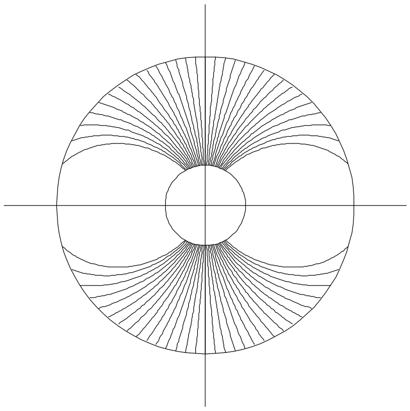
Magnetosphere - ionosphere coupling

- Inner boundary of the MHD domain located 2-4 R_E from Earth:
  - Numerical necessity: high Alfv$\acute{e}$n speeds would limit severely the stable timestep length.
  - Also makes physical sense: MHD scales and processes are of minor importance within 4 R_E, most processes are of kinetic nature and of small scale.
- The region between the inner boundary and the ionosphere is treated as a black box.
- Parameters, like field aligned currents (FACs) are mapped along static dipole field lines:



- Covers magnetic latitudes from 58^0 to 90^0.
- Coupling processes are parameterized.

Processes on auroral field lines

- Discrete electron precipitation by parallel potential drops in regions of upward field aligned current [*Knight, 1973; Lyons et al., 1979*]:

$$\Delta\Phi = f_1 K \max(0, -j_{\|}) \qquad , \qquad K = \frac{e^2 n_e}{\sqrt{2\pi m_e k T_e}}$$

$$F_E = \Delta\Phi_{\|} j_{\|} \qquad , \qquad E_0 = e\Delta\Phi_{\|}$$

- Diffuse electron precipitation due to pitch angle scattering of hot magnetospheric electrons:

$$F_E = f_2 n_e (kT_e/2\pi m_e)^{\frac{1}{2}} \qquad , \qquad E_0 = kT_e$$

- Model n_e and T_e are taken as the MHD number density and temperature. These depend significantly on the n and T MHD boundary conditions of the model. f_1 and f_2 are fudge factors.
- Model resolution in the auroral zone:
  - 0.5 to 3 degrees in magnetic latitude.
  - 5 to 15 degrees in magnetic longitude.
- Caveat: The model provides roughly the right total current, but averages out the fine structure. Because the M-I coupling parameterizations are non-linear:

$$F(<a>) \neq < F(a) >$$

Ionosphere potential equation

- Hall, Pedersen conductance from electron precipitation (the old way): [*Hardy et al., 1987*]:

$$\Sigma_P = [40E_0/(16+E_0^2)]F_E^{1/2} \qquad , \qquad \Sigma_H = 0.45E_0^{5/8}\Sigma_P$$

- Hall, Pedersen conductance from electron precipitation (the new way): provided by CTIM.
- Ionosphere potential:

$$\nabla \cdot \underline{\underline{\boldsymbol{\Sigma}}} \cdot \nabla\Phi = -j_{\|} \sin I$$

$\sin I$: sine of magnetic field inclination

- Conductance tensor:

$$\underline{\underline{\boldsymbol{\Sigma}}} = \begin{pmatrix} \Sigma_{\theta\theta} & \Sigma_{\theta\lambda} \\ -\Sigma_{\theta\lambda} & \Sigma_{\lambda\lambda} \end{pmatrix}$$

$$\Sigma_{\theta\theta} = \frac{\Sigma_P}{\sin^2 I} \quad , \quad \Sigma_{\theta\lambda} = \frac{\Sigma_H}{\sin I} \quad , \quad \Sigma_{\lambda\lambda} = \Sigma_P$$

Coupled Thermosphere Ionosphere Model (CTIM)

- Global multi-fluid model of the thermosphere - ionosphere system with long heritage (*Fuller-Rowell, Rees, Quegan, Moffett, Codrescu, Millward*).
- 2° latitude resolution, 18° longitude resolution.
- 15 pressure levels, from 80 km to about 700 km altitude for the neutral atmosphere, i.e., from below the mesopause to about the exobase. 80 to 10000 km for the ionosphere.
- The thermosphere part solves the continuity equation, momentum equation (horizontal), energy equation, and composition equations for the three major species (O, $\mathrm{O_2}$, $\mathrm{N_2}$).
- The ionosphere model part solves the continuity, vertical diffusion, and horizontal transport for $\mathrm{H^+}$ and $\mathrm{O^+}$, assumes chemical equilibrium for $\mathrm{N_2^+}$, $\mathrm{O_2^+}$, $\mathrm{NO^+}$, and $\mathrm{N^+}$, and solves for ion temperature.
- The perpendicular ion motion is governed by the magnetospheric electric field.
- Approximately 30 chemical and photo-chemical reactions.
- Timescale: relatively long, $\sim$ 1 min timesteps.
- CTIM is very efficient: runs much faster than realtime ($>$10 times) on contemporary CPUs (PII/400, R10000, IBM PowerPC).

CTIM inputs

- Forcing from below: tides (independent from space weather effects).
- Solar UV and EUV (parameterized using F10.7 cm flux).
- Electron precipitation: from statistical models, parameterized by power input index (PI) or Kp.
- Ionospheric electric field (potential): from statistical/empirical models (Foster, Heppner/Maynard models).

CTIM outputs relevant for space weather

- Electron density and related parameters: NmF2, hmF2, TEC.
- Communications disturbances resulting from N_e variations.
- Navigation disturbances resulting from TEC variations.
- Neutral density that affects drag on satellites and space debris.

Coupling issues

- CTIM receives the potential Φ, and the electron precipitation parameters $E_{0,disc}$, $F_{e,disc}$, $E_{0,diff}$, $F_{e,diff}$.
- CTIM returns Σ_P and Σ_H to the MHD model.
- MHD and CTIM use different spatial grids and different coordinates (SM, GEO) $\Longrightarrow$ use linear interpolation and appropriate coordinate transformations. The MHD and CTIM grids roughly match (1-2° latitude resolution in the auroral zone and polar cap, $\sim$10° azimuthal resolution.)
- MHD and CTIM timescales are vastly different: 0.2 to 0.5 second timesteps for MHD, 60 sec timesteps for CTIM $\Longrightarrow$ CTIM is only called every 60 seconds, Σ_P and Σ_H are kept at their most recent values between CTIM calls. While the numerical MHD timestep is very small, the meaningful MHD timescale is of the order of tens of seconds (gridsize $\div$ velocity.)
- MHD and CTIM run asynchronous on separate computational nodes: after CTIM receives Φ, $E_{0,disc}$, $F_{e,disc}$, $E_{0,diff}$, and $F_{e,diff}$ it returns Σ_P and Σ_H from its last step. Thus CTIM lags the MHD model by 60 seconds. This accounts in part for the finite M-I propagation times and makes the computation much more efficient.
- There is no need for a "framework." CTIM is simply a Fortran subroutine that is called from the main time step loop of the MHD code when appropriate. CTIM completes one step in 1-2 sec CPU time, and most of that is I/O.
- The same coupling approach should work with most other models as well (RCM, ring current models, radiation belt models.)

Lessons learned

- Model coupling of this kind can only be done by the respective model PIs. They are the only ones who have sufficient intimate knowledge of the models.
- Model coupling goes far beyond the technical issue of exchanging data and getting the coupled model to run. There are numerous scientific issues involved that need to be explored.
- Although we hade quite some success in coupling the UCLA MHD model with CTIM many questions are still open. It will take years to explore them.
- As models are coupled the complexity increases. It becomes much harder to pinpoint model deficiencies or failures.
- It is naive to assume that two coupled models will automatically produce better results as either of the models alone. It is essential to understand the feedback processes before one can speak of a “better” model.