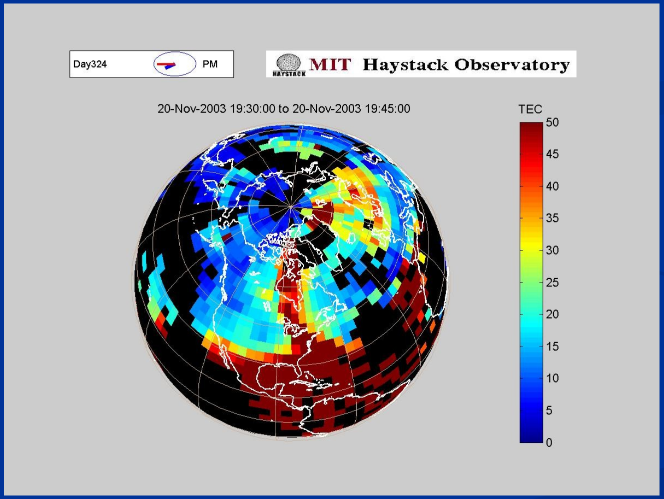
Electrodynamics in the Mid-Latitudes

Anthea Coster, MIT Haystack Observatory



References

- Kelley, M. C. 1989; 2009. *The Earth's ionosphere: Plasma physics and electrodynamics*. International Geophysics Series, vol 43. San Diego: Academic Press. (Hardcover - 2009/05/19)
- Kintner, P. M., et al., 2008. *Midlatitude Ionospheric Dynamics And Disturbances. Volume 181*. Series – AGU Geophysical Monograph.

• Rishbeth, Henry; Garriott, Owen K. Introduction to ionospheric physics, New, York, Academic Press, 1969. International geophysics series, v. 14

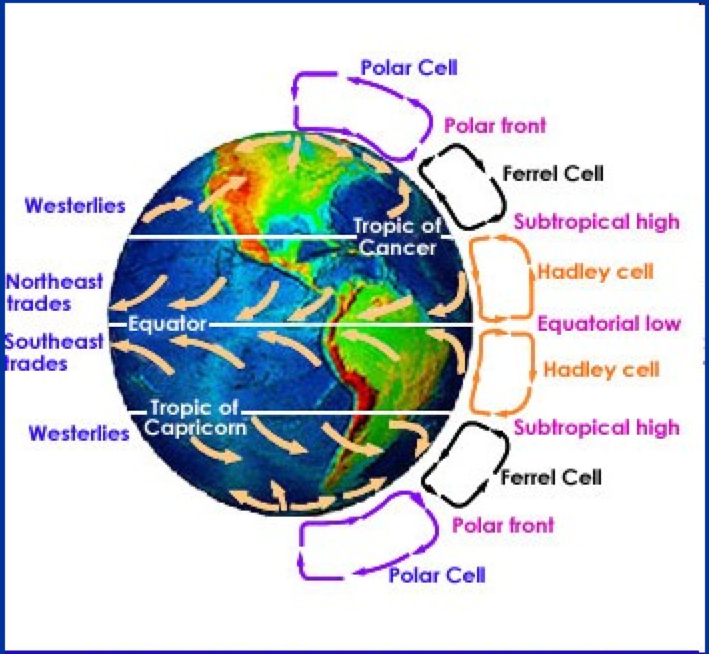
•Jursa, Adolph S., Handbook of Geophysics and the Space Environment, 4th edition, 1985, Air Force Geophysics Laboratory, Hanscom AFB, MA

Outline

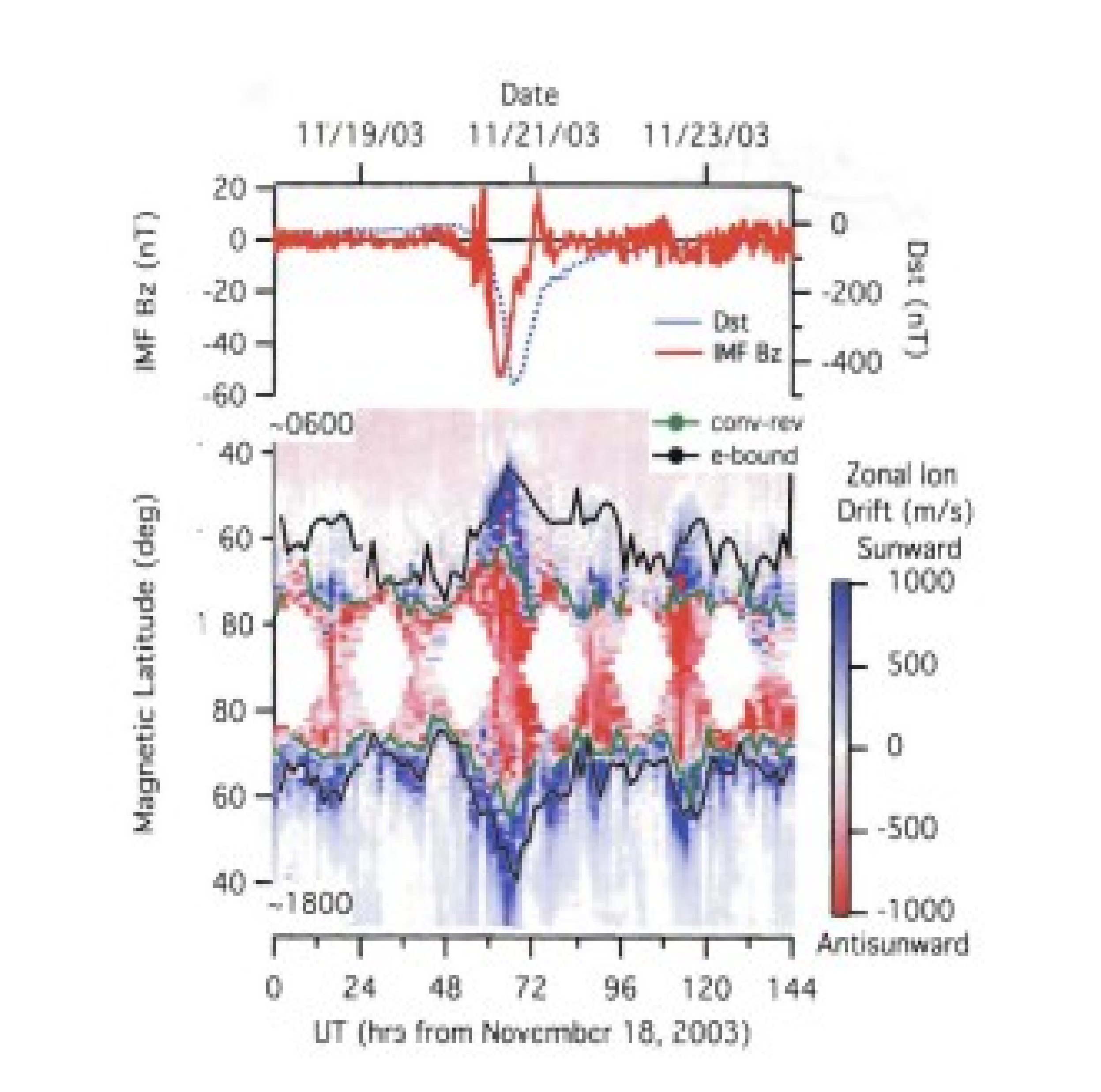
- Definition of mid-latitudes
- Conductivities in E and F region in mid-latitudes
- Ionospheric trough region
- Dynamo winds – electric fields
- Electrostatic Traveling Ionospheric Disturbances
- Storm time electric fields

What are the Mid-Latitudes?

- The **mid-latitudes** (sometimes **midlatitudes**) are the areas on earth between the tropics and the polar regions, approximately 30° to 60° north or south of the equator. The mid-latitudes are an important region in meteorology, having weather patterns which are generally distinct from weather in the tropics and the polar regions



Wind Circulation Patterns of Earth



R. A. Heelis, Low and Middle Latitude Ionospheric Dynamics Associated with Magnetic Storms, AGU MIDD

Northwest Territories, Canada

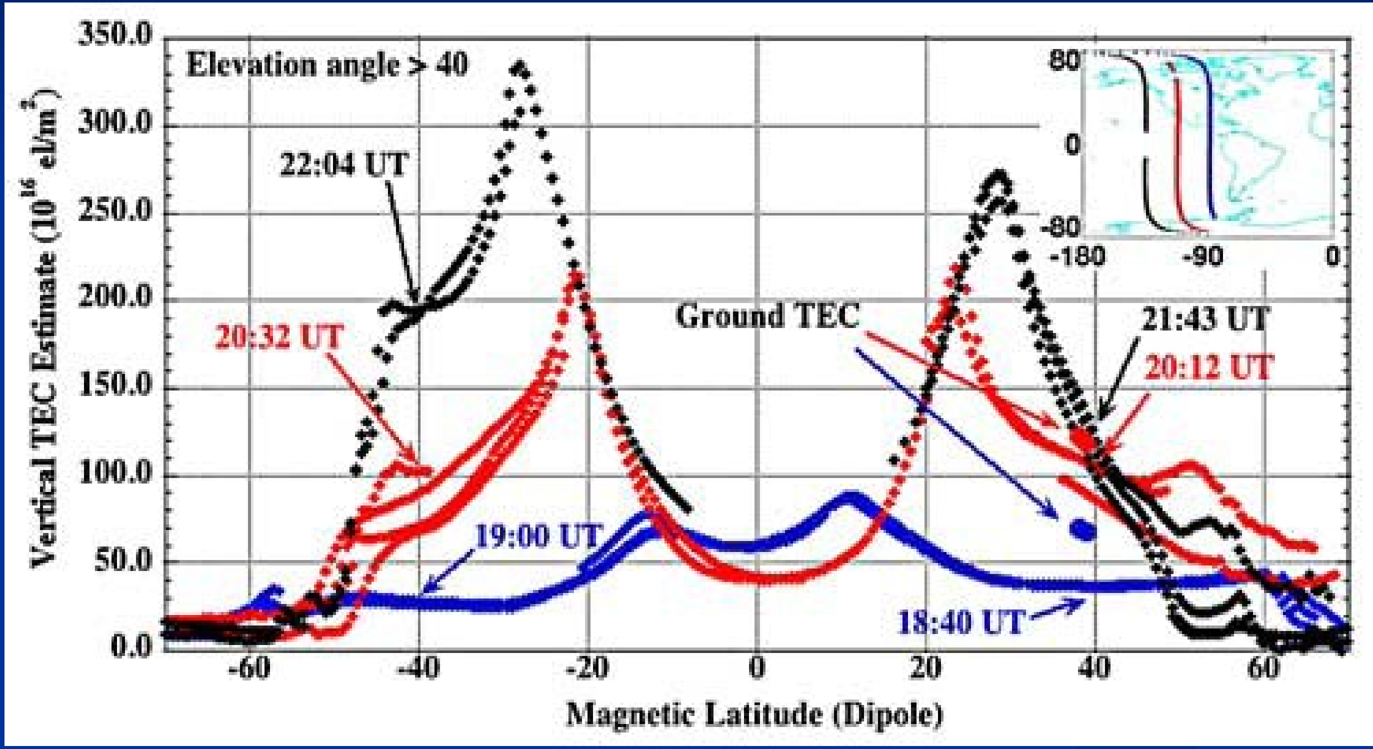
Socorro New Mexico 20 Nov 2003

(from astronomy picture of the day)

West Texas 15 Sept 2000 near El Paso Texas

(from astronomy picture of the day)

Storm-time Appelton Anomaly



Mannucci et al., 2005, GRL

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Why do we care about conductivities?

Ionosphere is a plasma with an embedded magnetic field.

$$\nabla \cdot [\sigma \cdot (\mathbf{E}(\mathbf{r},t) + \mathbf{U}(\mathbf{r},t) \times \mathbf{B}] = 0$$

“The resulting electric field is as rich and complex as the driving wind field and the conductivity pattern that produce it”, Kelley, Ch. 3

Equations of Motion

Parallel equation of motion

$$qE = m_i \nu_{in} u_i \qquad -eE = m_e \nu_{en} u_e$$

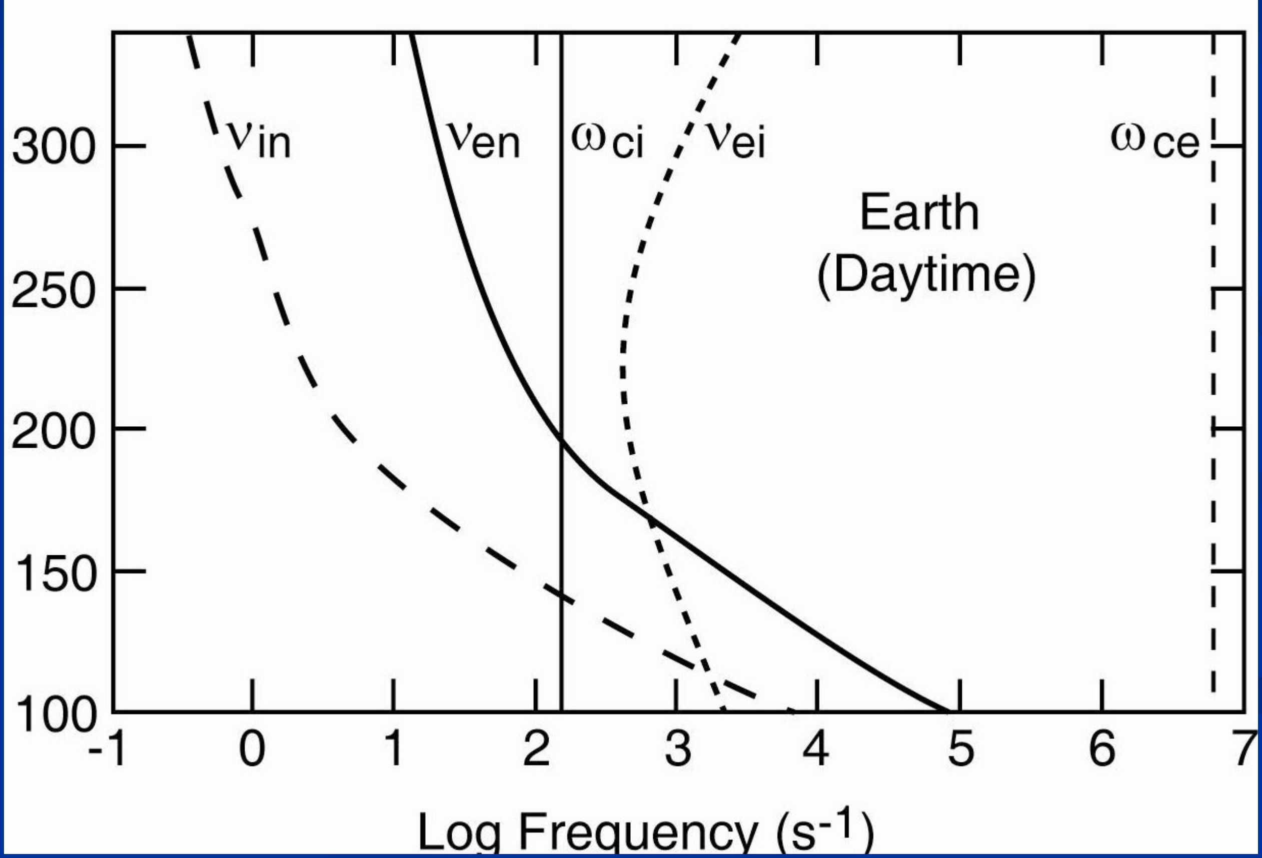
Perpendicular equation of motion

$$q\left(\mathbf{E}_\perp + \mathbf{u}_i \times \mathbf{B}\right) = m_i \nu_{in} \mathbf{u}_{\perp i}$$

$$-e\left(\mathbf{E}_\perp + \mathbf{u}_e \times \mathbf{B}\right) = m_e \nu_{en} \mathbf{u}_{\perp e}$$

Collision Frequencies

Ion and electrons collide with neutrals as they gyrate. How they move in response to electric fields depends very much on the collision frequency relative to the gyro-frequency.



Conductivity

$$\sigma_1 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\nu_{en}^2}{\nu_{en}^2 + \Omega_e^2}\right) + \frac{1}{m_i \nu_{in}}\left(\frac{\nu_{in}^2}{\nu_{in}^2 + \Omega_i^2}\right)\right] n_e e^2$$

- **Pedersen conductivity (along $E_\perp$) perpendicular B, parallel E; horizontal**

$$\sigma_2 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\Omega_e \nu_{en}}{\nu_{en}^2 + \Omega_e^2}\right) - \frac{1}{m_i \nu_{in}}\left(\frac{\Omega_i \nu_{in}}{\nu_{in}^2 + \Omega_i^2}\right)\right] n_e e^2$$

- **Hall conductivity (along E x B)**

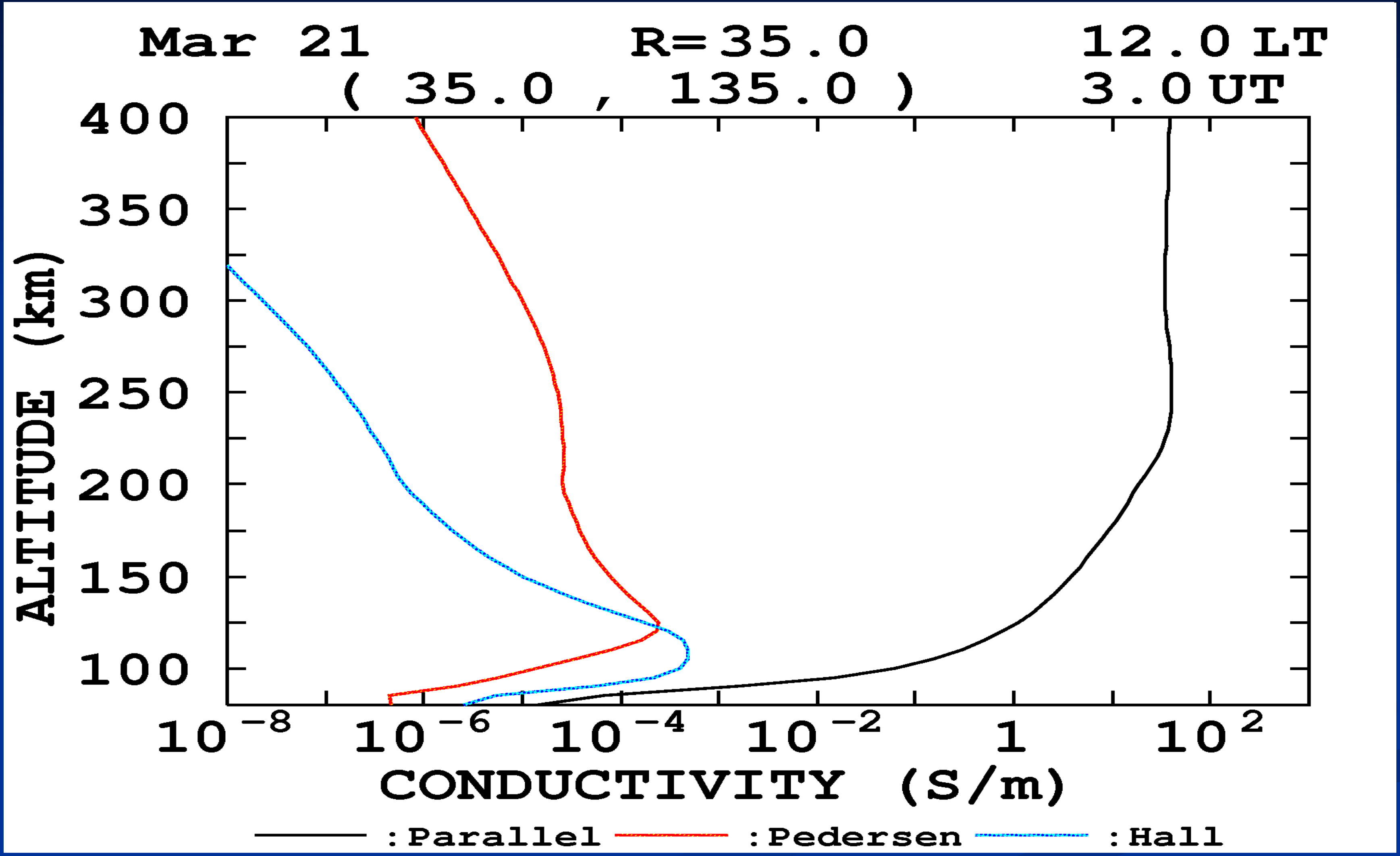
$$\sigma_0 = \left[\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}}\right] n_e e^2$$

- **Parallel conductivity**

$$j = \begin{pmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{pmatrix} \begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

- Conductivity tensor

http://wdc.kugi.kyoto-u.ac.jp/ionocond/exp/icexp.html



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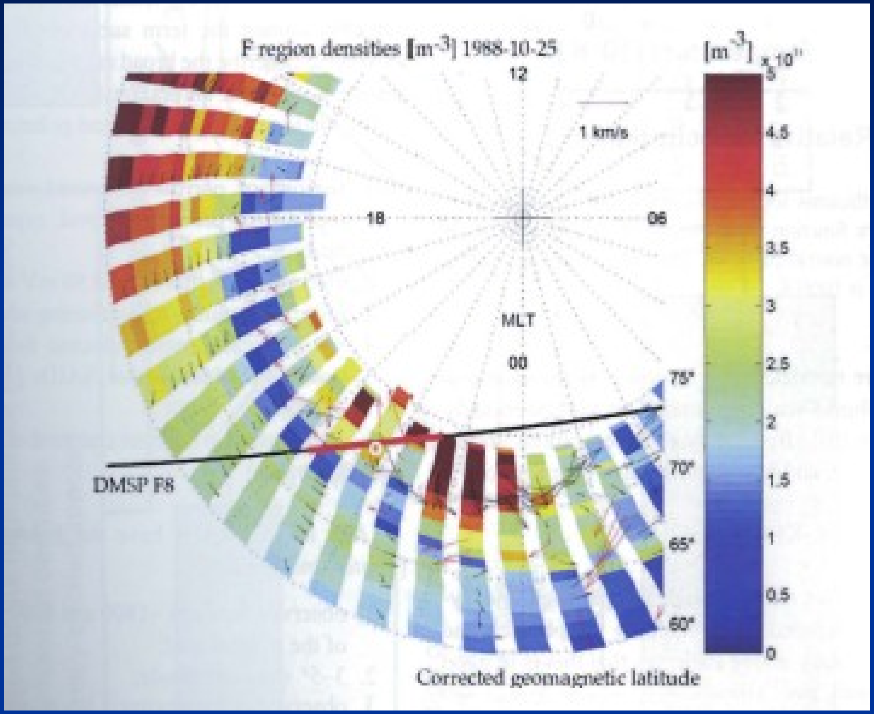
Ionospheric Trough



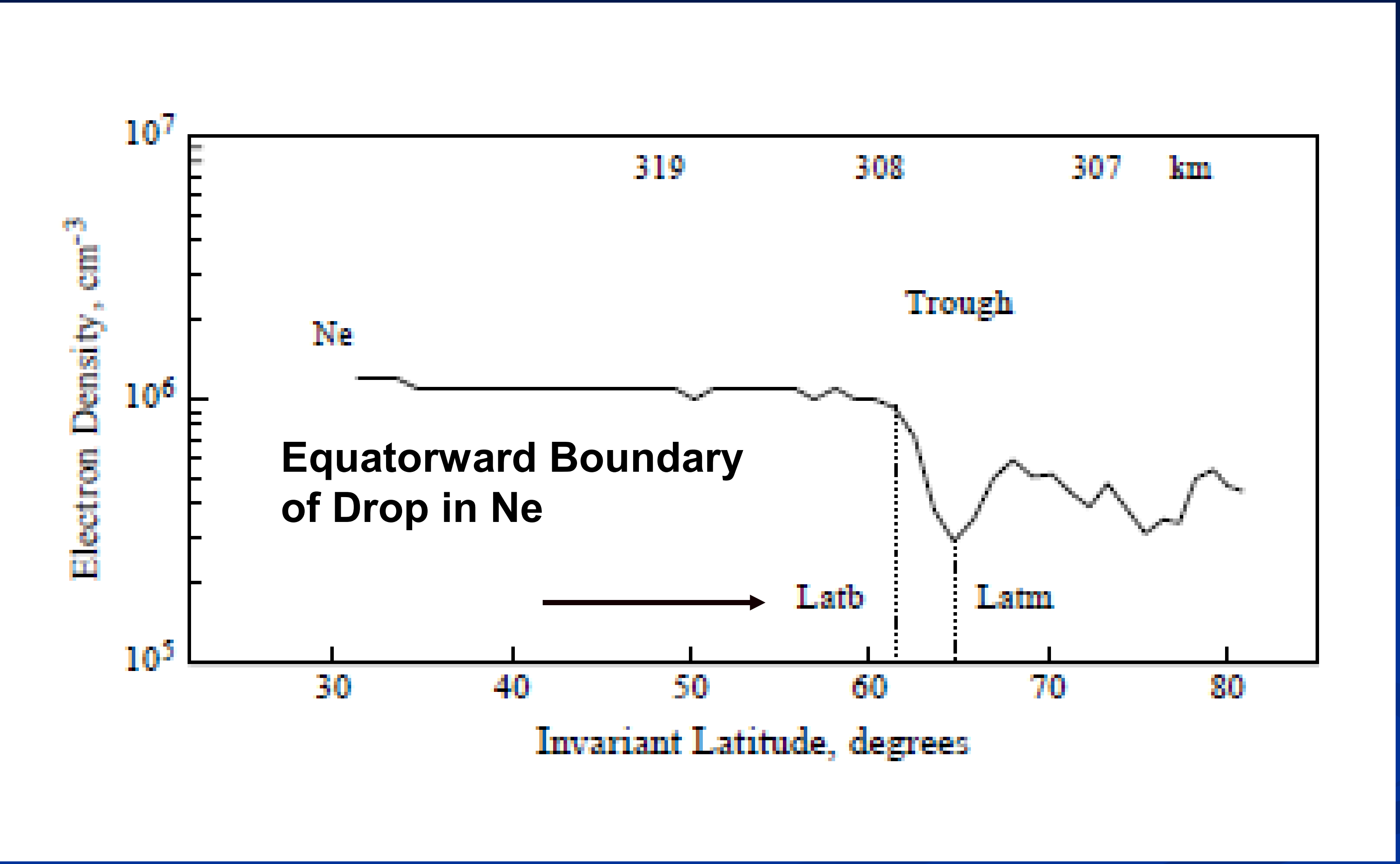
Major Feature of the F-region ionosphere that forms at the boundary between the mid-latitude and auroral ionosphere.

Primarily occurs in darkness

Important features: equatorward and poleward edges separated by the trough minimum

Rodger, The Mid-Latitude Trough – Revisited, MIDD

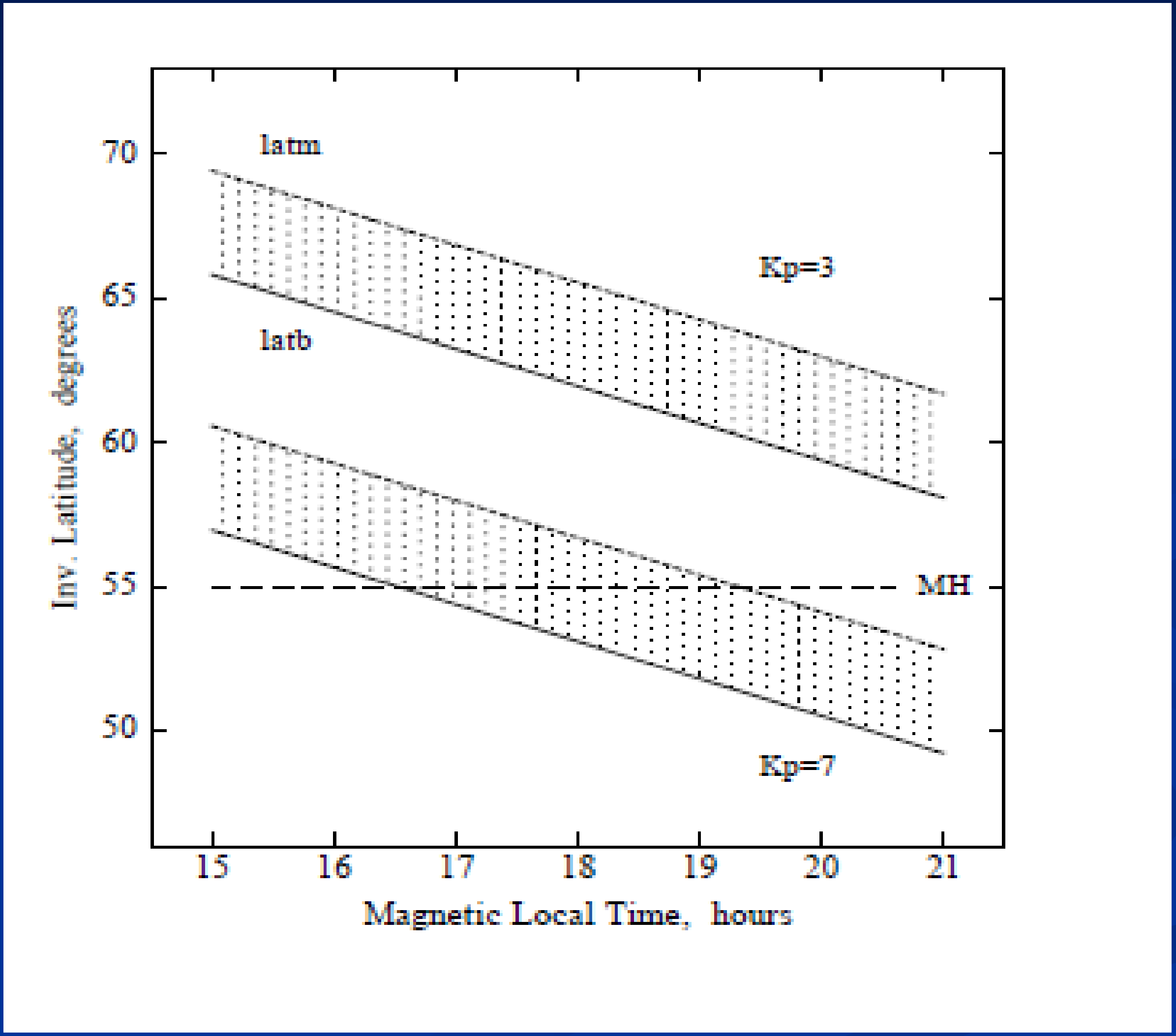
Electron density variation at middle and subauroral latitudes : Trough



Data from DE 2 satellite in N. hemisphere on 9 Dec. 1981 at 7.6 UT (6 pm local).

Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review MIDD

Variation of Trough Location as a function of Kp



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Ionospheric Dynamo

Produced by movement of charged particles of the ionosphere across B

Motion is driven by the tidal effects of the Sun and the Moon and by solar heating.

The ionospheric dynamo is thus controlled by two parameters: the distribution of winds and the distribution of electrical conductivity in the ionosphere.

Maximum conductivity:

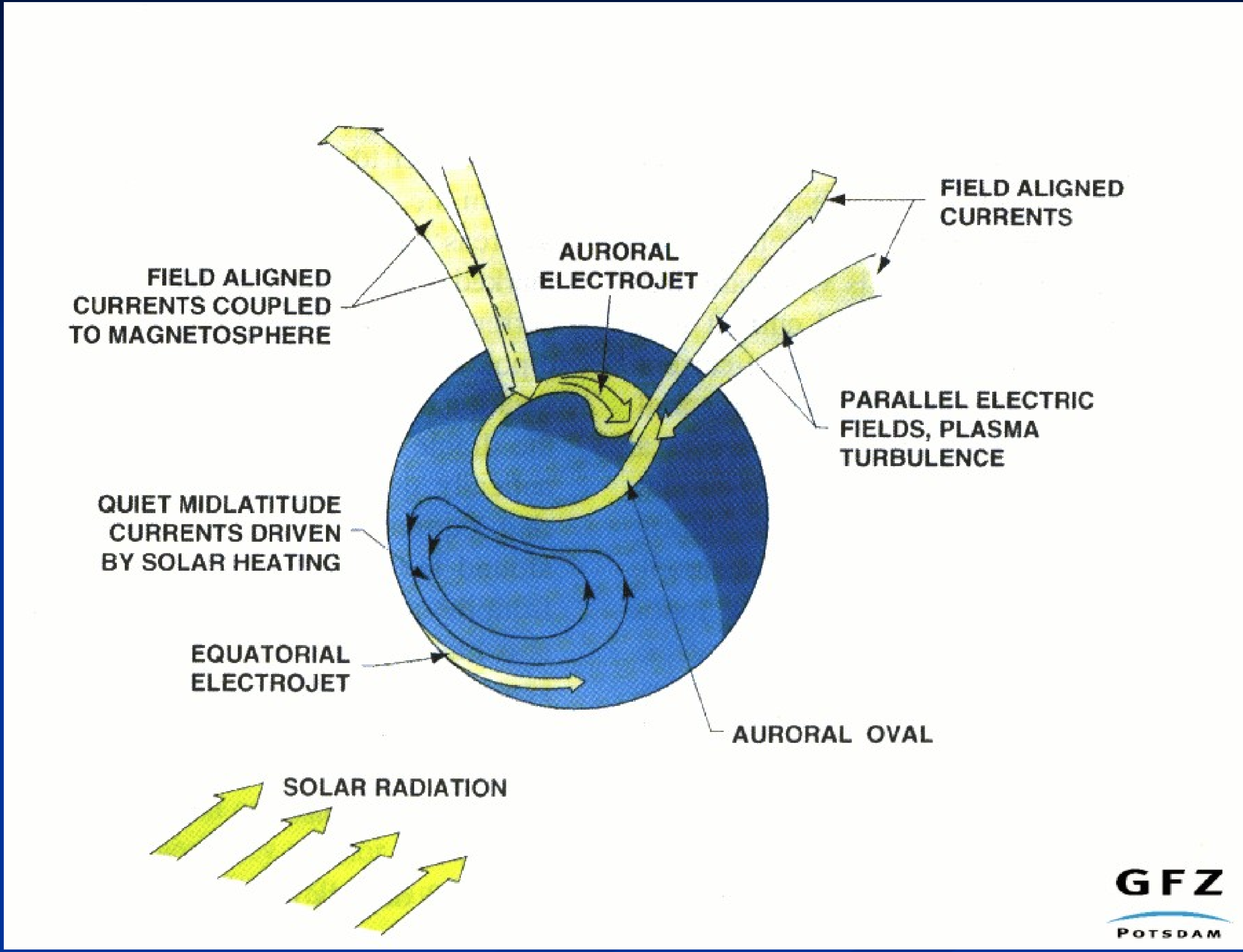
$$\nu_{i,n} = \omega_B^{\,i}$$

Transverse conductivity, especially Hall, confines to a rather narrow range of height (~ 125 km), the so called **dynamo layer**

Thermospheric Winds and Tides

- Thermospheric Neutral Winds
- Tides – Largest atmospheric tides are the diurnal and semidiurnal tides driven by solar heating; Next is the semidiurnal gravitational tide.
  - Tidal oscillations propagate upward, and associated wind speed amplitude grows
  - Diurnal tides can propagate vertically only below 30^o degrees latitude
  - Semi-diurnal tide is dominant at latitudes greater than 30^o degrees latitude (mid-latitudes)

Ionosphere Currents



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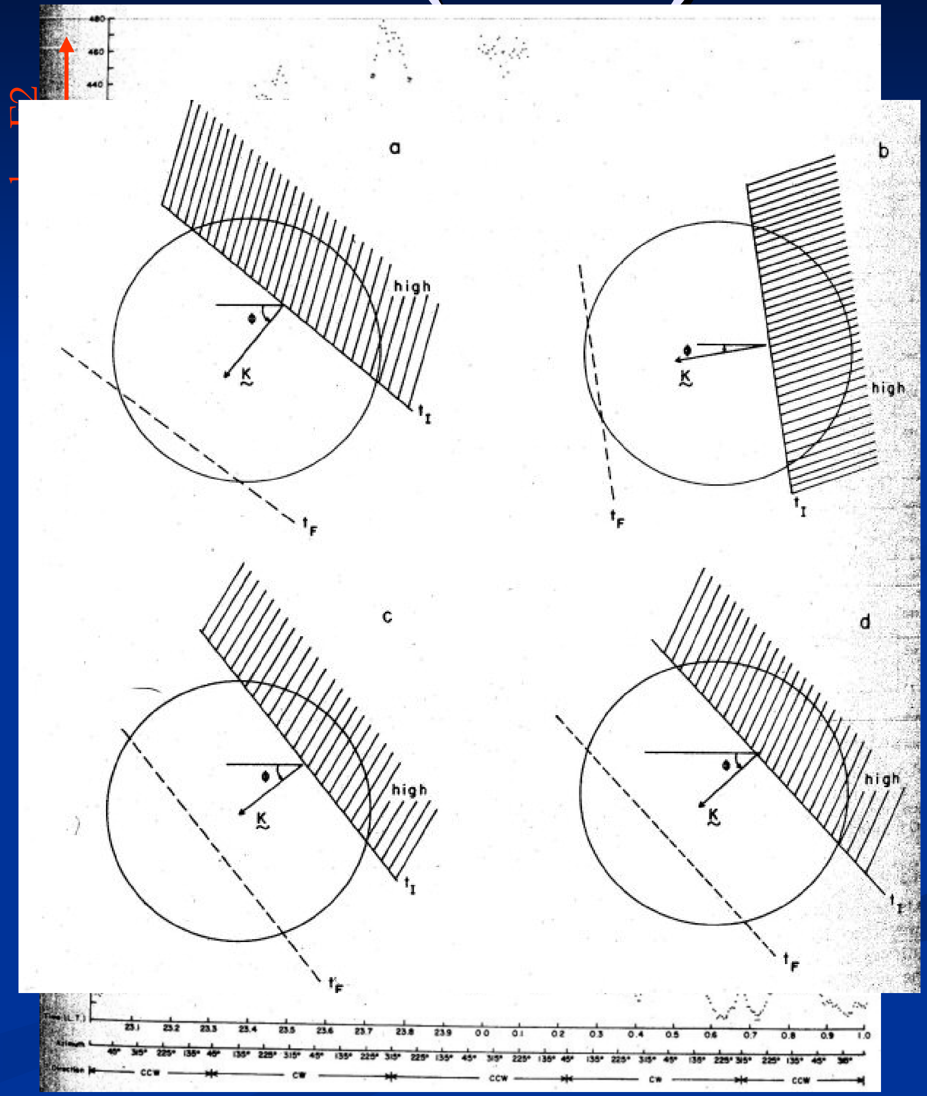
F-layer Height Bands (1973)

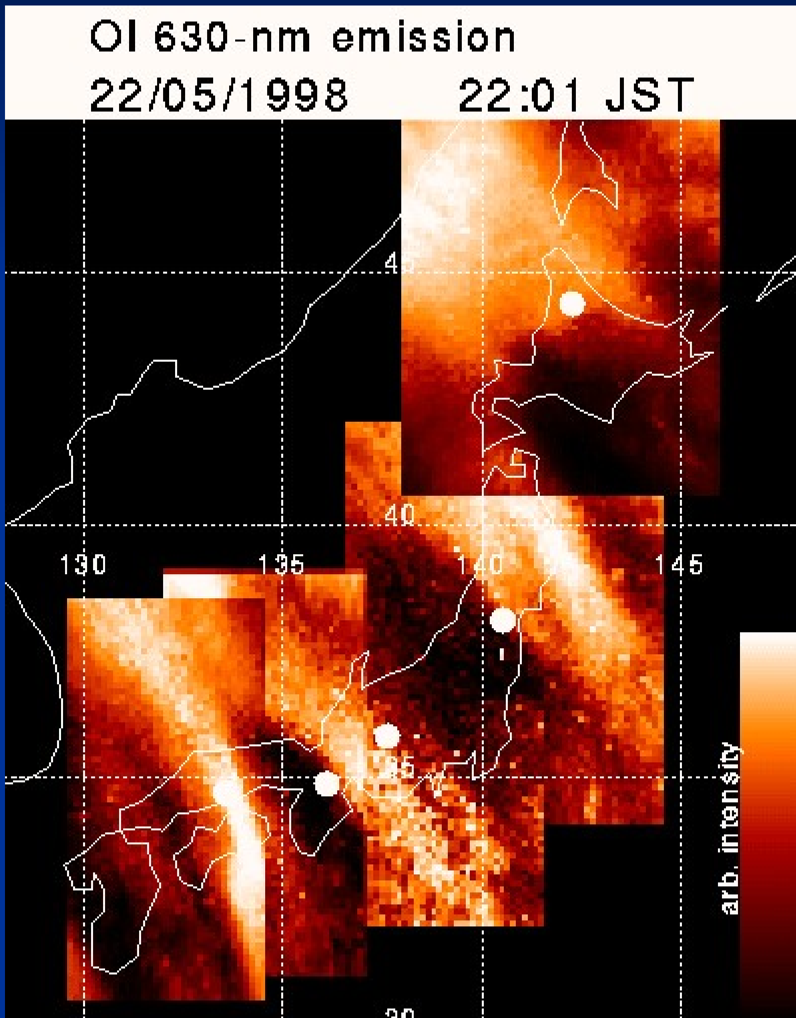
- Using the Arecibo ISR, Behnke (JGR, 1979) observed variations in the height of the F layer
  - 50 km in height over 10 km in horizontal direction
- Spatial structure inferred from "beam swinging" of the ISR
  - Aligned from NW to SE

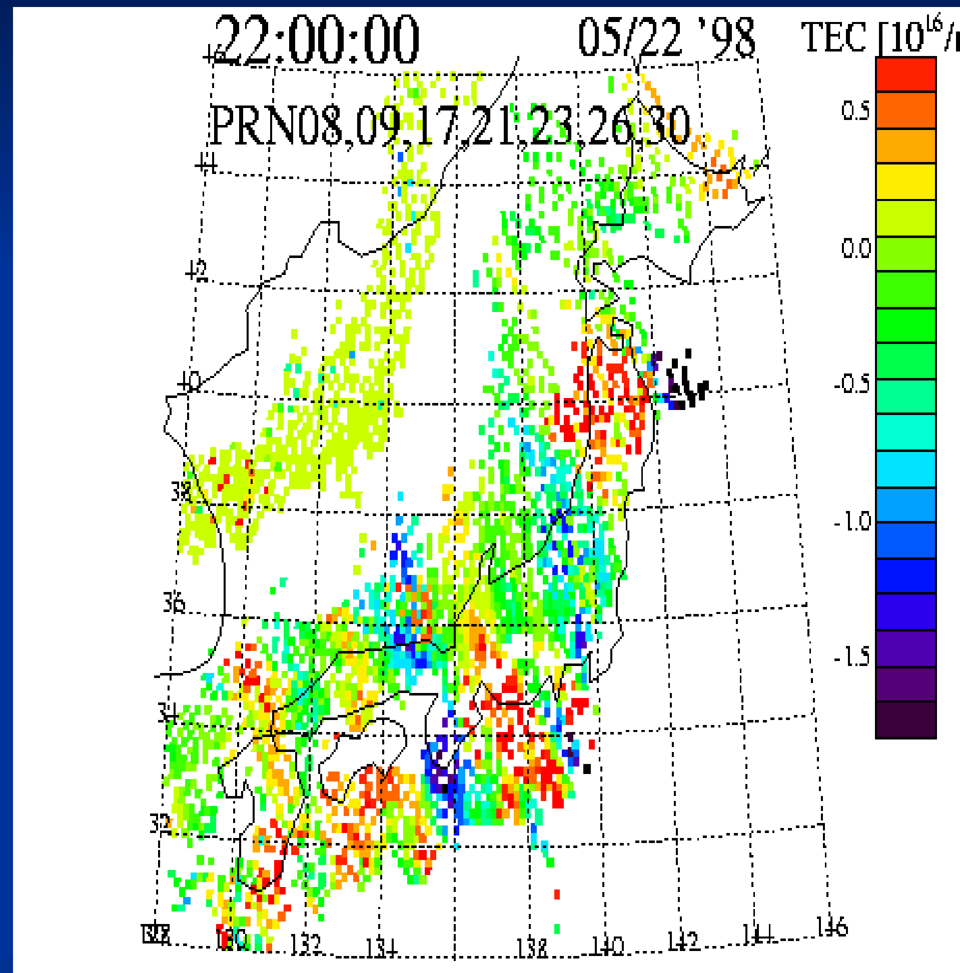


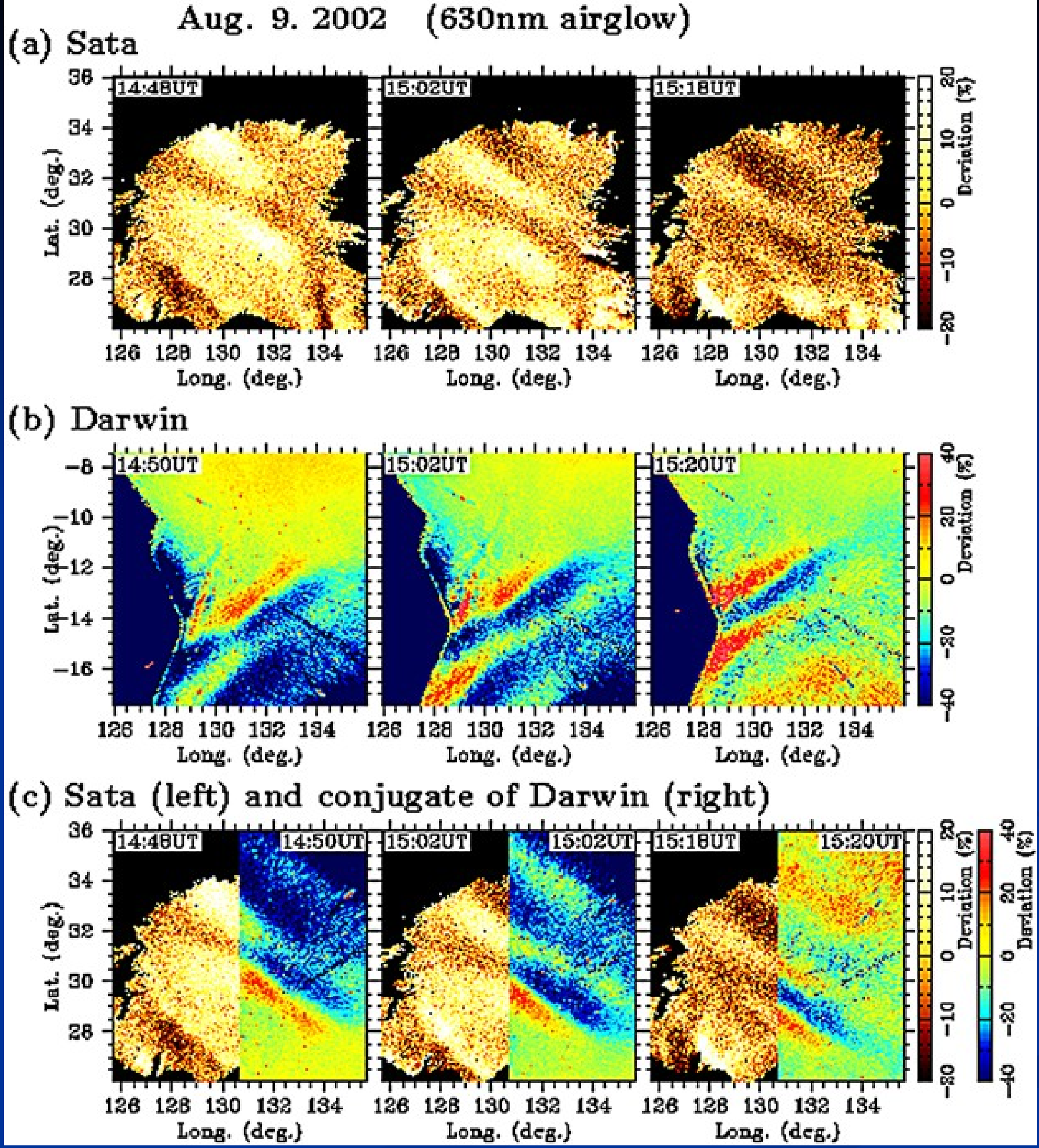
F-layer Height Bands (1973)

- Properties:
  - Δh_{max} ranged from 25 to 60 km
  - ϕ ranged from 218° to 265° (east of north)
  - Velocity ranged from 18 to 61 m/s
- Behnke, 1979 interpreted results in terms of the Perkins instability:
  - Equilibrium of nighttime F layer supported by **E×B**
  - Unstable to north-south electric field
  - Instability is seen as rising and falling bands of ionization

Nighttime MSTID Observations (TEC, Airglow) [*Saito et al.*, 2001]



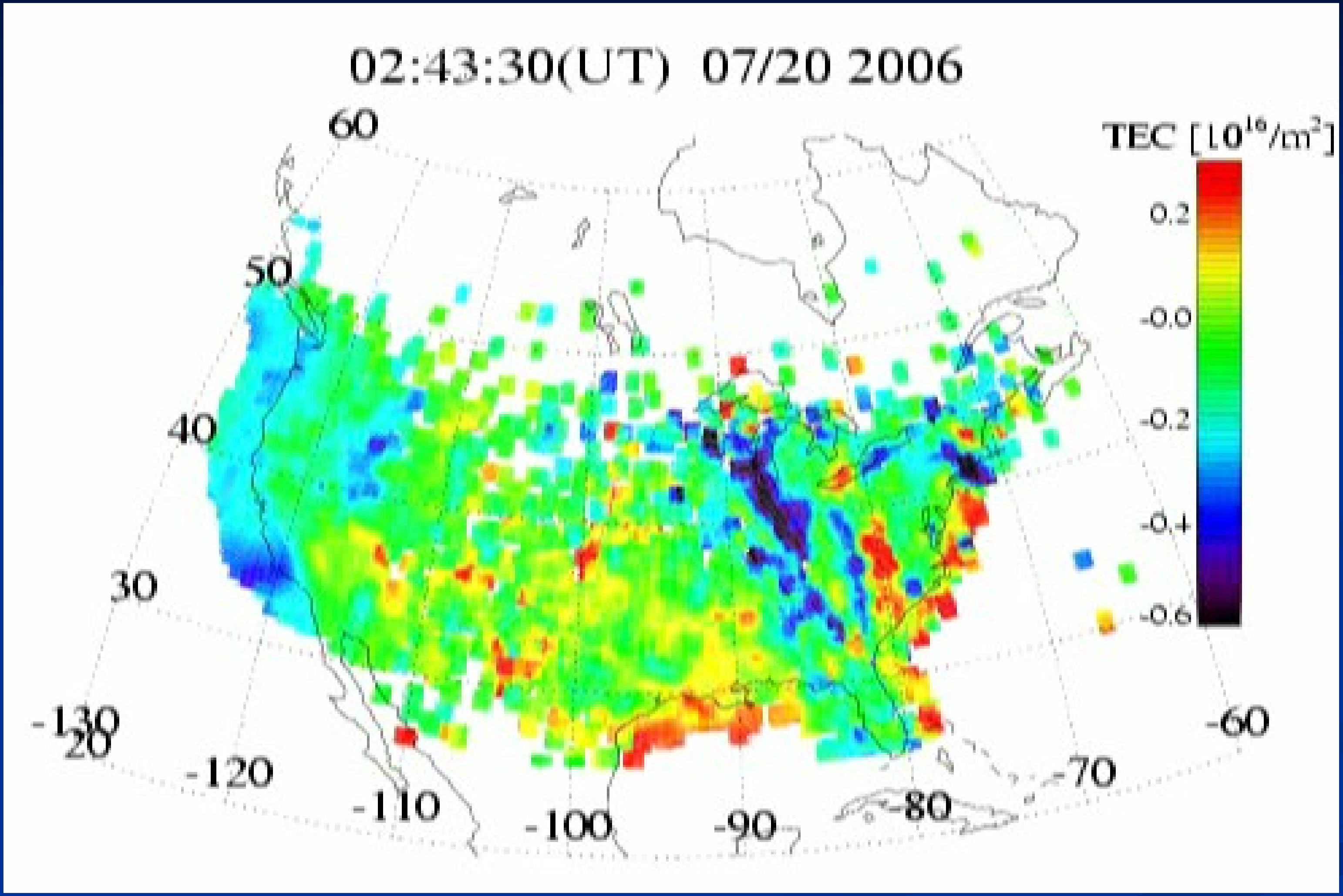




Otsuka et al., JGR 2004

Nighttime MSTID on Jul 20, 2006 (Kp_{max} = 1)

Tsugawa et al., URSI GA 2008



- Detrended TEC map (60-min window)
- 0.15°x0.15° with 7x7 smoothing (running average)

Nighttime MSTID : Summary

Tsugawa et al., URSI GA 2008

- Wavelength of 200-500 km
- Propagation velocity of 50-150 m/s
- Southwestward propagation
- High occurrence rate in summer and winter
- No clear correlation with geomagnetic activity

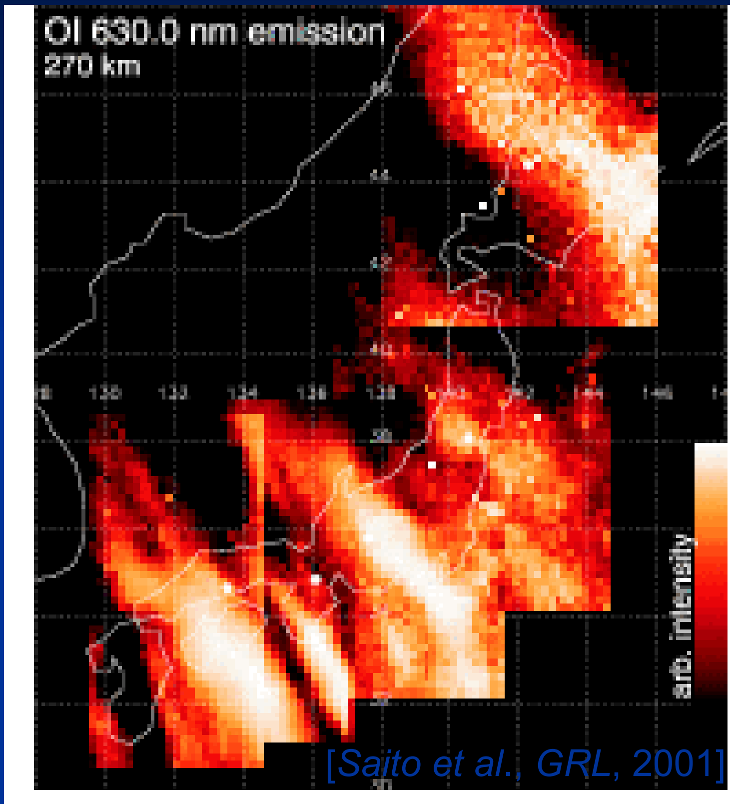
→ Consistent characteristics with the nighttime MSTIDs previously observed over Japan.

New findings

- Their wavefront can be extended from 35° to 55° N in MLAT.
- From their initial appearance, they have a long wavefront.
- Each TEC enhancement seems to decay in 2-4 hours.

Wavefront width of nighttime MSTID

- **Width of MSTID's wavefront**



Finite NW-SE structure

↓

Northwestward E_p

↓

Southwestward propagation

Kelley and Makela,
***GRL*, 2001**

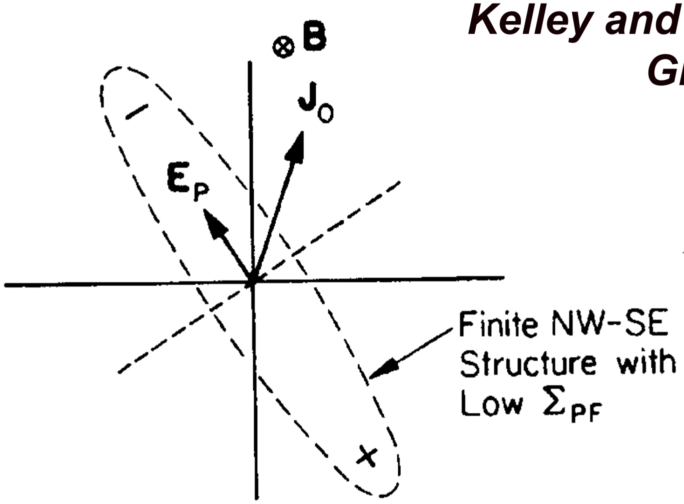


Figure 2. Polarization of a low Pedersen conductivity region in the presence of a wind-driven current.

→ This theory cannot fully explain the southwestward propagation of nighttime MSTIDs whose wavefronts extend from mid-latitudes to sub-auroral regions.

Tsugawa et al., URSI GA 2008

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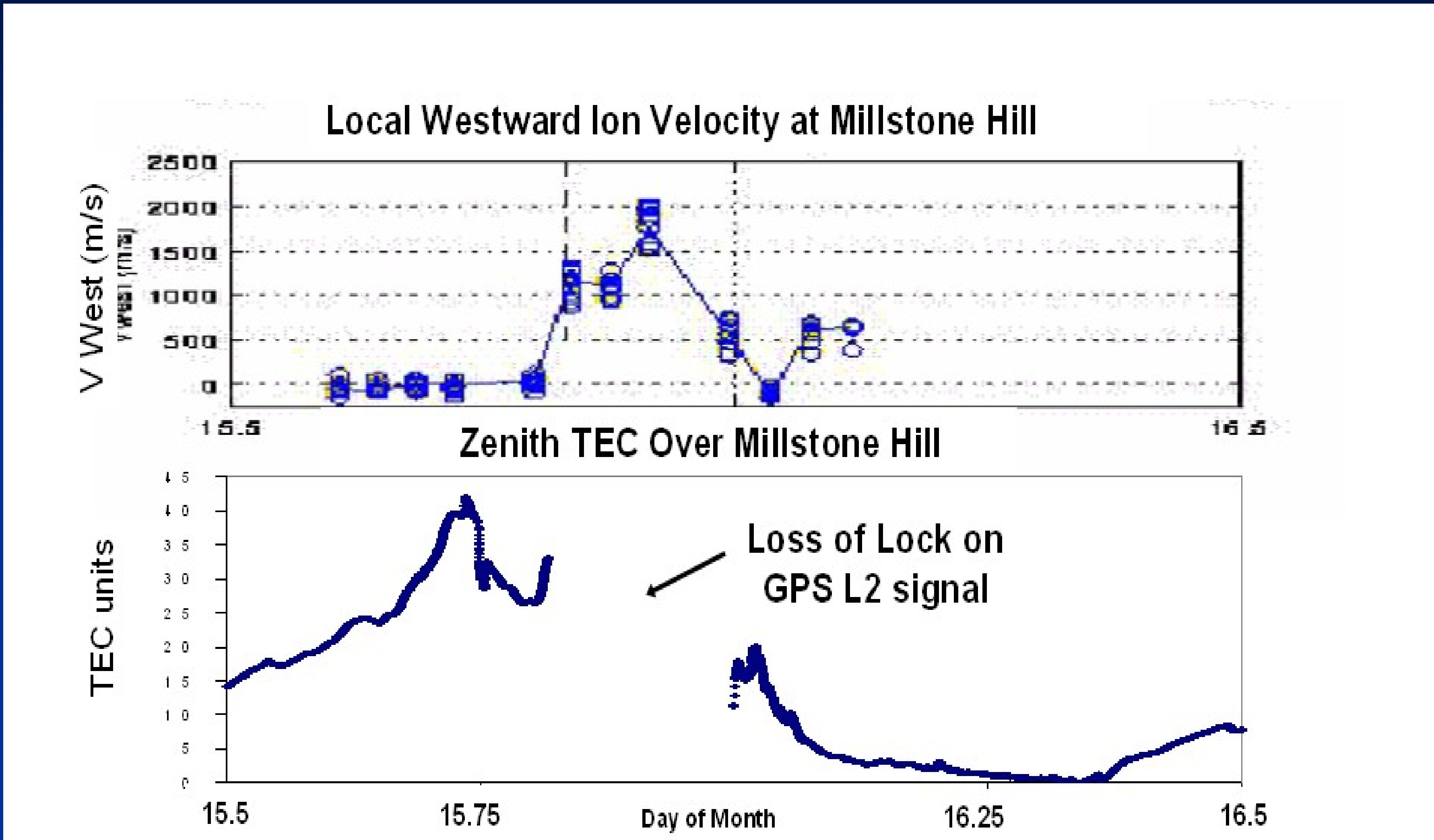
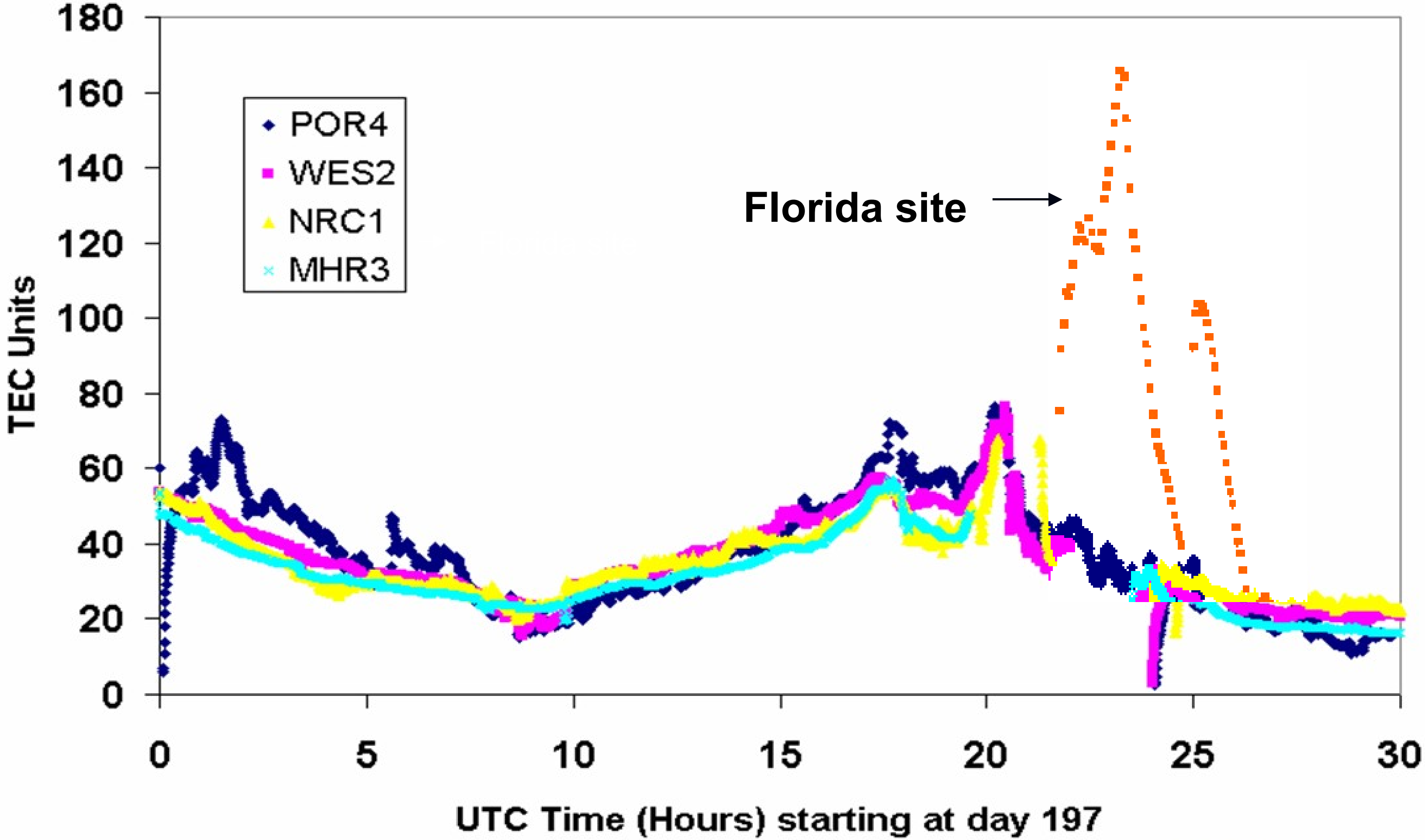
GPS Loss of Lock at Millstone Hill 15 July 2000

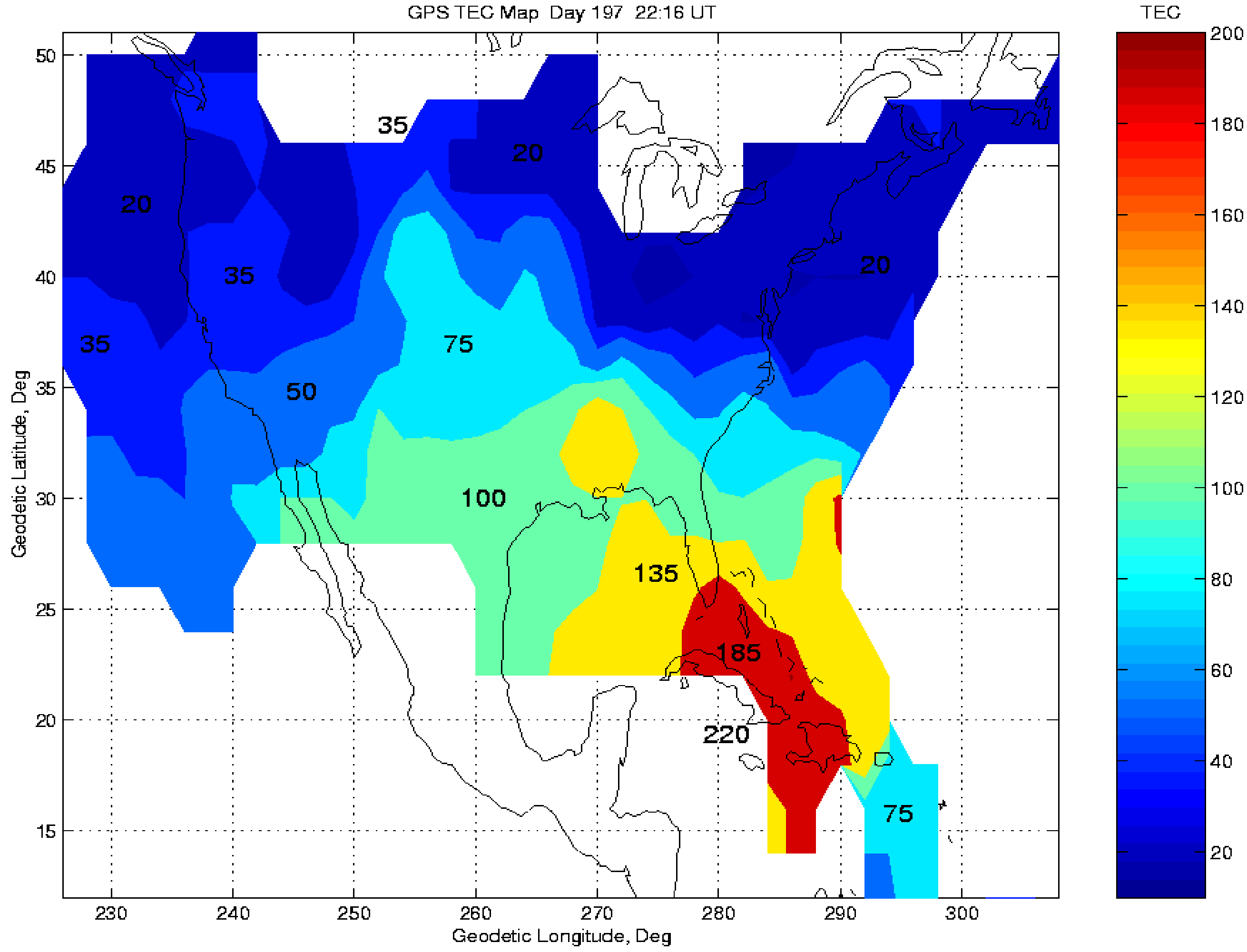


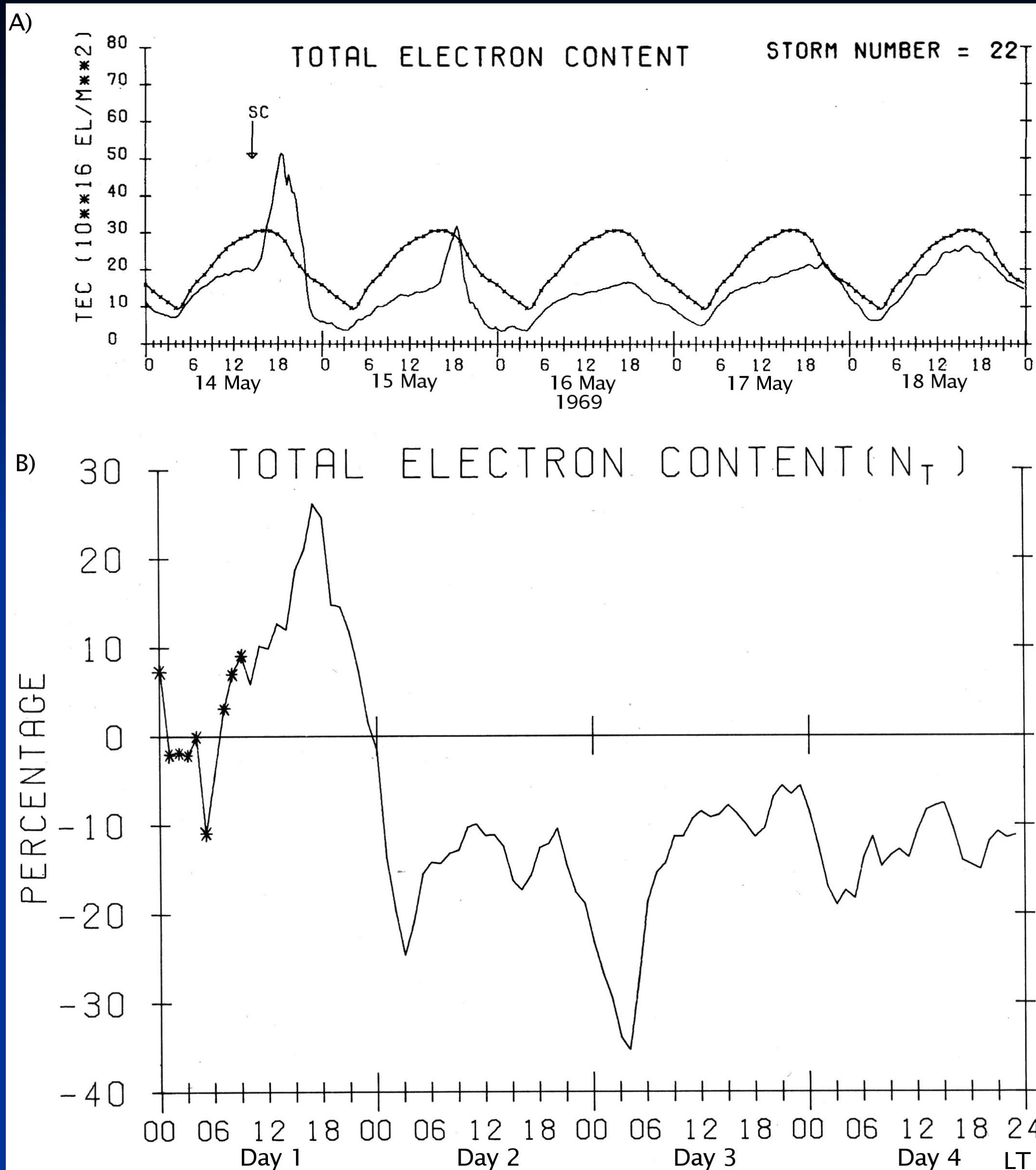
TEC Disturbances on 15 July 2000



GPS Total Electron Content Map

Illustration of Storm Enhanced Density

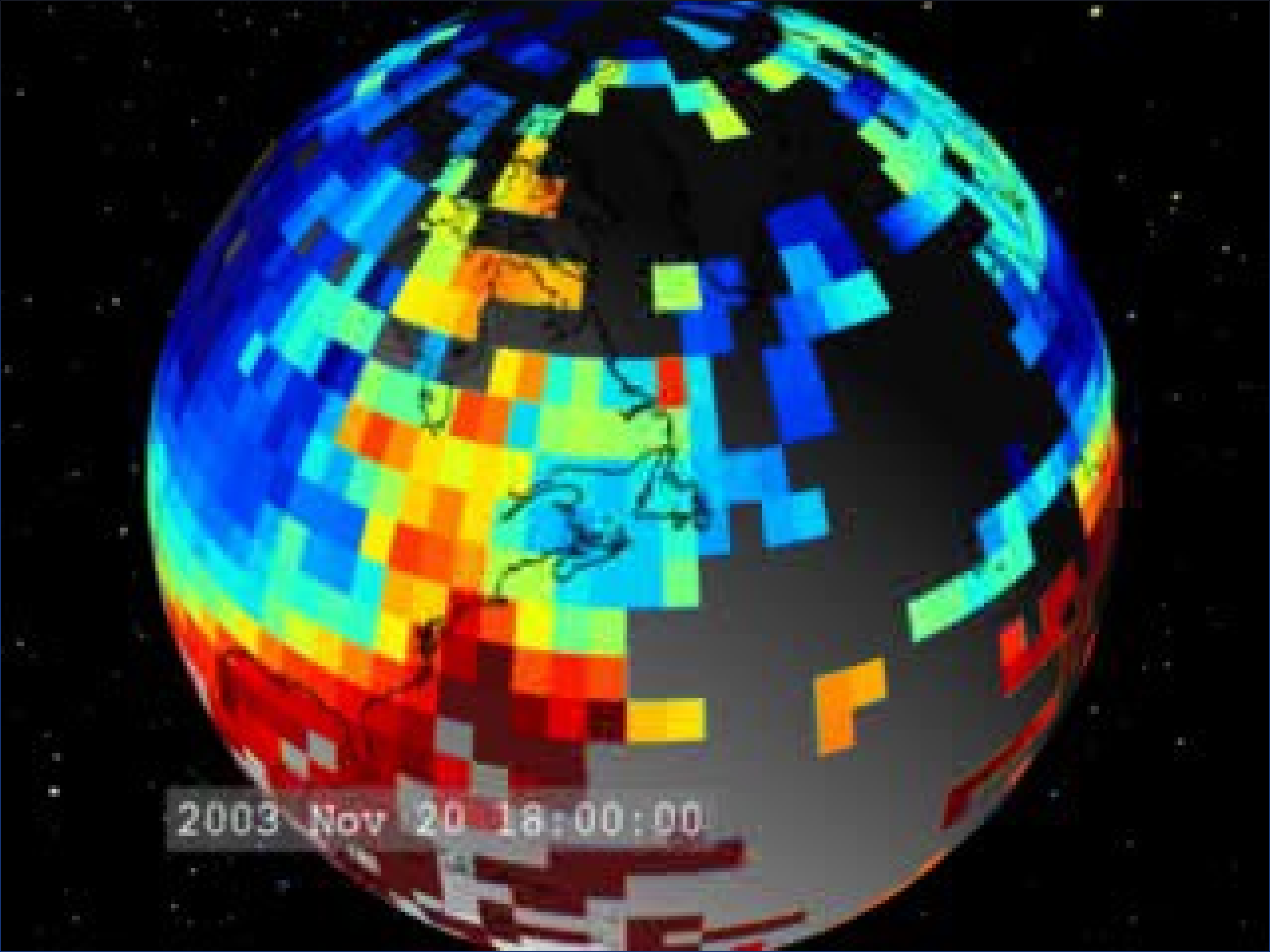




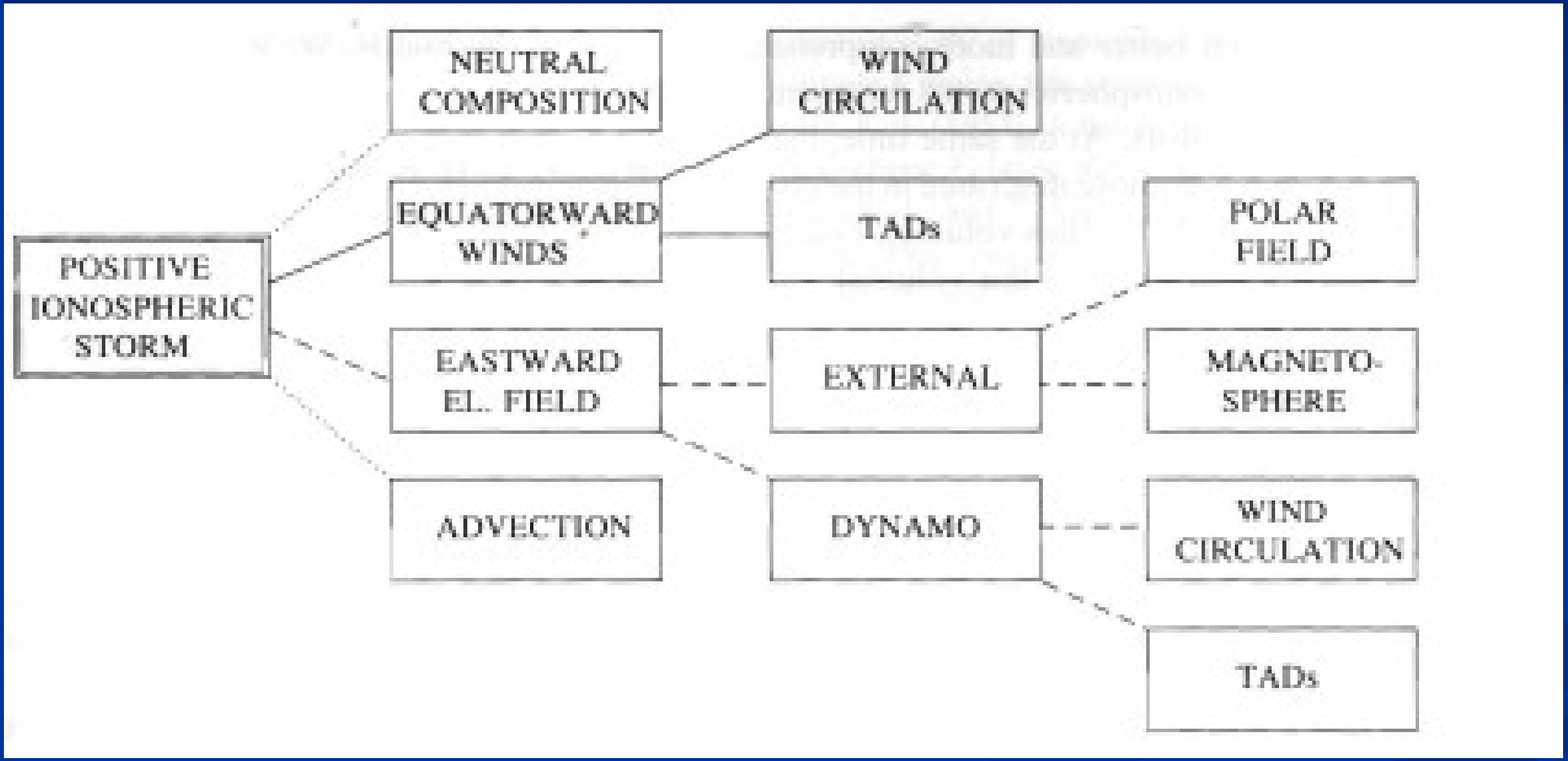
Data Collected at Sagamore Hill, MA using a Faraday Rotation Technique

14 May 1969

Mendillo and Klobuchar, Total Electron Content Storms, Radio Science 2006


2003 Nov 20 18:00:00

Mechanisms contributing to positive storms at mid-latitudes



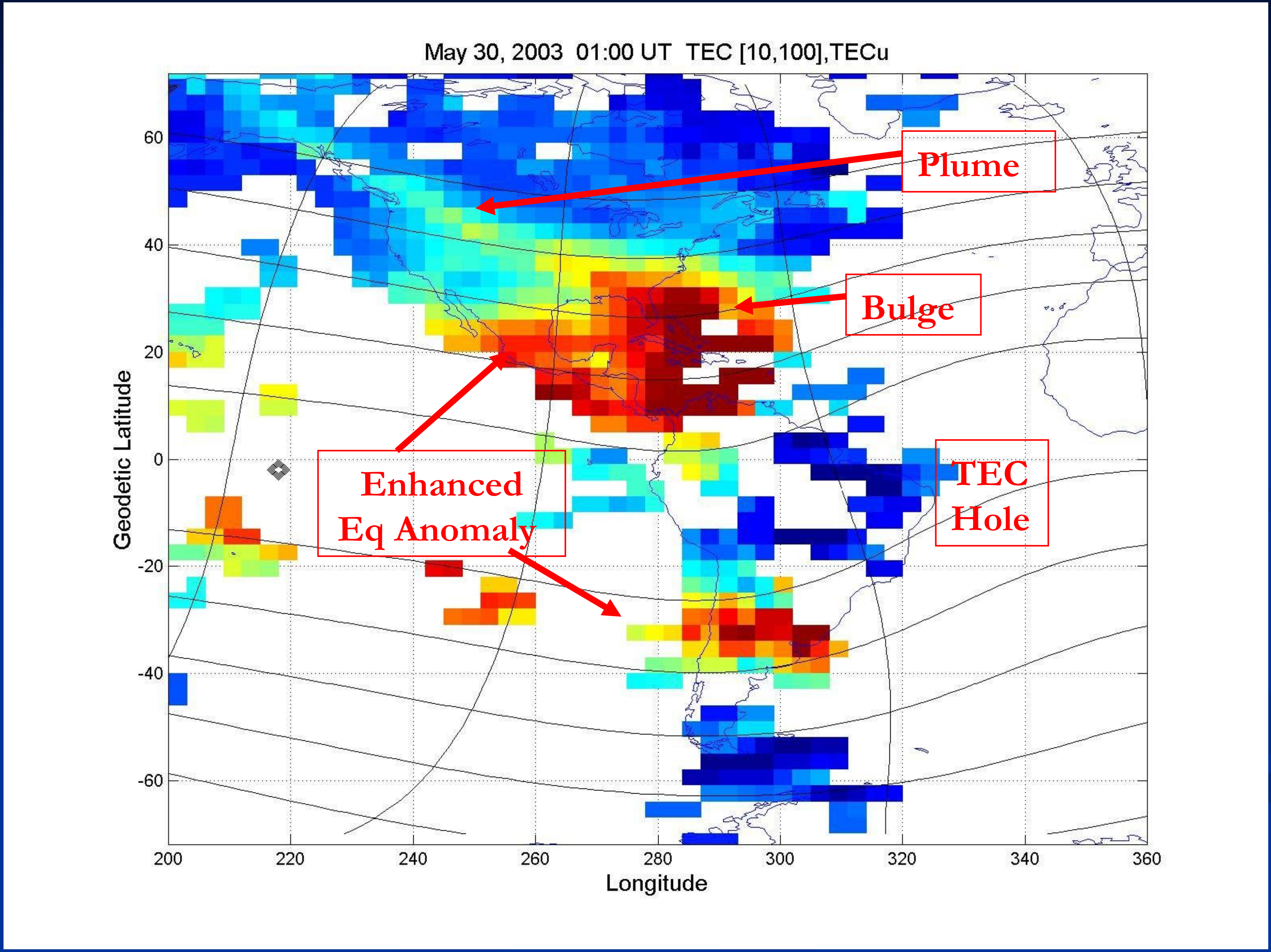
Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review MIDD

Mid-latitude F2 Layer is Uplifted

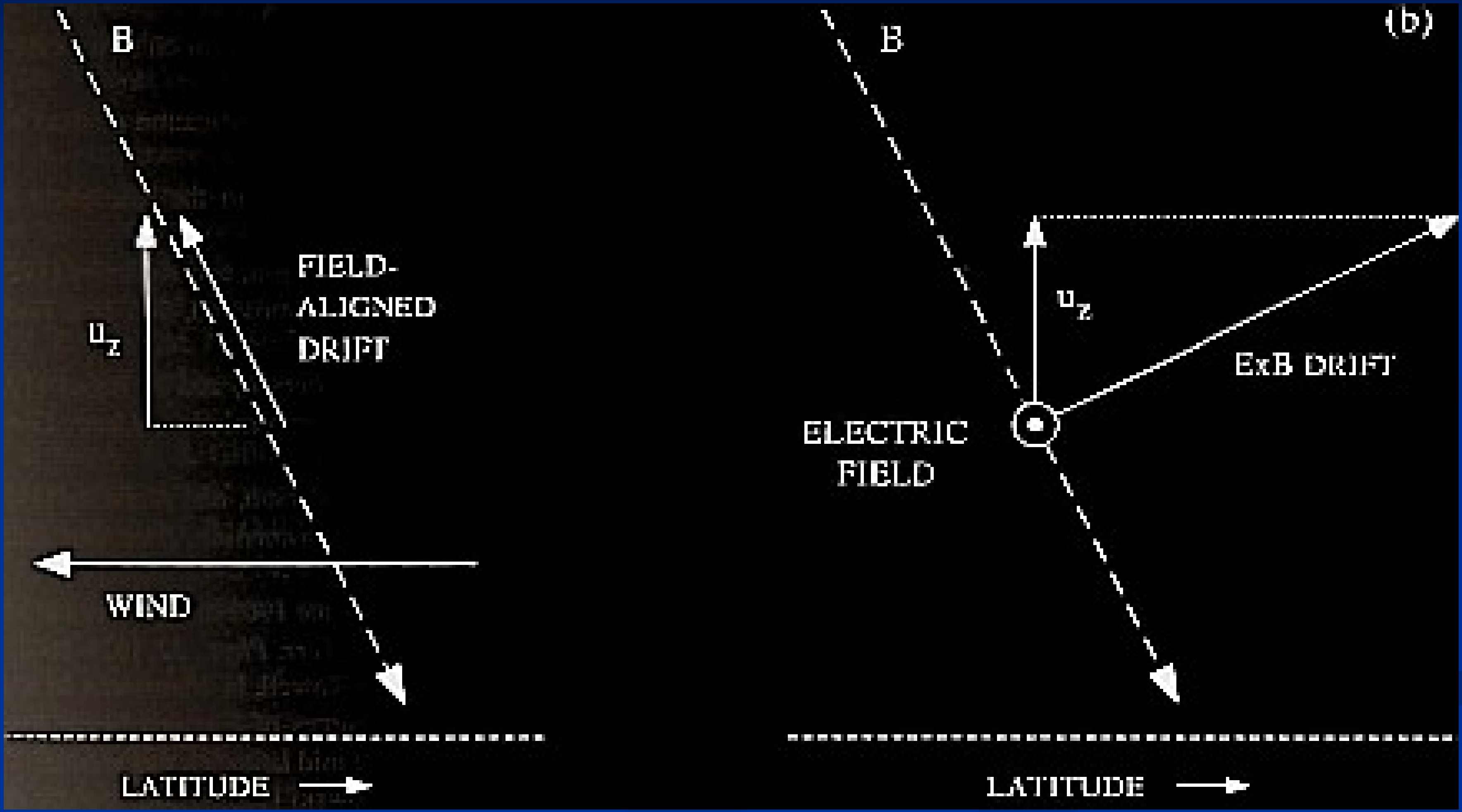
The crucial point is that the increase in the ionization density is preceded by a significant increase in the height of the F2 layer ……… This prior uplifting of the ionosphere is typical and is almost always observed. Therefore, any explanation of positive ionospheric storms must be consistent with this observation.

Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review MIDD

Enhanced TEC Region observed in the Mid-Latitudes



Two Mechanisms for uplifting plasma in midlatitudes



Prolss, Ionospheric Storms at Mid-Latitudes: A Short Review MIDD

Storm-time Electrodynamics

During geomagnetically active time periods, electric fields in the ionosphere are thought to originate from:

- **a disturbed wind dynamo, and**
- **those of magnetospheric origin**
  - **Penetration Electric Field**
  - **Subauroral Polarization Stream**

Huang, et al., EOS, 2006

References

- Definition of Storm-Time Penetration Electric Fields: Chaosong Huang, Stanislav Sazykin, Robert Spiro, Jerry Goldstein, Geoff Crowly, J. Michael Ruohoniemi [EOS, 87(13),doi:10.1029/2006EO130005, 2006]

- The Sub-Auroral Polarization Stream (SAPS) as defined by Foster and Burke [EOS, 83(36), 393, 2002]

- The ionospheric *disturbance* dynamo, *Blanc and Richmond*, M. *Blanc* and A.D. *Richmond*, JGR 85 (1980)

Disturbance Wind Dynamo

The direct penetration of the high-latitude electric field to lower latitudes, and the disturbance dynamo, both play a significant role in restructuring the storm-time equatorial ionosphere and thermosphere.

Although the fundamental mechanisms generating each component of the disturbance electric field are well understood, it is difficult to identify the contribution from each source in a particular observation.

Maruyama, N.; Richmond, A. D.; Fuller-Rowell, T. J.; Codrescu, M. V.; Sazykin, S.; Toffoletto, F. R.; Spiro, R. W.; Millward, G. H

Disturbed Dynamo vs. Penetration Electric Fields

- Both penetration and neutral disturbance dynamo electric fields occur at low latitudes during magnetic storms.

- For the first several hours, penetration electric fields can cause ionospheric disturbances simultaneously at all latitudes and dominate the dayside ionospheric evolution.

- In contrast, large-scale atmospheric gravity waves take two to three hours to travel from the auroral zone to the equatorial ionosphere, and a significant propagation delay can be identified at different latitudes.

Huang, et al., EOS,

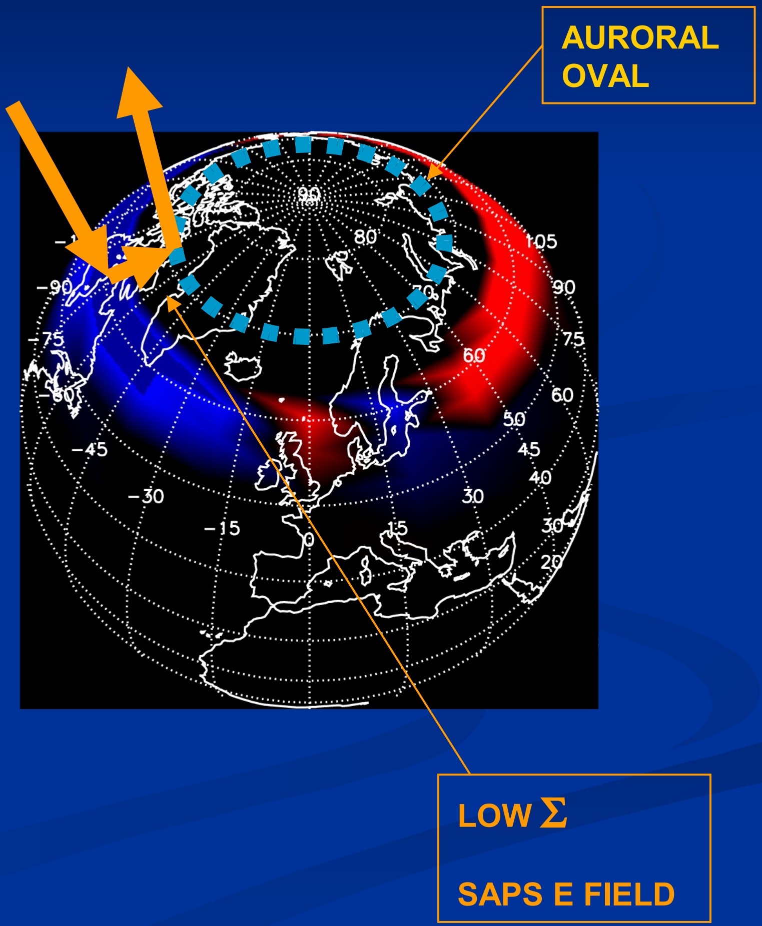
Storm-time Electric Fields

- Magnetospheric convection is enhanced following a southward turning of the interplanetary magnetic field (IMF). The initial high-latitude electric field will penetrate to the equatorial latitudes
  - Strong storm-time penetration eastward electric field uplifts equatorial ionosphere
    - Enhances the Equatorial anomaly
- Cross-tail electric fields energize and inject particles into the inner magnetosphere forming the disturbance Ring Current
  - Sub-auroral polarization Stream forms – which is an electric field that is radially outward at the equator and poleward at higher latitudes. Where the SAPS field overlaps the region of enhanced electron density in the mid-latitudes
    - Storm-Enhanced Density (SED)

Ring Current / SAPS/ SED Plume

(Sub Auroral Polarization Stream Electric Field)

- Duskside Region-2 FACs close poleward across low-conductance gap
- SAPS: Strong poleward Electric Fields are set up across the sub-auroral ionosphere
- SAPS erodes the cold plasma of the ionosphere and the outer plasmasphere



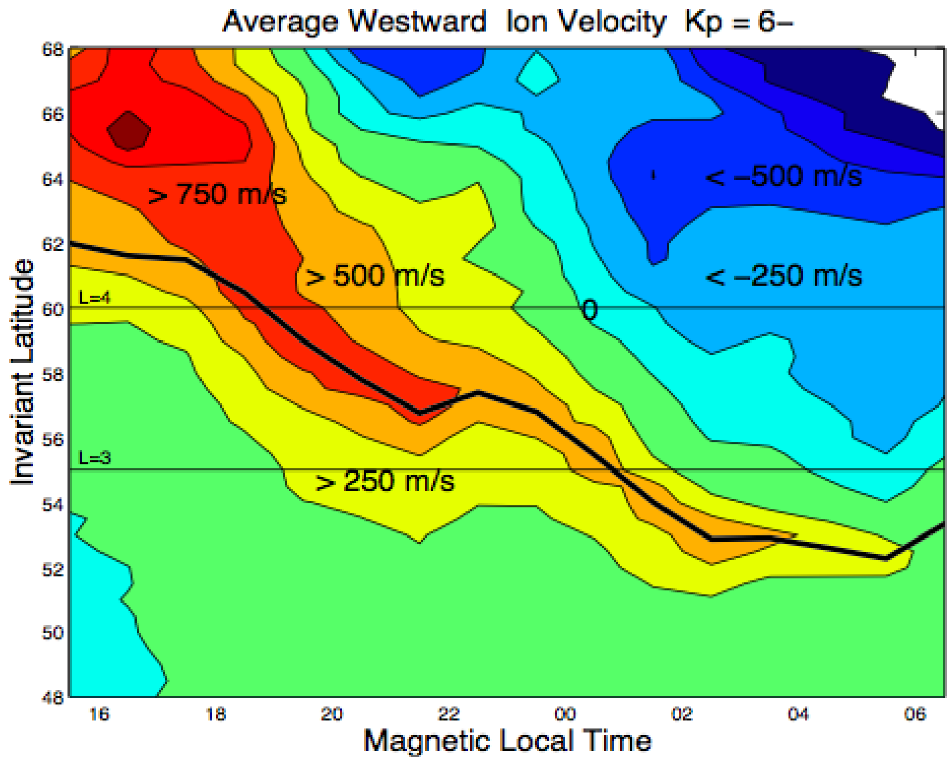


Figure 6. Bin-averaged westward ion velocity derived from Millstone Hill scans for Kp [5^+,6^0] for which SAPS has been identified. Scans at each MLT have been shifted in latitude such that the SAPS peak is aligned with the average SAPS latitude for the corresponding MLT and Kp. The heavy black curve indicates the average SAPS peak position.

Foster and Vo (2002)

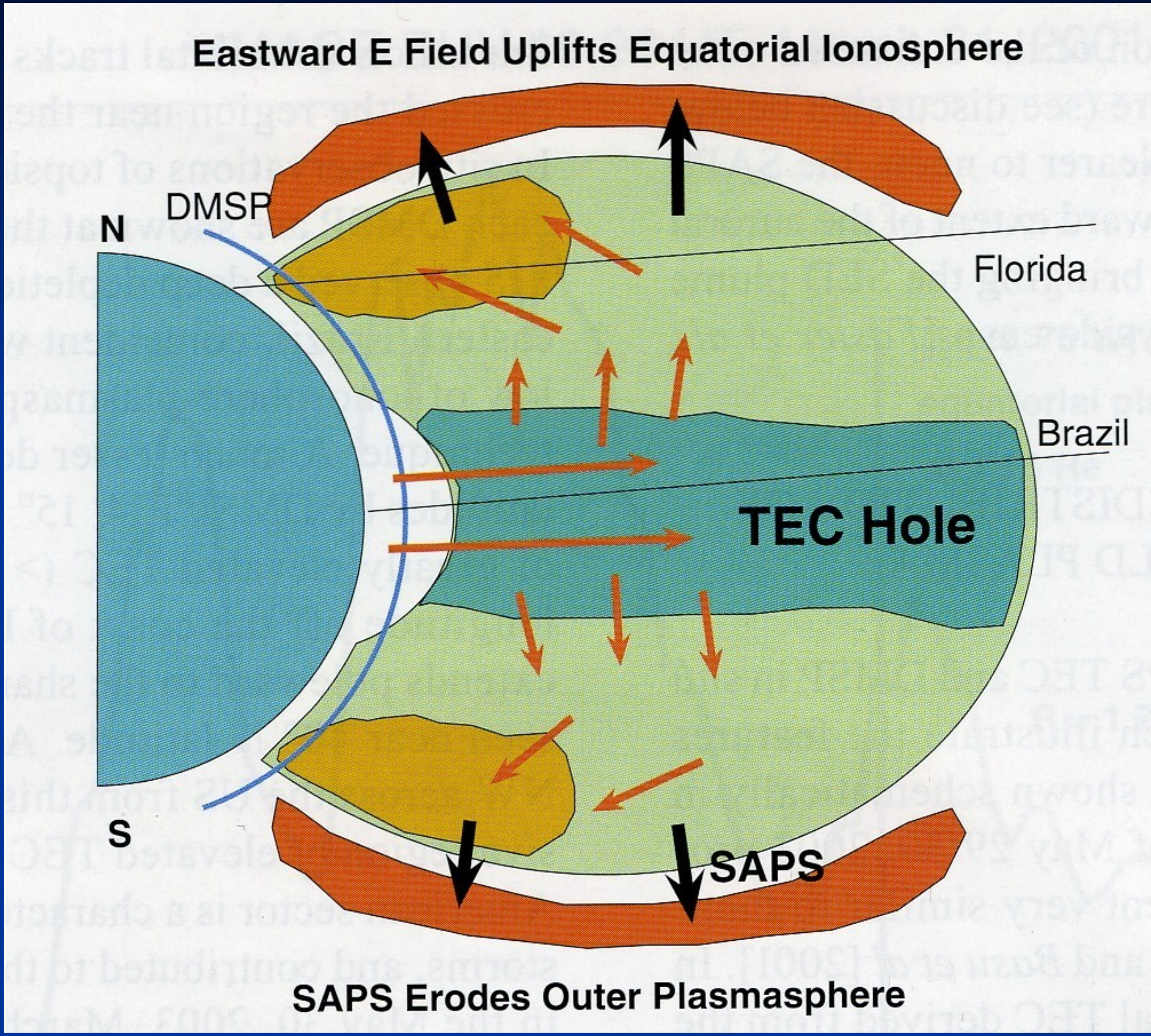
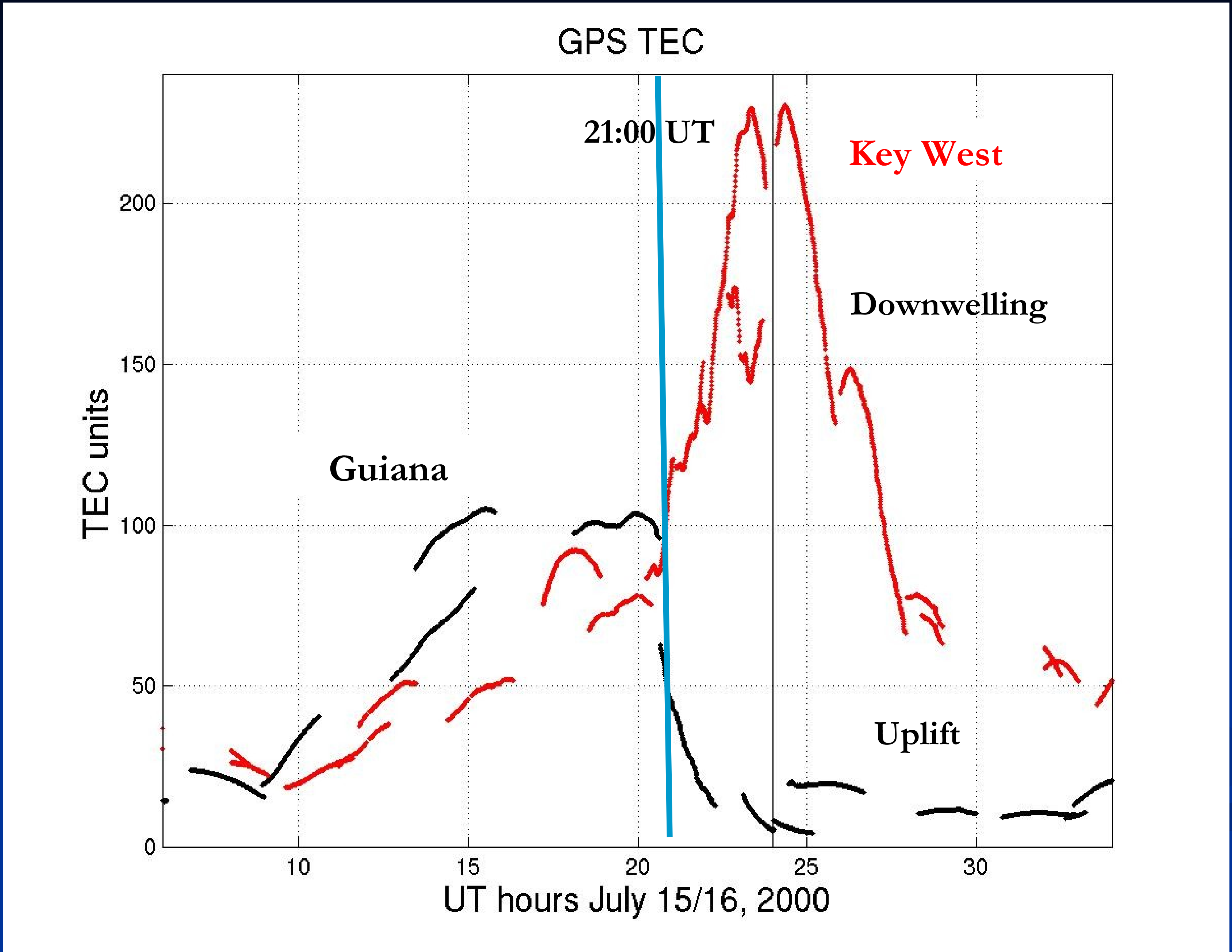
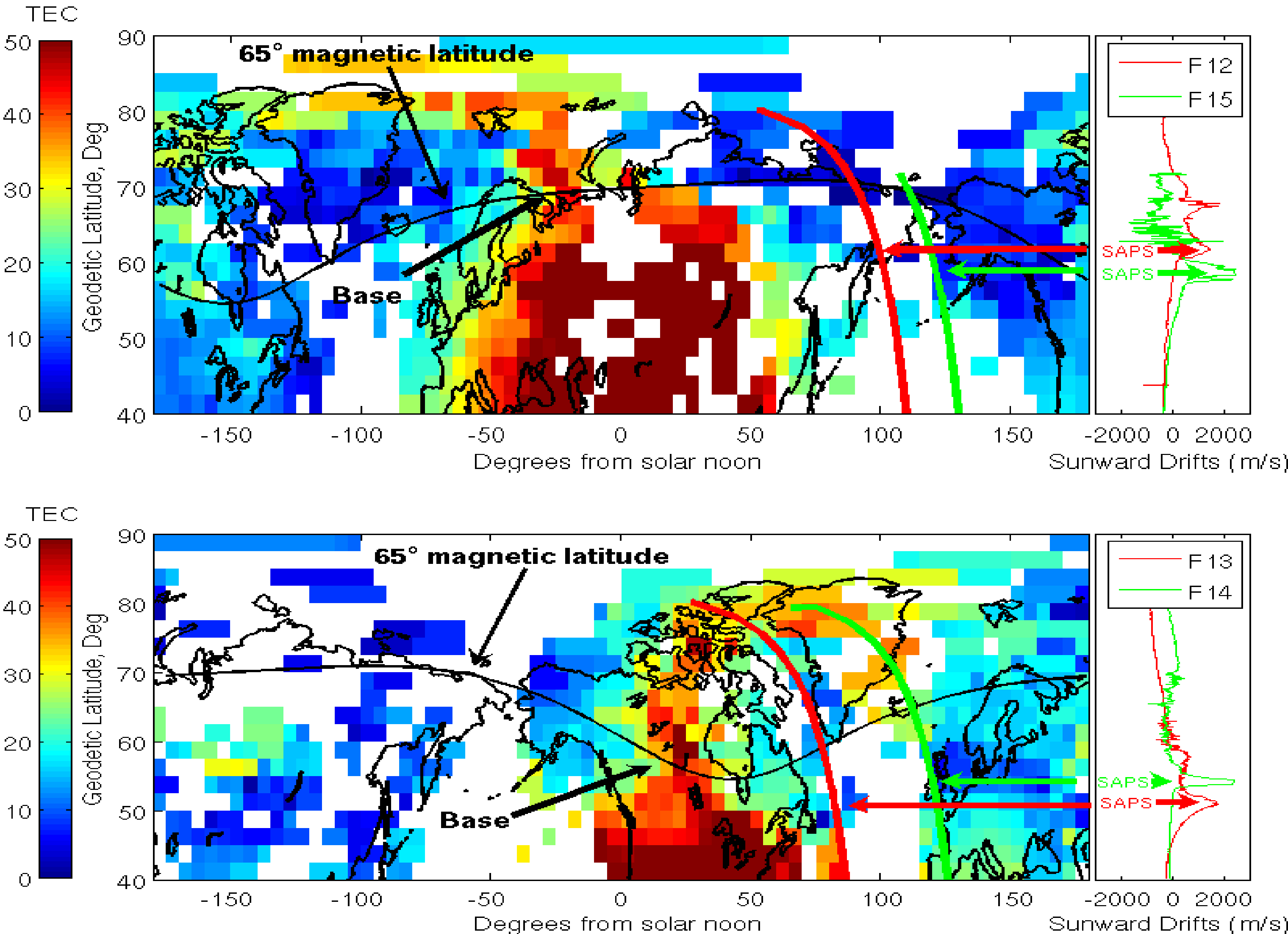


Figure courtesy of J. Foster



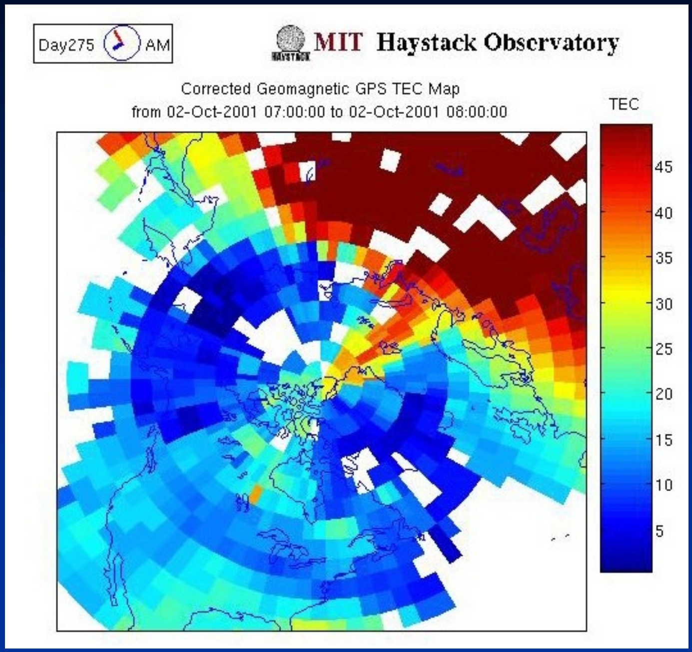
GPS TEC
21:00 UT
Key West
Downwelling
Guiana
Uplift
TEC units
200
150
100
50
0
10
15
20
25
30
UT hours July 15/16, 2000

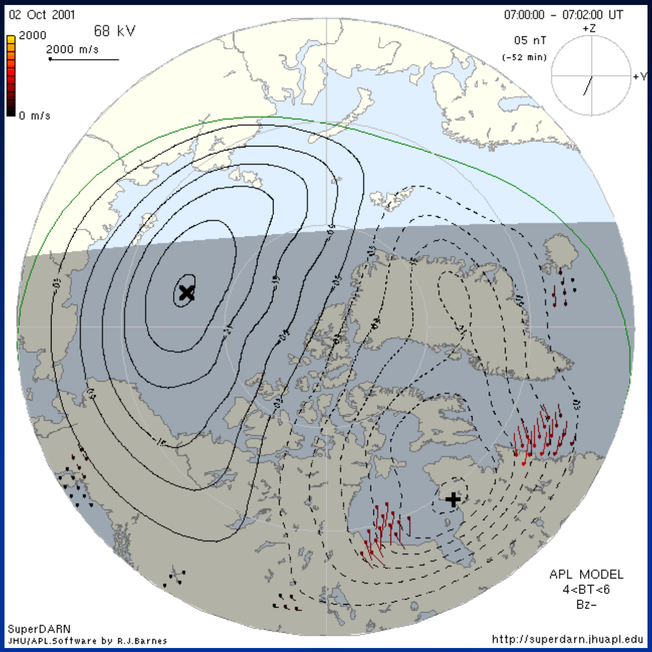


TEC
50
40
30
20
10
0
Geodetic Latitude, Deg
90
80
70
60
50
40
65° magnetic latitude
Base
SAPS
SAPS
F 12
F 15
-150
-100
-50
0
50
100
150
Degrees from solar noon
-2000
0
2000
Sunward Drifts (m/s)
TEC
50
40
30
20
10
0
Geodetic Latitude, Deg
90
80
70
60
50
40
65° magnetic latitude
Base
SAPS
SAPS
F 13
F 14
-150
-100
-50
0
50
100
150
Degrees from solar noon
-2000
0
2000
Sunward Drifts (m/s)

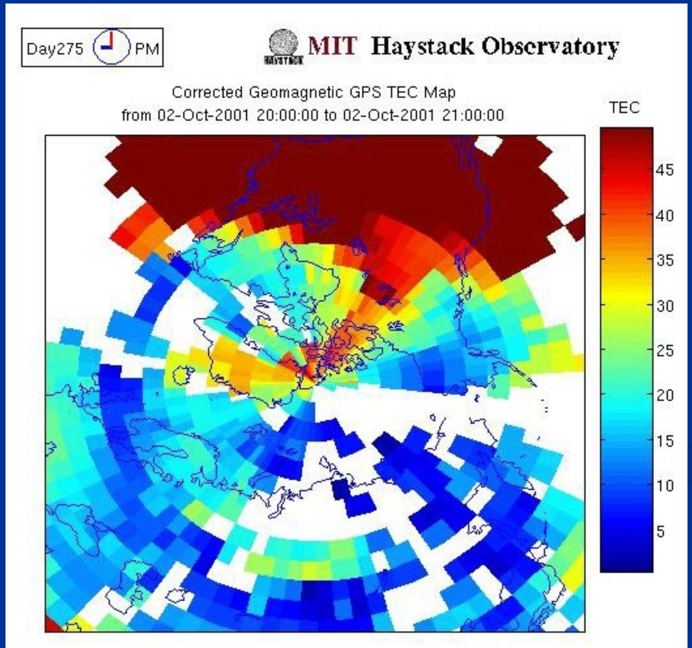
Northern Europe and American Sector SED Plumes

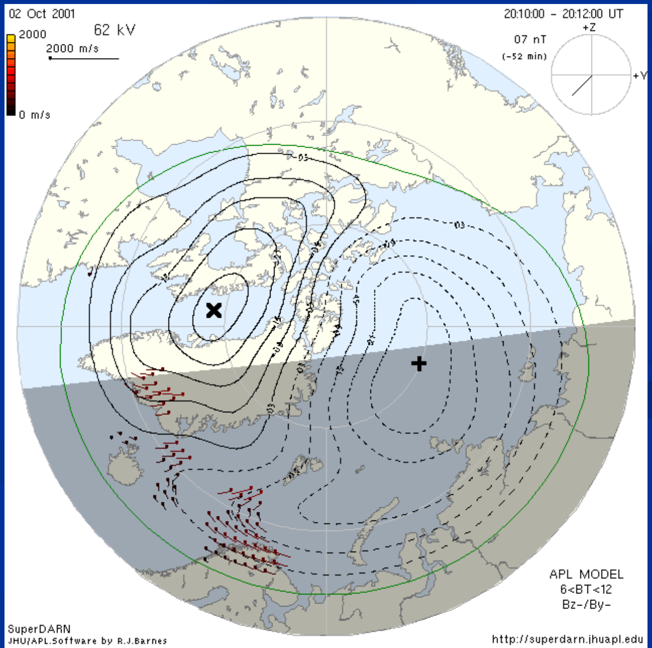
Northern Europe





American Sector





Plasmasphere

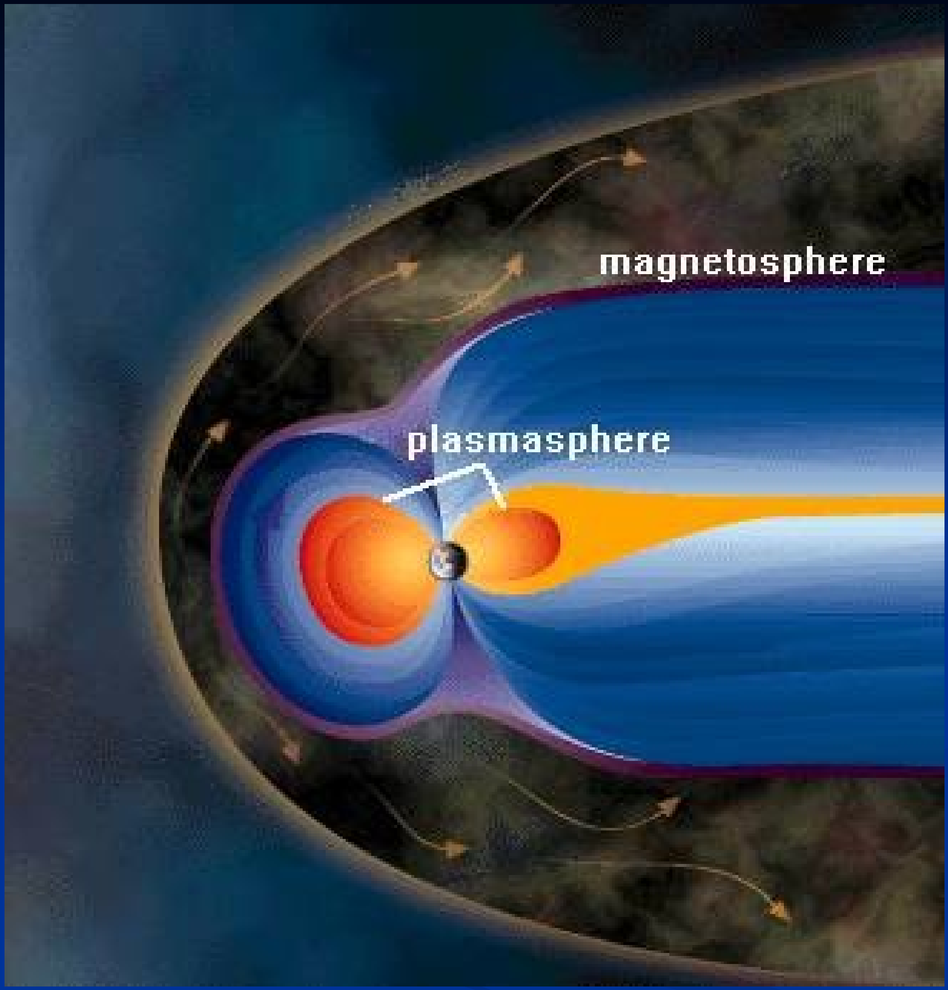
extension of ionosphere and part of the inner magnetosphere.

filled with ionospheric plasma from the mid- and low latitudes

plasma gas pressure is equalized along the entire field line.

plasma co-rotates with the Earth and its motion is dominated by the geomagnetic field.

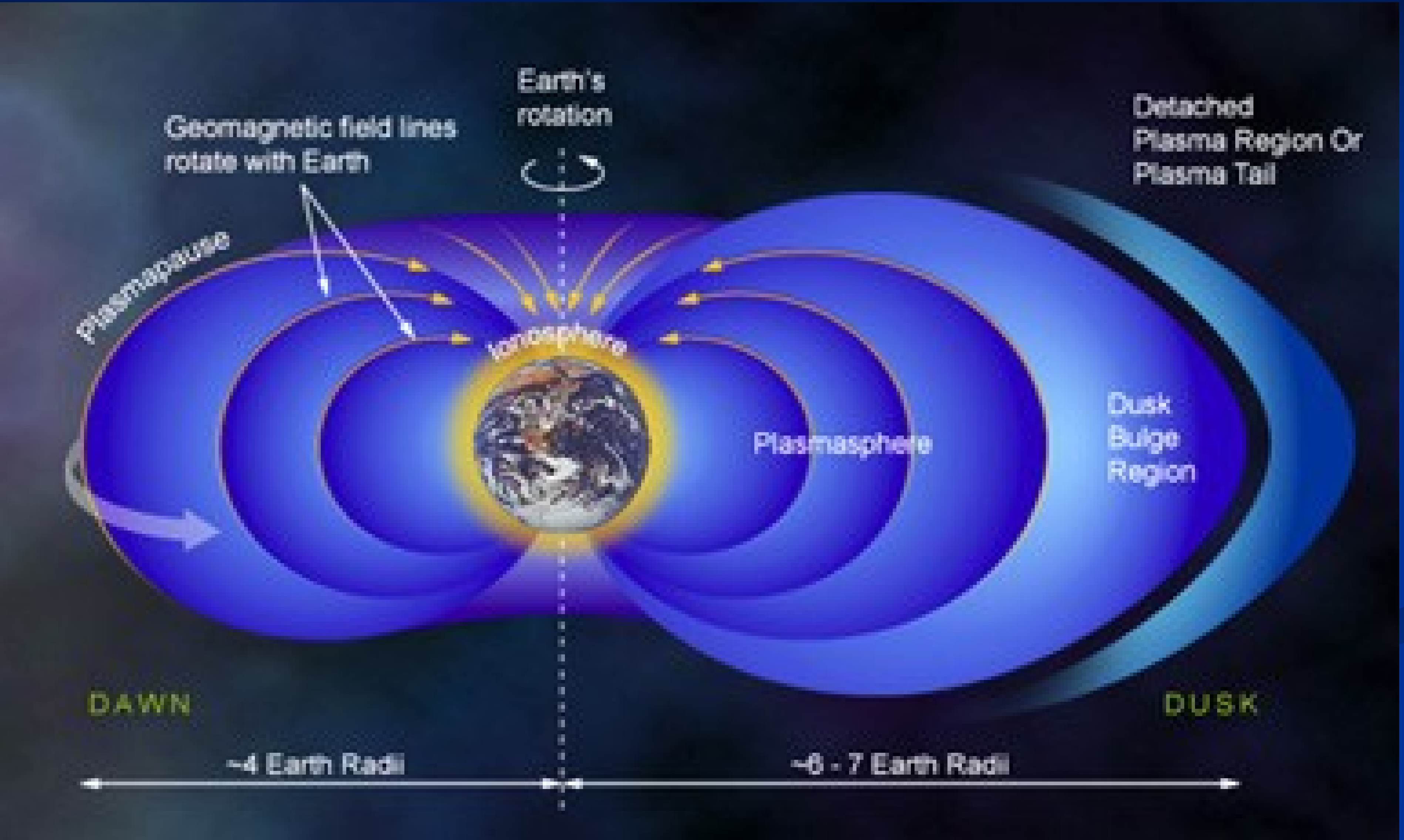
Plasma on magnetic field lines associated with higher latitudes (~ above 60 deg. geomagnetic lat.) is convected to the magnetopause



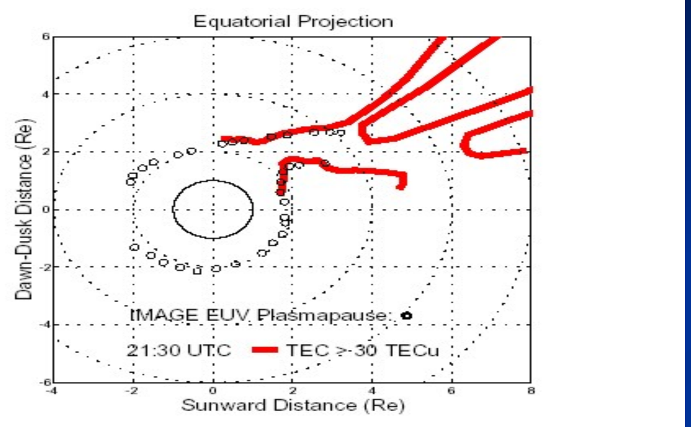
Quiet conditions - plasmapause may extend to ~ 7 Earth radii

Disturbed conditions – plasmapause can contract to ~3 or less Earth radii.

Plasmasphere



Plasmaspheric Tails and Storm Enhanced Density



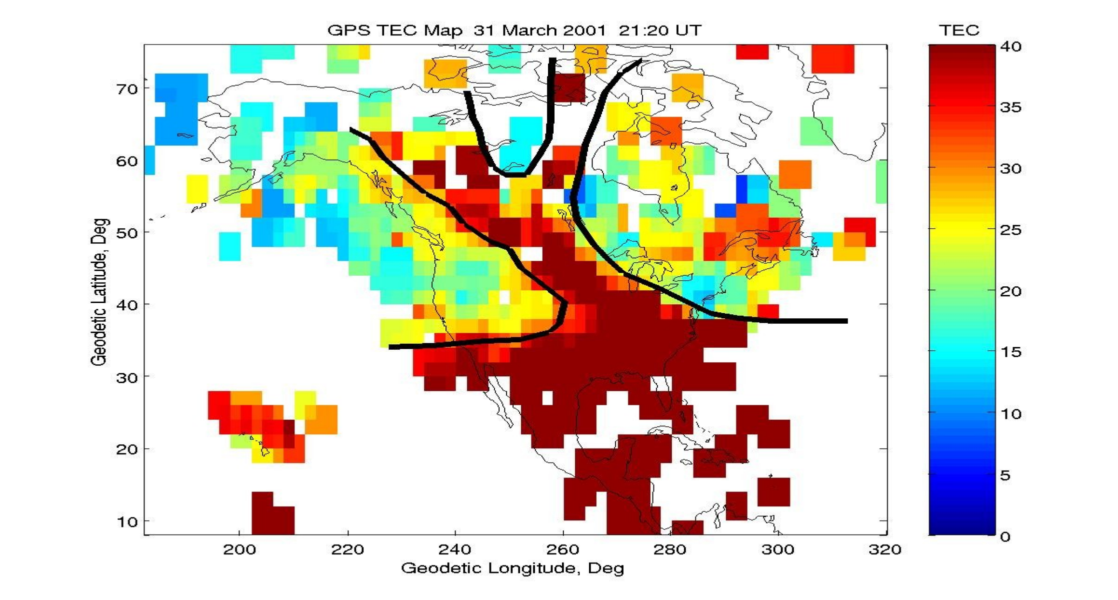
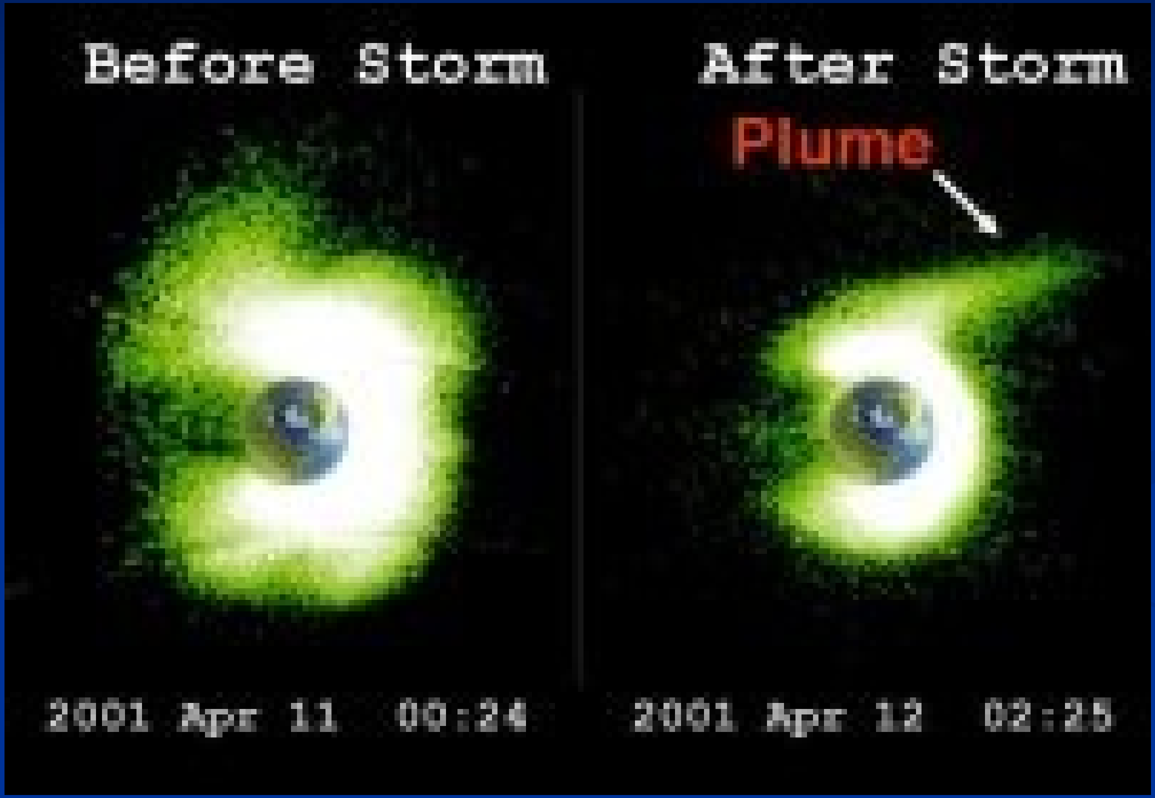
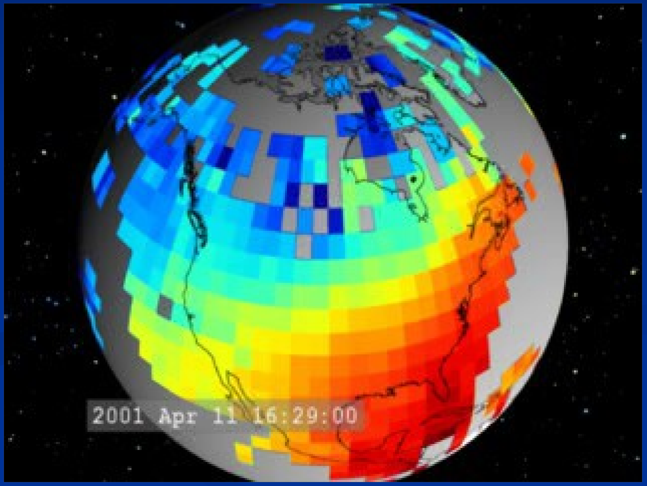
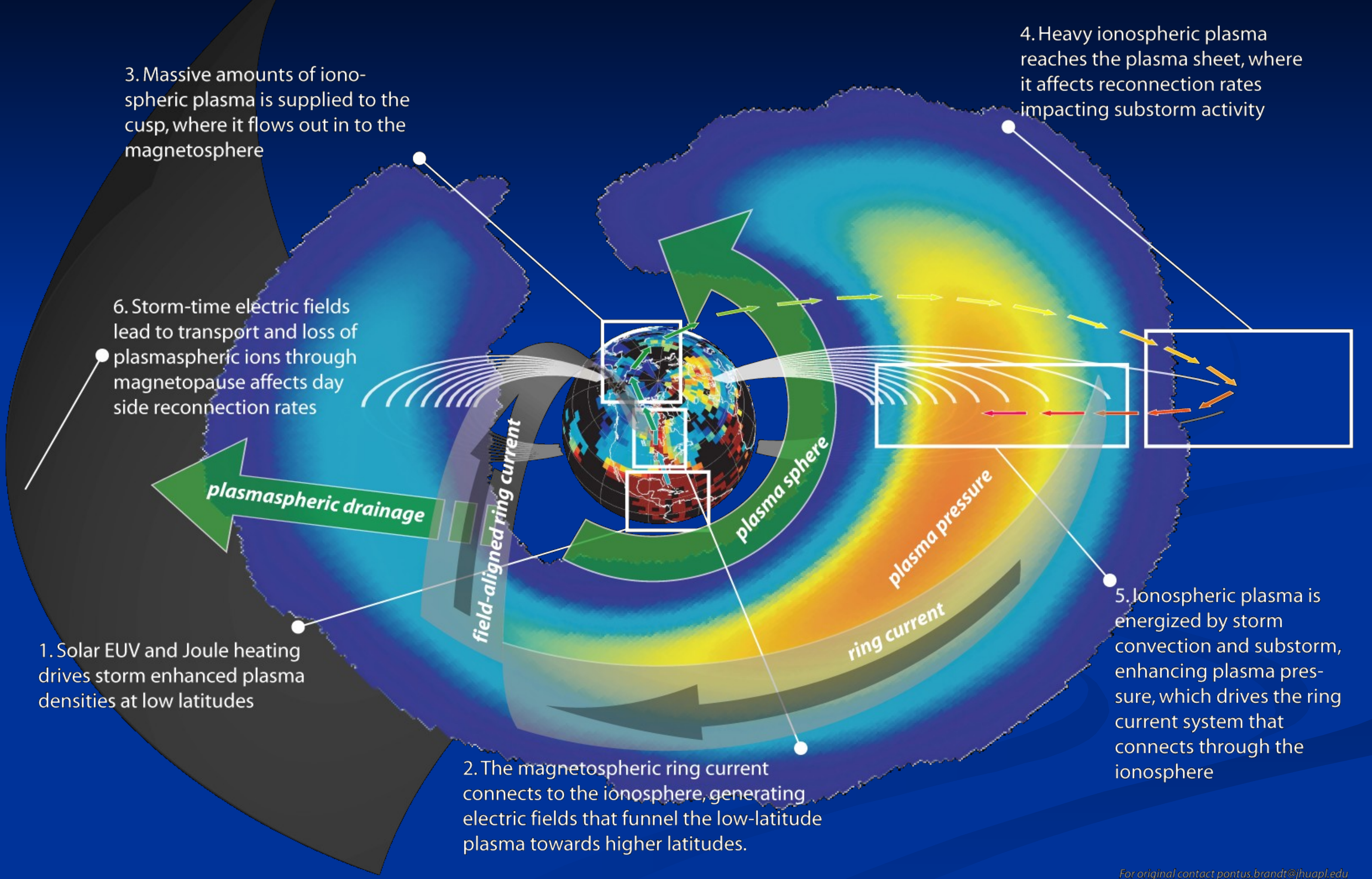


IMAGE Data of Plasmasphere





System-Science Model of Plasma Redistribution



Courtesy of P. Brandt