MODELING THE EARTH'S IONOSPHERE

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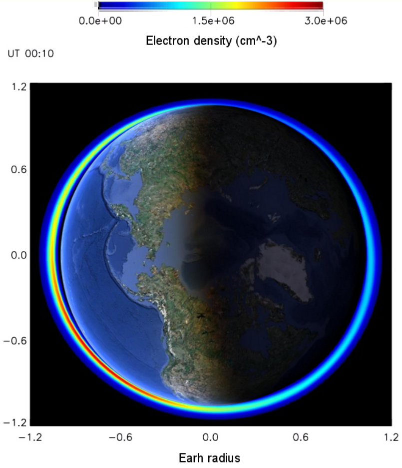
THE IONOSPHERE

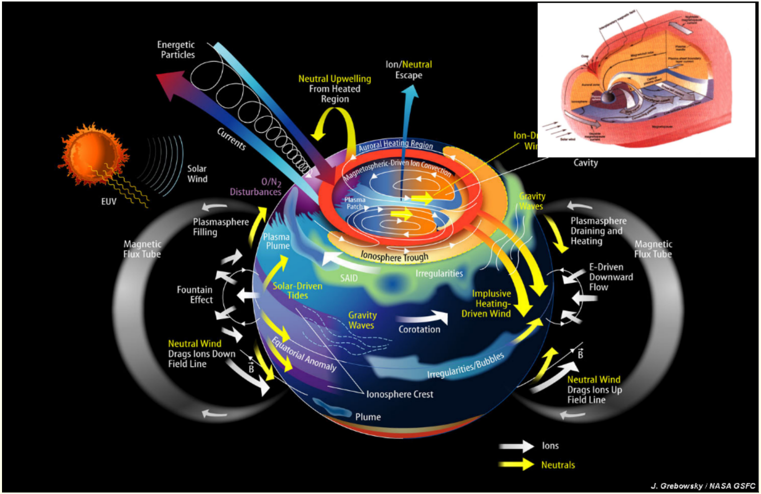
weakly ionized plasma surrounding the earth



- 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

BUT NOT AN ISOLATED SYSTEM

coupled to the thermosphere and magnetosphere



WHAT ARE THE INGREDIENTS?

- plasma dynamics
- neutral atmosphere
- photoionization
- chemistry
- magnetic field
- electric field

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

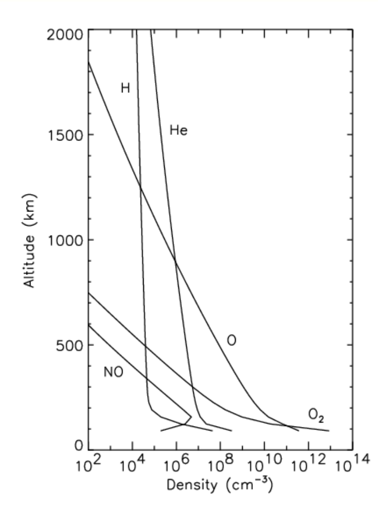
$$\frac{\partial T_e}{\partial t} - \frac{2}{3} \frac{1}{n_e k} b_s^2 \frac{\partial}{\partial s} \kappa_e \frac{\partial T_e}{\partial s} = Q_{en} + Q_{ei} + Q_{phe}$$

NEUTRAL ATMOSPHERE

- dominant species:
  atomic: H, He, N, O
  molecular: N_2, NO, O_2
- neutral density scale height:

$$H = kT/mg$$

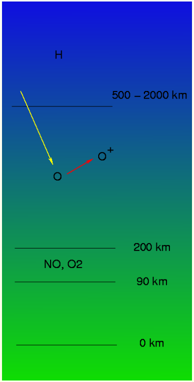
- empirical models
  - NLRMSISE-00 (*Picone et al.*)
    provides neutral densities and temperature
  - HWM93/HWM07 (*Hedin/Drob*)
    provides neutral wind
- first principle models
  - TIME-GCM (*Roble/Crowley*)
  - CTIP (*Fuller-Rowell*)
  - GTIM (*Ridley*)
  - USU (*Schunk*)



PHOTOIONIZATION

- dominant production mechanism for ionospheric plasma
- solar X-ray (1 – 170 Å) and EUV (170 – 1750 Å) radiation can ionize the ionosphere neutral gas

Species	IP (ev)	λ (Å)
H	13.6	912
He	24.6	504
N	14.5	853
O	13.6	911
N_2	15.6	796
NO	9.3	1340
O_2	10.1	1027

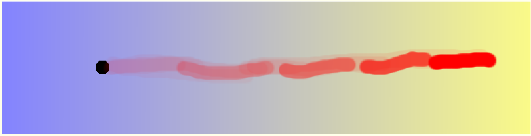


PHOTOIONIZATION: CALCULATION

- production (P) needs to be calculated
- continuity equation for ion species X^+

$$dX^+/dt = P_{X^+} = n_n(X) I_R \quad \text{where}$$

$$P_X = n_n(X) \sum_\lambda \underbrace{\sigma_X^{(i)}(\lambda)}_{\text{photoionization}} \underbrace{\exp\left[-\sum_m \sigma_m^{(a)}(\lambda) \int_z^\infty n_m(s)\, ds\right]}_{\text{photoabsorption}} \underbrace{\phi_\infty(\lambda)}_{\text{solar flux}}$$



PHOTOIONIZATION: SOLAR FLUX MODELS

- empirical models: flux $\phi_\infty(\lambda)$ is in 37 wavelength bins
  - Hinteregger
  - Torr and Torr
  - EUVAC (*Richards et al.*)
    function of geophysical conditions
    $\phi_i = F74113_i[1 + A_i(P - 80)]$ where
    $P = (F10.7A + F10.7)/2$
- data/model driven
  - NRLEUV (*Lean, Warren, and Mariska*)
  - SOLAR2000 (*Tobiska*)
  - FISM (*Chamberlin*)
  - HEUVAC (*Richards et al.*)
- photoionization/photoabsorption cross-sections tabulated

CHEMISTRY

- production (P) and loss (L) mechanism
- continuity equations for ion species X^+ and Y^+

$$dX^+/dt = P_{X+} - L_{X+} \quad \text{(e.g., } dH^+/dt = P_{H+} - L_{H+}\text{)}$$
$$dY^+/dt = P_{Y+} - L_{Y+} \quad \text{(e.g., } dO^+/dt = P_{O+} - L_{O+}\text{)}$$

- general chemical reaction (e.g., charge exchange)

$$X^+ + Y \rightarrow X + Y^+ \quad \mathrm{Rate}: k_{X+Y}$$
$$\text{(e.g., } H^+ + O \rightarrow H + O^+ \quad \mathrm{Rate}: k_{H+O}\text{)}$$

- thus, in continuity use

$$L_{X+} = P_{Y+} = k_{X+Y}n(X^+)n(Y)$$
$$\text{(e.g., } L_{H+} = P_{O+} = k_{H+O}n(H^+)n(O)\text{)}$$

CHEMICAL REACTION RATES

Chemical Reaction Rates:

Reaction	Rate, $cm^3 s^{-1}$
$H^+ + O \rightarrow O^+ + H$	$2.2 \times 10^{-11} T^{0.5}(H^+)$
$He^+ + N_2 \rightarrow N_2{}^+ + He$	3.5×10^{-10}
$He^+ + N_2 \rightarrow N^+ + N + He$	8.5×10^{-10}
$He^+ + O_2 \rightarrow O^+ + O + He$	8.0×10^{-10}
$He^+ + O_2 \rightarrow O_2{}^+ + He$	2.0×10^{-10}
$N^+ + O_2 \rightarrow NO^+ + O$	2.0×10^{-10}
$N^+ + O_2 \rightarrow O_2{}^+ + N(2D)$	4.0×10^{-10}
$N^+ + O \rightarrow O^+ + N$	1.0×10^{-12}
$N^+ + NO \rightarrow NO^+ + O$	2.0×10^{-11}
$O^+ + H \rightarrow H^+ + O$	$2.5 \times 10^{-11} T_n^{0.5}$
$O^+ + N_2 \rightarrow NO^+ + N$	k_1
$O^+ + O_2 \rightarrow O_2{}^+ + O$	k_2
$O^+ + NO \rightarrow NO^+ + O$	1.0×10^{-12}
$N_2{}^+ + O \rightarrow NO^+ + N(2D)$	$1.4 \times 10^{-10} T_{300}^{-0.44}(O+)$
$N_2{}^+ + O_2 \rightarrow O_2{}^+ + N_2$	$5.0 \times 10^{-11} T_{300}^{-0.5}(O+)$
$N_2{}^+ + O_2 \rightarrow NO^+ + NO$	1.0×10^{-14}
$N_2{}^+ + NO \rightarrow NO^+ + N_2$	3.3×10^{-10}
$O_2{}^+ + N \rightarrow NO^+ + O$	1.2×10^{-10}
$O_2{}^+ + N(2D) \rightarrow N^+ + O_2$	2.5×10^{-10}
$O_2{}^+ + NO \rightarrow NO^+ + O_2$	4.4×10^{-10}
$O_2{}^+ + N_2 \rightarrow NO^+ + NO$	5.0×10^{-16}

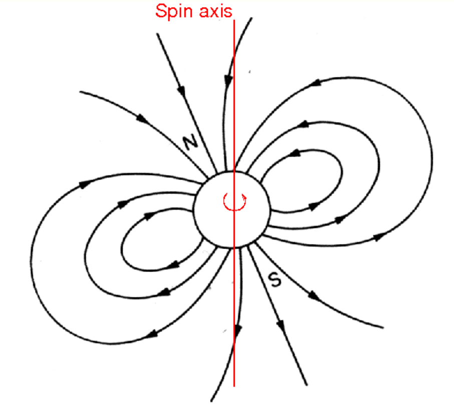
Recombination Rates:

Reaction	Rate, $cm^3\ s^{-1}$
$H^+ + e \rightarrow H$	$4.43 \times 10^{-12}/T_e^{0.7}$
$He^+ + e \rightarrow He$	$4.43 \times 10^{-12}/T_e^{0.7}$
$N^+ + e \rightarrow N$	$4.43 \times 10^{-12}/T_e^{0.7}$
$O^+ + e \rightarrow O$	$4.43 \times 10^{-12}/T_e^{0.7}$
$N_2{}^+ + e \rightarrow N_2$	$1.80 \times 10^{-7}/T_e^{0.39}$
$NO^+ + e \rightarrow NO$	$4.20 \times 10^{-7}/T_e^{0.85}$
$O_2{}^+ + e \rightarrow O_2$	$1.60 \times 10^{-7}/T_e^{0.55}$

$$
\begin{aligned}
k_1 &= 1.53 \times 10^{-12} - 5.92 \times 10^{-13} T_{300}(O^+) \\
&\quad +8.60 \times 10^{-14} T_{300}^2(O^+) \text{ for } T(O^+) < 1700K \\
k_1 &= 1.73 \times 10^{-12} - 1.16 \times 10^{-12} T_{300}(O^+) \\
&\quad +1.48 \times 10^{-13} T_{300}^2(O^+) \text{ for } T(O^+) > 1700K \\
k_2 &= 2.82 \times 10^{-11} - 7.74 \times 10^{-12} T_{300}(O^+) \\
&\quad +1.07 \times 10^{-12} T_{300}^2(O^+) - 5.17 \times 10^{-14} T_{300}^3(O^+) \\
&\quad +9.65 \times 10^{-16} T_{300}^4(O^+) \\
T_{300} &= T/300
\end{aligned}
$$

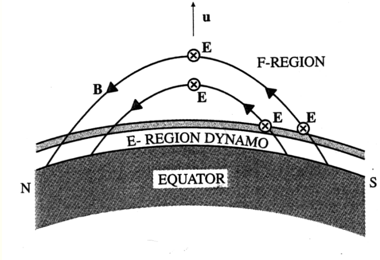
MAGNETIC FIELD

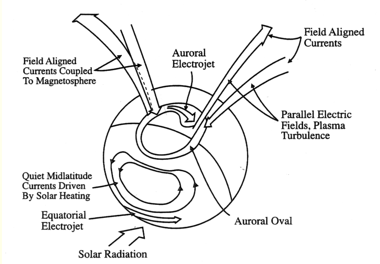
- appropriate field: IGRF
- modeled as a tilted (offset) dipole field, or IGRF-like
- low- to mid-latitude:
  closed field lines
- high latitude:
  open field lines



ELECTRIC FIELD

- Low latiutde: driven by neutral wind
    - empirical models (e.g., Fejer-Scherliess)
    - self-consistently determined
- high latitude: driven by solar wind/magnetosphere currents
    - data-driven models (e.g., AMIE)
    - empirical models (e.g., Heppner-Maynard, Weimer)
    - self-consistently determined from global magnetospheric models (e.g., LFM, RCM)





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: $\int \nabla \cdot \sigma \mathbf{E} \, ds = 0$

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

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

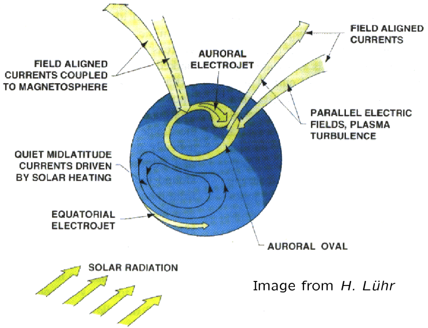


Image from *H. Lühr*

- Σ: field-line integrated Hall and Pedersen conductivities
- $J_{\|}$: magnetosphere driven
- V_n: solar and magnetosphere driven

HOW IS THE MODEL BUILT?

- transport
  - parallel
  - perpendicular
- grid
  - lagrangian
  - eulerian

TRANSPORT

magnetic field organizes plasma motion: $\perp$ and $\parallel$ components

- continuity equation

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

$$\frac{\partial n_i}{\partial t} + \nabla_\parallel \cdot \left(n_i \mathbf{V}_{i\parallel}\right) + \nabla \cdot (n_i \mathbf{V}_{i\perp}) = P_i - L_i n_i$$

  - parallel motion (diffusion/advection)

$$\frac{\partial n_i}{\partial t} + \nabla_\parallel \cdot \left(n_i \mathbf{V}_{\parallel i}\right) = P_i - L_i n_i \quad \text{for} \quad t \overset{\Delta t}{\rightarrow} t*$$

  - perpendicular motion (advection)

$$\frac{\partial n_i}{\partial t} + \nabla \cdot (n_i \mathbf{V}_{\perp i}) = 0 \quad \text{for} \quad t* \overset{\Delta t}{\rightarrow} t + \Delta t$$

PARALLEL TRANSPORT

$$\frac{\partial n_i}{\partial t} + b_s^2 \frac{\partial}{\partial s} \frac{n_i V_{is}}{b_s} = P_i - L_i n_i$$

$$0 = -b_s \frac{\partial (P_i/n_i m_i + P_e/n_e m_i)}{\partial s} + g_s - \nu_{in}(V_{is} - V_{ns}) - \sum_j \nu_{ij}(V_{is} - V_{js})$$

- procedure:
  $\rightarrow$ solve for ion velocity V_{is}
  $\rightarrow$ substitute into continuity
  $\rightarrow$ obtain fully implicit differencing scheme
  $\rightarrow$ iterate or direct solve to obtain a solution
- advantage: large time steps ($\sim$ 5 – 15 min)
- disadvantage: complexity, stability, limited species (e.g., no molecular transport)

PARALLEL TRANSPORT

SAMI2/3 method: include ion inertia

$$\frac{\partial n_i}{\partial t} + b_s^2 \frac{\partial}{\partial s} \frac{n_i V_{is}}{b_s} = P_i - L_i n_i$$

$$\frac{\partial V_{is}}{\partial t} + (\mathbf{V}_i \cdot \nabla) V_{is} = -\frac{1}{n_i m_i} b_s \frac{\partial (P_i + P_e)}{\partial s} + g_s - \nu_{in}(V_{is} - V_{ns}) - \sum_j \nu_{ij}(V_{is} - V_{js})$$

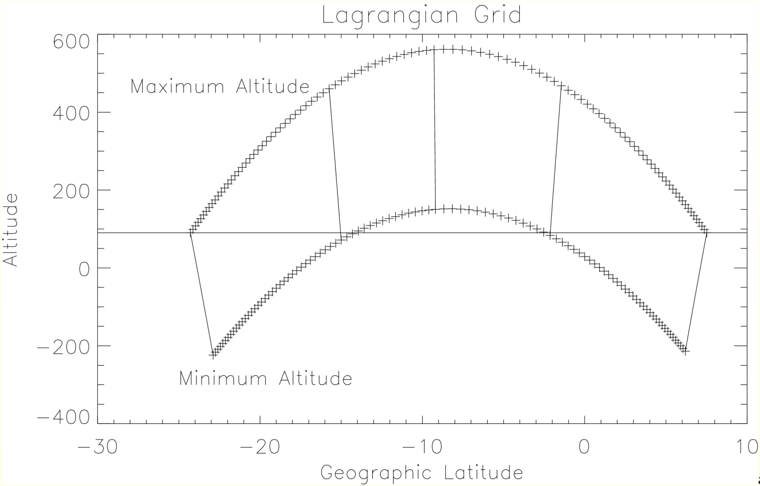
- procedure:
  $\rightarrow$ diffusion terms backward biased (implicit)
  $\rightarrow$ advection terms use donor cell method
  $\rightarrow$ obtain semi-implicit differencing scheme
- disadvantage: small time steps ($\sim$ 1 – 15 sec)
- advantage: simplicity, stability, flexibility, better description at high altitudes

PERPENDICULAR TRANSPORT

- perpendicular dynamics ($E \times B$ transport)
  - lagrangian grid: follow flux tube motion
  - eulerian grid: fixed mesh

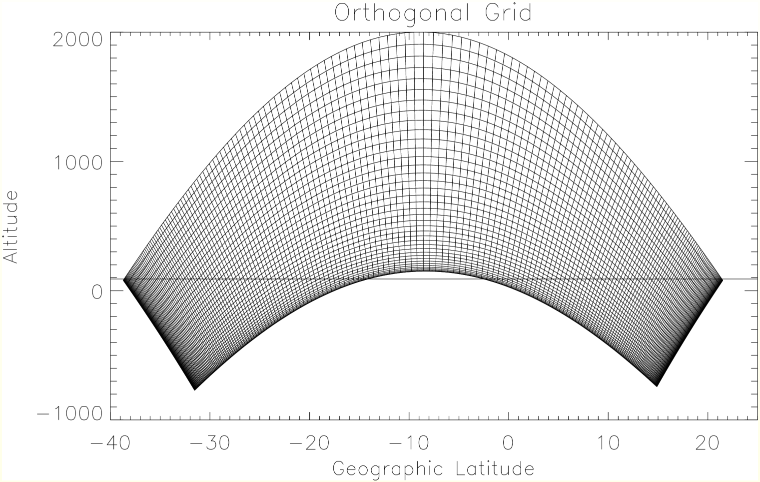
LAGRANGIAN GRID

Follow $E \times B$ drift of a flux tube



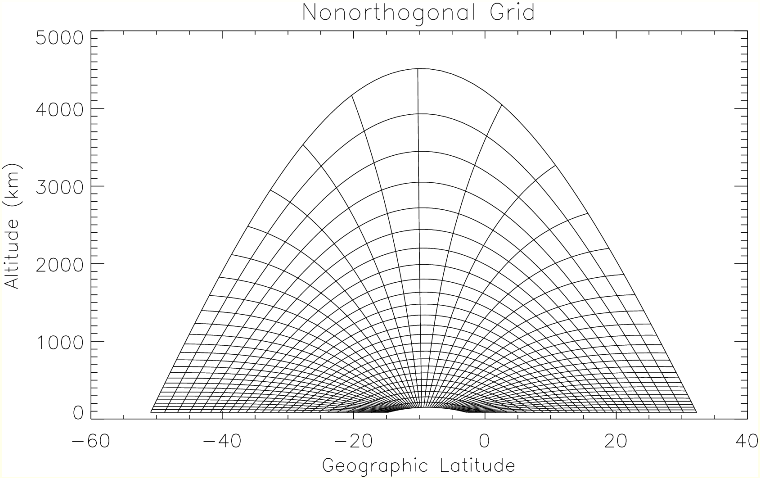
animate

EULERIAN GRID



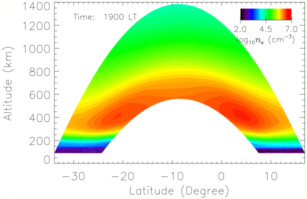
EULERIAN GRID

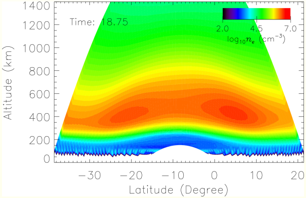
nonorthogonal: finite volume, donor cell method

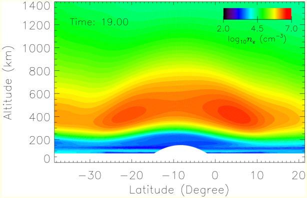


GRID COMPARISON

lagrangian, orthogonal eulerian, nonorthogonal eulerian

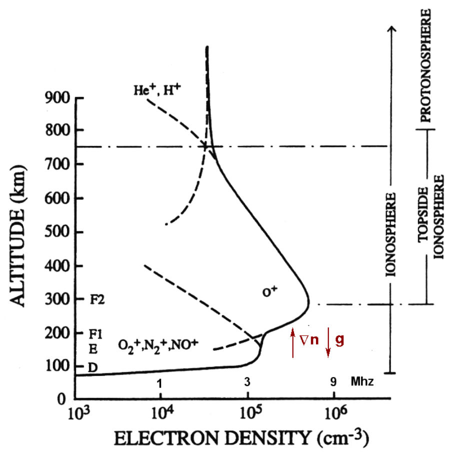






THE BEGINNING OF ESF

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

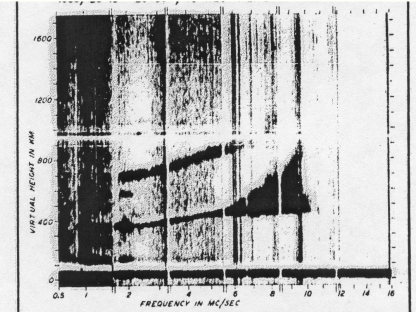
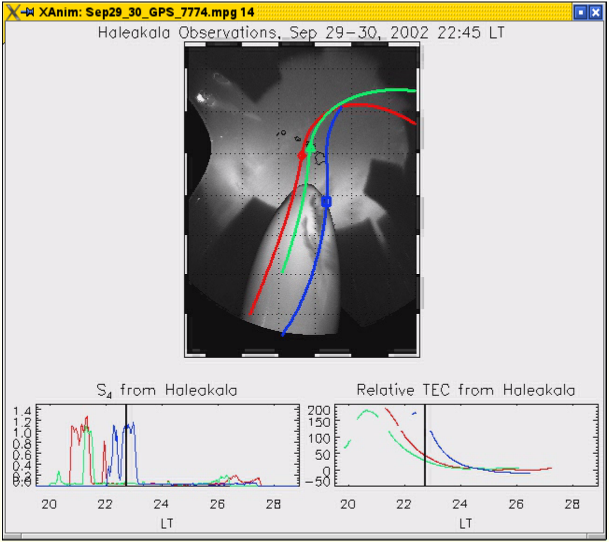


FIG. 2—RECORD SHOWING REGULAR AND DIFFUSE F-REGION ECHOES, HUANCAYO MAGNETIC OBSERVATORY, FEBRUARY 23, 1938, $21^h30^m-21^h45^m$, 75° WEST MERIDIAN HOURS

MODERN OBSERVATIONS

optical data (Jon Makela)



BUBBLE CARTOON

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

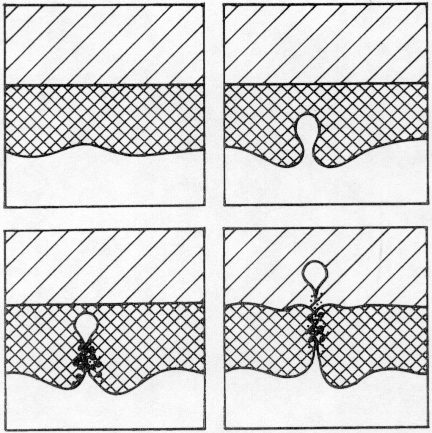
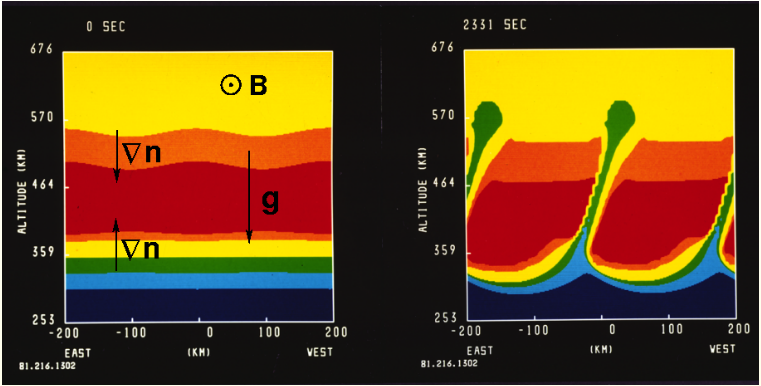


Fig. 9. Schematic representation of a three-density model of the ionosphere showing the formation of a bubble of low electron density and its propagation to the gravitationally stable top. The middle fluid is heavier than the top, and the top fluid heavier than the bottom.

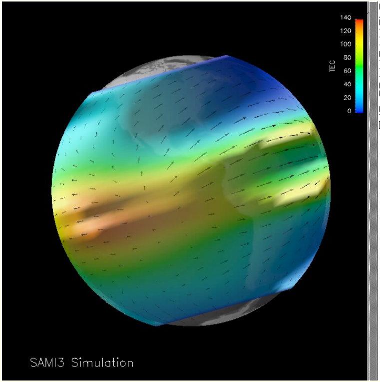
2D BUBBLE SIMULATION

Zalesak et al., *J. Geophys. Res.*, 1982



SAMI3

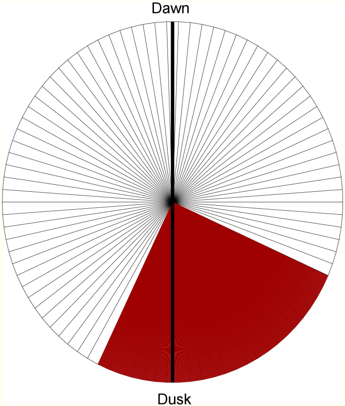
- comprehensive: multi-ion dynamics
- ions: H^+,O^+,He^+,N^+,N_2^+,NO^+,O_2^+
- self-consistent potential solver
  potential equation (for dipole field)
- neutral species: NRLMSISE00/HWM, TIMEGCM, and GITM
- EUV models (EUVAC, NRLEUV, FISM)
- global coverage ($\pm 89°$)
- nonorthogonal, nonuniform fixed grid (closed)



GLOBAL SOLUTION

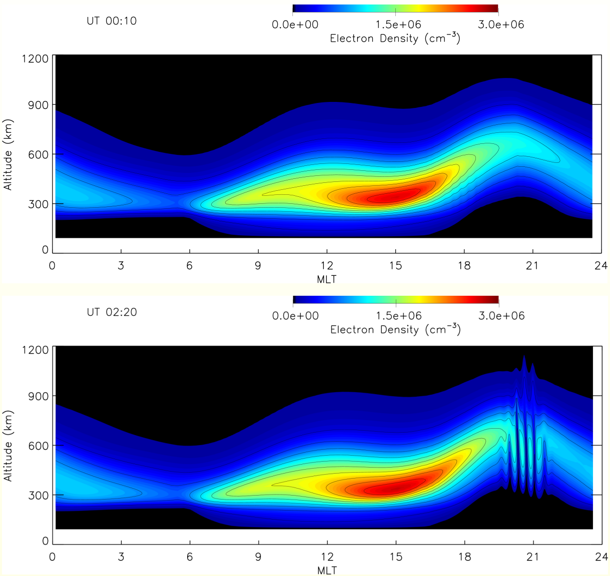
incorporate a high-resolution grid in a global model, i.e., SAMI3

- 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

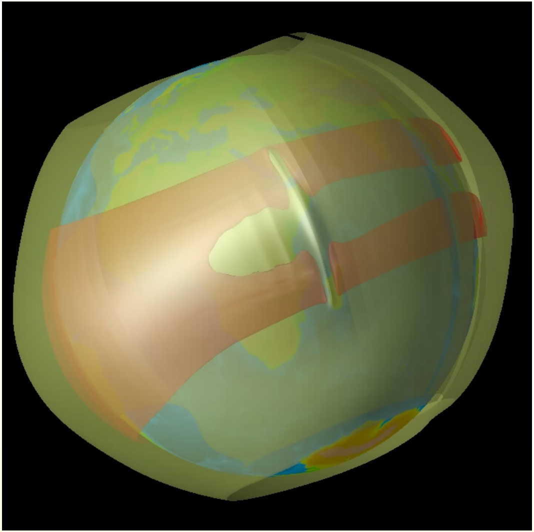


FIRST GLOBAL MODEL OF ESF

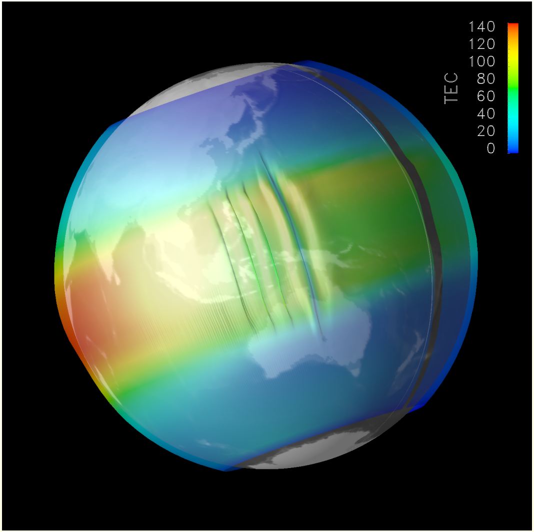
Huba and Joyce, *GRL*, 2010



RESULTS

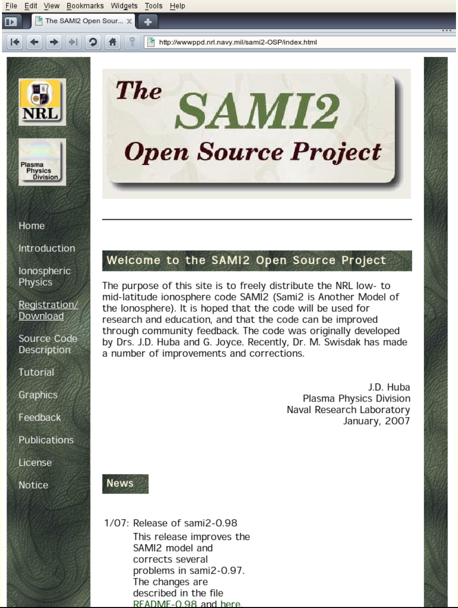


RESULTS



SAMI2 OPEN SOURCE PROJECT

http://wwwppd.nrl.navy.mil/sami2-OSP/index.html



- overview of SAMI2 model
  - basic equations
  - physical inputs
  - numerical methods