

Coupling of the Rice Convection Model to global MHD codes

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Why?

- GGCM=Geospace General Circulation Model, main eventual goal of GEM)
- Early idea within GEM was to use a modular approach, where different regions with different physics processes are treated separately and then they all are put together in some fashion
- Later, global MHD codes were suggested as a “backbone” for a GGCM
 - Global MHD are first-principles models that come closer to GGCM idea
 - Appear to simulate (imitate) some of the fundamental magnetospheric physics phenomena
- However, some important regions such as the ring current/inner magnetosphere are not treated properly by global MHD due to breaking approximations and numerical reasons.
- Come up with a “coupled” model that it “almost” first-principles and has an inner magnetosphere module that “corrects” ideal MHD equations to account for gradient/curvature drift physics—the two approaches can be complimentary.

What is involved: Global Ideal MHD

$$\frac{\partial \rho}{\partial t} + \mathbf{u} \cdot \nabla \rho + \rho \nabla \cdot \mathbf{u} = 0$$

$$\rho \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{u} \cdot \nabla \mathbf{u} + \nabla p - \mathbf{j} \times \mathbf{B} = 0 \quad \mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

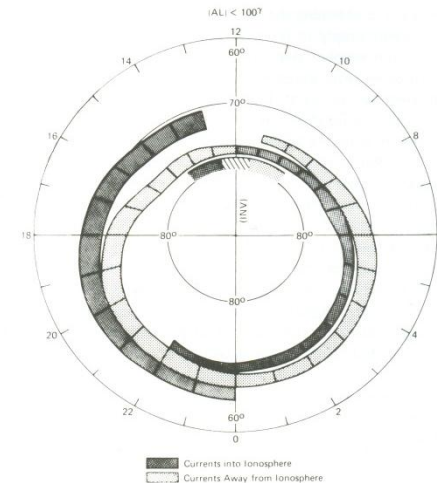
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times \mathbf{E} = 0 \quad \mathbf{E} = -\mathbf{u} \times \mathbf{B}$$

$$\frac{\partial p}{\partial t} + \mathbf{u} \cdot \nabla p + \gamma p \nabla \cdot \mathbf{u} = 0$$

- Modeling region extends from the upstream solar wind to ~200 RE down the magnetotail. Region close to the Earth ($R < 2-3$ RE) is usually excluded for numerical reasons.
- Ideal MHD equations are integrated in time and space by different numerical methods in different codes.

Global Ideal MHD: Why do they need an inner magnetosphere module?

- Global MHD codes don't include gradient/curvature drift physics in the ring current region. Single-fluid approximation is invalid.
- Inner magnetospheric pressure is too low (no ring current).
- Inner plasma sheet is too cold
- Region close to the Earth is difficult to model with adequate resolution.
- Region-2 Birkeland currents, which are generated at the inner edge of the plasma sheet via pressure gradients. Region-1 currents, which map out to high-latitude plasma sheet boundary and the magnetopause, are OK.



Iijima and Potemra, 1978

Model of Inner Magnetosphere: RCM

- The RCM is limited to the slow-flow, quasi-static-equilibrium region of the magnetosphere.
 - Treats electrons and ions separately and splits the particle distribution into dozens or hundreds of energy channels so that transport by gradient/curvature drift can be included accurately.
 - Often set out boundary at $\sim 8-10 R_E$ from Earth. The potential and plasma distribution function needs to be specified on this boundary.
 - Self-consistent within its regime, except that it doesn't calculate \mathbf{B} .
- 2-D model in terms of magnetic field-line integrated quantities:
 - pressure is assumed isotropic along magnetic field lines-- $V = \int ds/B$

$$\lambda_s = W_s V^{2/3}; \quad \eta_s = n_s V; \quad P = 2/3 V^{-2/3} \sum_s \lambda_s \eta_s$$

RCM Equations

- Particle advection equations:

$$\left[\frac{\partial}{\partial t} + \frac{\mathbf{B} \times (\Phi + (\lambda_s / q_s) V^{-2/3})}{B^2} \cdot \nabla \right] \eta_s = -L$$

- Ionospheric potential:

$$\nabla \cdot (-\hat{\Sigma} \cdot \nabla (\Phi - \Phi_c)) = \hat{b} \cdot \nabla V \times \nabla P$$

- Model needs B-field everywhere and boundary conditions on the E-field and particle fluxes as a function of time. These could be taken from a global MHD code.

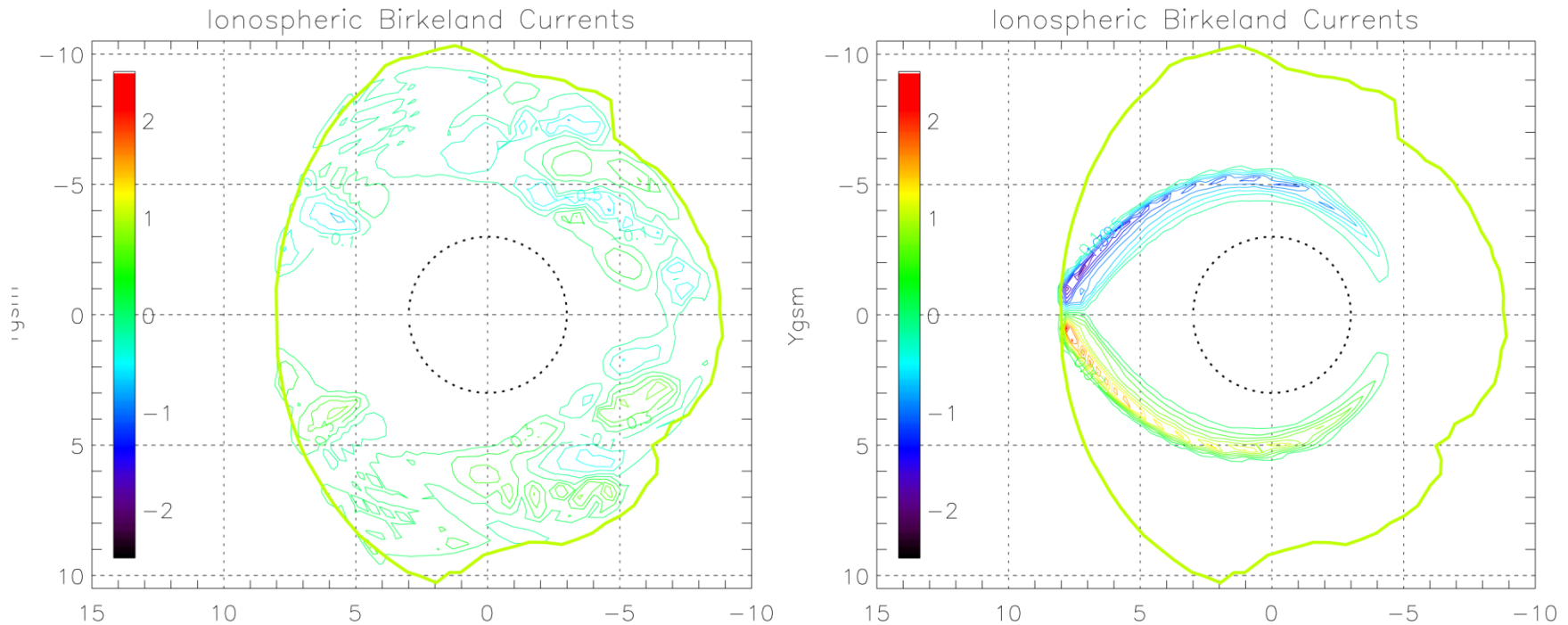
How?

- The RCM is limited to the slow-flow, quasi-static-equilibrium region of the magnetosphere lying on closed magnetic field lines.
 - Pressure is constant along field lines.
 - The potential and plasma distribution function needs to be specified on the high-latitude boundary.
 - Extensive field-line integration is required.
- MHD feeds the RCM information on
 - Magnetic field in inner magnetosphere
 - Boundary conditions
- RCM feeds back
 - Inner-magnetospheric pressures (and eventually densities)
- The flow of information between the codes is complicated, because they use very different formulations and very different grids.
- Either routine can compute Birkeland currents and potentials in RCM region.

History of “coupling” projects with RCM

- Mid-1990s: RCM coupled 2-way to the MRC global MHD code.
 - Actual coupling was done (a module within MHD)
 - Code used MHD electric field in the RCM region
 - The largest difficulty was in the enormous amounts of time required to trace magnetic field lines in the complicated 3-D grid of the MHD code.
 - Code ran, no science results
- Mid-1990s: one-way LFM-RCM coupling
 - Use LFM steady-state solution to drive the RCM
 - Trivial coupling (via writing/reading files).
 - Resulted in an M.S. thesis
 - Showed some of big difficulties lying ahead
 - A plan was suggested to for LFM to carry a second, B-field-aligned grid for the RCM (never implemented).
 - Tests indicated that even cold plasma sheet in the LFM should generate well-defined (but not realistic) region-2 currents.

Example of an early 1-way LFM-RCM coupling



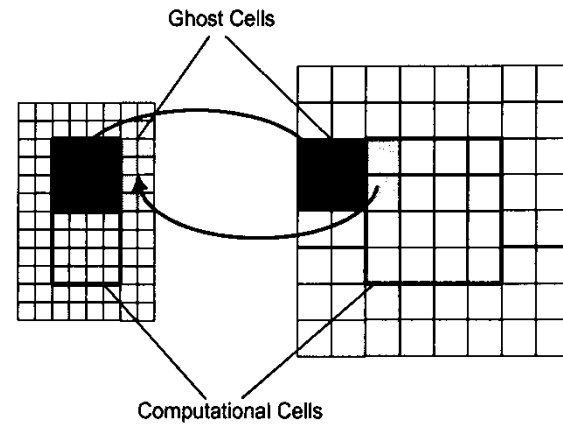
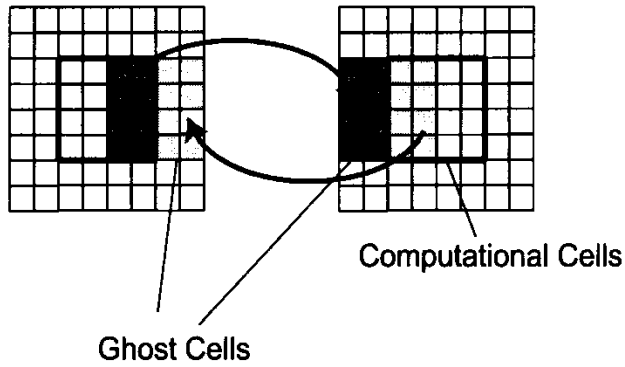
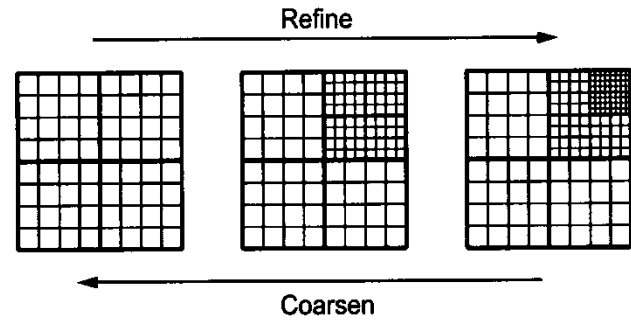
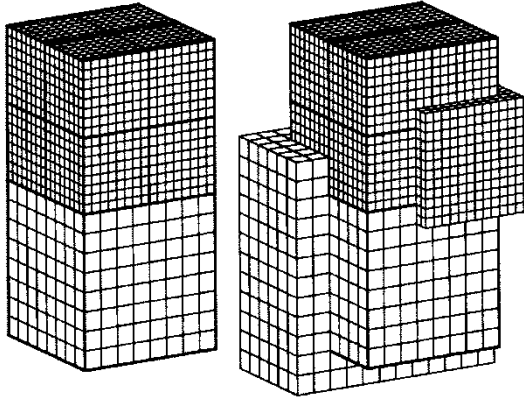
Birkeland currents into the ionosphere added for both hemispheres at $t=0$ (left) and $t=8$ hrs (right), for the case of “cold” plasma in the RCM. Currents are in $\mu\text{A}/\text{m}^2$.

M. Hojo, Rice M.S. Thesis, 1997

History of “coupling” projects with RCM

- 2000 to present: RCM and J. Raeder’s MHD code
 - Code coupling (RCM is part of MHD)
 - One-way: MHD drives the RCM.
 - Work in progress...
 - Code ran, no science results
- 1999 to present: coupling of RCM to BATSRUS
 - Full two-way coupling as part of developing a “Sun-to-mud” first principles computational model.
 - RCM was re-written for the project (including parallelization)
 - First publication was submitted Nov. 2003 to JGR (*De Zeeuw et al*).
 - Code is available for scientific investigations
- 2002 to present: coupling of RCM to LFM
 - Part of CISM project, for which LFM is a “backbone”.
 - First results were obtained last Friday, but the code does not work yet.

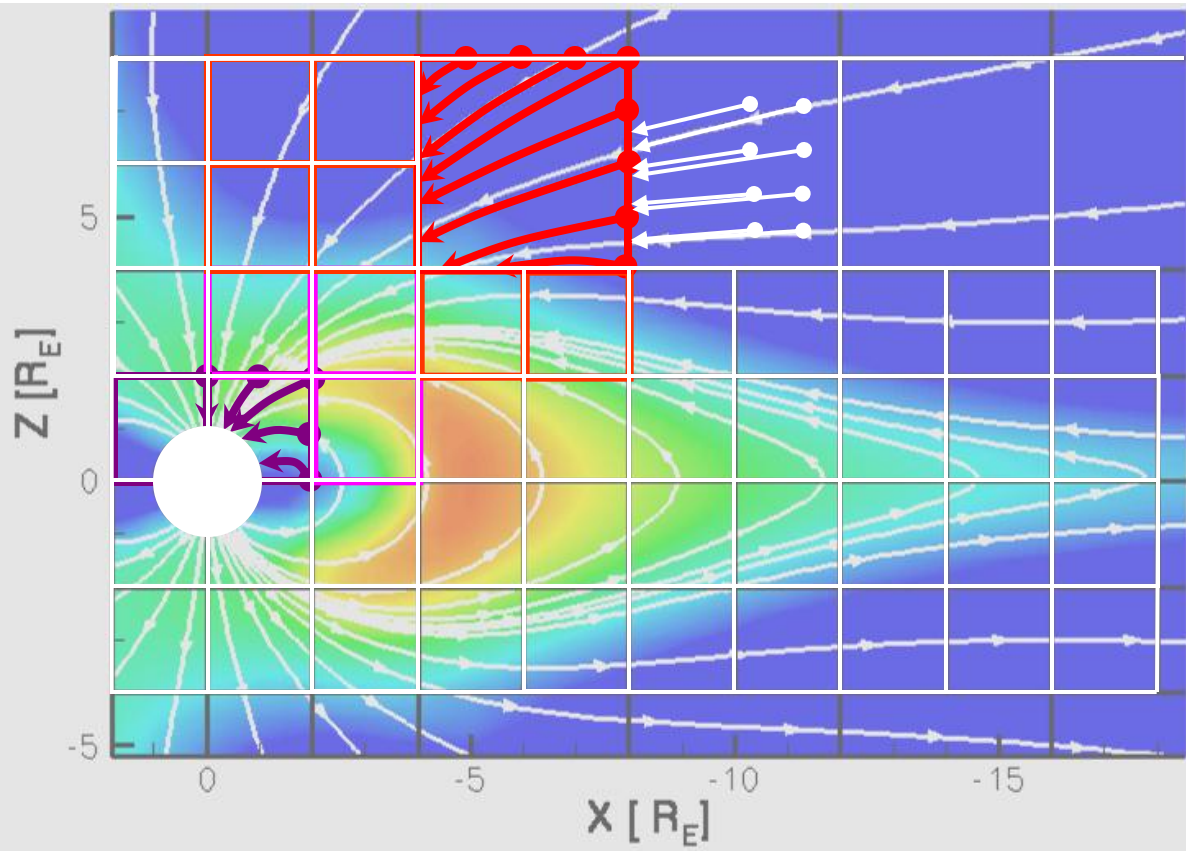
Adaptive Mesh Refinement



Coupling: Parallel Ray Tracing

- Conversion from MHD 3-D \mathbf{B} , P , and ρ to 2-D RCM field-line integrated quantities requires tracing (and integrating along) B lines on the RCM 2-D ionospheric grid every coupling time step (1-10 min). Straightforward tracing is not desirable because:
 - Slow
 - Technically difficult on a mesh with AMR.
- A novel technique (Toth-DeZeeuw) was invented to solve this problem efficiently.

Interpolated Tracing Algorithm



1.

2.

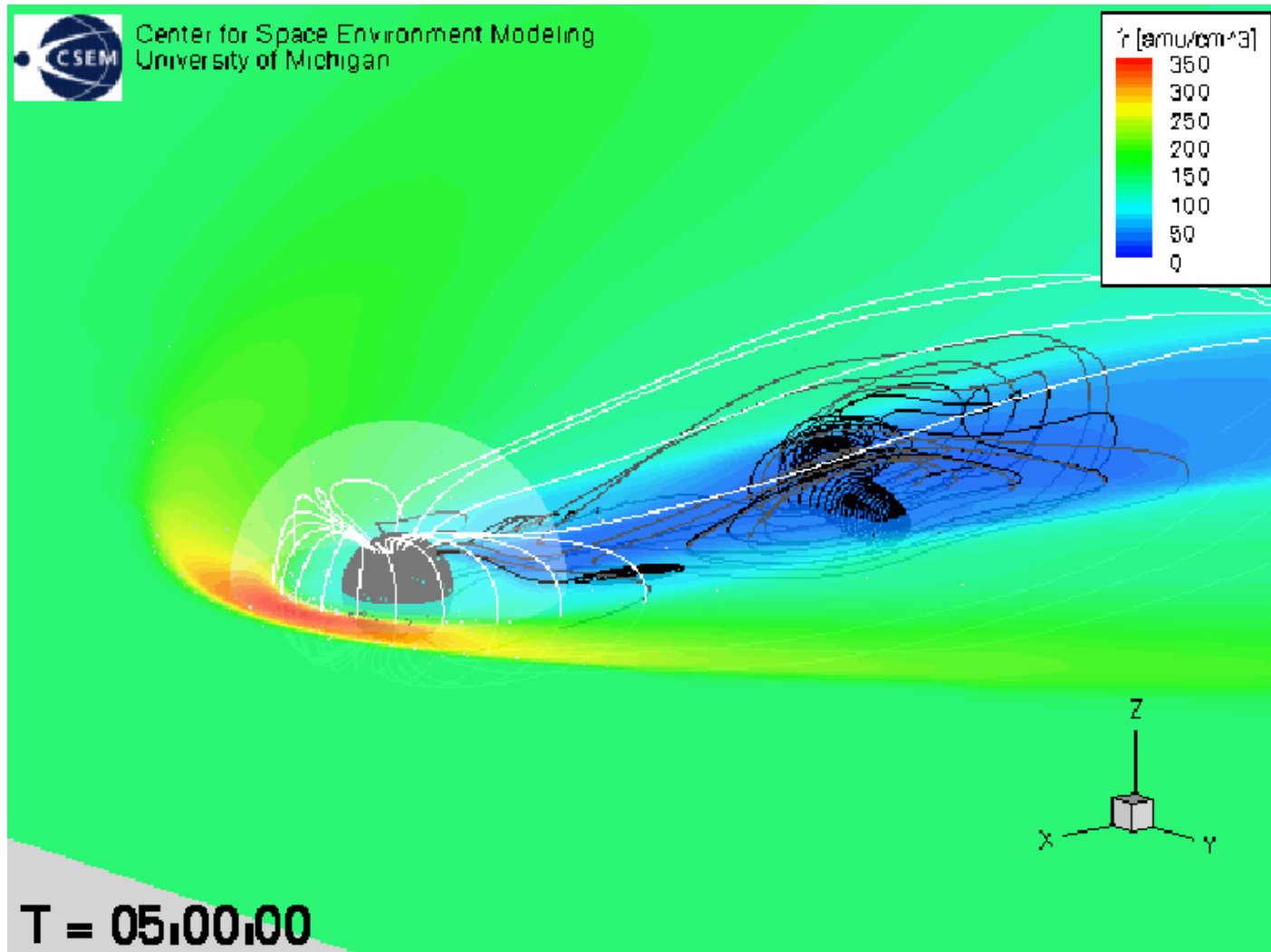
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2.

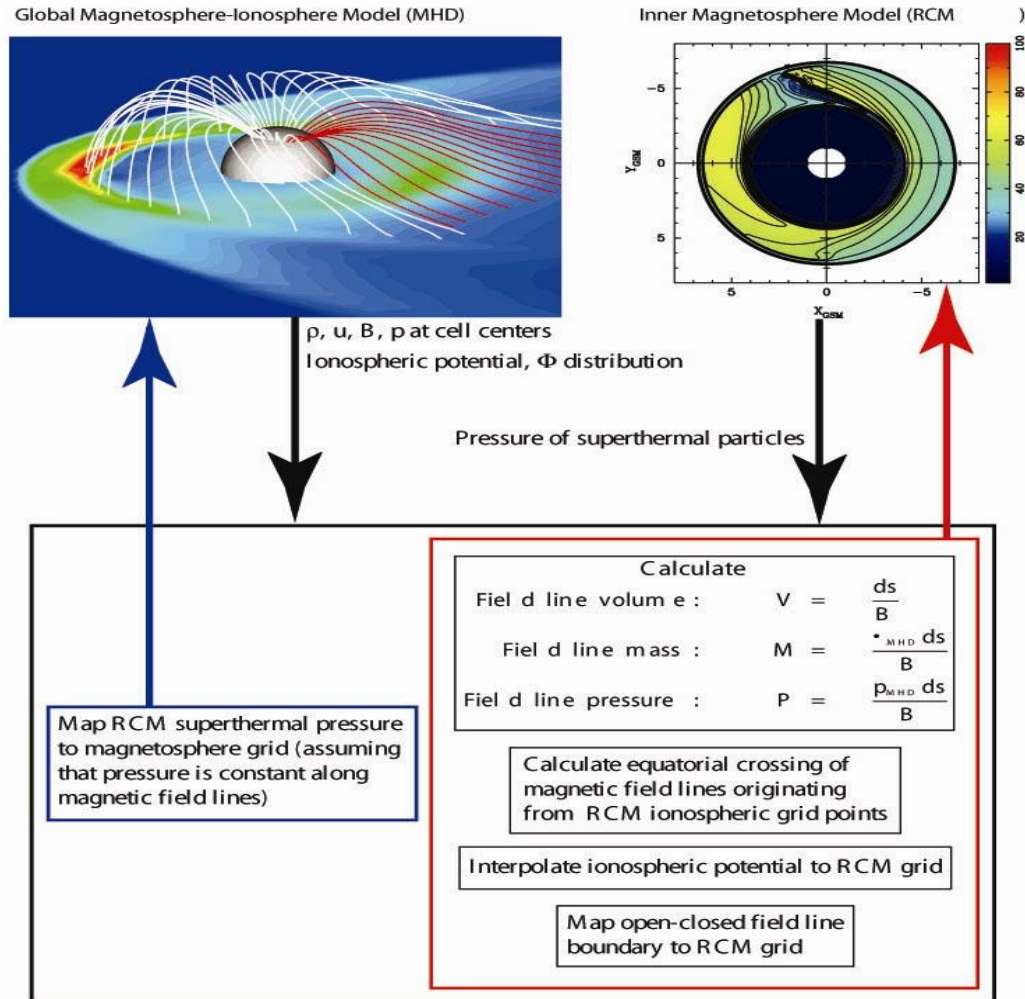
4.

5.

... and this is where tracing is needed:

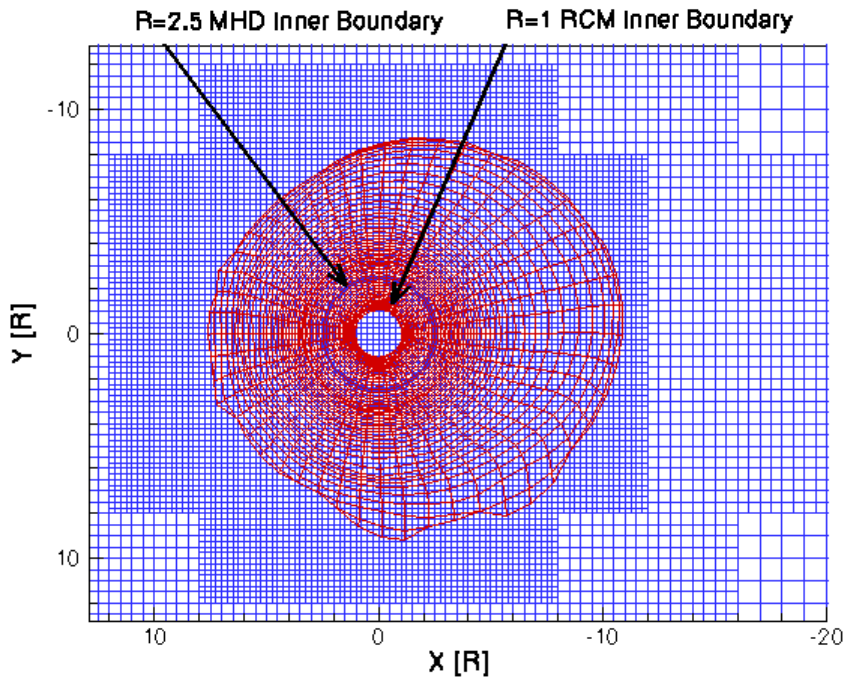


Physics of coupled BATS-R-US—RCM model



Two Way Coupling between BATS-R-US and RCM

The pressure that is fed back to the MHD code by the RCM is used to drive the MHD pressure.



- ① Pressure is fed back on RCM grid
- ② Pressure is interpolated to the MHD grid
- ③ Comparison between MHD and RCM pressures with the driver computed as:

$$p_{MHD}^{n+1} = p_{MHD}^n + \frac{\Delta t}{\tau} (p_{RCM} - p_{MHD}^n)$$

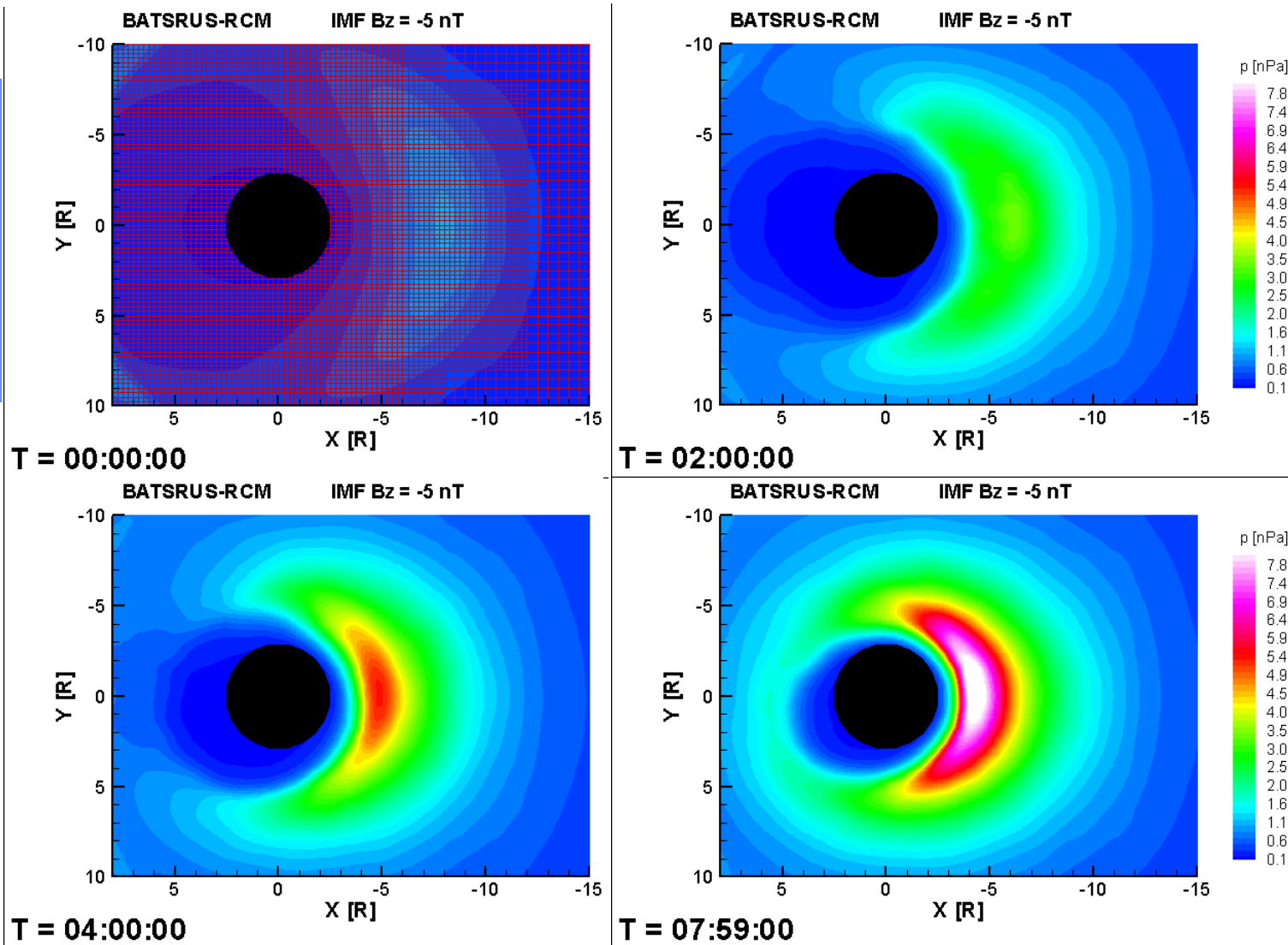
τ is usually on the order of $100\Delta t$ so with each iteration there is a $\approx 1\%$ change made in the MHD pressure on closed field lines within about $10 R_E$.

Run Description

- Steady solar wind conditions: IMF $B_x=B_y=0$, $B_z=-5$ nT.
- At T=8 hours, $B_z=-5$ nT \rightarrow +5 nT suddenly at upstream boundary ($X_{\text{gsm}}=32 R_E$).
- Ionospheric conductances: $\Sigma_p=4$ S, $\Sigma_H=0$ in MHD and RCM. There is no auroral zone enhancement to Σ (problem with grid overlap).
- Full 2-way MHD-RCM coupling every 10 seconds.
- 854,016 computational cells are used in the MHD grid (smallest: $0.25 R_E$, largest: $8 R_E$).
- Inner boundary for MHD is at $2.5 R_E$ ($3.5 R_E$ for mapping J_{\parallel})
- MHD (IONO) solves for the potential, RCM uses its own potential to move particles but no direct feedback.
- No dipole tilt.
- Second run is same but without the RCM (pure MHD).

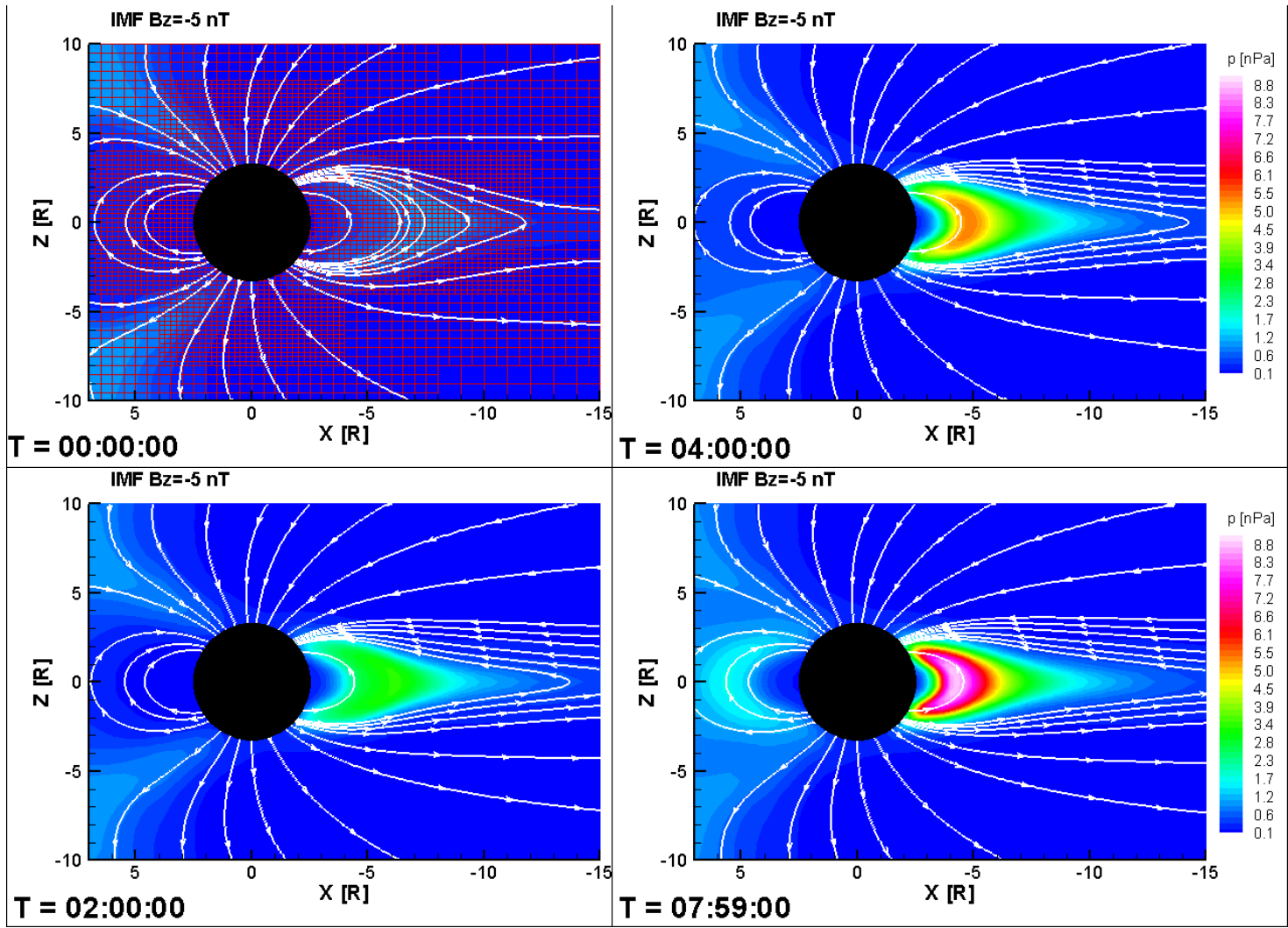
Plasma pressure build up during period of IMF $B_z = -5$ nT: Equatorial plane view

Grid overlay

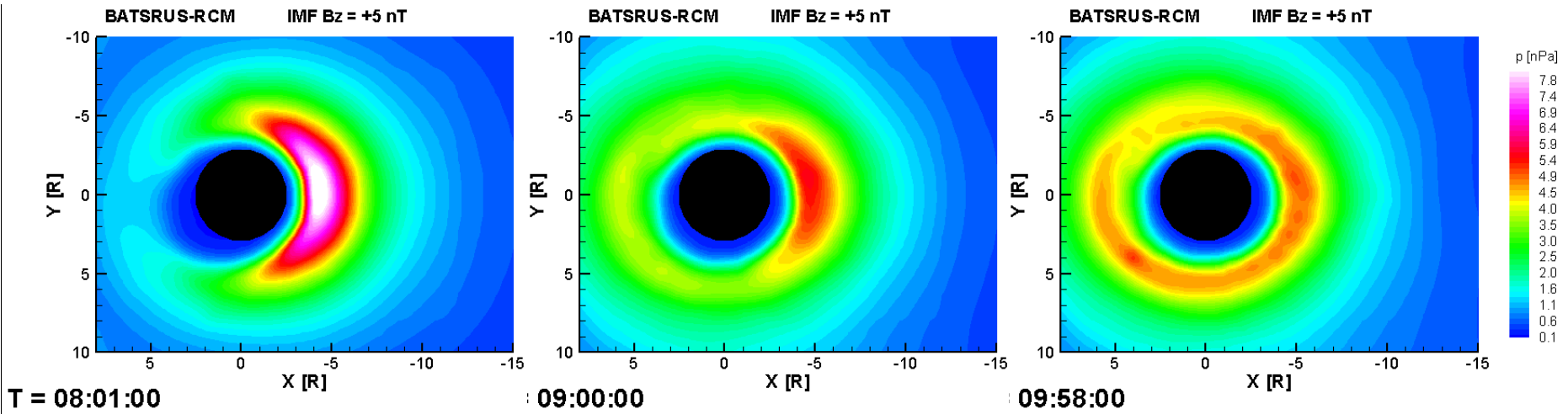


Plasma pressure build up and magnetic field (white lines) stretching during period of IMF $B_z = -5$ nT: Noon-midnight merid. plane view

Grid overlay



Plasma pressure symmetrizes after northward turning

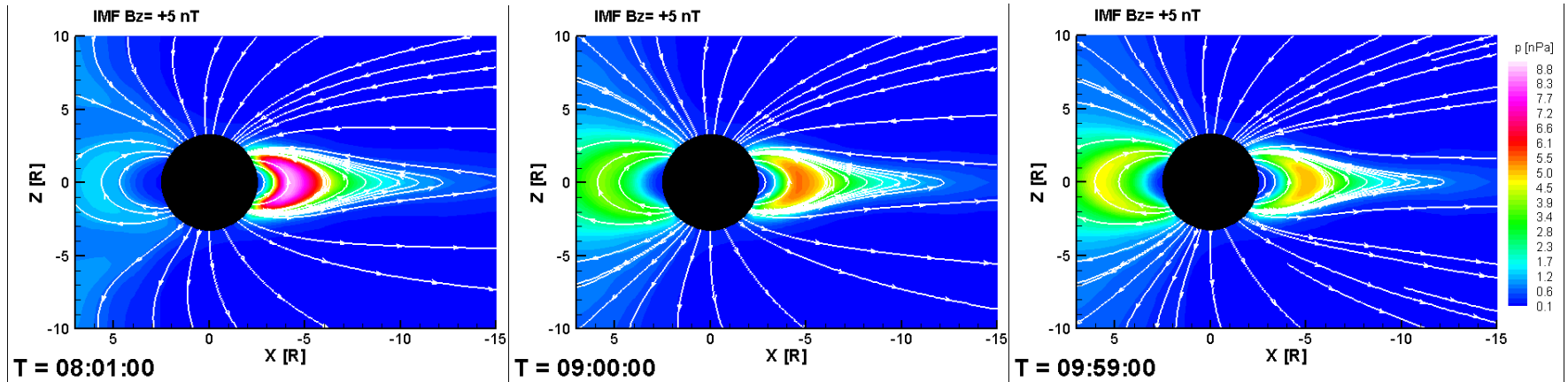


After 8 hrs of strong driving, pressure has a peak at $\sim 4 R_e$ at midnight

Following northward B_z turning, pressure weakens on the night side

... and becomes much more symmetric in MLT 2 hrs later.

Plasma pressure and magnetic field (white lines) after northward turning: Pressure symmetrizes, B-field dipolarizes

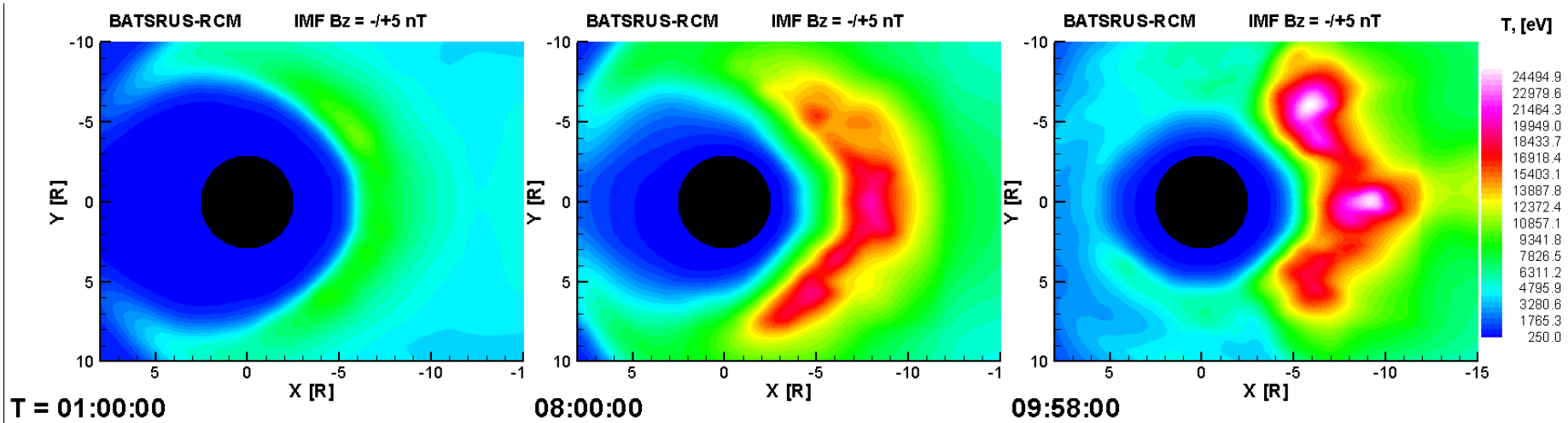


After 8 hrs of strong driving, magnetic field lines on the night side are highly stretched.

Following northward Bz turning, magnetic field becomes “less stretched” ...

... and becomes much more dipolar-like after 2 hrs, consistent with magnetic field and plasma being in approximate force-balance.

Plasma sheet temperature (whole run): Equatorial plane view



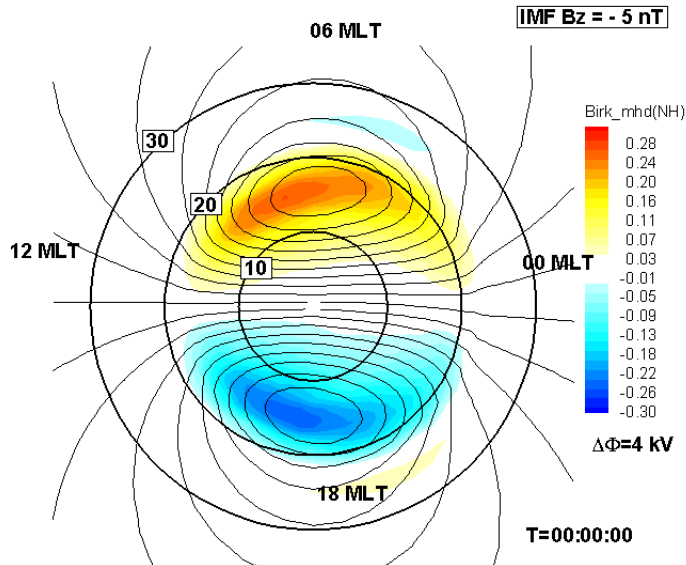
Before coupling is established, plasma sheet is unrealistically cold (typical of MHD only)

After 8 hrs of $B_z < 0$ driving, plasma sheet within 10 RE is much warmer (more realistic)

After northward turning, tail B-field dipolarizes, further increasing plasma temperature in the ring current.

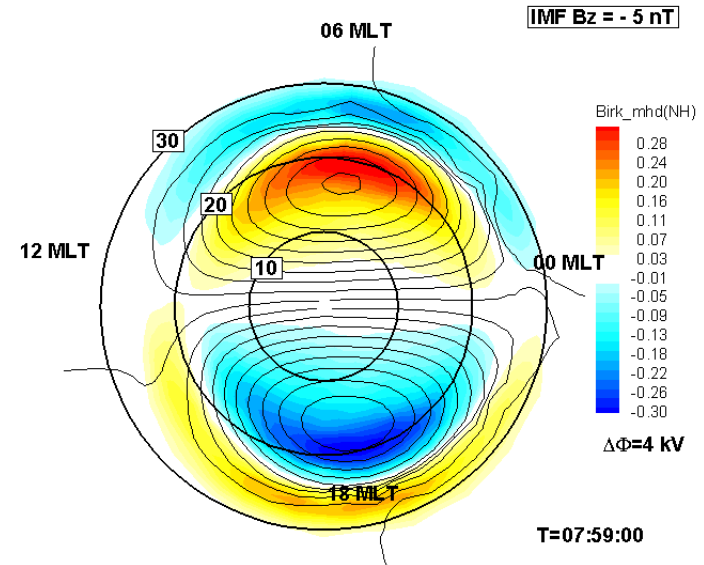
M-I coupling electrodynamics during $B_z < 0$ period: Formation of realistic region-2 Birkeand currents

BATSRUS-RCM IONOSPHERIC POTENTIAL AND FAC



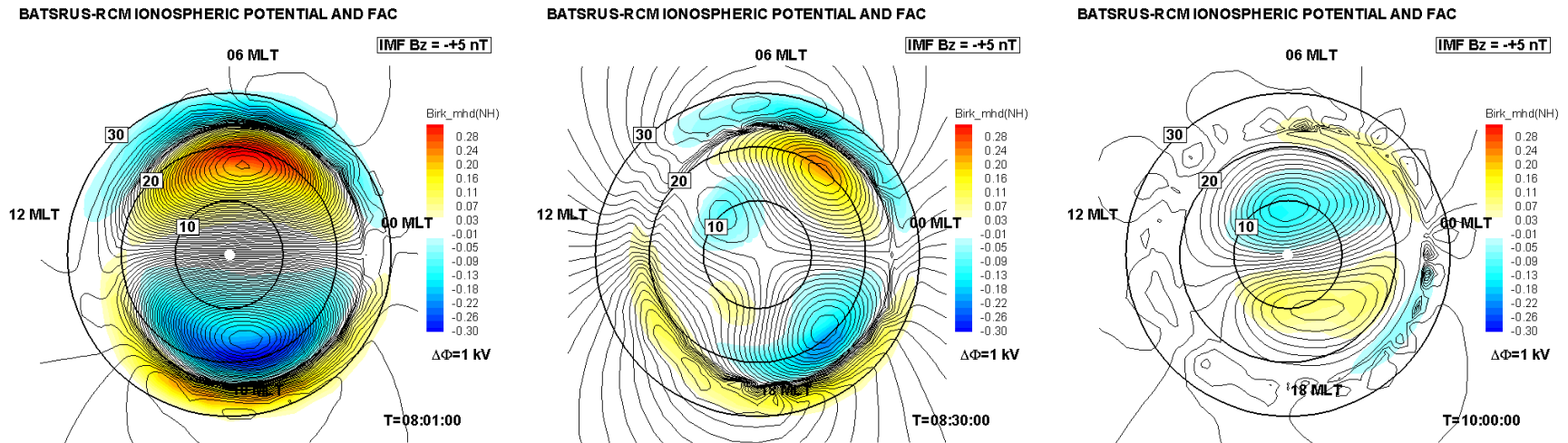
Without RCM, MHD has negligible region-2 field-aligned currents, and convection electric field is not shielded from low latitudes (equipotentials “leak” to lower lats).

BATSRUS-RCM IONOSPHERIC POTENTIAL AND FAC



In a steady-state with RCM coupling, region-2 currents are of magnitudes similar to region-1, and there is noticeable shielding (convection pattern is more confined to auroral zone).

M-I coupling electrodynamics after $B_z > 0$ turning: Overshielding by region-2 currents

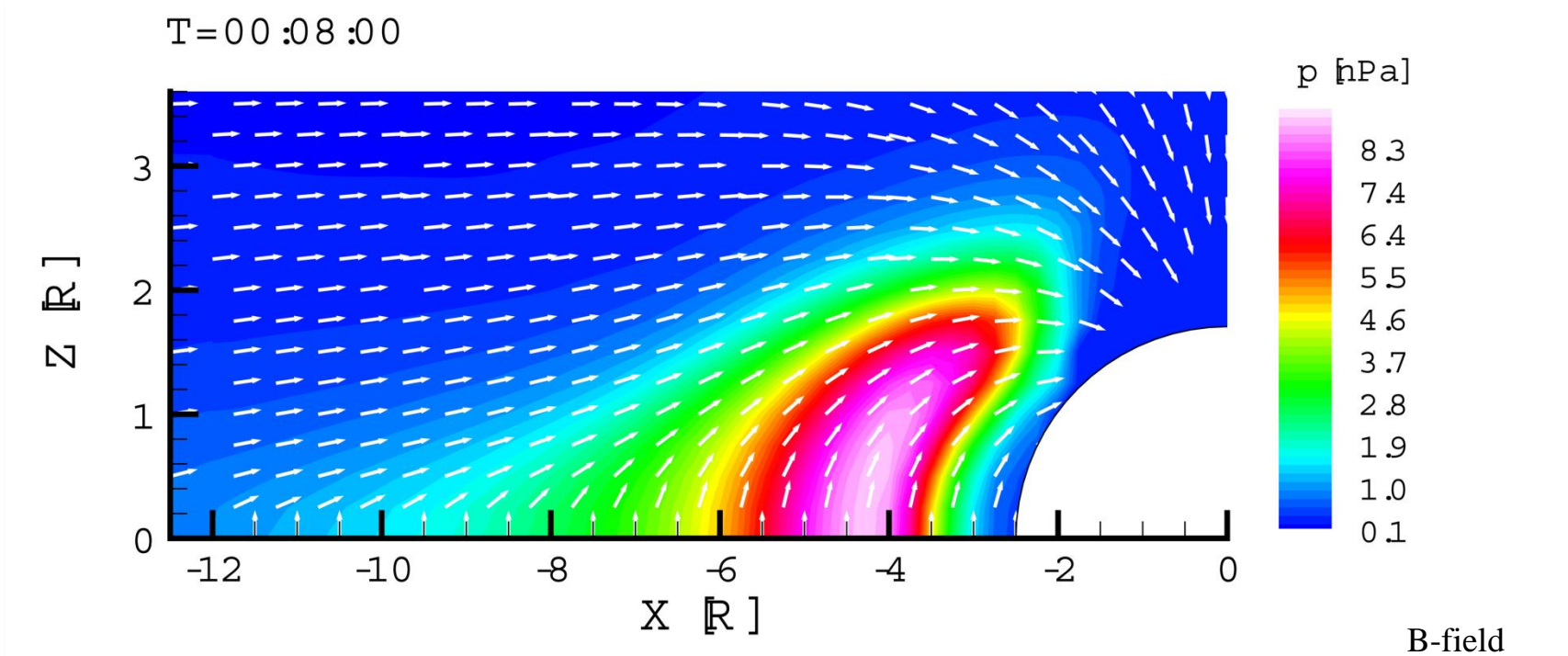


At the time of northward turning, strong convection, well-developed region-2 currents, strong shielding.

After northward turning, overshielding pattern

...that eventually settles down to a weaker convection

Is P really constant along B-field lines?



Outside 3.5 RE, projected B-field lines tend to be parallel to contours of constant pressure. Closer to Earth, deviations do not have much effect:

$J_{\parallel} \sim \text{grad}(V)$, and V is contained near the equatorial plane. For a dipole field, 75% of V comes from between $0.84R_0$ and R_0 .

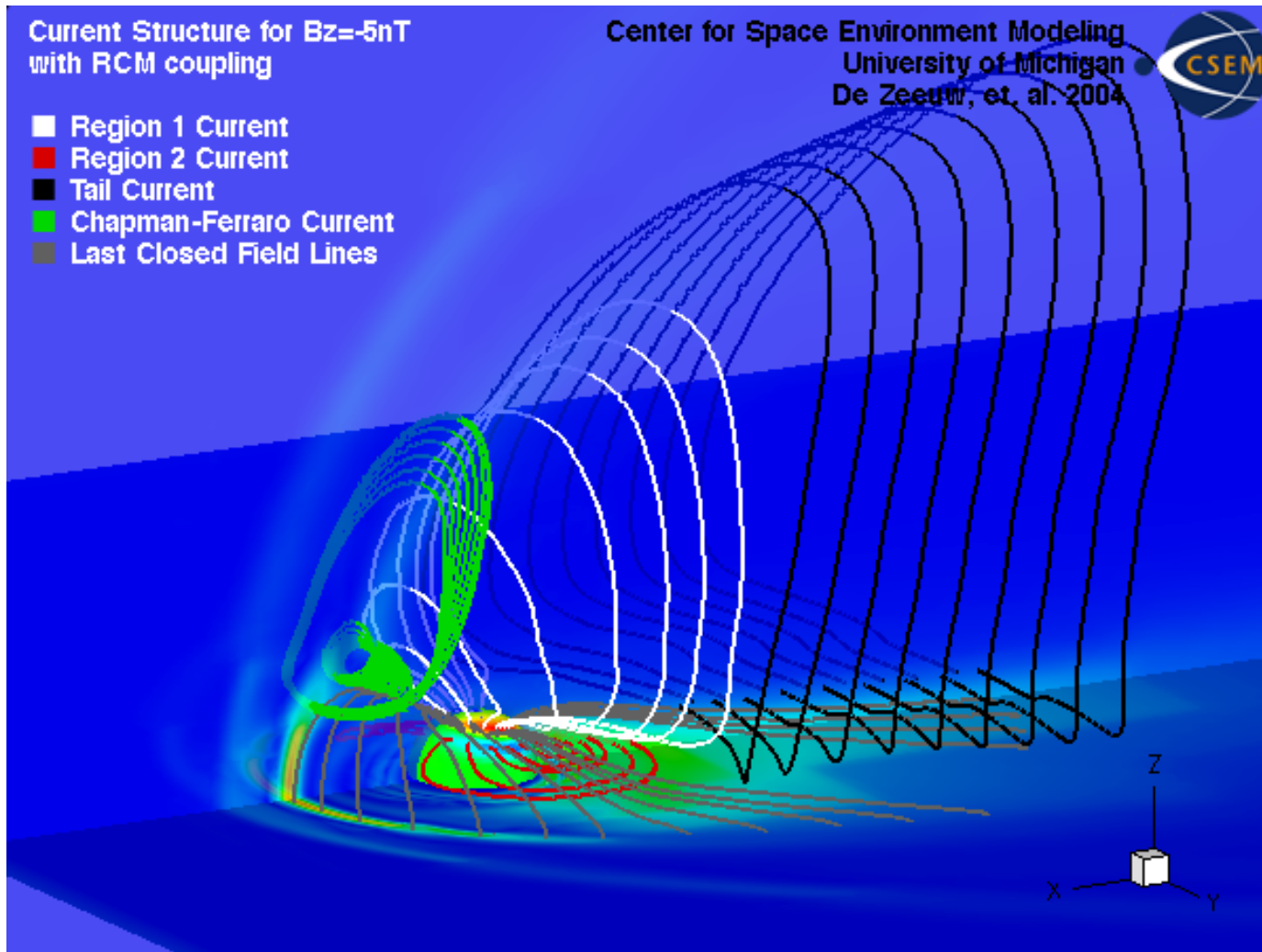
Role of R-2 FAC in determining PCP drop

Hill et al. [1976], and Siscoe et al. [2002]: PCP drop is limited by region-1 FAC:

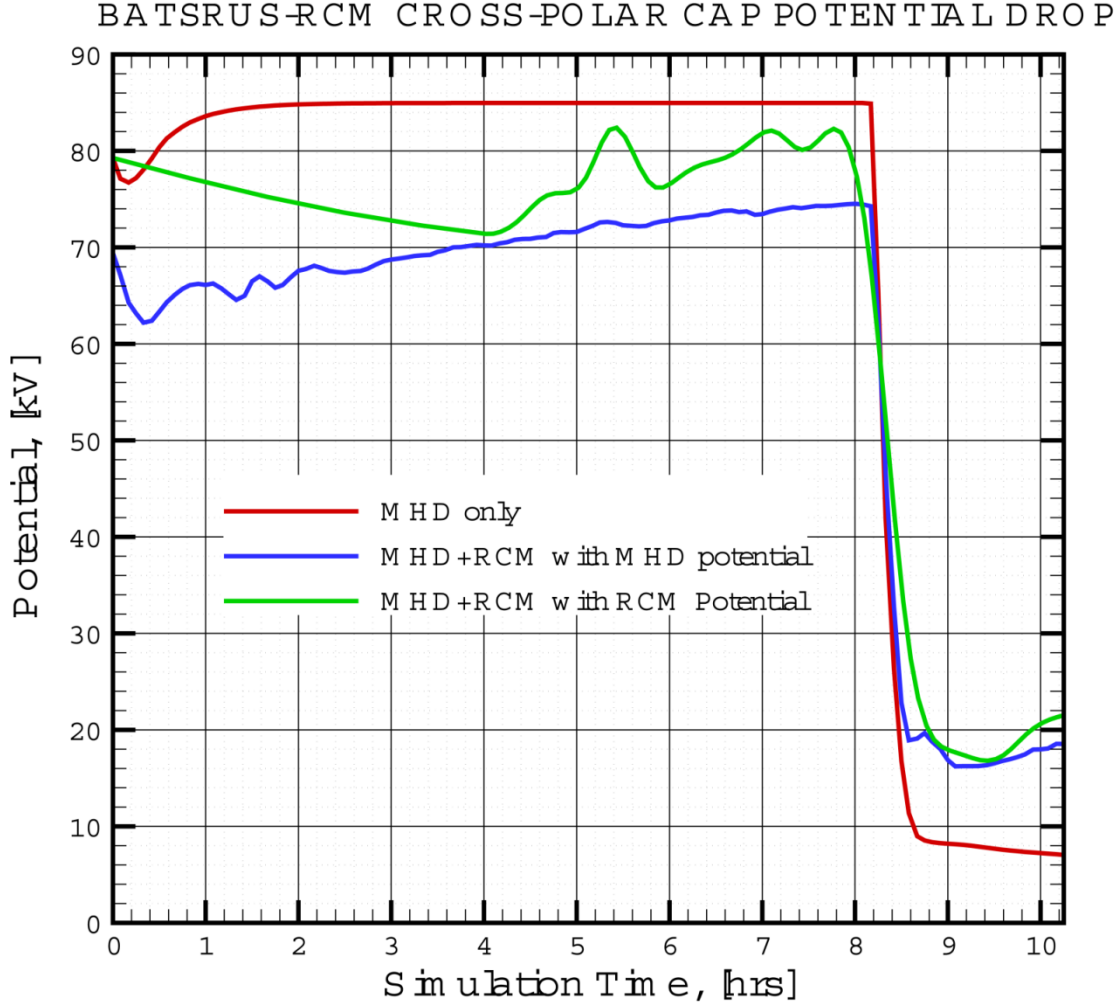
$$\Phi = \frac{57.6 p_{sw}^{1/3} IEF}{p_{sw}^{1/2} + 0.01 \xi \Sigma IEF}$$

Siscoe et al. [2002] also predicted that having region-2 FAC in MHD models would reduce PCP due to increased effective conductance.

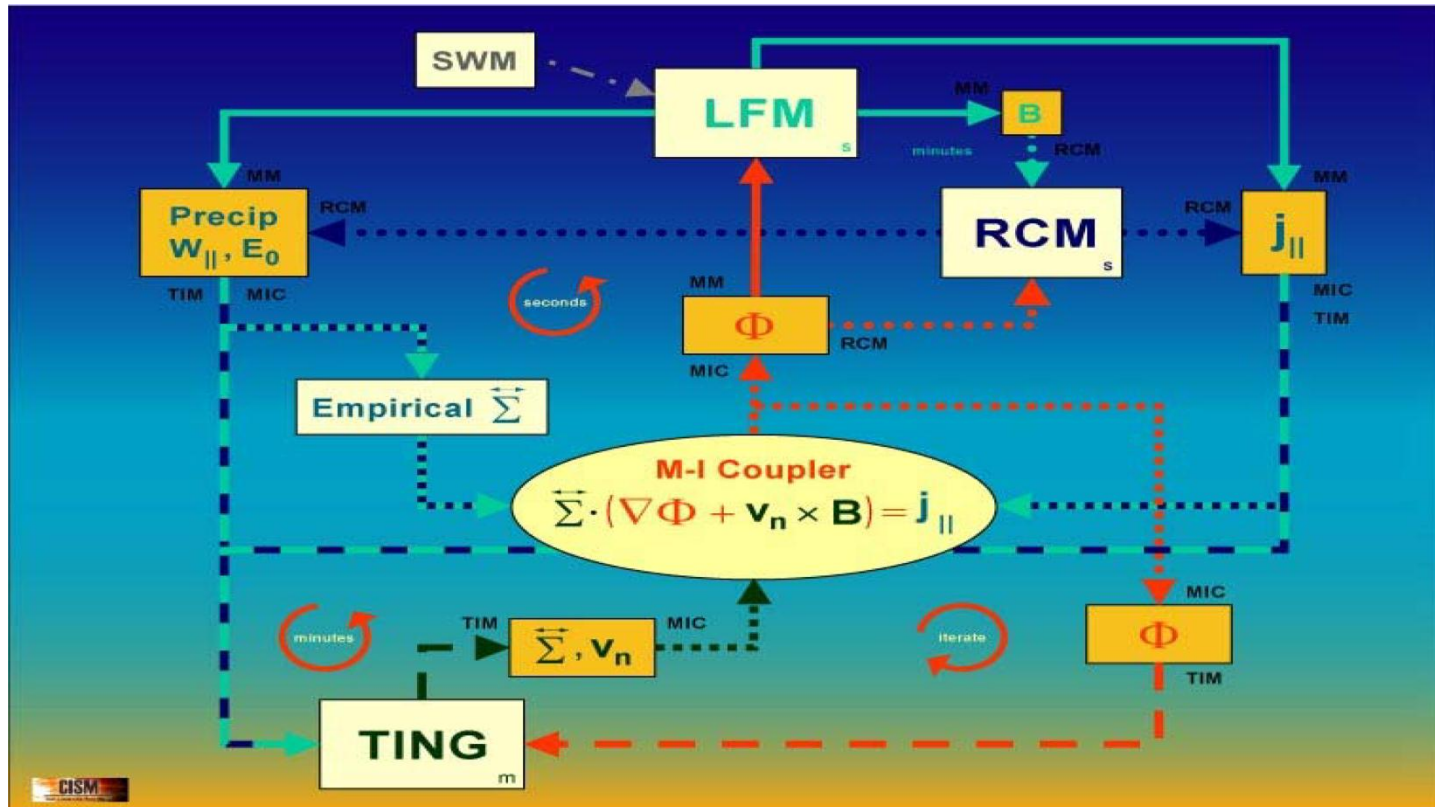
Region-2 currents due to RCM coupling provide an additional closure path for region-1 currents, thus modifying PCP drop.



Time History of PCP drop with and without RCM coupling



- CISM Project



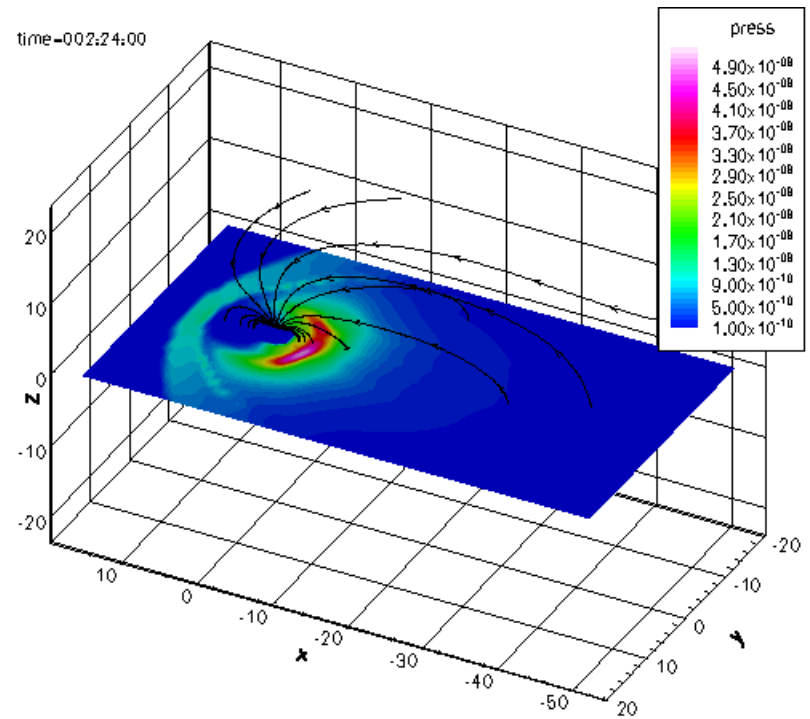
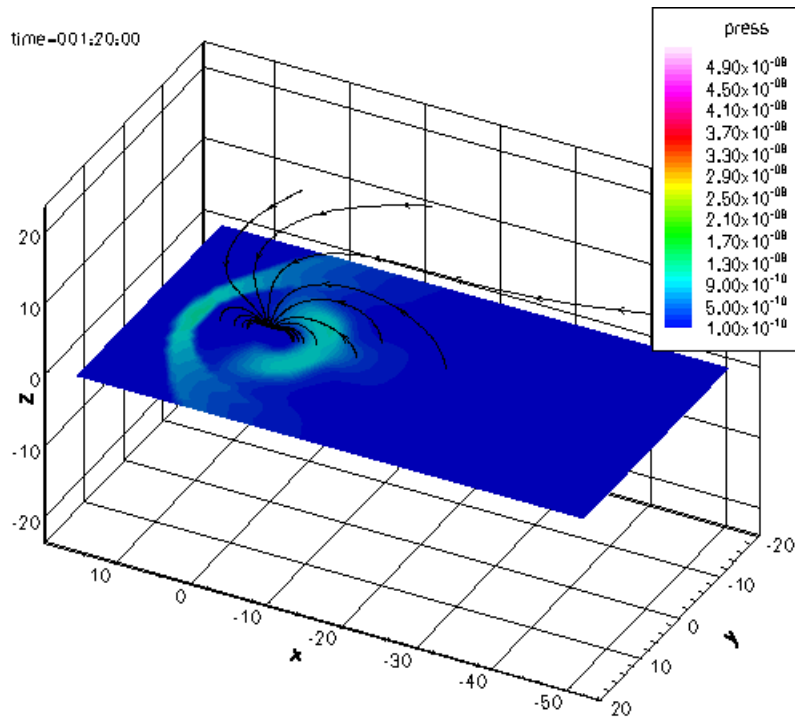
LFM-RCM: Initial 2-way coupling

- First 2-way coupling has been done. The two codes are run independently and exchange information via writing/reading files.
- The ultimate goal is to use the InterComm library (software package) that allows different codes to exchange information. This does not require re-writing existing large computer codes. The current scheme of coupling via files was designed to mimic InterComm-style information exchange before InterComm became available.
- Magnetic field-line tracing is done by re-interpolating MHD and RCM data structures on an intermediate 3-D rectangular grid. Since the version of the LFM used is an OpenMP code, this works well, but it is not clear if this is suitable in the future.
- LFM supplies to the RCM 1-minute average physical quantities, and the RCM overwrites P and ρ .

LFM-RCM: Initial Trial Run

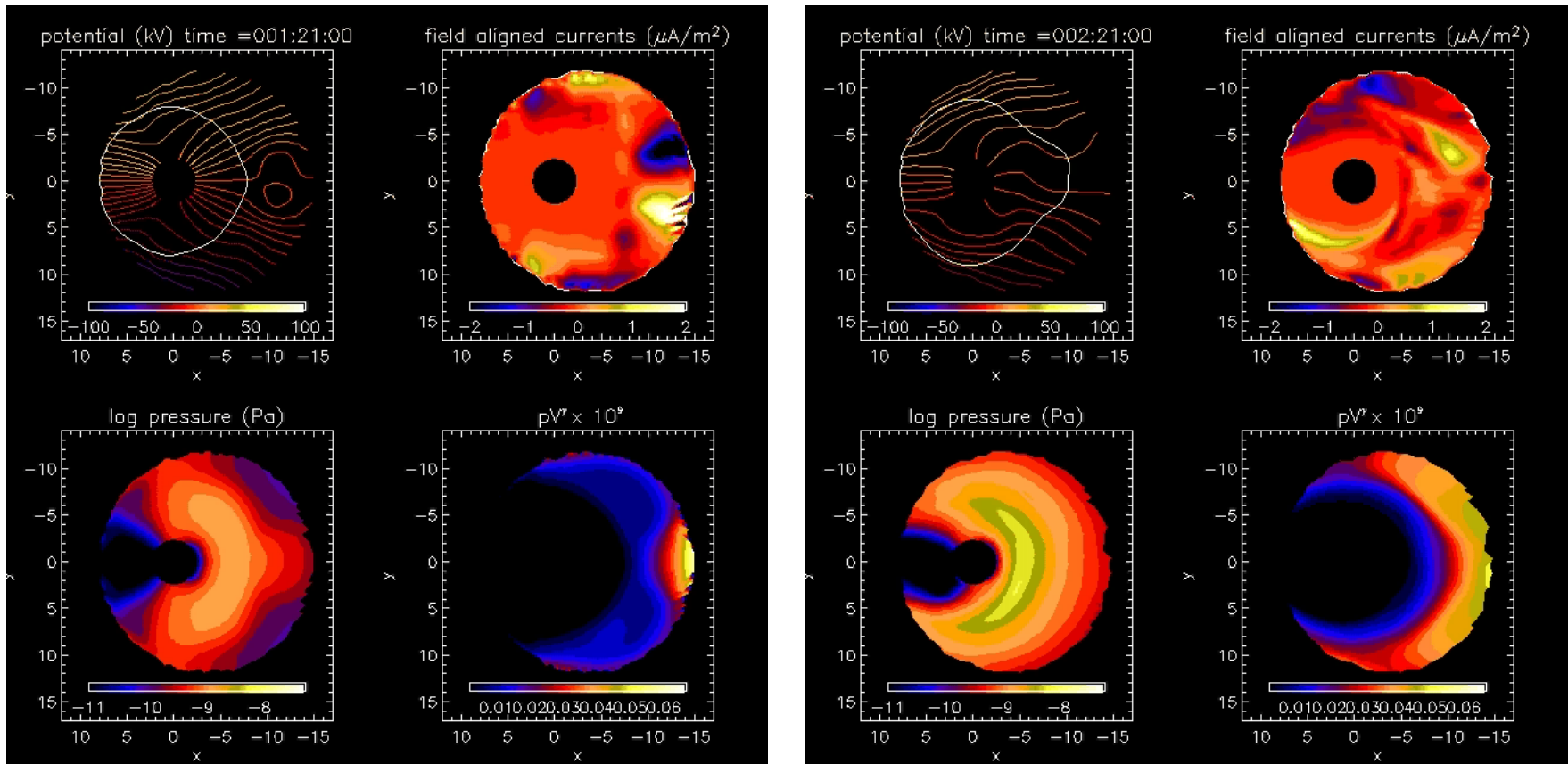
- Steady-state conditions.
- IMF $B_z = -5$ nT
- LFM inner boundary at 2.5 RE.
- Ionospheric conductances are supplied by LFM.
- Coupling time is 1 min.

LFM-RCM



- During 1 hour of coupled simulation, a partial ring current begins to form and the corresponding inflation in the magnetic field can be seen.
- Pressure increase at ~ 8 RE is up to 4 nPa.
- However, there are instabilities problems arising in the LFM, the nature of them is not clear yet.

LFM-RCM 2-way coupling:



In this short run, region-2 currents begin to form in the RCM after ~ 1 hr.
Work is in progress...

Summary

- Technically challenging problem. Not clear if it can be done at all.
- Work on BATSRUS-RCM started ~5 years ago, and very good progress has been made (there is a working code available for science investigations).
- Work on LFM-RCM started <2 years ago (CISM), and initial results are just now being obtained.
- The process can be broken down into 3 levels:
 - Level 0: achieve increase in P, formation of a partial ring current, and inflation of B in global MHD codes, also formation of region-2 currents (most difficult). Done with BATSRUS, in progress with LFM.
 - Level 1: design a self-consistent way to handle ionospheric electric field and conductances in both codes (we know how to do it, about to be done with BATSRUS. Work under way with LFM, but it goes beyond the RCM).
 - Level 2: further additions to codes, such as diffuse auroral precipitation, field-aligned potential drops, anisotropic pressure in the RCM. Not clear how to do, mostly have not thought about it.
- Instabilities possibly related to coupling are not understood well, although they seem to be common to more than one coupled code and may be a physical property of the magnetospheric system.

Science Applications

- We are applying BATSRUS-RCM to the problem of time-dependence of prompt-penetration ionospheric electric fields. It can only be done with a coupled code.
- We are estimating the induction electric fields in the RCM within the coupled BATSRUS-RCM code in view of their possible role on plasmaspheric structuring observed by IMAGE EUV.
- Aside from some missing pieces, we now have computational capability to solve a complete and reasonably defensible set of equations for the inner magnetosphere. MHD codes model the coupling between the magnetosphere and solar wind, which eliminates the need for a lot of boundary conditions in the RCM, which are not available directly from observations.
- It may be time to start attacking the problem of magnetic storms, substorms, and related phenomena (sawtooth events, etc) with these coupled codes, assuming that MHD codes model non-adiabatic processes in a way the Nature does. Possibly will need some sort of data assimilation.

Some Specific Science Questions

- Some sample scientific questions:
 - What are the essential non-adiabatic processes that occur in the middle plasma sheet at substorm onset? We can't treat the kinetic processes in detail in these large-scale codes, but if we can parameterize their effects and achieve agreement with observations, that will place very strong constraints on the microphysical processes.
 - What causes auroral breakup, westward traveling surge? Do these follow automatically from appropriate non-adiabatic reduction of $PV^{5/3}$, given an appropriate algorithm for estimating field-aligned potential drops?
 - Same for the dispersion signatures observed in particles at geosynchronous orbit in a substorm.
 - What is the role of the magnetospheric interchange instability in producing the observed features of substorms and storms, particularly as reflected in auroral emission patterns?