IONOSPHERE/THERMOSPHERE/MAGNETOSPHERE: ITM ELECTRODYNAMIC COUPLING

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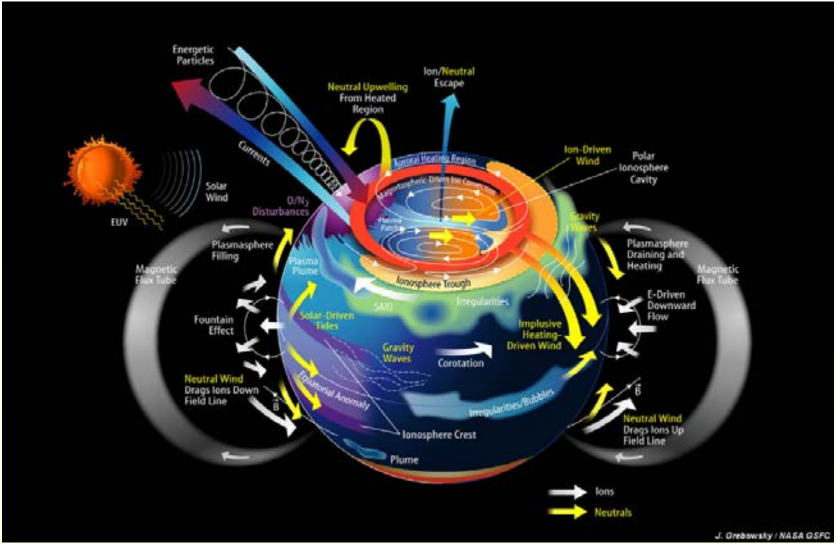
ITM SYSTEM

lots of physics



ITM CURRENT SYSTEM

simplified picture

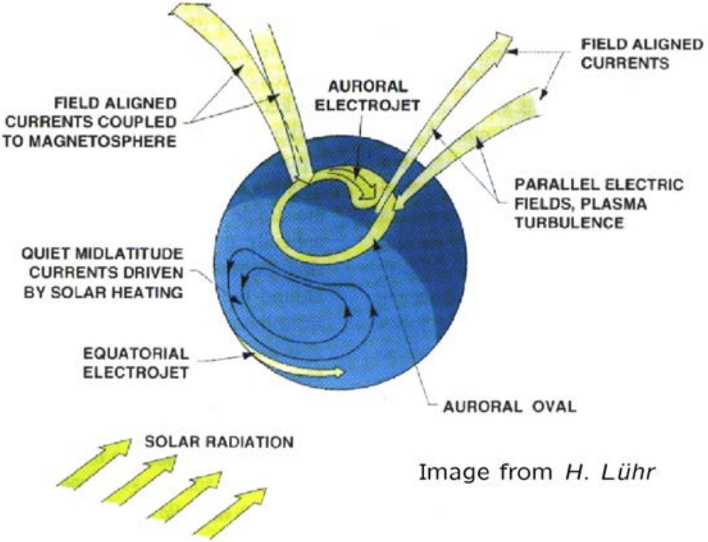
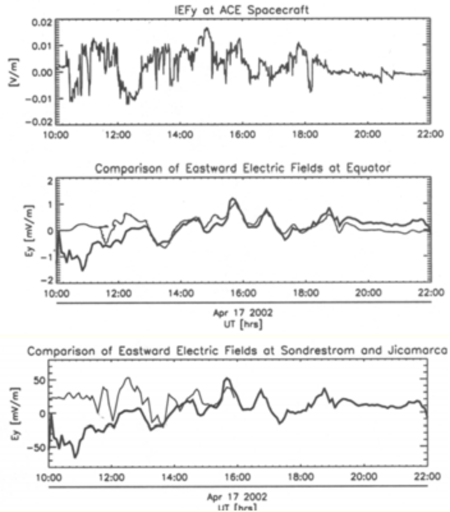


Image from *H. Lühr*

ELECTRIC FIELD PENETRATION

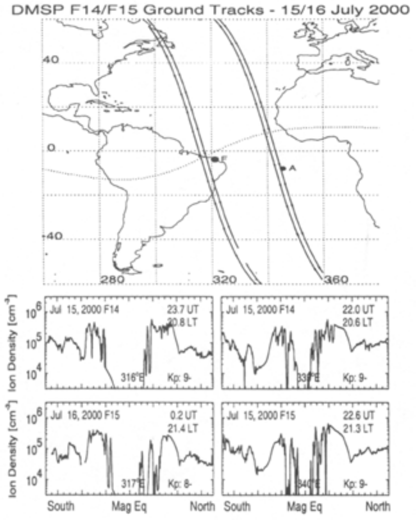
- Penetration of solar wind electric field into the M-I system
- Intense, long duration electric field event on April 17, 2002
- Observations using ACE satellite and radar facilities (Jicamarca, Sondrestrom)
- Strong temporal correlation



STORM-TIME M-I EFFECTS

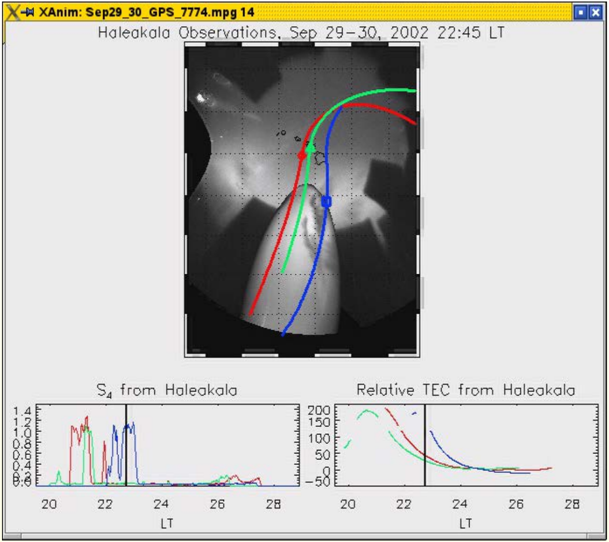
equatorial ionosphere impact [*Basu et al.*, 2001]

- 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)



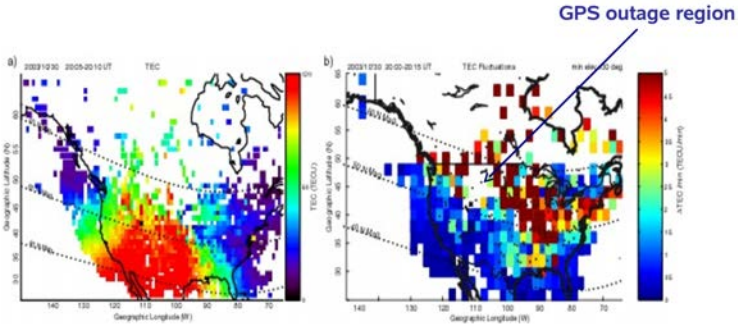
ESF IMPACT ON RF PROPAGATION

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

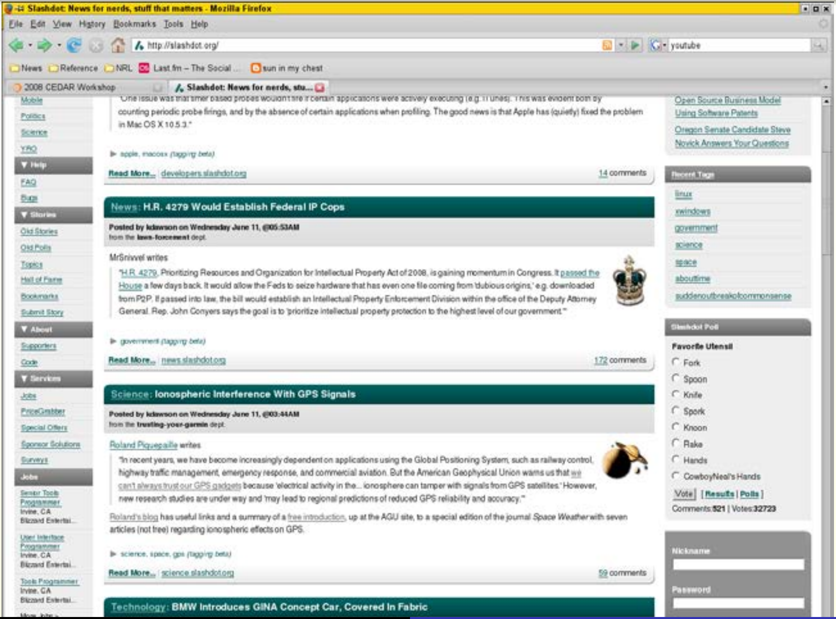


Intense GPS Phase Fluctuations (Delta TEC/MIN) Occur in the Auroral Region and along the Storm Enhanced Total Electron Content (TEC) Gradient. GPS outage caused WAAS to be non-operational for 11 hours

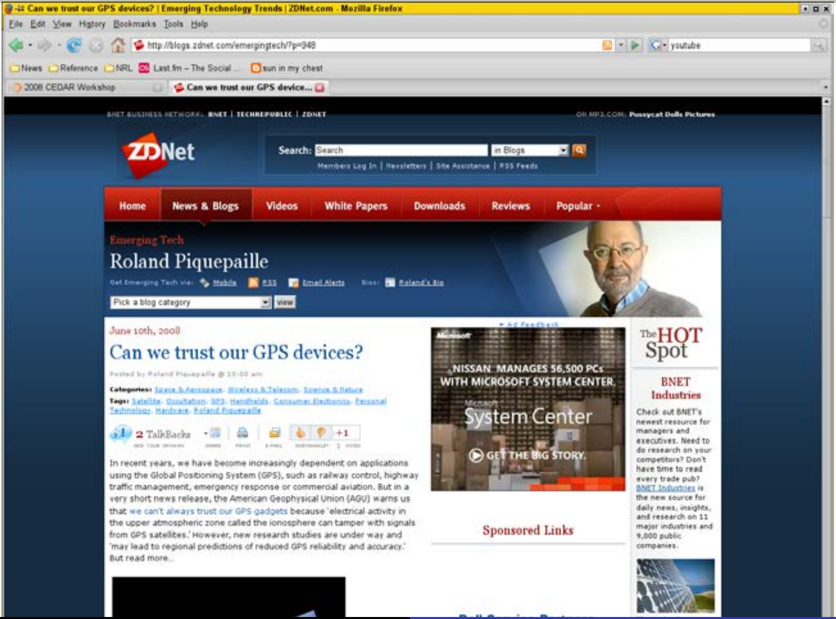
(Su Basu et al., GRL, 2005)

EVEN SLASHDOTTED!!!

link to Space Weather



FOLLOW-UP LINK



MAIN IONOSPHERE DRIVERS

- Ion Velocity

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

$$-\nu_{in} (\mathbf{V}_i - \mathbf{V_n}) - \sum_j \nu_{ij} \left(\mathbf{V}_i - \mathbf{V}_j \right)$$

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

- Ion Velocity

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

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- Electric field: $\mathbf{E}$
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ELECTRODYNAMIC COUPLING

based on current conservation

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

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

$$\nabla \cdot \mathbf{\Sigma} \nabla \Phi = S(J_{\|}, V_n, \ldots)$$

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

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

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

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

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

$$\frac{\partial \mathbf{V}_\alpha}{\partial t} + \mathbf{V}_\alpha \cdot \nabla \mathbf{V}_\alpha = -\frac{1}{\rho_\alpha} \nabla \mathbf{P}_\alpha + \frac{e_\alpha}{m_\alpha} \mathbf{E} + \frac{e_\alpha}{m_\alpha c} \mathbf{V}_\alpha \times \mathbf{B} + \mathbf{g}$$

$$-\nu_{\alpha n}(\mathbf{V}_\alpha - \mathbf{V}_n) - \sum_j \nu_{\alpha j} (\mathbf{V}_\alpha - \mathbf{V}_j)$$

- 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 1: perpendicular current

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

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

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

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

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

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

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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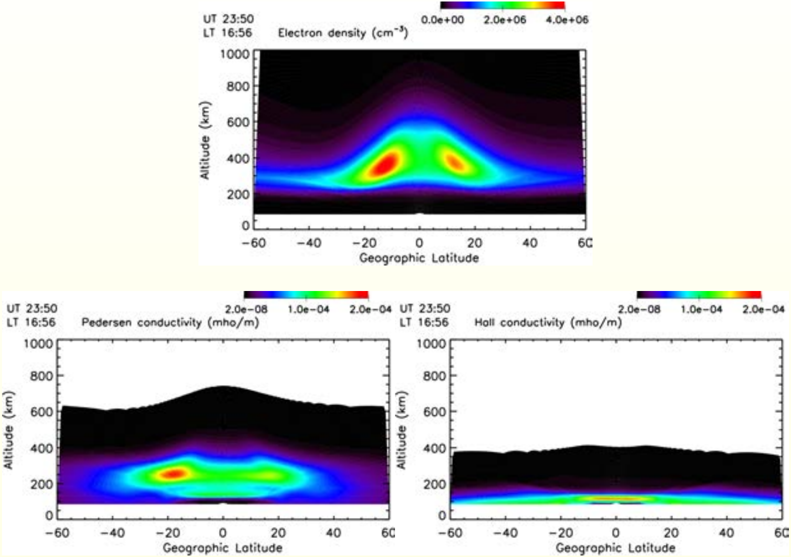
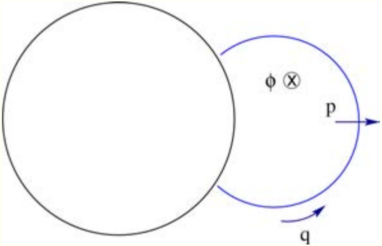
CONDUCTIVITIES

typical values and spatial dependence



DERIVATION OF POTENTIAL EQUATION

gets uglier: dipole coordinates



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

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

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

POTENTIAL EQUATION

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

in dipole coordinates

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

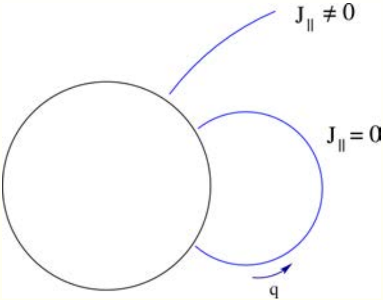
where

$$h_p = \frac{r_0 \sin^3\theta}{\left(1 + 3\cos^2\theta\right)^{1/2}}$$

$$h_q = \frac{r^3}{r_0^2}\frac{1}{\left(1 + 3\cos^2\theta\right)^{1/2}}$$

$$h_\phi = r\sin\theta$$

POTENTIAL EQUATION



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

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

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

THE POTENTIAL EQUATION

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

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

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

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

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

THE POTENTIAL EQUATION

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

AND DEFINITIONS ...

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

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

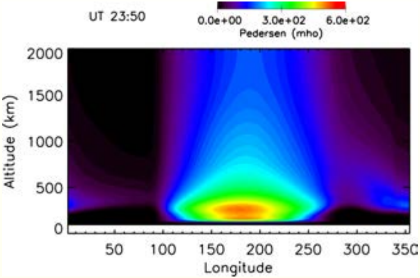
$$F_{\phi V} = \int \frac{B_0}{c} \frac{r_0 \sin^3\theta}{\Delta} (-\sigma_P V_{np} + \sigma_H V_{n\phi}) dq$$

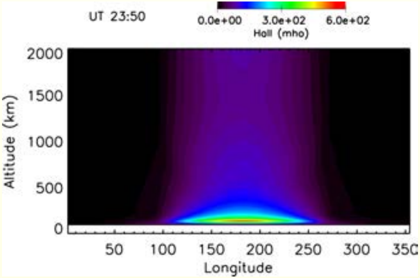
$$\sigma_P = \sum_i \frac{n_i ec}{B} \frac{\nu_{in}/\Omega_i}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e ec}{B} \frac{\nu_{en}/\Omega_e}{1 + \nu_{en}^2/\Omega_e^2}$$

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

CONDUCTANCES

typical values and spatial dependence

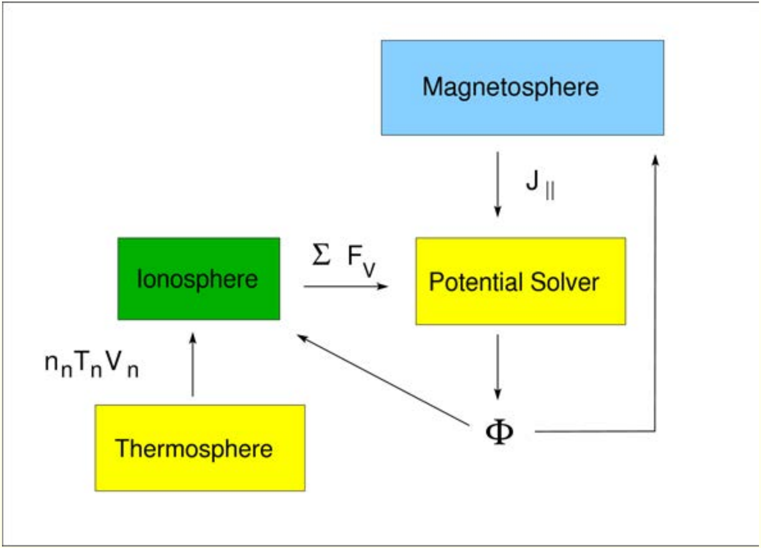




THE POTENTIAL EQUATION

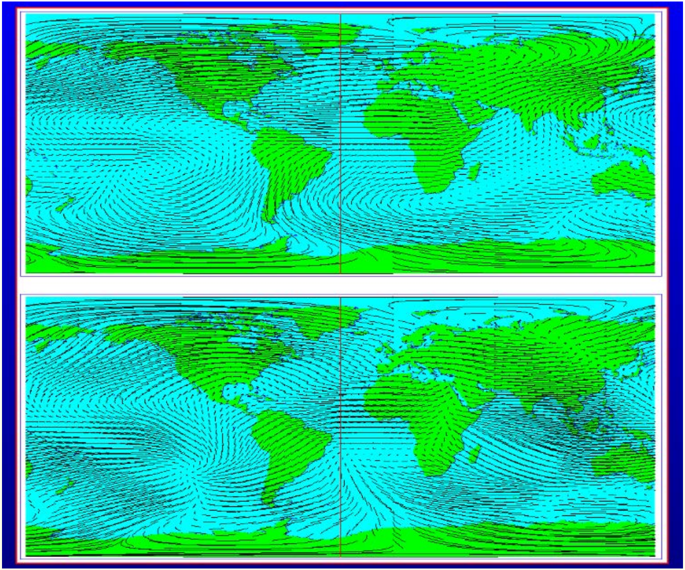
- Derivation in (p, ϕ) space: solved in the magnetic equatorial plane (essentially (r, ϕ) space)
- Can also be solved in (θ, ϕ) space: map magnetic apex height (p) to base of the field line to define associated latitude θ
- Richmond (magnetic apex model) and Heelis (*Plan. Space Sci. 22*, 743, 1974)

PUTTING IT ALL TOGETHER



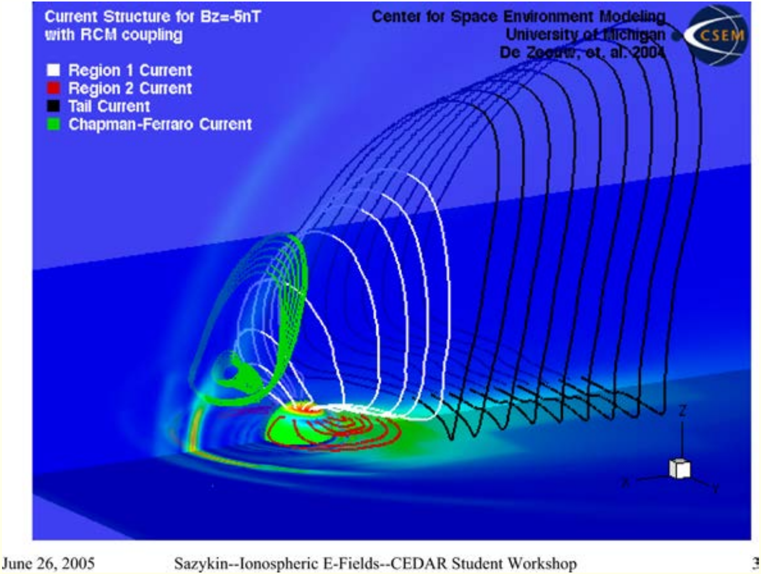
THERMOSPHERIC WINDS

drives dynamo electric field (HWM07- Doug Drob)



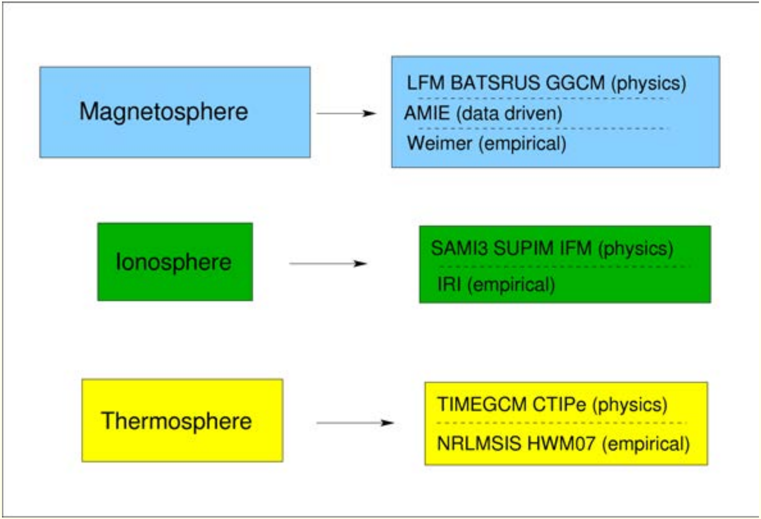
MAGNETOSPHERIC CURRENTS

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



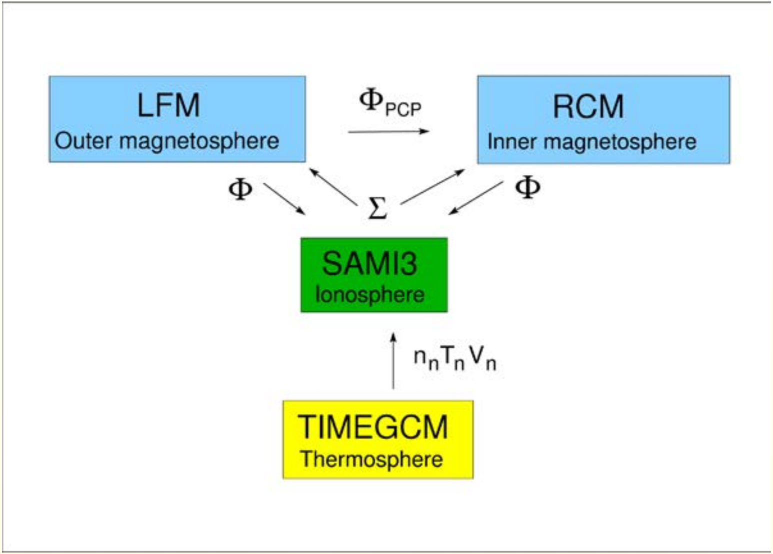
EXAMPLE OF MODELS

not all-inclusive



SELF-CONSISTENT COUPLING: PRESENT

at NRL/RICE/ASTRA



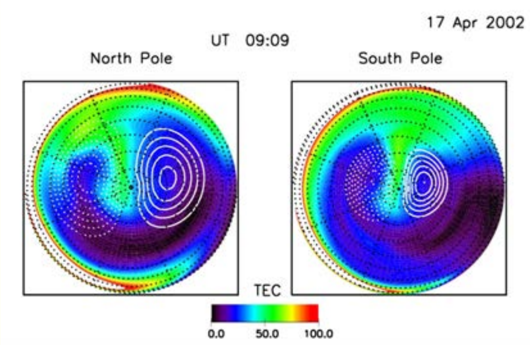
- The fundamental coupling of LFM/RCM and SAMI3 is through the solution of the potential equation

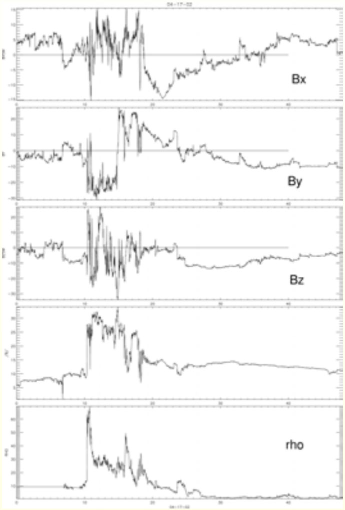
$$\nabla \cdot \underbrace{\Sigma}_{SAMI3} \cdot \nabla\Phi = \underbrace{J_\parallel}_{LFM/RCM}$$

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

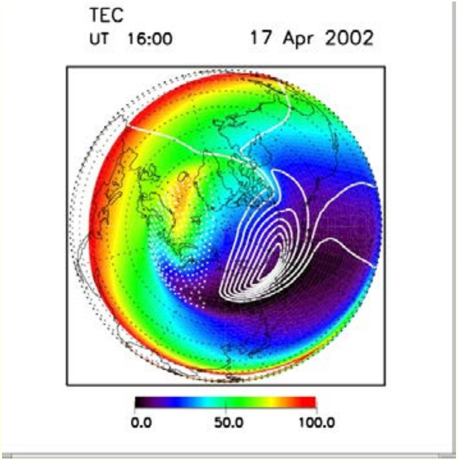
SAMI3/LFM RESULTS

17 April 2002 storm





SAMI3/RCM RESULTS



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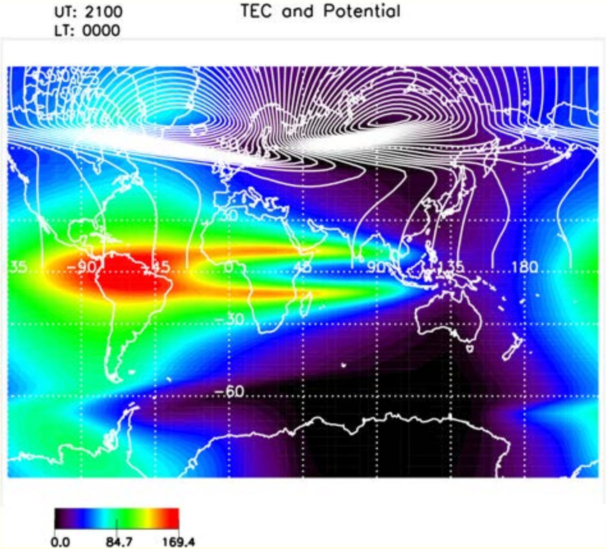
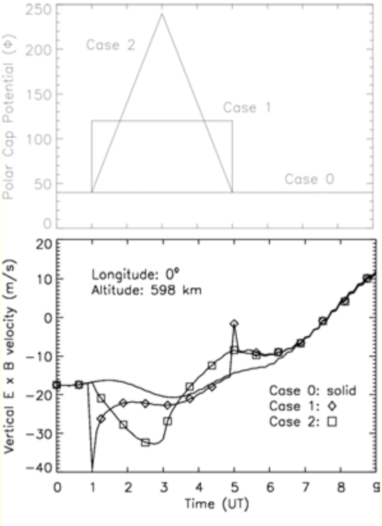


PENETRATION FIELD

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

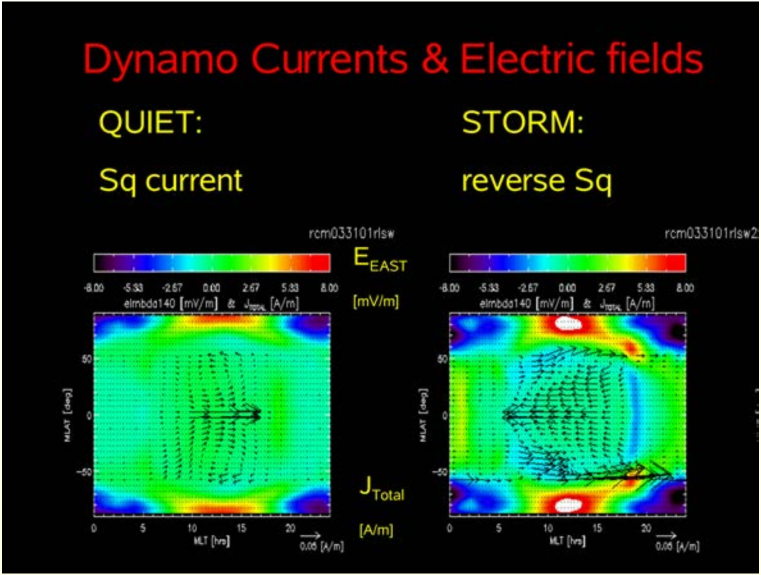


DILEMMA: HIGH LATITUDE COUPLING

- 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 Φ 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 Φ in both codes?

DYNAMO ELECTRIC FIELD

from Naomi Maruyama (CTIPe)



SUMMARY

- 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