Magnetospherically-Generated Ionospheric Electric Fields

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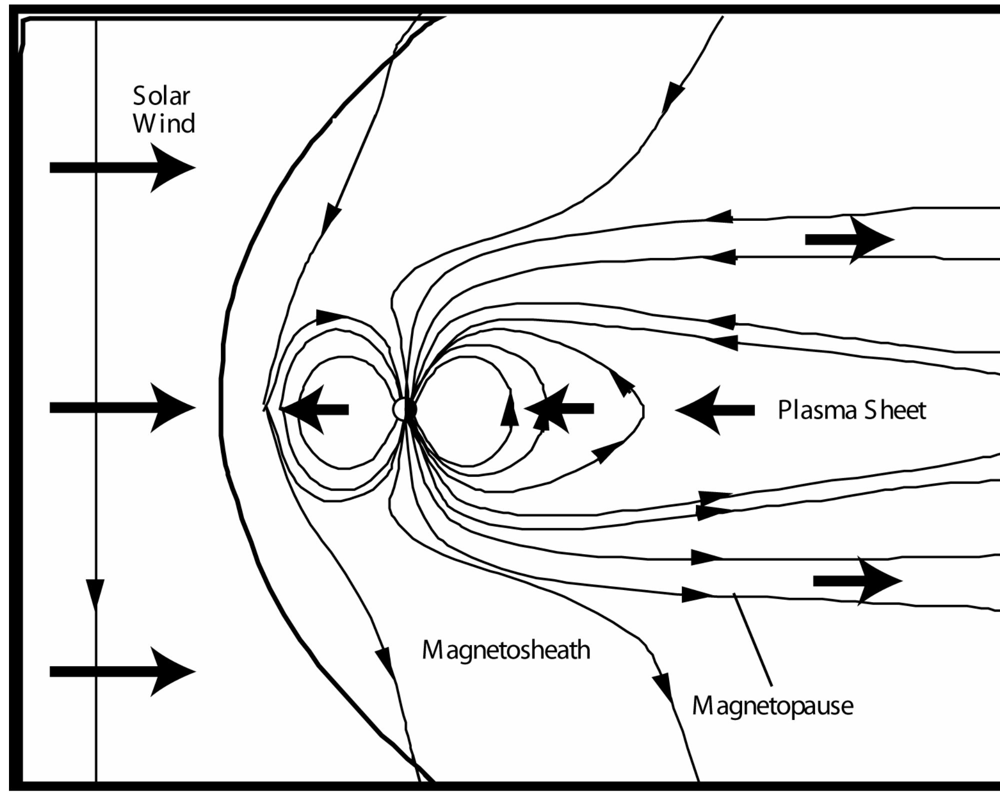
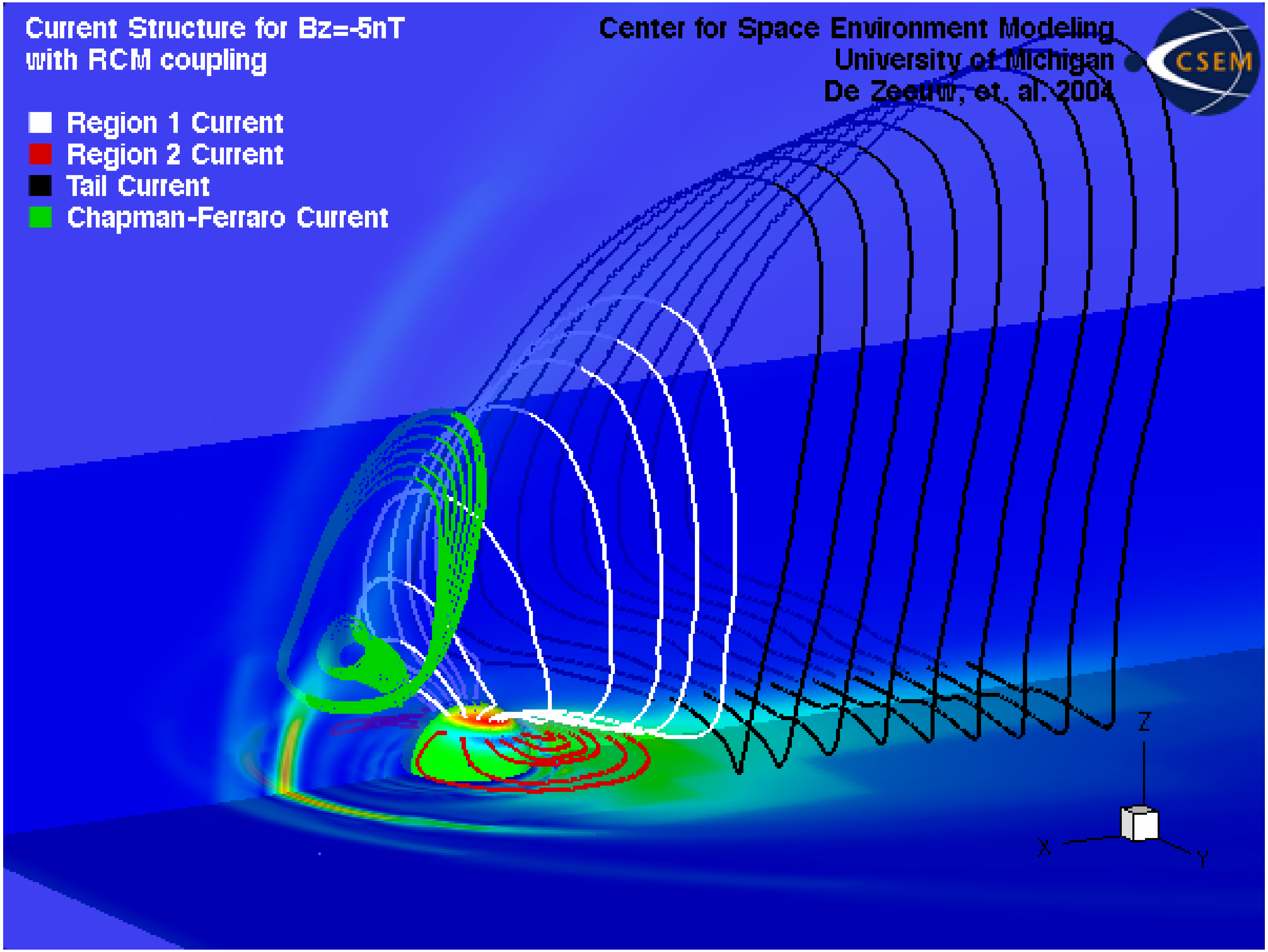
Overall Magnetospheric Flow Pattern

- Fine lines with arrows are magnetic field lines.
- Thick arrows are flow velocities.
- Overall flow is antsunward in outermost magnetosphere, sunward in interior.
  - Called “magnetospheric convection”

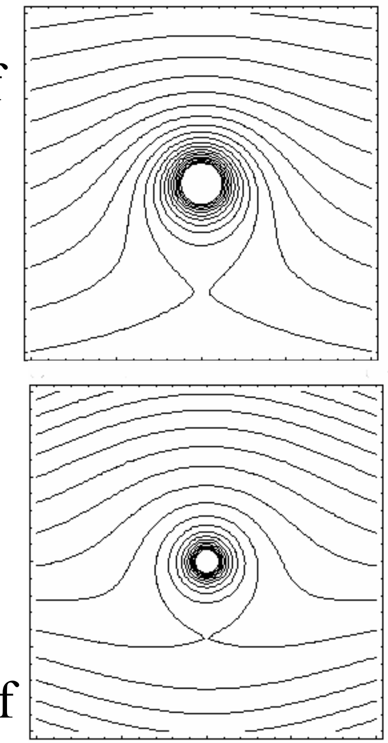



Current Structure for Bz=-5nT
with RCM coupling
Region 1 Current
Region 2 Current
Tail Current
Chapman-Ferraro Current
Center for Space Environment Modeling
University of Michigan
De Zeeuw, et. al. 2004
CSEM
Z
X
Y

What's to come

- Convection E-field from ionospheric point of view
  - No neutral wind effects
  - Inner Magnetosphere = Subauroral Ionosphere (coupling along B-field)
- What laws govern magnetospheric generators of inner magnetospheric **E**?
- Shielding of the Inner Magnetosphere from convection E-field
  - Basic Physics
  - Overshielding
  - Undershielding
- Subauroral Polarization Streams (opposite of shielding)

Magnetospherically Driven Inner-Magnetospheric Electric Fields



- The large-scale electric field in the magnetosphere is that of magnetospheric convection.
  - Simplest approximation:

$$\Phi = -E_o y - \frac{B_o \omega_E R_E^3}{r}$$

Uniform dawn-dusk field — Corotation

- – Next simplest approximation–Stern-Volland and corotation

$$\Phi = -Ayr - \frac{B_o \omega_E R_E^3}{r}$$

- Neither of these simple models captures the complexity of the real system. This talk will concern 2 effects that are not captured by these simple models:
  - Shielding/overshielding/undershielding (Penetration E-fields)
  - SubAuroral Polarization Stream (SAPS) E-field structures

What Determines Inner Magnetospheric E-field: Governing Equations

- Ohm's law for ionosphere:

$$\mathbf{J}_h = \hat{\Sigma} \cdot \left(-\nabla \Phi \right) + \left(\hat{\Sigma} \cdot \mathbf{v}_n \right) \times \mathbf{B} \qquad (1)$$

Field-line-integrated current (includes both hemispheres)

Field-line-integrated Conductivity (both hemispheres)

Field-line integrals of products of Hall and Pedersen conductivities and neutral winds

- Conservation of ionospheric current: $\nabla \cdot \mathbf{J}_h = J_{\|} \sin(I)$ (2)

- *Vasyliunas* [1970] equation: $\dfrac{J_{\|in} - J_{\|is}}{B_i} = \dfrac{\hat{\mathbf{b}} \cdot \nabla V \times \nabla p}{B}$ (3)

- Substituting (1) and (2) into (3), and neglecting winds, gives the "Fundamental equation of ionosphere-magnetosphere coupling":

$$\nabla_i \cdot \left[\hat{\Sigma} \cdot \left(-\nabla_i \Phi \right) \right] = \hat{\mathbf{b}} \cdot \nabla_i V \times \nabla_i p \sin(I)$$

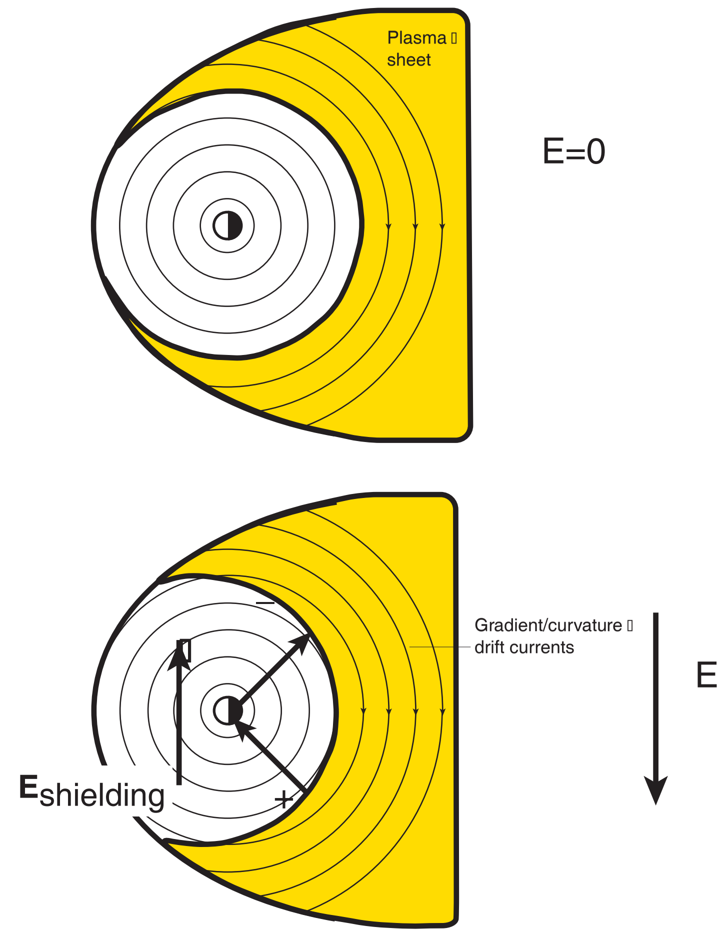
References on equations and formulation of Rice Convection Model (RCM):

Toffoletto et al., *Space Sci. Rev*., *107*, 175, 2003.

Wolf, in *Solar Terrestrial Physics*, ed. Carovillano and Forbes, 1983.

Magnetospheric Effects: Shielding

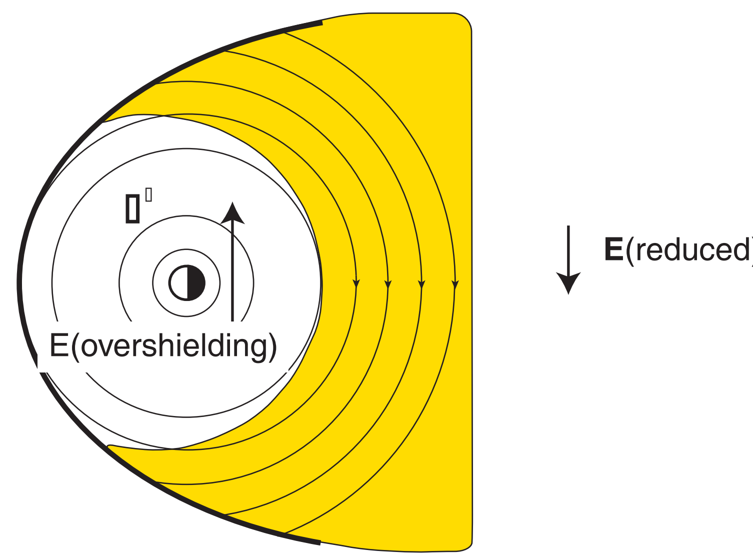
- Top diagram shows equilibrium condition no convection, with plasma-sheet edge aligned with contours of constant V.
  - Particles gradient/curvature drift along contours of constant V
- Effect of applying cross-tail E (bottom) is to move edge sunward
  - Causes a partial westward ring across night side
  - Dusk side of edge charges +, dawn side –.
    - Charging occurs near eq. plane and in ionosphere
  - Currents flow up from dawnside ionosphere near inner edge, down to dusk side.
    - Those are the region-2 currents.
- They tend to shield the near-Earth region from the dawn-dusk **E**. Dusk-dawn polarization **E** opposes convection in the inner magnetosphere.



$$\mathbf{v}_d = \frac{\mathbf{E}\times\mathbf{B}}{B^2} + \frac{\lambda\mathbf{B}\times\nabla V^{-2/3}}{qB^2} \qquad \frac{J_{\|in} - J_{\|is}}{B_i} = \frac{\hat{\mathbf{b}}\cdot\dot{\nabla} V \times \dot{\nabla} p}{B}$$

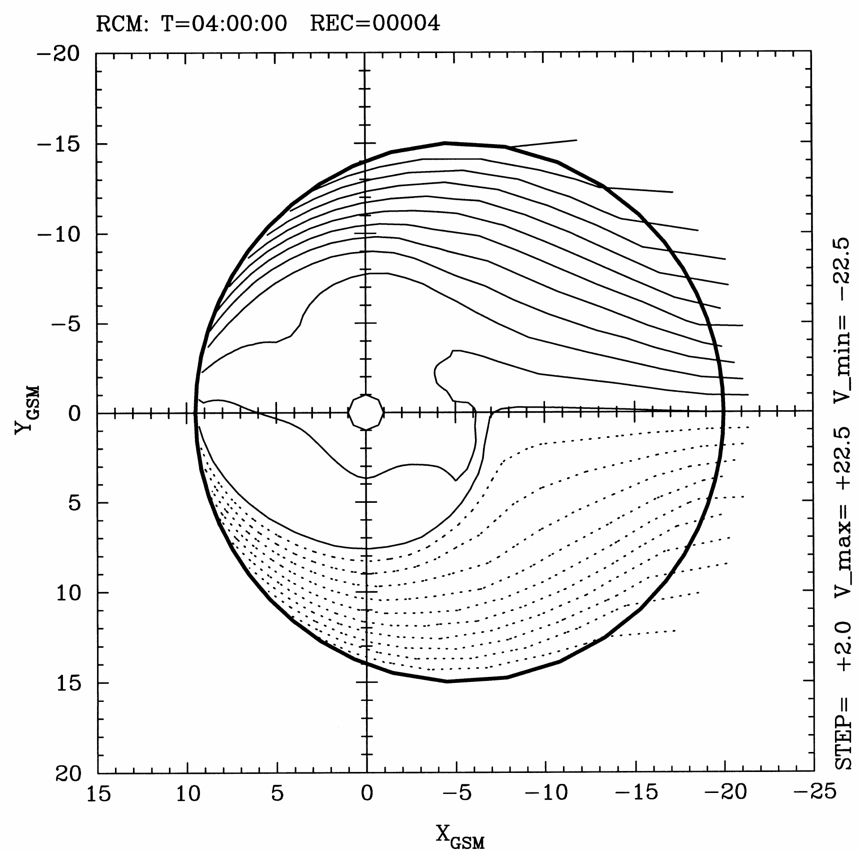
Under(Over)shielding: The Idea

- If the shielding layer is configured to shield the inner magnetosphere from a strong convection field, and that convection field suddenly increases, due to a southward turning of the IMF, the result will be a partial **E** field (dawn to dusk) in the inner magnetosphere, until the shielding layer readjusts.
- If IMF turns northward (convection decrease, there is suddently a backwards (dusk to to dawn) E-field temporarily
- Originally seen in Jicamarca data by Kelley et al. (*GRL*, *6*, 301, 1977)
  - Observations were interpreted in terms of overshielding picture

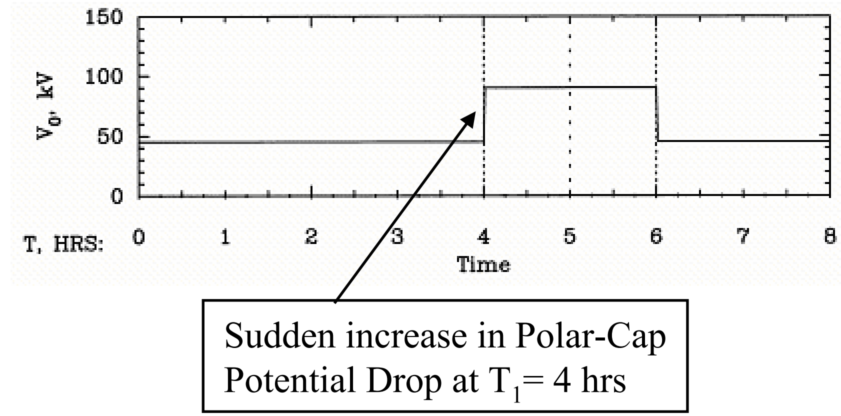


Southward IMF Turning Causes Undershielding

RCM-Calculated penetration field



Steady-state solution at $T=T_1-\varepsilon$



- Modeled electrostatic E-field in response to idealized changes in strength of magnetospheric convection
- Shown is potential mapped out to the equatorial plane but in the frame rotating with the Earth

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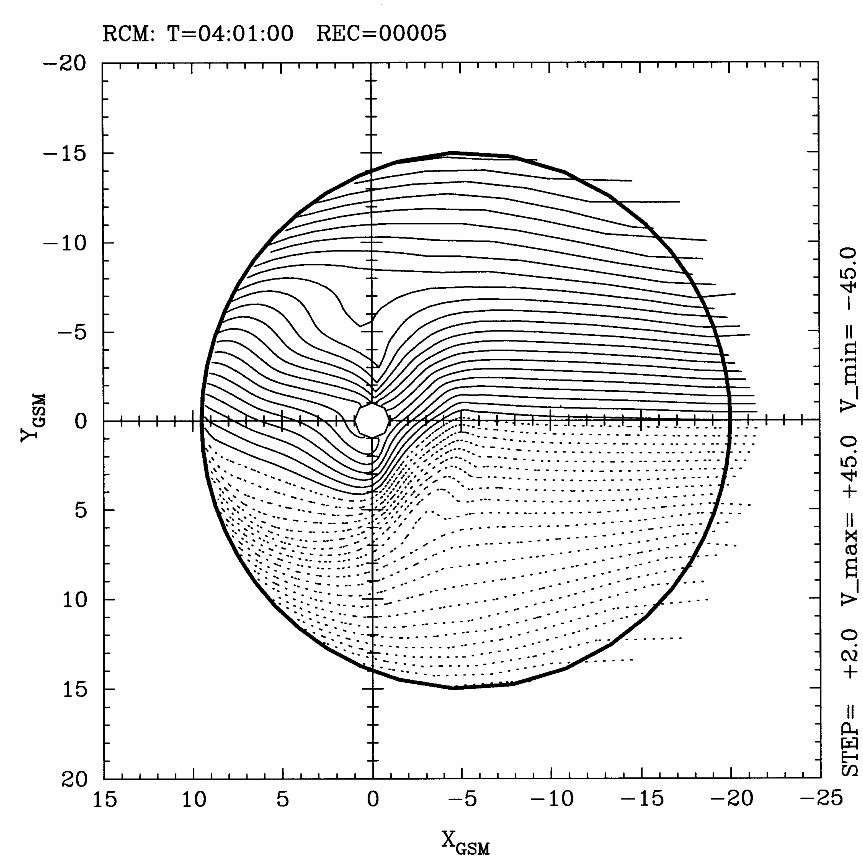
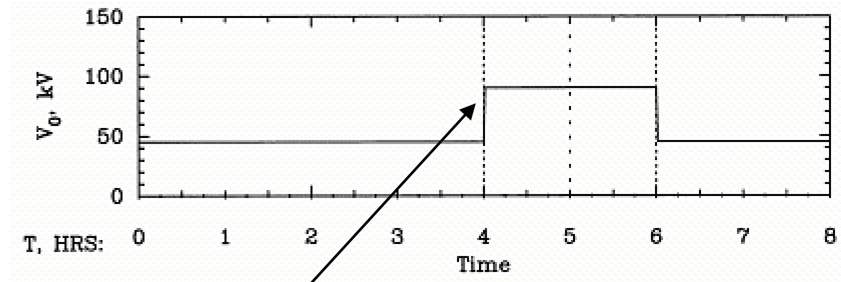


Solution at $T=T_1+1$ min (transient response)



Sudden increase in Polar-Cap Potential Drop at $T_1 = 4$ hrs

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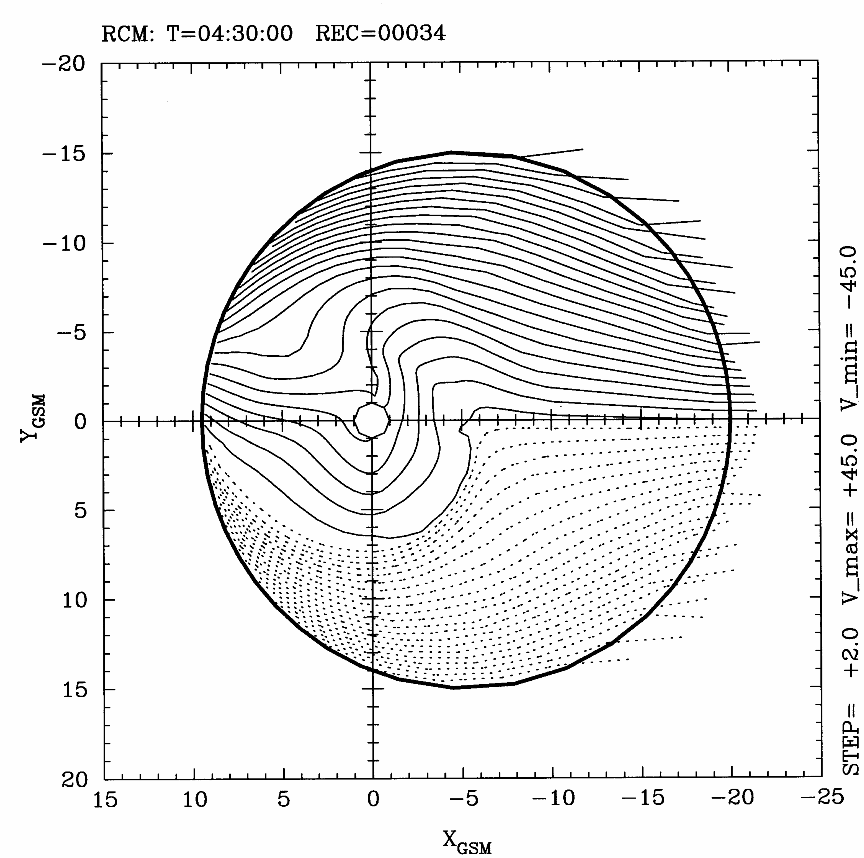
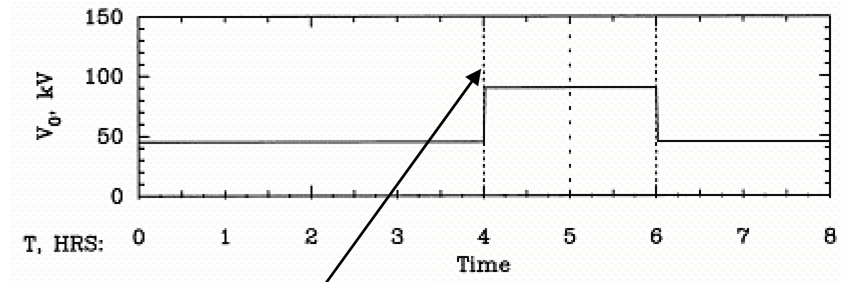


Solution at $T=T_1+30$ min (transient response)



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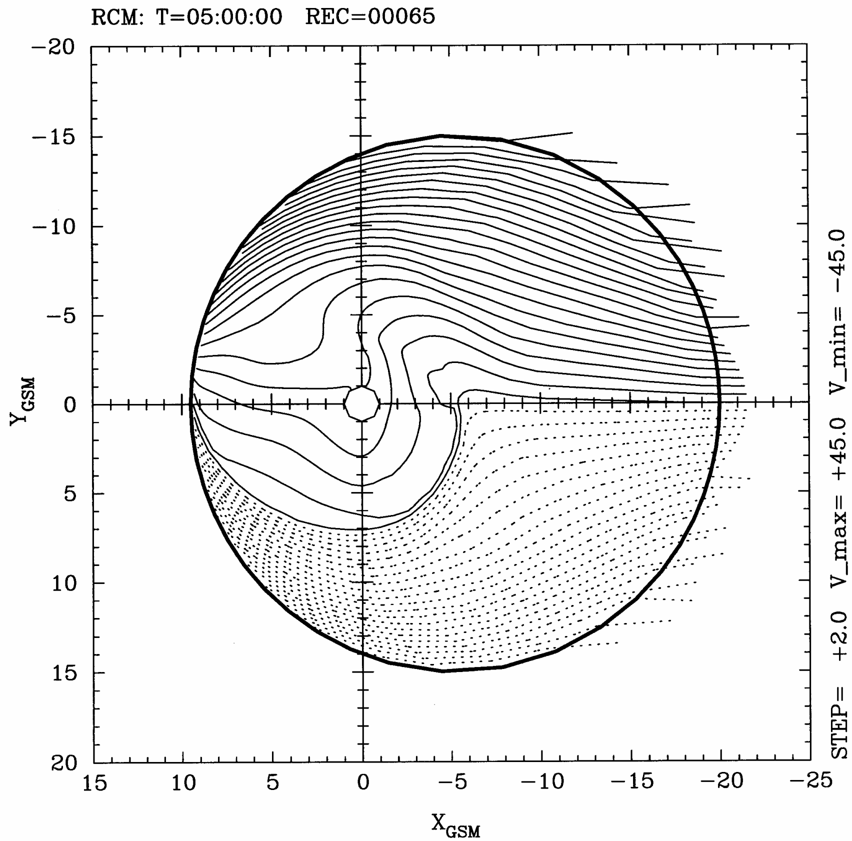
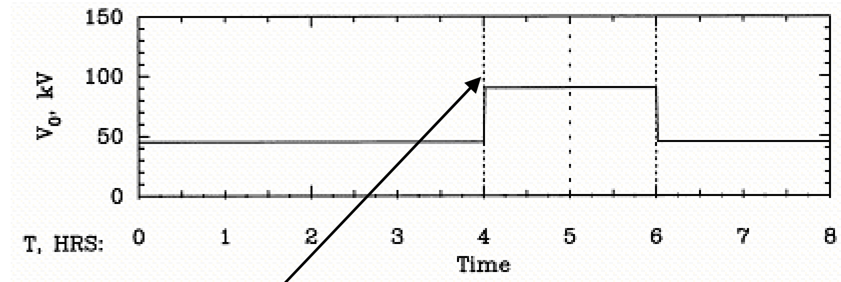


Solution at $T=T_1+1$ hr (new steady-state)



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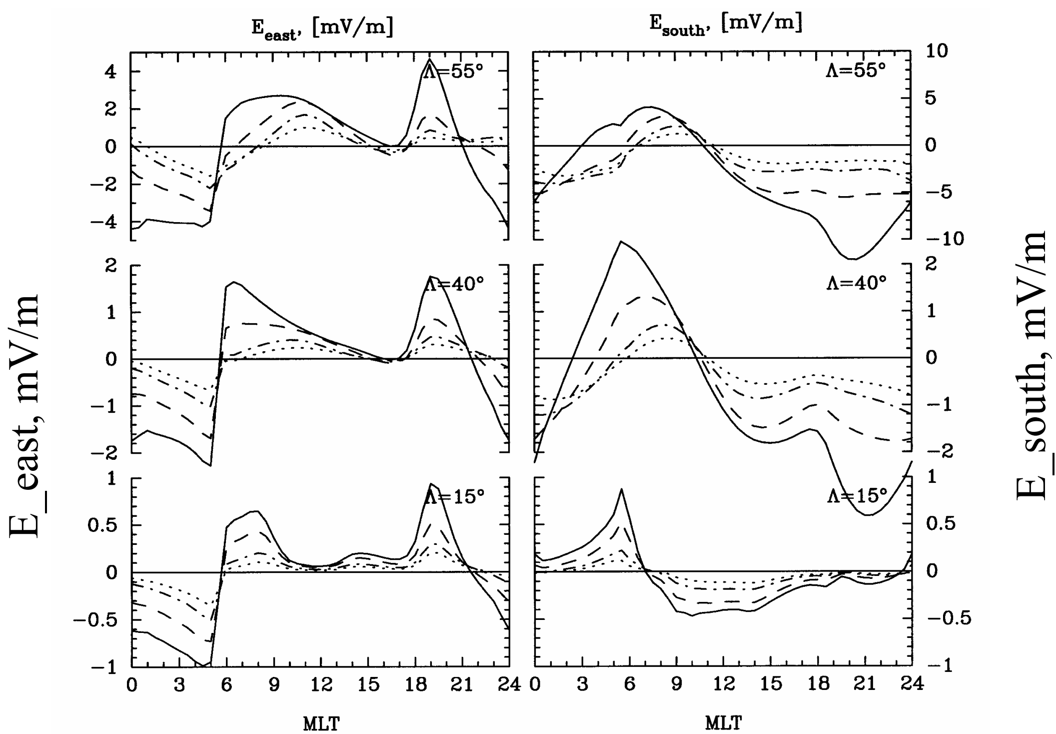
Southward IMF Turning Causes Undershielding

RCM-Calculated penetration field—MLT profiles at 100 km altitude

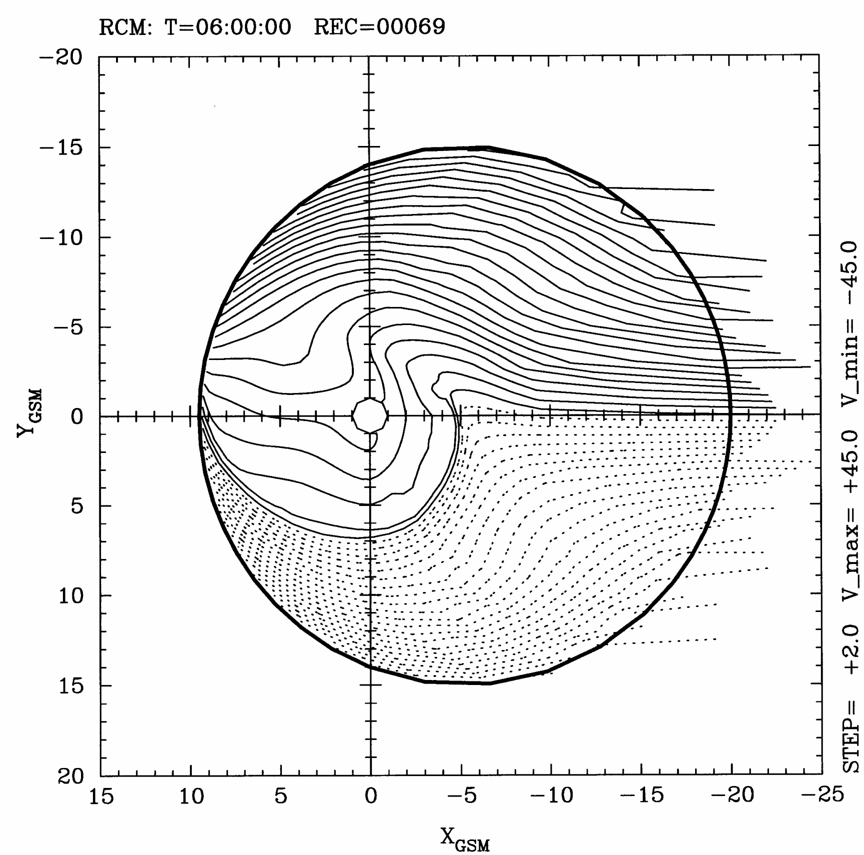


- Undershielding is temporary penetration of dawn-dusk electric field in times of increasing convection.
- Pattern at low *L* is : westward penetration electric field post-midnight, eastward during daytime
- At equator, upward drift velocity during daytime and post-dusk, downward at night
- MLT pattern is not sine wave but is distorted.

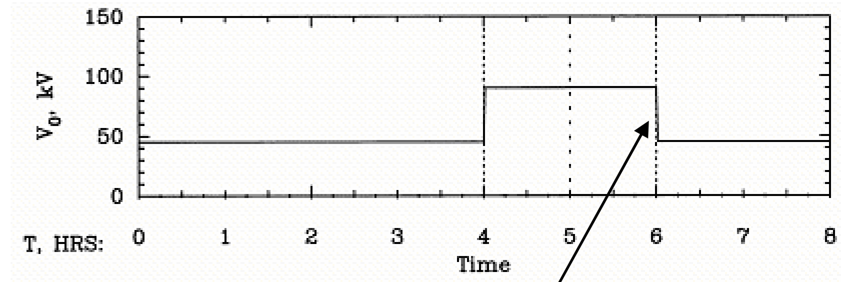
Local time patterns of electric fields at different invariant latitudes caused by an increase in the polar cap potential drop, for several time delays. Solid lines, *T*1+1 min; dashed, *T*1+10 min, dash-dotted, *T*1+30 min; dotted, *T*1+60 min.

Northward IMF Turning Causes Overshielding

RCM-Calculated penetration field



Steady-state solution at $T=T_2-\varepsilon$



Sudden drop in Polar-Cap Potential Drop at T_2= 6 hrs

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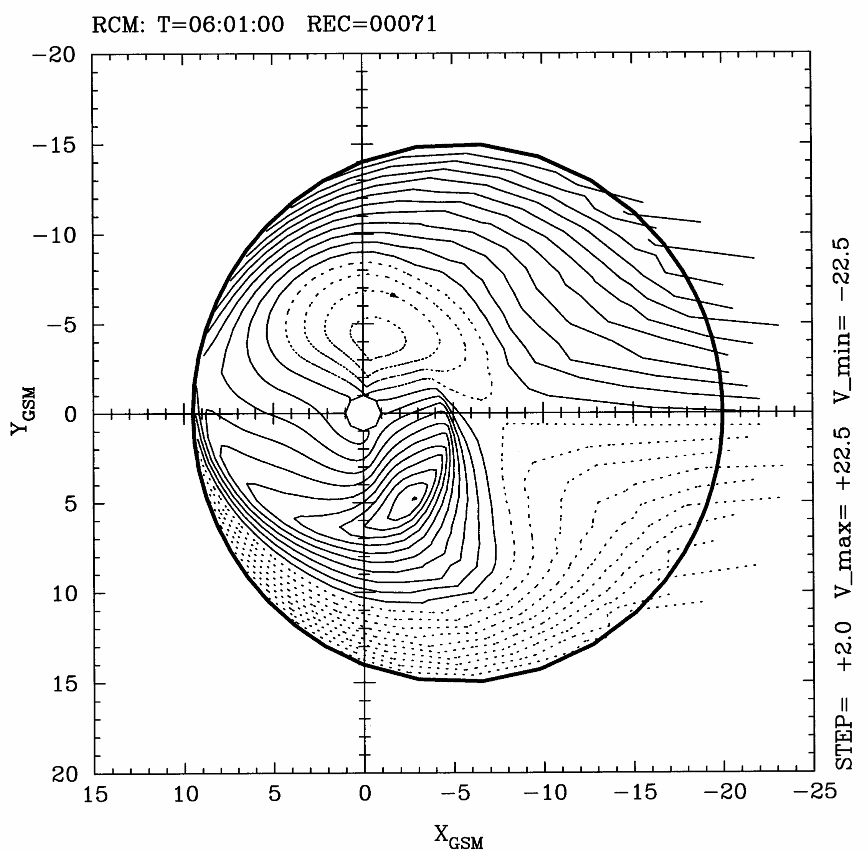
Northward IMF Turning Causes Overshielding

RCM-Calculated penetration field



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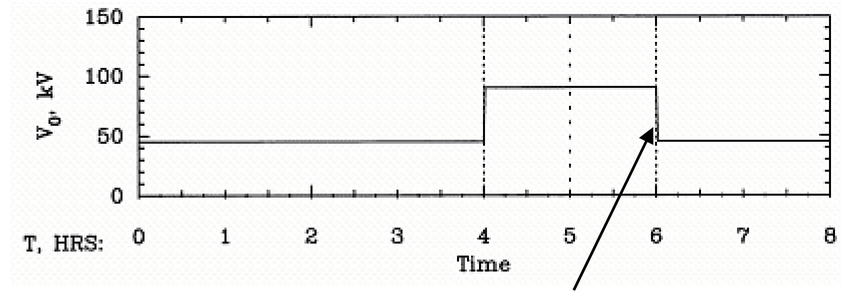

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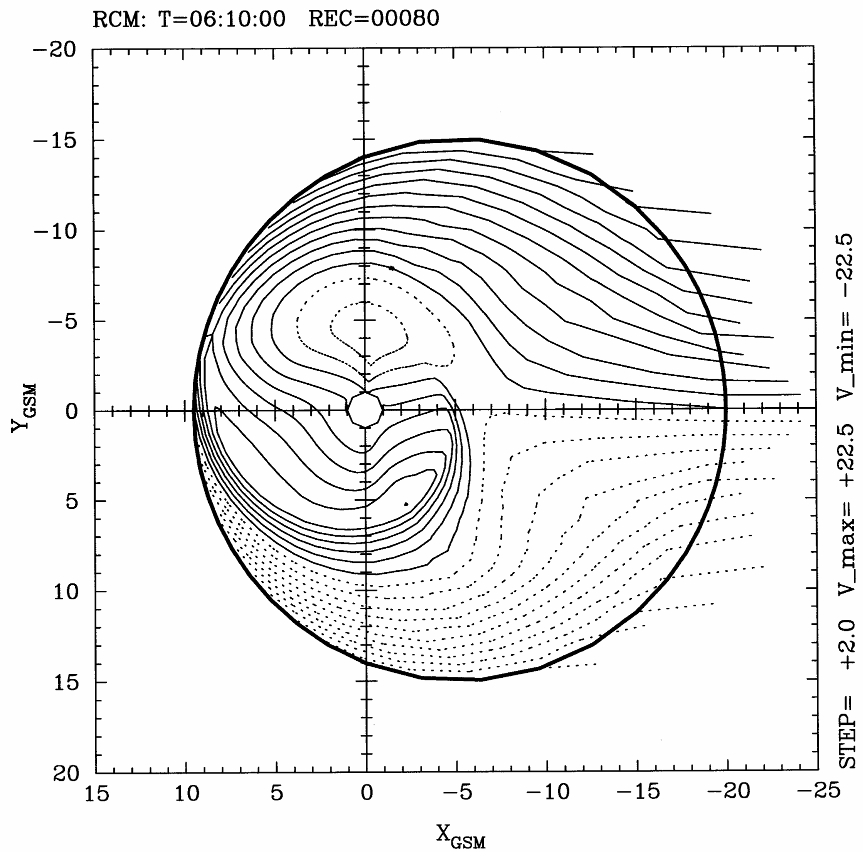
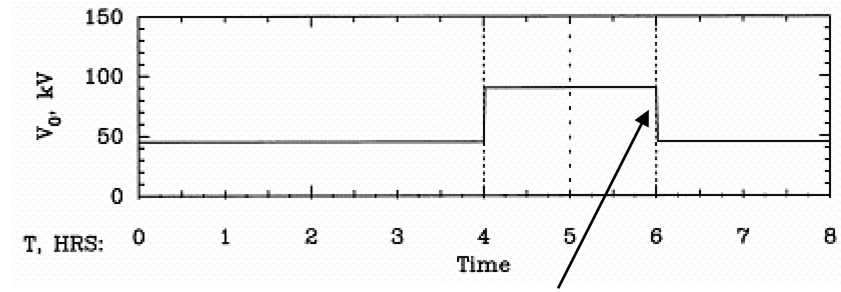


Solution at $T=T_2+10$ min (transient response)



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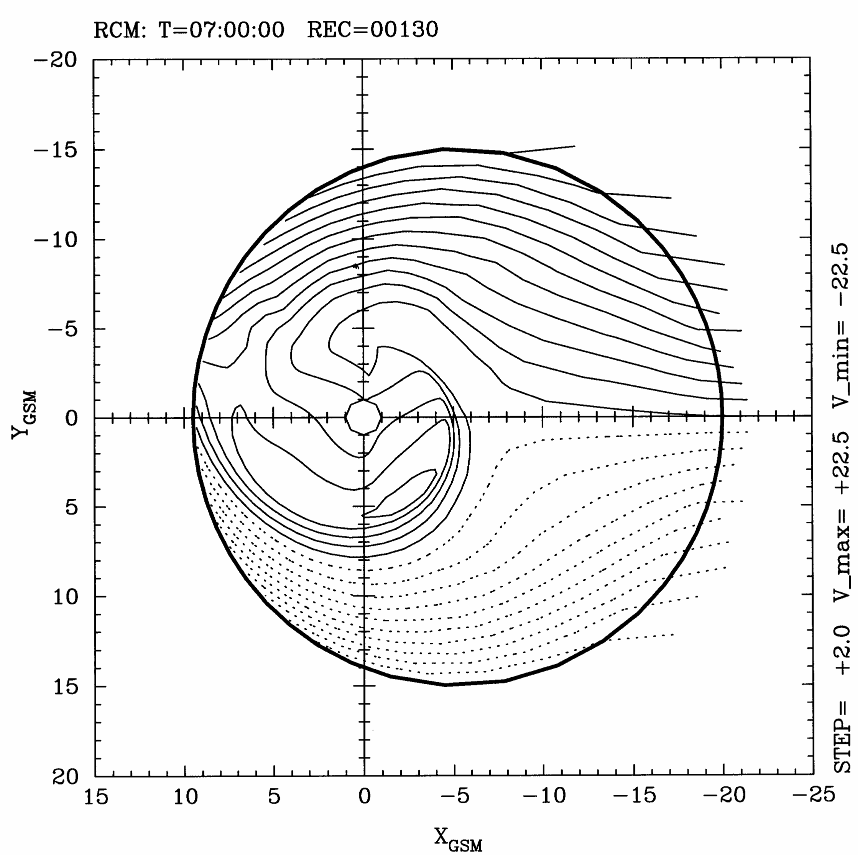
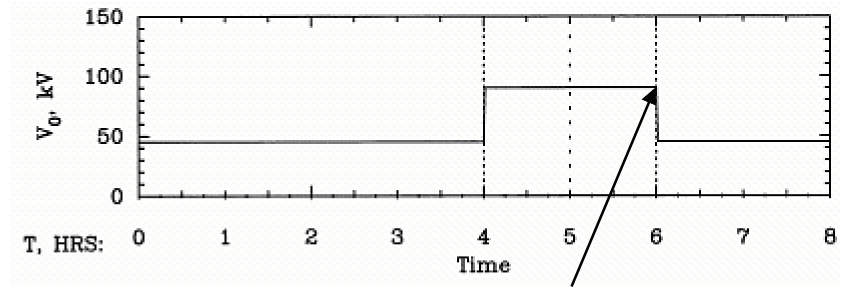


Solution at $T=T_2+1$ hr



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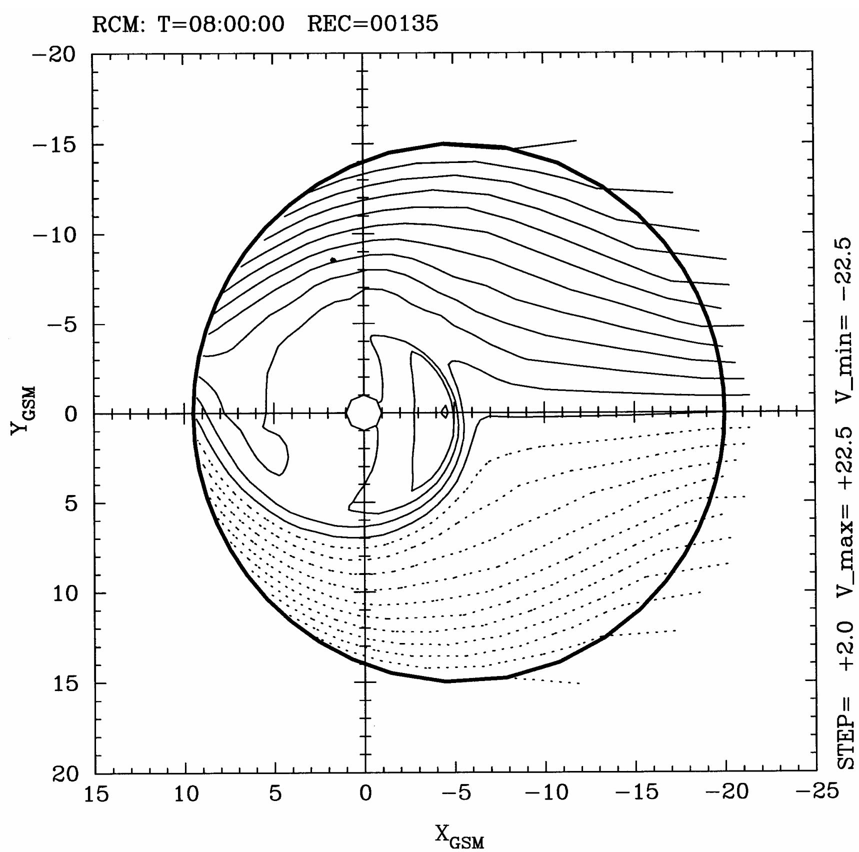

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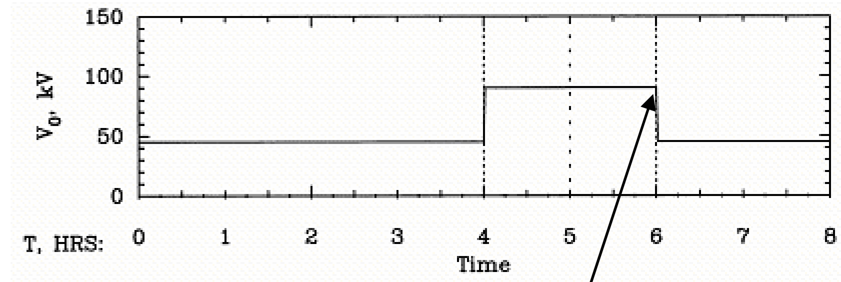

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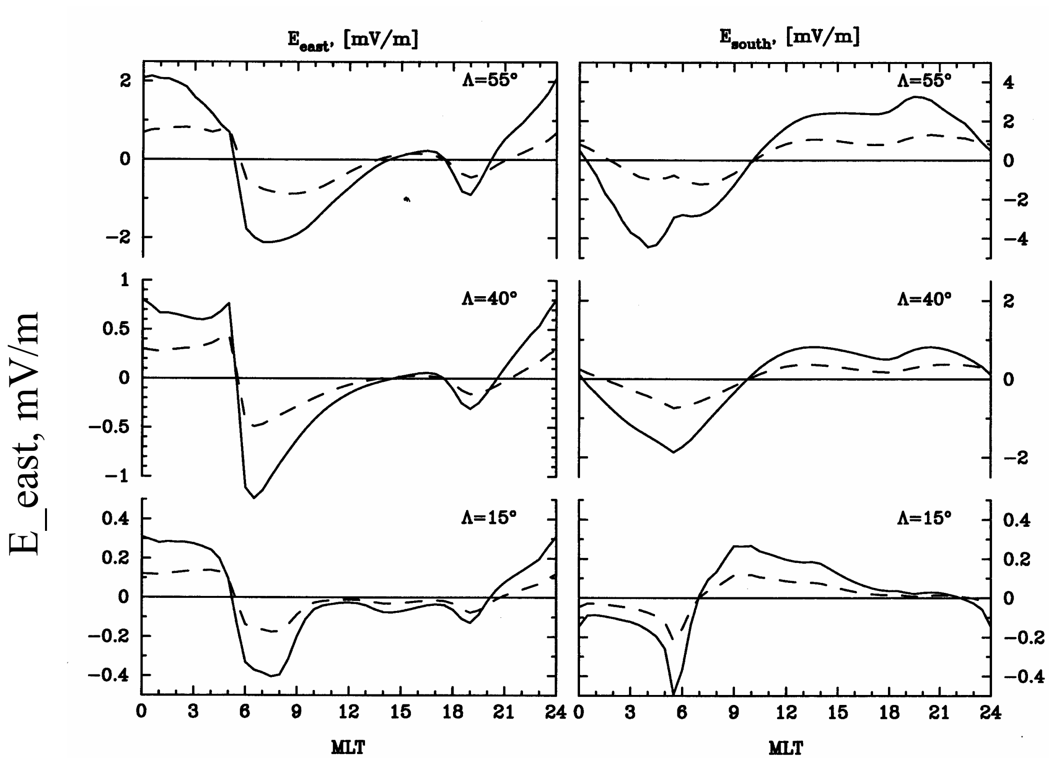
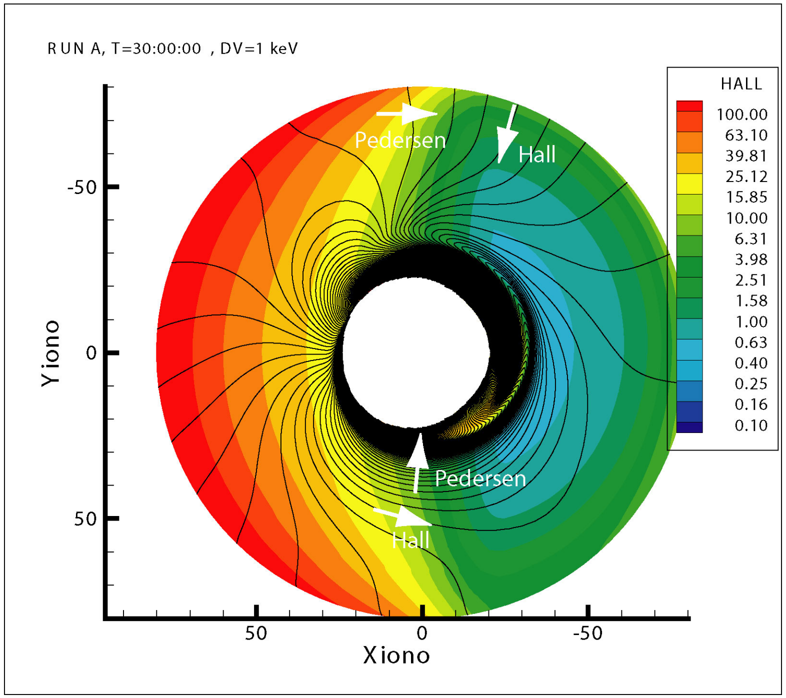


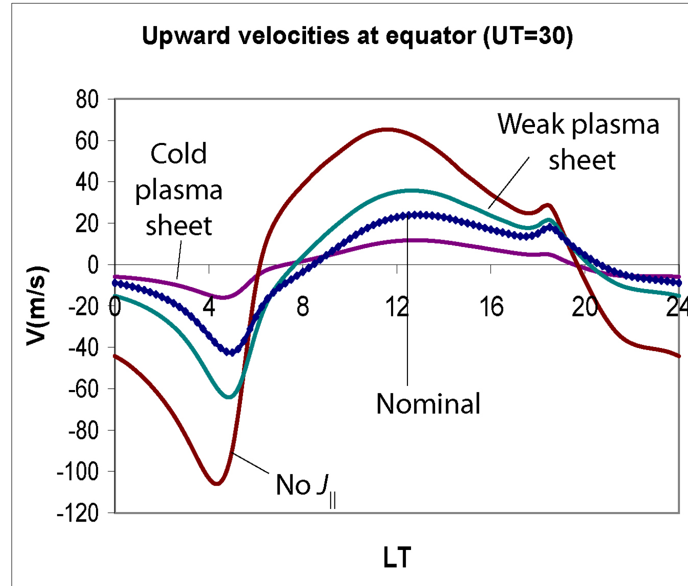
- Overshielding is temporary penetration of dusk-to-dawn electric field in times of decreasing convection.
- Pattern at low *L* is reversed: eastward penetration electric field post-midnight, westward during daytime [upward vertical drift at equator at night, down during day].
- MLT pattern is not sine wave but is distorted.

Local time patterns of electric fields at different invariant latitudes caused by a drop in the polar cap potential drop, solid lines, *T*1+30 min. Ignore dashed lines.

Physical Reason for Distortion of Pattern: Effects Near the Terminators

Lines are ionospheric equipotentials
Color-coded is Hall conductance





Dawn side:
- Contours are more dramatically distorted away from simple sunward convection.
- Hall currents avoid crossing terminator.
- Strong downward flow at pre-dawn equator.

Dusk side:
- Hall currents on the dusk side deposit + charge near terminator.
- Pedersen currents transport charge poleward to highly conducting auroral zone.
- Causes bump in upward equatorial velocity just past dusk.

$$\nabla_i \cdot \left[\hat{\Sigma} \cdot \left(-\nabla_i \Phi \right) \right] = \hat{\mathbf{b}} \cdot \nabla_i V \times \nabla_i p \sin(I)$$

Why are (Prompt) Penetration E-fields Important?

- $E \times B$ drift is one of the main transport terms in the equations governing global distributions of ionospheric electron densities.
- Particulary at equatorial latitudes, E-field is the prinicipal parameter controlling growith rates of plasma instabilities (spread F).
- Plasmasphere driving force.
- It is possible for plasmas to be transported from mid-latitudes where particles co-rotate on closed trajectories to high-latitudes where they are a possible source of plasma in the outer magnetosphere.

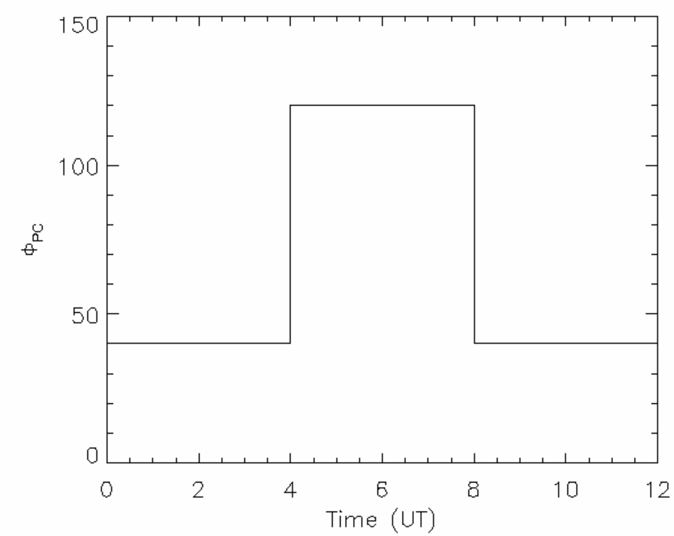
COUPLED SAMI3/RCM MODEL

- The fundamental coupling of RCM and SAMI3 is through the solution of the potential equation

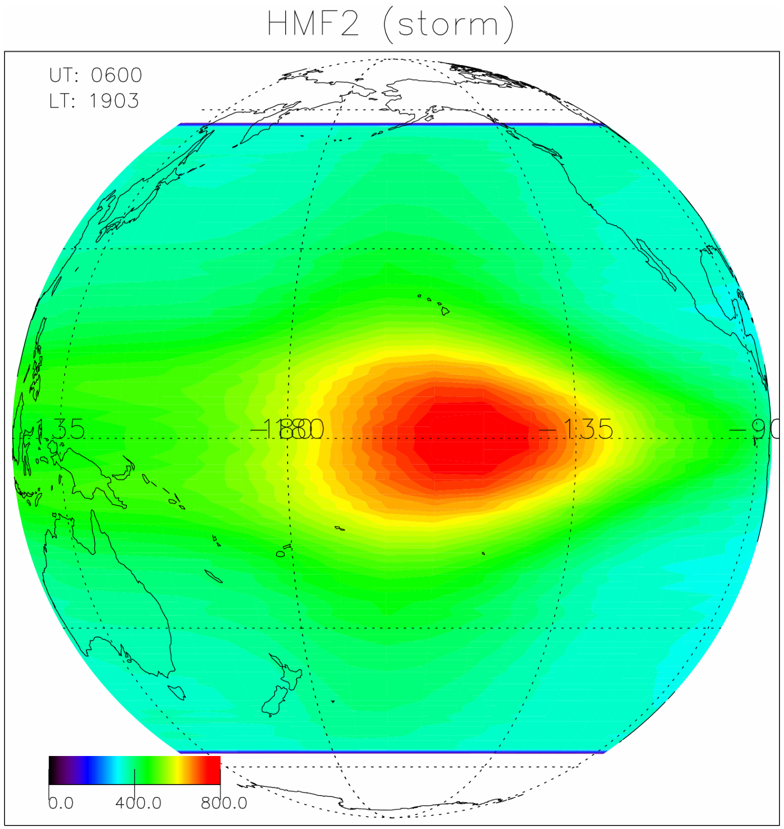
$$\nabla \cdot \underbrace{\Sigma}_{SAMI3} \cdot \nabla \underbrace{\Phi}_{RCM} = J_{\|}$$

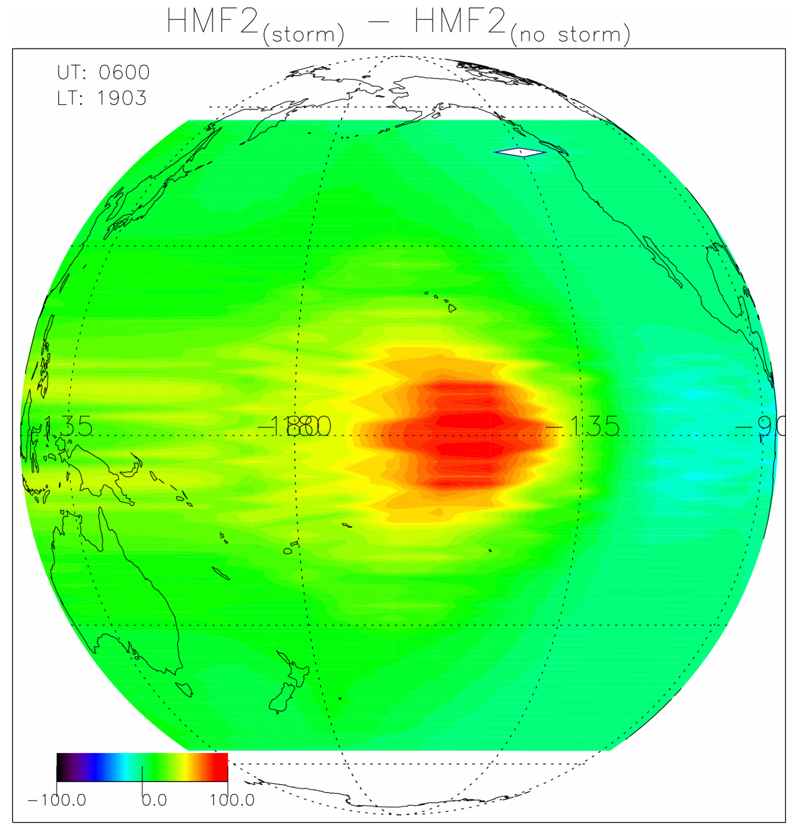
→ SAMI3 provides the ionospheric
→ RCM solves the potential equati
→ RCM provides the Φ to SAMI3
→ SAMI3 and RCM use Φ to calcu
→ Transport the plasma

- The coupled model provides a self-c electrodynamicdescription of the ior magnetosphere system



Ionospheric Dynamics in Response to an Idealized Event: Prompt-Penetration (Undershielding) and HmF2

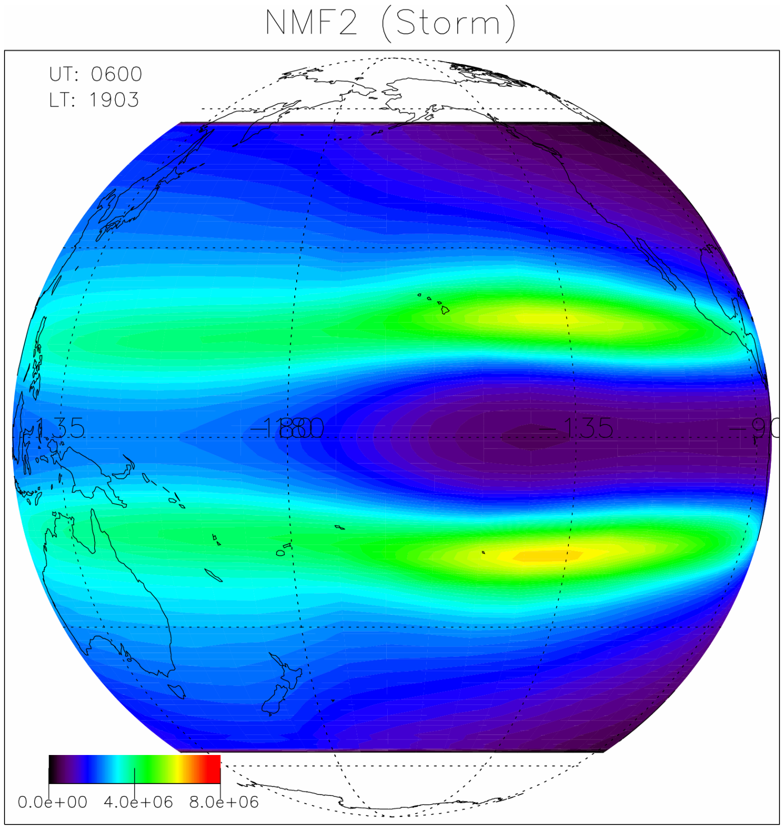


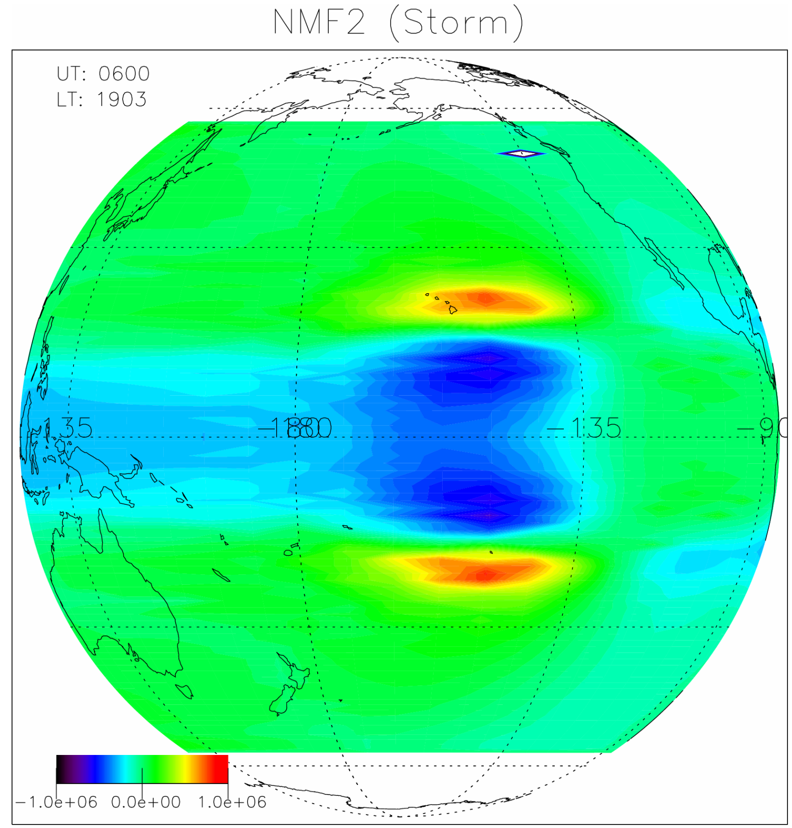


Prompt penetration E-field in the undershielding case increases HmF2 by 15% (raises the hight of the F-layer 100 km)

Figure courtesy of J. Huba, NRL

Ionospheric Dynamics in Response to an Idealized Event: Prompt-Penetration (Undershielding) and NmF2

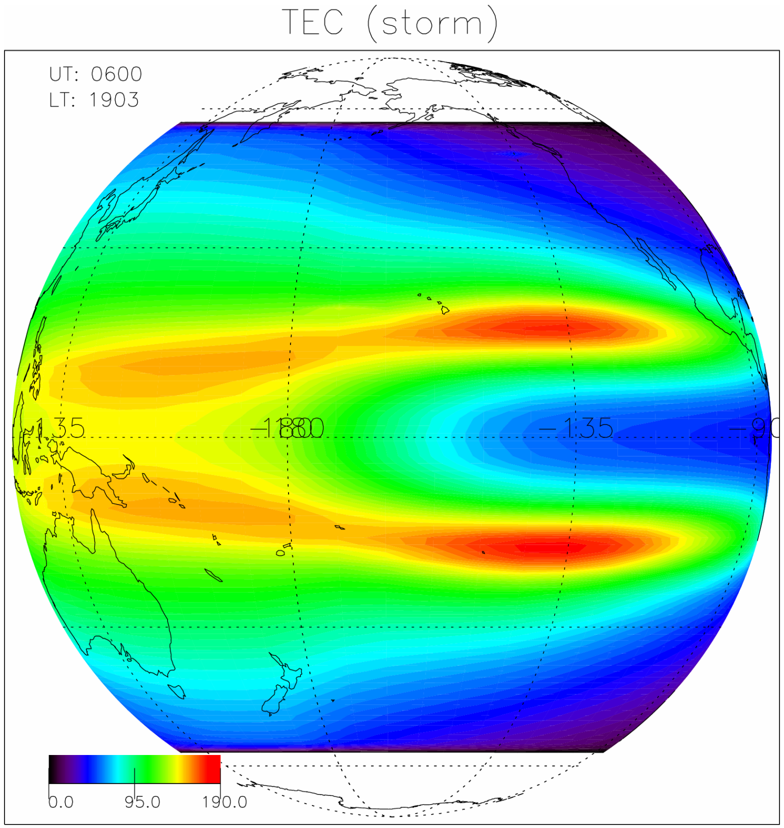


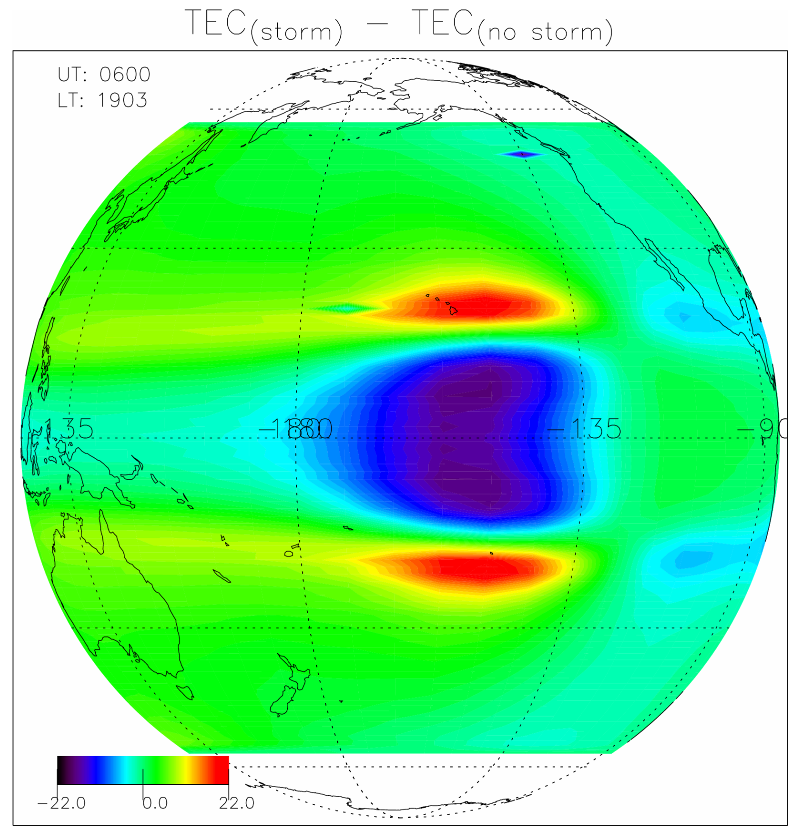


Prompt penetration E-field in the undershielding case changes NmF2 ±20% (equatorial density is lower, Appletop peaks are higher)

Figure courtesy of J. Huba, NRL

Ionospheric Dynamics in Response to an Idealized Event: Prompt-Penetration (Undershielding) and TEC



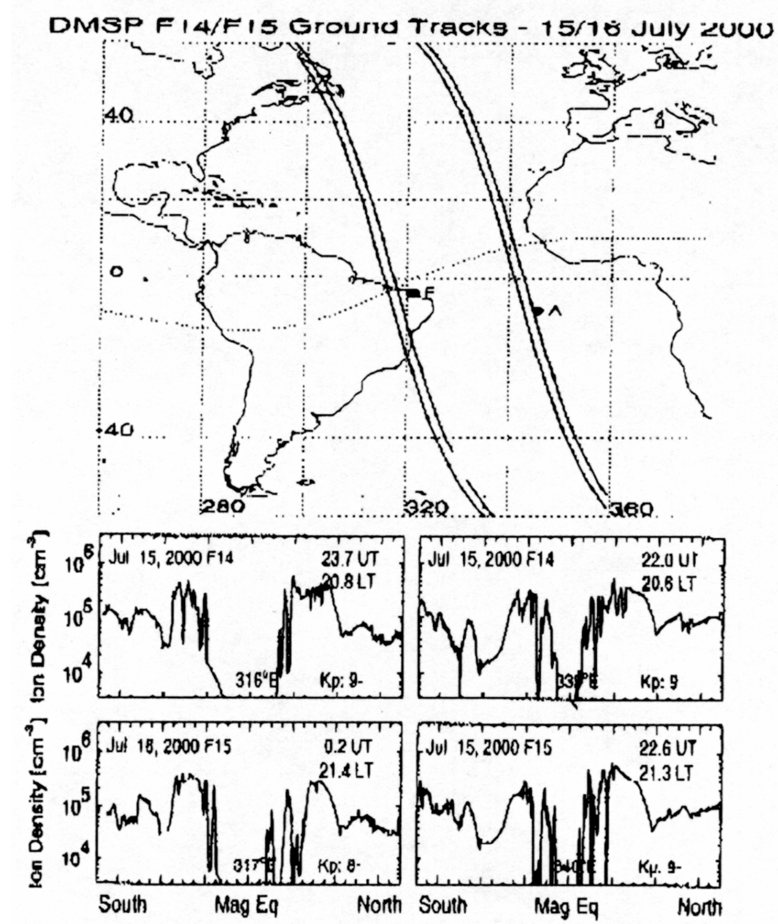


Prompt penetration E-field in the undershielding case changes TEC ±15%

Figure courtesy of J. Huba, NRL

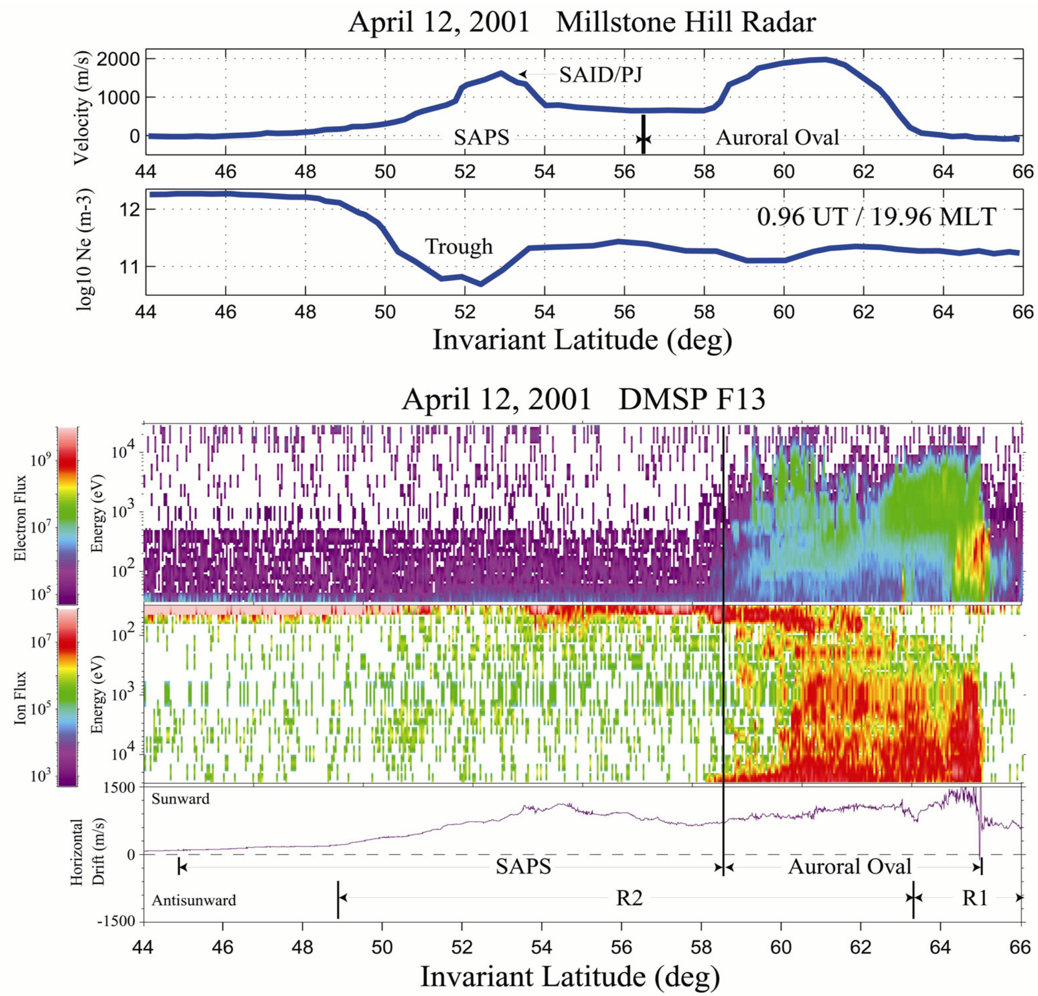
Effect of Strong Penetration on Equatorial Ionosphere

- Basu et al. (*GRL*, *28*, 3577, 2001) showed dropout of the equatorial ionosphere at 840 km altitude in main phase of the Bastille Day storm. They interpreted that as the result of upward drift of the F-layer above that altitude.
- This uplift was accompanied by strong scintillations.Eastward electric field causes a downward drag that acts like increased gravity and encourages the Rayleigh-Taylor instability that causes spread F.
- Note: Massive rearrangements of the low-latitude ionosphere imply massive changes in conductance. Proper modeling of something like this requires active coupling of ionosphere and magnetosphere models–haven't done that yet.



SubAuroral Polarization Streams (SAPS)

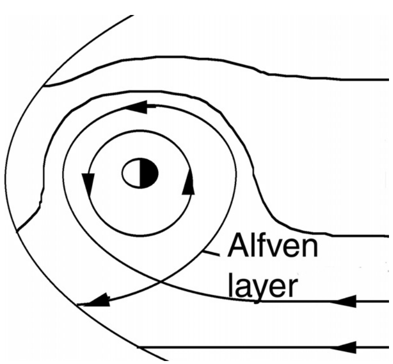
- During times of high activity, there is often strong westward flow in the ionosphere, equatorward of the auroral zone, in the dusk-midnight sector, sometimes extending post midnight.
- Seen in ionosphere and near the eq. plane (*Rowland and Wygant*, *JGR*, *103*, 14959, 1998; *Burke et al.*, *JGR*, *103*, 29399, 1998).
- Characteristic peak in the poleward electric field separated from the auroral sunward convection that maps to the electron density trough.
- There are stronger E-fields in the inner magnetosphere than in the tail – the opposite of shielding.



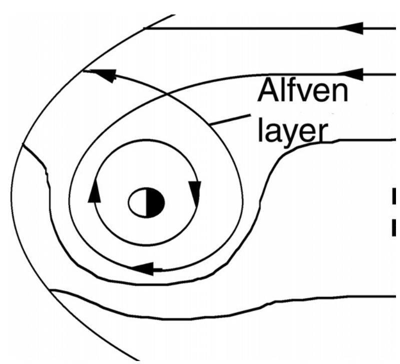
From Foster et al. (*JGR*, *107*(A12), 1475, 2002)

Physical Interpretation of SAPS

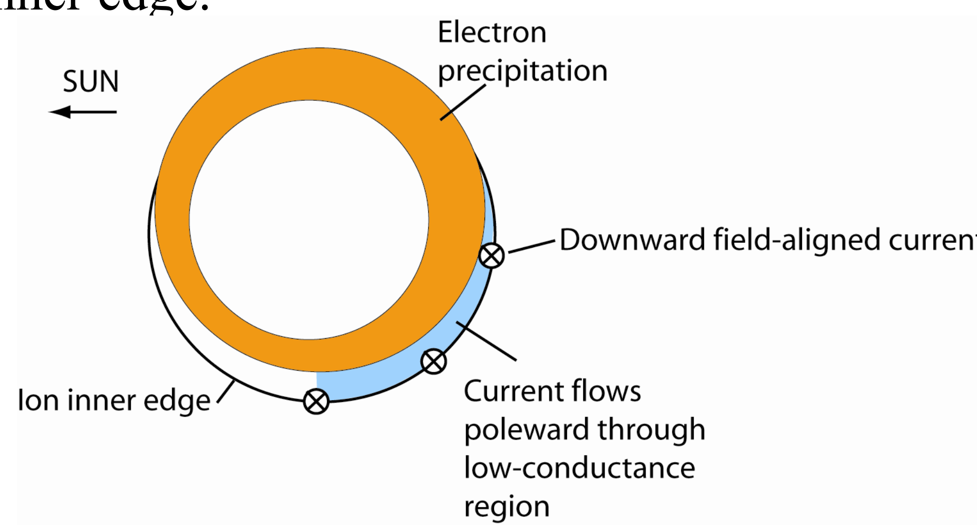
- In pre-midnight sector, plasma-sheet ions drift closer to Earth than electrons.
- Electrons mostly control ionospheric conductance.
- Therefore, in the premidnight sector, the inner edge of the plasma-sheet ions lies at lower L than the auroral conductance enhancement.
- Most of region-2 current is driven by ions (they carry ~85% of pressure).
- Therefore, some region-2 current flows into low-conductance, subauroral ionospheric region in the pre-midnight sector.
- This gap between these two regions becomes larger in great storms, because precipitation erodes the electron inner edge.



Electrons

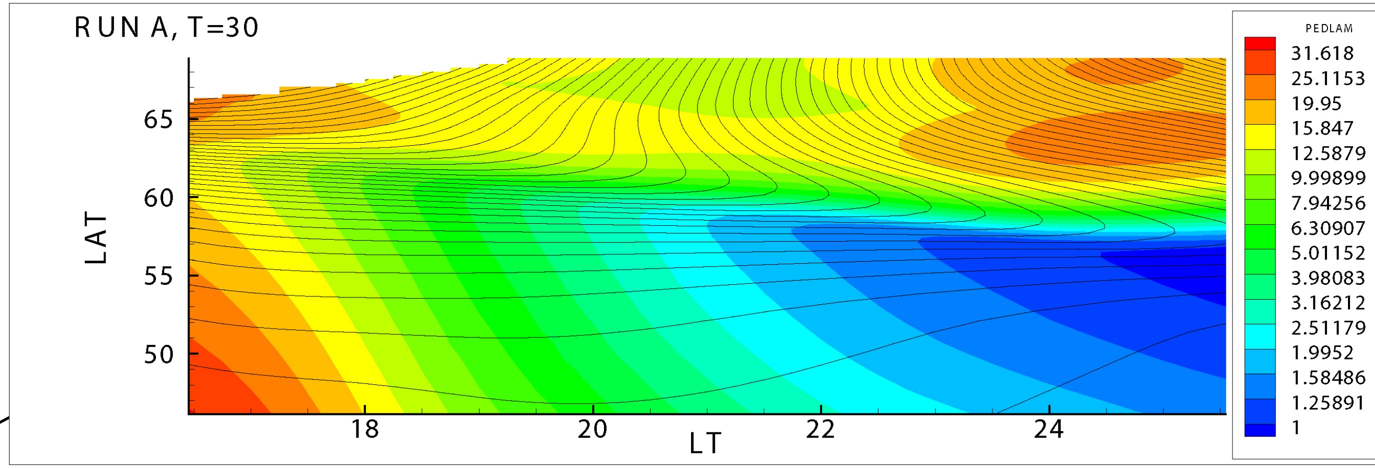


Ions



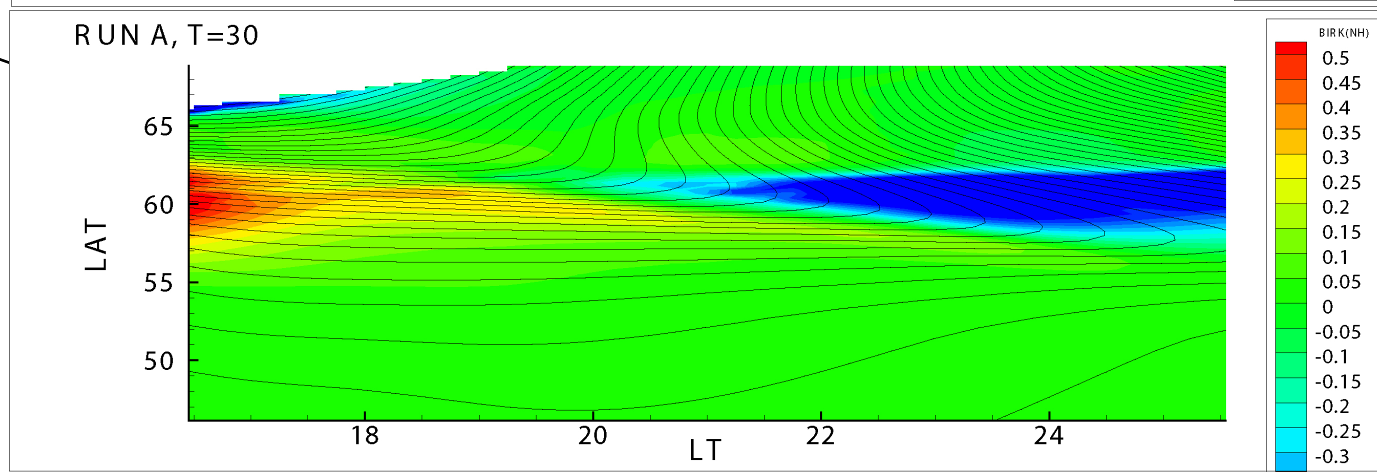
SubAuroral Polarization Stream – RCM Simulations

Equipotentials and Pedersen conductance at peak of main phase.



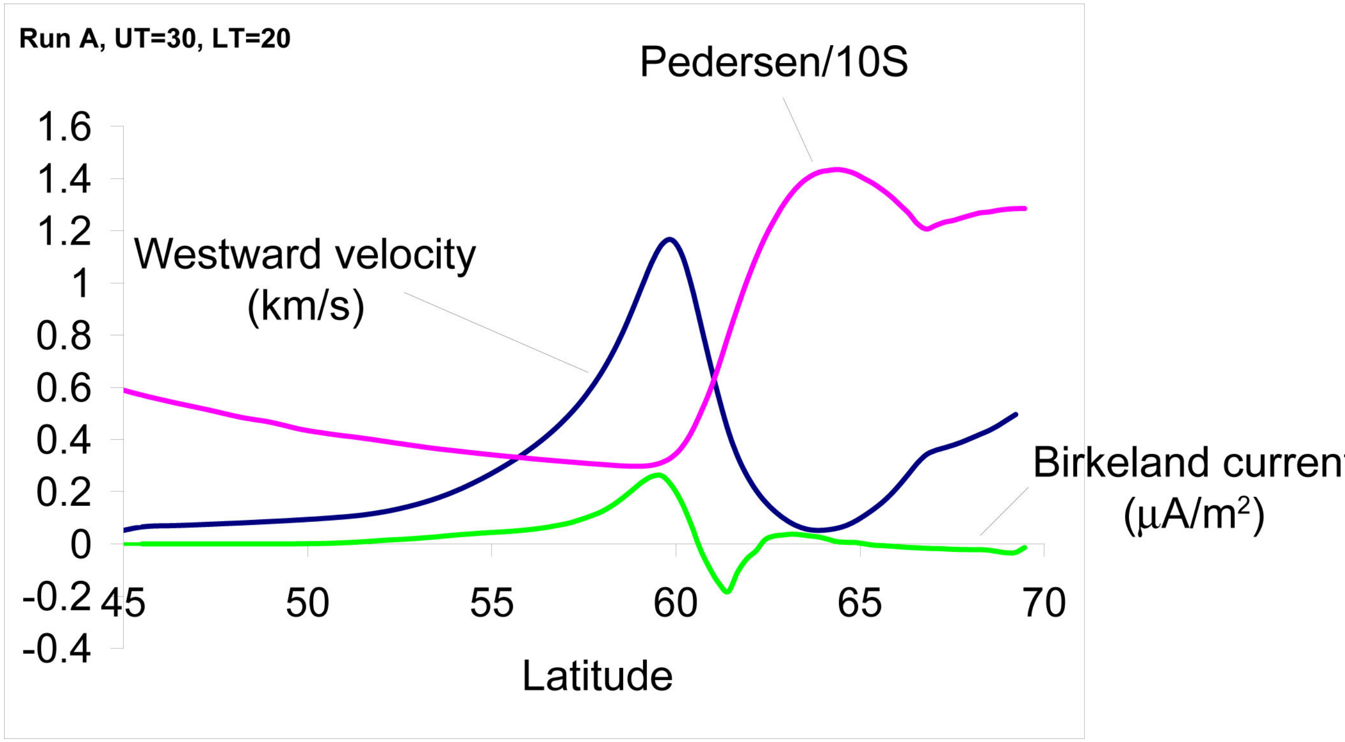
SAPS

Equipotentials and $J_{||}$. Positive current (yellow, red) is downward.

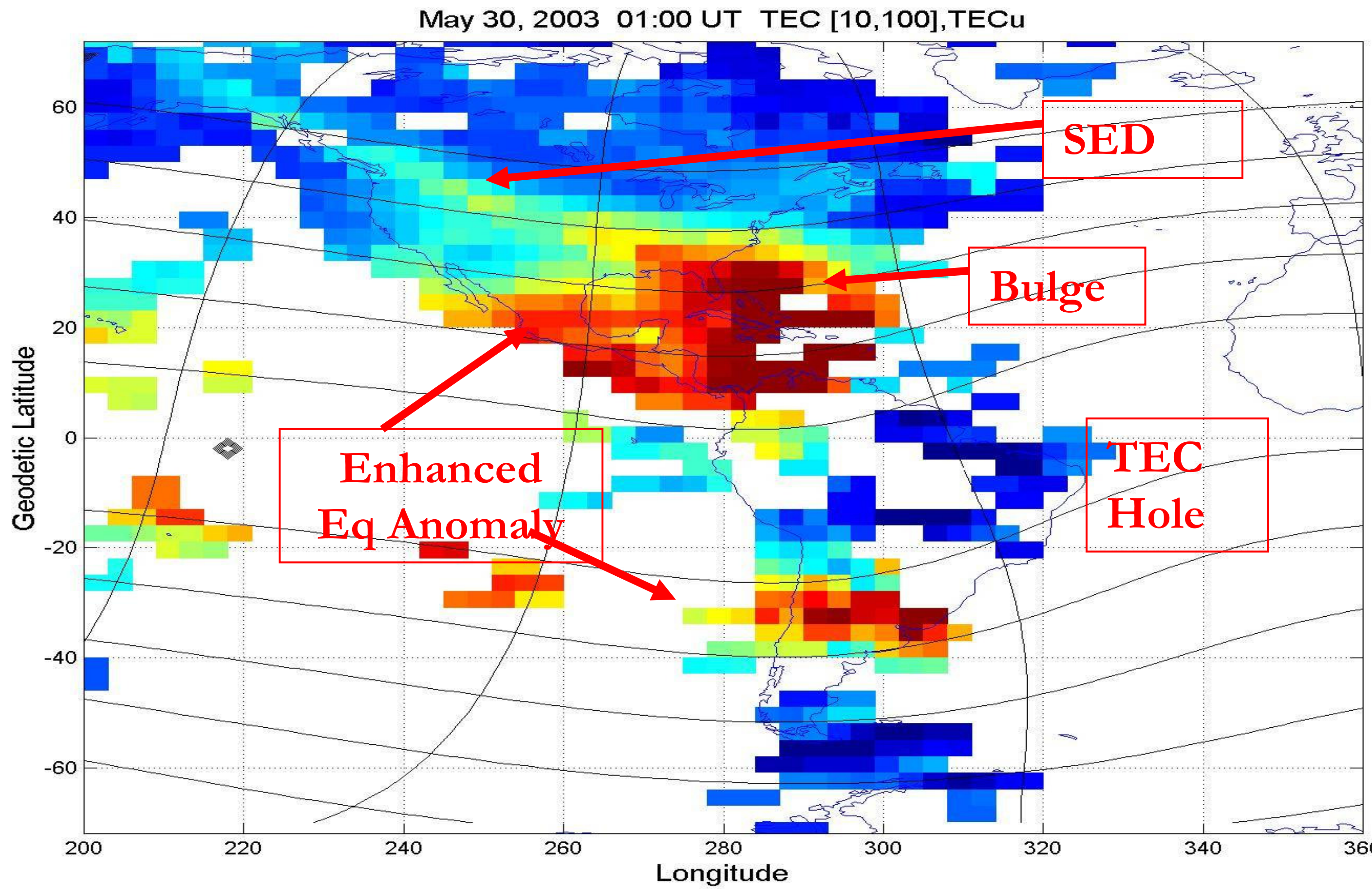


- SAPS occurs in evening trough region, just below auroral conductance enhancement and mostly in a region of weak downward Birkeland current.

Latitudinal Cut Through a SAPS



- In the RCM, a SAPS lies on the equatorward edge of the diffuse-auroral conductance enhancement.
- Equatorward part of SAPS lies in a region of weak downward current.



Global storm-time E×B transport of ionospheric electron density?

Courtesy of John Foster

Summary

- Magnetosphere imposes a “convection” E-field on the ionosphere; ionosphere modifies it, mostly via conductivity feedback.
- Under quiet conditions, convection E-field is shielded by region-2 field-aligned currents at latitudes below the auroral zone
- When convection in the magnetosphere changes with time, shielding breaks down and
  - Undershielding: times of stronger convection; at equator, azimuthal E-field is eastward during day (upward drift), westward at night (downward)
  - Overshielding: times of weakening convection, the effect is the opposite.
  - This is prompt penetration (away from source).
- In subauroral ionosphere (dusk side), convection E-field can be greatly amplified to form a (usually) narrow band of poleward E-field (SAPS), usually during geomagnetically disturbed times.
- SAPS and the shielding layer are sometimes called “penetration E-fields”.
- Plenty of challenges: from modeling the coupled system self-consistently to understanding observations.