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
- \( n_e \lesssim 10^6 \text{ cm}^{-3} \) but \( n_n \lesssim 10^{10} \text{ cm}^{-3} \)
- multi-ion plasma
- very low \( \beta \) plasma: \( \beta \sim 10^{-5} \)
- on the cold side \( T \lesssim 3000 \text{K} \) (or .3 eV)
- anisotropic conductivities: \( \sigma_\parallel \gg \sigma_\perp \)
- 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
ion continuity

\[ \frac{\partial n_i}{\partial t} + \nabla \cdot (n_i V_i) = P_i - L_i n_i \]

ion velocity

\[ \frac{\partial V_i}{\partial t} + V_i \cdot \nabla V_i = -\frac{1}{\rho_i} \nabla P_i + \frac{e}{m_i} E + \frac{e}{m_i c} V_i \times B + \mathbf{g} \]

\[ -\nu_{in} (V_i - V_n) - \sum_j v_{ij} (V_i - V_j) \]

ion temperature

\[ \frac{\partial T_i}{\partial t} + V_i \cdot \nabla T_i + \frac{2}{3} T_i \nabla \cdot V_i + \frac{2}{3} \frac{1}{n_i k} \nabla \cdot Q_i = Q_{in} + Q_{ij} + Q_{ie} \]
bullet electron momentum

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

bullet electron temperature

\[ \frac{\partial T_e}{\partial t} - \frac{2}{3} \frac{1}{n_e k} b_s \frac{\partial}{\partial s} \kappa_e \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe} \]
The potential equation based on current conservation is:
\[
\nabla \cdot \Sigma \nabla \Phi = S(g, V_n, J_\parallel) \quad \text{E} = -\nabla \Phi
\]

\[
\frac{\partial}{\partial \theta} \Sigma_{pp} \frac{\partial \Phi}{\partial \theta} + \frac{\partial}{\partial \phi} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} - \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial \theta} + \frac{\partial}{\partial \theta} \Sigma_H \frac{\partial \Phi}{\partial \phi} =
\]

Pedersen

\[
- \frac{1}{2} \frac{\partial F_{pV}}{\partial \theta} + \frac{1}{2} \frac{\partial F_{pg}}{\partial \theta} + \frac{1}{2 \sin^2 \theta \tan \theta} \left( \frac{\partial F_{\phi V}}{\partial \phi} + \frac{\partial F_{\phi g}}{\partial \phi} \right)
\]

Hall

neutral wind and gravity

region 1/2 currents

\[
- \frac{\alpha(\theta) R_E^2 \sin^4 \theta \ J_\parallel}{(1 + 3 \cos^2 \theta)^{1/2}}
\]
THE BEGINNING OF ESF
Booker and Wells, *J. Geophys. Res.* 43, 249 (1938)
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
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):

$$ \gamma = \frac{\sum F_P}{\sum F_P + \sum F_P} \frac{1}{L_n} \left( V_p + U_n^P + gL/\nu_{in}^{eff} \right) - R_T $$

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)
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
global electrodynamics impacts ESF development (e.g., pre-reversal enhancement of the eastward electric field)

- 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
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 $\sim 0.0625^\circ$ or $\sim 7$ km
\[ \nabla \cdot \Sigma \nabla \Phi = S(g, V_n) \quad \text{E} = -\nabla \Phi \]

\[ \frac{\partial}{\partial p} p \Sigma_{pp} \frac{\partial \Phi}{\partial p} + \frac{\partial}{\partial \phi} \frac{1}{p} \Sigma_{p\phi} \frac{\partial \Phi}{\partial \phi} \]

pedersen

\[ -\frac{\partial}{\partial p} \Sigma_H \frac{\partial \Phi}{\partial \phi} + \frac{\partial}{\partial \phi} \Sigma_H \frac{\partial \Phi}{\partial p} \]

hall

= \left[ \frac{\partial F_{pV}}{\partial p} + \frac{\partial F_{\phi V}}{\partial \phi} \right]

neutral wind dynamo

= \left[ -\frac{\partial F_{pg}}{\partial p} + \frac{\partial F_{\phi g}}{\partial \phi} \right]

gravity driver

plus corotation potential:

\[ \phi_{cr} = -\frac{B_0}{0.31} \frac{92}{p} \text{kV} \]
FIRST GLOBAL MODEL OF ESF

Huba and Joyce, GRL, 2010
FIRST GLOBAL MODEL OF ESF

Huba and Joyce, *GRL*, 2010
RESULTS

pre-sunset perturbations; one bubble can initiate another
RESULTS

global view of isocontours
RESULTS

global view of TEC
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:
\[ \int \nabla \cdot \sigma \mathbf{E} \, ds = 0 \]

\[ \nabla \cdot \Sigma \nabla \Phi = S(J_\parallel, V_n, g) \]
\[ \mathbf{E} = -\nabla \Phi \]

- \( \Sigma \): 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
driver: region 1 and 2 current systems
SAMI3/LFM are coupled electrodynamically
(and ionization caused by precipitating electrons)
- SAMI3/RCM are coupled electrodynamically
- preliminary storm-time run
SAMI3 solves potential

- 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)
• Ohm’s law (electrons frozen into magnetic field)

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

• Current definition (assumes quasineutrality)

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

• Electric field is written as

\[ \mathbf{E} = -\frac{1}{c} \mathbf{V}_i \times \mathbf{B} + \frac{1}{ne} \mathbf{J} \times \mathbf{B} \]

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

relevance: plasma opening switch

- Ideal MHD
- Hall MHD
\[ V_n = V_A \left( \frac{c}{\omega_{pi}} \frac{1}{n} \frac{\partial n}{\partial x} \right) \]
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
sami2 personified