IONOSPHERE/THERMOSPHERE/MAGNETOSPHERE: ITM ELECTRODYNAMIC COUPLING

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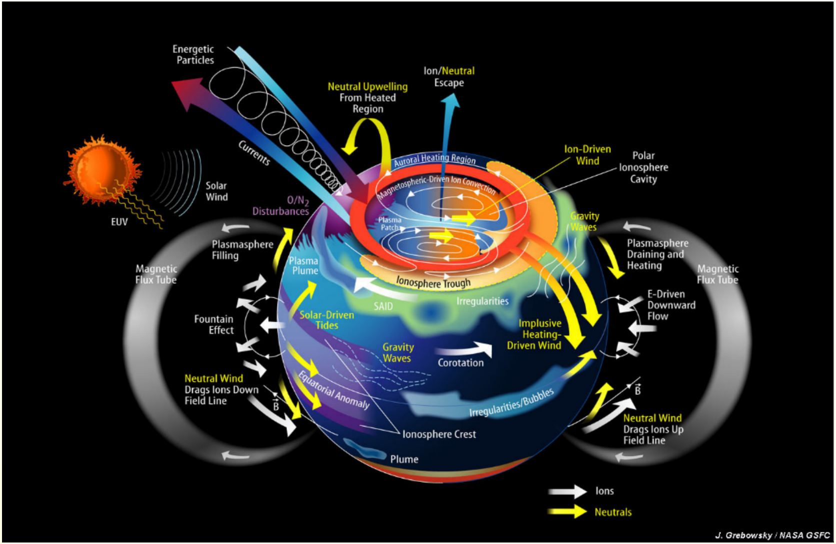
ITM SYSTEM

lots of physics



ITM CURRENT SYSTEM

simplified picture

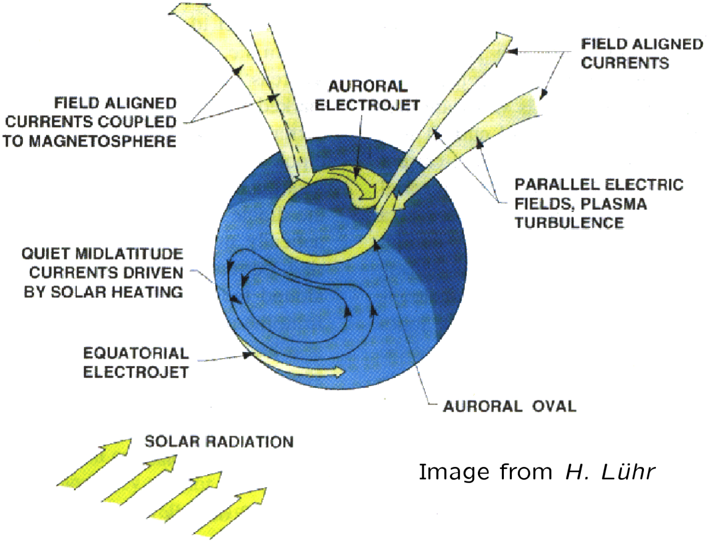
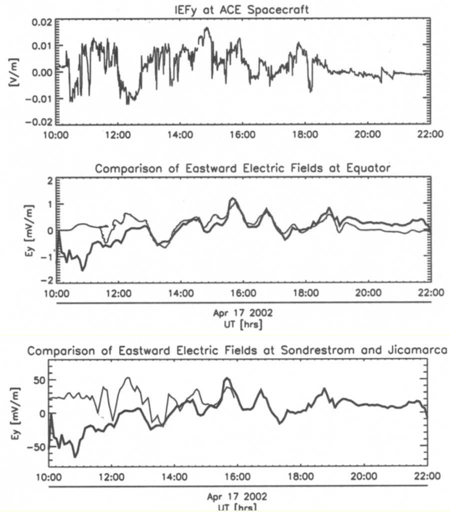


Image from *H. Lühr*

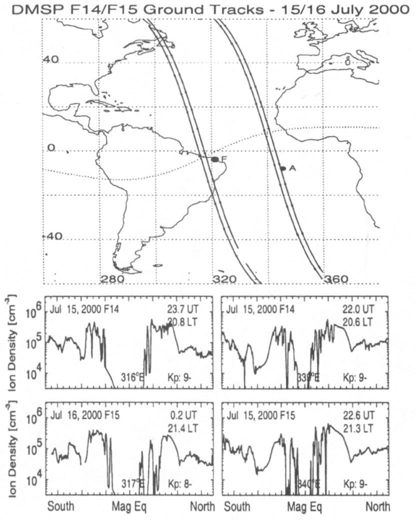
- Penetration of solar wind electric field into the M-I system
- Intense, long duration electric field event on April 17, 2002
- Observations using ACE satellite and radar facilities (Jicamarca, Sondrestrom)
- Strong temporal correlation



STORM-TIME M-I EFFECTS

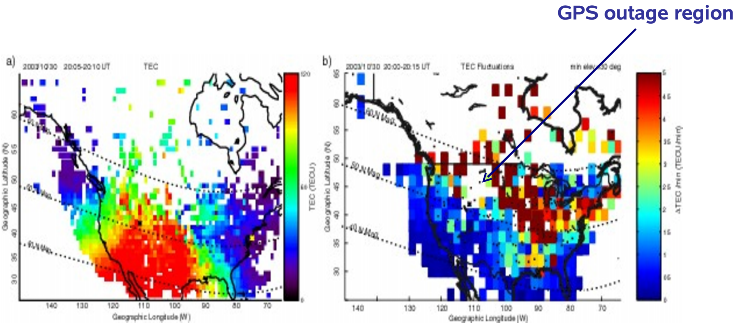
equatorial ionosphere impact [*Basu et al.*, 2001]

- 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)



STORM TIME IMPACT ON NORTH AMERICA

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

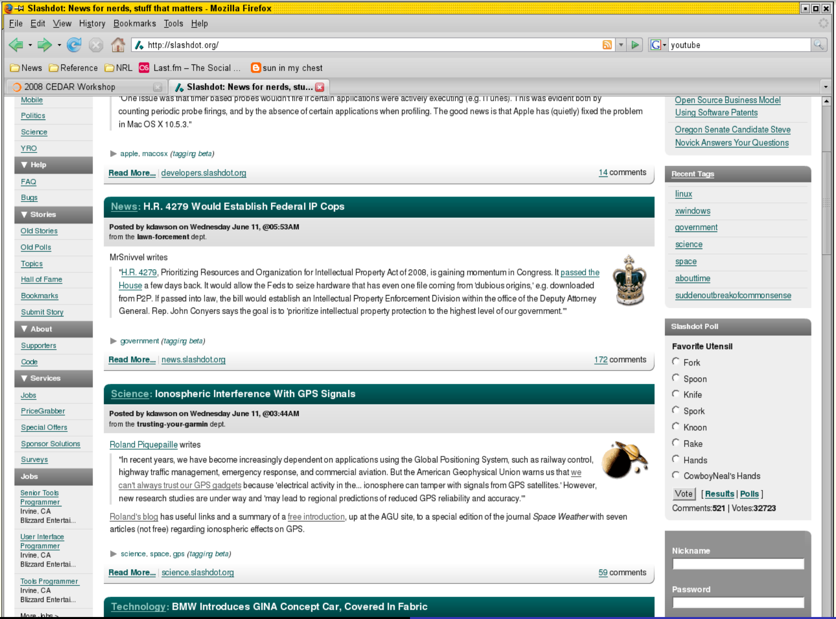


Intense GPS Phase Fluctuations (Delta TEC/MIN) Occur in the Auroral Region and along the Storm Enhanced Total Electron Content (TEC) Gradient. GPS outage caused WAAS to be non-operational for 11 hours

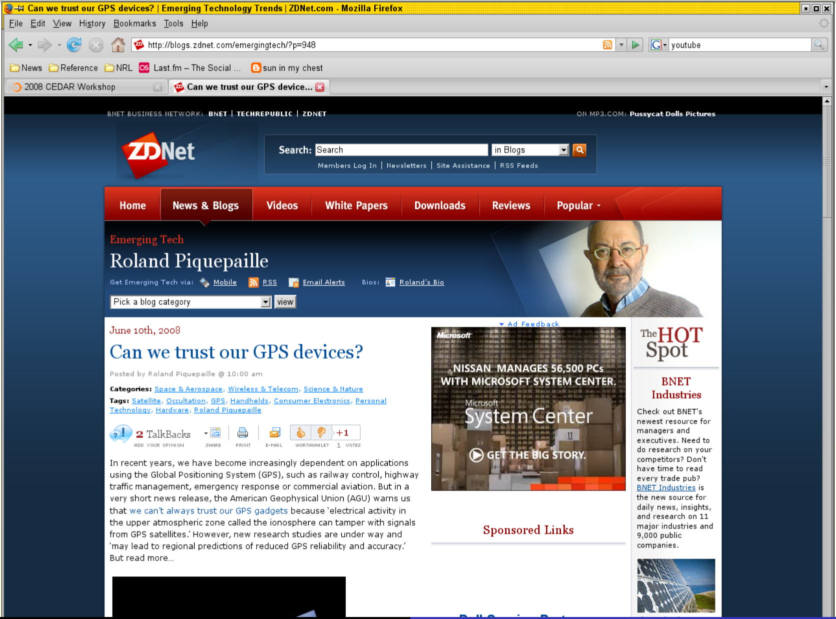
(Su Basu et al., GRL, 2005)

EVEN SLASHDOTTED!!!

link to Space Weather

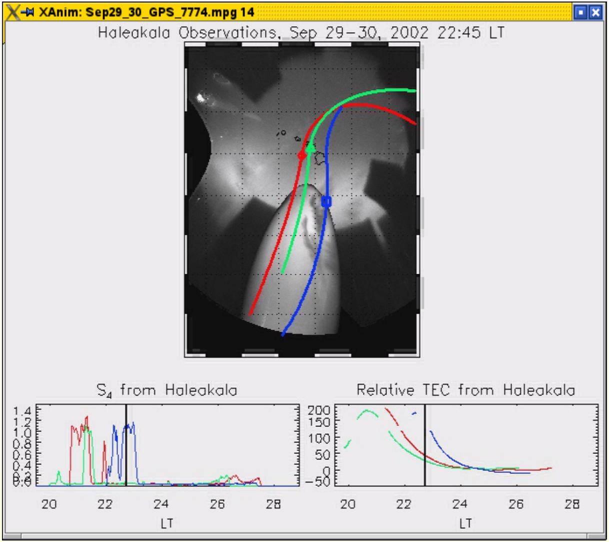


FOLLOW-UP LINK



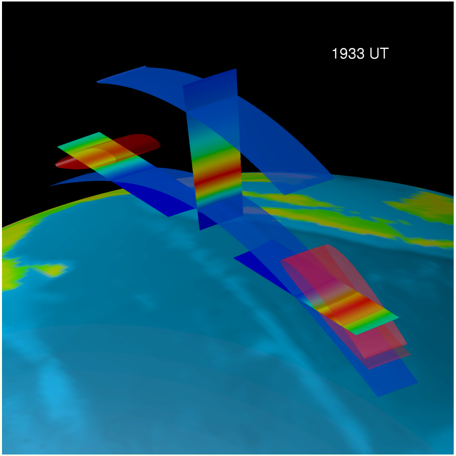
ESF IMPACT ON RF PROPAGATION

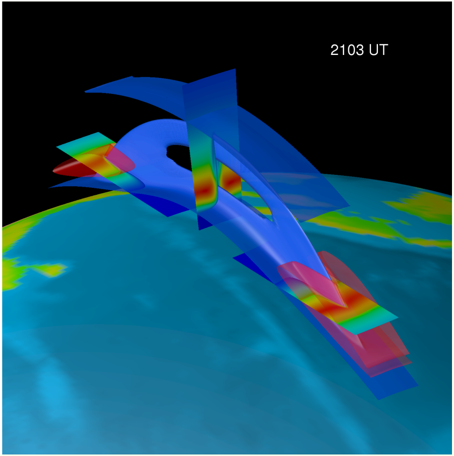
combined optical and propagation data: Jonathan Makela



SAMI3/ESF SIMULATION

Huba et al., GRL (2008)





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!

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ELECTRODYNAMIC COUPLING

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

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

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

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

- 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

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

DERIVATION OF POTENTIAL EQUATION

some gory details 1: perpendicular current

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

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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

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

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

DERIVATION OF POTENTIAL EQUATION

some gory details 2: perpendicular current

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

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

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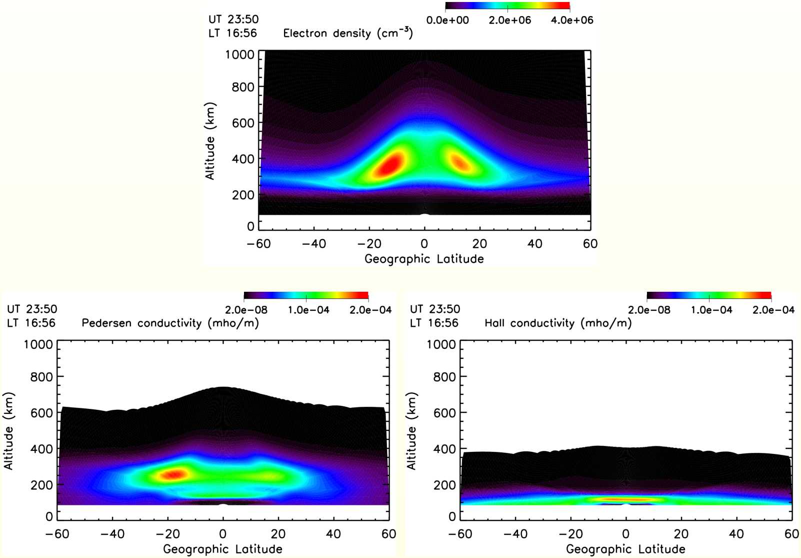
$$\sigma_H = \frac{ec}{B}\left[-\frac{n_i}{1+\nu_{in}^2/\Omega_i^2} + \frac{n_e}{1+\nu_{en}^2/\Omega_e^2}\right]$$

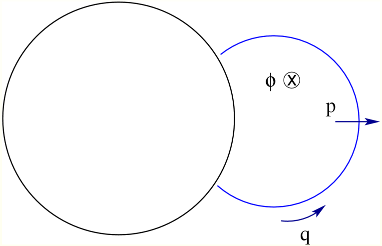
CONDUCTIVITIES

typical values and spatial dependence



DERIVATION OF POTENTIAL EQUATION

gets uglier: dipole coordinates



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

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

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

POTENTIAL EQUATION

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

in dipole coordinates

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

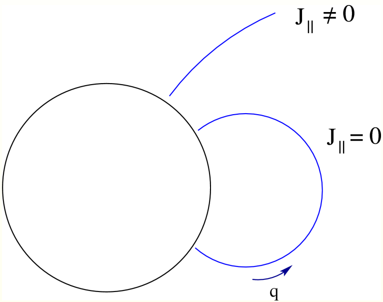
where

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

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

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

POTENTIAL EQUATION



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

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

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

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

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

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

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

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

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

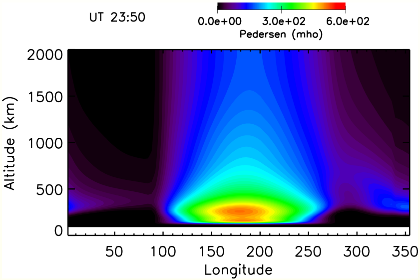
$$F_{\phi V} = \int \frac{B_0}{c} \frac{r_0 \sin^3\theta}{\Delta} (-\sigma_P V_{np} + \sigma_H V_{n\phi}) dq$$

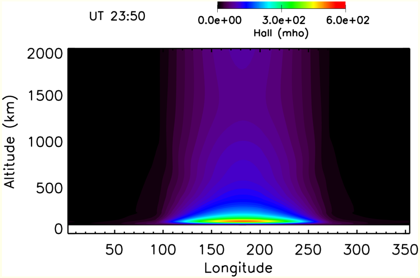
$$\sigma_P = \sum_i \frac{n_i e c}{B} \frac{\nu_{in}/\Omega_i}{1 + \nu_{in}^2/\Omega_i^2} + \frac{n_e e c}{B} \frac{\nu_{en}/\Omega_e}{1 + \nu_{en}^2/\Omega_e^2}$$

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

CONDUCTANCES

typical values and spatial dependence

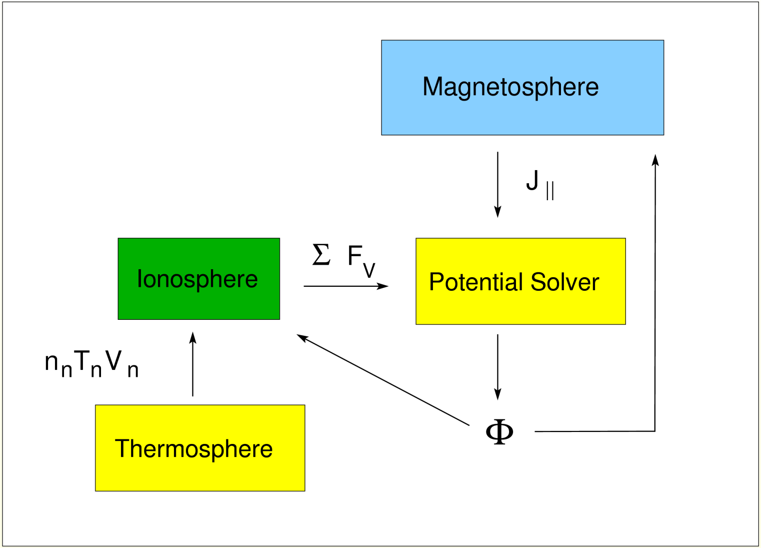




THE POTENTIAL EQUATION

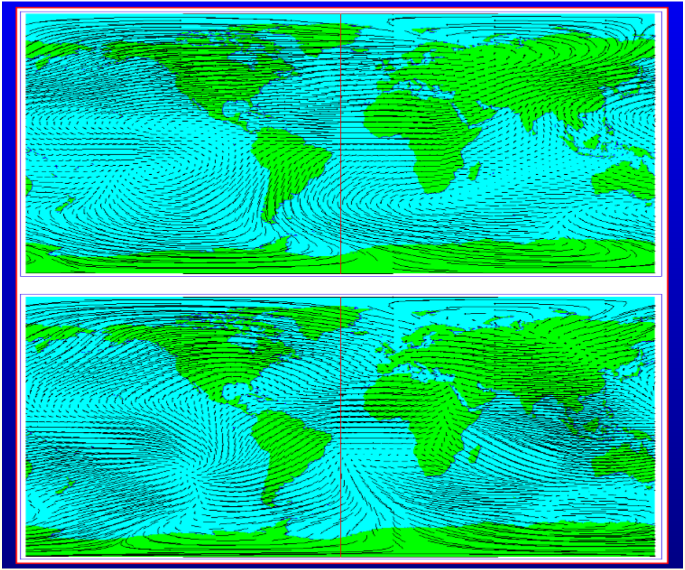
- Derivation in (p, ϕ) space: solved in the magnetic equatorial plane (essentially (r, ϕ) space)
- Can also be solved in (θ, ϕ) space: map magnetic apex height (p) to base of the field line to define associated latitude θ
- Richmond (magnetic apex model) and Heelis (*Plan. Space Sci. 22*, 743, 1974)

PUTTING IT ALL TOGETHER



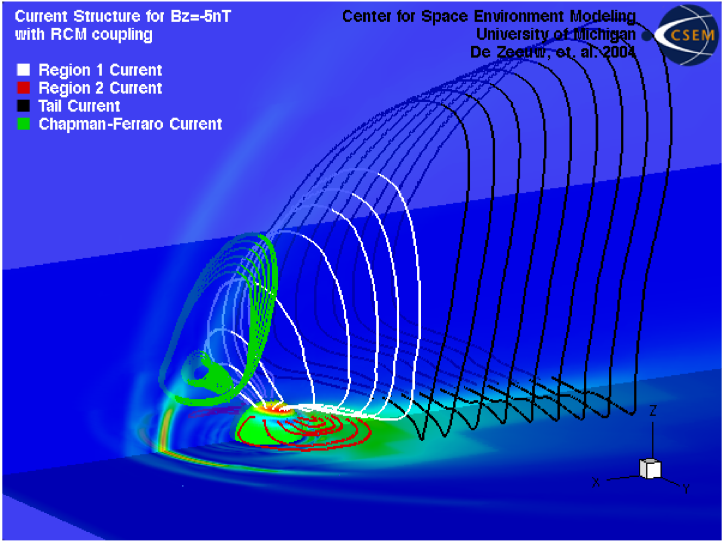
THERMOSPHERIC WINDS

drives dynamo electric field (HWM07- Doug Drob)



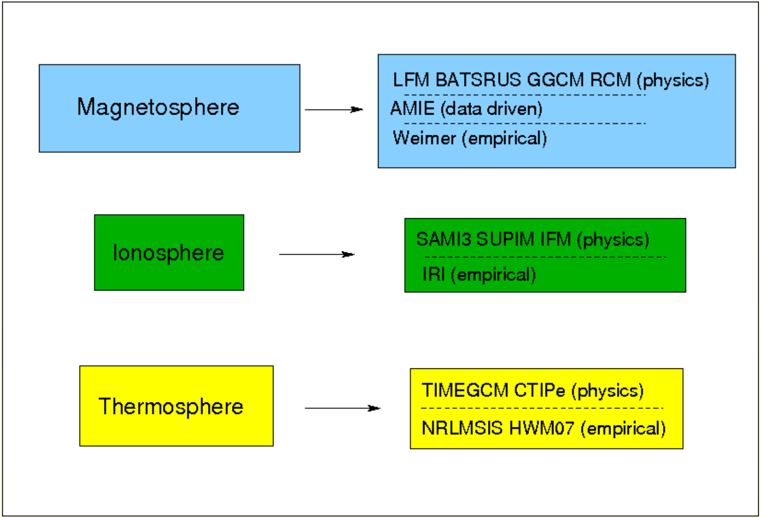
MAGNETOSPHERIC CURRENTS

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



EXAMPLE OF MODELS

not all-inclusive



COUPLED SAMI3/RCM AND SAMI3/LFM MODEL

Self-consistent coupling through Φ

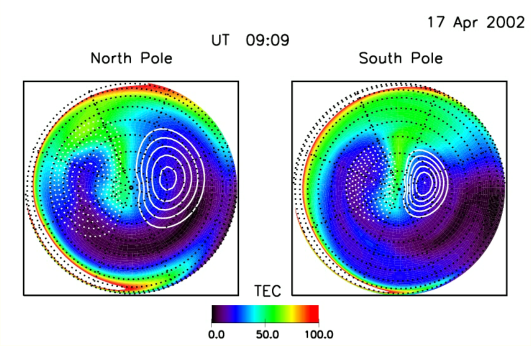
- The fundamental coupling of LFM/RCM and SAMI3 is through the solution of the potential equation

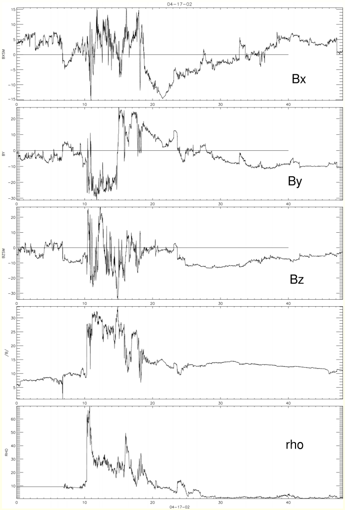
$$\nabla \cdot \underbrace{\Sigma}_{SAMI3} \cdot \nabla \Phi = \underbrace{J_{\parallel}}_{LFM/RCM}$$

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

SAMI3/LFM RESULTS

17 April 2002 storm





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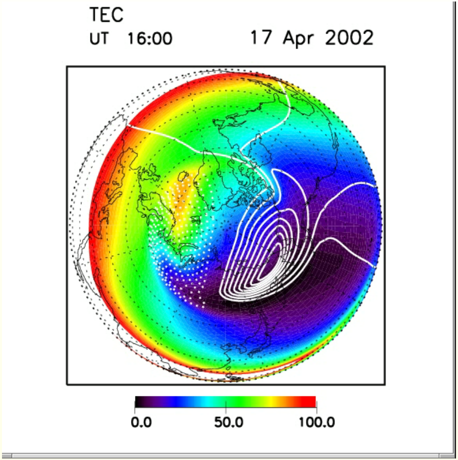

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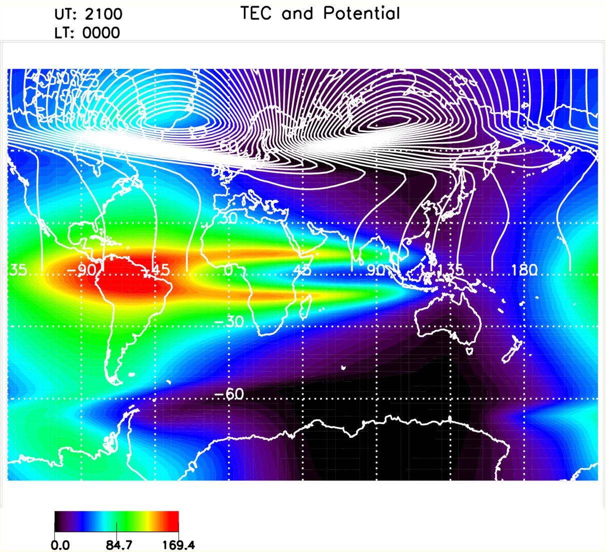
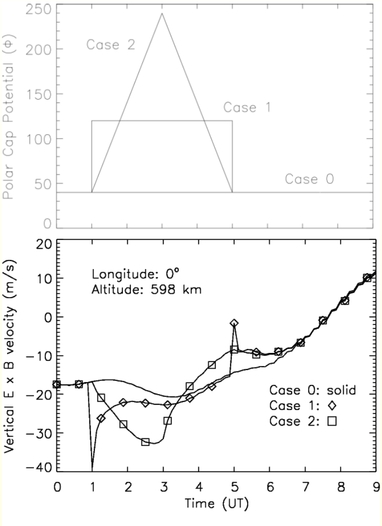


PENETRATION FIELD

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

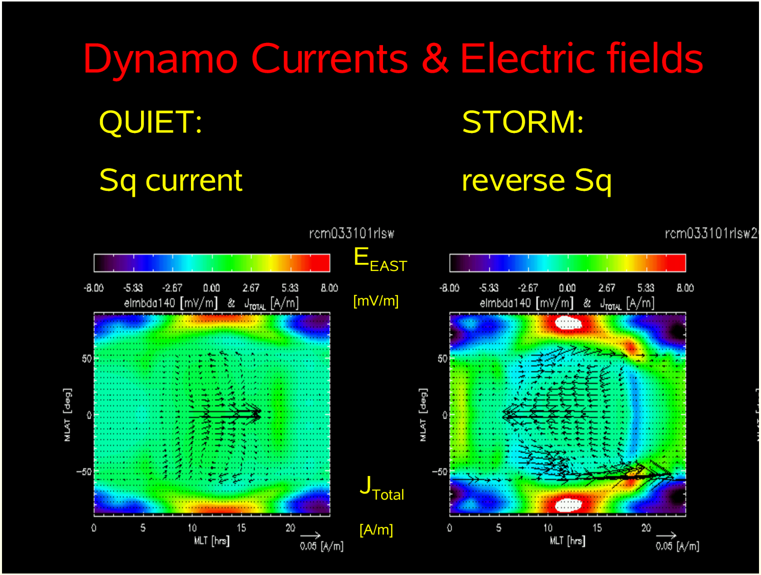


DILEMMA: HIGH LATITUDE COUPLING

- 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