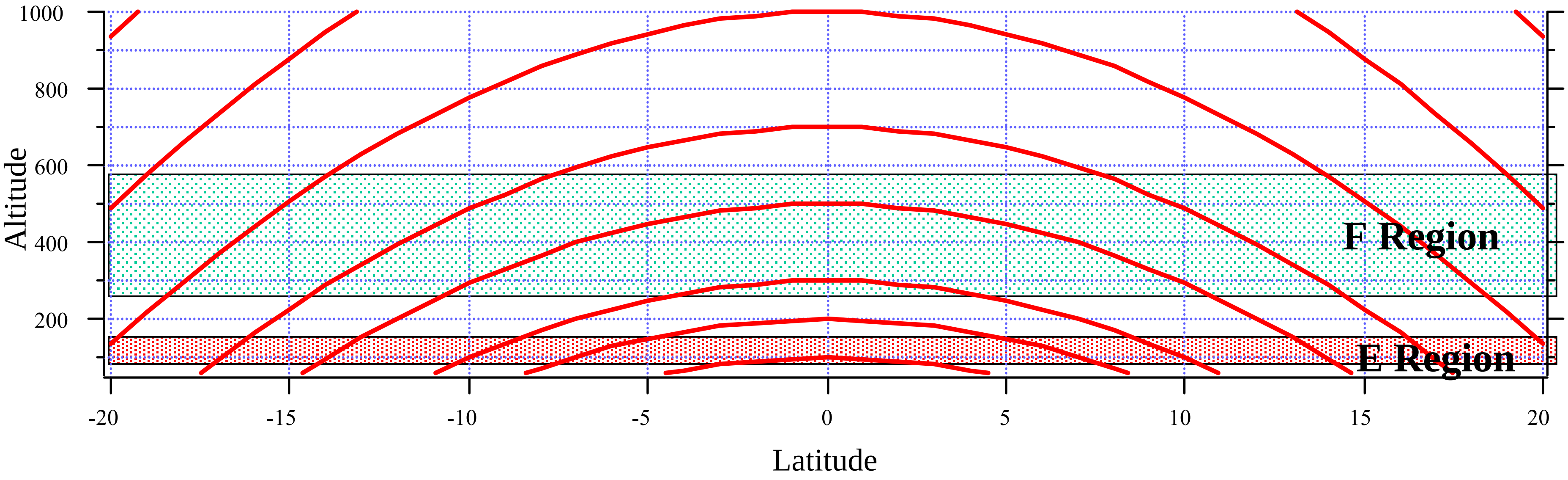
Observed ExB Drifts

- **Mapped to the F-region, meridional field produces zonal drifts westward during day and eastward at night.**
- **Day/Night asymmetry in amplitude of zonal drifts is not explained by E-region dynamo.**



Fejer et. al., J. Geophys. Res., *96*, 13,901, 1991

F-Region Winds



Winds drive ions along B and in direction UxB.

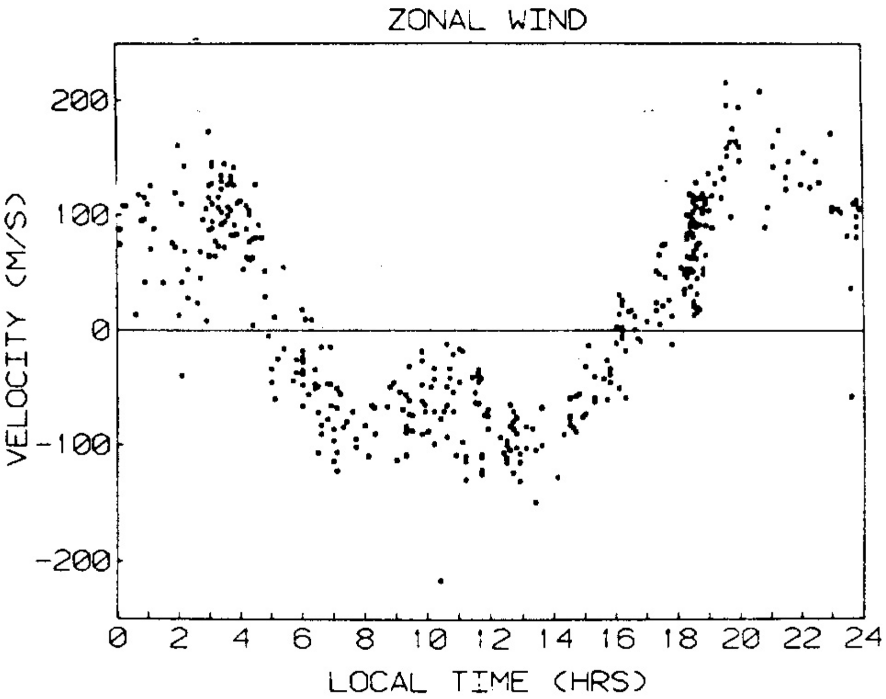
Zonal Winds drive ions perpendicular to B up and down.

Meridional winds

Drive a small currrent compared to zonal winds since field lines are almost horizontal.

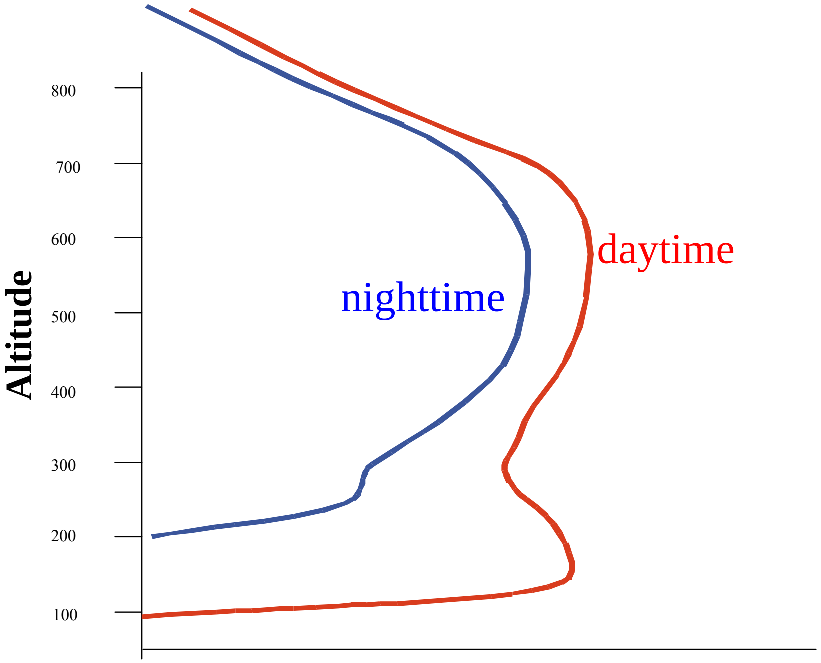
Cause asymmetries in ion distribution along B affecting flux tube integrated condcutivity.

F-Region Winds and Currents



Wharton et al., Geophys. Res. Lett, *11*, 531, 1984

- **Meridional winds have small component perpendicular to B and are neglected compared to zonal winds.**
- **Zonal winds above 250 km essentially constant with altitude.**

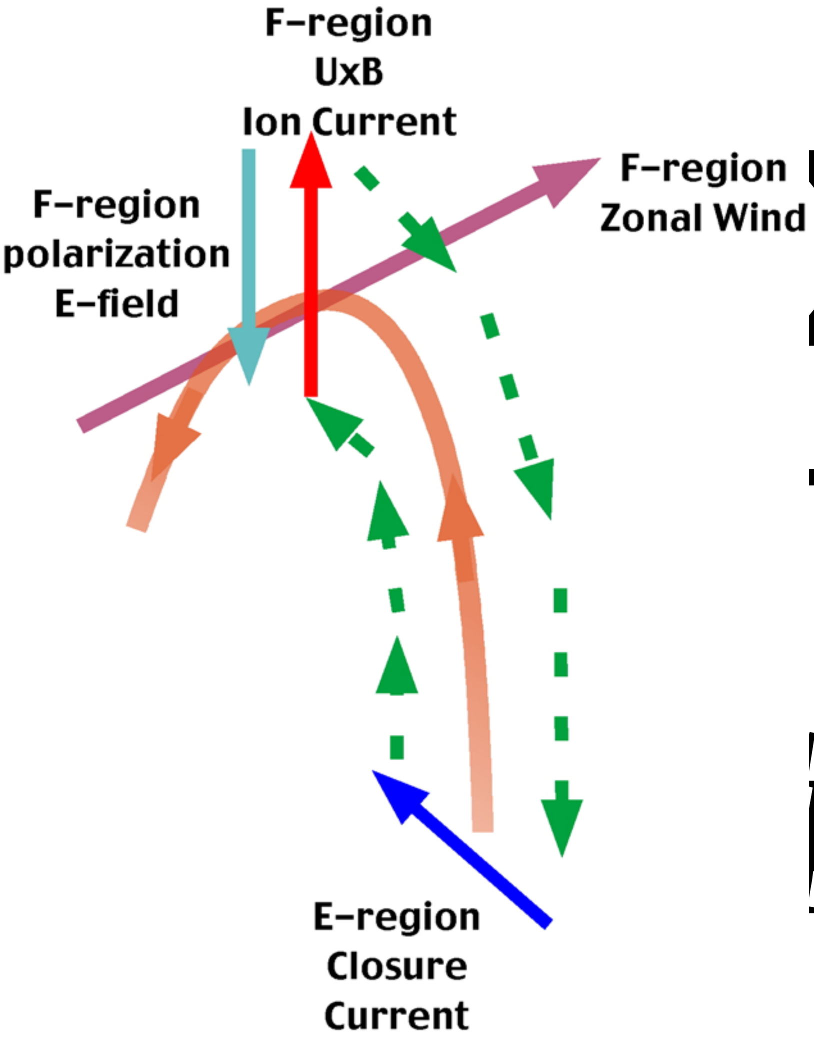


Flux-tube-integrated Pedersen conductivity

- **Zonal winds drive ions perpendicular to magnetic field --up and down.**

$$J_\perp = \Sigma_p U_z B$$

F-Region Dynamo

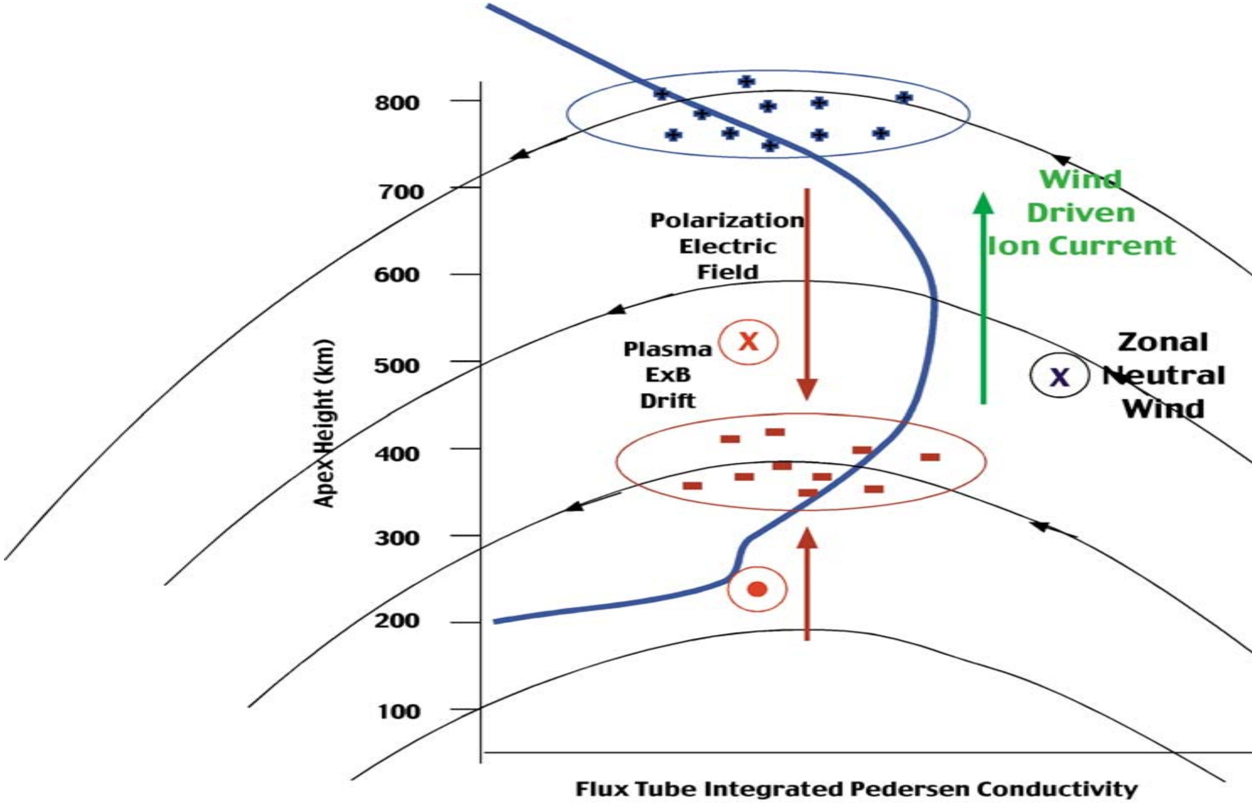


- Winds drive ions in direction UxB.
- Divergence in wind driven current in topside and bottomside of flux-tube integrated F-region
- Polarization fields form at the terminator and throughout the night when poor conductivity of E-region prevents field-aligned currents from flowing.

$$\frac{\Sigma_p{}^F UB}{\Sigma_p{}^F + \Sigma_p{}^E}$$

$$E_p = \frac{\Sigma_p{}^F UB}{\Sigma_p{}^F + \Sigma_p{}^E}$$

F-Region Dynamo

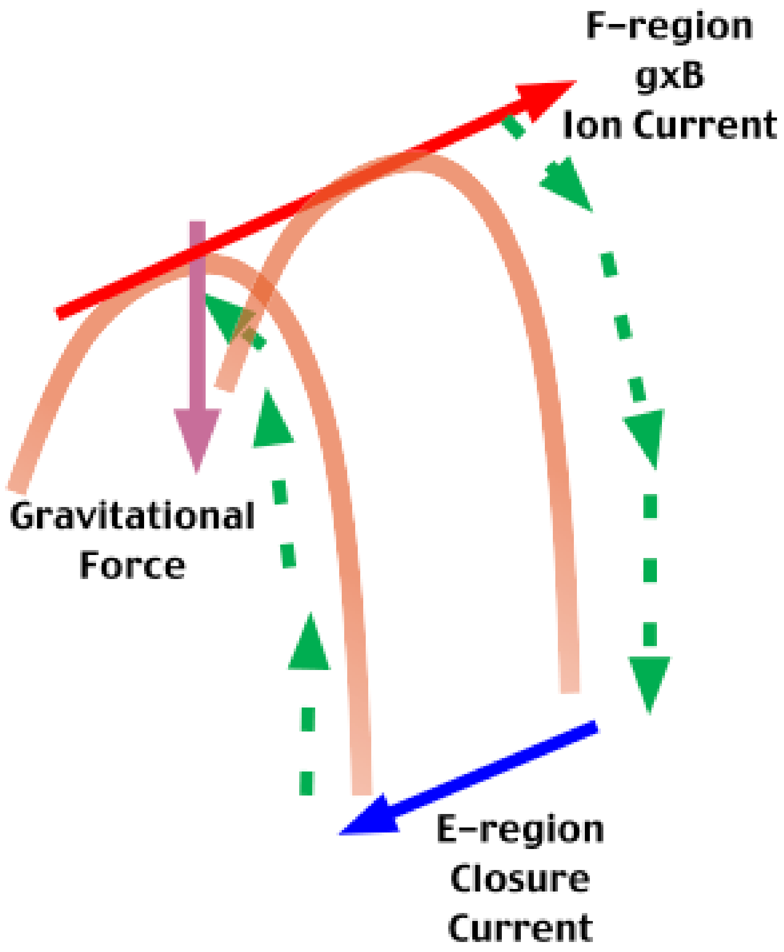


$$E_p = \frac{\Sigma_p{}^F U B}{\Sigma_p{}^F + \Sigma_p{}^E}$$

Bottomside F-region polarization field drives ions eastward above the bottomside (asymmetry in east-west drifts) and westward below it. (so-called evening vortex)

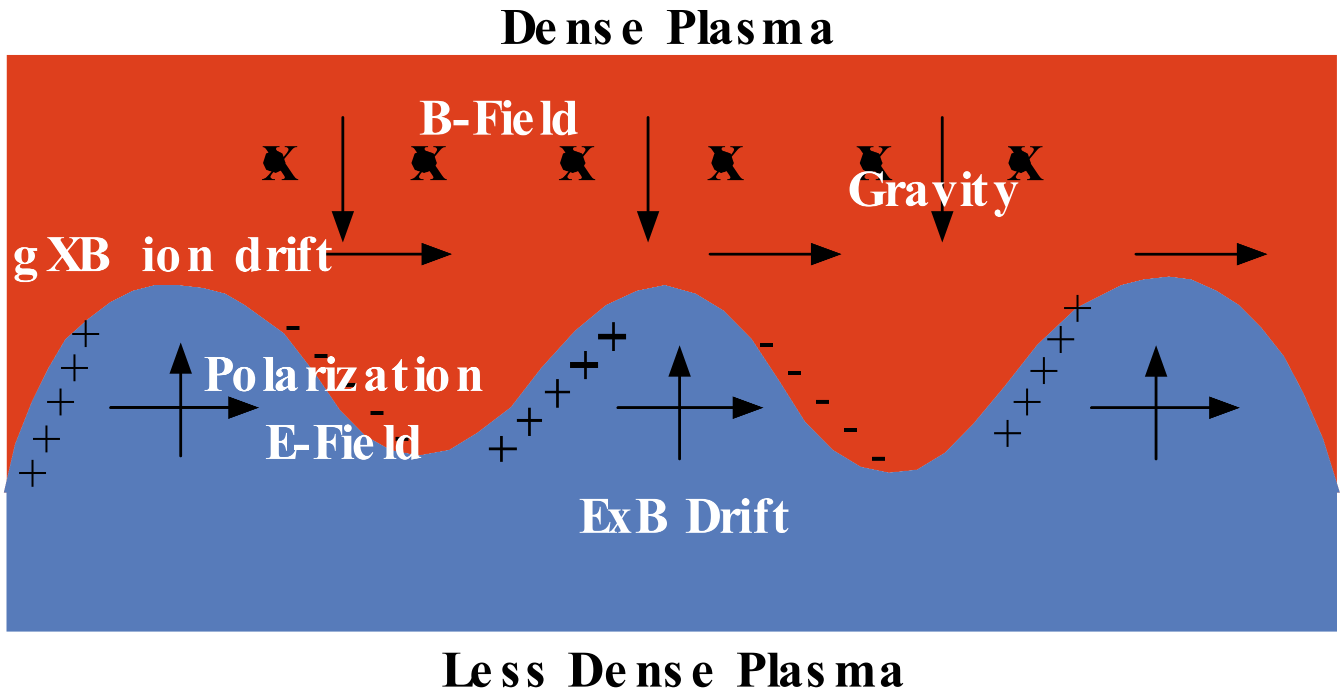
Bottomside F-region polarization charges produce pre-sunset eastward field. (so-called pre-reversal enhancement)

Gravity Dynamo



- Gravitational force produces eastward drift of ions in F-region.
- Gravity driven current has divergences where gradients in the flux tube integrated conductivity exist.
- Polarization charges accumulate at night when E-region prevents current closure.

Gravitational Rayleigh-Taylor Instablity

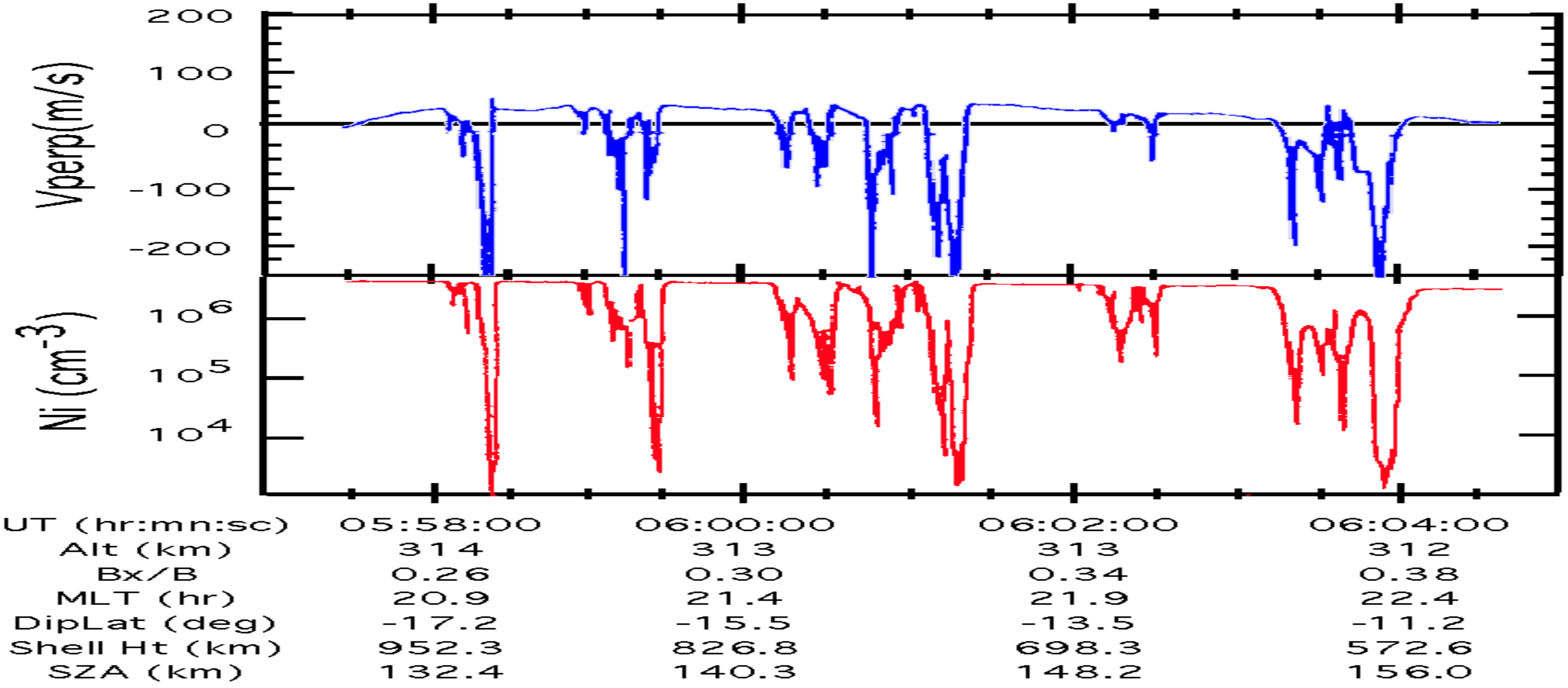


Flux tubes with low conductivity (low density) drift upwards.

Depleted flux tubes appear in F-region called spread-F

Note: zonal current can also be produced by zonal electric field.

Spread-F Depletion Drifts



Hanson and Bambgboye, J. Geophys. Res., *89*, 8997, 1984.

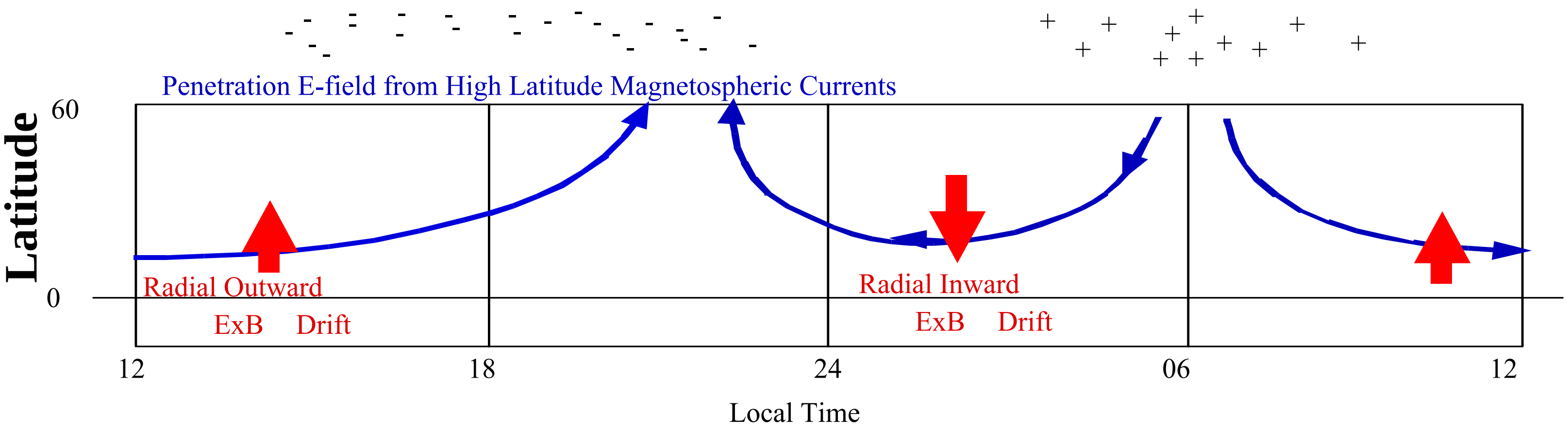
Depletions in the ion density in the F-region create gradients in the current driven by electric fields, gravity and neutral winds.

$$E_z{}^{depl} = \frac{\Sigma_p{}^{back}}{\Sigma_p{}^{depl}} E_z{}^{back} + \frac{\Sigma_{h,i}{}^{back} - \Sigma_{h,i}{}^{depl}}{\Sigma_p{}^{depl}} \frac{mg}{q}$$

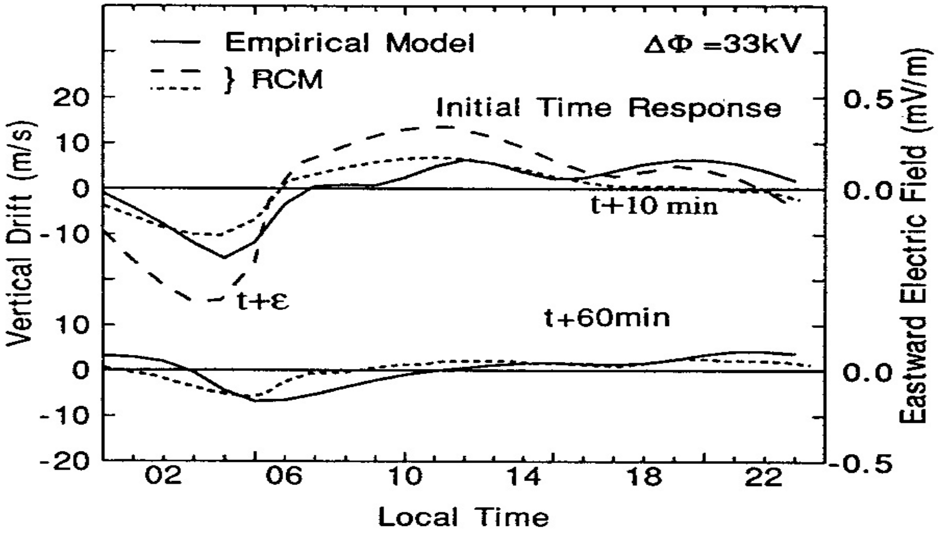
Depletion drifts are not a local phenomenon.

External Influences

The high latitude potential distribution can penetrate to lower latitudes when the cross-polar cap potential and internal magnetospheric potentials are not matched.



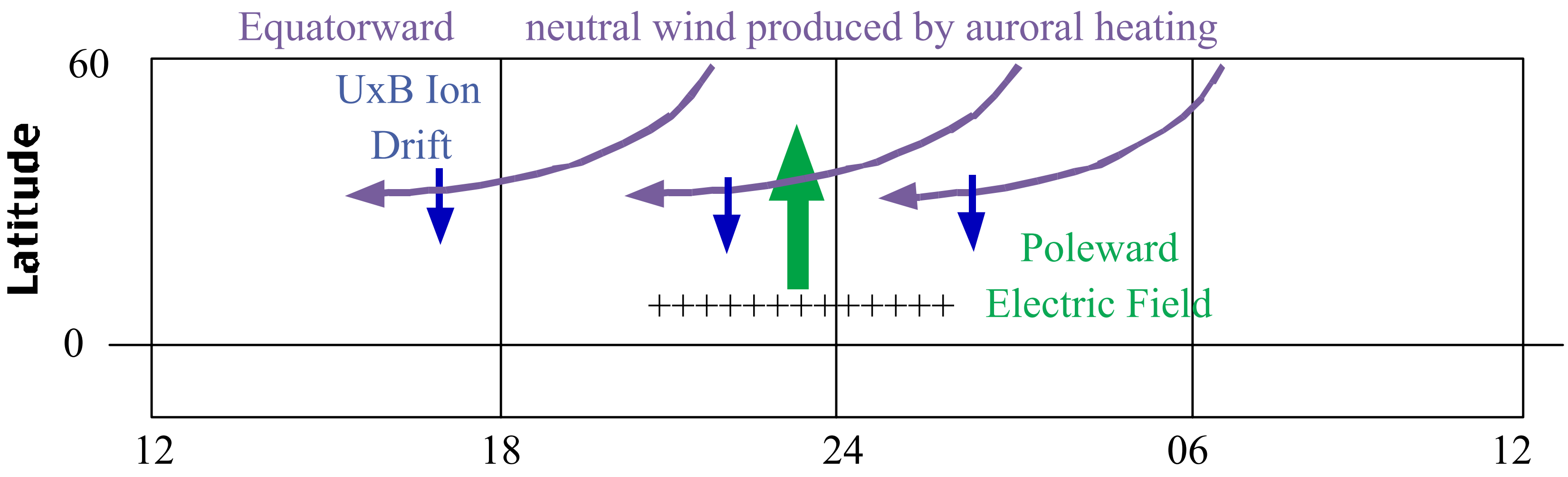
Detailed local time distribution depends upon high latitude current distribution and middle and low latitude conductivity distribution.



Fejer and Scherliess, Geophys. Res. Lett., *22*, 851, 1985

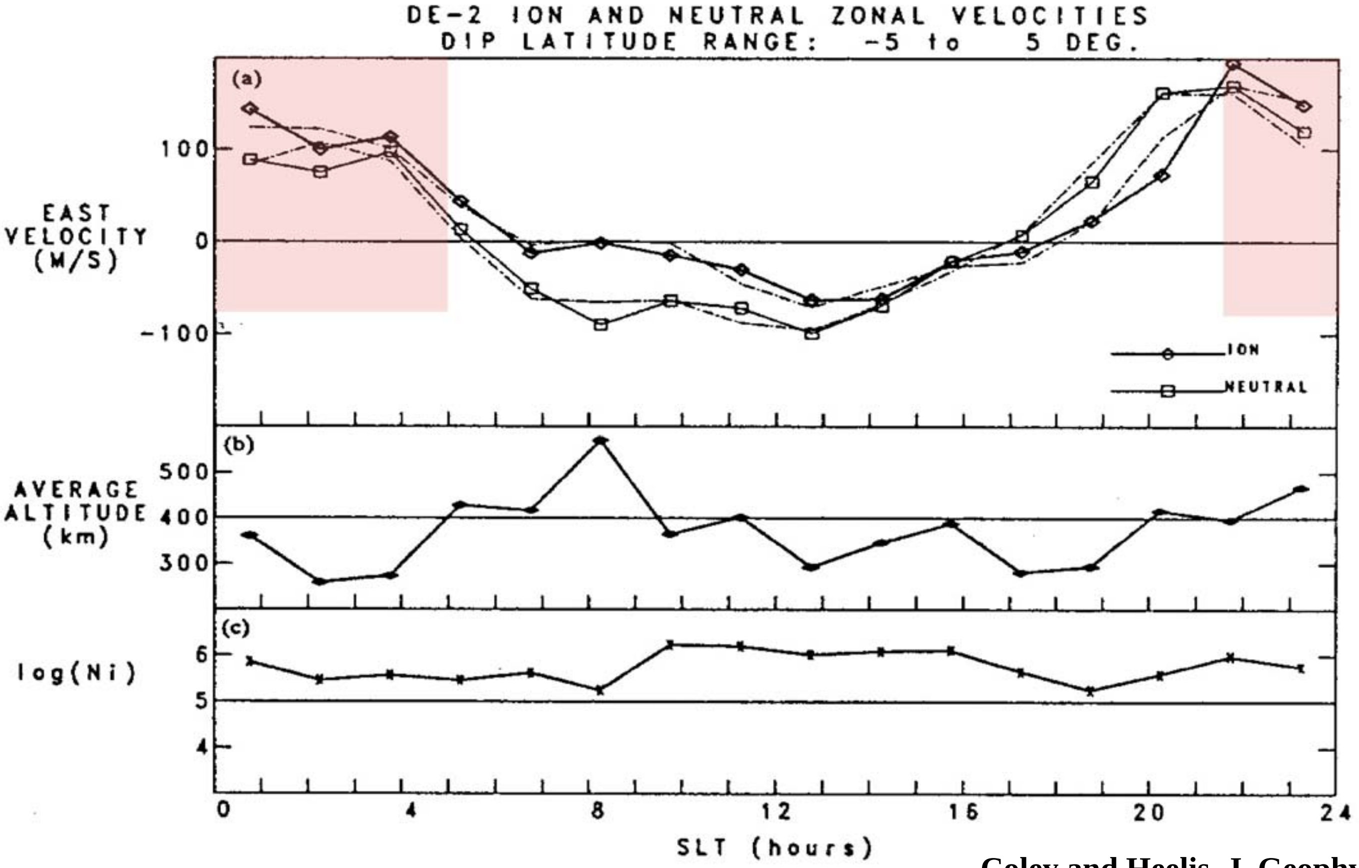
External Influences

- **Auroral heating from energetic particles and Joule heating produces equatorward wind.**
- **Conservation of momentum produces westward and equatorward neutral winds.**
- **UxB ion current maximizes at middle latitudes.**
- **Poleward polarization field produces westward ExB drift in the F region**
- **Local time distribution depends on details of auroral heating.**



Challenges

Local equatorial F-region ion drifts can be larger than the local neutral wind.



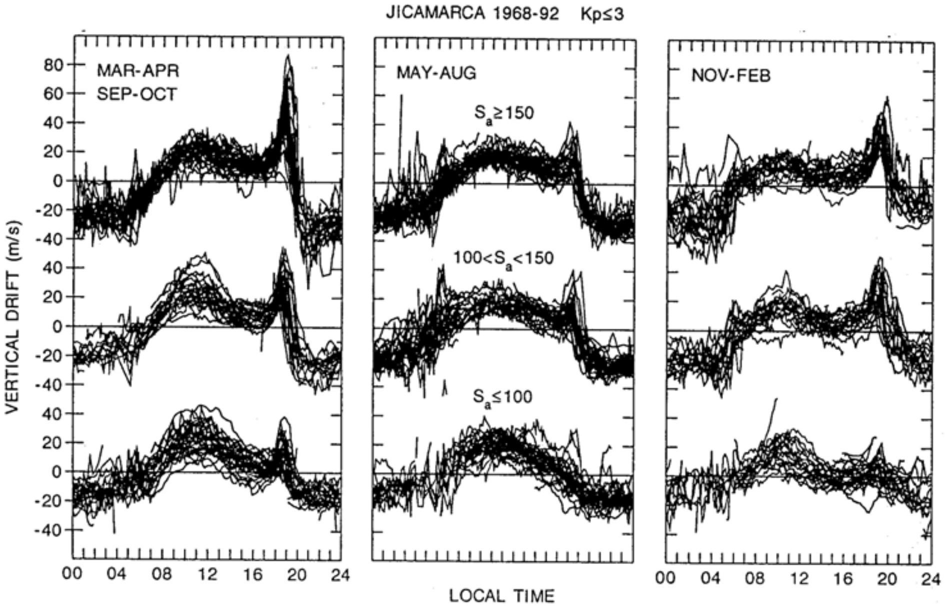
Coley and Heelis, J. Geophys. Res, 99, 341, 1994

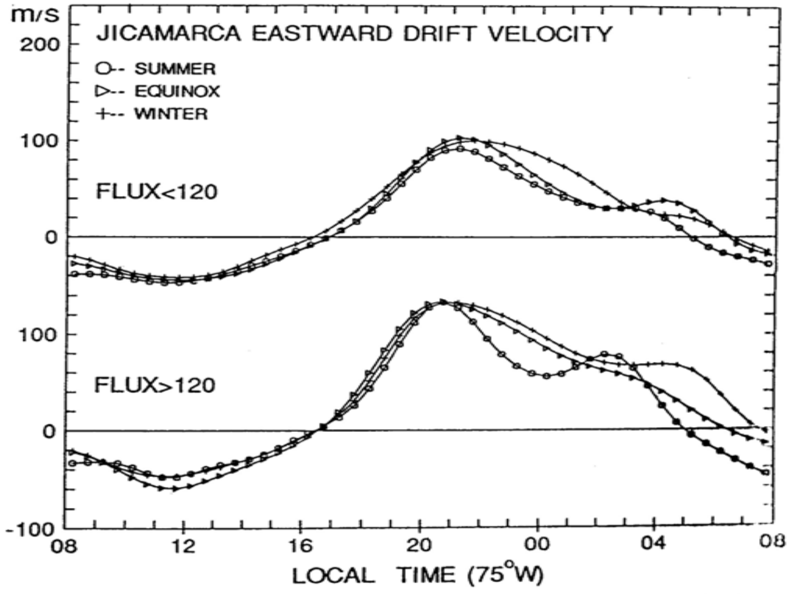
What is the relative contribution of the E and F-region winds ?

Are their significant altitude and latitude gradients in the neutral wind velocity ?

Challenges

Variations in the pre-reversal enhancement drift with season are not shown by the zonal drift.





What are seasonal variations in flux-tube integrated conductivity ?

What effect does the pre-reversal enhancement drift have on the flux-tube integrated conductivity ?

Summary

Equatorial Ionospheric Electrodynamics

E-region tidal winds contribute to the electric field everywhere in the equatorial and mid-latitude ionosphere.

E-region tidal modes alone are insufficient to explain the large scale variations in the electric field with local time and season.

F-region dynamo winds provide a significant contribution to the low and middle latitude electric field.

F-region generated fields depend upon the flux-tube integrated wind driven current.

Little information is available about altitude and latitude variations in the F-region wind and conductivity.

Knowledge of these variations inside plasma depletions is required to understand the dynamics of equatorial spread-F.

Questions concerning relative ion and neutral drifts, and seasonal and solar activity variations in electric fields will be resolved when this information is available.