MODELING GLOBAL IONOSPHERIC PHENOMENA

(SAMI3, equatorial spread F, electrodynamics, ...)

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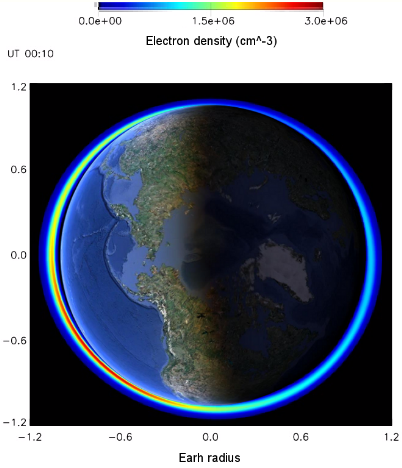
THE IONOSPHERE

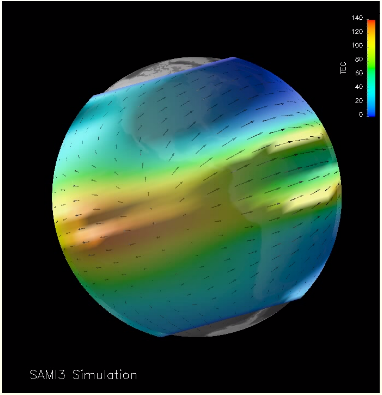
weakly ionized plasma surrounding the earth



- neutrals ionized by sun's EUV radiation (10Å- 1000Å)
- extends from 90 km to 1000s km
- $n_e \lesssim 10^6$ cm^{-3} but $n_n \lesssim 10^{10}$ cm^{-3}
- multi-ion plasma
- very low β plasma: $\beta \sim 10^{-5}$
- on the cold side $T \lesssim 3000$K (or .3 eV)
- anisotropic conductivities: $\sigma_{\|} >> \sigma_{\perp}$
- assume magnetic field lines are equipotentials

SAMI3

- ions: H^+,O^+,He^+,N^+,N_2^+,NO^+,O_2^+
- interhemispheric model
- vertical and zonal $E \times B$ drift
- neutral species: NRLMSISE00/HWM93/TIMEGCM/GITM
- fully parallelized using MPI
- nonorthogonal, nonuniform fixed grid
- solve continuity, velocity, temperature, and potential equations



PLASMA DYNAMICS

- ion continuity

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_i) = P_i - L_i n_i$$

- ion velocity

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

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

- ion temperature

$$\frac{\partial T_i}{\partial t} + \mathbf{V}_i \cdot \nabla T_i + \frac{2}{3} T_i \nabla \cdot \mathbf{V}_i + \frac{2}{3} \frac{1}{n_i k} \nabla \cdot \mathbf{Q}_i = Q_{in} + Q_{ij} + Q_{ie}$$

PLASMA DYNAMICS

- electron momentum

$$0 = -\frac{1}{n_e m_e} b_s \frac{\partial P_e}{\partial s} - \frac{e}{m_e} E_s$$

- electron temperature

$$\frac{\partial T_e}{\partial t} - \frac{2}{3} \frac{1}{n_e k} b_s^2 \frac{\partial}{\partial s} \kappa_e \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe}$$

POTENTIAL EQUATION

based on current conservation: $\nabla \cdot \mathbf{J} = 0$

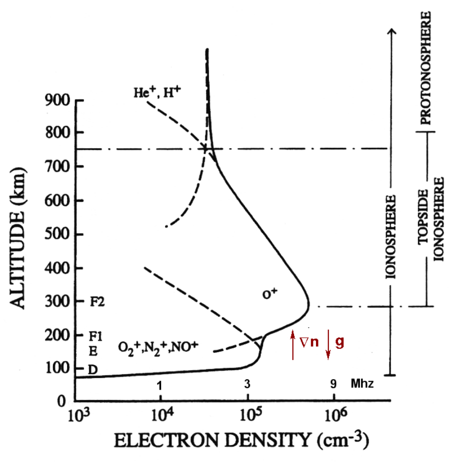
$$\nabla \cdot \Sigma \nabla \Phi = S(g, V_n, J_{\|}) \qquad \mathbf{E} = -\nabla \Phi$$

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

$$\underbrace{-\frac{1}{2} \frac{\partial F_{pV}}{\partial \theta} + \frac{1}{2} \frac{\partial F_{pg}}{\partial \theta} + \frac{1}{\sin^2 \theta \tan \theta} \left(\frac{\partial F_{\phi V}}{\partial \phi} + \frac{\partial F_{\phi g}}{\partial \phi} \right)}_{\text{neutral wind and gravity}} \underbrace{- \frac{\alpha(\theta) R_E^2 \ \sin^4 \theta \ J_{\|}}{(1 + 3 \cos^2 \theta)^{1/2}}}_{\text{region 1/2 currents}}$$

THE BEGINNING OF ESF

Booker and Wells, *J. Geophys. Res.* *43*, 249 (1938)



SCATTERING OF RADIO WAVES BY THE *F*-REGION OF THE IONOSPHERE

By H. G. Booker and H. W. Wells

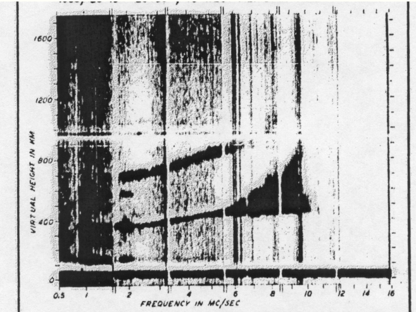
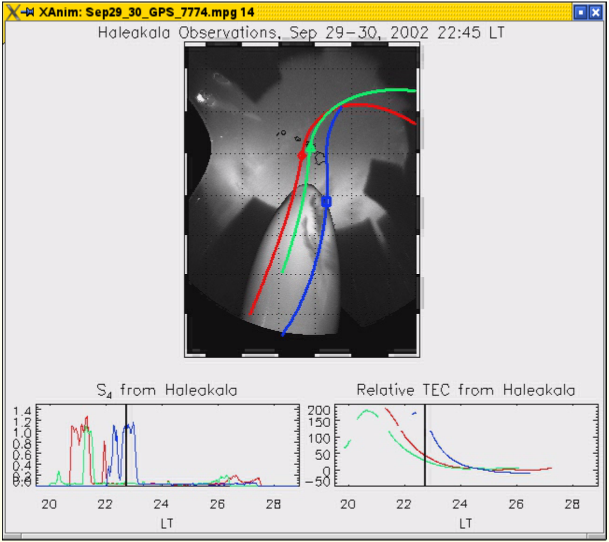


FIG. 2—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 23, 1938, 21^h30^m–21^h45^m, 75° WEST MERIDIAN HOURS



XAnim: Sep29_30_GPS_7774.mpg 14
Haleakala Observations, Sep 29–30, 2002 22:45 LT
S4 from Haleakala
1.4
1.2
1.0
0.8
0.6
0.4
20
22
24
26
28
LT
Relative TEC from Haleakala
200
150
100
50
0
−50
20
22
24
26
28
LT

BUBBLE CARTOON

Woodman and LaHoz, *J. Geophys. Res. 81*, 5447 (1976)

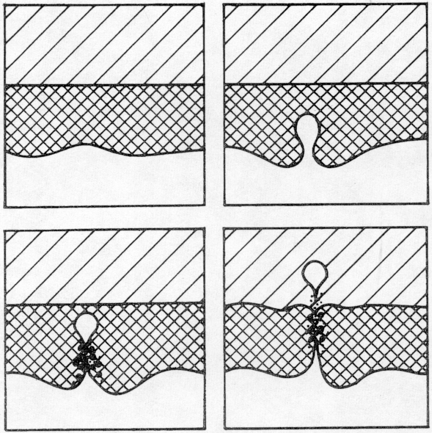
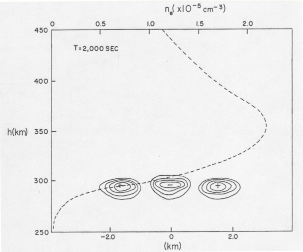
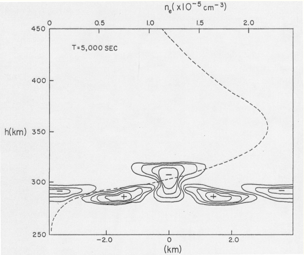


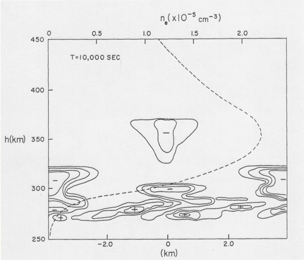
Fig. 9. Schematic representation of a three-density model of the ionosphere showing the formation of a bubble of low electron density and its propagation to the gravitationally stable top. The middle fluid is heavier than the top, and the top fluid heavier than the bottom.

FIRST BUBBLE SIMULATION

Scannapieco and Ossakow *Geophys. Res. Lett. 3*, 451 (1976)





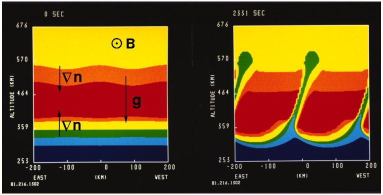


EQUATORIAL SPREAD F

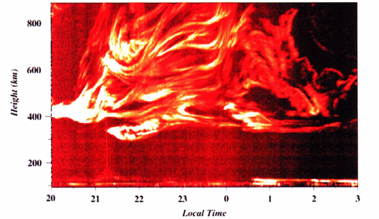
- equatorial spread F is the development of ionospheric irregularities in the nighttime equatorial ionosphere.
- it is fundamentally a Rayleigh-Taylor instability
- linear growth rate (*Sultan*, 1996):

$$\gamma = \frac{\Sigma_P^F}{\Sigma_P^E + \Sigma_P^F} \frac{1}{L_n} \left(V_p + U_n^P + g_L/\nu_{in}^{eff} \right) - R_T$$

- plasma 'bubbles' nonlinearly penetrate the topside ionosphere
- range of electron density irregularities: 10s km - 10s cm
much less than global scales: 1000s km



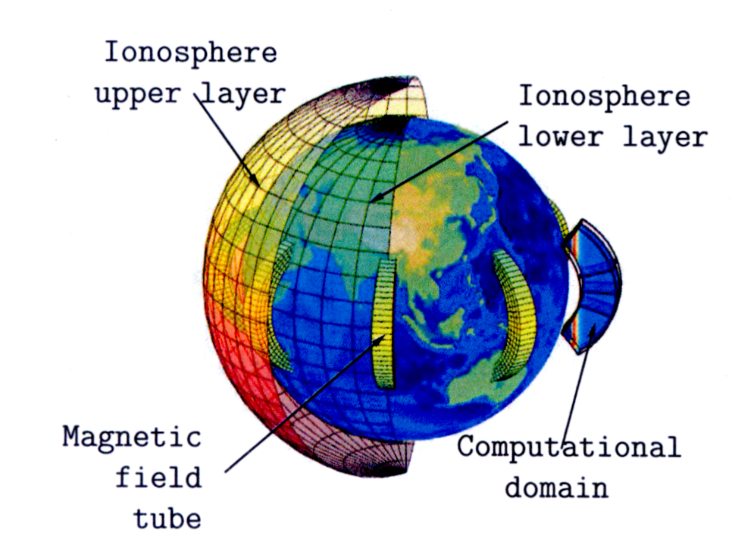
Computer simulation of ESF (*Zalesak et al.*, 1982).



Radar backscatter from 3m irregularities at Jicamarca (*Hysell*).

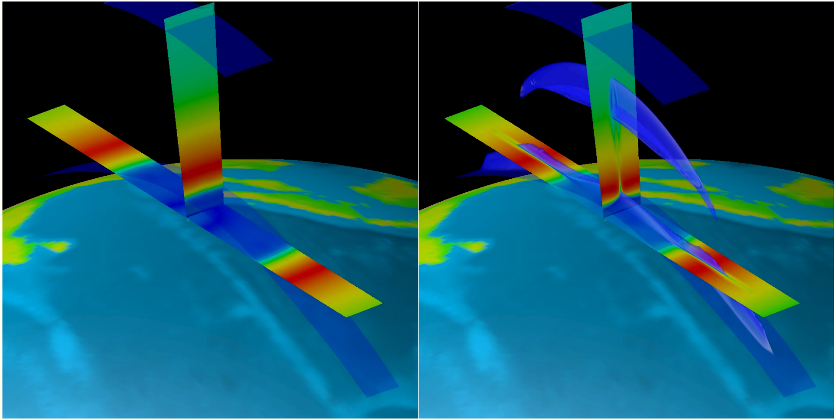
SAMI3/ESF WEDGE MODEL

from Besse et al. (2006)



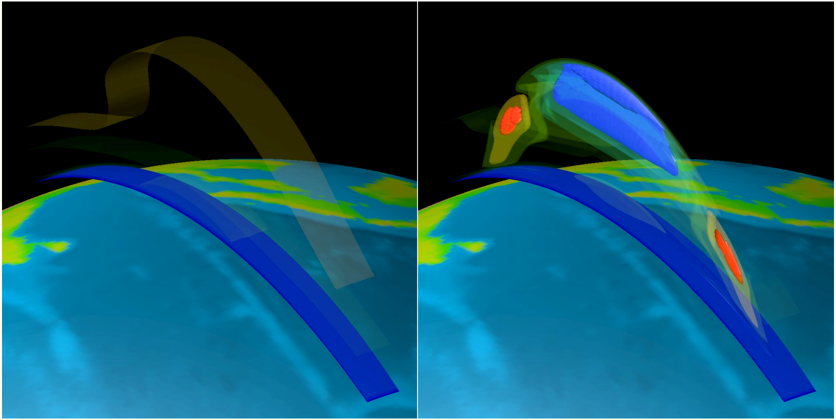
ELECTRON DENSITY

Huba et al., *GRL 35*, L10102, 2008



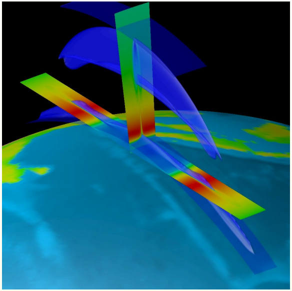
ELECTRON TEMPERATURE

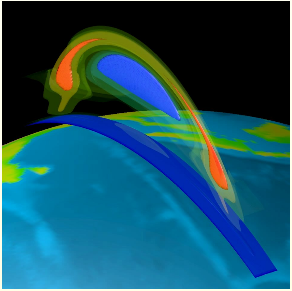
Huba et al., *GRL 36*, L15102, 2009



SAMI3/ESF SUMMARY

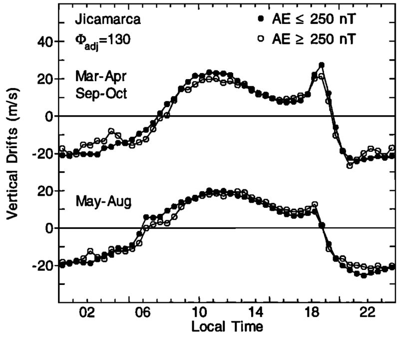
- substantial progress in ESF modeling in past few years (9 papers in 2008-10; 7 in GRL)
  - multi-ion dynamics
  - ion and electron temperatures
  - zonal and meridional wind effects
  - why do bubbles stop rising?
  - density enhancements
  - MSTIDs
- next big step: embed ESF in global SAMI3 model





EQUATORIAL PLASMA BUBBLES

Fejer and Scherliess, *JGR*, 1997

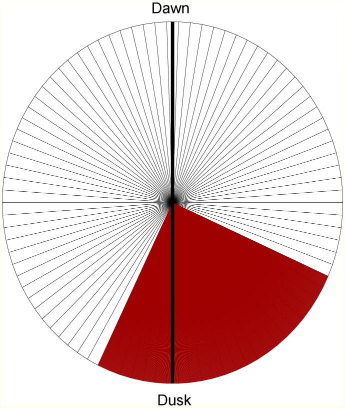


- global electrodynamics impacts ESF development (e.g., pre-reversal enhancement of the eastward electric field)
- the problem:
  - global length scales 100s - 1000s km
  - bubble length scales 10s - 100s km
- frontier problem: need to develop model that captures physical processes on these disparate scales

GLOBAL SOLUTION

incorporate a high-resolution grid in a global model, i.e., SAMI3

- reference frame: copernican (sun-fixed: rotating earth)
- coarse mesh: 90 grid points
- zonal resolution $\sim$ 500 km
- high resolution mesh: 956 grid points between $\sim$ 16:30 MLT - 22:30 MLT
- zonal resolution $\sim$ .0625° or $\sim$ 7 km



POTENTIAL EQUATION

based on current conservation: $\nabla \cdot \mathbf{J} = 0$: caveat - aligned dipole

$$\nabla \cdot \Sigma \nabla \Phi = S(g, V_n) \qquad \mathbf{E} = -\nabla \Phi$$

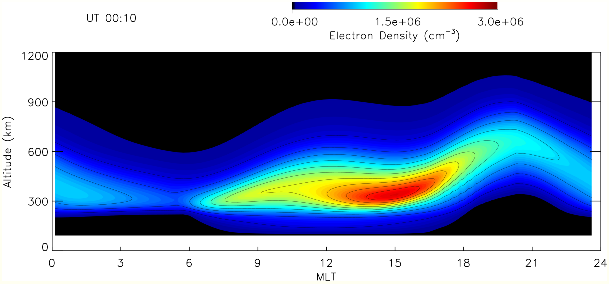
$$\underbrace{\frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \frac{1}{p} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi}}_{\text{pedersen}} \quad \underbrace{-\frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p}}_{\text{hall}}$$

$$= \quad \underbrace{\frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi}}_{\text{neutral wind dynamo}} \quad \underbrace{-\frac{\partial F_{pg}}{\partial p} + \frac{\partial F_{\phi g}}{\partial \phi}}_{\text{gravity driver}}$$

plus corotation potential: $\phi_{\text{cr}} = -\frac{B_0}{.31} \frac{92}{p} \text{kV}$

FIRST GLOBAL MODEL OF ESF

Huba and Joyce, *GRL*, 2010



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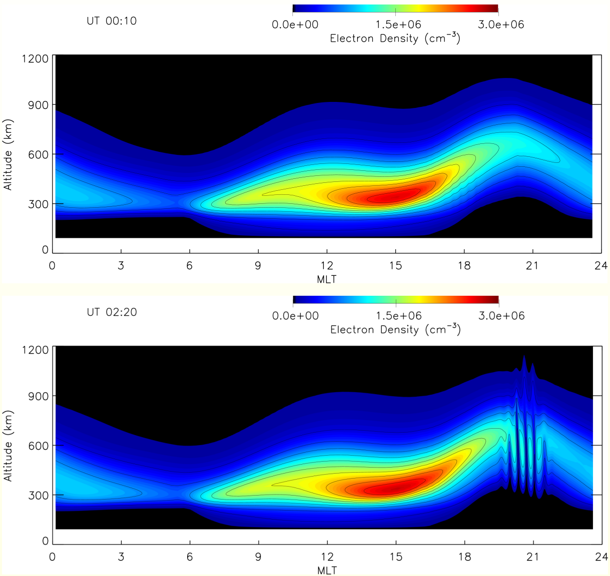
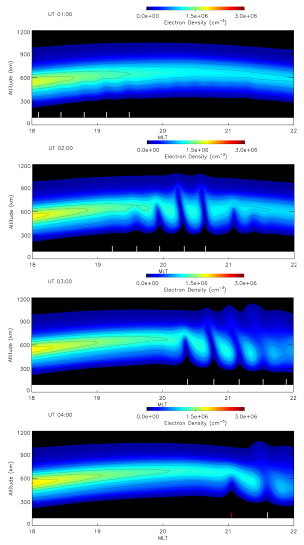
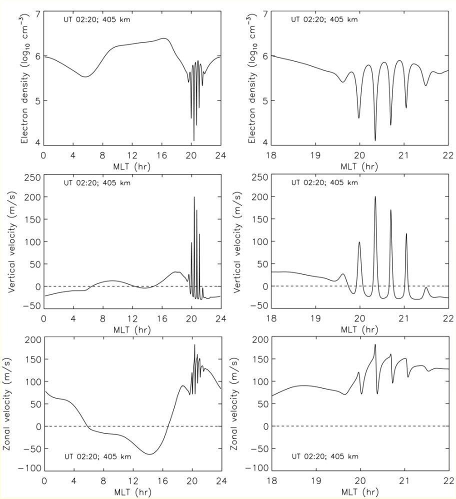


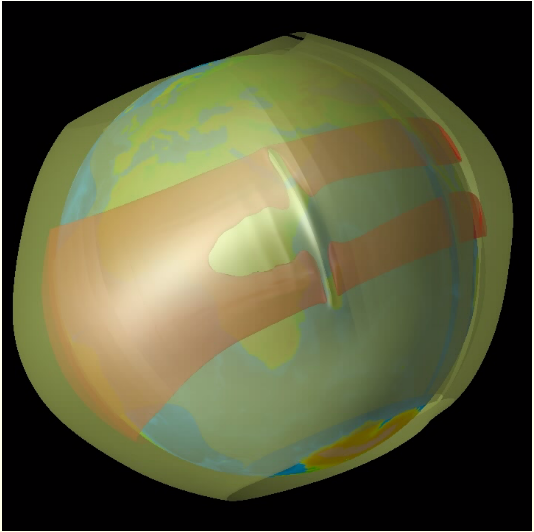
RESULTS

pre-sunset perturbations; one bubble can initiate another

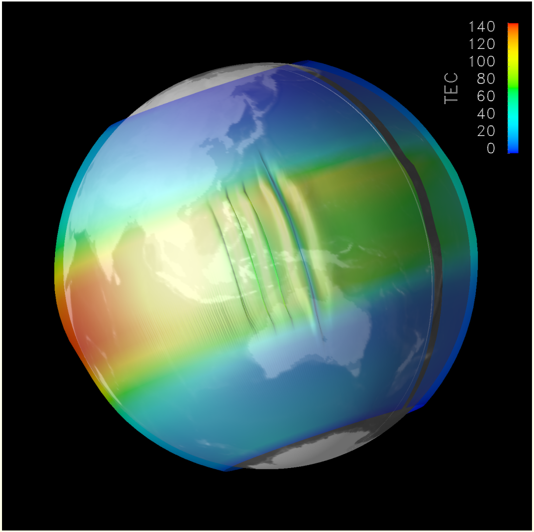




RESULTS



RESULTS



NOW WHAT?

- parameter studies
  e.g., vary perturbation altitude, geophysical parameters, location of high resolution region
- code improvement: high order transport scheme
  e.g., partial donor cell method
- 3D electrodynamics
- gravity wave seeding

GLOBAL ELECTRODYNAMICS

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

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

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

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

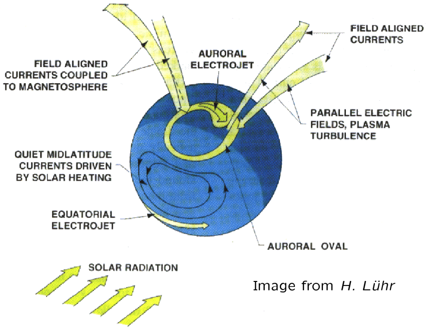
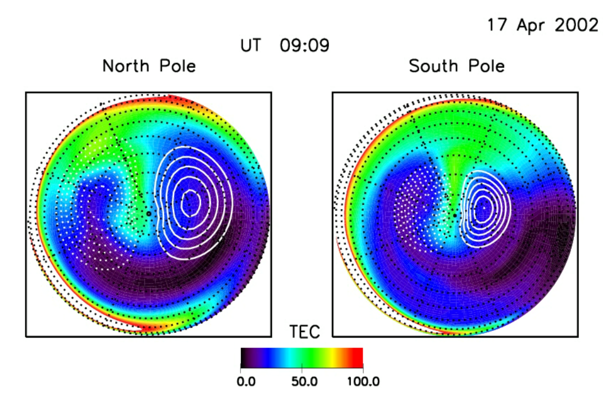


Image from *H. Lühr*

- Σ: field-line integrated Hall and Pedersen conductivities (SAMI3)
- $J_{\parallel}$: magnetosphere driven (RCM/LFM)
- V_n: solar and magnetosphere driven (HWM/TIMEGCM)
- problem is tying everything together self-consistently

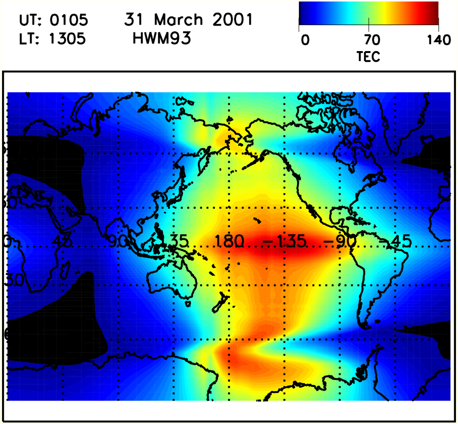
ELECTRODYNAMIC COUPLING

- driver: region 1 and 2 current systems
- SAMI3/LFM are coupled electrodynamically
- (and ionization caused by precipitating electrons)



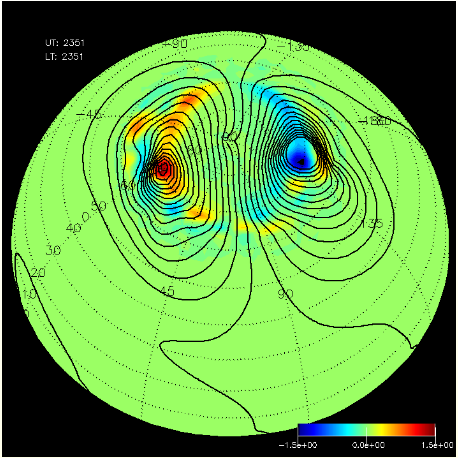
ELECTRODYNAMIC COUPLING

- SAMI3/RCM are coupled electrodynamically
- preliminary storm-time run



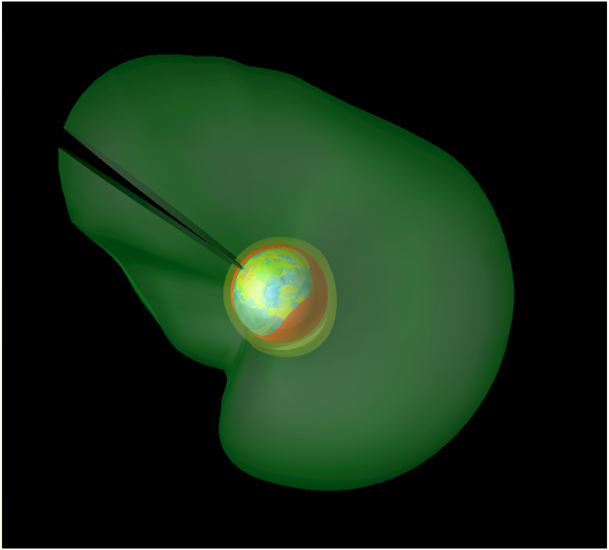
CURRENT PROGRESS

- use region 1/2 currents from LFM (color contours)
- also use energy and energy flux from LFM to prescribe ionization from precipitating electrons
- use HWM93 wind model
- upper boundary is 89°



CURRENT PROGRESS

pushing into the plasmasphere (modified Volland-Stern potential plus corotation)



NOW FOR SOMETHING COMPLETELY DIFFERENT

- Ohm's law (electrons frozen into magnetic field)

$$\mathbf{E} + \frac{1}{c}\mathbf{V}_e \times \mathbf{B} = 0$$

- Current definition (assumes quasineutrality)

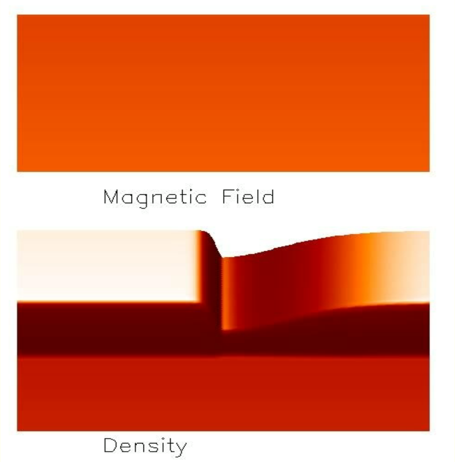
$$\mathbf{J} = ne(\mathbf{V}_i - \mathbf{V}_e) \quad \Rightarrow \quad \mathbf{V}_e = \mathbf{V}_i - \frac{1}{ne}\mathbf{J}$$

- Electric field is written as

$$\mathbf{E} = -\frac{1}{c}\mathbf{V}_i \times \mathbf{B} + \overbrace{\frac{1}{nec}\mathbf{J} \times \mathbf{B}}^{Hall\ term}$$

- Physically, the Hall term decouples ion and electron motion on ion inertial length scales: $L \lesssim c/\omega_{pi}$

IDEAL VS HALL MHD

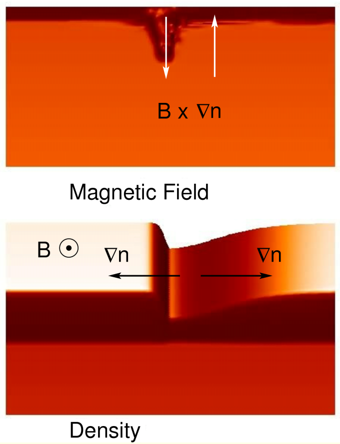


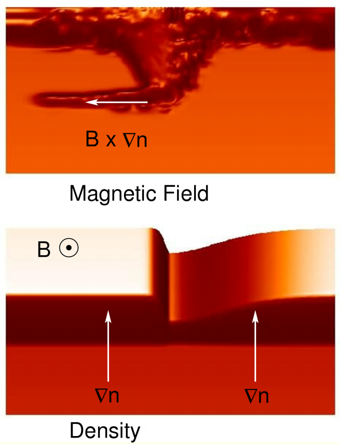
- Ideal MHD
- Hall MHD

HALL MAGNETIC DRIFT WAVE (KMC)

Huba, *Phys. Fl. B*, 1991

$$V_n = V_A \left(\frac{c}{\omega_{pi}} \frac{1}{n} \frac{\partial n}{\partial x} \right)$$





SUMMARY

- considerable progress in modeling equatorial spread F using the SAMI3 wedge model and the global SAMI3
- future work will focus on day-to-day variability and code improvements (e.g., 3D electrodynamics, high-order transport scheme, coupling to thermosphere with TIMEGCM, gravity wave seeding)
- improving SAMI3 to model global electrodynamics and its impact on low-latitude ionosphere as well as the plasmasphere

WHAT SAMI2 LOOKS LIKE

WHAT SAMI2 LOOKS LIKE