Heliophysics in Atmospheres

Thermosphere-Ionosphere Response to Geomagnetic Storms

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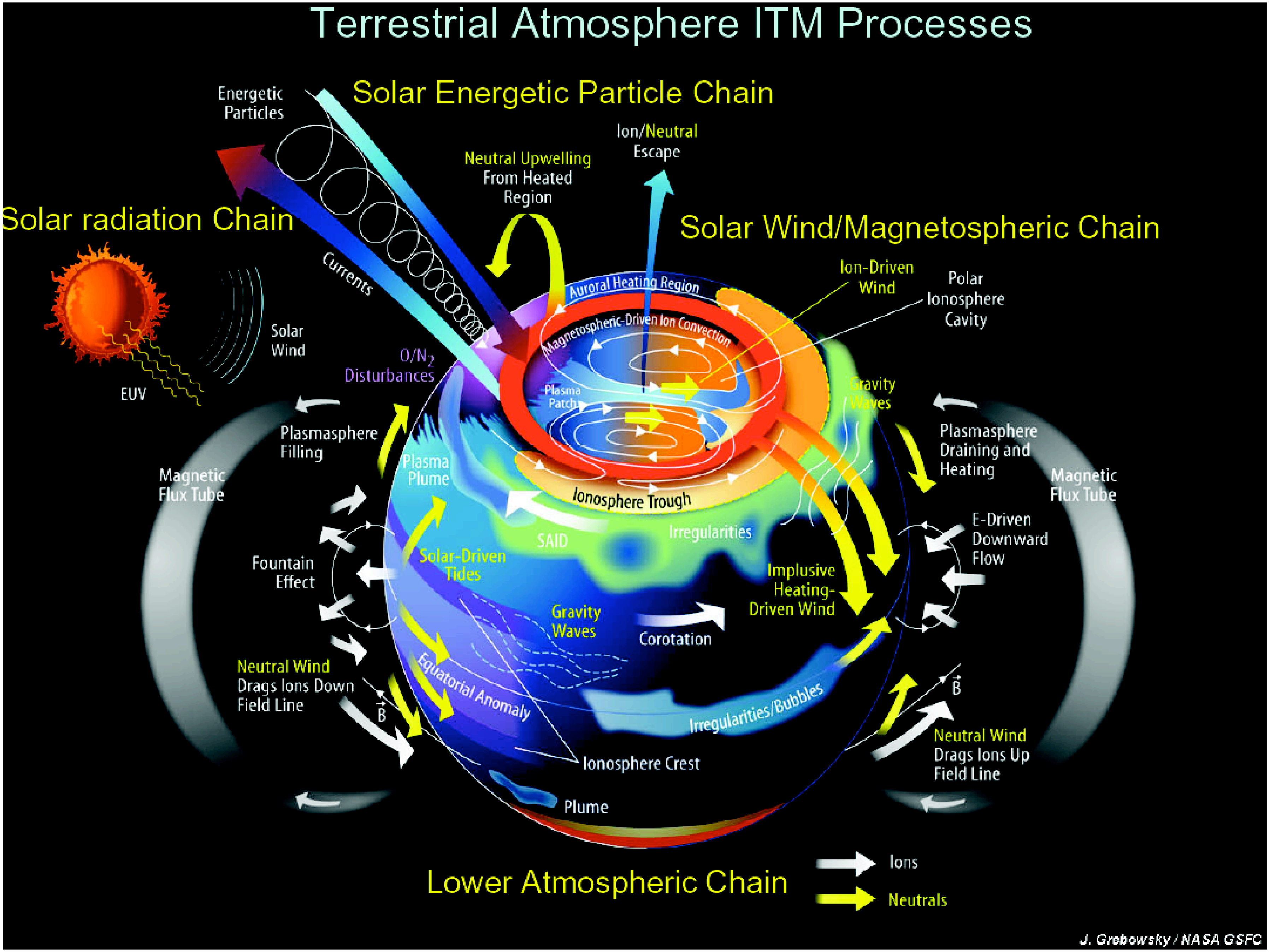
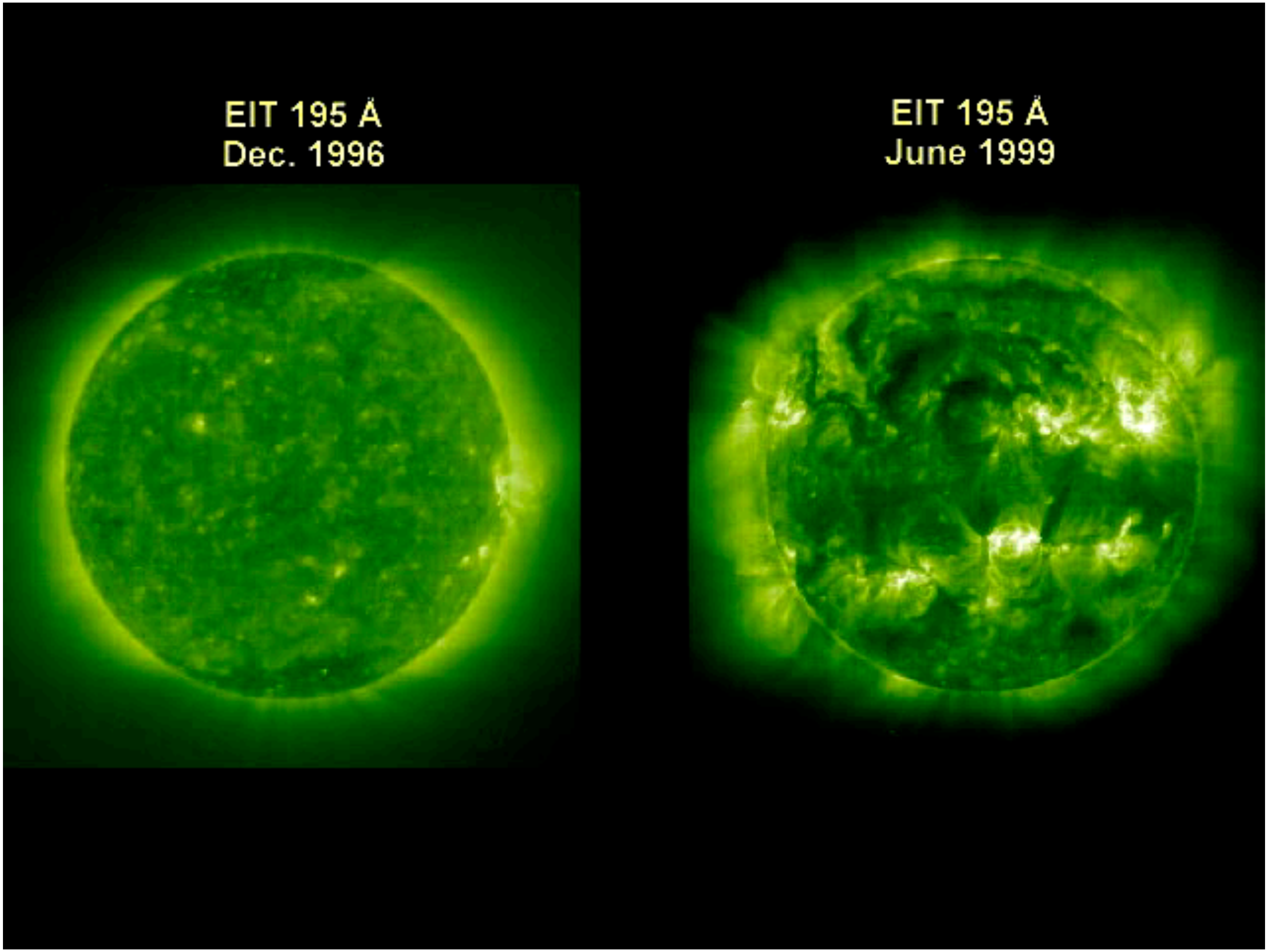

Terrestrial Atmosphere ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Solar radiation Chain
Solar Wind/Magnetospheric Chain
Currents
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Solar Wind
EUV
O/N_2 Disturbances
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasma Plume
Plasmasphere Draining and Heating
Magnetic Flux Tube
Ionosphere Trough
Magnetic Flux Tube
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals
J. Grebowsky / NASA GSFC


EIT 195 Å
Dec. 1996
EIT 195 Å
June 1999

Atmospheres

- Gravitationally bound
- Collision dominated - kinetic theory
- Partially ionized < 1% (100-600km altitude)
- Magnetic field - 99% invariant on short timescales

Space Weather Impacts on Near-Earth Systems

- Upper atmosphere is dominated by a collision-dominated, gravitationally-bounded, neutral fluid
  - Satellite drag, orbit prediction, collisional avoidance, positioning, re-entry - neutral mass density and winds
- Most other impacts on systems are due to the upper atmosphere being a weakly-ionized plasma, < 1% charged particle
  - HF communications - 3D Ne, NmF2, hmF2, D-region absorption
  - GNSS positioning and navigation - line of sight total electron content
  - Satellite communications - irregularities, ΔNe

M-I Coupling

- Magnetosphere interacts with the thermosphere/ionosphere through electrodynamics (conductivity, currents, electric fields) and mass flux
- Current system connecting the ionosphere and magnetosphere
- Electromagnetic energy flow (Poynting flux) - normally downward, spatially there can be regions of upward flux
- Joule heating + kinetic energy
- Recovery - flywheel effect, ionosphere/thermosphere as a generator - flux upward
- Mass flux: particle precipitation and outflow, also carries field-aligned current
- Alfven waves - communicates imbalance between M-I

Energy Flow

magnetospheric energy
500 - 1000 GW

particle precipitation <20%

heat, ionization,
airglow e.g. auroral
illumination

electromagnetic energy >80%

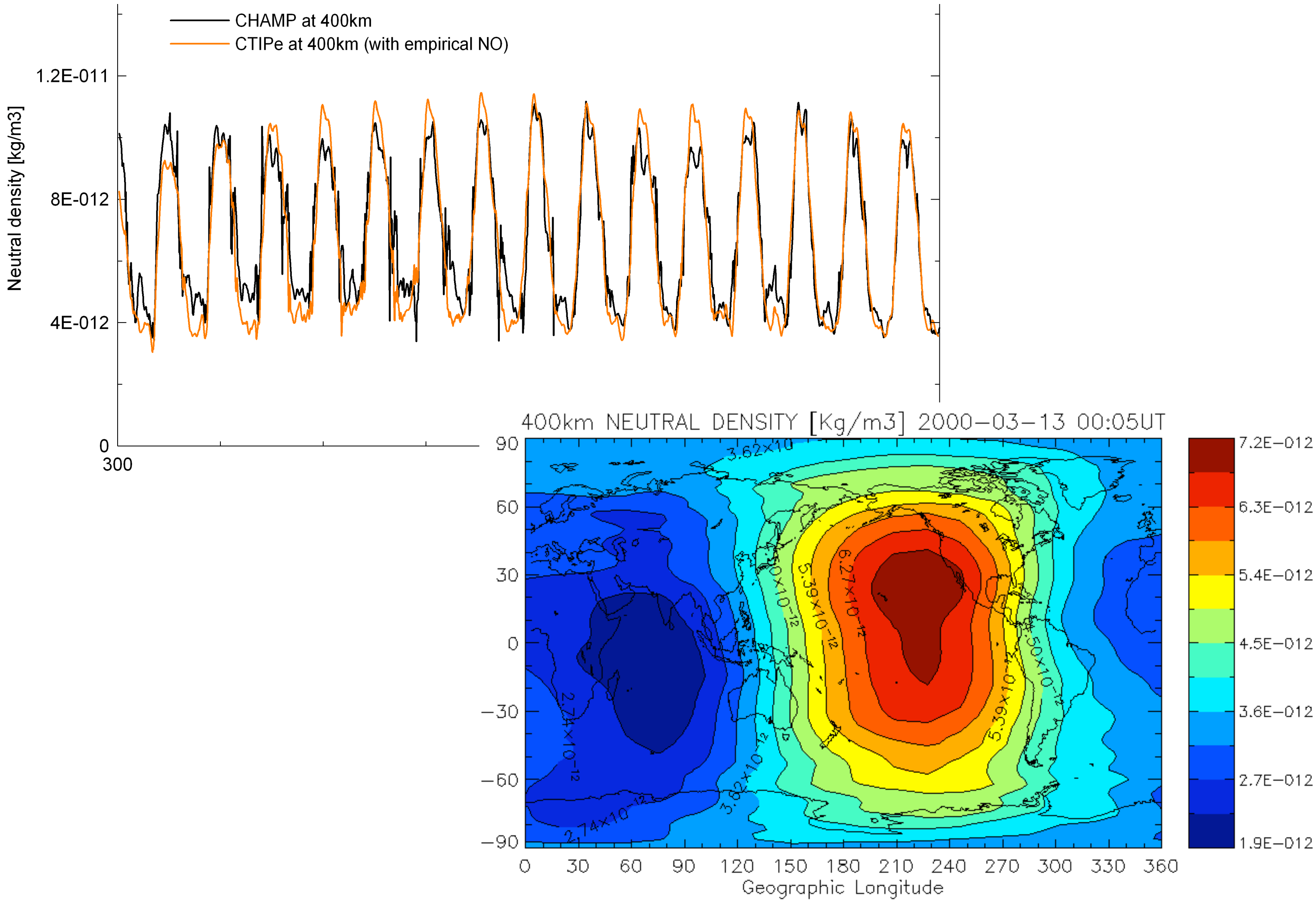
Joule heating
$\mathbf{J} \,.\, (\mathbf{E} + \mathbf{U} \mathrm{x} \mathbf{B})$
>80%

heat, pressure
gradients, winds, etc.

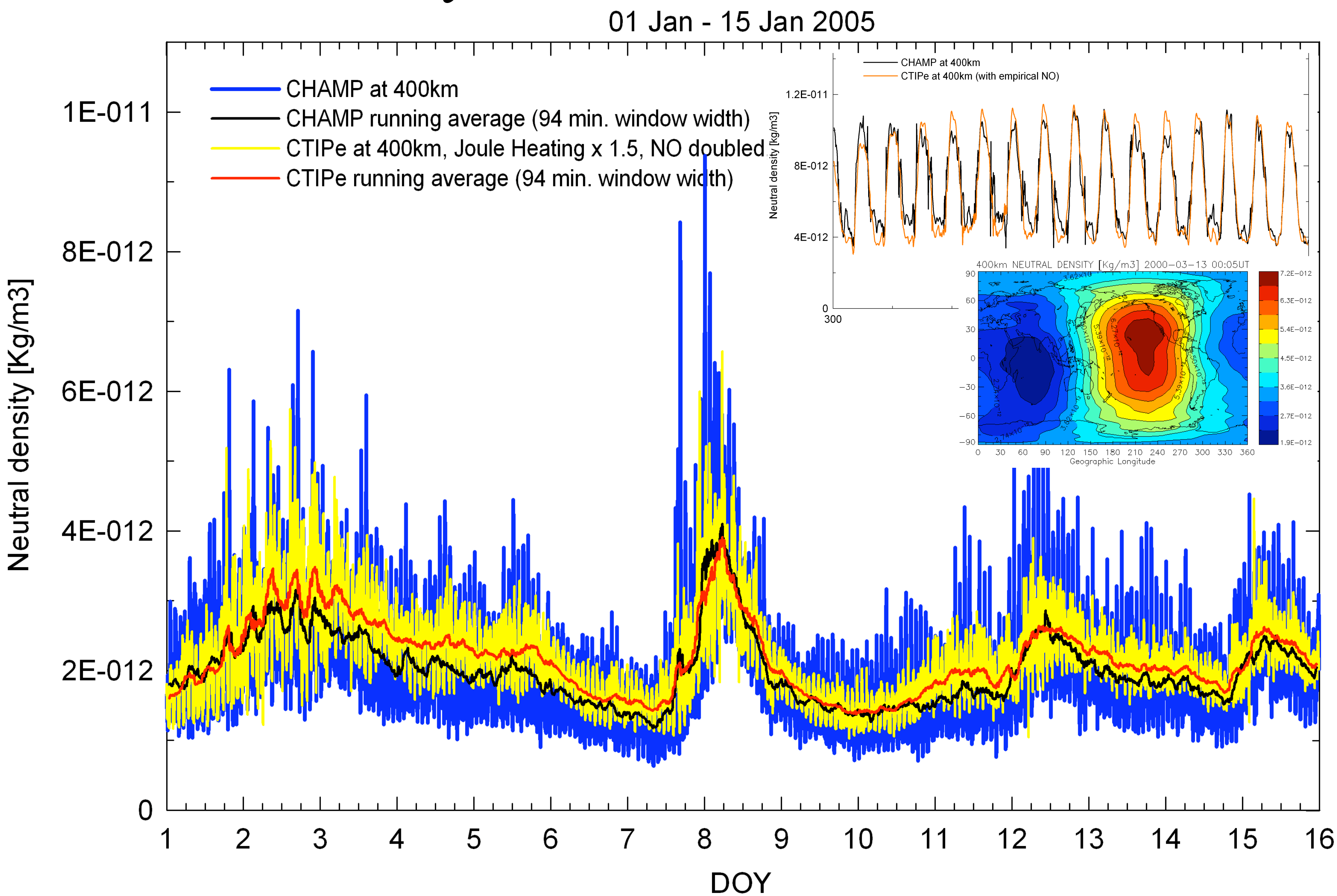
kinetic energy
$\mathbf{U} \,.\, (\mathbf{J} \mathrm{x} \mathbf{B})$
<20%

Ion drag drives
neutral winds

Neutral density Jan 2005 CHAMP vs CTIPe

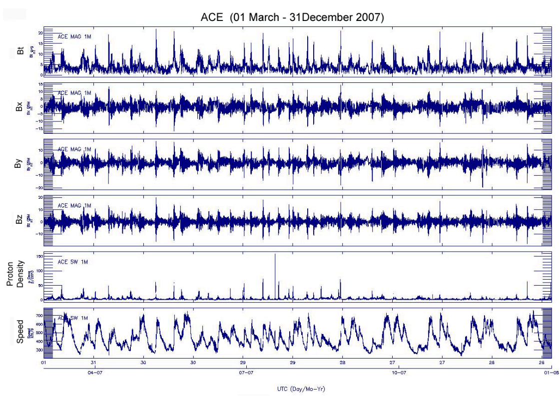


Neutral density Jan 2005 CHAMP vs CTIPe

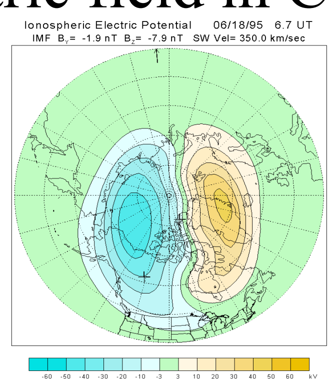


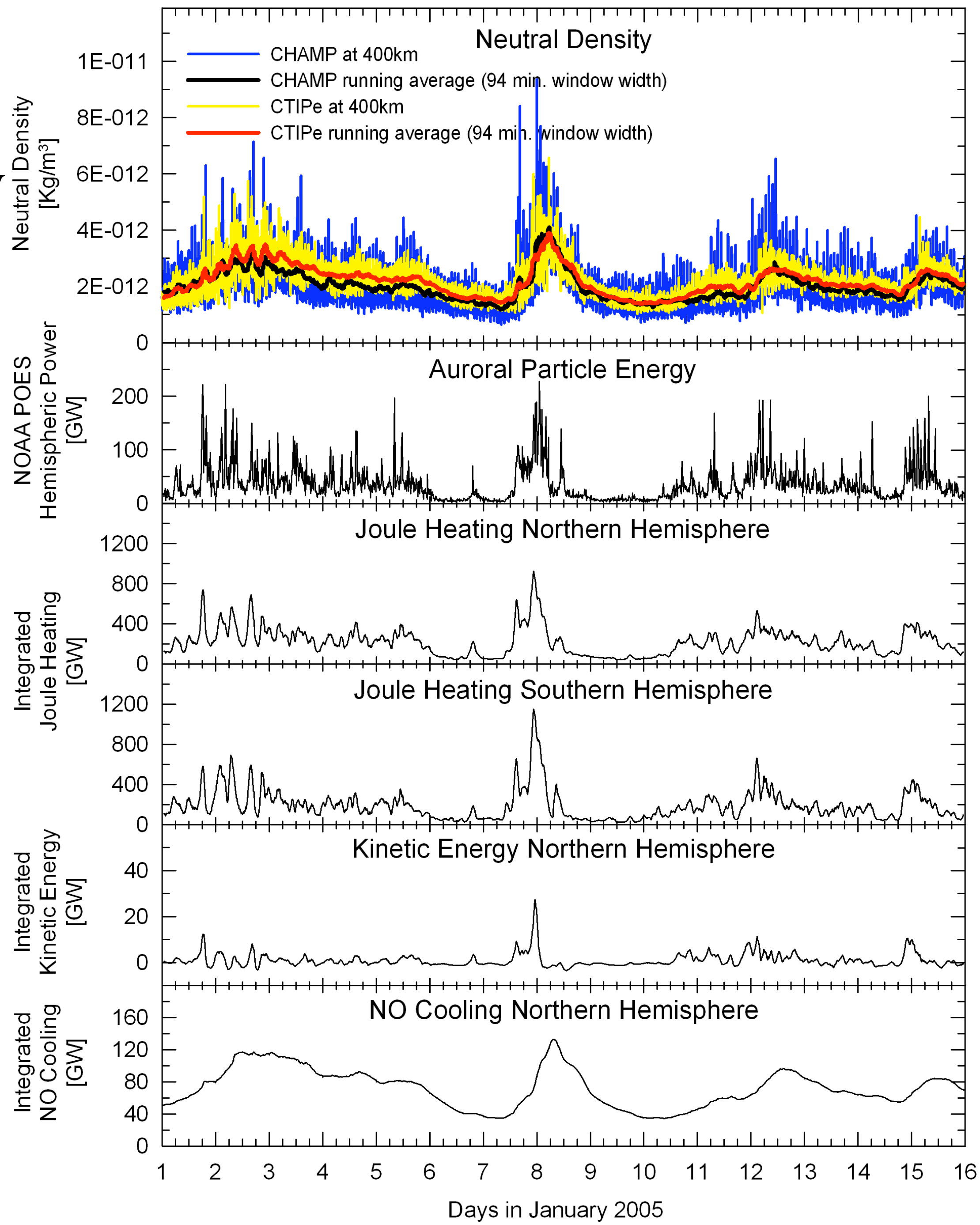
Implies certain magnitude of energy sources and sinks

ACE solar wind data



- drives Weimer electric field in CTIPe



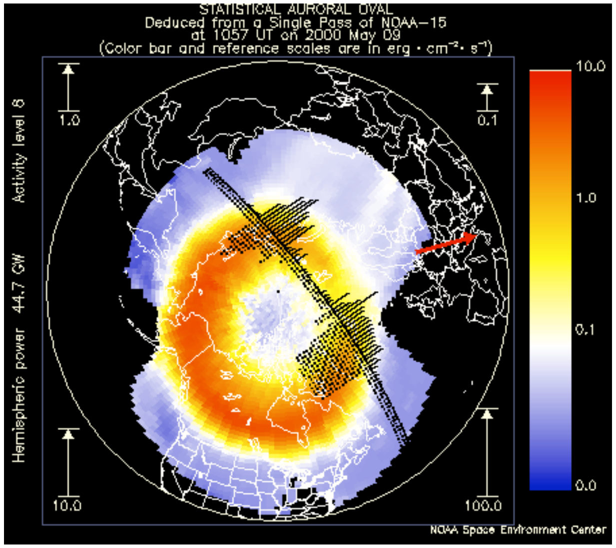


Thermosphere-Ionosphere Responses to Magnetospheric Sources

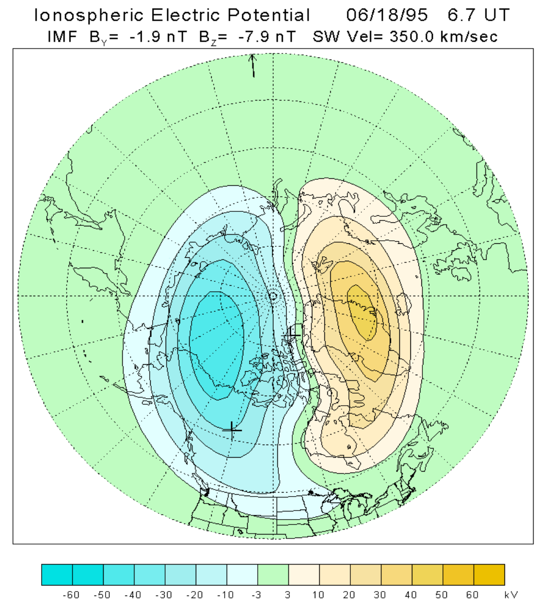
- Auroral precipitation enhances conductivity at high latitudes
- Magnetospheric electric fields enhances plasma transport at high latitudes
- Magnetospheric “penetration electric fields” imposed globally in less than a second
- Ion drag drives high latitude wind system up to ~ 1 km/s
- Joule and particle energy heats atmosphere
- Thermal expansion, neutral density increase, horizontal pressure gradients, equatorward wind surges
- Changes in global circulation
- Neutral composition changes
- Disturbance dynamo
- Positive and negative ionospheric storm phases

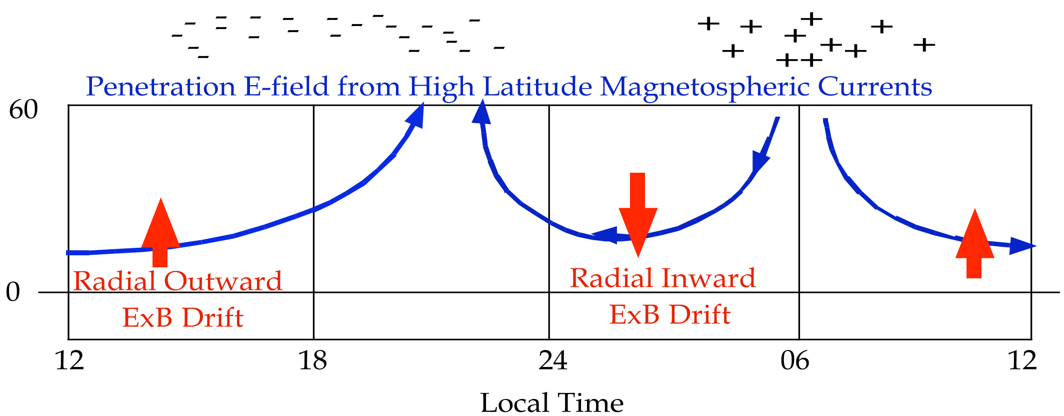
Magnetospheric Storm Forcing

TIROS/NOAA auroral precipitation patterns driven by power index:



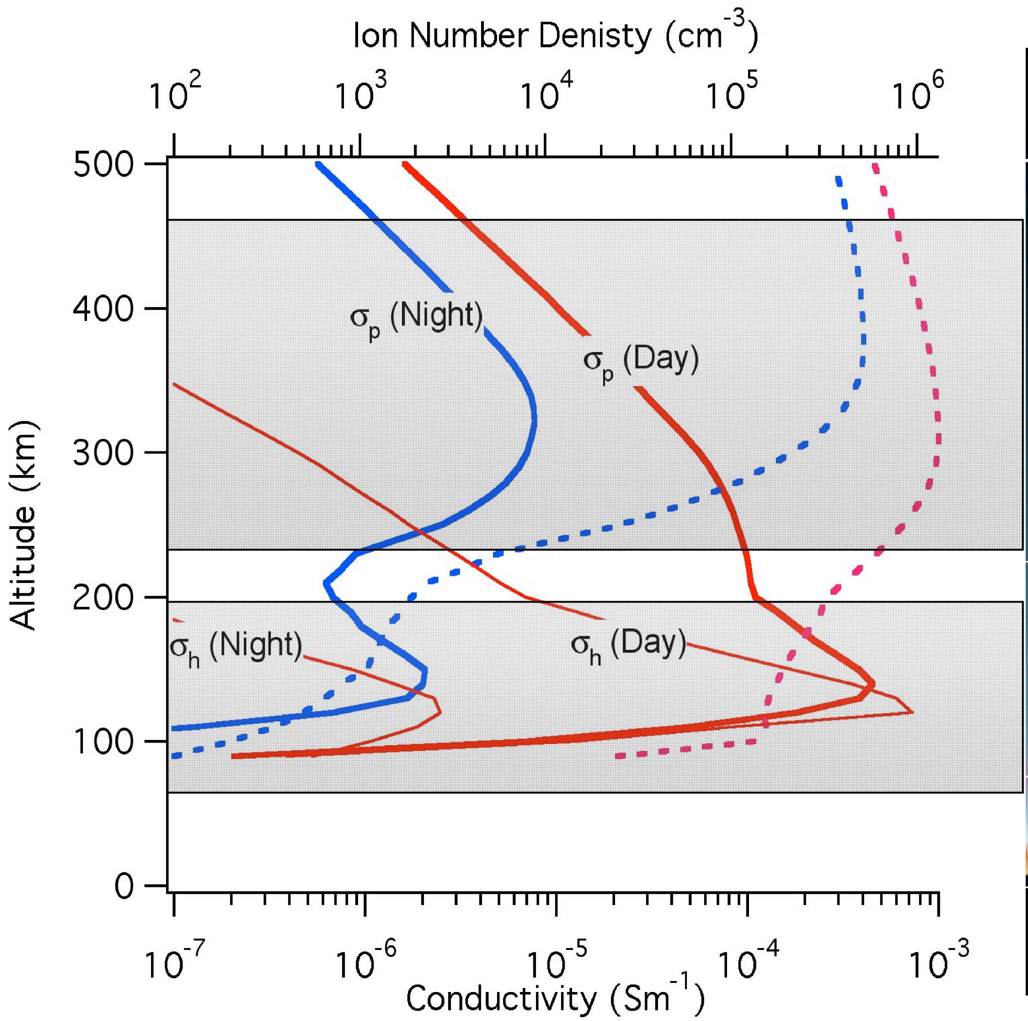
Weimer electric field patterns driven by solar wind data:

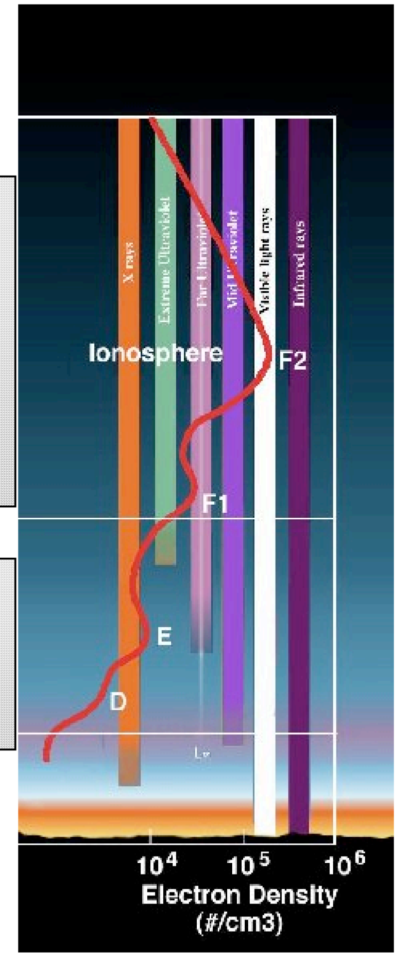




plus
SAPS

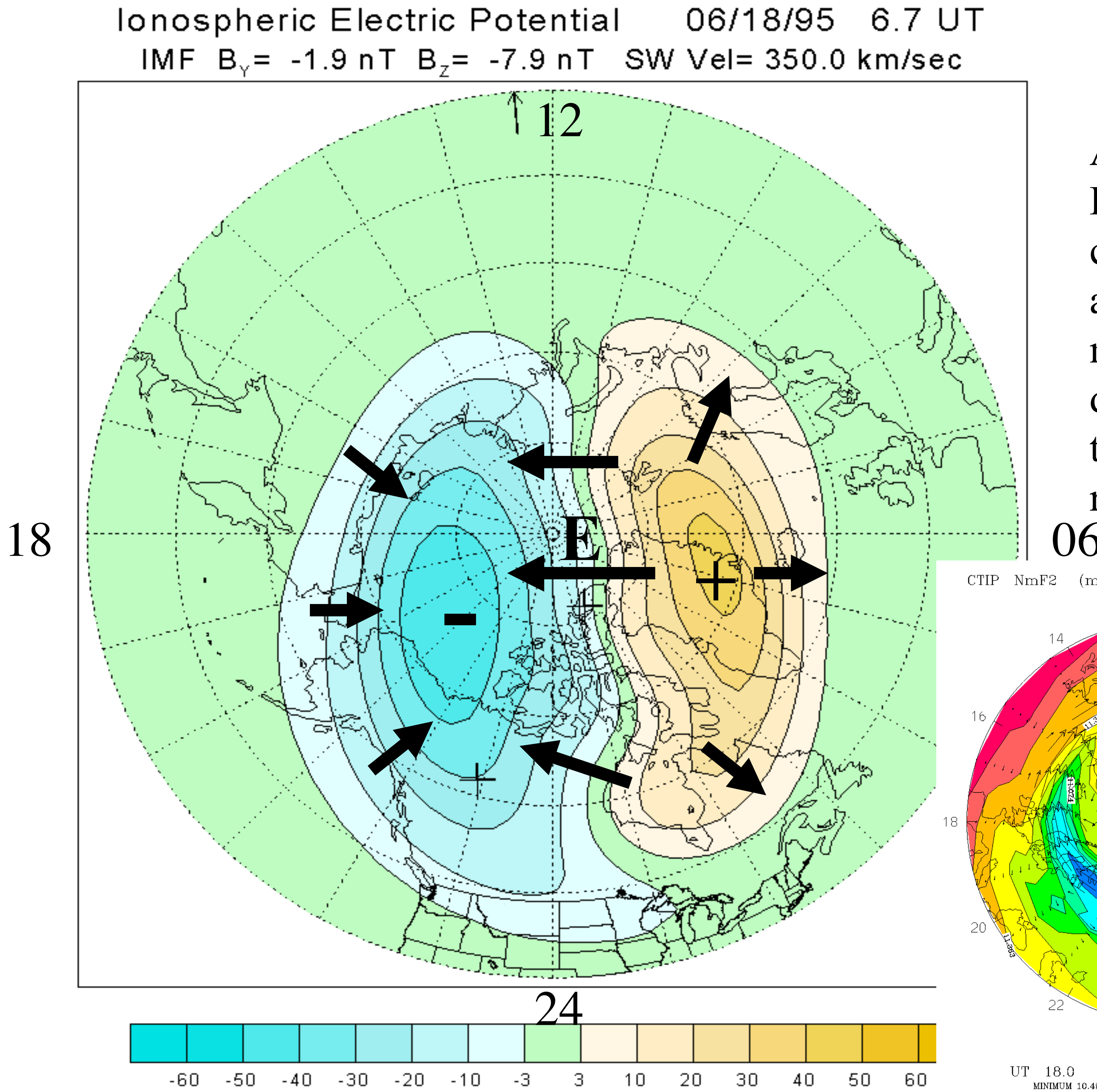
Pedersen and Hall Conductivity





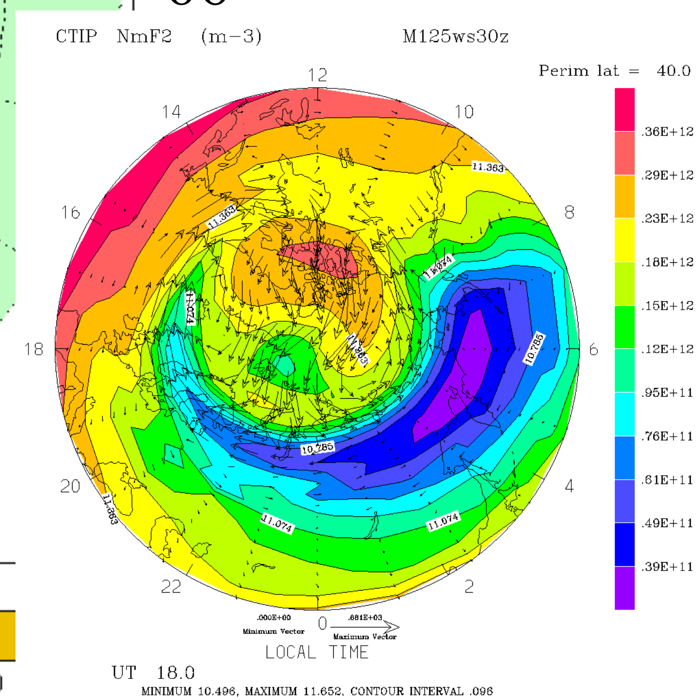
Ion motion

- Coulomb force - e **E**
- Lorentz force - e **VxB**
- Collisions with neutrals - $m\upsilon(\boldsymbol{V}-\boldsymbol{U})$,
- Gravity



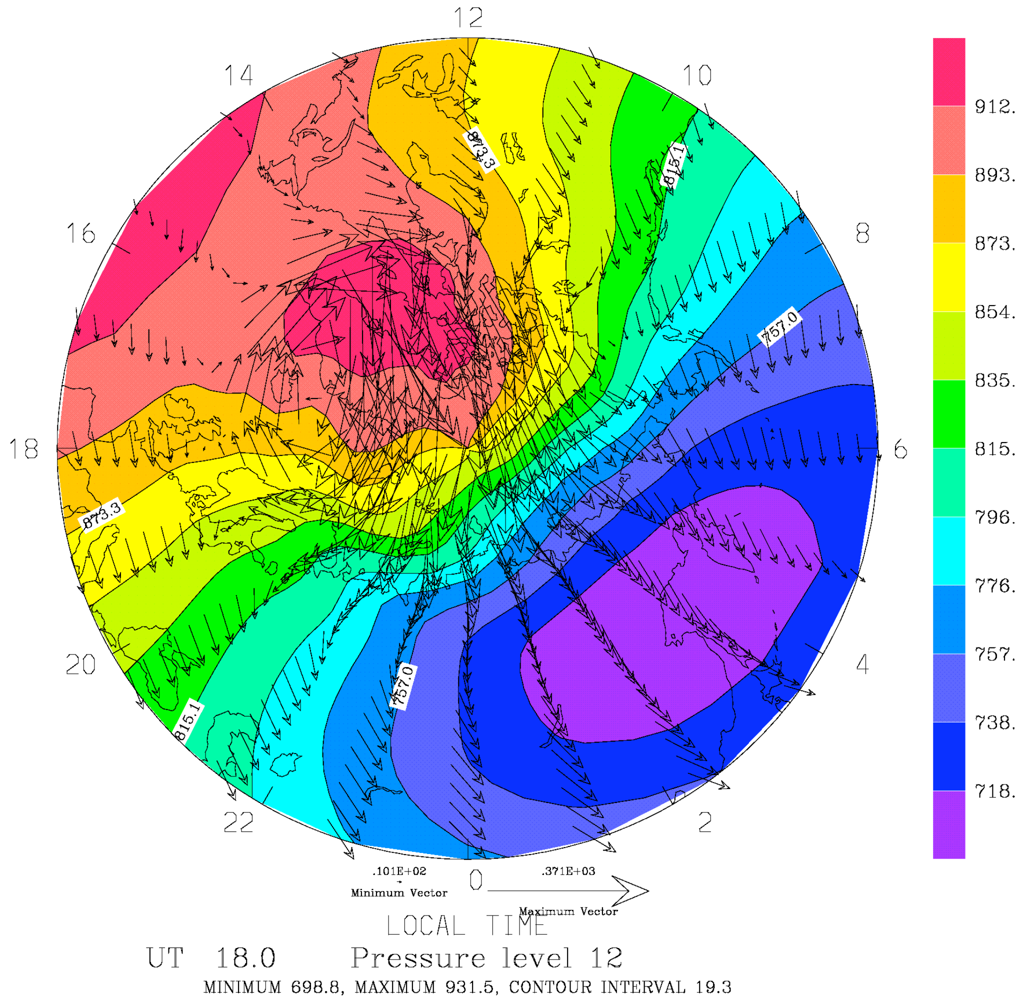
Ion drift:

Above ~160 km **ExB**
Below 160 km as collision with neutral atmosphere become more important ion drift rotates towards the **E**-field vector and reduces in magnitude



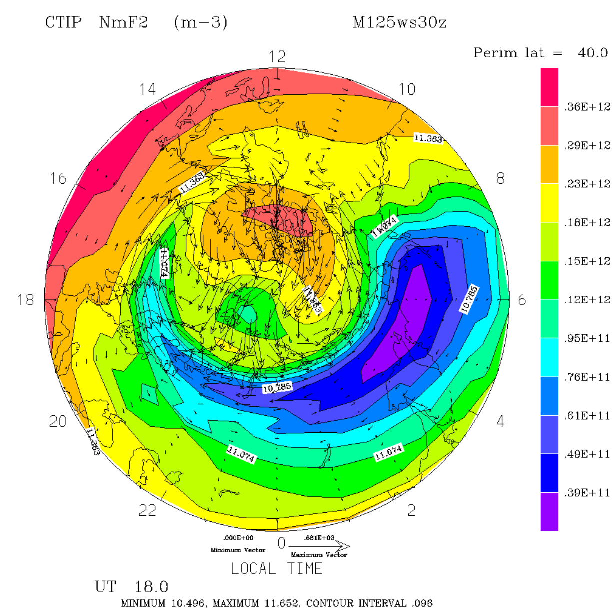
Ion-neutral collisions in upper thermosphere frequent enough to drive high velocity neutral wind

Neutral Winds and Temperature: 300 km altitude

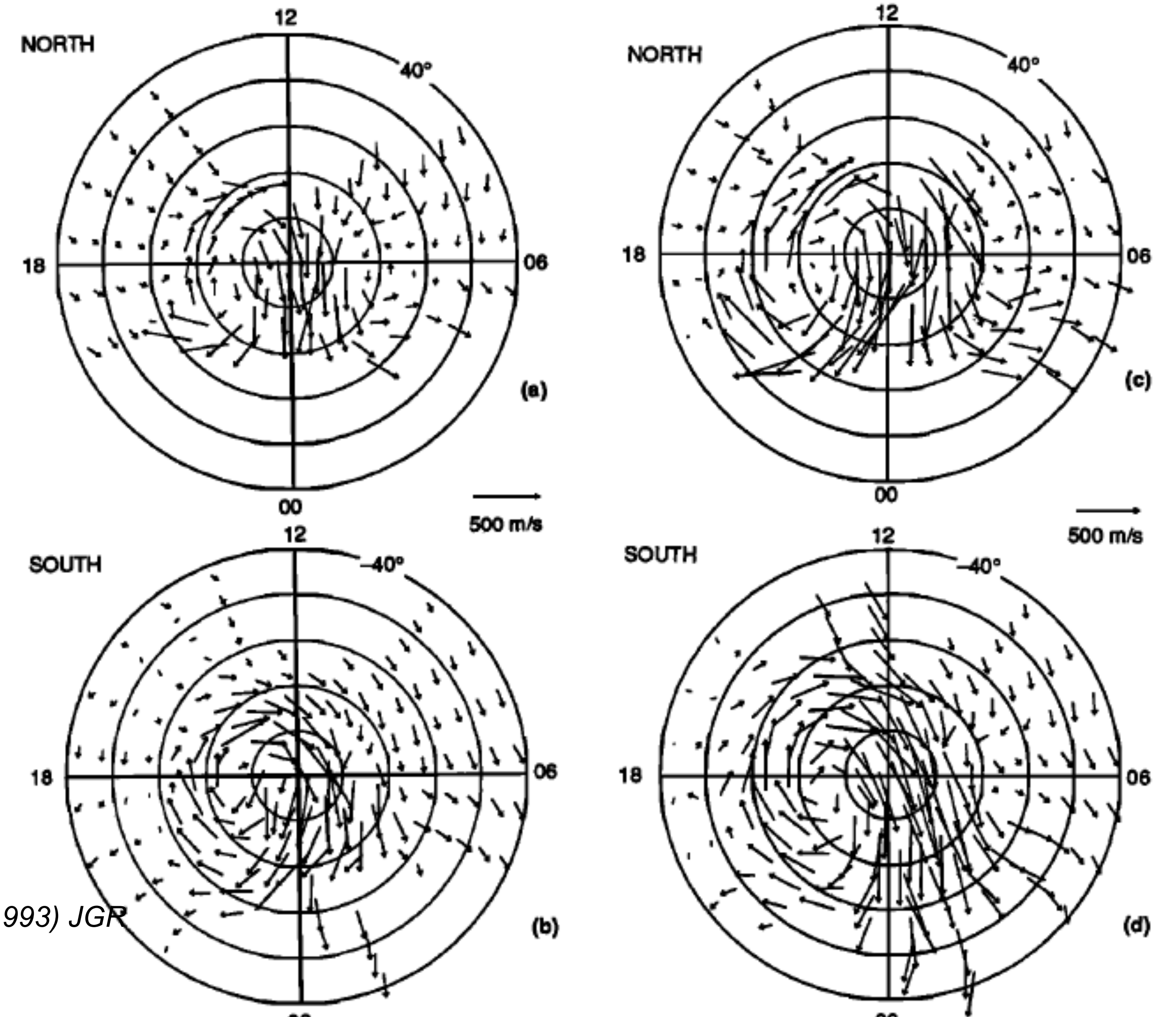


Maximum wind speed observed by DE-2 ~ 1400 m/s

ExB ion drift and NmF2



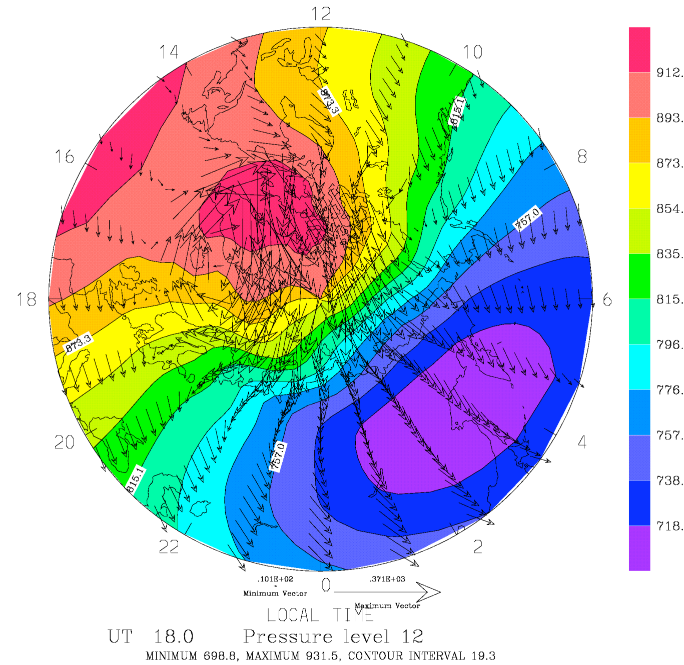
Polar Thermospheric Winds



Thayer and Killeen (1993) JGR

Fig. 1. Averaged DE 2 thermospheric neutral wind maps for December solstice, solar maximum conditions in geomagnetic coordinates during periods of $K_p \leq 3$ for (*a*) northern and (*b*) southern high-latitude regions and periods of $3+ \leq K_p \leq 6$ for (*c*) northern and (*d*) southern high-latitude regions.

Non-linear effects



- Compare with hurricane speeds:

  150 mph ≡ 60 m/s

  1500 mph ≡ 600 m/s
- Transport/advection and acceleration terms are strong
- Asymmetry in response in dawn and dusk sectors
- Inertial motion on a non-rotating sphere is a great circle
- Spherical co-ords e.g. east/west, is not cartesian system
- Introduces “curvature” terms
- Inertial oscillation

Equations of Motion in pressure coordinates

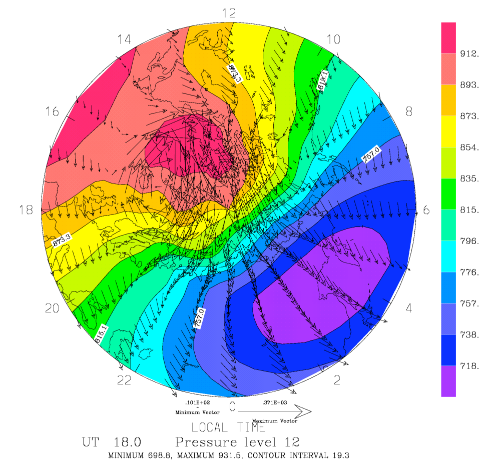
$$\frac{\partial}{\partial t}V_\theta = -\frac{V_\theta}{r}\frac{\partial}{\partial \theta}V_\theta - \frac{V_\phi}{r\sin\theta}\frac{\partial}{\partial \phi}V_\theta - \omega\frac{\partial}{\partial p}V_\theta - \frac{g}{r}\frac{\partial}{\partial \theta}h + \left(2\Omega + \frac{V_\phi}{r\sin\theta}\right)V_\phi\cos\theta + g\frac{\partial}{\partial p}\left[\left(\mu_m + \mu_T\right)\frac{p}{H}\frac{\partial}{\partial p}V_\theta\right] - \nu_{ni}\left(V_\theta - U_\theta\right)$$

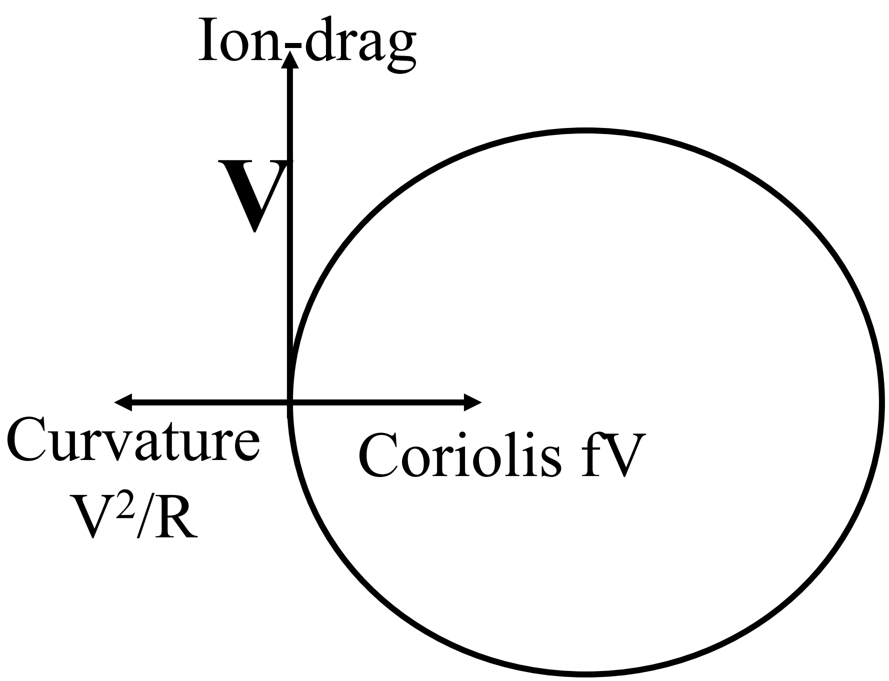
$$\frac{\partial}{\partial t}V_\phi = -\frac{V_\theta}{r}\frac{\partial}{\partial \theta}V_\phi - \frac{V_\phi}{r\sin\theta}\frac{\partial}{\partial \phi}V_\phi - \omega\frac{\partial}{\partial p}V_\phi - \frac{g}{r}\frac{\partial}{\partial \phi}h - \left(2\Omega + \frac{V_\phi}{r\sin\theta}\right)V_\theta\cos\theta + g\frac{\partial}{\partial p}\left[\left(\mu_m + \mu_T\right)\frac{p}{H}\frac{\partial}{\partial p}V_\phi\right] - \nu_{ni}\left(V_\phi - U_\phi\right)$$

advection pressure Coriolis viscosity ion drag

$$\frac{1}{p}\frac{\partial p}{\partial h} = -\frac{g}{RT} \qquad V_z = \left(\frac{\partial h}{\partial t}\right)_p - \frac{\omega}{\rho g} \qquad \frac{\partial \omega}{\partial p} = -\nabla_p \cdot \overline{V}$$

Inertial Oscillation: balance between centrifugal (curvature) and Coriolis

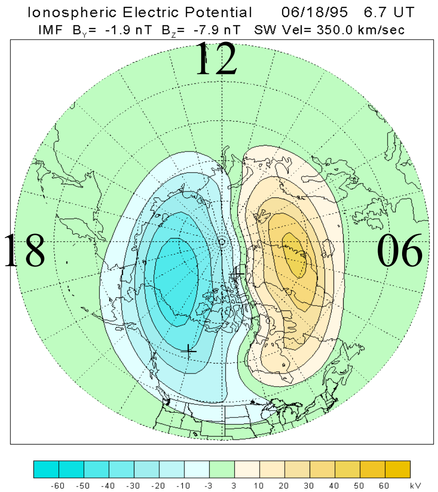




$$\frac{V^2}{R} = -fV$$

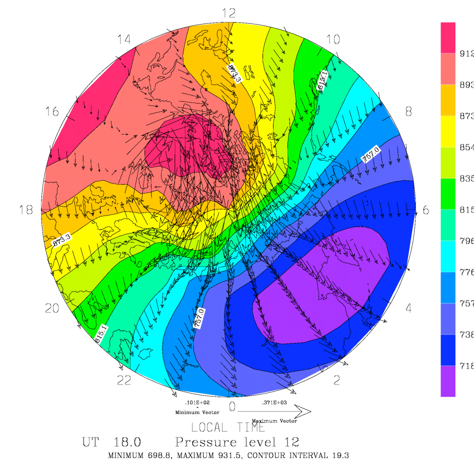
Radius of curvature R=20° latitude
Coriolis high latitude $f=1.4\text{x}10^{-4}$
V~300m/s, convergent if slower, divergent if stronger

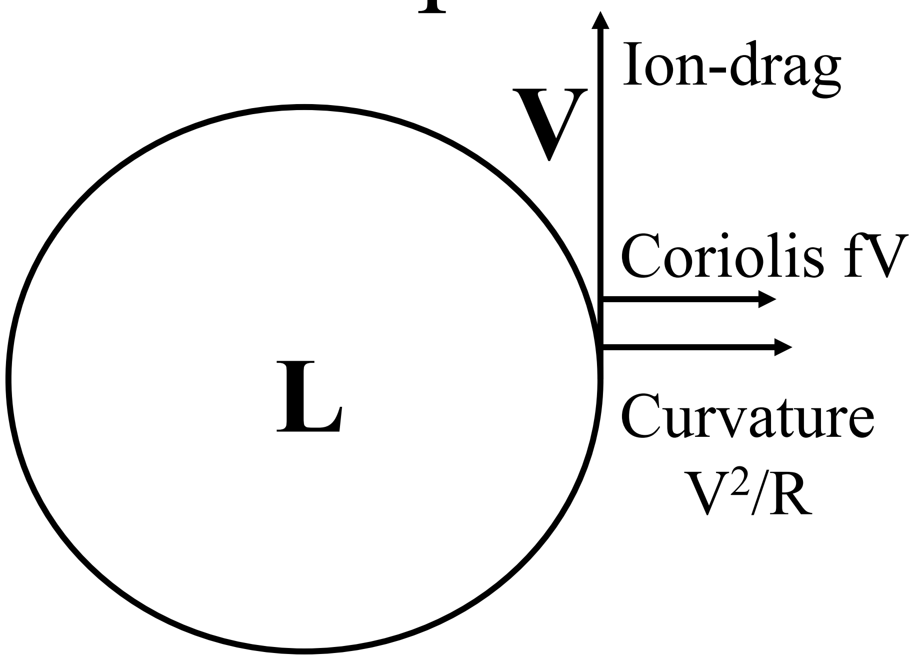
Inertial Resonance



- Coriolis force directs winds towards the right in the northern hemisphere
- Tends to move parcels of gas in clockwise vortex, similar to dusk plasma convection cell
- In dusk sector Coriolis tends to constrain parcels within curvature of auroral oval
- In dawn sector gas tends to be expelled equatorward
- Gas constrained within auroral oval can be accelerated to high velocities
- Dawn sector momentum spread over wider area.

Dawn Cell: centrifugal (curvature) and Coriolis assist ⇒ low pressure cell



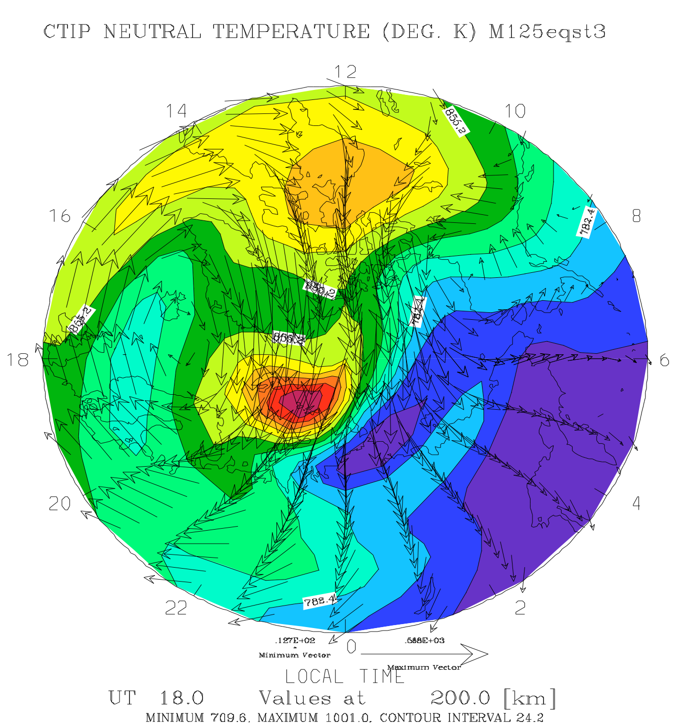


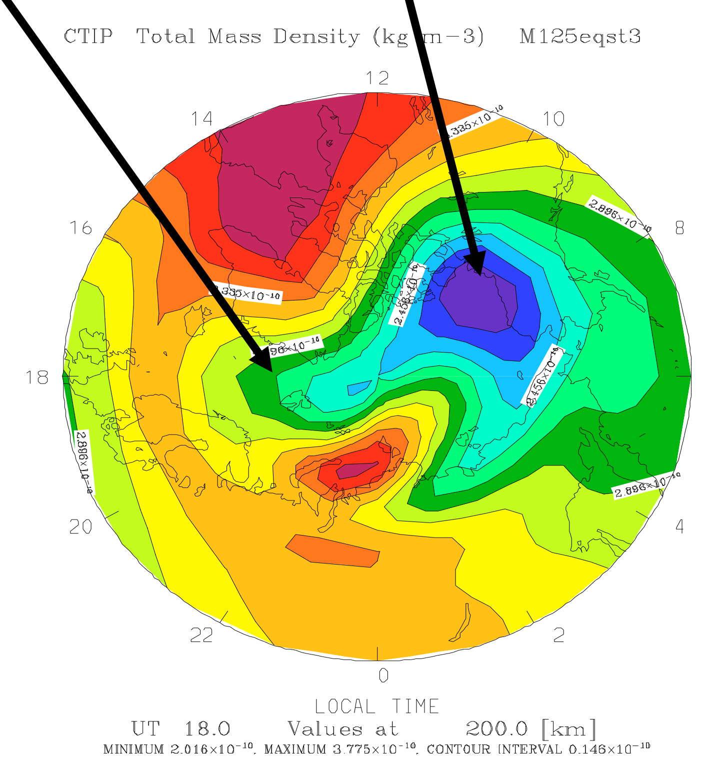
$$\frac{V^2}{R} + fV = -\frac{1}{\rho}\frac{\partial p}{\partial n}$$

Vortex in dawn cell always divergent if ion-drag forcing is cyclonic (anti-clockwise)

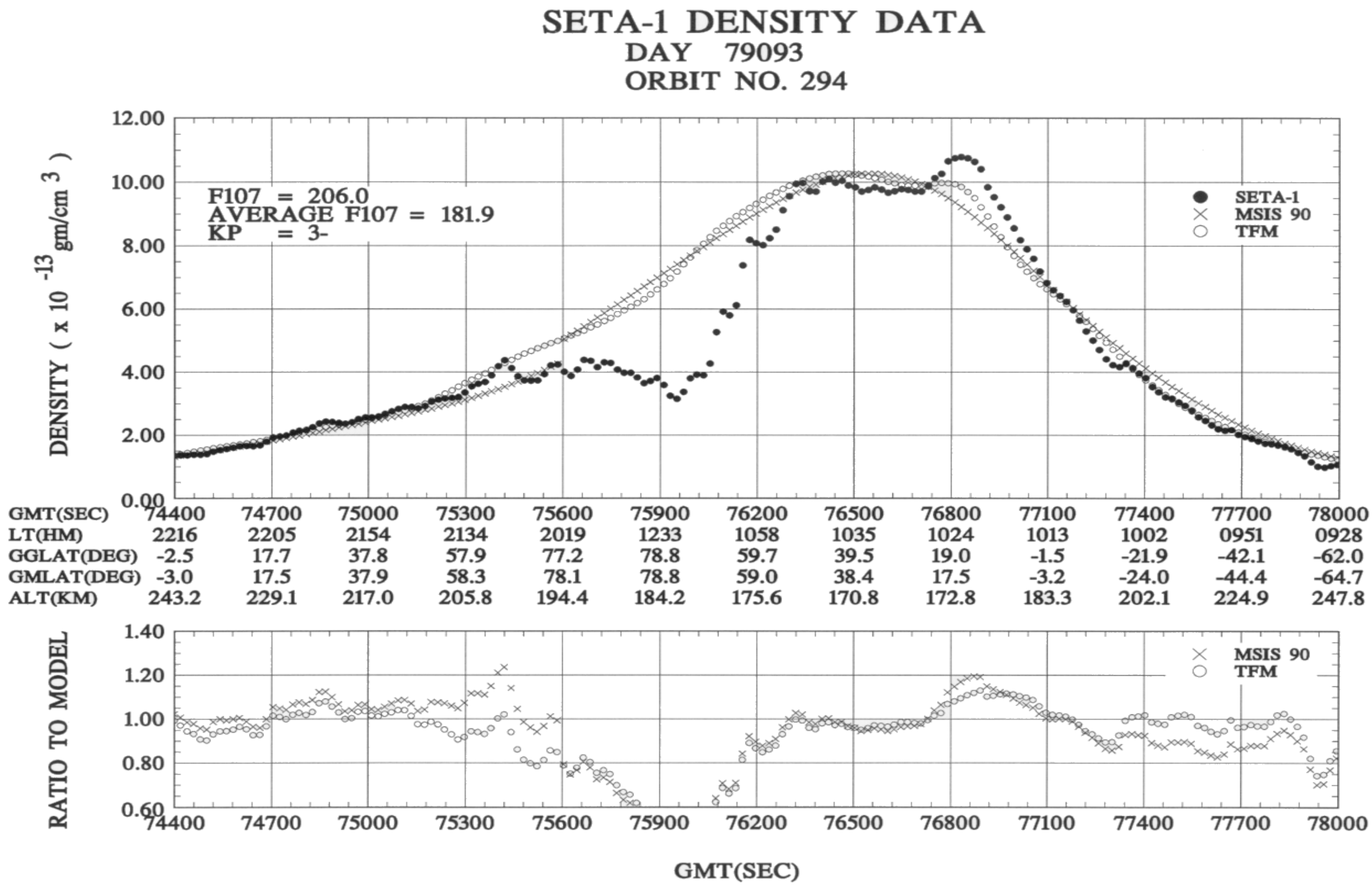
Storm-time neutral winds produce dynamically driven “holes”

Dawn cell always divergent - typically see density hole
Dusk cell only divergent when wind speeds exceed 300 or 400 m/s

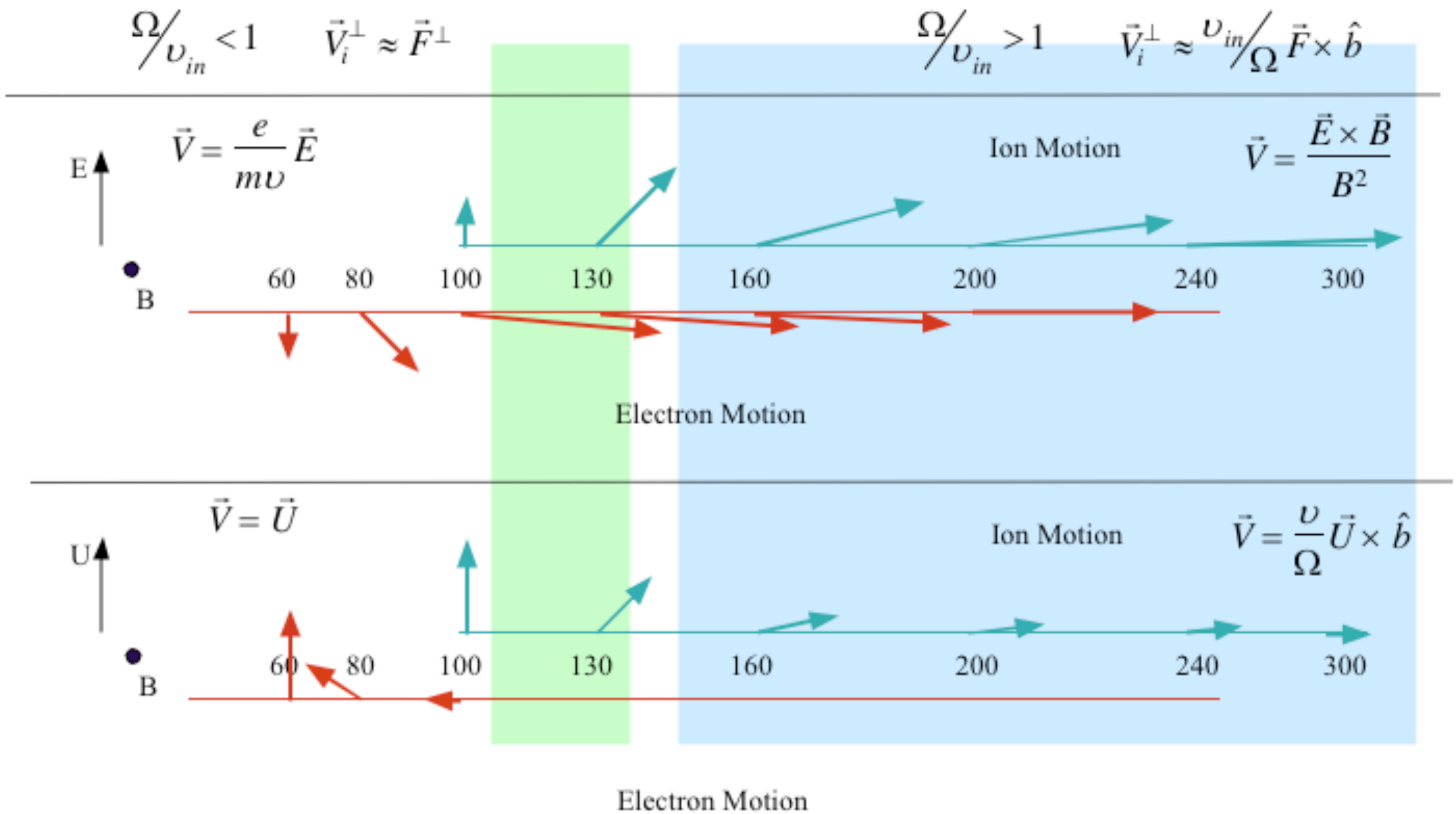




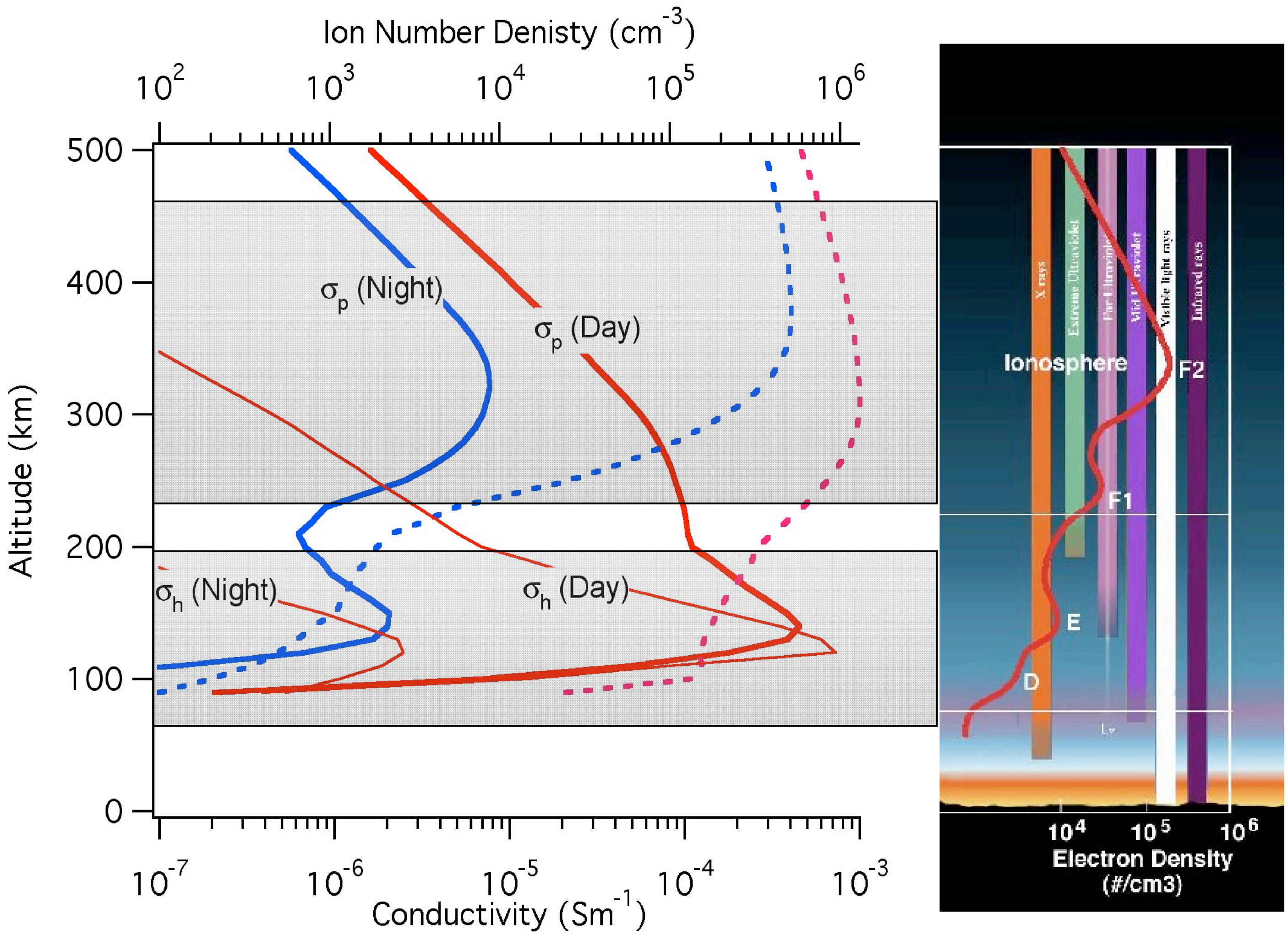
Neutral density holes - dynamically driven?



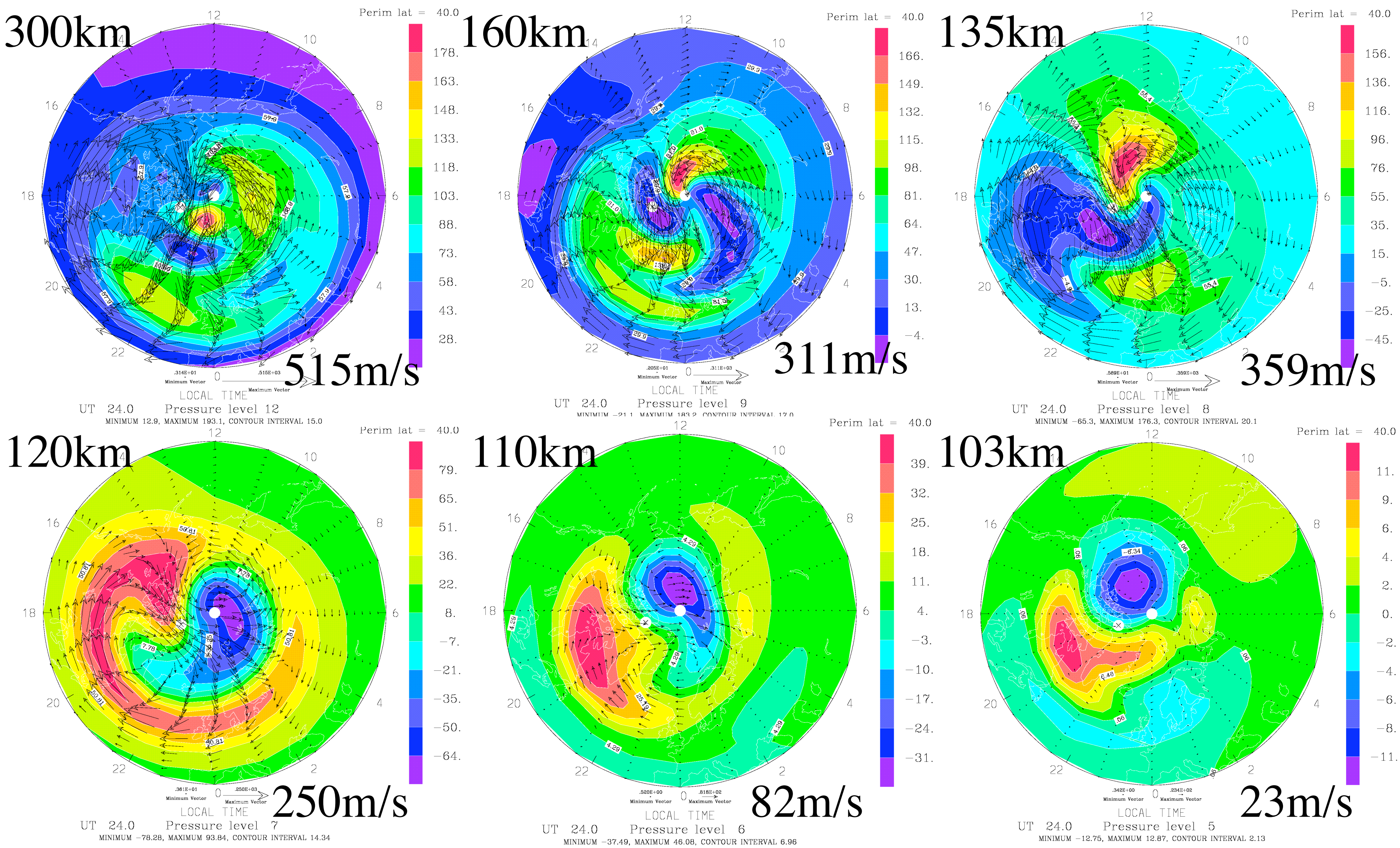
Ion Motion perpendicular to B



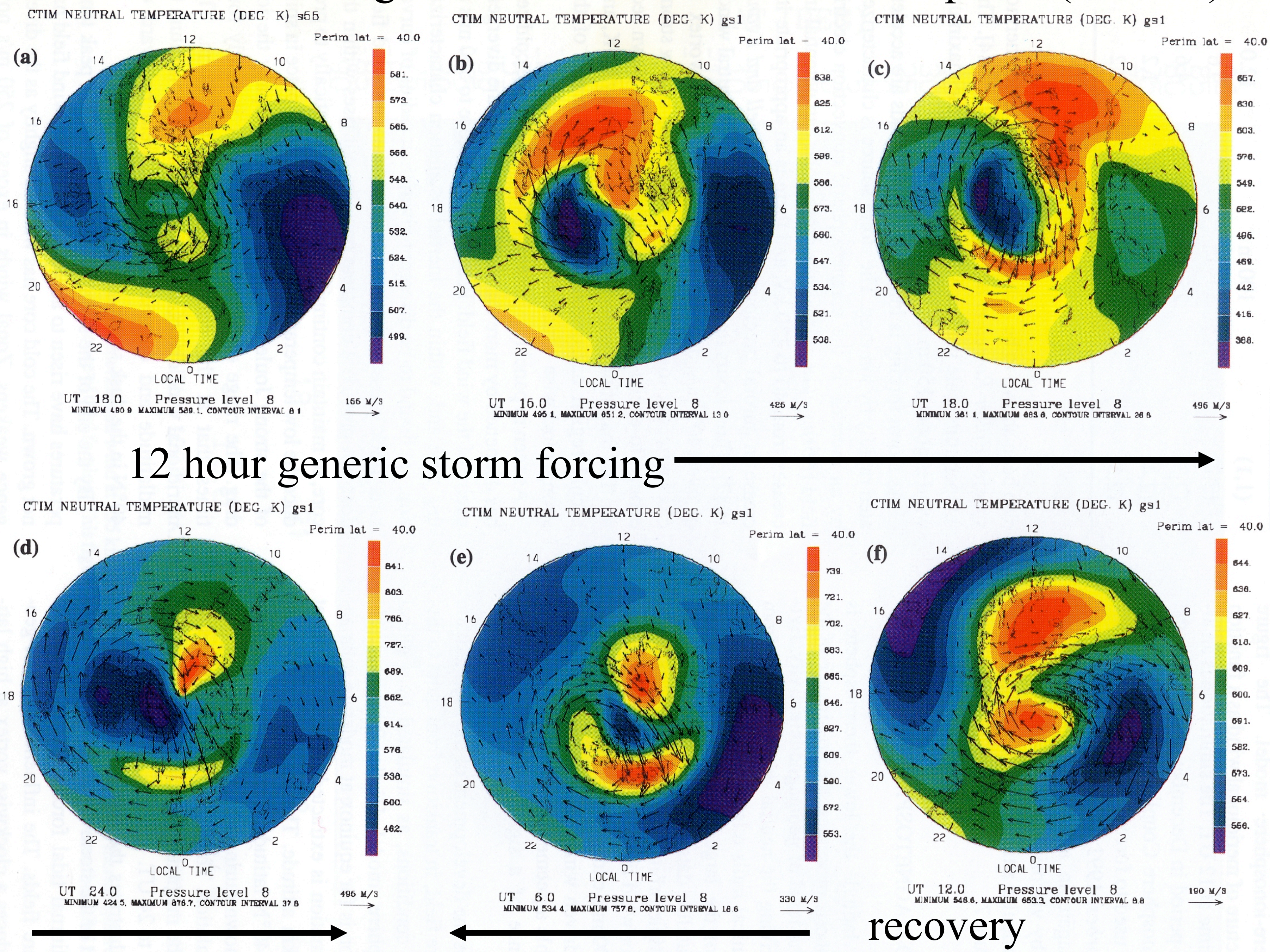
Pedersen and Hall Conductivity



Altitude Dependence:
balance of forces change with altitude

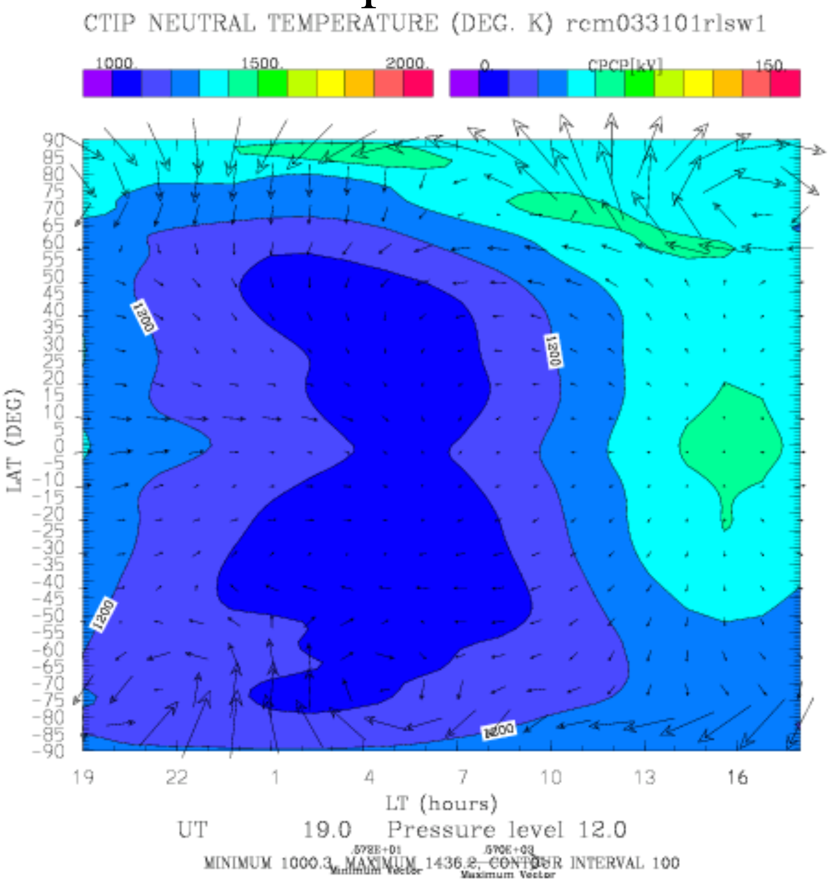


Simulation of long-lived vortex in lower thermosphere (140 km)

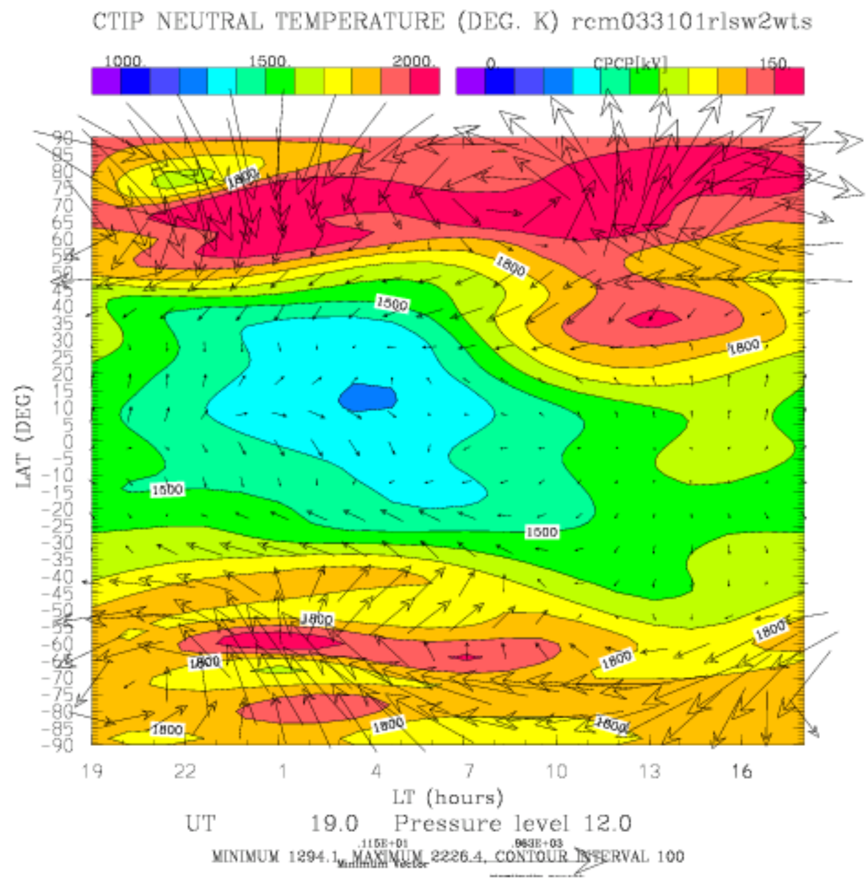


Joule heating: J . (E + V x B)
Large temperature and circulation changes in the upper thermosphere

quiet

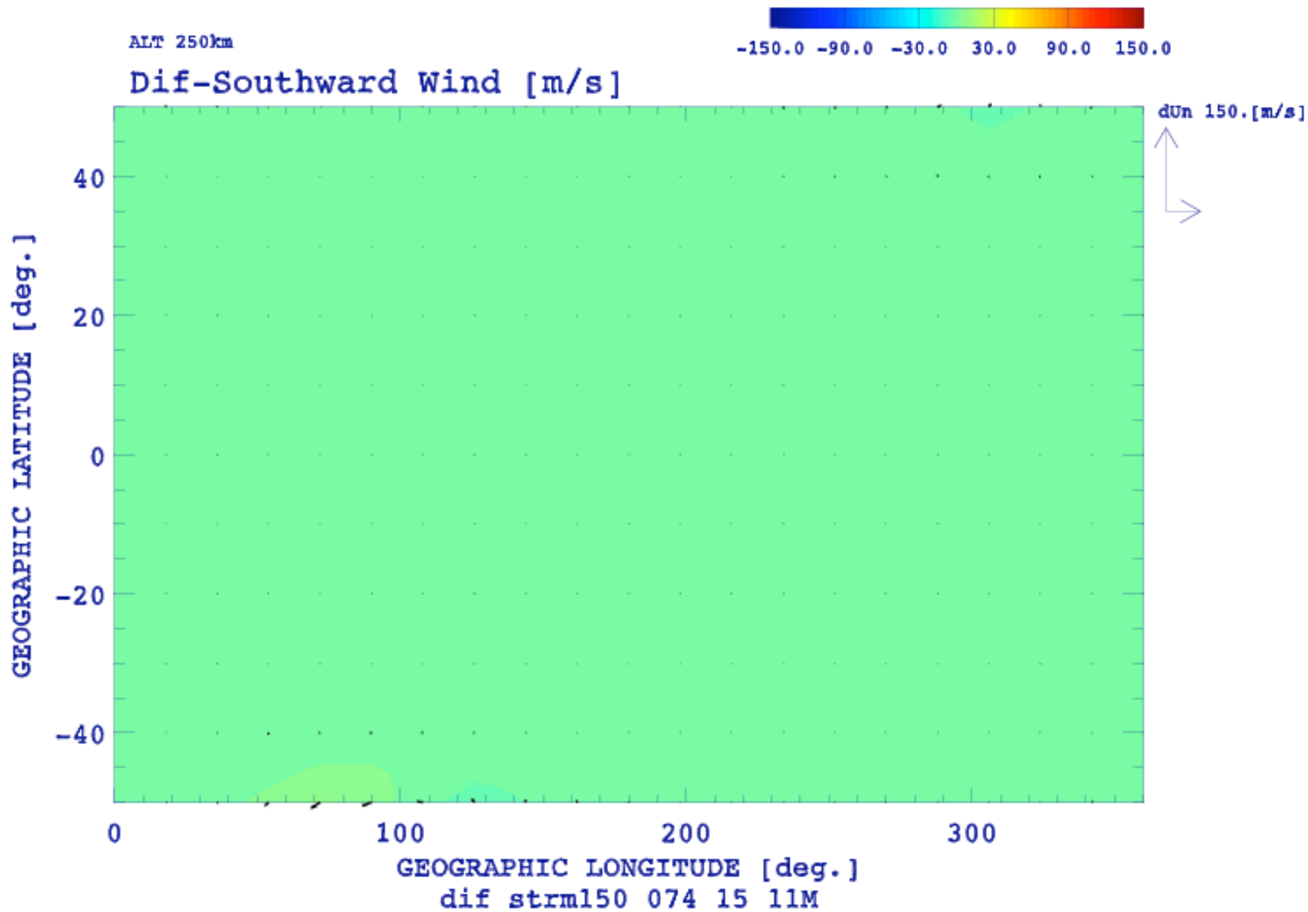


disturbed

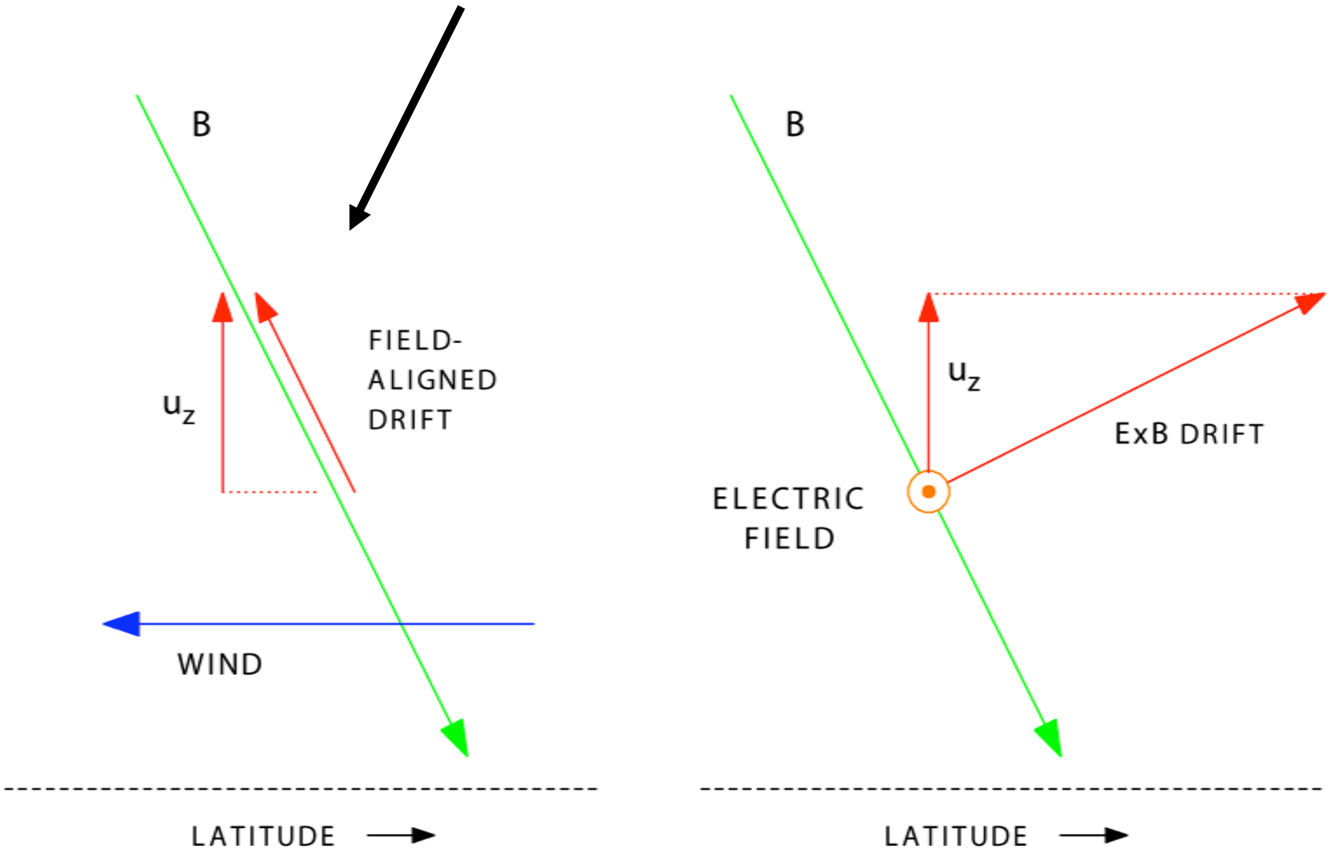


Neutral wind response to “simple” storm

Generic model storm forcing: 30 minute ramp up to activity level 10, and solar wind conditions consistent with Kp 6, 11.5 hrs at elevated storm levels, 30 minute ramp down to quiet for 12 hrs

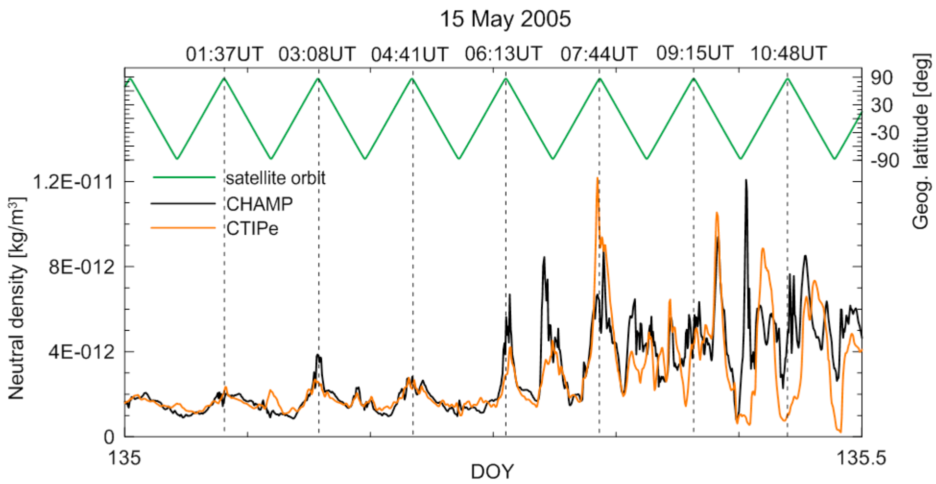


Equatorward wind at mid latitudes with inclined magnetic field pushes plasma upward along the magnetic field direction to regions of different neutral composition

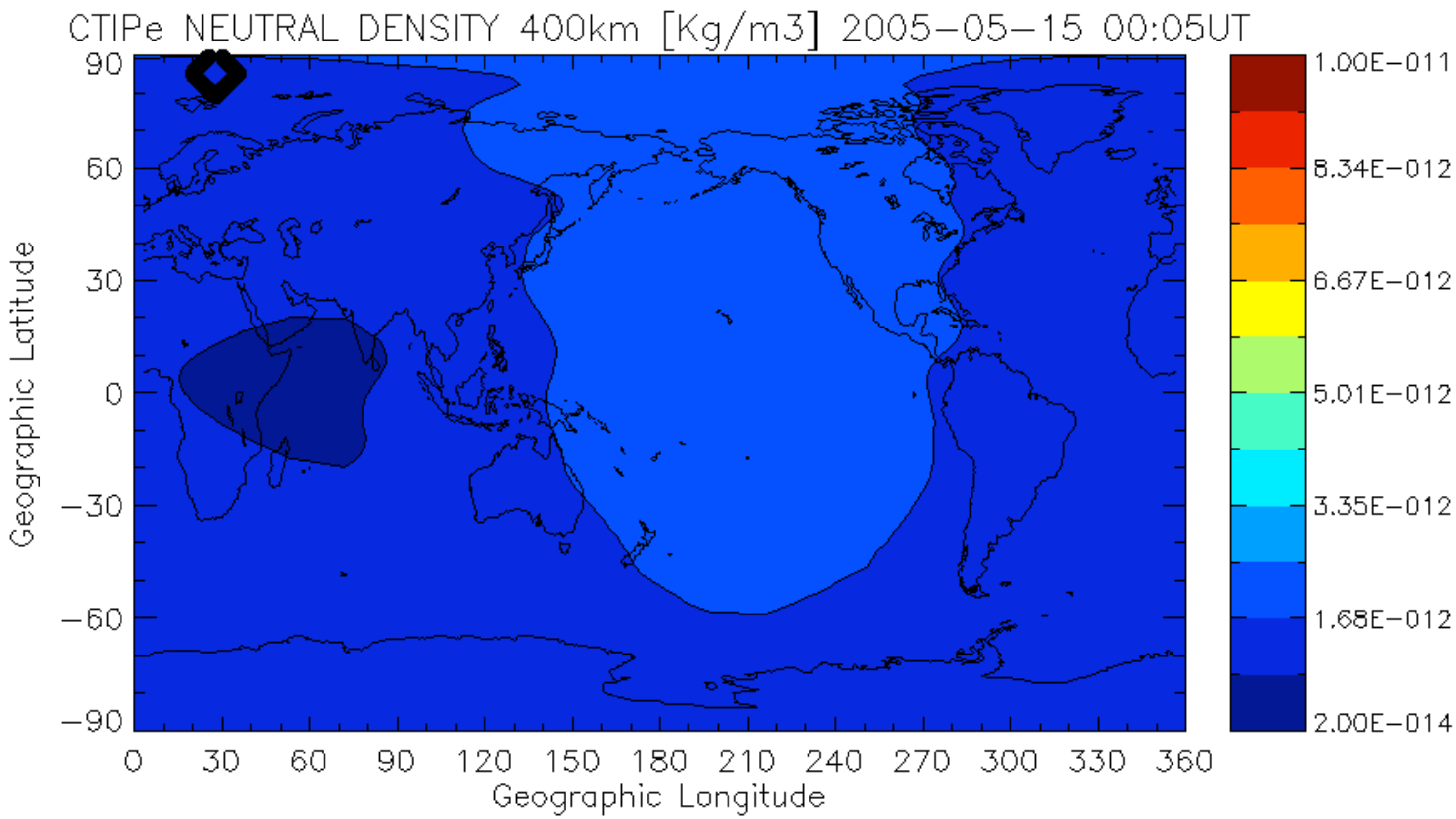


Wind effect on ionosphere at mid-latitudes with inclined magnetic field

- Equatorward wind pushes plasma upward in the direction of the geomagnetic field to regions of less molecular species N_2 and O_2, slowing loss rates, and driving a "positive phase" in the ionosphere
- Thermal expansion creates a vertical wind which can also push plasma along an inclined magnetic field to higher altitudes



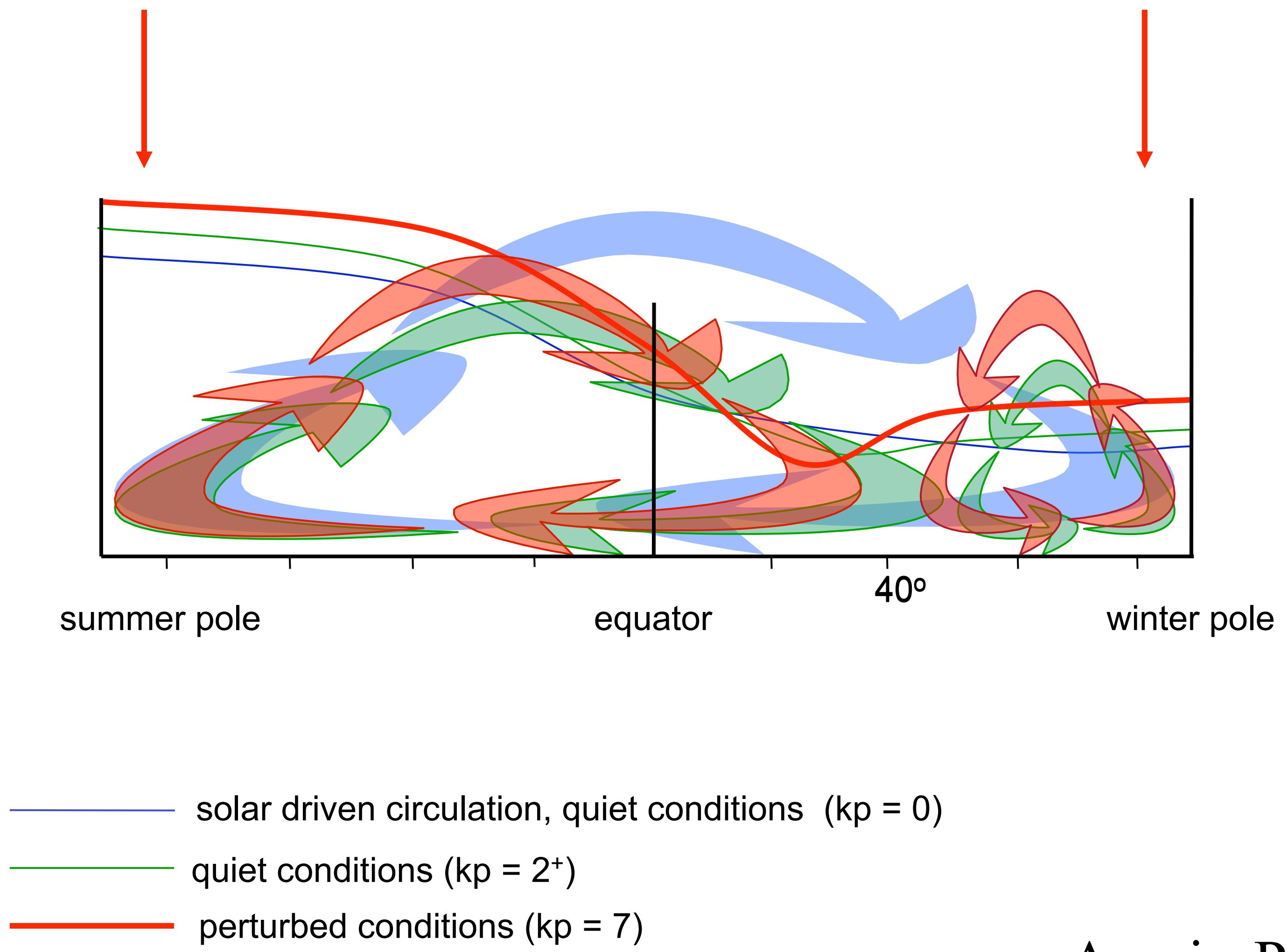
CHAMP vs CTIPe neutral density response May 15th 2005



A few basics on neutral composition change

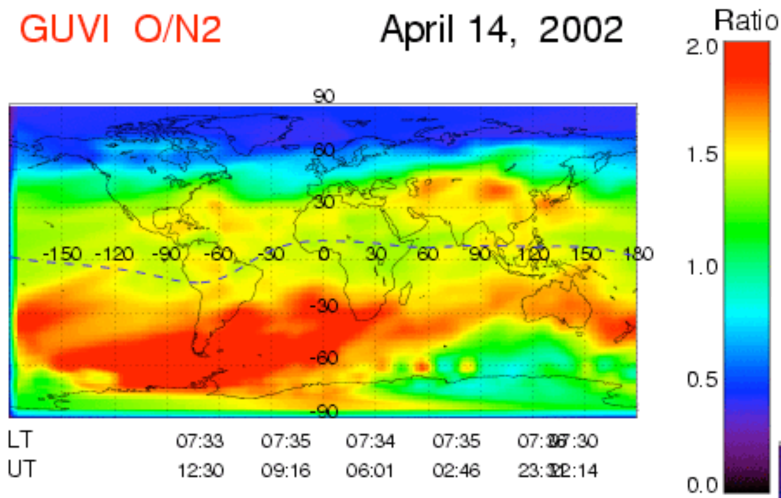
- Hydrostatic equilibrium is not the same as diffusive equilibrium
- Heating the gas and thermal expansion change the ratio of neutral species (O/N_2) on height levels
- Heating and thermal expansion does not change the ratio of neutral species (O/N_2) on pressure surfaces
- Pressure surfaces are important because they represent layers of constant optical depth or level of deposition of an ionizing photon or electron
- "Real" changes in neutral composition is caused by upwelling through pressure surfaces, which is driven by divergence of horizontal winds

Global circulation

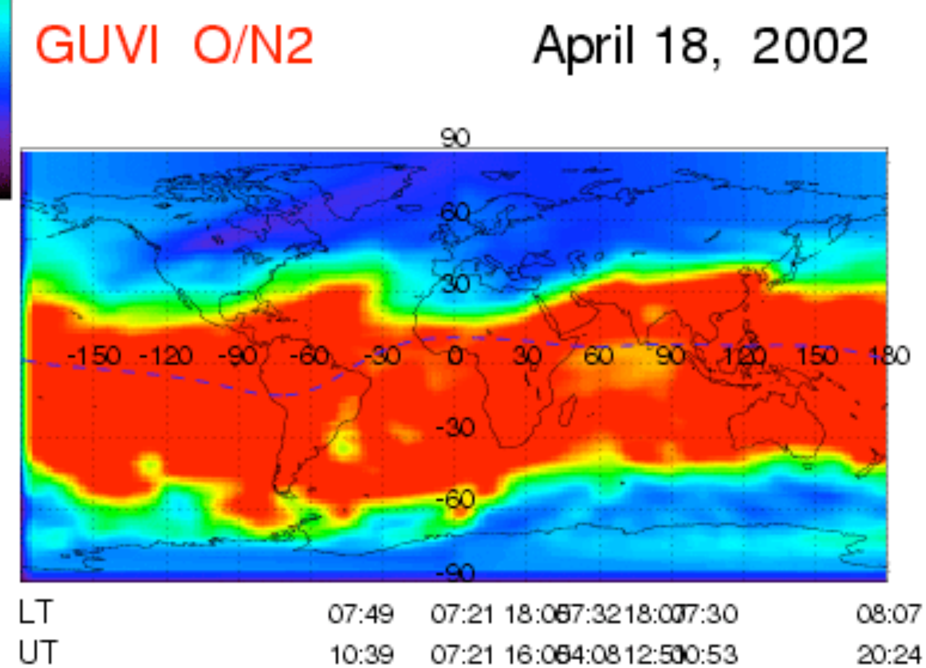


Araujo-Pradere et al

Global neutral composition structure looks more like equinox as high latitude heating begins to dominate

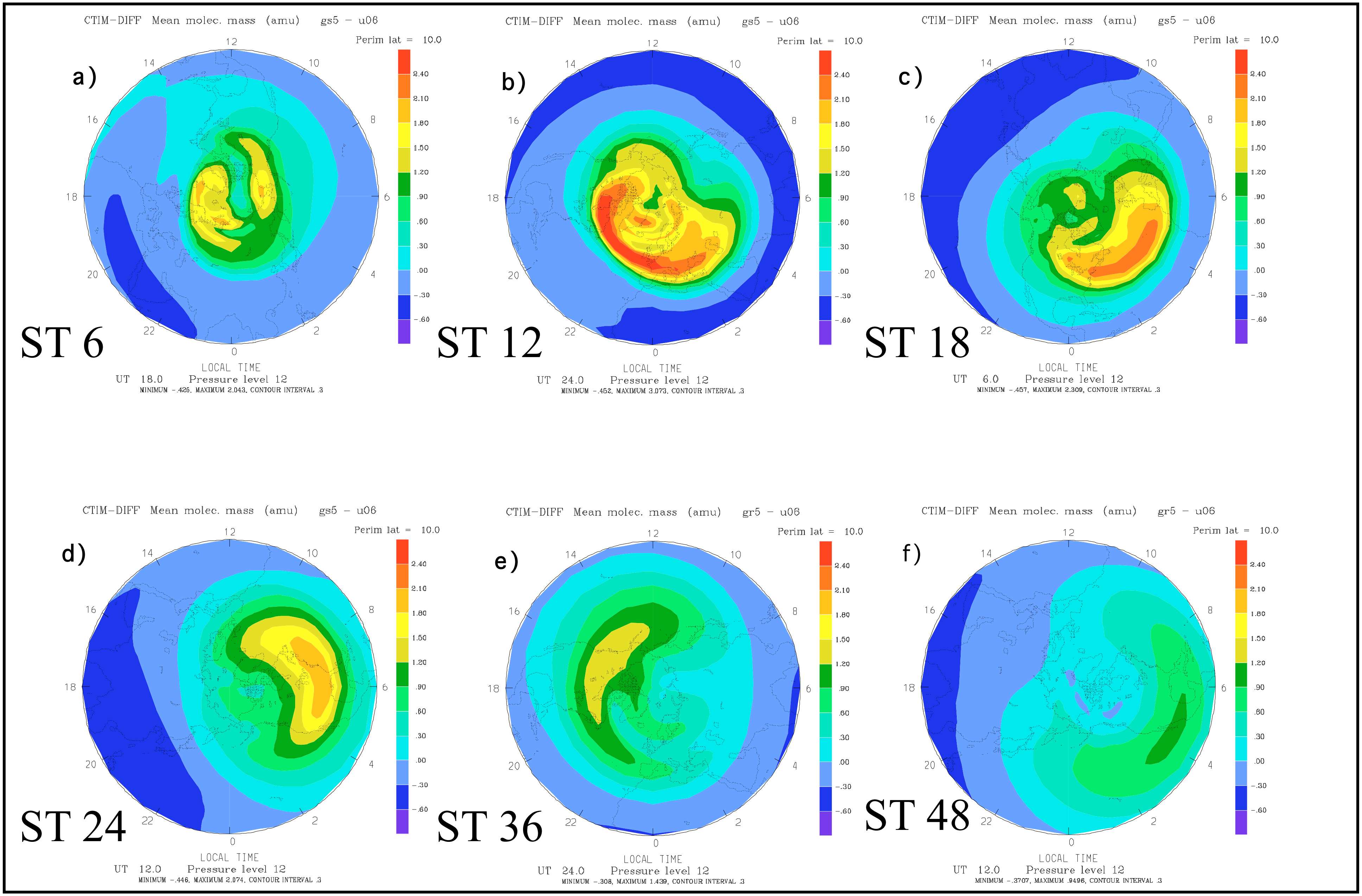


Ratio of height integrated O and N_2



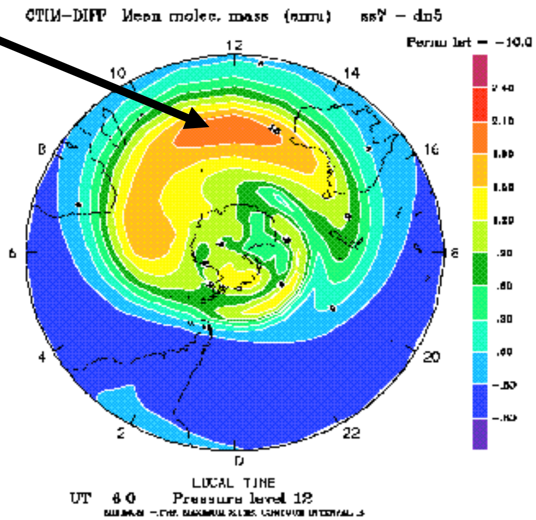
GUVI/TIMED

Composition transport at solstice

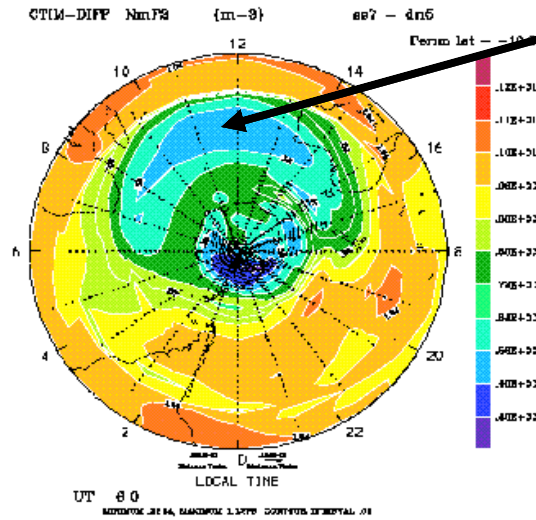


At mid-latitudes: can be high correlation between composition changes and ion density

Increase in N_2

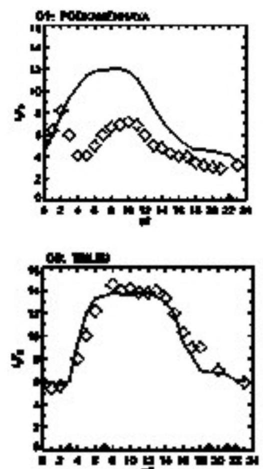


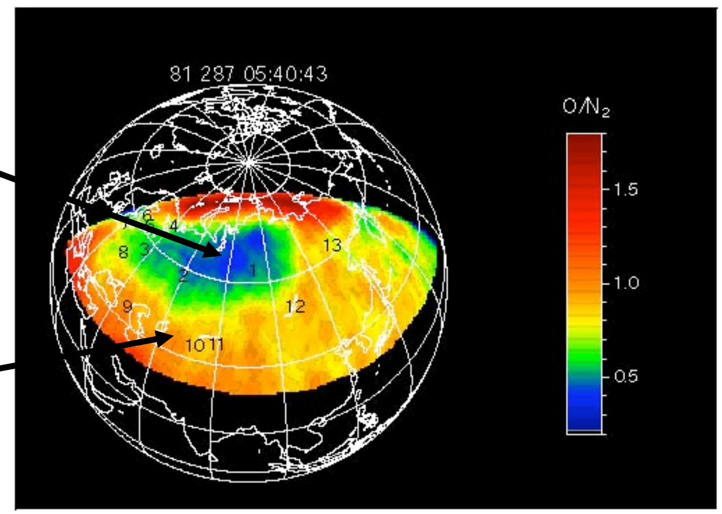
Ionospheric depletion



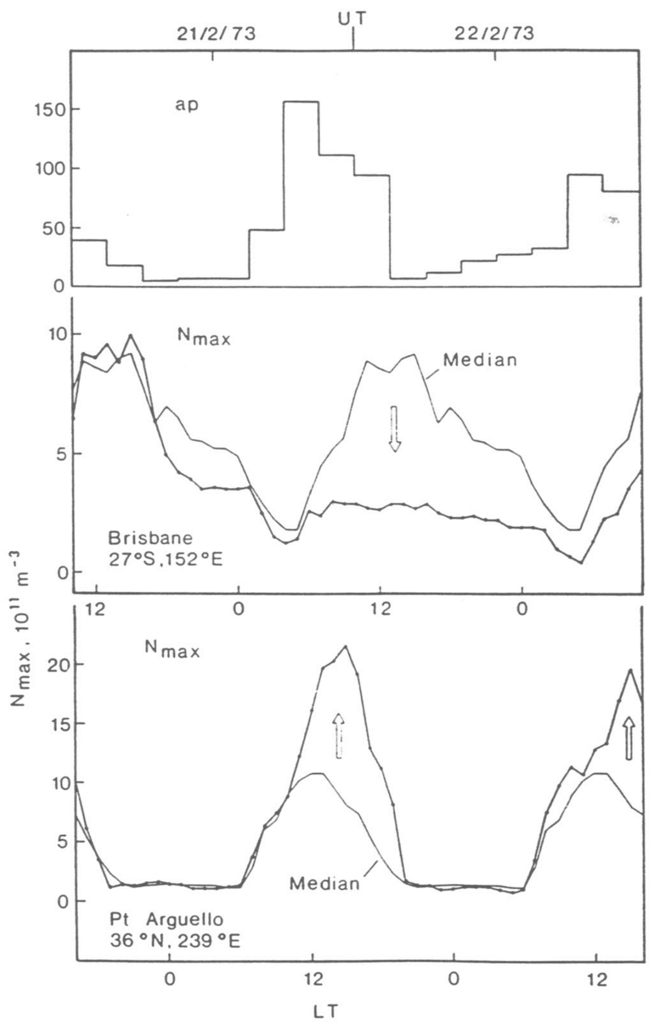
Modeling

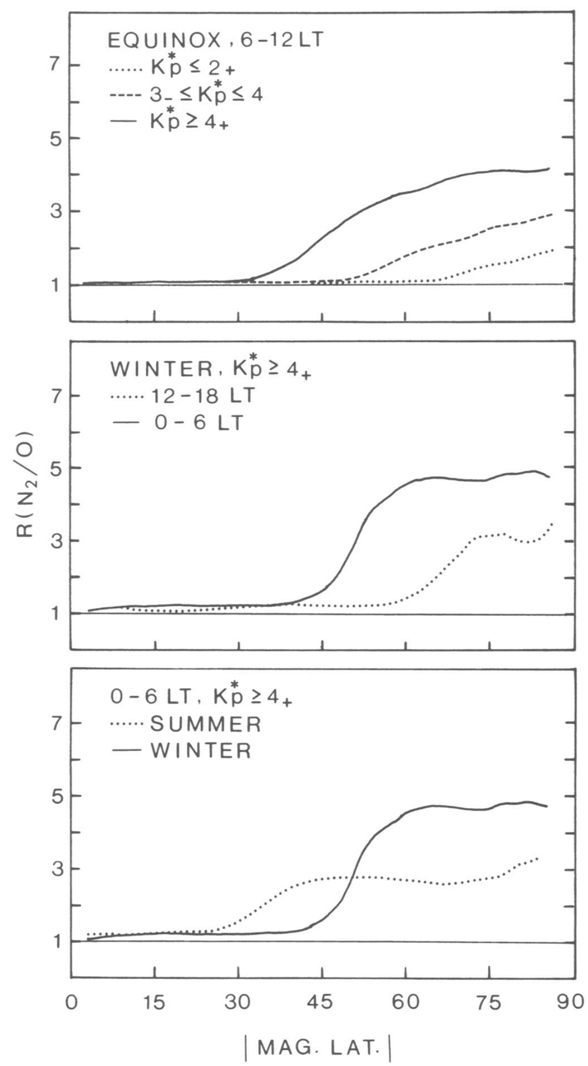
Observations





Neutral composition and positive and negative ionospheric phases



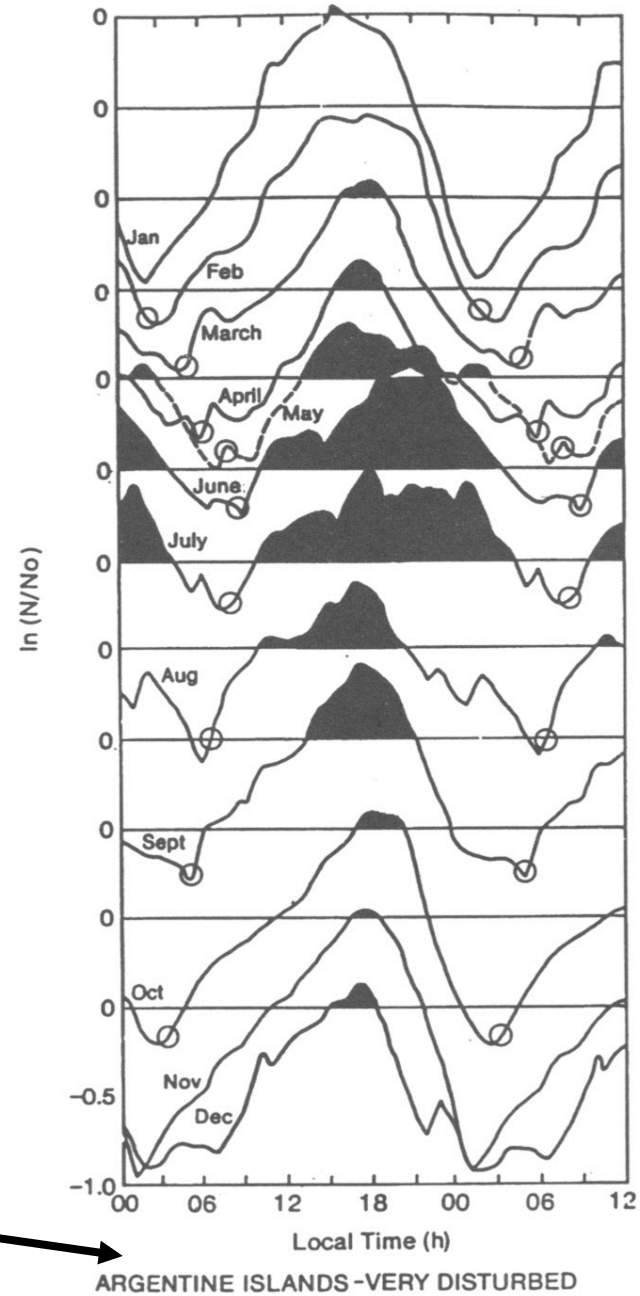


Prölss 1997

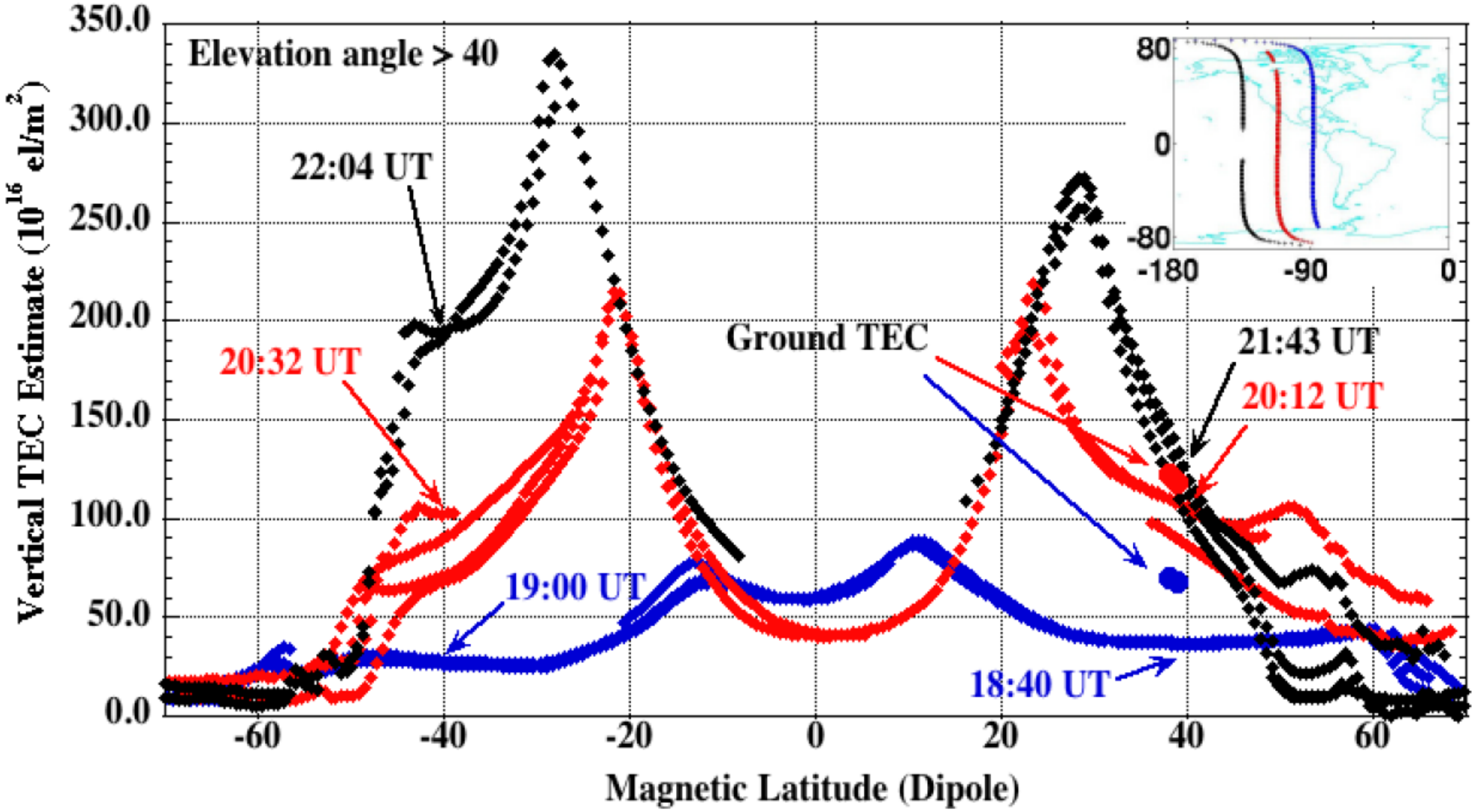
Seasonal/local time variation in ionospheric response at mid-latitudes
Rodger et al. 1989

- Negative phase peaks in summer
- Positive phase peaks in winter
- Negative phase peaks at dawn
- Positive phase peaks at dusk
- Response to summer/winter seasonal circulation and poleward/equatorward diurnal wind variation

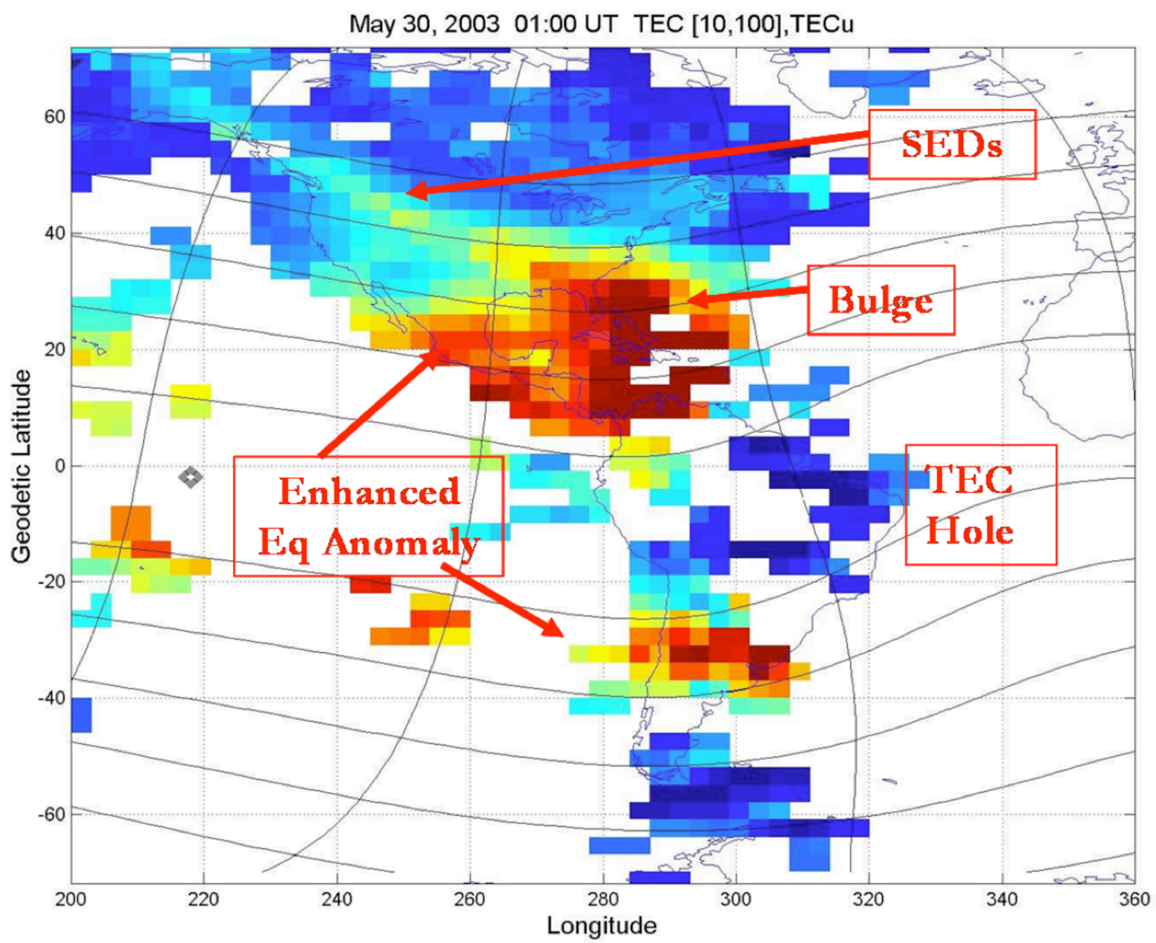
(southern hemisphere mid-latitude station)



“Positive” phase
CHAMP (400 km) OSEC: Halloween
Mannucci et al. 2005



Plasma "bulge" and Storm Enhanced Density



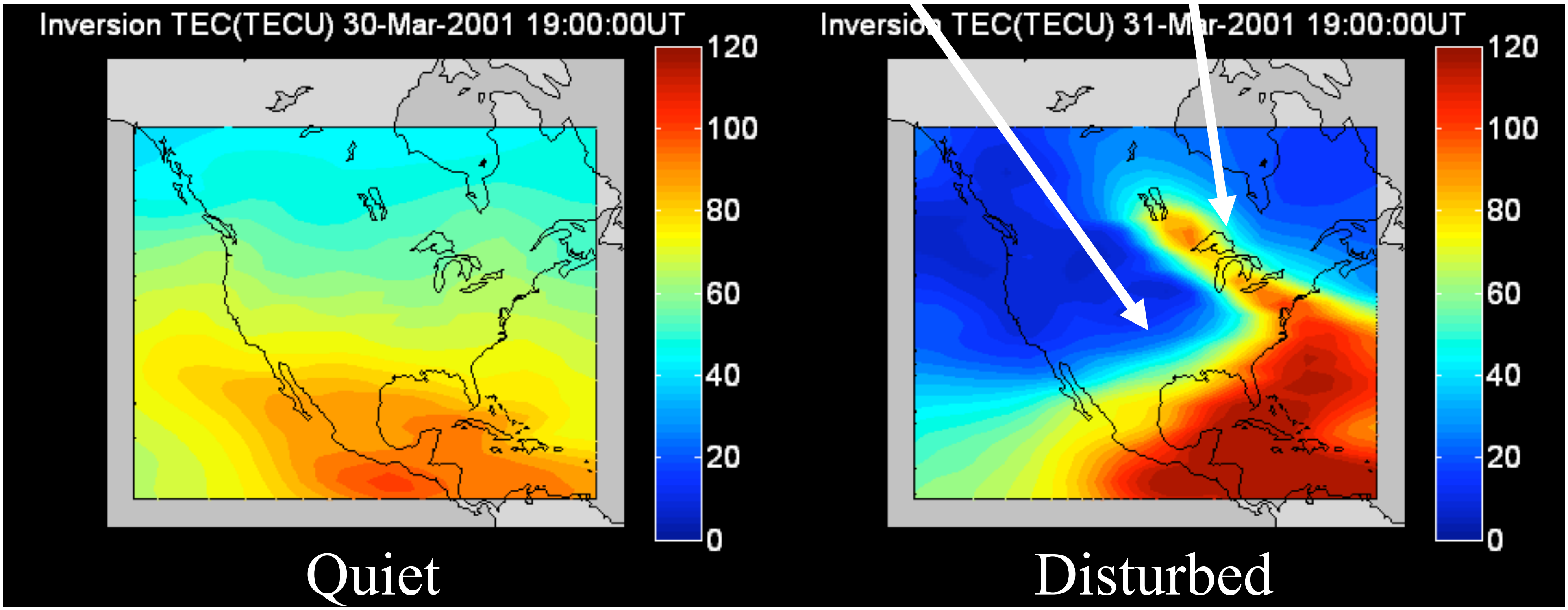
M-I Coupling (cont)

- SAPS/SAID polarization in inner magnetosphere
- penetration electric fields

US-TEC – SWPC
IRI plus data

“positive phase”
and tongue of ionization

“negative phase”



Low latitude ionosphere strongly influenced by electrodynamics

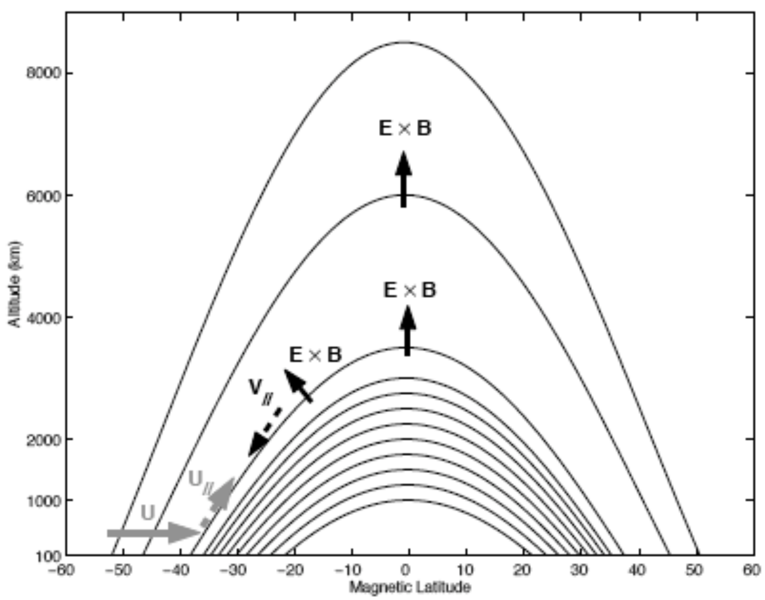


Figure 6. Schematic of the competing effect of the downward field-aligned diffusion and the upward movement of the plasma produced by an equatorward neutral wind at mid latitudes.

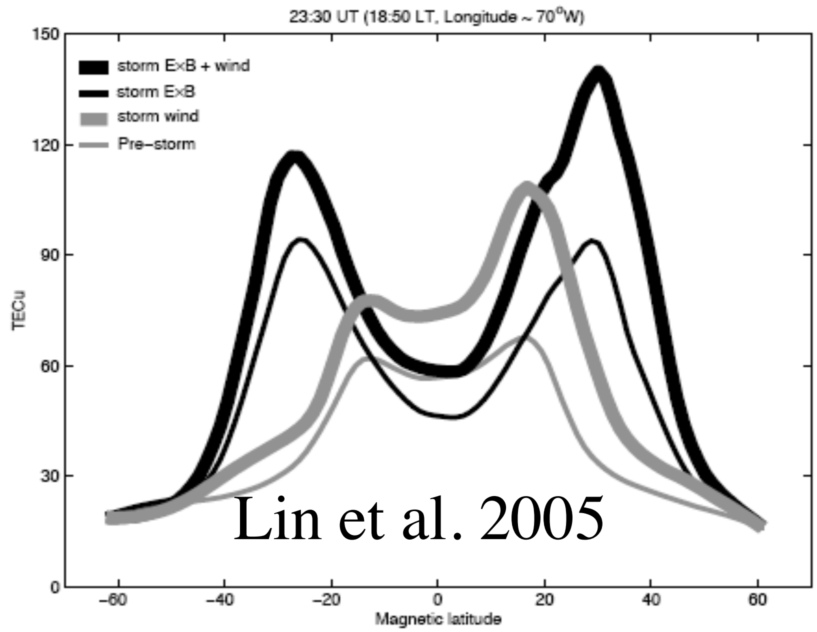
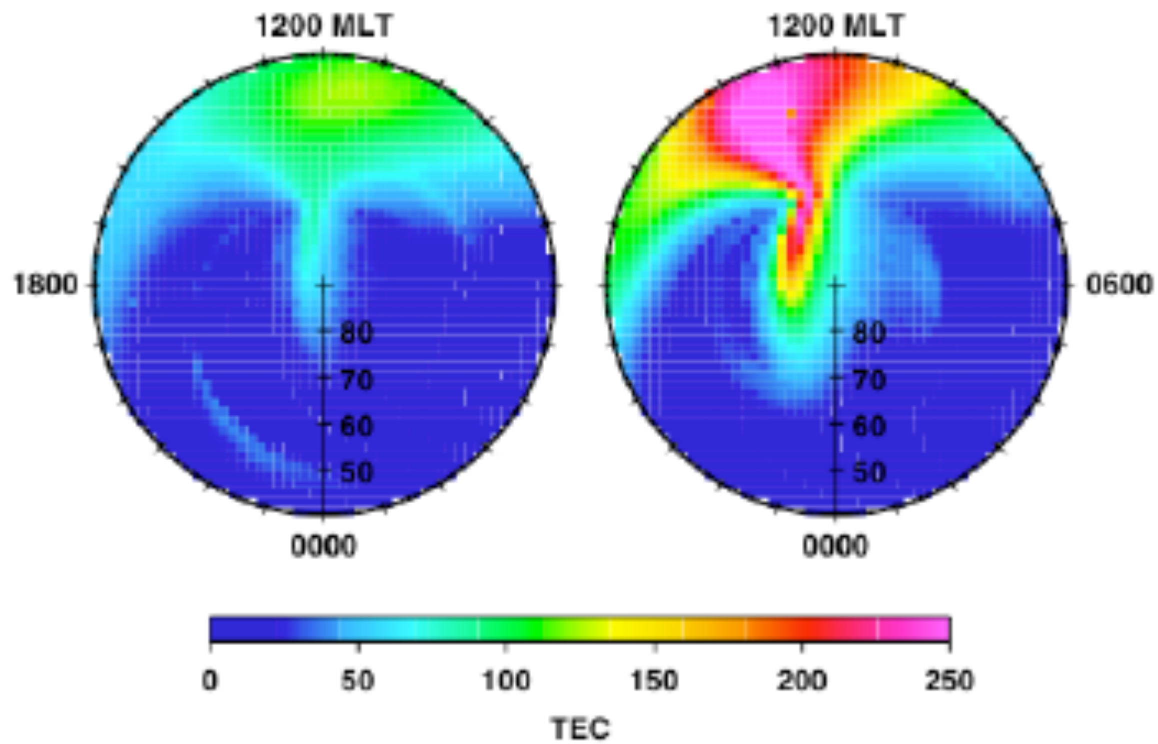


Figure 10. The total electron content (TEC) between altitudes 100 and 2000 km from the SUPIM results at 23:30 UT (18:50 LT) at -70° geographic longitude on the pre-storm day (thin gray line), case 1 (bold gray line), case 2 (thin black line), and the case 3 (bold black line).

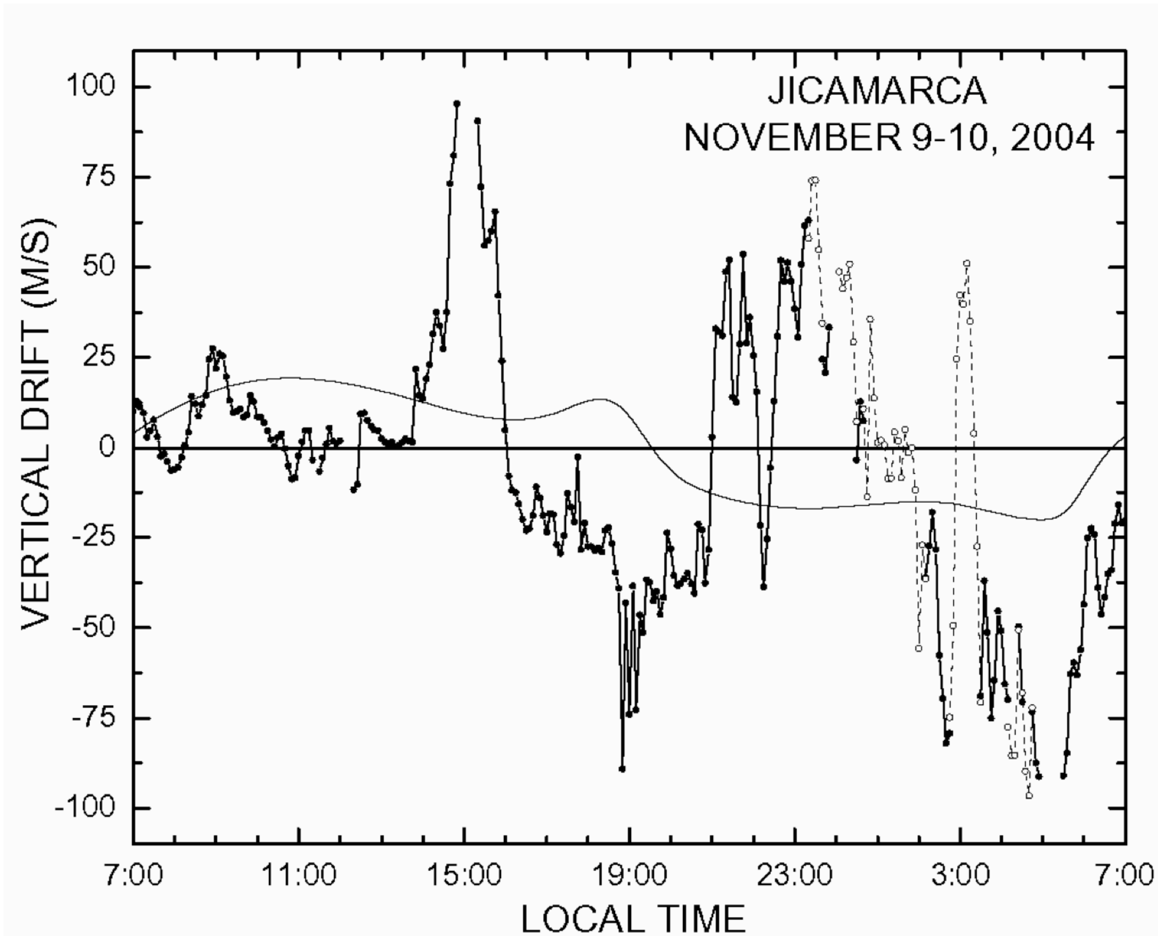
- **What is the relative importance and lifetime of penetration and dynamo electric fields during the different phases of a storm on the day and nightside, and how do they interact?**

Source of plasma "Bulge"
Expanded convection?

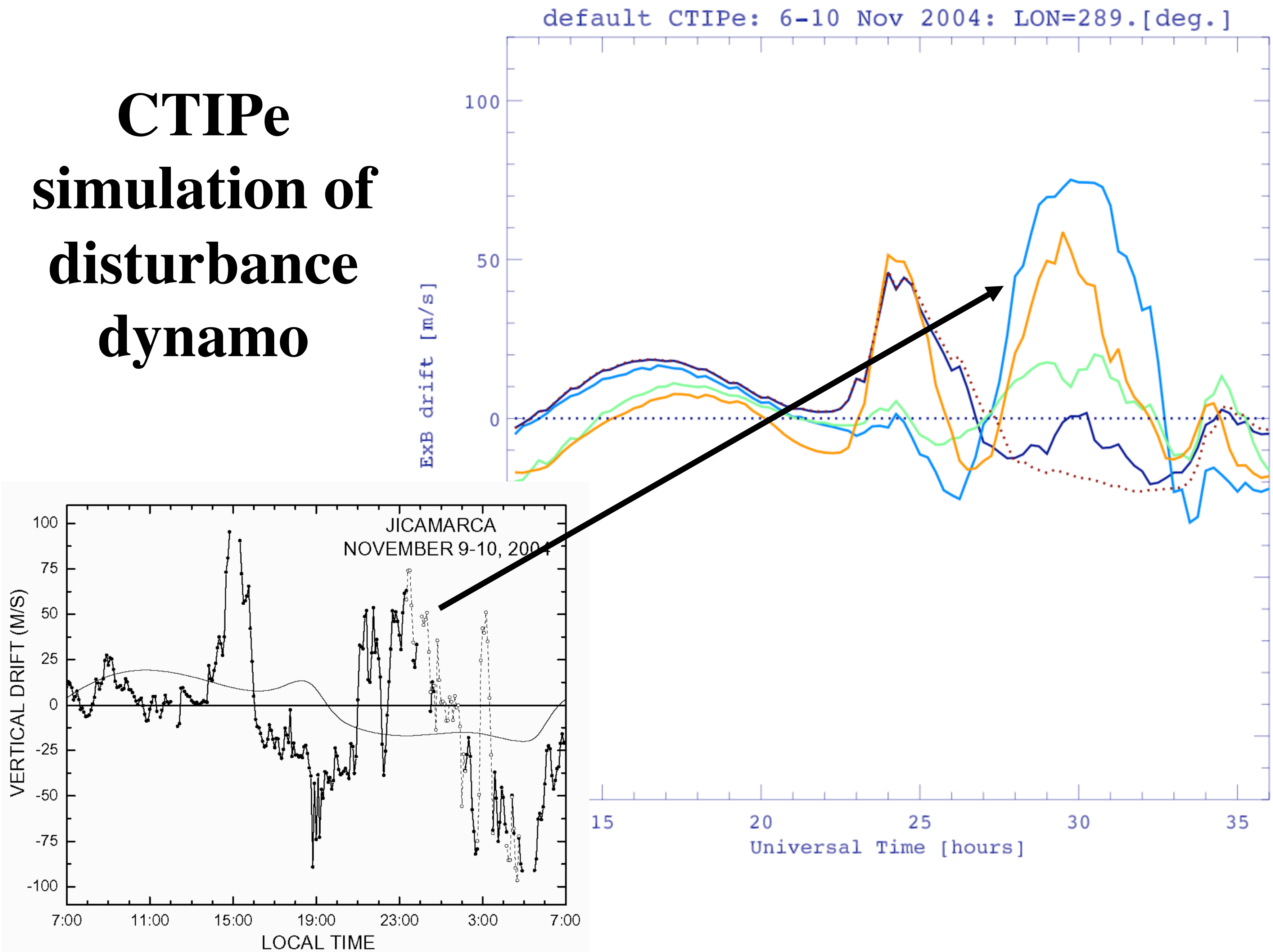


Heelis et al., 2009

Jicamarca vertical drift Nov 9-10, 2004



CTIPe simulation of disturbance dynamo



Storm-Time Electrodynamics: disturbance dynamo

Blanc and Richmond (1980) theory:

•Equatorward winds drive zonal winds at mid-latitude through the action of the Coriolis force
•Zonal winds → equatorward Pedersen current
•Equatorward wind → equatorward Hall current
•Positive charge builds up at the equator producing a poleward directed electric field which balance the wind driven equatorward current
•Eastward Hall current causes +ve charge build up at the dusk terminator and -ve charge build-up at dawn
•Reverse S_q

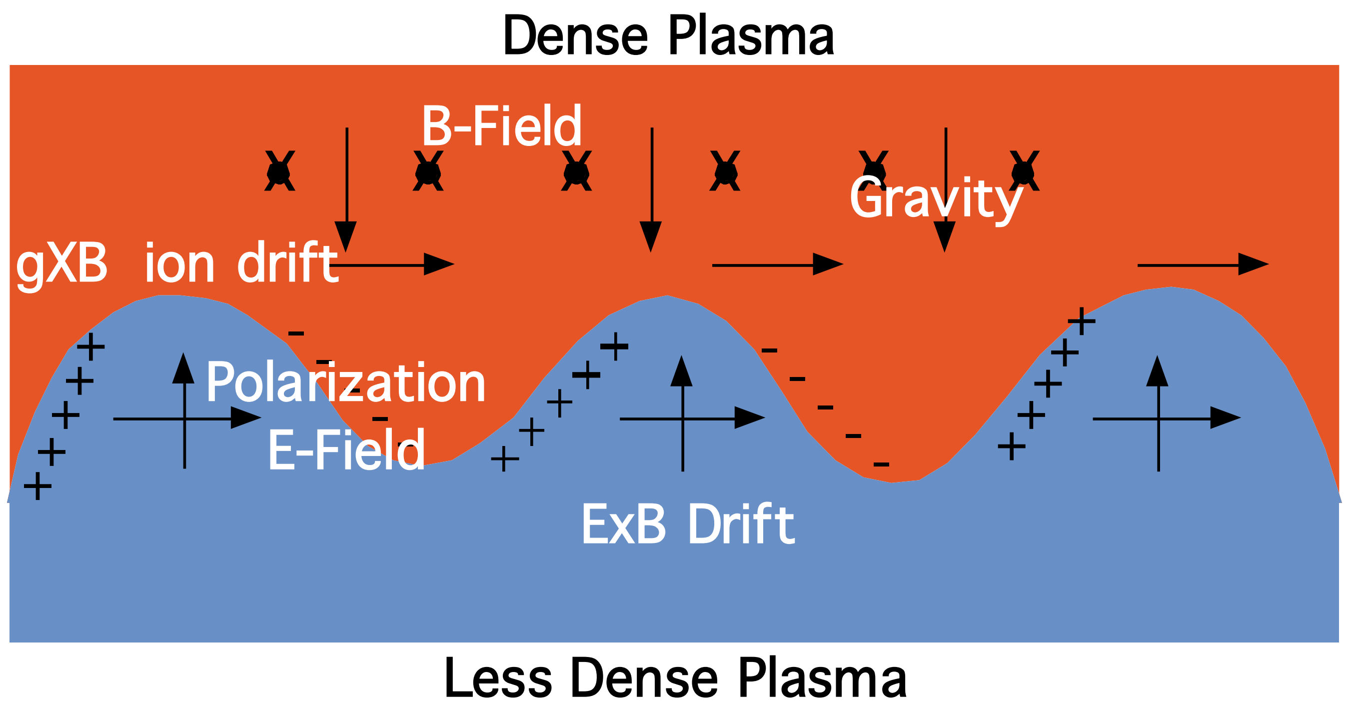
$$J_{\vartheta u} = -\frac{\sigma_1}{\sin I} u_\phi B + \sigma_2 u_\theta B$$

$$J_{\phi u} = \sigma_1 \sin I u_\theta B + \sigma_2 u_\phi B$$

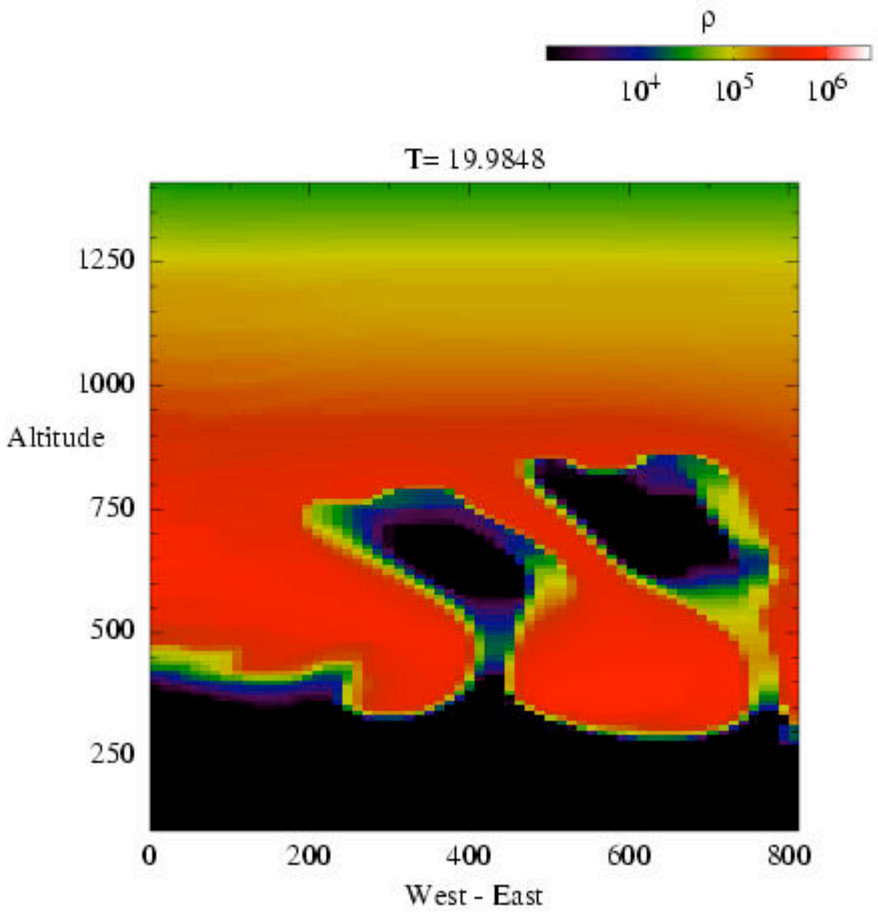
$$J_{\theta E} = \frac{\sigma_1}{\sin I} E_\varepsilon + \frac{\sigma_2}{\sin I} E_\phi$$

$$J_{\phi E} = -\sigma_2 E_\varepsilon + \sigma_1 E_\phi$$

Ionospheric Irregularities



Plasma Bubble Evolution



Mesoscale Model

Describes temporal development of plasma structure

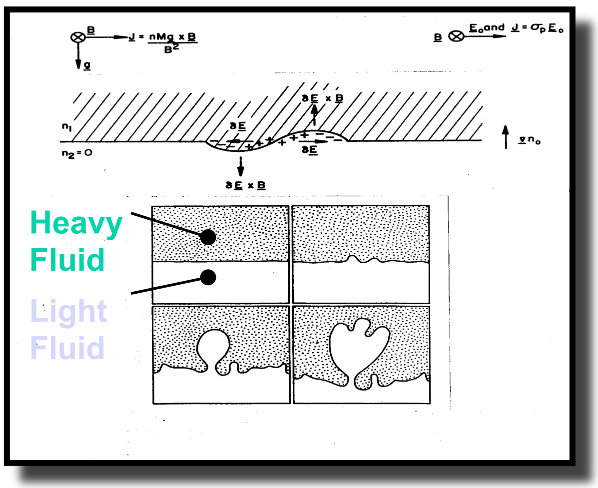
Uses nonlinear continuity and momentum equations

Includes self-consistent electric fields

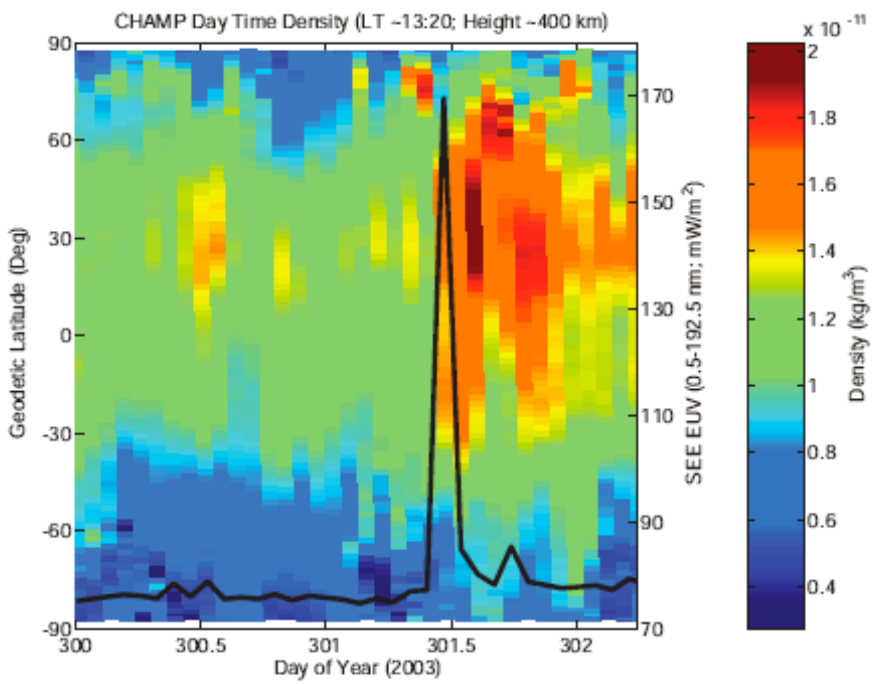
Coupled to ambient background

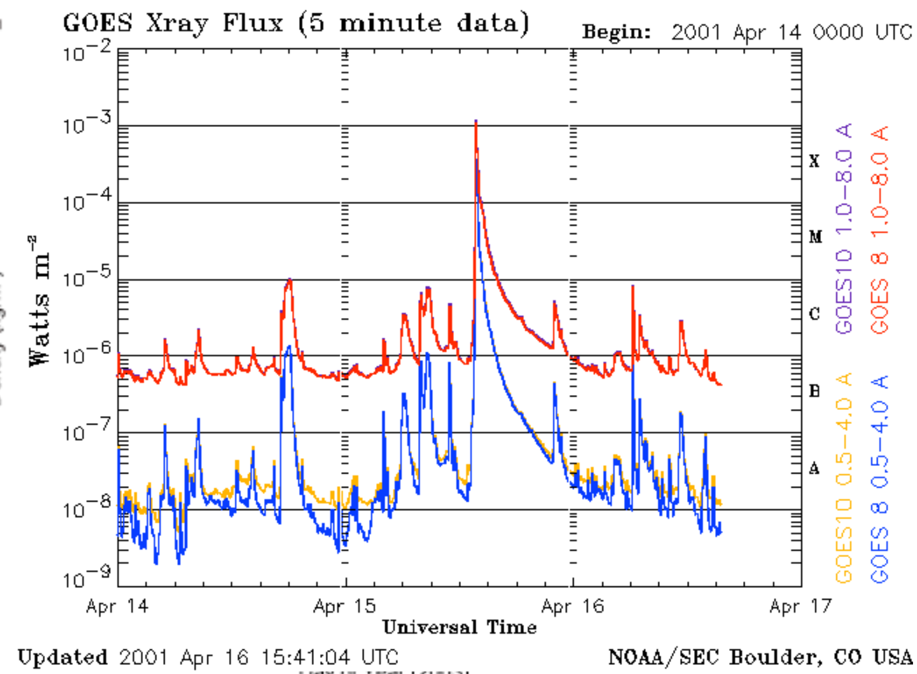
Estimates spectrum of density fluctuations

Retterer (1999)



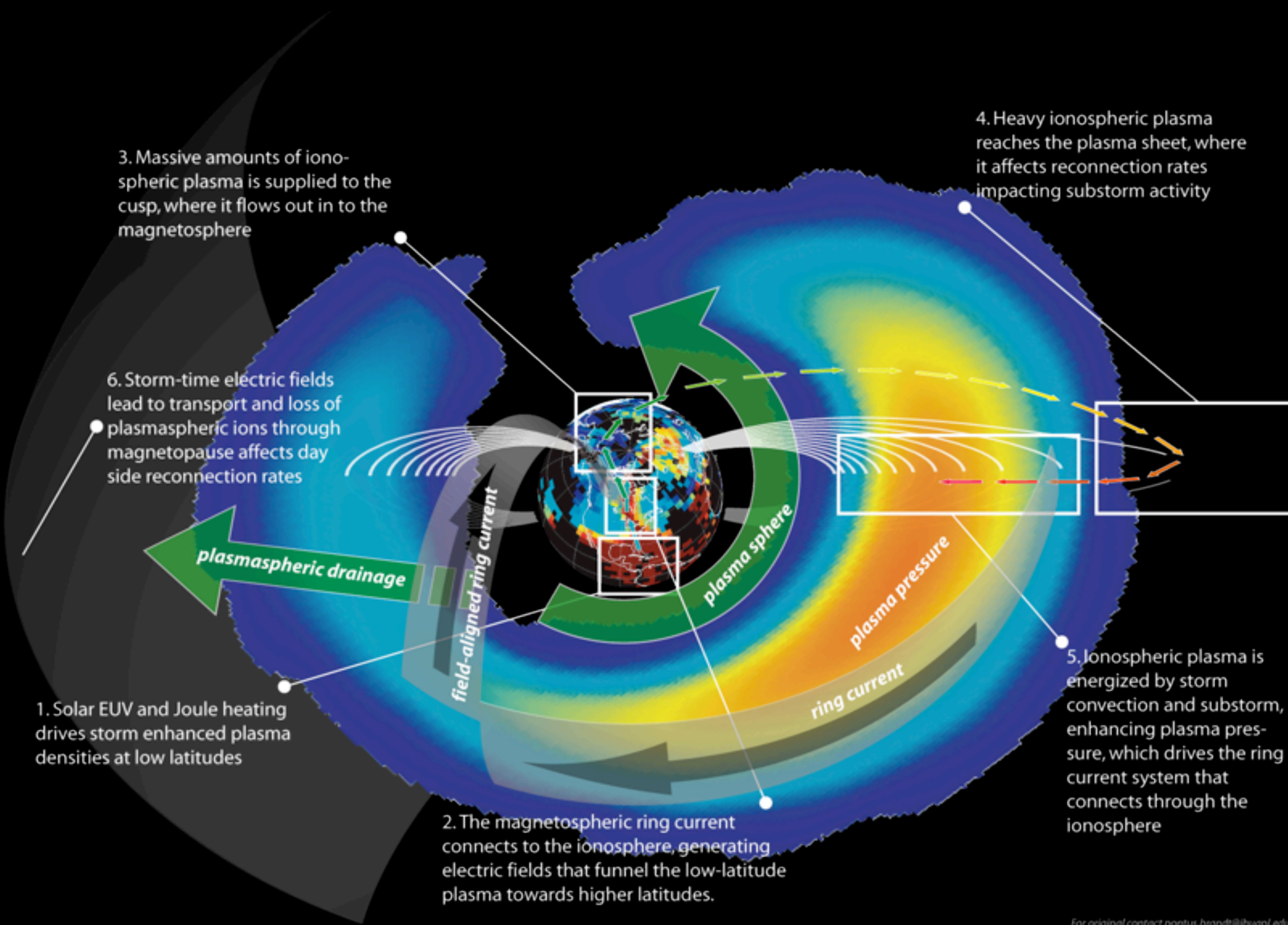
Neutral density response to flares
(Sutton and Forbes)



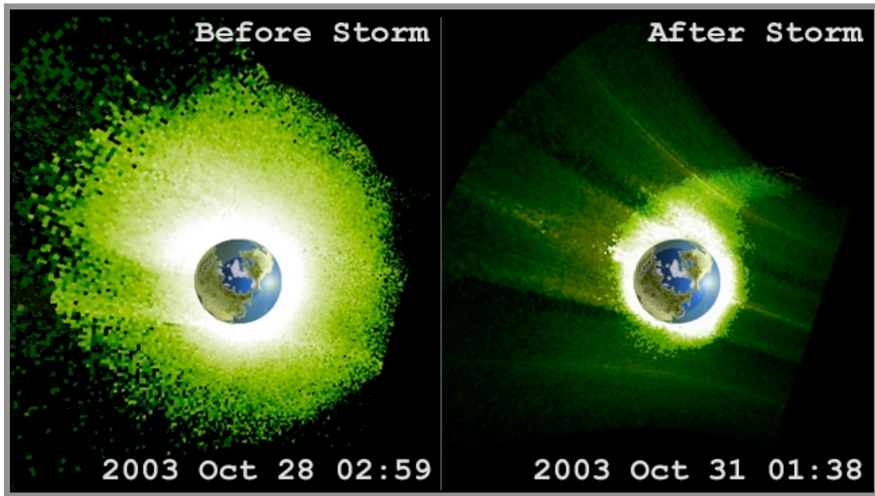


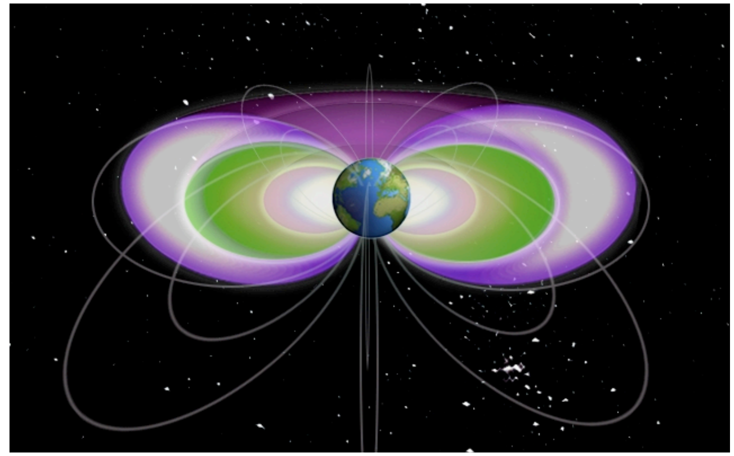
CHAMP satellite data

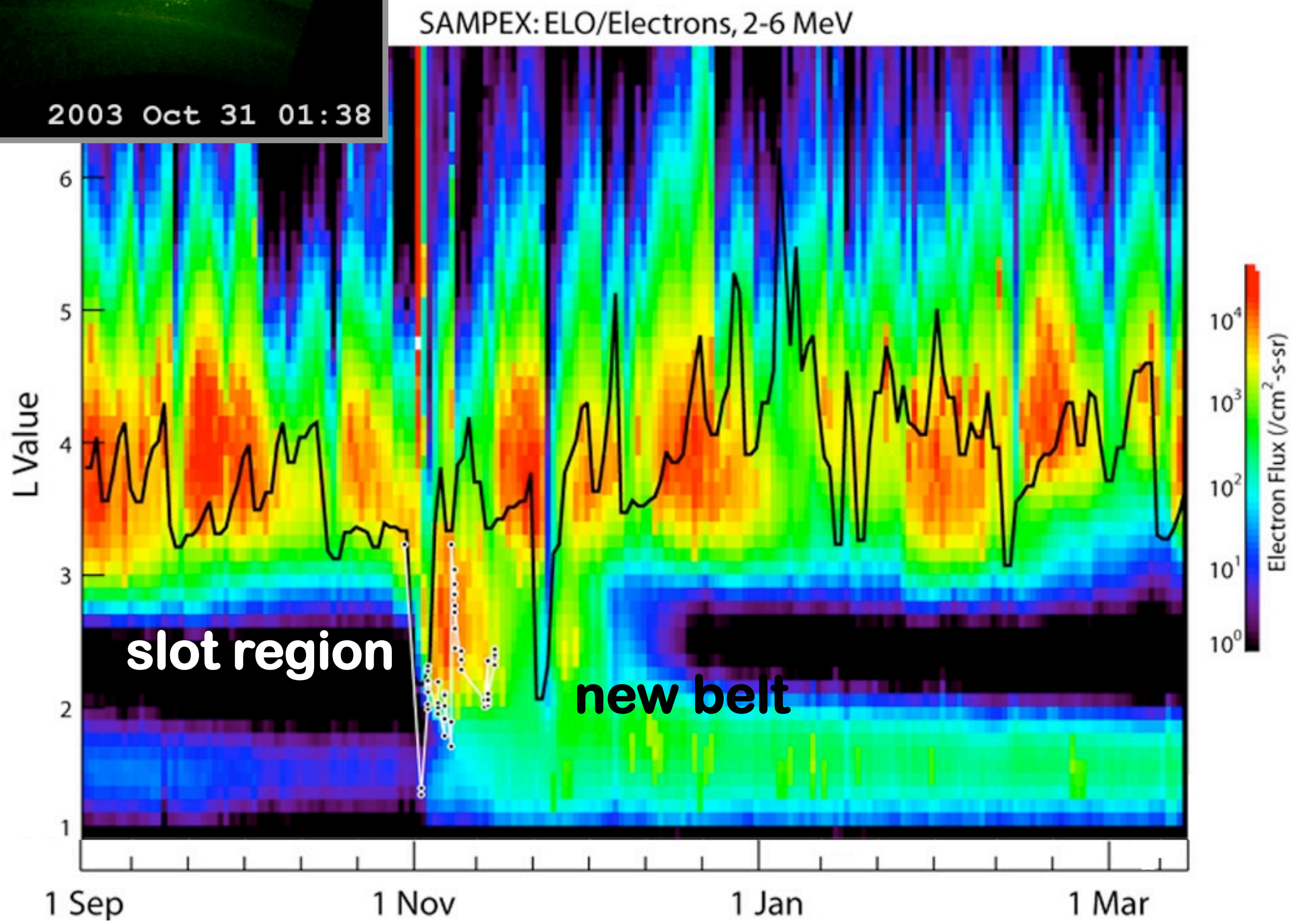
The flow of plasma through geospace



Effect on the Radiation Belts



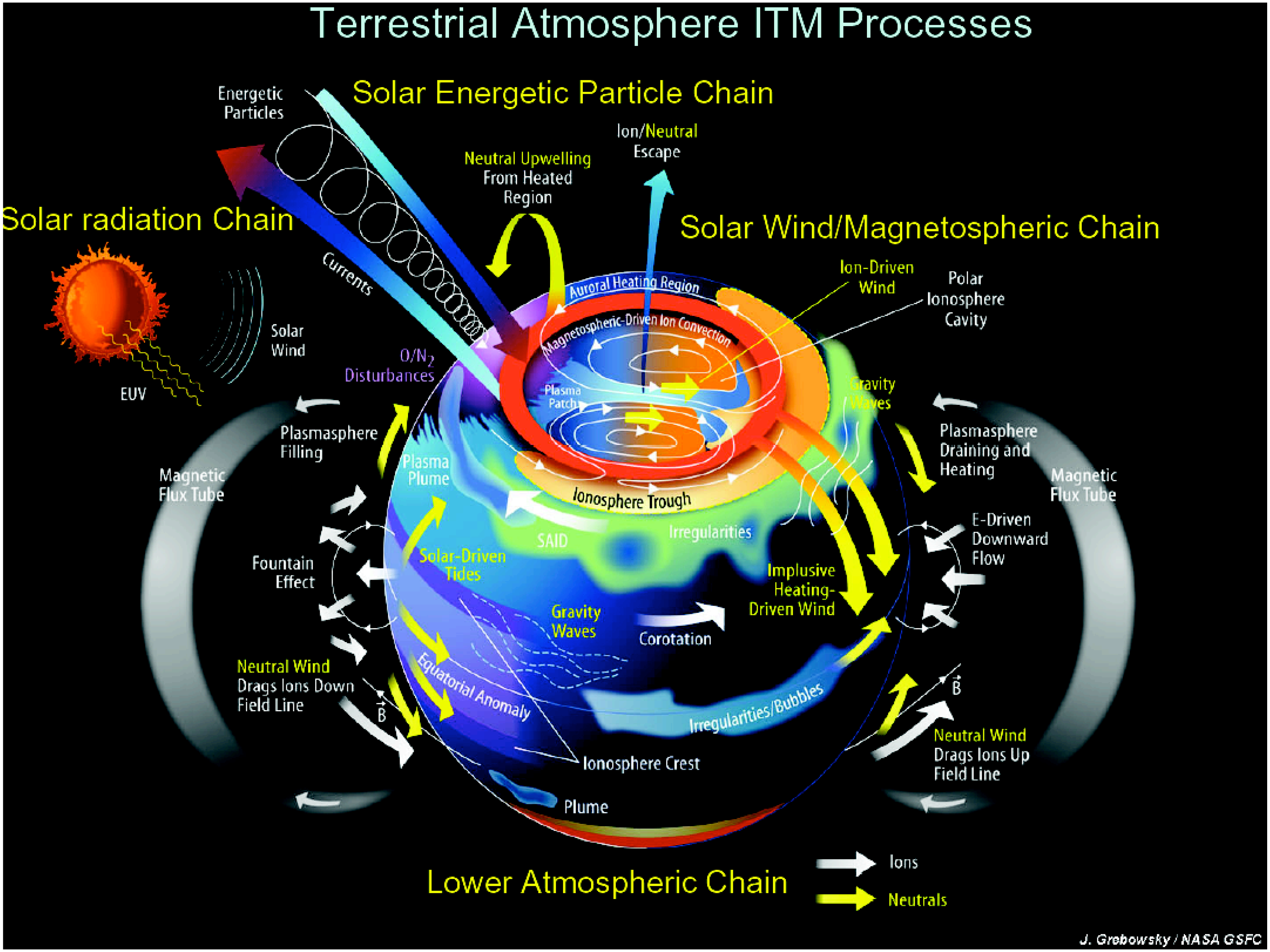




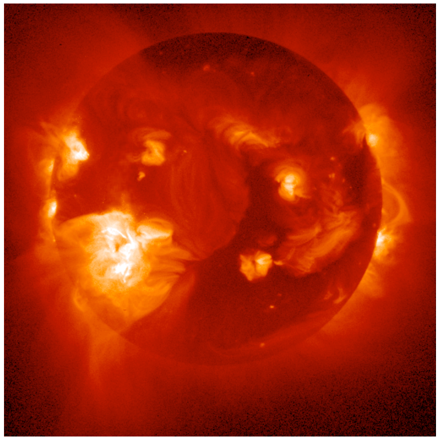
[*Baker et al., 2004, Nature*]

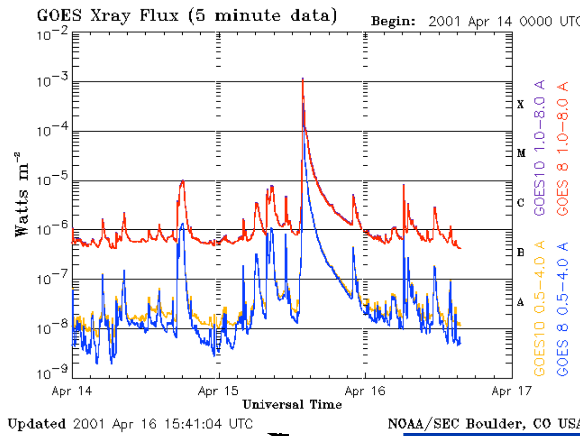
Summary: main points

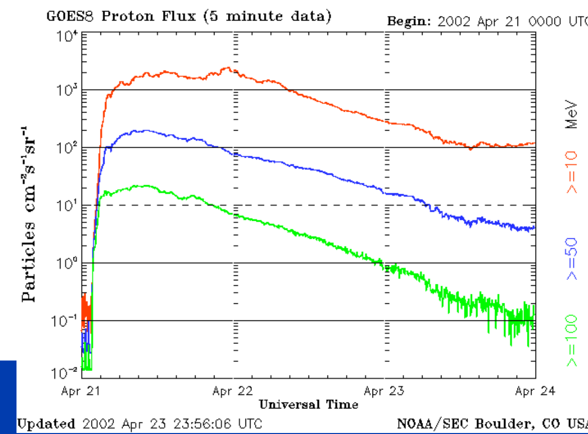
- A multitude of processes are operating in the thermosphere-ionosphere during a geomagnetic storm
- Electromagnetic energy is the dominant source at high latitude
- Neutral dynamic response influence the dissipation and is the conduit for many of the changes that occur in the upper atmosphere during a geomagnetic storm
- At high latitudes, large in-track neutral winds and neutral density holes influence satellite drag
- Neutral composition responds to the storm-time circulation and impacts the ionosphere at mid-latitudes
- Electrodynamic forcing also important at mid and low latitudes - prompt penetration and disturbance dynamo
- We understand many of the physical processes, but their relative importance during the various phases of a storm has yet to be elucidated



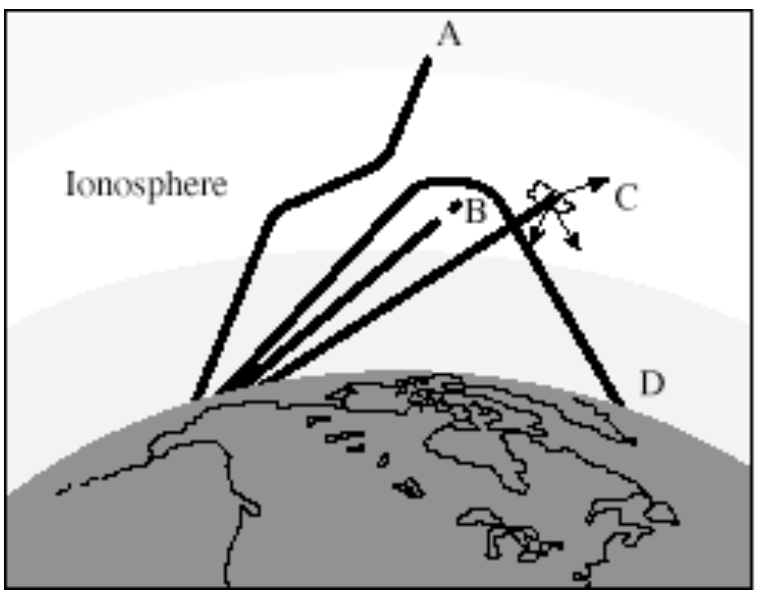
Terrestrial Atmosphere ITM Processes
Solar Energetic Particle Chain
Energetic Particles
Ion/Neutral Escape
Neutral Upwelling From Heated Region
Solar radiation Chain
Solar Wind/Magnetospheric Chain
Currents
Auroral Heating Region
Magnetospheric-Driven Ion Convection
Ion-Driven Wind
Polar Ionosphere Cavity
Solar Wind
EUV
O/N2 Disturbances
Plasma Patch
Gravity Waves
Plasmasphere Filling
Plasma Plume
Plasmasphere Draining and Heating
Magnetic Flux Tube
Magnetic Flux Tube
Ionosphere Trough
SAID
Irregularities
E-Driven Downward Flow
Fountain Effect
Solar-Driven Tides
Implusive Heating-Driven Wind
Gravity Waves
Corotation
Neutral Wind Drags Ions Down Field Line
Equatorial Anomaly
Irregularities/Bubbles
Neutral Wind Drags Ions Up Field Line
Ionosphere Crest
Plume
Lower Atmospheric Chain
Ions
Neutrals
J. Grebowsky / NASA GSFC

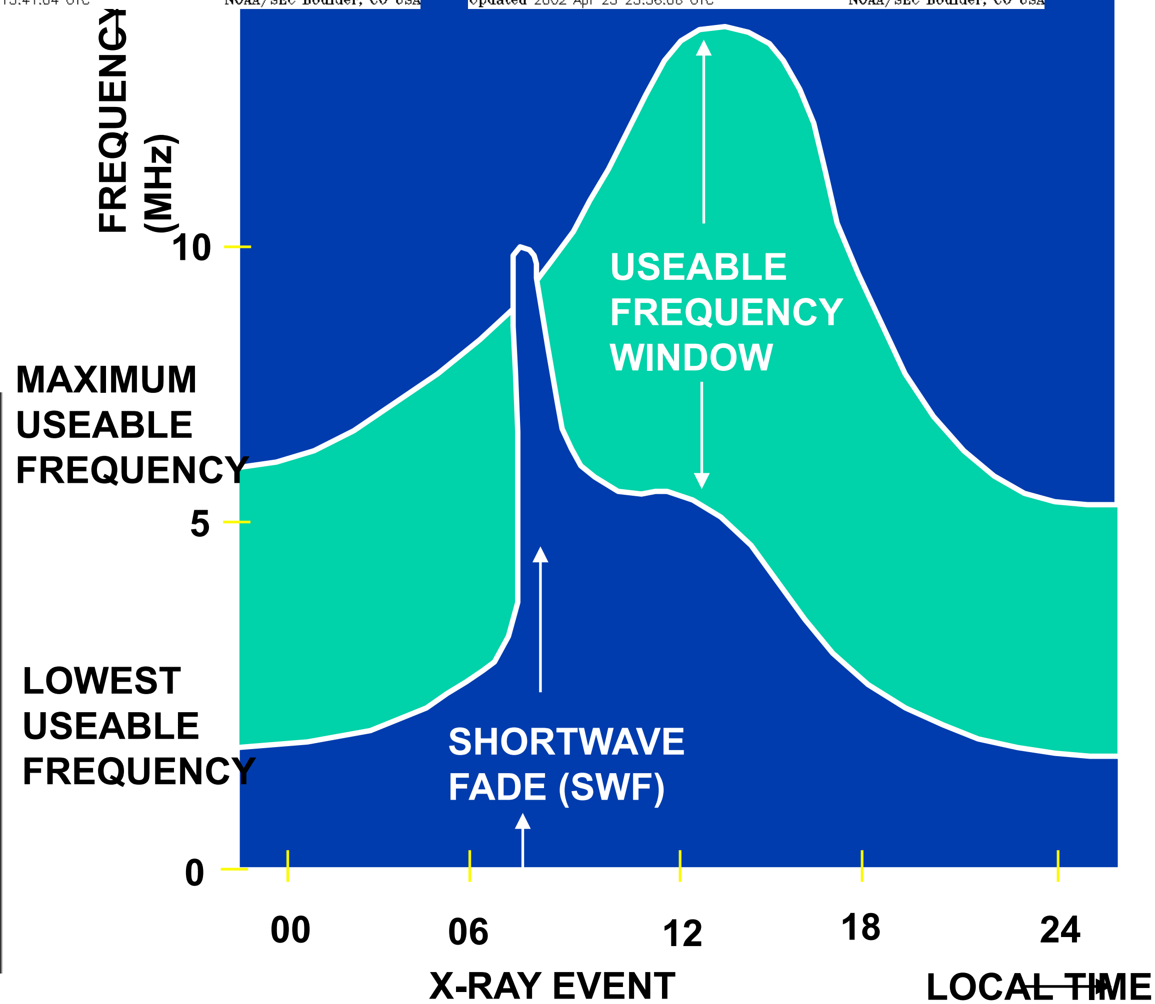


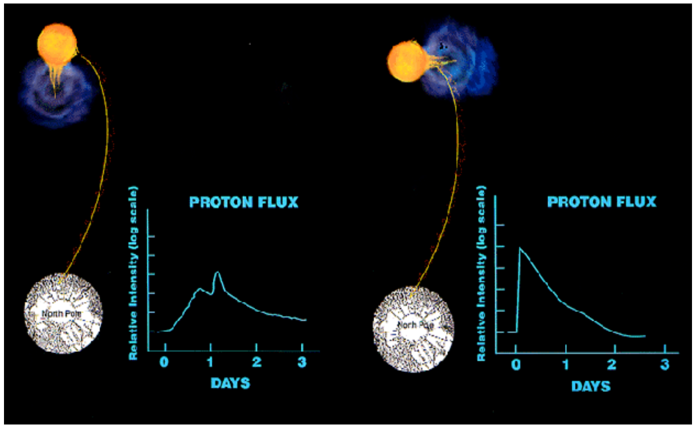


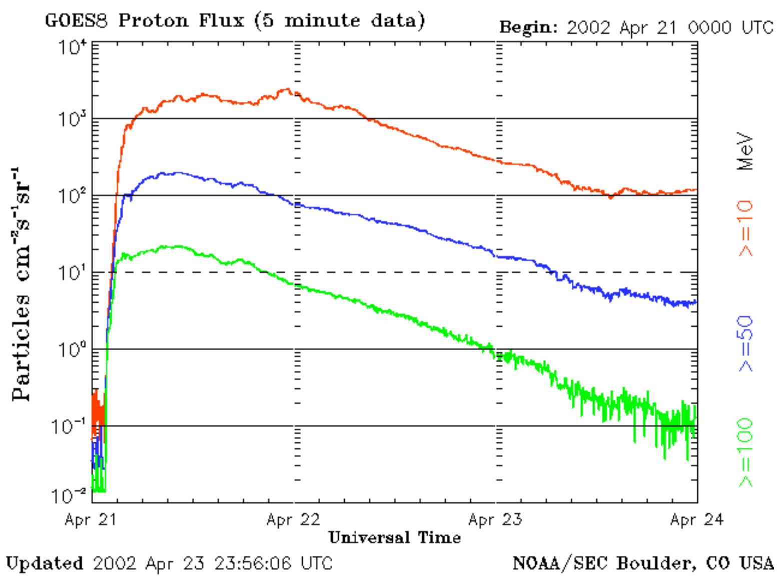


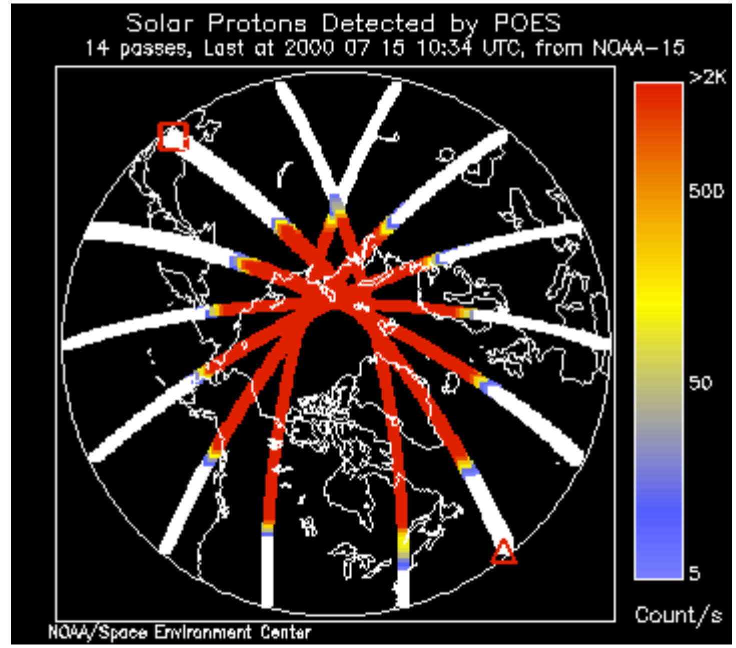
Flares and SPE:
HF Absorption
Radio Blackout

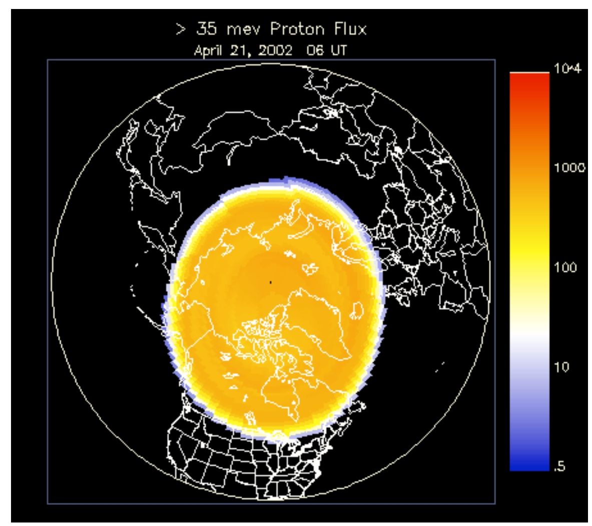





PROTON FLUX
Relative Intensity (log scale)
0
1
2
3
DAYS
PROTON FLUX
Relative Intensity (log scale)
0
1
2
3
DAYS


GOES8 Proton Flux (5 minute data)
Begin: 2002 Apr 21 0000 UTC
Particles cm⁻²s⁻¹sr⁻¹
MeV
>=10
>=50
>=100
Apr 21
Apr 22
Apr 23
Apr 24
Universal Time
Updated 2002 Apr 23 23:56:06 UTC
NOAA/SEC Boulder, CO USA


Solar Protons Detected by POES
14 passes, Last at 2000 07 15 10:34 UTC, from NOAA-15
>2K
500
50
5
Count/s
NOAA/Space Environment Center


> 35 mev Proton Flux
April 21, 2002 06 UT
1000
100
10
.5