Introduction to the Ionosphere

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Beginnings….

- The ionosphere is that part of the atmosphere where radio propagation is affected (even that is a fairly ambiguous definition!)
- Reflection from the upper atmosphere was demonstrated by Marconi in the 1900s. Serious research started in the 1930s with Breit and Tuve and with Appleton in the UK.
- They found there was a reflection layer - Appleton Layer or Heaviside Layer if you were American. Nowadays more commonly called the E-region – the E was originally for Electric for the nature of the reflection
- As more work was done they found increased frequencies penetrated farther up – they developed a variable frequency sounder:
- The ionospheric sounder or ionosonde became the main tool of research into this for 20 years. The traces are called "ionograms"
- A layer was found above the E-layer – so it was called the F-layer. One below was the D-layer. Is there a C-layer?
- The F-layer was found to be two regions – the F1 and F2 regions. In the equatorial zone maybe even an F3…..

The Ionosonde basics:

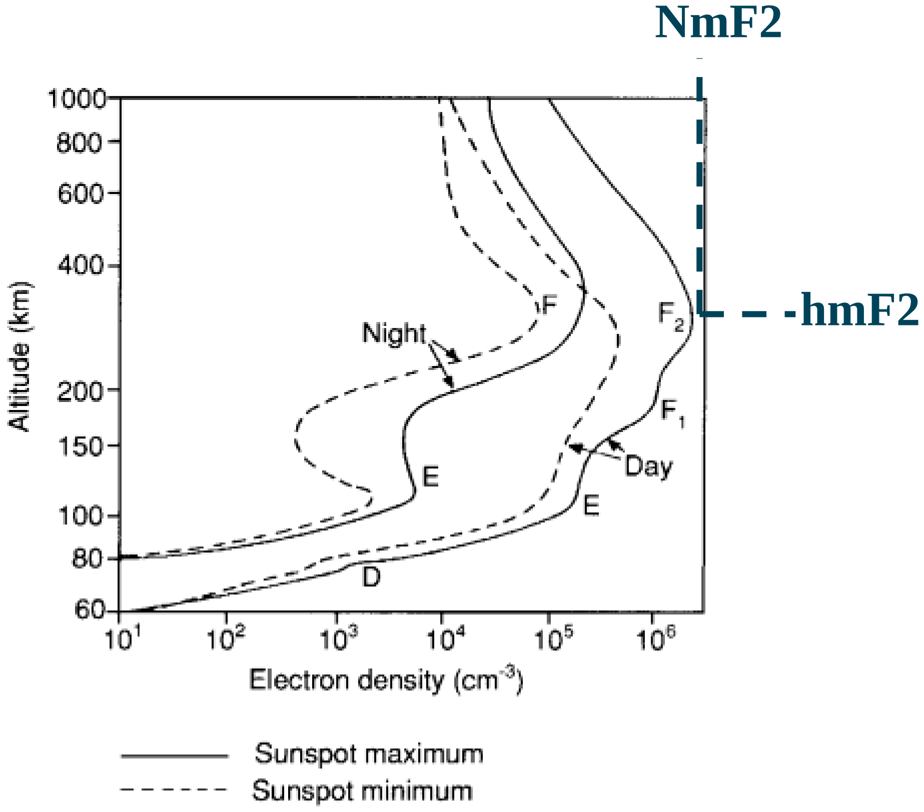
- A Radio wave projected upwards was reflected at an altitude where the plasma had a density that gave the electrons a natural frequency of oscillation called the plasma frequency.
- $\omega_0 = \sqrt{(N e^2/\varepsilon_0 m)}$
- A simple variant is that $f = 9\sqrt{N_e}$ if N_e is in m^{-3} and f in Hz
- If higher frequencies penetrated higher then electron density must increase with height
- Above peak frequency the radio waves did not reflect – they passed through into space

The Ionosphere

Structure and Formation of the Ionosphere

Structure

The F2 layer peak (hmF2) occurs between 250 and 400 km altitude, is higher at night than day and higher at solar maximum conditions. In contrast to the F1 region, the F2 layer is maintained at night. The E region is strongest at daytime

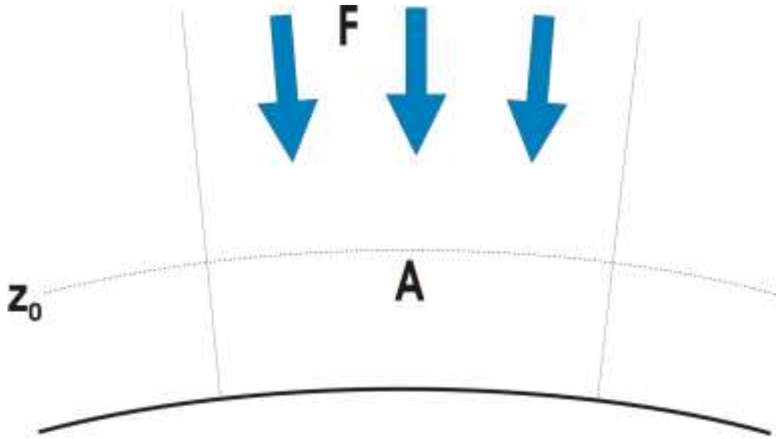


First let us include some concepts to do with the neutral atmosphere which generally is always much denser than the ionic component.

Up to around 100 km the atmosphere is perfectly turbulently mixed and has a more or less constant (relative) composition. Above that height – the “turbopause” or “homopause” – the gases separate out and distribute themselves vertically independent of each other – so called diffusive equilibrium, determined by molecular diffusion.

To understand what this means we need to know the concept of the “scale height “

The **pressure** is defined as the force (per surface area) due to the weight of the atmosphere above a point:



$$p(z_0) = \frac{F}{A} = \int_{z=z_0}^{\infty} \rho(z) \cdot g(z)\, dz$$

and the change or pressure with height is given by:

$$dp = -\rho \cdot g \; dz$$

Pressure decreases with altitude since the weight of the atmosphere above becomes smaller for increasing altitude.

From the ideal gas law:

$$p = n\,k\,T$$

and:

$$\frac{dp}{dz} = -\rho \cdot g = -\overline{m} \cdot n \cdot g$$

$\overline{m}$ is the mean molecular mass (in units of mass)

we get:

$$\frac{dp}{dz} = -\frac{\overline{m} \cdot g}{kT} \cdot p = -\frac{1}{H} \cdot p$$

where:

$$H = \frac{kT}{\overline{m}g}$$

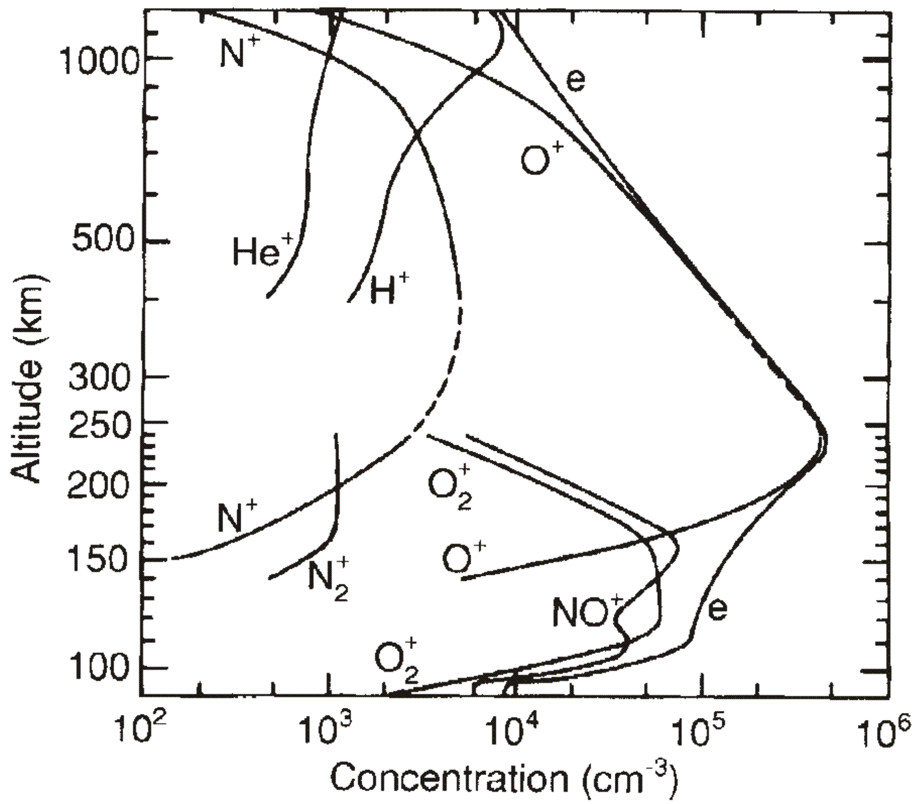
is the **scale height**

giving:

$$p(z) = p(z_0) \cdot e^{-\frac{z - z_0}{H(z)}}$$

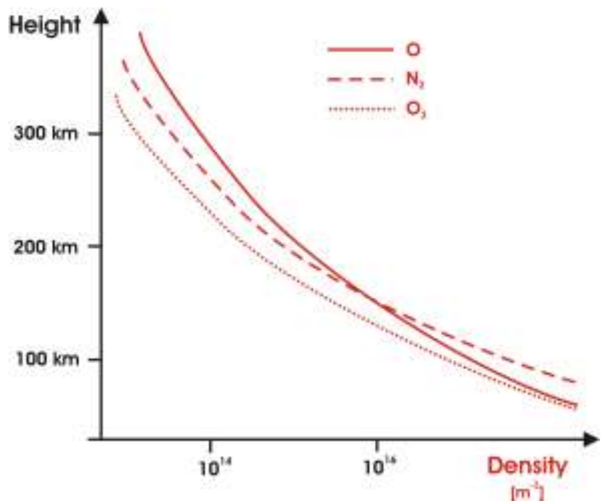
So, when moving up by one scale height, pressure decreases by a factor of 1/e ~ 0.37.

Ionosphere composition



Dayside ionosphere composition at solar minimum.

Major F-region ions is O^+, followed by H^+ at the top and NO^+ and O_2^+ at the bottom. Note that neutral gas concentration at 300 km is around 10^{14} m^{-3}, so ion concentrations are 2 orders of magnitude smaller. Negative ions are found only in the lower ionosphere (D region). The net charge of the ionosphere is zero.



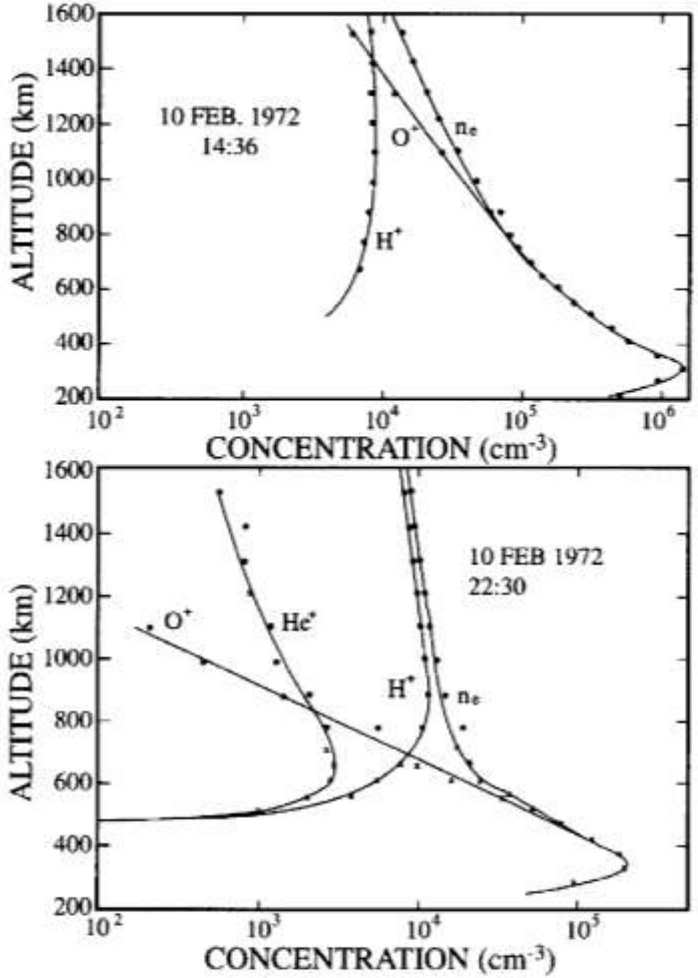
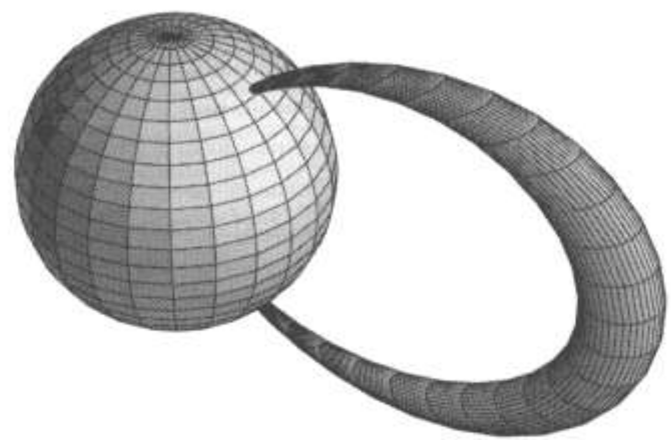


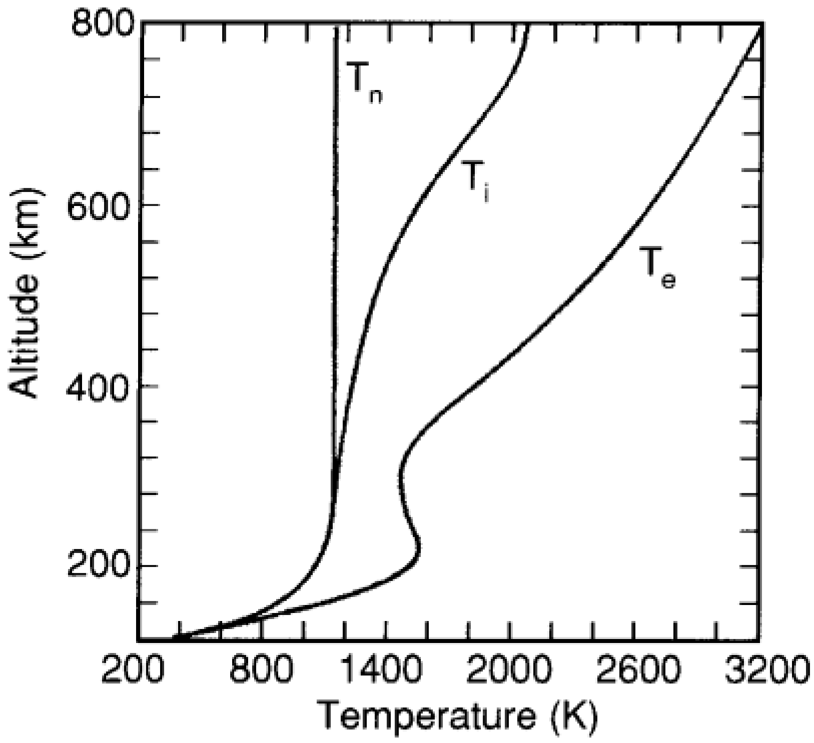
Figure 11.14 Altitude profiles of ion composition for the daytime (top panel) and nighttime (bottom panel) ionosphere. The profiles were measured with the incoherent scatter radar at Arecibo, Puerto Rico.[17]

Above around 1400 km (day) and 700 km (night), H^+ becomes the dominant ion, forming a layer commonly referred to as the **Protonosphere**.

At low latitudes, closed magnetic field lines reach out to several Earth radii, forming flux tubes. This region is referred to as the **Plasmasphere**.



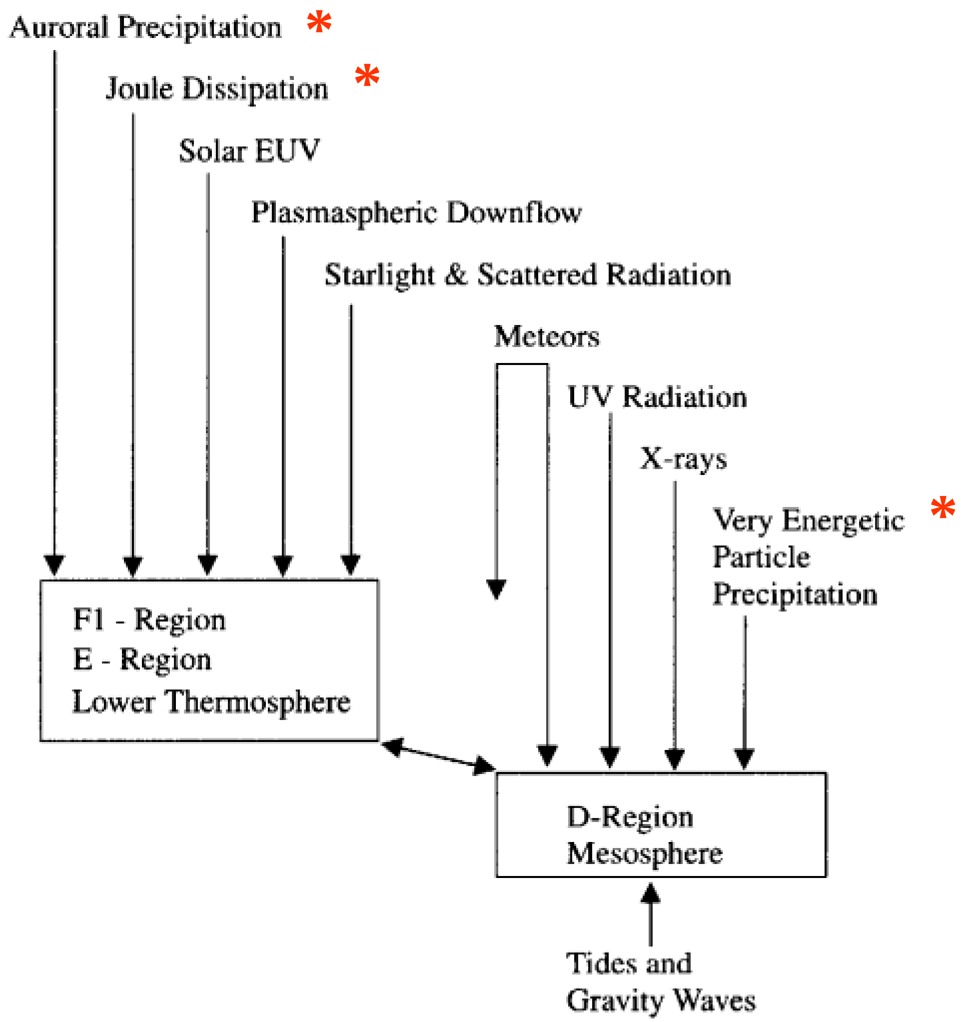
Ionosphere temperatures



In the ionosphere, we distinguish between ion temperatures, T_i, and electron temperatures, T_e. Ions and electrons receive thermal energy during the photoionization and lose thermal energy through collisions. Since recombination lifetimes are smaller than the timescale for losing the excess thermal energy, the ion and electron temperatures above 300 km are both larger than the neutral temperatures, T_n :

$$T_n \leq T_i \leq T_e$$

External coupling of the ionosphere



* **mainly at high latitudes**

Ion/Electron Continuity Equation

$$\frac{\partial N}{\partial t} = q - l(N) - \vec{\nabla}(N\vec{V})$$

Production — Loss — Transport

D, E, F1 region: q ≈ l >> del(NV); Transport mostly unimportant
photochemical regime, described by Chapman layers

F2 region: Transport matters, p and l << del(NV) no longer dominant
optically thin, not Chapman layer

b) Formation of the F2 region

* **key reactions**

Photoionization:

$$O + h\nu \rightarrow O^+ + e^-$$ (λ<911Å) (1) *

$$N_2 + h\nu \rightarrow N_2^+ + e^-$$ (λ< 796Å) (2a)

$$N_2^+ + O \xrightarrow{(fast)} NO^+ + N$$ (2b)

$$O_2 + h\nu \rightarrow O_2^+ + e^-$$ (λ< 1026Å) (3)

Dissociative recombination (rapid) **:**

$$O_2^+ + e^- \rightarrow O + O + h\nu$$ (λ= 6300Å) "Airglow" (4) * $k_{O_2^+} \approx 3\times10^{-7}\,cm^{-3}s^{-1}$

$$NO^+ + e^- \rightarrow N + O$$ (5) * $k_{NO^+} \approx 3\times10^{-7}\,cm^{-3}s^{-1}$

$$N_2^+ + e^- \rightarrow N + N$$ (6)

$$O_2^+ + N(^4S) \rightarrow NO + O$$ (7)

Radiative recombination (slow) :

$$O^+ + e^- \rightarrow O^* \rightarrow O + h\nu \quad (7774\ \text{Å}) \qquad (8)$$

Charge transfer:

$$O^+ + O_2 \rightarrow O_2^+ + O \qquad (9) \qquad * \quad k_{O_2} \approx 2\times10^{-11}\, cm^{-3} s^{-1}$$

$$N^+ + O \rightarrow O^+ + N \qquad (10)$$

$$O_2^+ + NO \rightarrow NO^+ + O_2 \qquad (11)$$

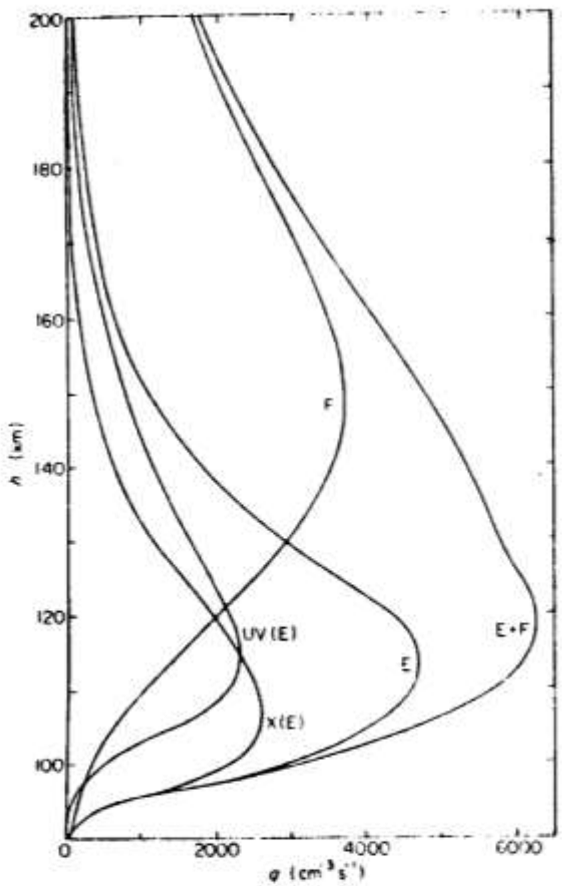
Ion-atom interchange:

$$O^+ + N_2 \rightarrow NO^+ + N \qquad (12) \qquad * \quad k_{N_2} \approx 1\times10^{-12}\, cm^{-3} s^{-1}$$

$$N^+ + O_2 \rightarrow NO^+ + O \qquad (13)$$

$$N^+ + O_2 \rightarrow O_2^+ + N(^4S) \qquad (14)$$

Electron production profiles



Ionization peaks occur at optical depth = 1

Curves are:

X(E)…. XEUV (8-140 Å)

UV(E).. UV (796-1027 Å)

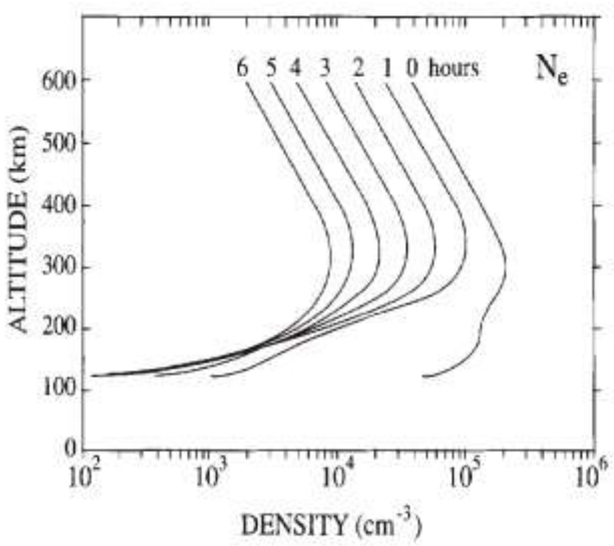
F…….. UV (140-796 Å)

E…….. UV(E)+X(E)

E+F…. Total (8-1027 Å)

Note that peak production occurs near 120 km, whereas the F2 peak is located near 300 km! Loss rate (~[N_2]) decreases faster with height than production rate (~[O]) since (O/ N_2) increases with height.

One can see that the production of ionization depends largely on the [O] density, while photochemical loss is determined by the abundance of N_2 and, to lesser degree, O_2 (reactions 2a, 2b, 5, 10).



This figure shows calculated electron density profiles (Ne) at selected times after photoionization is set to zero. It illustrates the role of photoionization in maintaining the ionosphere.

2) Ion and Electron Dynamics

Gravity — Pressure gradient — Electric field — Lorentz force

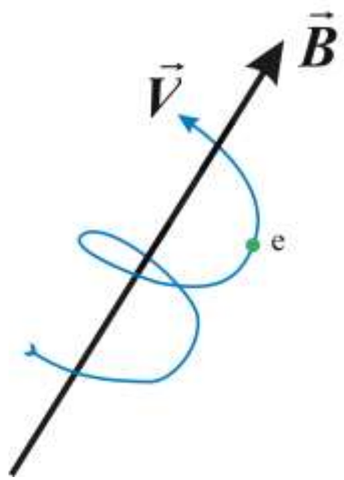
$$m_i \frac{\partial \vec{V}_i}{\partial t} = m_i \vec{g} - \frac{1}{N_i} \vec{\nabla} N_i k T_i + e \cdot \vec{E} + e \cdot \vec{V}_i \times \vec{B} - m_i \nu_{in} (\vec{V}_i - \vec{U}) - m_e \nu_{ie} (\vec{V}_i - \vec{V}_e)$$

Ion-neutral collisions — Ion-electron collisions

Ions

$$m_e \frac{\partial \vec{V}_e}{\partial t} = m_e \vec{g} - \frac{1}{N_e} \vec{\nabla} N_e k T_e - e \cdot \vec{E} + e \cdot \vec{V}_e \times \vec{B} - m_e \nu_{en} (\vec{V}_e - \vec{U}) - m_e \nu_{ei} (\vec{V}_e - \vec{V}_i)$$

Electrons

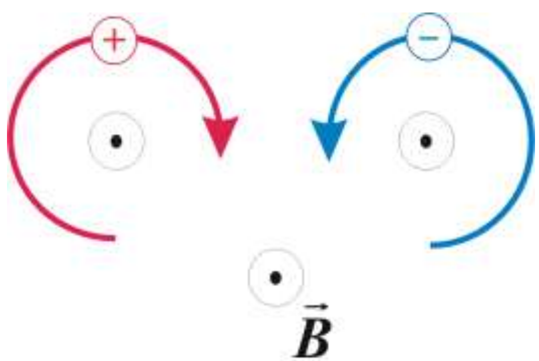


For $\vec{V} \perp \vec{B}$: $$m\frac{V^2}{r} = e\,V\,B$$

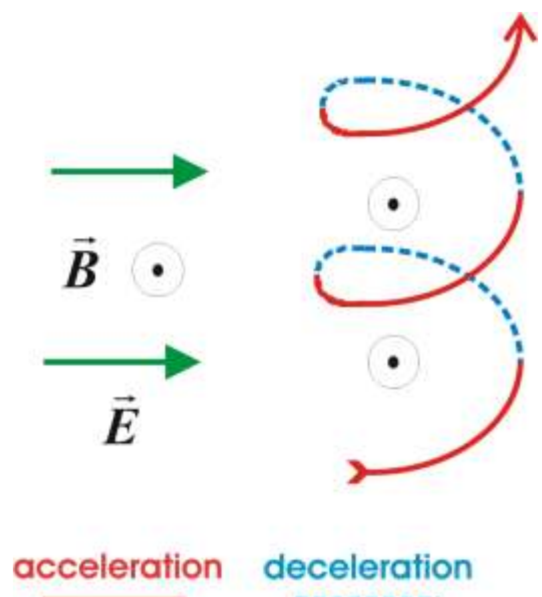
Define: $$\omega = \frac{V}{r}$$

$\Rightarrow$ **Gyrofrequency:** $$\omega = \frac{B\,e}{m}$$

Since $m_e << m_p$: $$\omega_e >> \omega_p$$



Positive and negative charges gyrate in opposite directions around the magnetic field lines.



In the presence of an ***E*** field, particles are partly accelerated and decelerated while gyrating. This causes net drift in the ***E***×***B*** direction.

The motion of charged particles is determined primarily by:

- Collisions with the neutral gas particles (at collision frequency ***ν***)
- External electric field, ***E***
- Orientation and strength of magnetic field, ***B***

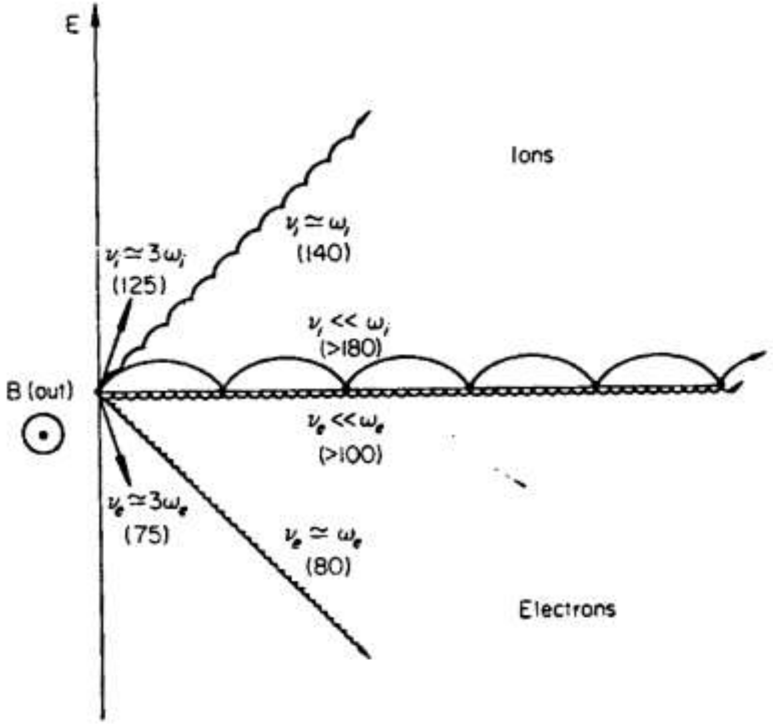
Consider: $\vec{U} \times \vec{B}$ *and* $\vec{E} \times \vec{B}$

Case 1: $\nu \gg \omega$ — Frequent particle collisions, ***B*** field plays no role, charged particles follow neutral wind. Applies below around 80 km.

Case 2: $\nu \approx \omega$ — Charged particles affected by ***E***, ***B*** and neutral gas motion, leading to interesting behaviour. Applies in E region.

Case 3: $\nu \ll \omega$ — Charged particles gyrate around ***B*** field lines. ***E*** field causes ***E***x***B*** drift (same direction for ions and electrons). Neutral wind causes ***U***x***B*** drift, opposite for ions and electrons, resulting in an electric current. Applies above around 200 km.

$\vec{U} = 0 \quad and \quad \vec{E} \times \vec{B}$



Idealized electron and ion trajectories resulting from a magnetic field and perpendicular electric field. Charged particles collide with neutrals at regular intervals of 1/***v***. Numbers in brackets are approximate heights (km) where the situation applies. Note that neutral winds, ***U***, are assumed zero here.

Below 180 km ions and electrons drift into different directions.

Above 180 km ions and electrons drift in the same direction (***E*x*B***). Note that the presence of neutral winds however produces a current.

Plasma Diffusion

Simplifying the momentum equation and assuming vertical components only, as well as a vertical ***B*** field, give:

$$\frac{d(N_i k T_i)}{dh} = -N_i m_i g + N_i e E - N_i m_i \nu_{in}(W_i - W_n)$$

$$\frac{d(N_e k T_e)}{dh} = -N_e m_e g - N_e e E - N_e m_e \nu_{en}(W_e - W_n)$$

where ***W*** are vertical drift velocities.
When further assuming $\boldsymbol{m_i} >> \boldsymbol{m_e}$, $\boldsymbol{N_i} = \boldsymbol{N_e} = \boldsymbol{N}$, $\boldsymbol{W_i} = \boldsymbol{W_e} = \boldsymbol{W_D}$ (plasma drift velocity) and $\boldsymbol{W_n} = 0$ (neutral air at rest) and $\boldsymbol{m_i \nu_{in}} >> \boldsymbol{m_e \nu_{en}}$ (electron-neutral collisions less important than ion-neutral collisions) we obtain for the drift velocity:

$$\boldsymbol{W_D = \frac{1}{m_i \nu_{in}}\left(\frac{1}{N}\frac{d}{dh}\left[Nk(T_i + T_e)\right] + m_i g\right)}$$

This expression can be rewritten as:

$$W_D = D\left(\frac{1}{N}\frac{dN}{dh} + \frac{1}{T_p}\frac{dT_p}{dh} + \frac{1}{H_p}\right)$$

with the following definitions:

$$T_p = \frac{1}{2}\left(T_e + T_i\right)$$

Plasma temperature

$$H_p = \frac{2kT_p}{m_i g}$$

Plasma scale height
(plasma has average particle mass 0.5****m_i***,
since electron mass is negligible)

$$D = \frac{k\left(T_i + T_e\right)}{m_i \nu_{in}}$$

Plasma diffusion coefficient

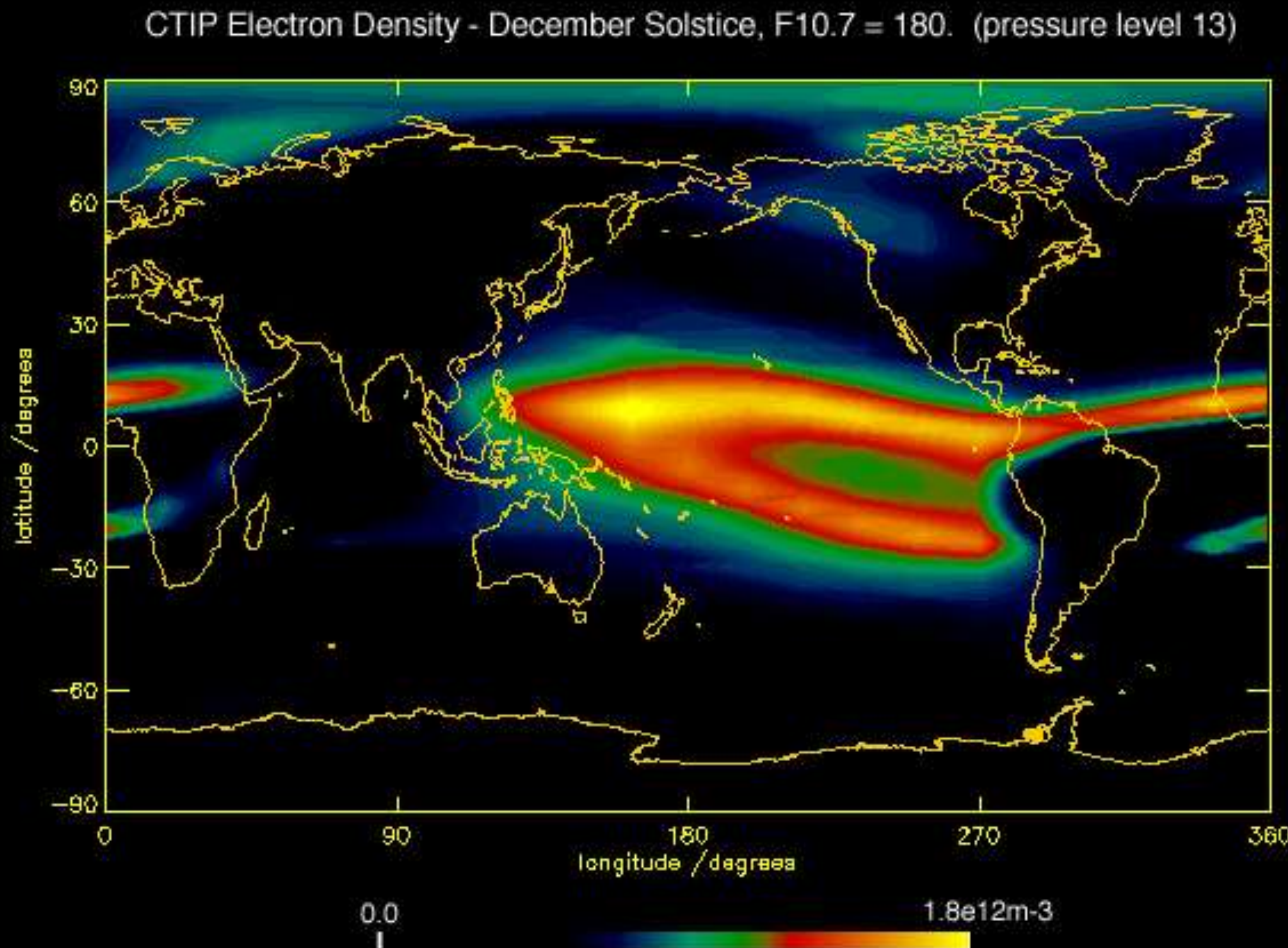
Assuming $T_i = T_e = T$ gives:

$$D_{AP} = \frac{2kT}{m_i \nu_{in}}$$

Ambipolar diffusion coefficient

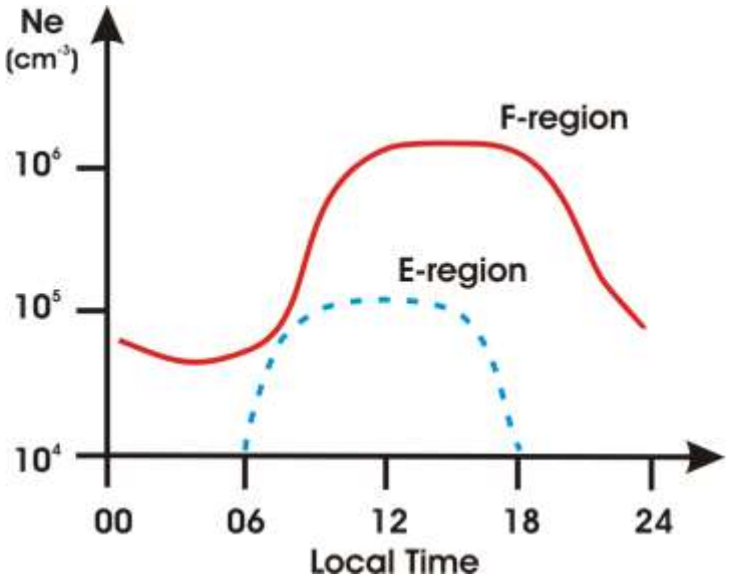
The end result is complex electron density behaviour

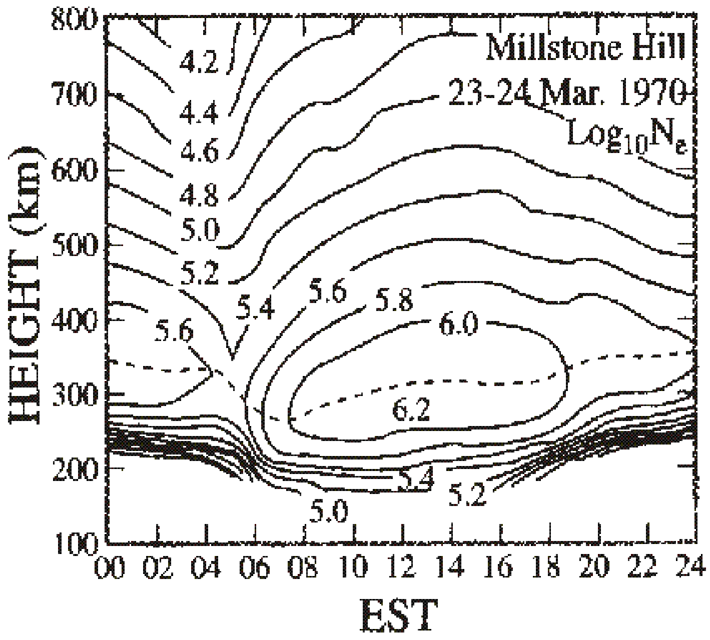
The magnetic field orientation plays a big part in determining the morphology and dynamics


CTIP Electron Density - December Solstice, F10.7 = 180. (pressure level 13)
90
60
30
0
-30
-60
-90
latitude /degrees
0
90
180
270
360
longitude /degrees
0.0
1.8e12m-3

3) F2 Region Morphology

a) Diurnal behaviour



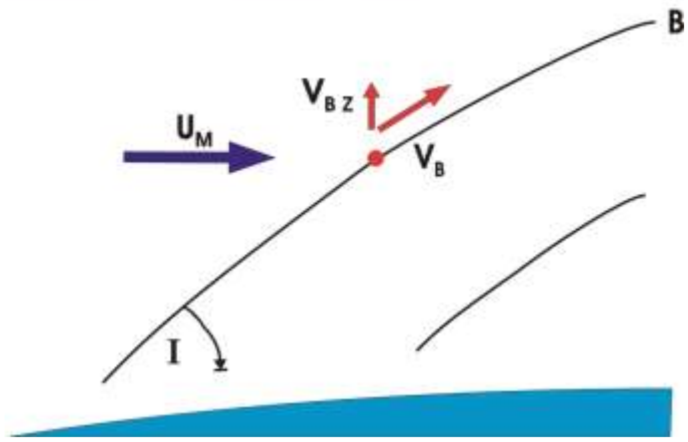


Key features:

- Daytime Ne ~ O/N_2
- Longevity due to slow recombination (9, 12)
- Daytime hmF2 < nighttime hmF2

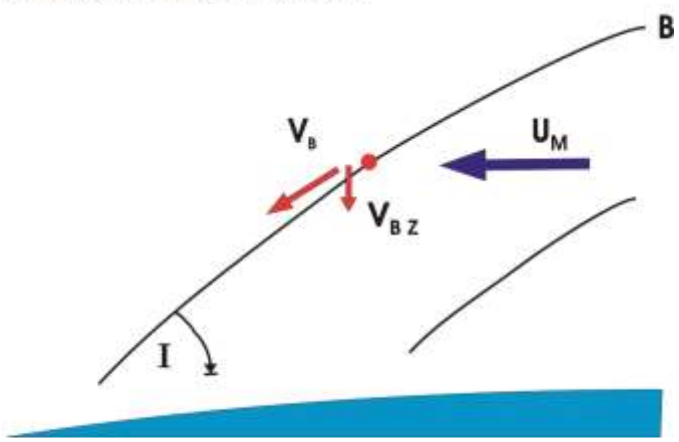
Neutral wind influence on plasma distribution

Equatorward neutral winds:



Nighttime scenario:
Neutral winds blow plasma **up** the magnetic field lines, into regions of lower recombination (hence slow deterioration of F2 layer at night and larger hmF2).

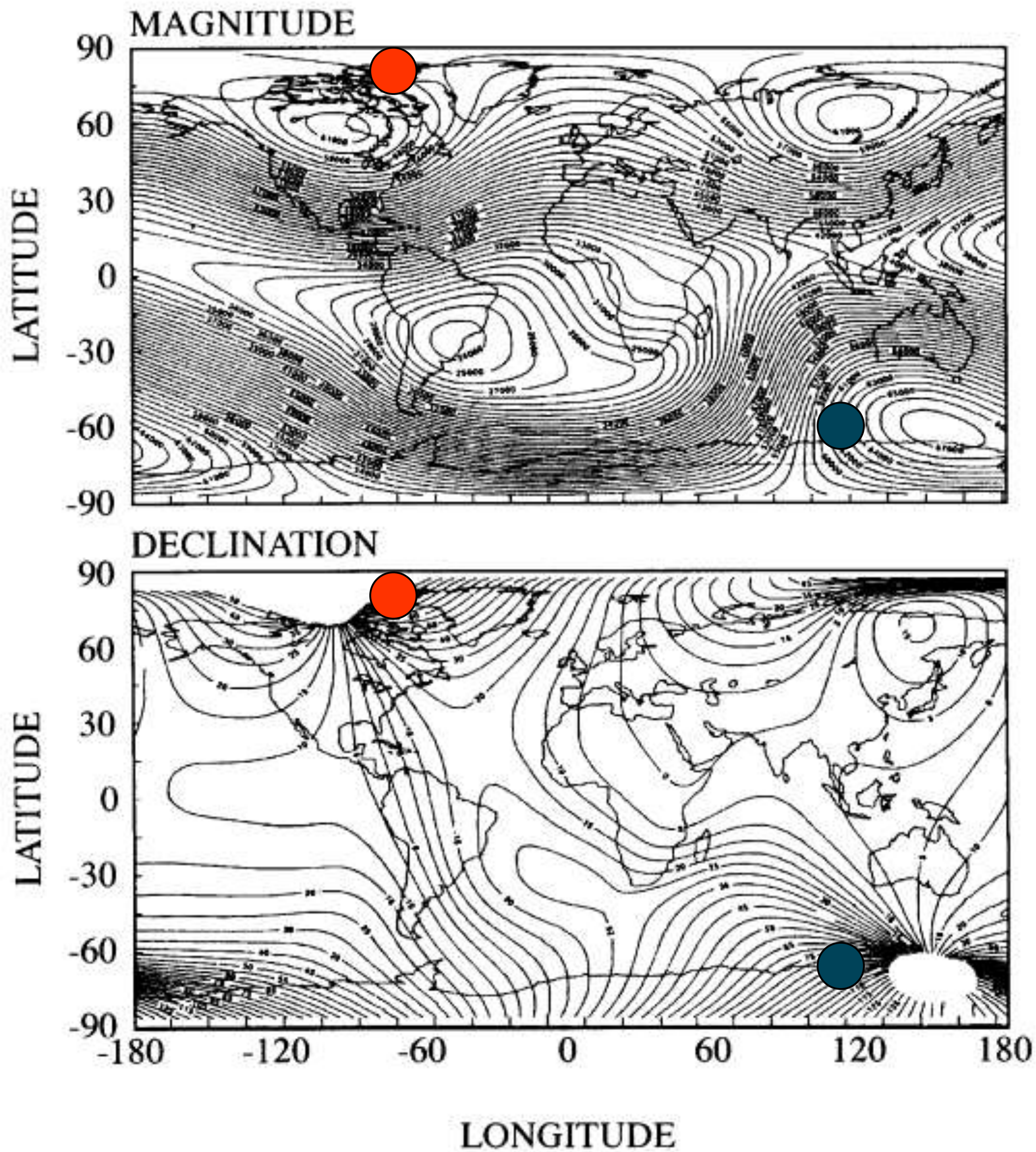
Poleward neutral winds:



Daytime scenario:
Neutral winds blow plasma **down** the magnetic field lines, into regions of stronger recombination. Therefore, hmF2 is lower at day than night.

$$V_{BZ} = U_M \cdot \sin(I) \cdot \cos(I) \quad \Rightarrow \quad V_{BZ} \text{ largest for dip angle } I = 45^\circ$$

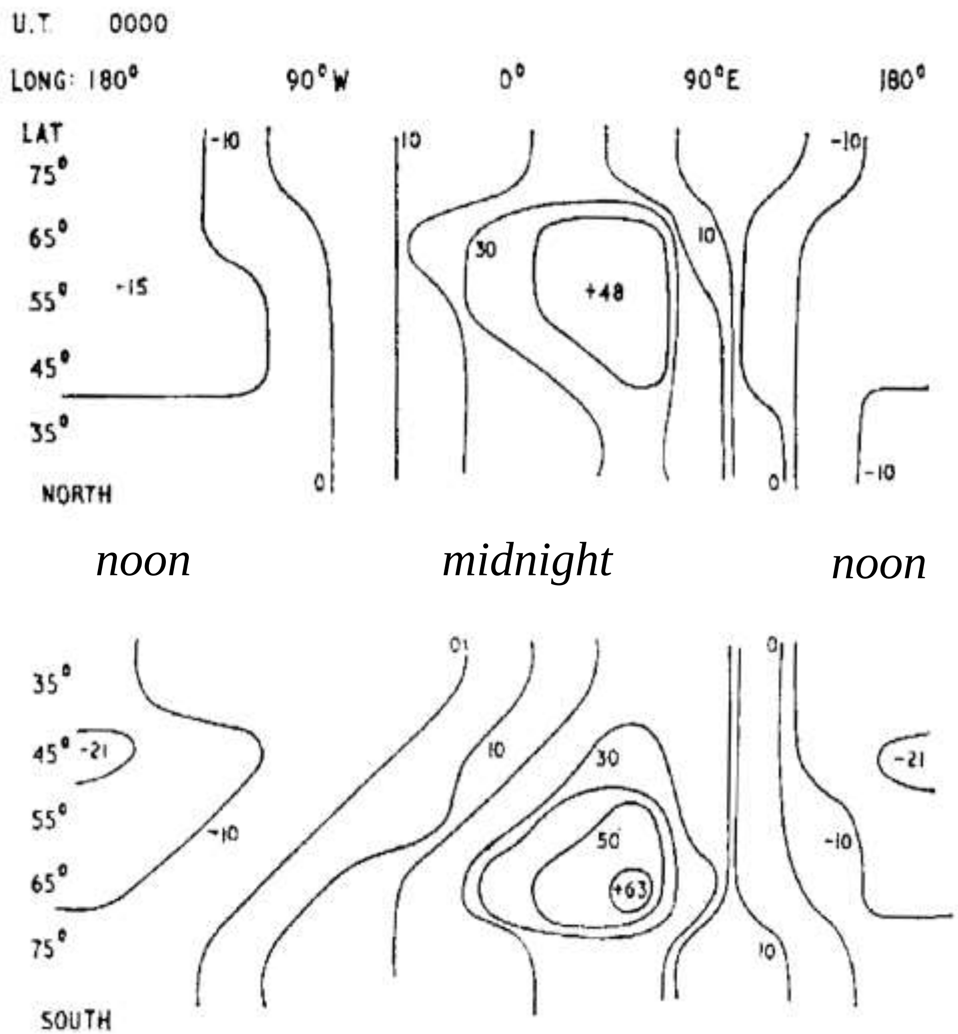
The Earth's geomagnetic field



The Earth's magnetic field is a **tilted**, **offset** dipole field, giving rise to **longitude-dependence** of the coupling between plasma and neutral winds.

Approximate location of geomagnetic poles:

80ºN / 69ºW
79 ºS / 111ºE



noon *midnight* *noon*

The coupling between plasma and neutral winds depends on:

• **Latitude** due to the B_{vert} being largest at the magnetic pole and smallest over the magnetic equator

• **Longitude** due to the geographic and geomagnetic poles being offset

• **Local time** due to the change of *neutral wind direction* and *electron density* (Ne): at night, Ne is lowest, so the slow-down of neutral winds by ions is least effective, giving larger neutral winds at night and stronger vertical plasma drifts.

Therefore, neutral-ion coupling in the F2 region is very complex.

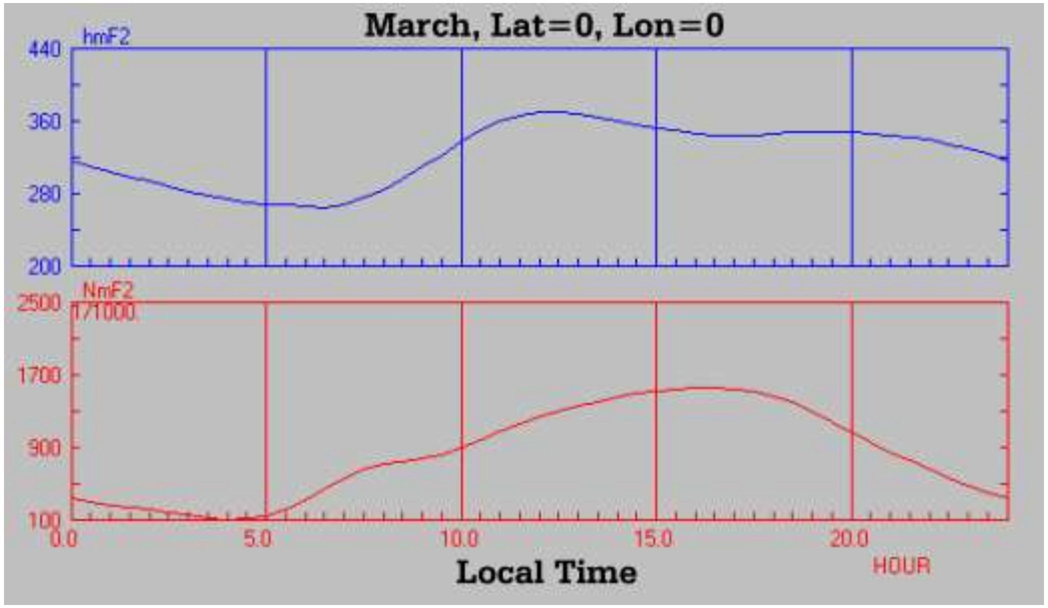
What about the equatorial ionosphere?

Differences are:

B field horizontal ⇒

- No vertical diffusion, only horizontal
- No vertical transport due to meridional winds

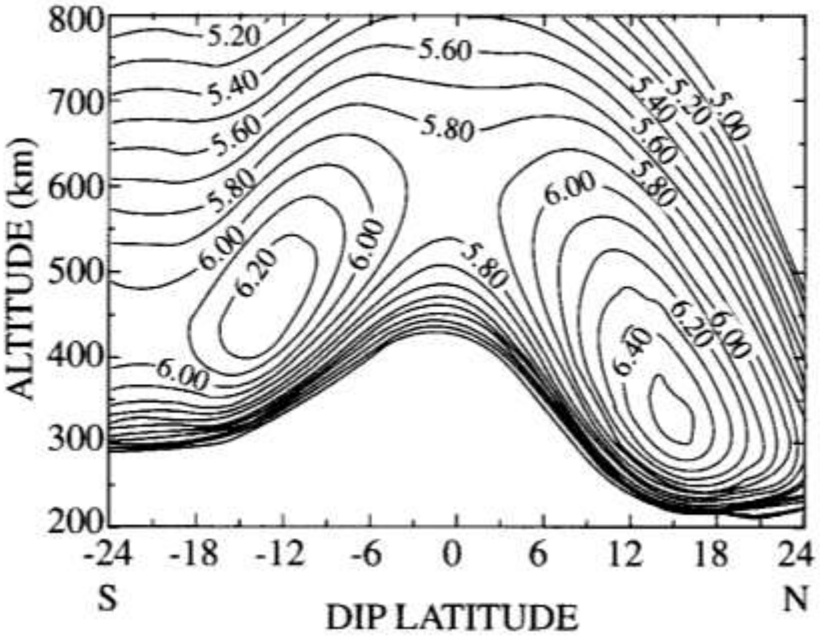
What are the consequences of this?



Output from International Reference Ionosphere (IRI) model.

Note: hmF2 **larger** at **day** than night (other than at mid-latitudes!)

Latitudinal structure of Ne at low latitudes



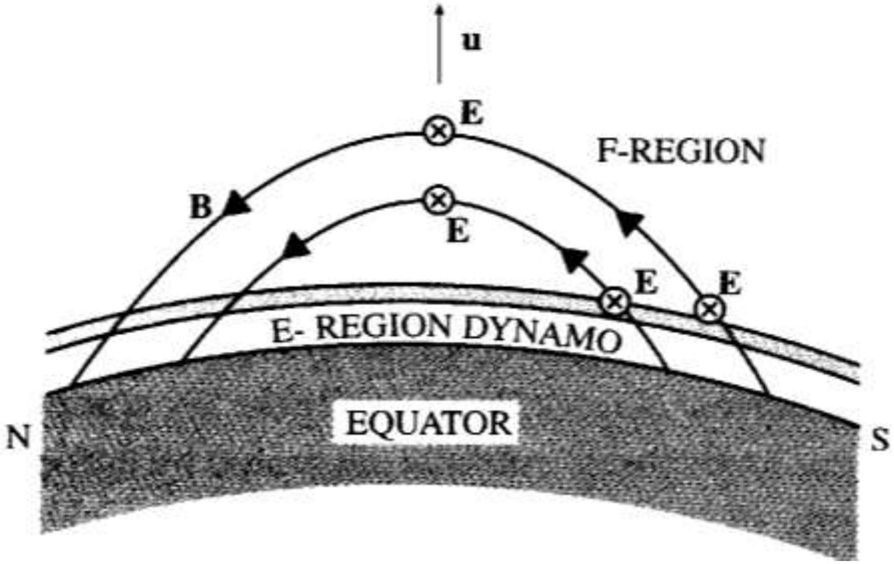
Calculated Ne (in Log10) for December, 20:00 LT.

Note:

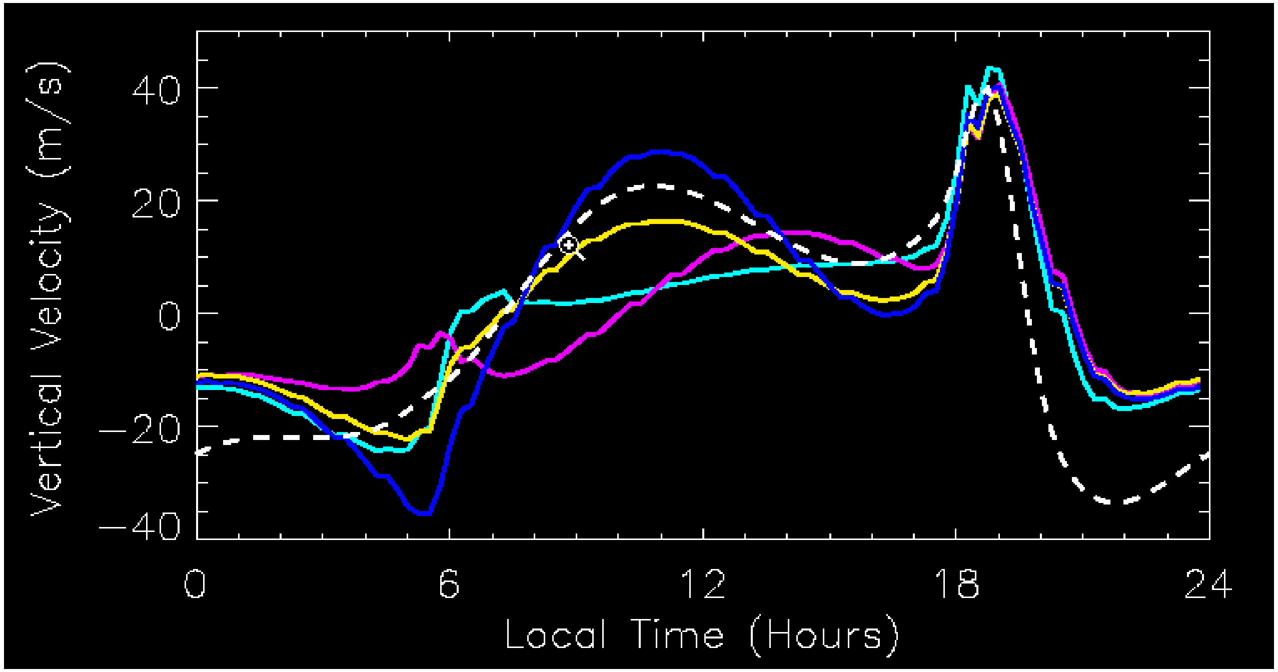
- hmF2 larger over magn. Equator
- build-up of ionization at low latitudes

This effect is called the **Appleton Anomaly** or **Fountain Effect**.

The key to understanding its cause are the zonal neutral winds

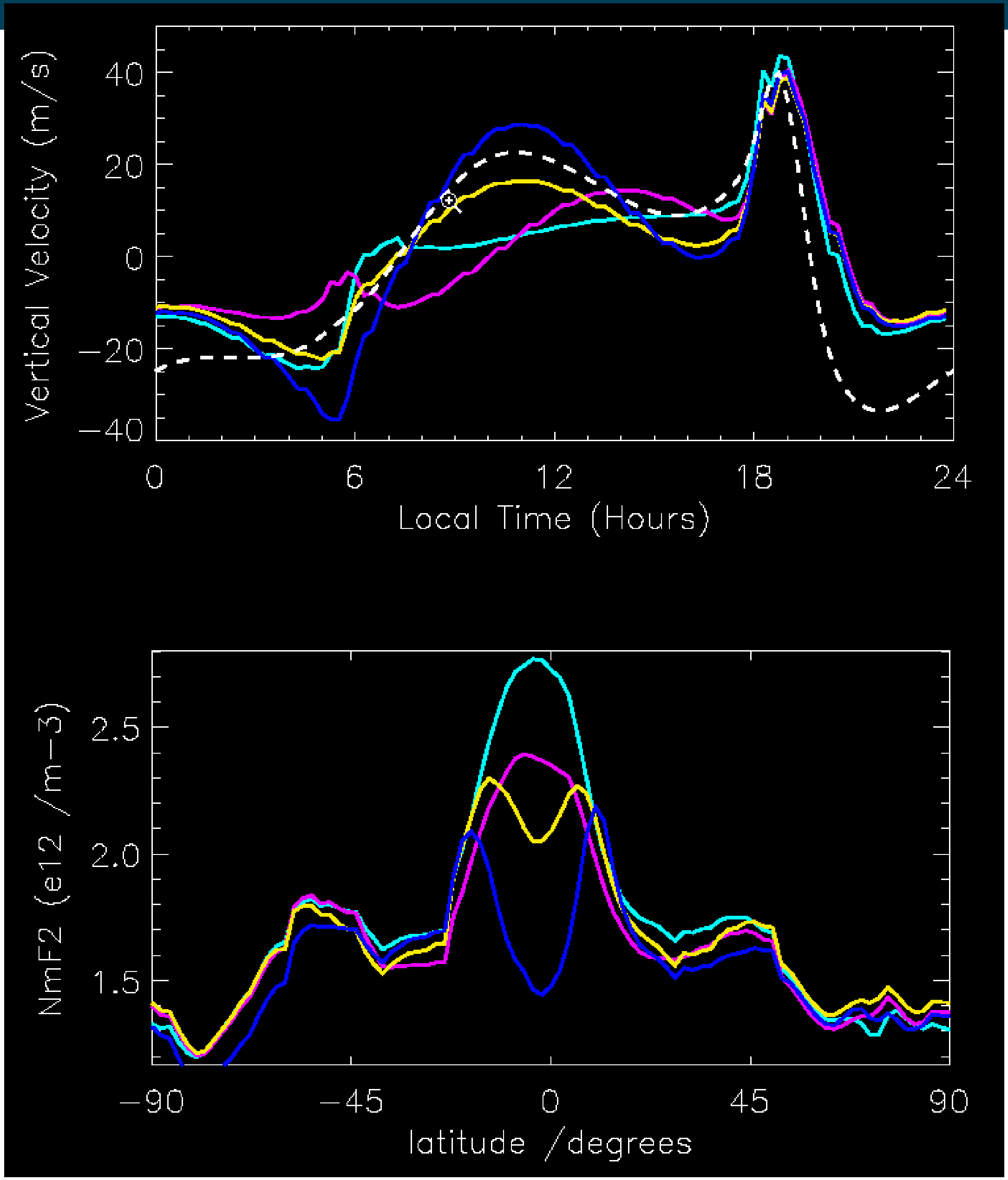


Thermospheric winds in the equatorial E region drag ions across the magnetic field lines ***B***, creating during the daytime an eastward **dynamo electric field**, which is mapped along the magnetic field lines into the F region. This, combined with a northward ***B*** field creates an upward **E×*B*** plasma drift. At dusk, the eastward winds are strongest, producing a particularly strong vertical drift ("**pre-reversal enhancement**").



The pre-reversal enhancement causes Rayleigh-Taylor Instabilities, which may generate small scale structure such as "Equatorial Spread-F".

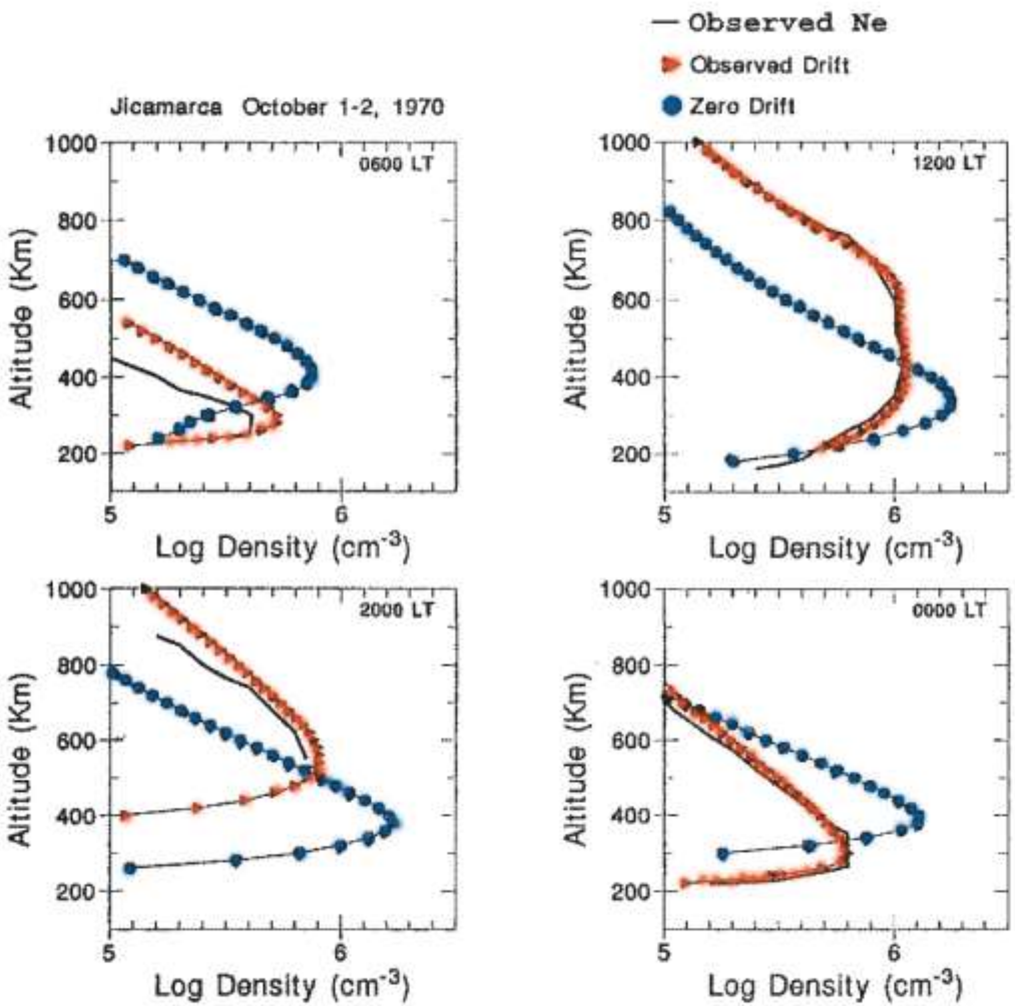
Note the differences in neutral wind-plasma coupling at low and mid latitudes (shown earlier)!



The equatorial vertical plasma drifts are strongly dependent on neutral winds in the E region. The shown lines are simulations for different tidal diurnal and semidiurnal modes….

…. with considerable impact on the shape and magnitude of the Appleton anomaly.

This effect is an example for effective coupling between the thermosphere and ionosphere at different altitudes as well as latitudes!



The impact of vertical drifts on the vertical electron density (Ne) profile at Jicamarca, Peru (xxN/xxW).

These simulations show that vertical plasma drifts move the Ne profile up during day and down during night, with respect to the solution without plasma drifts (**blue**).

Including realistic plasma drifts considerably improves the agreement between modeled (**red**) and observed (**black**) Ne.

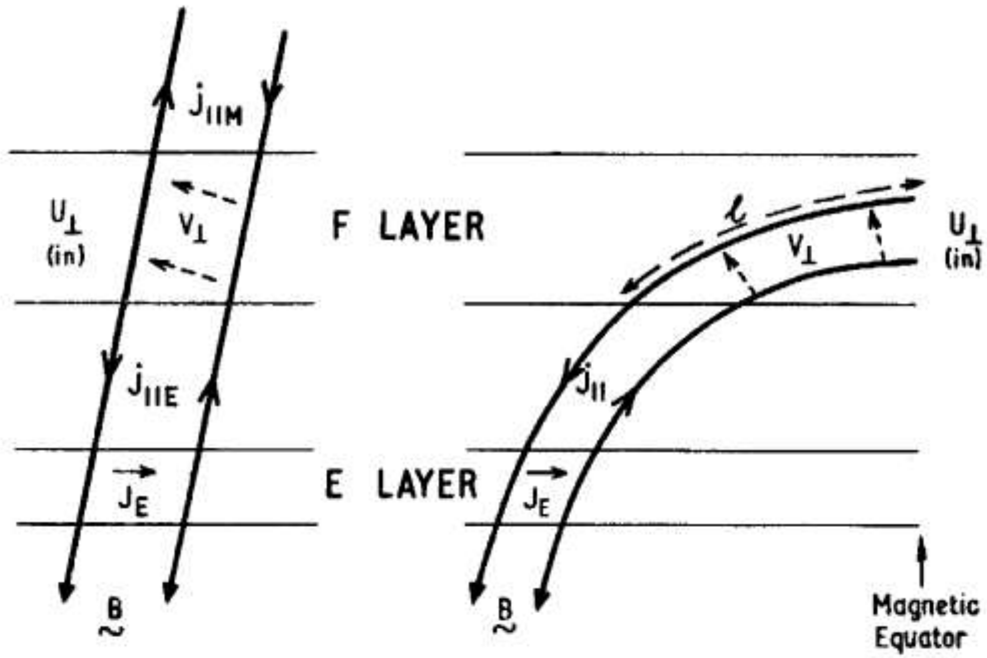


FIG. 2. AN EASTWARD WIND $U_\perp$ IN THE F-LAYER (DIRECTED INTO THE PLANE OF THE FIGURE) PRODUCES AN ION DRIFT $V_\perp$ (BROKEN ARROWS) NORMAL TO THE GEOMAGNETIC FIELD **B**. Field-aligned current $j_{||}$ and an E-layer current J_E complete the circuit. (a) Mid-latitude case. The field-aligned current comprises a current $j_{||E}$ linking with the E-layer current and a magnetospheric current $j_{||M}$. (b) Equatorial case. No current flows across the magnetic equator (right-hand edge of diagram) if there is symmetry about the equator. The length l of a field line within the F-layer is greater than in the mid-latitude case.

The E region:

This is chemically controlled and thus tied more tightly to solar insolation variations

The dynamics has little effect and local creation and loss dominate the morphology

This is modified a little by the coupling to the F-region along the field lines and the presence of strong electric fields

The chemistry is that of molecular ions O_2^+ and NO^+ rather than O^+

Ion/Electron Continuity Equation

$$\frac{\partial N}{\partial t} = q - l(N) - \vec{\nabla}(N\vec{V})$$

Loss

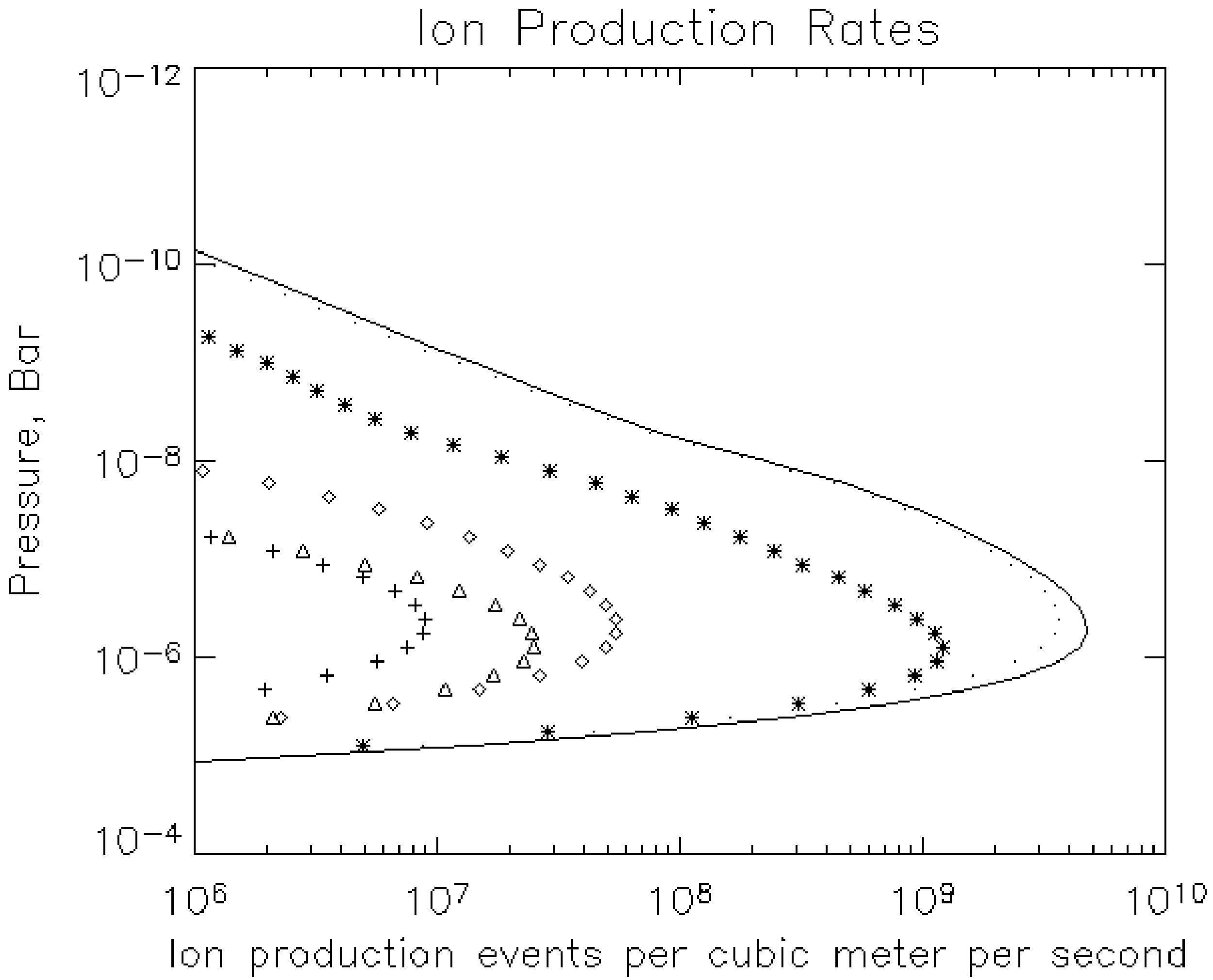
Production

Transport

D, E, F1 region: q~l(N) >> del(NV) Transport mostly unimportant
photochemical regime, described by Chapman layers

F2 region: Transport matters, q and l(N) no longer dominant
optically thin, not Chapman layer

The Chapman Profile now is the main feature of the height variabilty. On Mars and other planets this is the dominant distribution



(D profile) - is complex

-extremely energetic particles,

-Water cluster ions

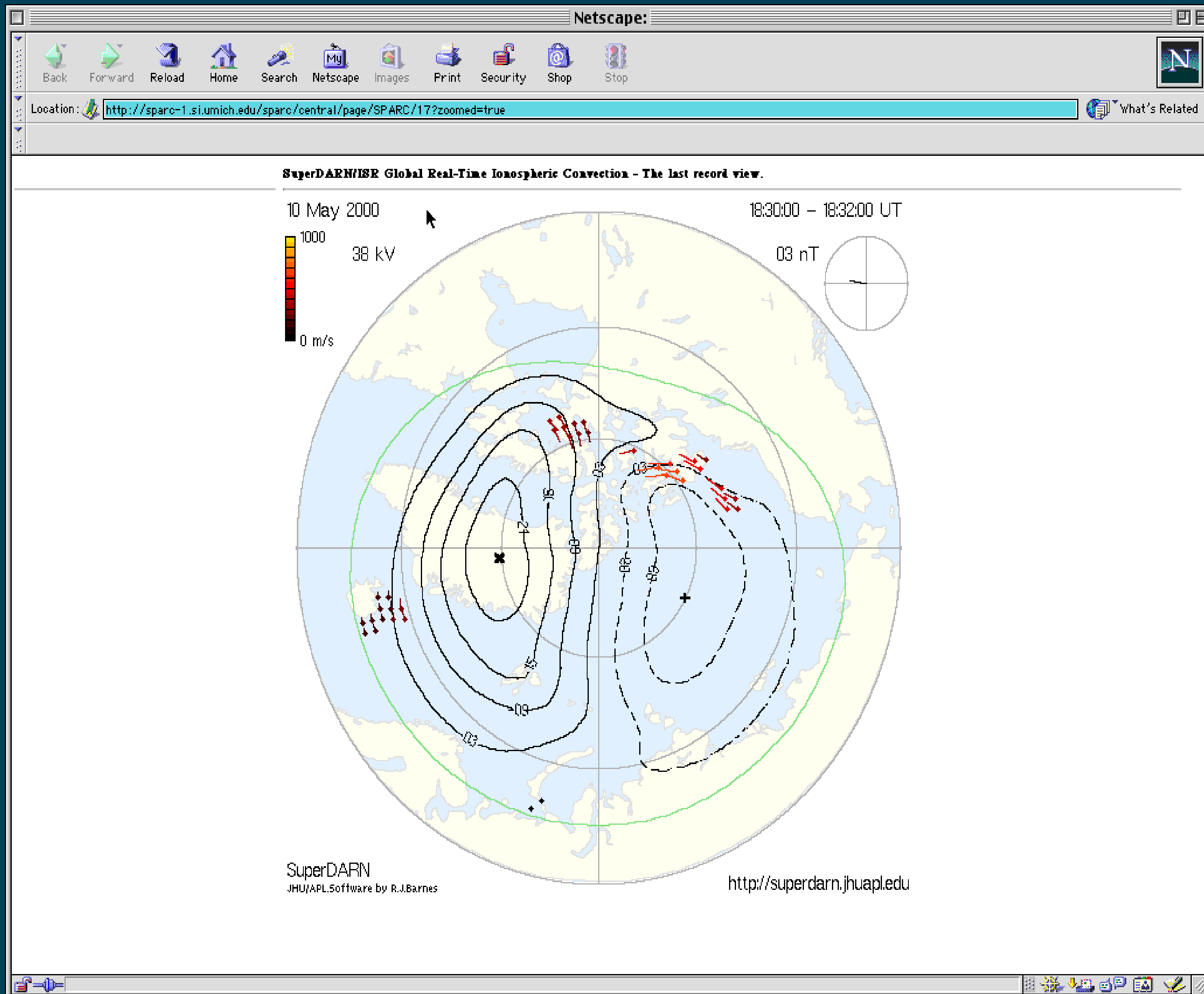
-Complex chemistry

Is that the full story?

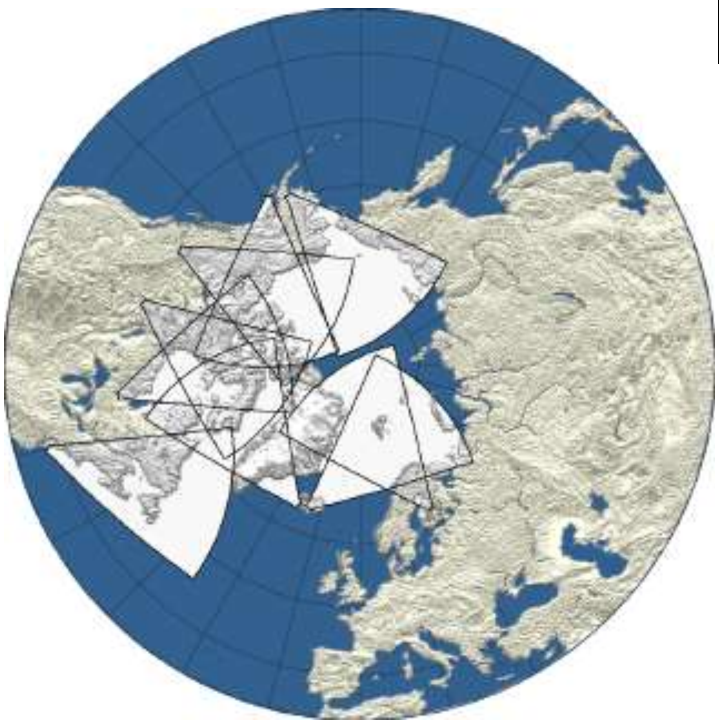
In a more comprehensive analysis we find there are layered features in the E region (sporadic E layers) and the equatorial F-region (spread-F).

In the auroral zone the distribution in both E and F regions is often controlled by the particle precipitation. And high auroral electric fields and plasma convection are important for the plasma distribution above about 60 degrees latitude. In the auroral zones the ionosphere is in many ways an extension of the magnetosphere

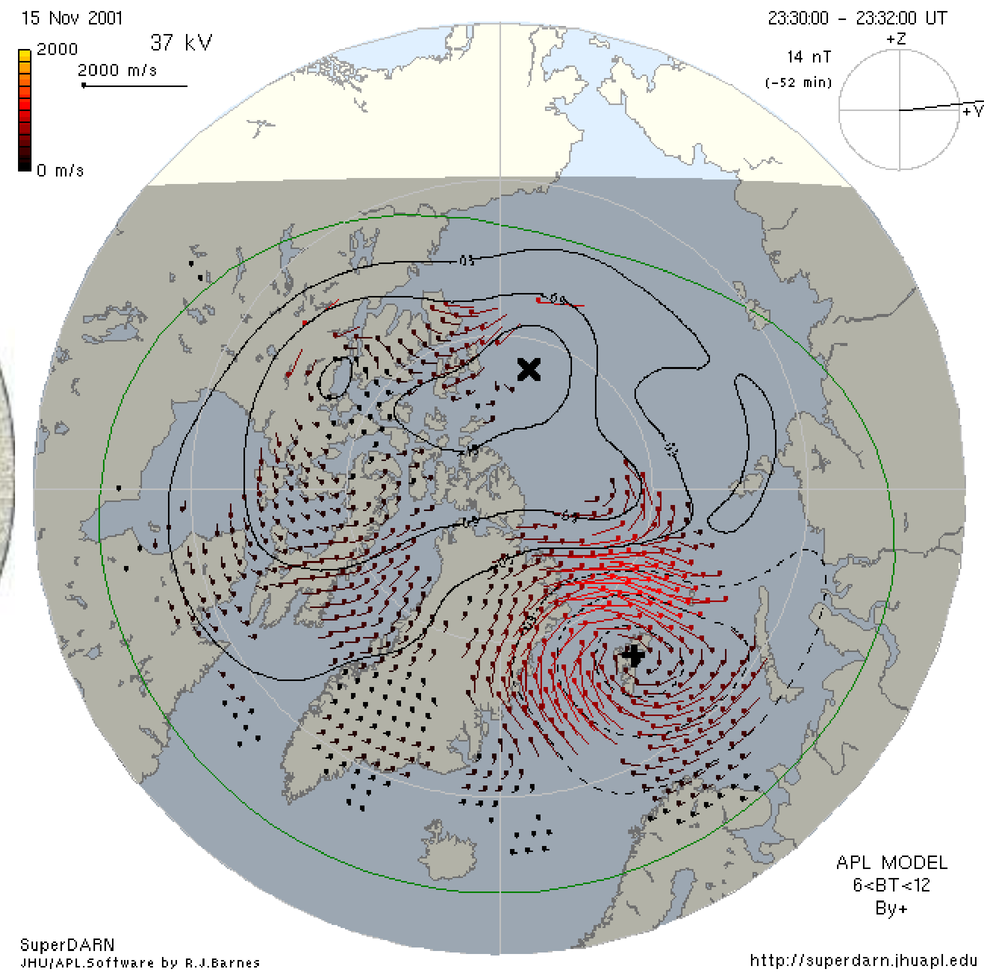
We see the magnetospheric input as a convection pattern and a precipitation pattern – momentum and energy input:


Netscape:
Back
Forward
Reload
Home
Search
Netscape
Images
Print
Security
Shop
Stop
Location: http://sparc-1.si.umich.edu/sparc/central/page/SPARC/17?zoomed=true
What's Related
SuperDARN/ISR Global Real-Time Ionospheric Convection - The last record view.
10 May 2000
18:30:00 – 18:32:00 UT
1000
0 m/s
38 kV
03 nT
SuperDARN
JHU/APL Software by R.J.Barnes
http://superdarn.jhuapl.edu

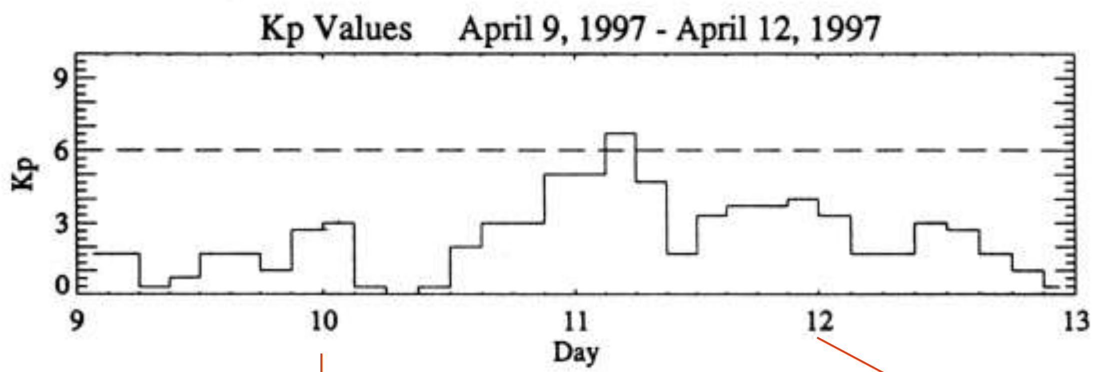
SuperDARN
Super Dual Auroral Radar Network



Northern Hemisphere



But complications continually arise: the response to storms is not simple:

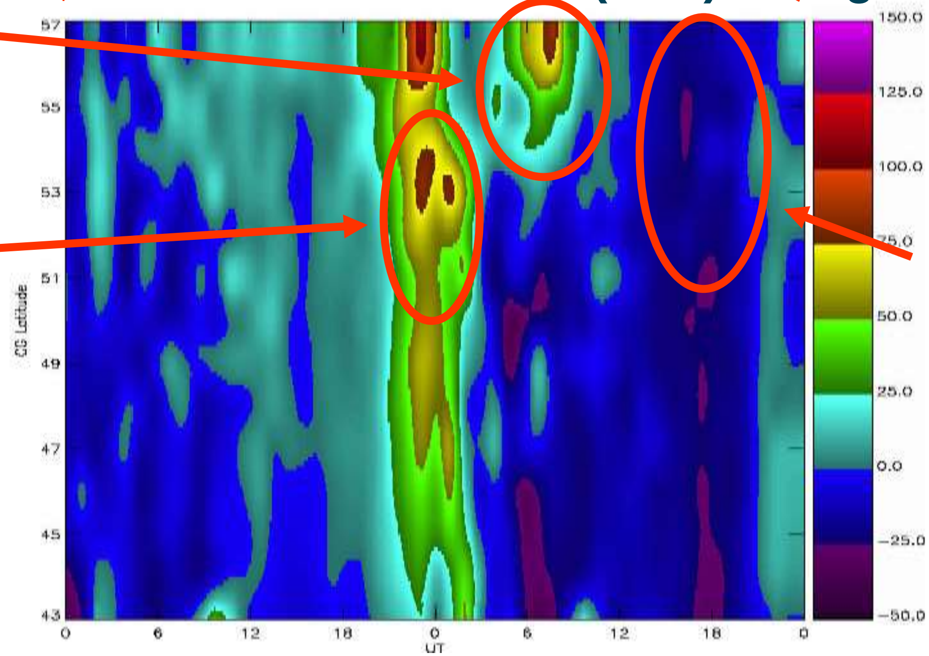


Storm event

TEC enhancement (particle precipitation)

Dusk effect (neutral winds)

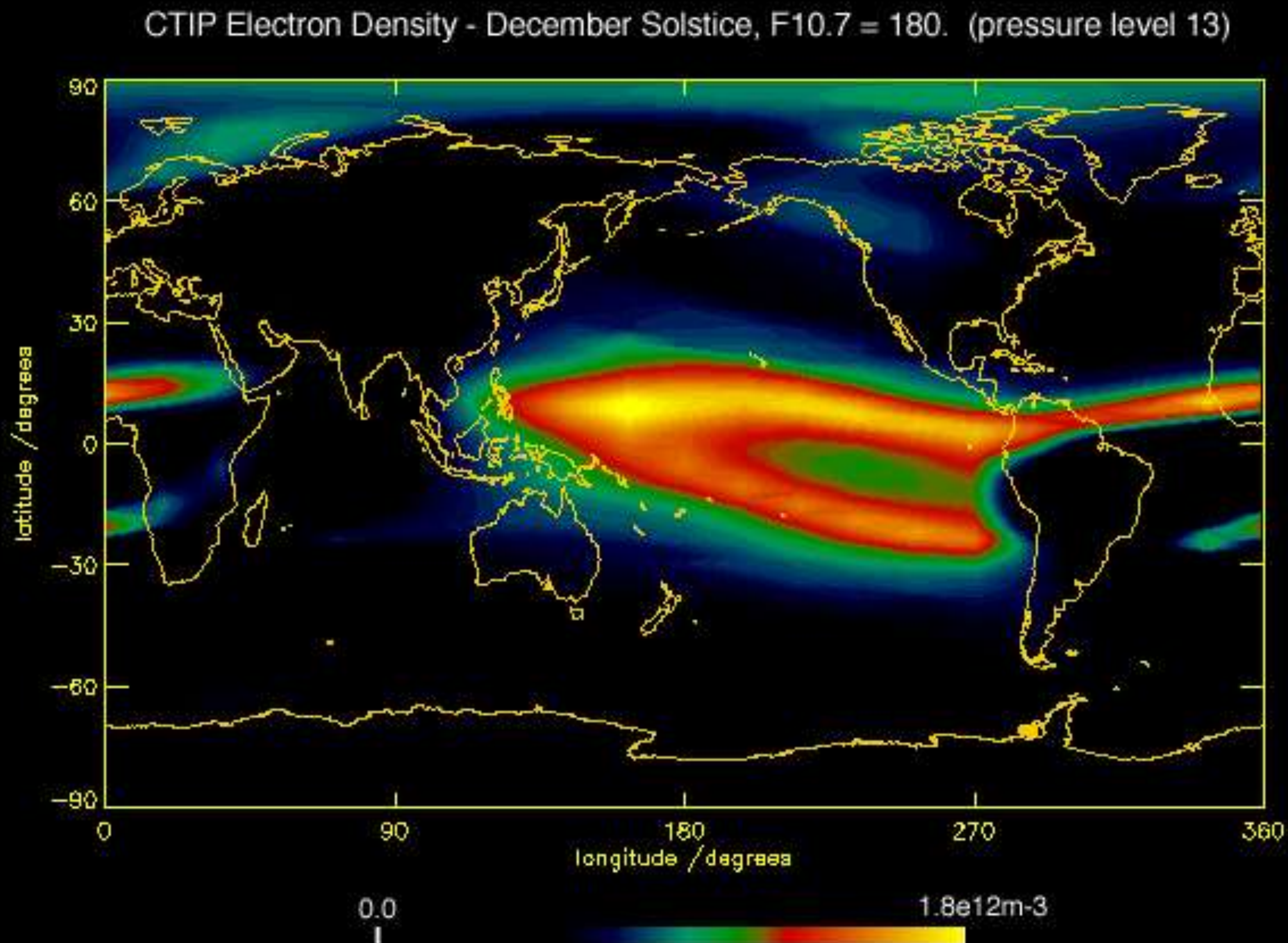
Total Electron Content (TEC) change



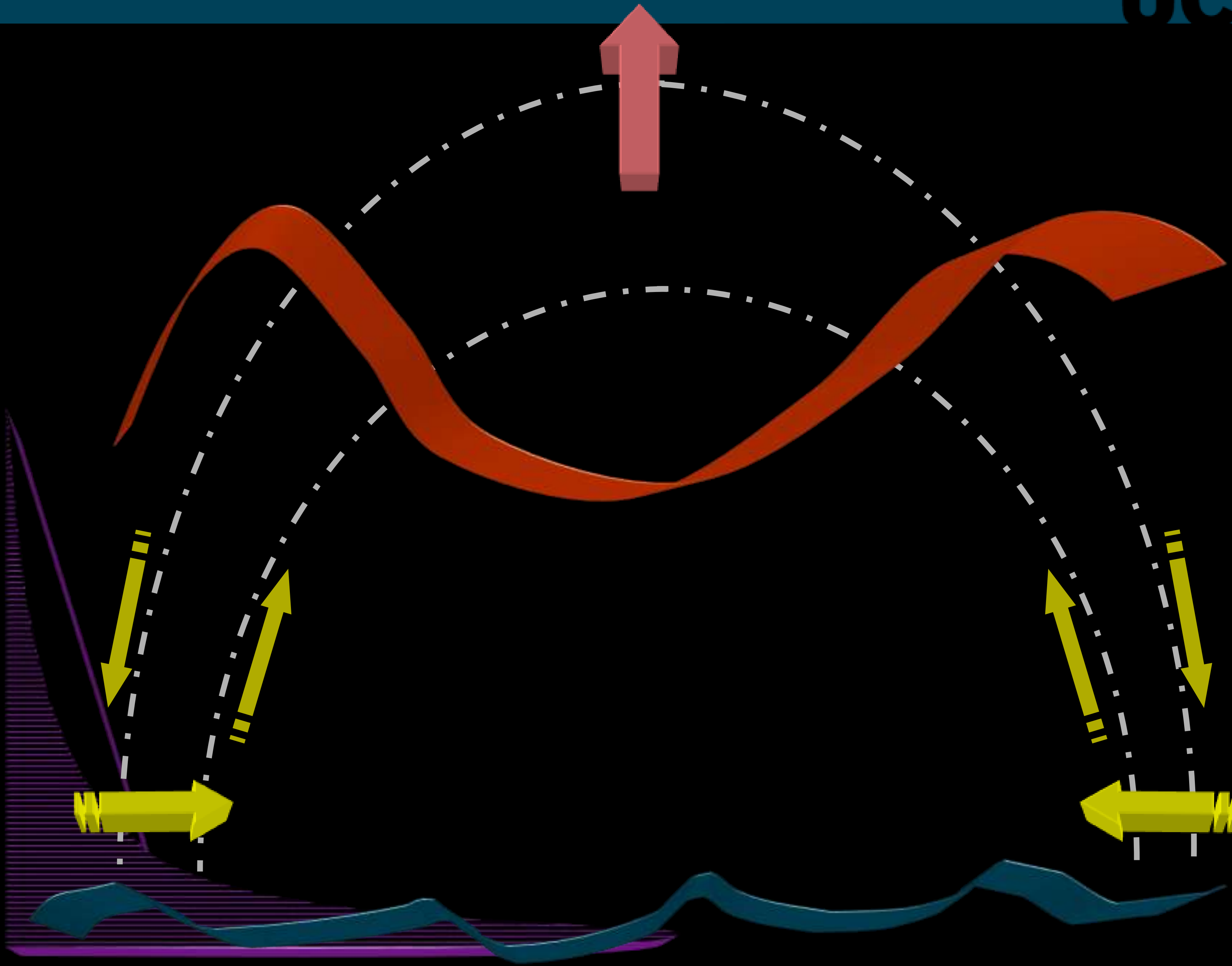
Negative phase (neutral gas composition)

And its not just the auroral response that is complex.

If we go back to look at that equatorial region:


CTIP Electron Density - December Solstice, F10.7 = 180. (pressure level 13)
90
60
30
0
-30
-60
-90
latitude / degrees
0
90
180
270
360
longitude / degrees
0.0
1.8e12m-3

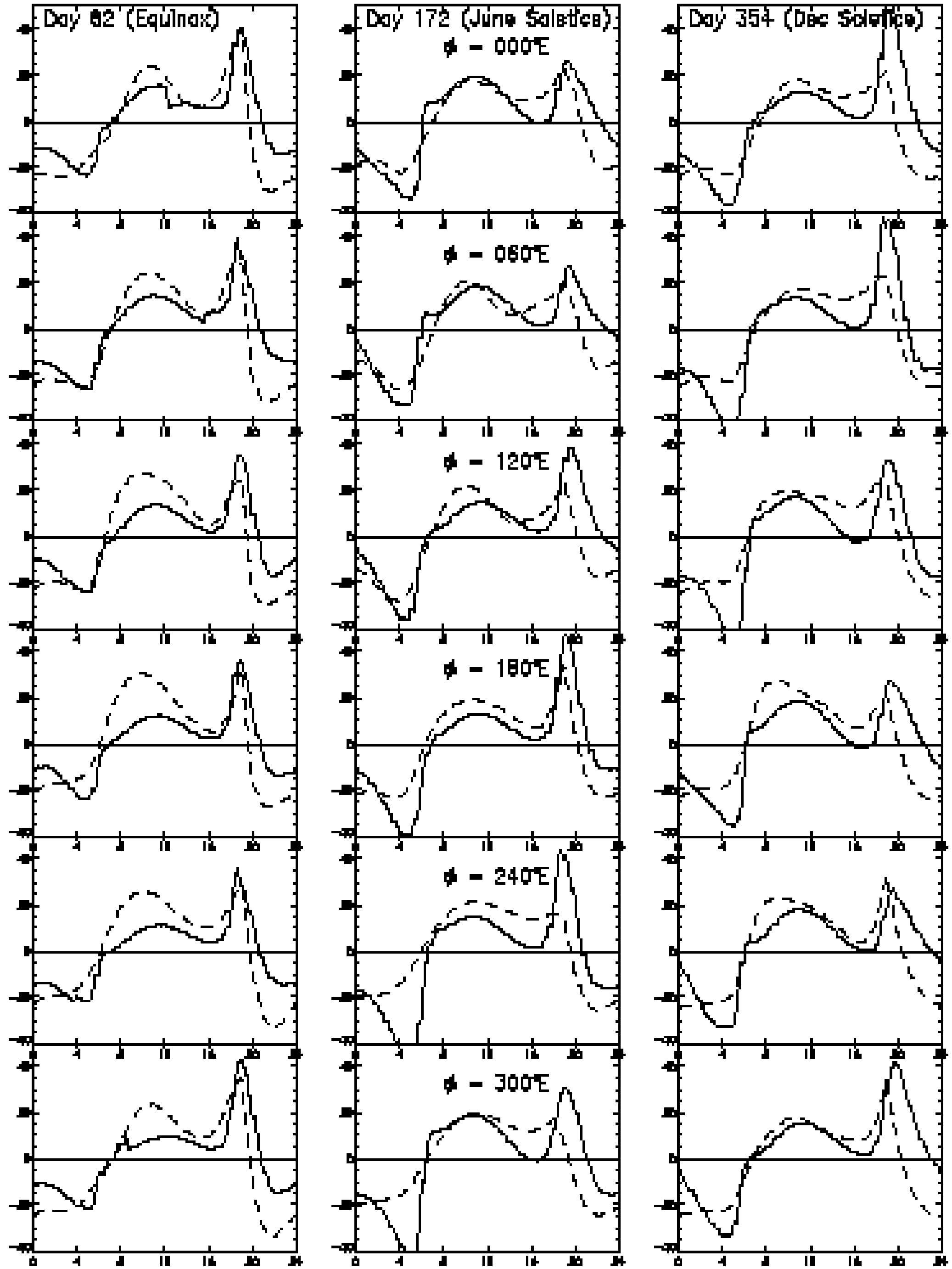
V = E x B (20 - 40 m/s)

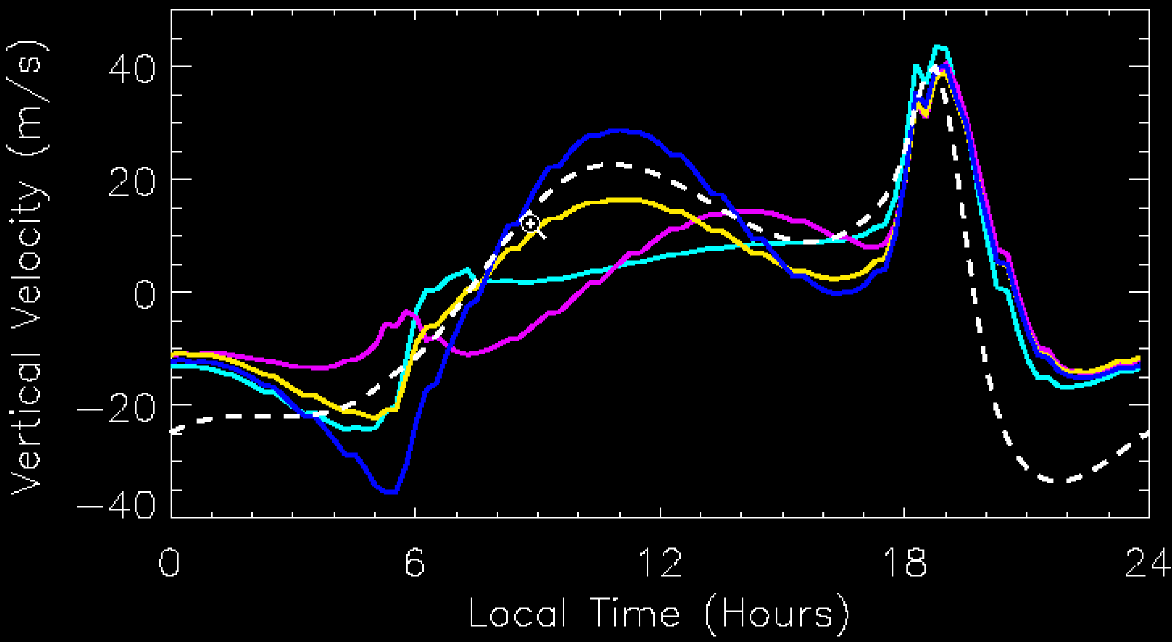


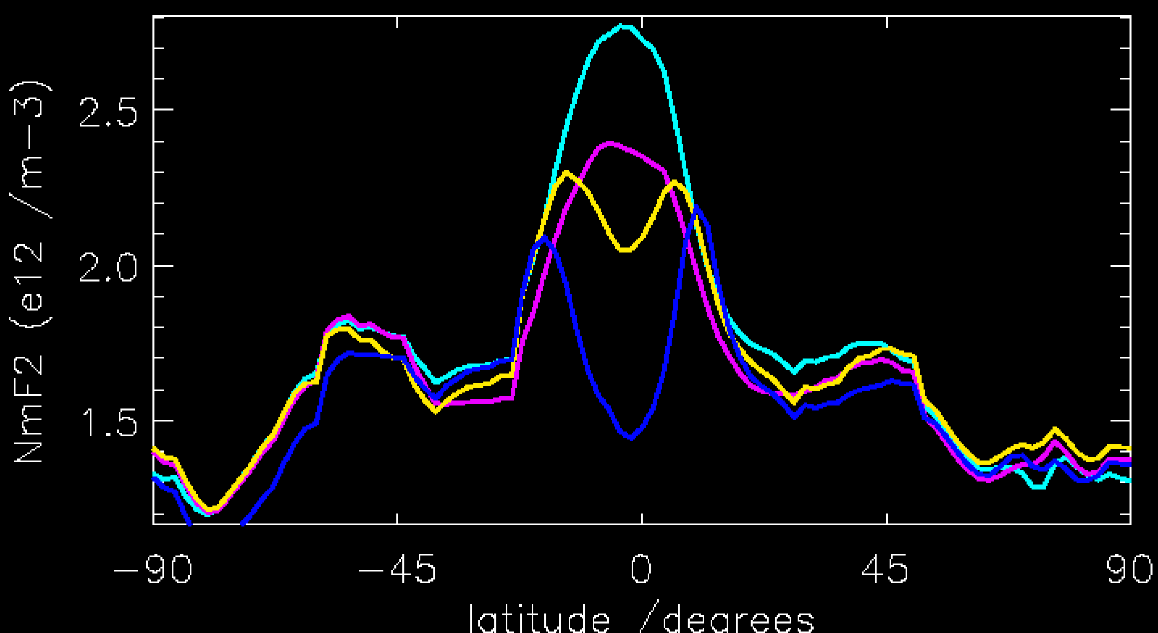
CTIP Electrodynamics

Equatorial vertical ion motion (seasons and longitudes) - CTIP model predictions vs empirical data

shows the 'pre-reversal enhancement'




Vertical Velocity (m/s)
40
20
0
−20
−40
0
6
12
18
24
Local Time (Hours)


NmF2 (e12 /m−3)
2.5
2.0
1.5
−90
−45
0
45
90
latitude /degrees

CTIP STORM ELECTRODYNAMICS

Runs looking at how winds at high and mid-latitudes affect storm-time electrodynamics

(A) Ezonal - storm - quiet (2hours into major magnetic storm)

(B) As (A) - but only winds equatorward of 60deg contribute to electrodynamics

(C) As (A) - but only winds poleward of 60 deg contribute to electrodynamics

Result: Similarity of (A) and (B) shows that High-latitude electrodynamics are insignificant in storm-time electrodynamics; Mid/low lat winds are Key.

Large blue stripe in (A) and (B) indicates that Pre-reversal enhancement collapses during Storm. Two hours into the storm information has only propagated to fairly high mid-lats. This strongly suggests that the pre-reversal enhancement feature is connected to winds at fairly high-lats (50 - 60 deg).

Zonal Electric fields (Storm - Quiet diff)