

# IONOSPHERE/THERMOSPHERE/MAGNETOSPHERE: ITM ELECTRODYNAMIC COUPLING

J.D. Huba

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Washington, DC

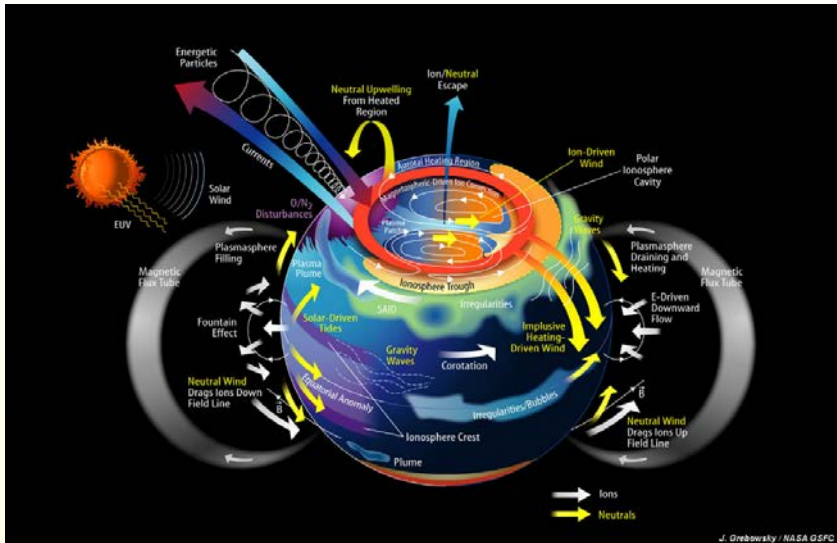
2008 CEDAR Student Workshop

Zermatt, Utah

June 16, 2007

Acknowledge: G. Joyce, S. Slinker, G. Crowley, S. Sazykin, R. Wolf, R. Spiro

Research supported by ONR and NASA



# ITM CURRENT SYSTEM

simplified picture

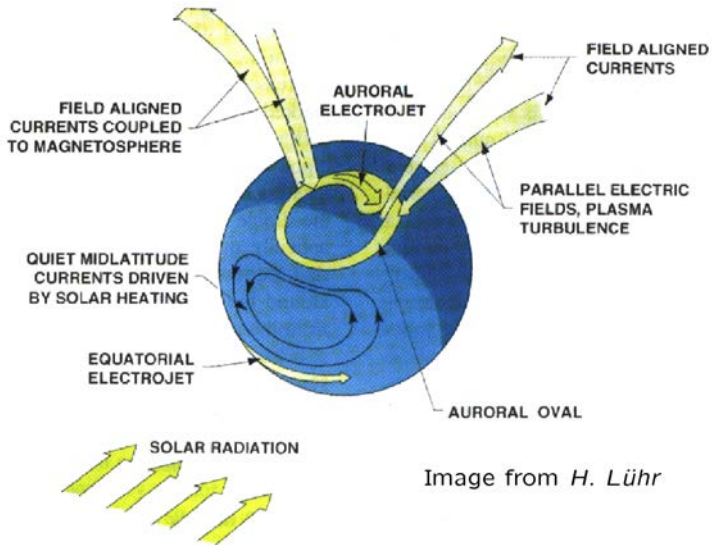
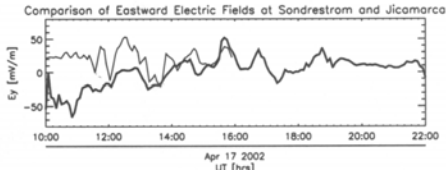
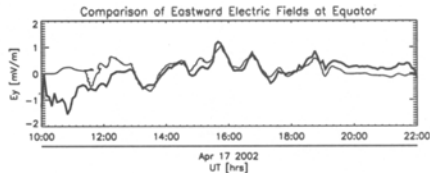
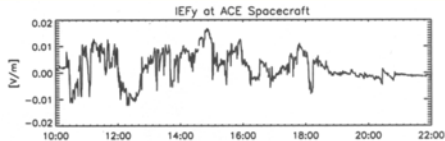


Image from *H. Lühr*

# ELECTRIC FIELD PENETRATION

global penetration [Kelley et al., 2003]

- Penetration of solar wind electric field into the M-I system
- Intense, long duration electric field event on April 17, 2002
- Observations using ACE satellite and radar facilities (Jicamarca, Sondrestrom)
- Strong temporal correlation

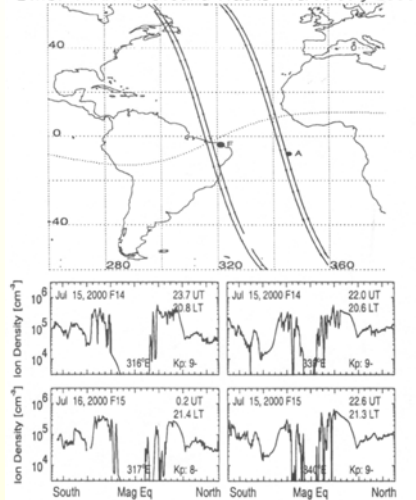


# STORM-TIME M-I EFFECTS

equatorial ionosphere impact [*Basu et al., 2001*]

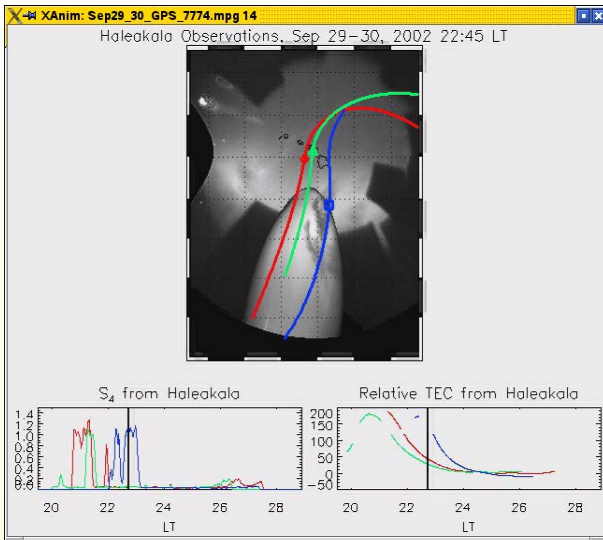
- Magnetic storm of July 15, 2000
- Large bite-outs of electron density in the equatorial region after sunset (e.g., enhanced fountain effect)
- Strong scintillations at 250 MHz and L-band
- Strong upward and southward drifts at 600 km (ROCSAT)

DMSP F14/F15 Ground Tracks - 15/16 July 2000



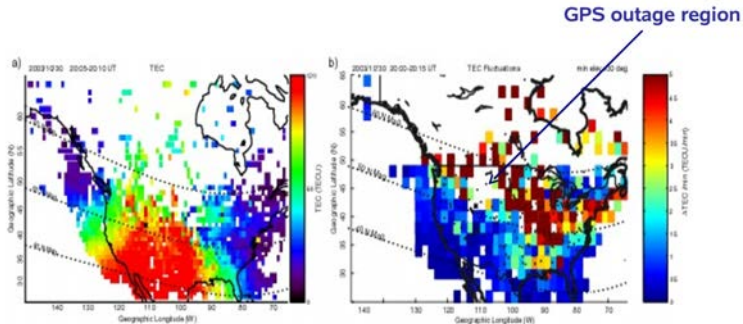
# ESF IMPACT ON RF PROPAGATION

combined optical and propagation data: Jonathan Makela



# STORM TIME IMPACT ON NORTH AMERICA

## Highly Enhanced Total Electron Content and GPS Phase Fluctuations During October 30, 2003 Storm



Intense GPS Phase Fluctuations ( $\Delta\text{TEC}/\text{MIN}$ ) Occur in the Auroral Region and along the Storm Enhanced Total Electron Content (TEC) Gradient. **GPS outage caused WAAS to be non-operational for 11 hours**

(Su Basu et al., GRL, 2005)

Slashdot: News for nerds, stuff that matters - Mozilla Firefox

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2008 CEDAR Workshop

Slashdot: News for nerds, stu...  
 "One issue was that timer based probes wouldn't fire if certain applications were actively executing (e.g. iTunes). This was evident both by counting periodic probe firings, and by the absence of certain applications when profiling. The good news is that Apple has (quietly) fixed the problem in Mac OS X 10.5.3."

apple, macosx (tagging beta)

[Read More...](#) [developers.slashdot.org](#) 14 comments

**News: H.R. 4279 Would Establish Federal IP Cops**

Posted by [kblawson](#) on Wednesday June 11, @05:53AM  
 from the [law-enforcement](#) dept.

MrGravel writes

"H.R. 4279, Prioritizing Resources and Organization for Intellectual Property Act of 2008, is gaining momentum in Congress. It passed the House a few days back. It would allow the Feds to seize hardware that has even one file coming from dubious origins, e.g. downloaded from P2P. If passed into law, the bill would establish an Intellectual Property Enforcement Division within the office of the Deputy Attorney General. Rep. John Conyers says the goal is to 'prioritize intellectual property protection to the highest level of our government.'"

government (tagging beta)

[Read More...](#) [news.slashdot.org](#) 172 comments

**Science: Ionospheric Interference With GPS Signals**

Posted by [kblawson](#) on Wednesday June 11, @03:44AM  
 from the [trust-top-your-garmin](#) dept.

[Roland Piquepaille](#) writes

"In recent years, we have become increasingly dependent on applications using the Global Positioning System, such as railway control, highway traffic management, emergency response, and commercial aviation. But the American Geophysical Union warns us that [we can't always trust our GPS gadgets](#) because electrical activity in the... ionosphere can tamper with signals from GPS satellites." However, new research studies are under way and may lead to regional predictions of reduced GPS reliability and accuracy."

[Roland's blog](#) has useful links and a summary of a [free introduction](#), up at the AGU site, to a special edition of the journal Space Weather with seven articles (not free) regarding ionospheric effects on GPS.

science, space, gps (tagging beta)

[Read More...](#) [science.slashdot.org](#) 59 comments

**Technology: BMW Introduces GINA Concept Car, Covered In Fabric**

Open Source Business Model  
 Using Software Patents  
 Oregon Senate Candidate Steve  
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# FOLLOW-UP LINK

The screenshot shows a Mozilla Firefox browser window displaying a ZDNet blog post. The browser's address bar shows the URL <http://blogs.zdnet.com/emergingtech/?p=948>. The ZDNet website header includes the logo, a search bar, and navigation tabs for Home, News & Blogs, Videos, White Papers, Downloads, Reviews, and Popular. The article is by Roland Piquepaille, dated June 10th, 2008. The main content discusses the reliability of GPS devices, mentioning the American Geophysical Union (AGU) and the ionosphere. A sponsored link for Microsoft System Center is visible on the right side of the page.

Can we trust our GPS devices? | Emerging Technology Trends | ZDNet.com - Mozilla Firefox

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<http://blogs.zdnet.com/emergingtech/?p=948> [youtube](#)

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2008 CEDAR Workshop Can we trust our GPS device...

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**Roland Piquepaille**

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June 10th, 2008

## Can we trust our GPS devices?

Posted by Roland Piquepaille @ 10:00 am

Categories: [Search & Analytics](#) [Storage & Telecom](#) [Spreadsheets](#) [Network](#)

Tags: [Satellite](#) [Globalization](#) [GPS](#) [Hardware](#) [Consumer Electronics](#) [Personal Technology](#) [Hardware](#) [Roland Piquepaille](#)

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In recent years, we have become increasingly dependent on applications using the Global Positioning System (GPS), such as railway control, highway traffic management, emergency response or commercial aviation. But in a very short news release, the American Geophysical Union (AGU) warns us that we can't always trust our GPS gadgets because 'electrical activity in the upper atmospheric zone called the ionosphere can tamper with signals from GPS satellites.' However, new research studies are under way and 'may lead to regional predictions of reduced GPS reliability and accuracy.' But read more...

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NISSAN MANAGES 56,500 PCs WITH MICROSOFT SYSTEM CENTER

Microsoft System Center

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**BNET Industries**

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- Ion Velocity

$$\frac{\partial \mathbf{V}_i}{\partial t} + \mathbf{V}_i \cdot \nabla \mathbf{V}_i = -\frac{1}{\rho_i} \nabla \mathbf{P}_i + \frac{e}{m_i} \mathbf{E} + \frac{e}{m_i c} \mathbf{V}_i \times \mathbf{B} + \mathbf{g}$$

$$- \nu_{in} (\mathbf{V}_i - \mathbf{V}_n) - \sum_j \nu_{ij} (\mathbf{V}_i - \mathbf{V}_j)$$

- Electric field:  $\mathbf{E}$
- Neutral wind:  $\mathbf{V}_n$
- Not independent drivers!

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$$\nabla \cdot \mathbf{J} = 0 \quad \mathbf{J} = \sigma \mathbf{E} \quad \rightarrow \quad \nabla \cdot \sigma \mathbf{E} = 0$$

Field-line integration:  $\int \nabla \cdot \sigma \mathbf{E} ds = 0$

$$\nabla \cdot \Sigma \nabla \Phi = S(J_{\parallel}, V_n, \dots)$$

$$\mathbf{E} = -\nabla \Phi$$

- $\Sigma$ : Field-line integrated Hall and Pedersen conductivities
- $J_{\parallel}$ : Magnetosphere driven
- $V_n$ : Solar and magnetosphere driven

# DERIVATION OF POTENTIAL EQUATION

some gory details 1: **perpendicular current**

- Step 1: calculate  $\mathbf{J}$

$$\mathbf{J} = e(n_i \mathbf{V}_i - n_e \mathbf{V}_e)$$

- Step 2: calculate  $\mathbf{V}_\alpha$

$$\begin{aligned} \frac{\partial \mathbf{V}_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla \mathbf{V}_\alpha = & -\frac{1}{\rho_\alpha} \nabla P_\alpha + \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} + \mathbf{g} \\ & -\nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n) - \sum_j \nu_{\alpha j} (\mathbf{V}_\alpha - \mathbf{V}_j) \end{aligned}$$

- Step 3: simplify  $\mathbf{V}_\alpha$  equation

$$0 = \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} - \nu_{\alpha n} (\mathbf{V}_\alpha - \mathbf{V}_n)$$

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# DERIVATION OF POTENTIAL EQUATION

some gory details 2: **perpendicular current**

- Step 4: solve for  $\mathbf{V}_\alpha$  take ( $\mathbf{B} = B \mathbf{e}_z$ )

$$\mathbf{V}_\alpha = \frac{1}{1 + \nu_{\alpha n}^2 / \Omega_\alpha^2} \left[ \left( \frac{c\mathbf{E}}{B} + \frac{\nu_{\alpha n}}{\Omega_\alpha} \mathbf{V}_n \right) \times \hat{\mathbf{e}}_z + \frac{\nu_{\alpha n}}{\Omega_\alpha} \left( \frac{c\mathbf{E}}{B} + \frac{\nu_{\alpha n}}{\Omega_\alpha} \mathbf{V}_n \right) \right]$$

- Step 5: solve for  $\mathbf{J}$  from definition

$$\mathbf{J} = \sigma_P \left( \mathbf{E} + \frac{B}{c} \mathbf{V}_n \times \hat{\mathbf{e}}_z \right) + \sigma_H \left( \frac{B}{c} \mathbf{V}_n - \mathbf{E} \times \hat{\mathbf{e}}_z \right)$$

where

$$\sigma_P = \frac{ec}{B} \left[ \frac{n_i \nu_{in} / \Omega_i}{1 + \nu_{in}^2 / \Omega_i^2} + \frac{n_e \nu_{en} / \Omega_e}{1 + \nu_{en}^2 / \Omega_e^2} \right]$$
$$\sigma_H = \frac{ec}{B} \left[ -\frac{n_i}{1 + \nu_{in}^2 / \Omega_i^2} + \frac{n_e}{1 + \nu_{en}^2 / \Omega_e^2} \right]$$



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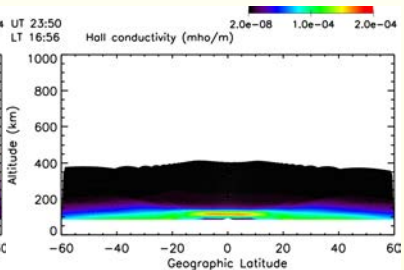
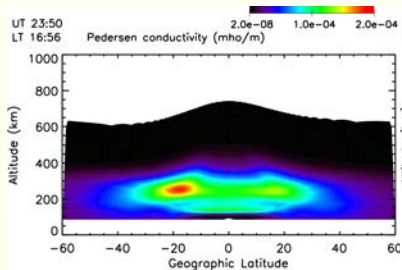
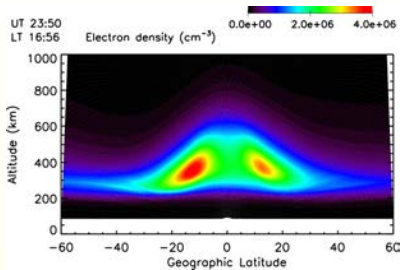
$$\mathbf{J} = \sigma_P \left( \mathbf{E} + \frac{B}{c} \mathbf{V}_n \times \hat{\mathbf{e}}_z \right) + \sigma_H \left( \frac{B}{c} \mathbf{V}_n - \mathbf{E} \times \hat{\mathbf{e}}_z \right)$$

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$$\sigma_H = \frac{ec}{B} \left[ -\frac{n_i}{1 + \nu_{in}^2 / \Omega_i^2} + \frac{n_e}{1 + \nu_{en}^2 / \Omega_e^2} \right]$$

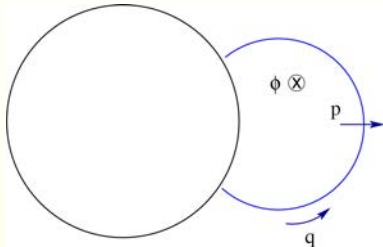
# CONDUCTIVITIES

typical values and spatial dependence



# DERIVATION OF POTENTIAL EQUATION

gets uglier: dipole coordinates



$$q = \frac{r_0^2 \cos \theta}{r^2} \quad p = \frac{r}{r_0 \sin^2 \theta} \quad \phi = \phi$$

$$J_p = \sigma_P \left( E_p + \frac{B}{c} V_{n\phi} \right) + \sigma_H \left( -E_\phi + \frac{B}{c} V_{np} \right)$$

$$J_\phi = \sigma_P \left( E_\phi - \frac{B}{c} V_{np} \right) + \sigma_H \left( E_p + \frac{B}{c} V_{n\phi} \right)$$

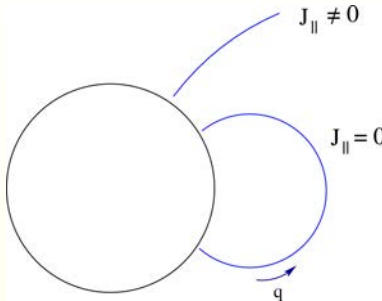
$$\nabla \cdot \mathbf{J} = 0$$

in dipole coordinates

$$\left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial q} (h_p h_\phi J_q) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] = 0$$

where

$$h_p = \frac{r_0 \sin^3 \theta}{(1 + 3 \cos^2 \theta)^{1/2}}$$
$$h_q = \frac{r^3}{r_0^2} \frac{1}{(1 + 3 \cos^2 \theta)^{1/2}}$$
$$h_\phi = r \sin \theta$$



$$\int \nabla \cdot \mathbf{J} dq = 0$$

$$\int \left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial q} (h_p h_\phi J_q) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] dq = 0$$

$$\int \left[ \frac{\partial}{\partial p} (h_q h_\phi J_p) + \frac{\partial}{\partial \phi} (h_p h_q J_\phi) \right] dq = -h_p h_\phi J_q \quad (\propto J_\parallel)$$

- Electric field in dipole coordinates:  $\mathbf{E} = \nabla\Phi$

$$E_p = -\frac{\Delta}{r_0 \sin^3 \theta} \frac{\partial \Phi}{\partial p} \quad E_\phi = -\frac{1}{r \sin \theta} \frac{\partial \Phi}{\partial \phi}$$

- Substitute  $h$ 's,  $\mathbf{E}$ 's into potential equation

$$\underbrace{\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \frac{\Sigma_{p\phi}}{p} \frac{\partial \Phi}{\partial \phi}}_{\text{Pedersen}} - \underbrace{\frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}}_{\text{Hall}}$$

$$= \underbrace{\frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi}}_{\text{Neutral winds}} + \underbrace{+f(J_{\parallel})}_{\text{High latitude currents}}$$

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$$= \underbrace{\frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi}}_{\text{Neutral winds}} + \underbrace{+f(J_{\parallel})}_{\text{High latitude currents}}$$

$$\Sigma_{pp} = \int \sigma_P \frac{\Delta}{b_s} dq \quad \Sigma_{p\phi} = \int \sigma_P \frac{1}{b_s \Delta} dq \quad \Sigma_H = \int \sigma_H \frac{1}{b_s} dq$$

$$F_{pV} = \int \frac{B_0}{c} r \sin \theta (\sigma_P V_{n\phi} + \sigma_H V_{np}) dq$$

$$F_{\phi V} = \int \frac{B_0}{c} \frac{r_0 \sin^3 \theta}{\Delta} (-\sigma_P V_{np} + \sigma_H V_{n\phi}) dq$$

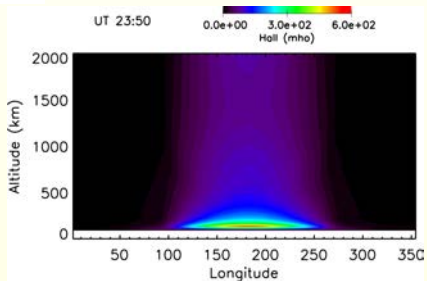
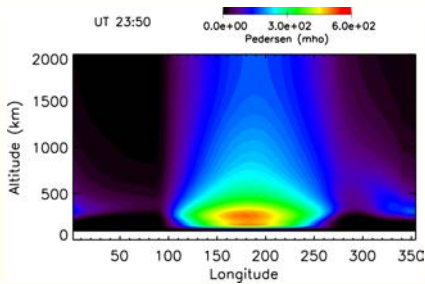
$$\sigma_P = \sum_i \frac{n_i e c}{B} \frac{\nu_{in}/\Omega_i}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e e c}{B} \frac{\nu_{en}/\Omega_e}{1 + \nu_{en}^2/\Omega_e^2}$$

$$\sigma_H = - \sum_i \frac{n_i e c}{B} \frac{1}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e e c}{B} \frac{1}{1 + \nu_{en}^2/\Omega_e^2}$$



# CONDUCTANCES

typical values and spatial dependence



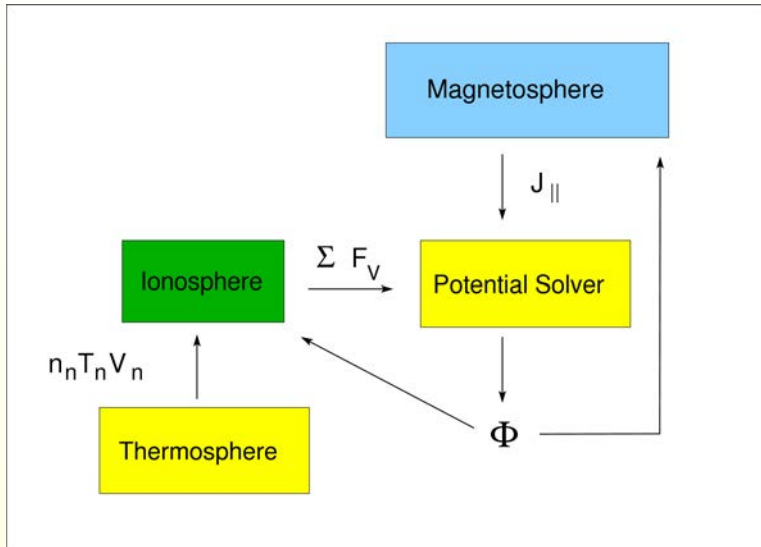
# THE POTENTIAL EQUATION

alternative formulation

- Derivation in  $(p, \phi)$  space: solved in the magnetic equatorial plane (essentially  $(r, \phi)$  space)
- Can also be solved in  $(\theta, \phi)$  space: map magnetic apex height  $(p)$  to base of the field line to define associated latitude  $\theta$
- Richmond (magnetic apex model) and Heelis (*Plan. Space Sci.* 22, 743, 1974)

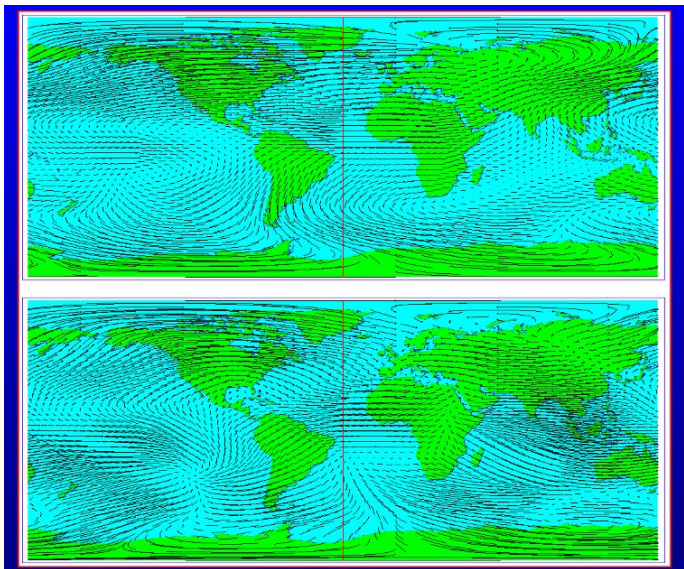
# PUTTING IT ALL TOGETHER

pieces of the picture



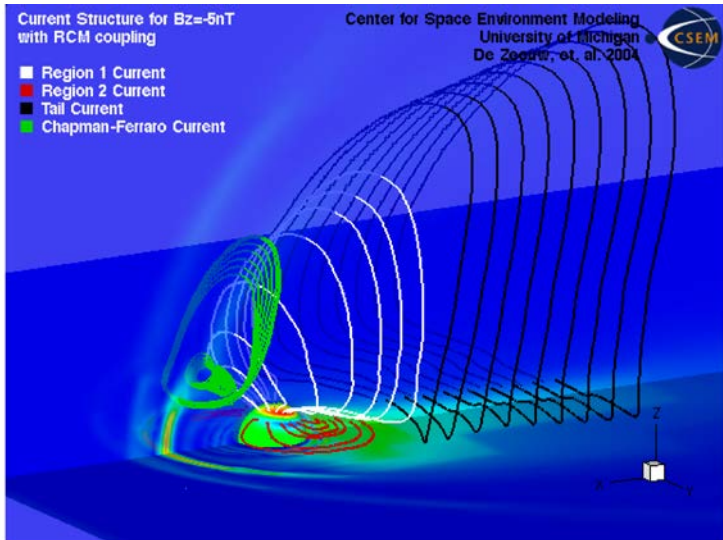
# THERMOSPHERIC WINDS

drives dynamo electric field (HWM07- Doug Drob)



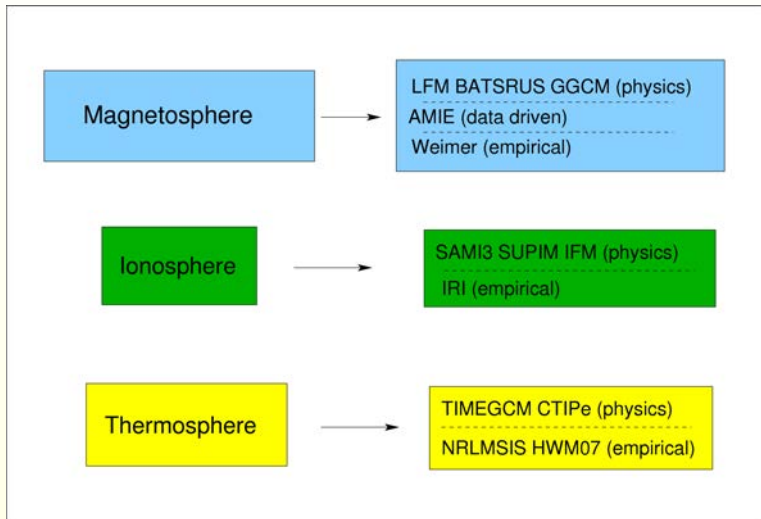
# MAGNETOSPHERIC CURRENTS

origin of  $J_{\parallel}$ : flow shear



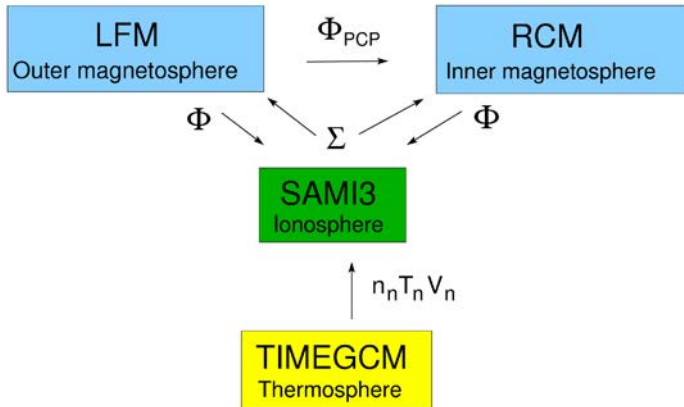
# EXAMPLE OF MODELS

not all-inclusive



# SELF-CONSISTENT COUPLING: PRESENT

at NRL/RICE/ASTRA



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

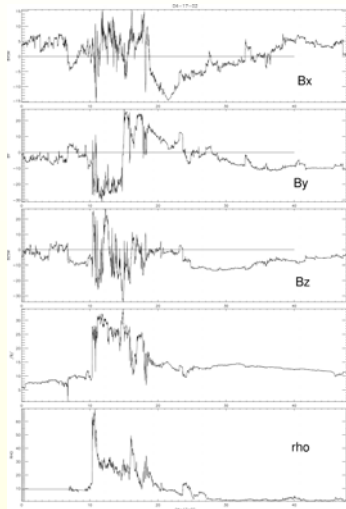
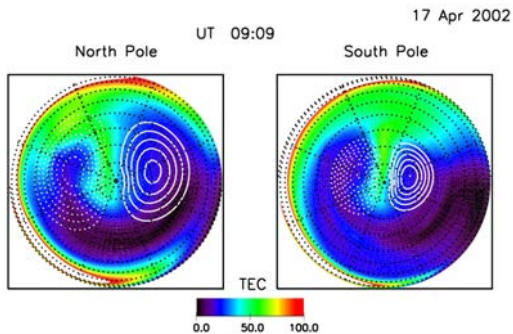
$$\nabla \cdot \underbrace{\Sigma}_{\text{SAMI3}} \cdot \nabla \Phi = \underbrace{J_{\parallel}}_{\text{LFM/RCM}}$$

- SAMI3 provides the ionospheric conductance to LFM/RCM
- LFM/RCM solves the potential equation to determine  $\Phi$
- LFM/RCM provides the  $\Phi$  to SAMI3
- SAMI3 and RCM use  $\Phi$  to calculate the electric field
- Transport the plasma

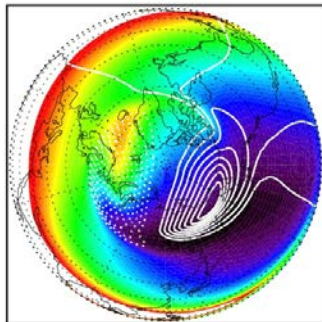


# SAMI3/LFM RESULTS

17 April 2002 storm

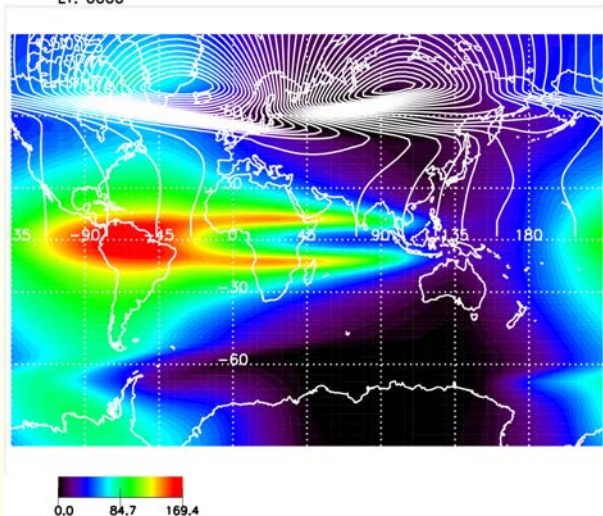


TEC  
UT 16:00      17 Apr 2002



UT: 2100  
LT: 0000

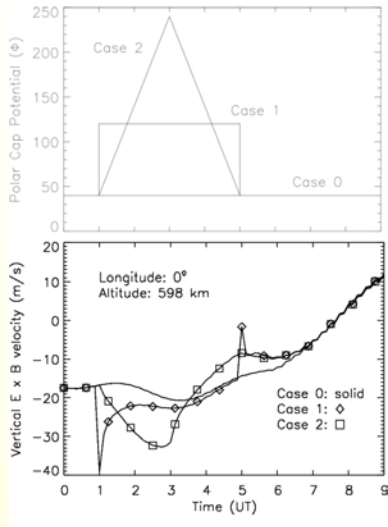
TEC and Potential



# PENETRATION FIELD

time dependence (different simulation)

- Vertical  $E \times B$  drift
- Time-dependence of  $\Phi$  important: integrated effect
- Decay time  $\sim 30 - 60$  min following impulse



- LFM
  - Restricted to magnetic latitudes  $\gtrsim 55^\circ$
  - Potential  $\Phi = 0$  on boundary
  - Limited resolution of region 2 current system
- RCM
  - Restricted to magnetic latitudes  $\lesssim 75^\circ$
  - Potential  $\Phi$  specified on boundary
  - Limited resolution of region 1 current system
  - Dipole field aligned with earth's spin axis
  - Interhemispheric symmetry ( $B_y = 0$ )
- Resolution: blend/average currents from both codes and use resulting  $\Phi$  in both codes?

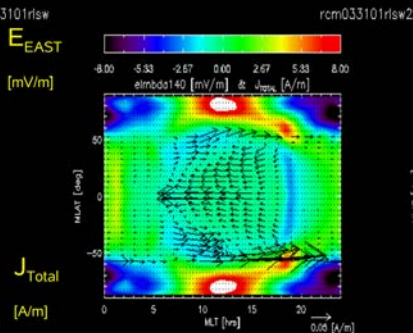
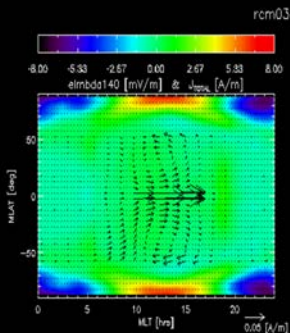
## Dynamo Currents & Electric fields

QUIET:

Sq current

STORM:

reverse Sq



- ITM electrodynamic coupling can have a major impact on the low- to mid-latitude ionosphere during storms
  - Penetration electric fields can lead to large increases in the daytime mid-latitude TEC (storm enhanced densities) as well as large decreases in the post-sunset equatorial region
  - Dynamo electric field can be strongly modified by storm driven neutral winds (coupling to the thermosphere required)
- Other coupling issues
  - High-latitude Joule heating
  - Ionospheric outflow