

Inputs for Magnetosphere Models

**Determining what you need
and how it impacts simulation results**

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This Lecture:

Definitions & Assumptions For This Lecture

- **Models** can be first-principles-based or regression-based (but focus will be on FPB)
- **Magnetosphere models** can be *any* model of the magnetosphere or its parts. Think beyond global MHD!
- Model **inputs** refers to any model requirement, not just solar wind.
- This talk is designed for **model users**, not *developers* or *power users*.

Learning Objectives: *in 50 minutes, you will be able to...*

- Identify inputs required for a given magnetospheric model
- Recognize how inputs can impact a numerical simulation
- Given research goals, critically assess the strengths and weaknesses of the set of model inputs used for the study

What are *Inputs*?

Inputs are anything you need to run your model

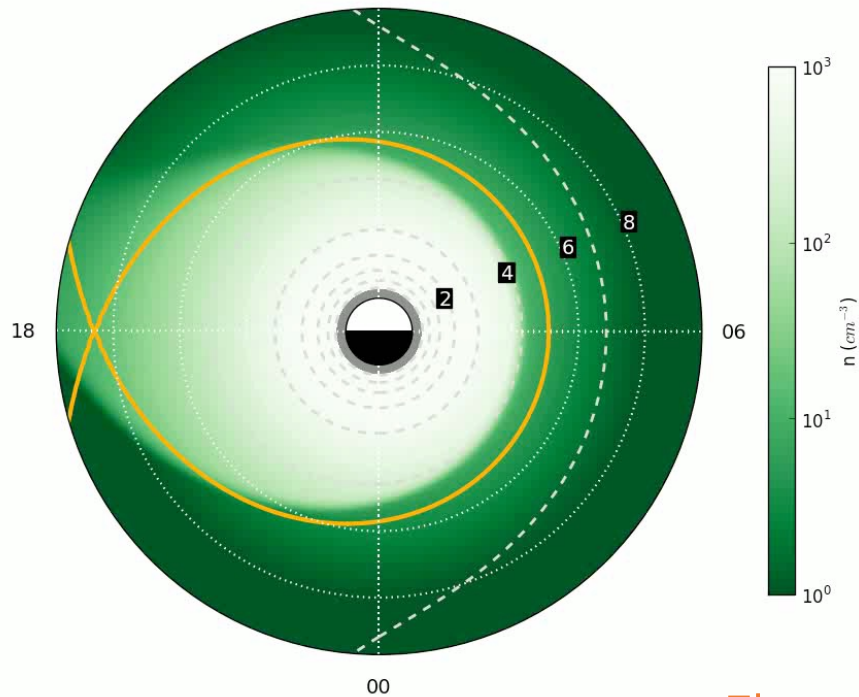
- Initial Conditions
- Boundary Conditions
- Source & Loss Terms
- Variables not explicitly solved by numerical scheme
- Values used to create regression-based models (*features* in ML parlance)
- Configuration and parameter set of the numerical scheme, including spatial grid, solver order, time-stepping scheme, etcetera. Model config is a *huge* topic that requires its own deep-dive.

It is a critical step in scientific investigations!

A Case Study: DGCPM

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$$\nabla \cdot (\overrightarrow{U_{\perp}} N) + \frac{\partial N}{\partial t} = S_{\text{iono}}$$

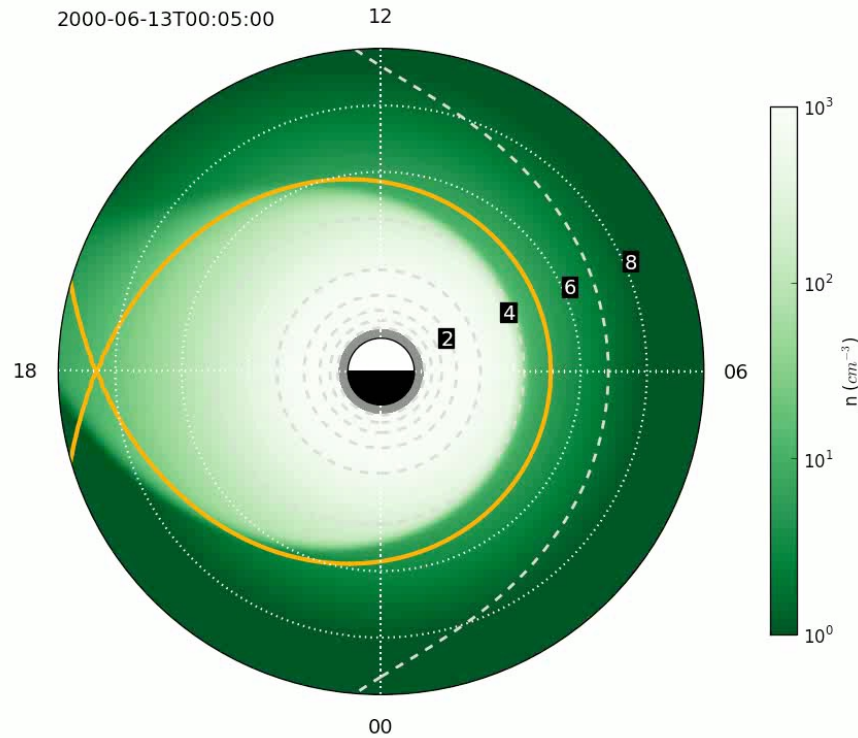
$\overrightarrow{E} \times \overrightarrow{B}$ drift (km/s) Flux tube content (n electrons)
Ionosphere refilling (N/s)

The Dynamic Global Core Plasma Model is a model of equatorial plasmasphere content.

- Simple continuity equation for N : flux tube content (electrons per flux tube) as a function of local time, L-shell, and time.
- Solves for N using a second-order upwind scheme with a Superbee limiter.
- Assumes a dipole field.
- Ionosphere refills flux tubes on dayside (S_{iono}).

What are the inputs to this model?

Case Study: DGCPM Inputs



$$\nabla \cdot (\overrightarrow{U_{\perp}} N) + \frac{\partial N}{\partial t} = S_{\text{iono}}$$

What are the inputs to this model?

Initial conditions:

N at all local times and L-shells

Boundary conditions:

None: outer boundary is lossy,
Neumann inner boundary

Source & Loss Terms:

Refilling via *Carpenter & Anderson, 1992*

Variables not solved for:

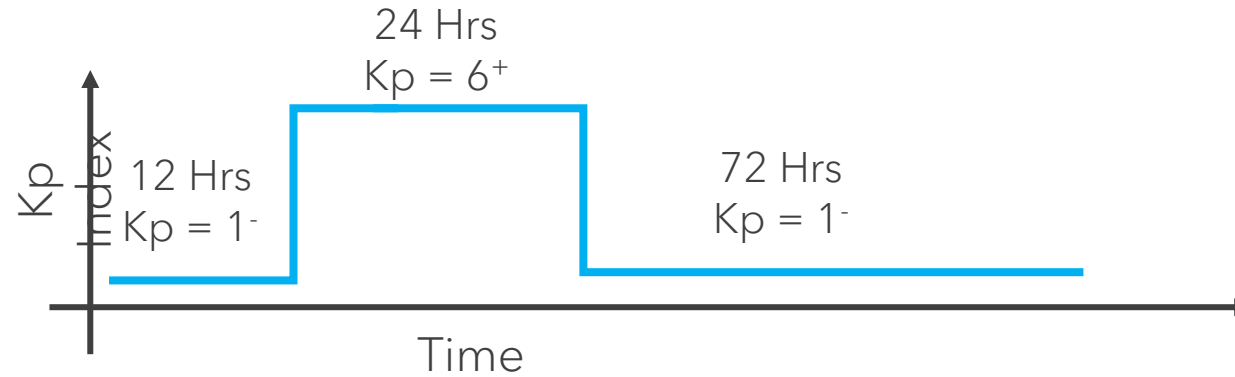
$$\overrightarrow{U_{\perp}} = \vec{E} \times \vec{B}$$

Input data for relationships:

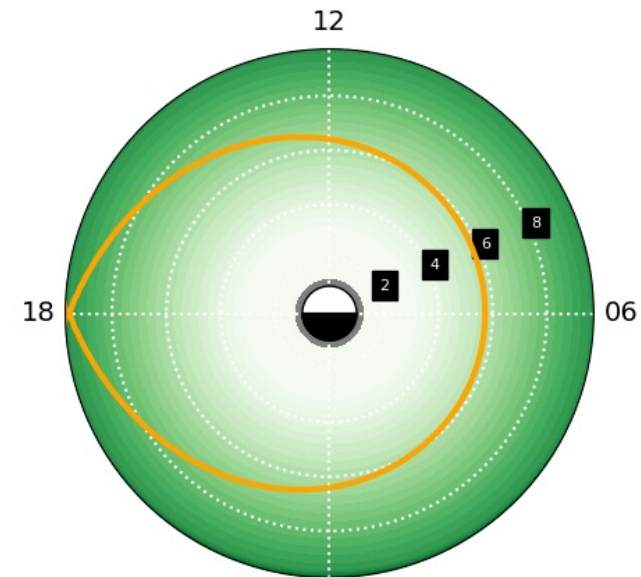
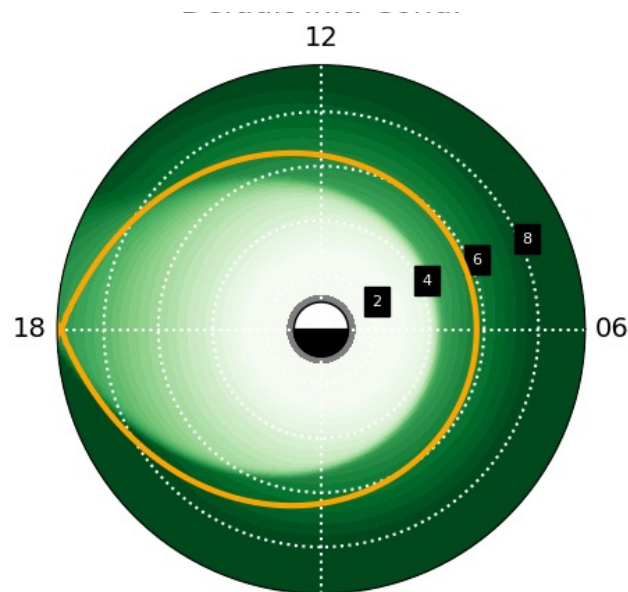
None.

Initial Condition Choices Impact Simulations

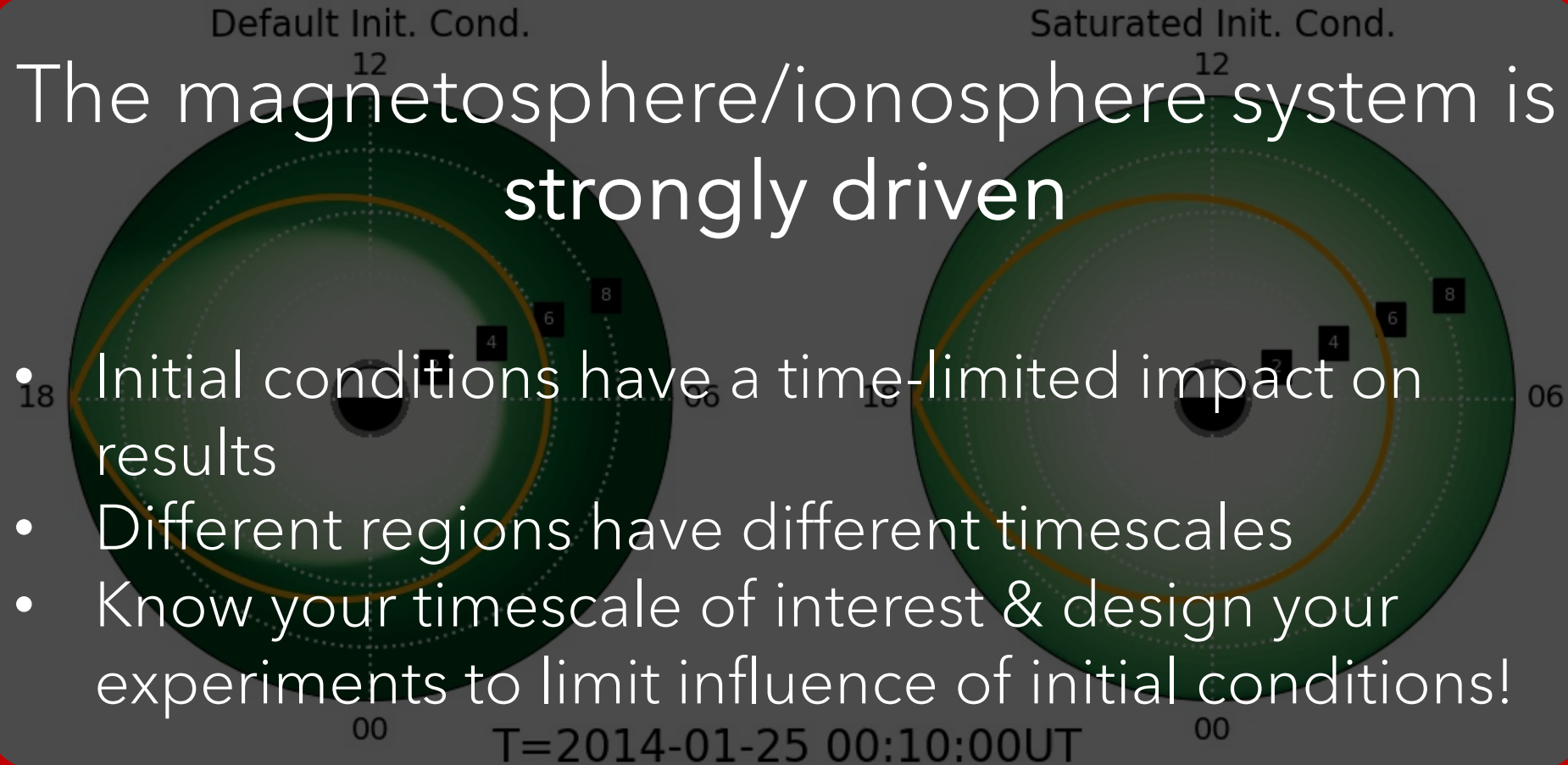
- Let's run DGCPM for a synthetic storm:



- Let's use two choices for initial conditions:



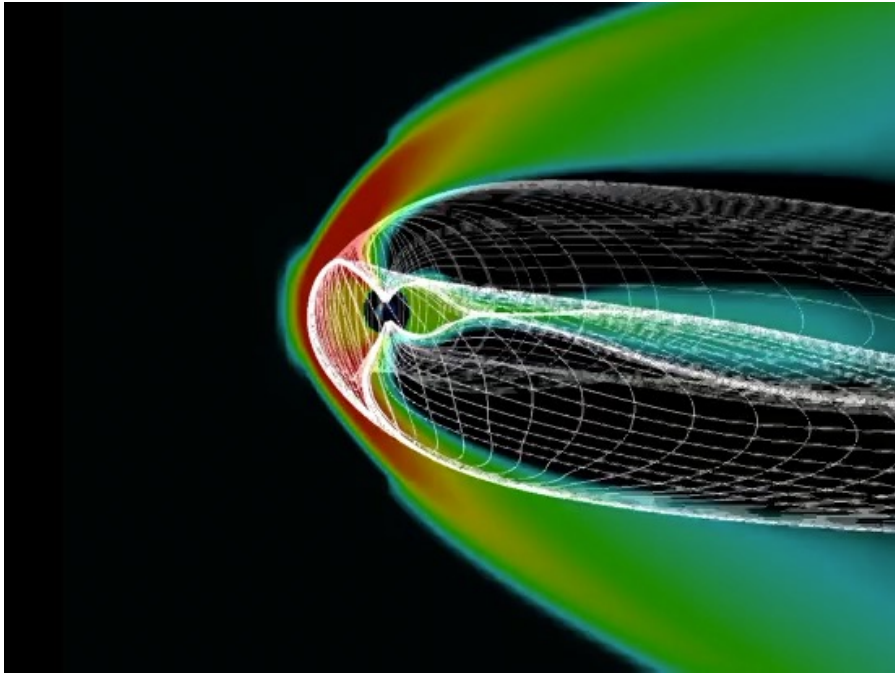
Initial Conditions in DGCPM



Building Initial Conditions in Magnetosphere Models

- BATS-R-US employs a “steady state” mode to build initial condition
 - Uniform density, dipole magnetic field, zero flow.
 - Solar wind conditions corresponding to run start applied at upstream boundary
 - Code iterates without advancing time until pseudo steady state obtained
- LFM/Gamera uses 12+ hour preconditioning period
 - Solar wind density & velocity held constant
 - IMF begins northward, turns southward for several hours, then northward again.
- Inner magnetosphere models (ring current, rad belt, plas sphere) use quiet time conditions built from observation statistics
- Thermosphere models (e.g., GITM) will begin simulation 1-2 days before period of interest to wash out simple initial conditions.

Case Study: Global MHD



$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{\mathbf{u}}) &= 0 \\ \rho \frac{\partial \bar{\mathbf{u}}}{\partial t} + \rho \bar{\mathbf{u}} \cdot \nabla \bar{\mathbf{u}} + \nabla p - \bar{\mathbf{j}} \times \bar{\mathbf{B}} &= 0 \\ \frac{\partial p}{\partial t} + \bar{\mathbf{u}} \cdot \nabla p + \gamma p \nabla \cdot \bar{\mathbf{u}} &= 0 \\ \frac{\partial \bar{\mathbf{B}}}{\partial t} - \nabla \times (\bar{\mathbf{u}} \times \bar{\mathbf{B}}) &= 0\end{aligned}$$

Global MagnetoHydroDynamics can solve for the dynamics of the whole magnetosphere

- Continuity equations for mass, momentum, and energy
- Induction equation ties $\bar{\mathbf{B}}$ and $\bar{\mathbf{u}}$
- 8 state variables:

$\rho \rightarrow$ mass density, $(\frac{kg}{m^3})$

$p \rightarrow$ thermal pressure, (Pa)

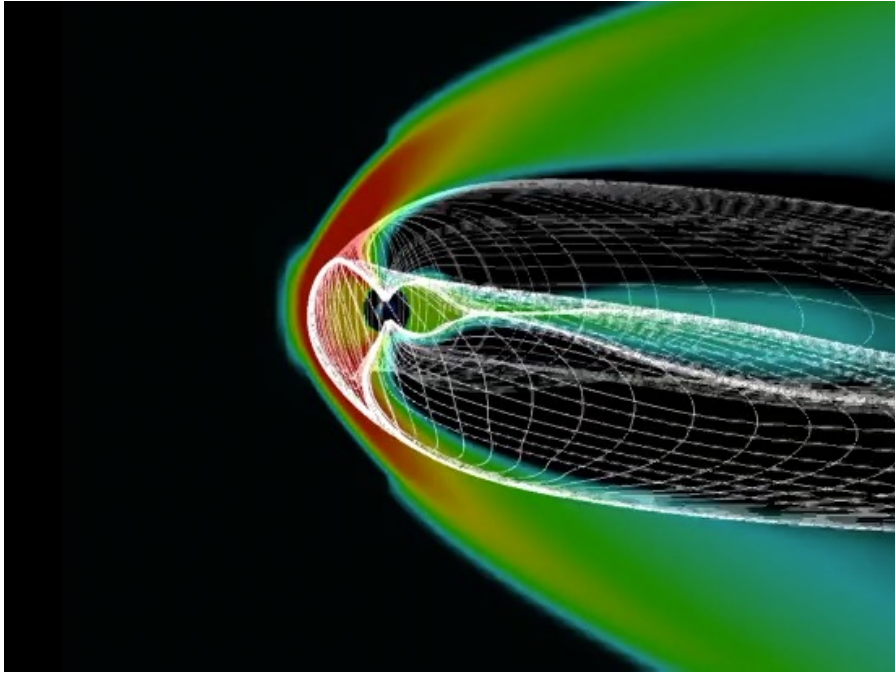
$\bar{\mathbf{u}} \rightarrow$ bulk velocity, $(\frac{m}{s})$

$\bar{\mathbf{B}} \rightarrow$ magnetic field, (T)

- Many implementations (OpenGGCM, GAMERA, BATS-R-US)

What are the inputs to this

Case Study: Global MHD



$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla(\rho \bar{u}) &= 0 \\ \rho \frac{\partial \bar{u}}{\partial t} + \rho \bar{u} \cdot \nabla \bar{u} + \nabla p - \bar{j} \times \bar{B} &= 0 \\ \frac{\partial p}{\partial t} + \bar{u} \cdot \nabla p + \gamma p \nabla \cdot \bar{u} &= 0 \\ \frac{\partial \bar{B}}{\partial t} - \nabla \times (\bar{u} \times \bar{B}) &= 0\end{aligned}$$

What are the inputs to this model?

Initial conditions:

Uniform initial with wind-up phase

Boundary conditions:

Must set all 8 state variables at inner and outer boundaries

Upstream & downstream:
inflow & outflow, otherwise float

Source & Loss Terms:

None for ideal MHD

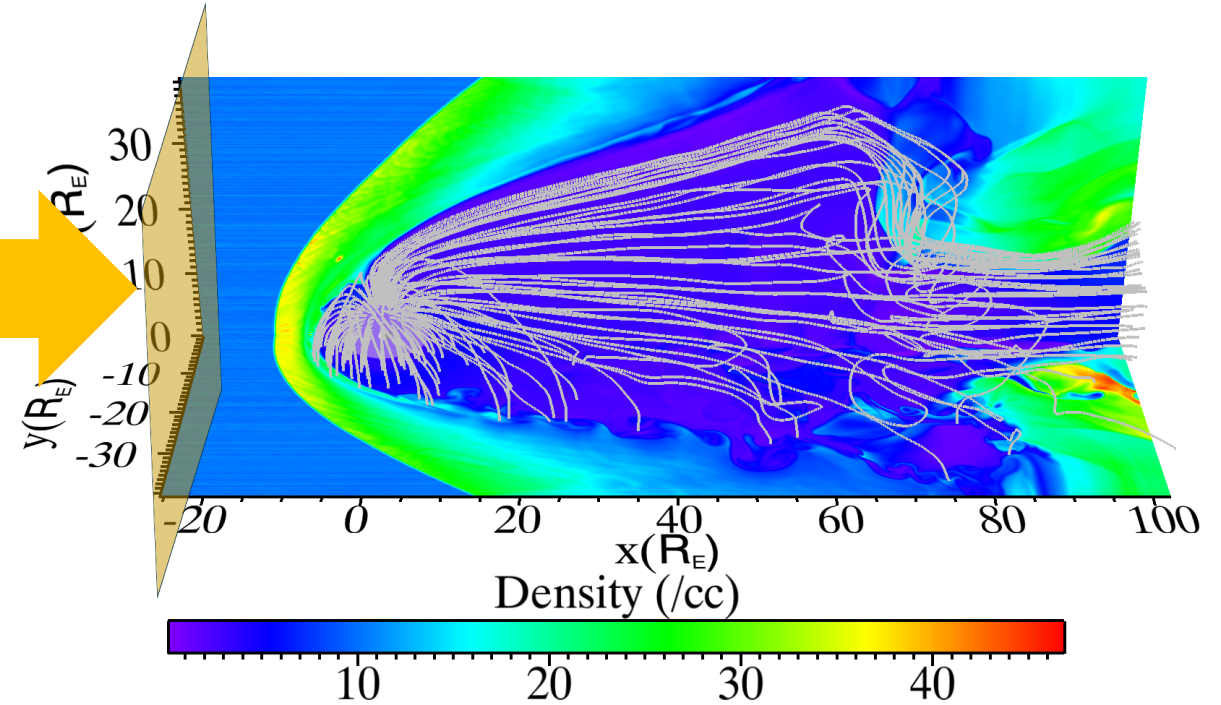
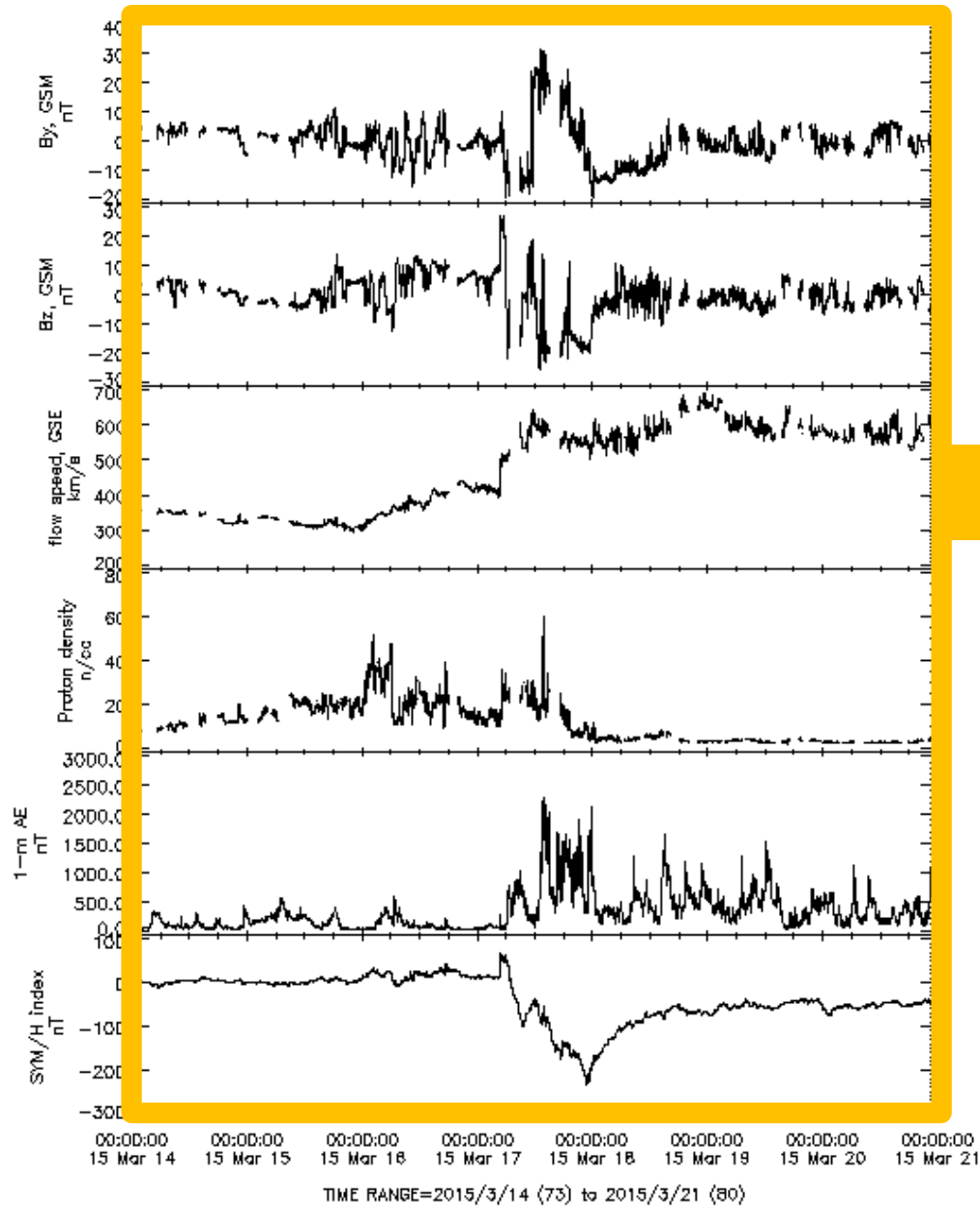
Variables not solved for:

None (yet).

Input data for relationships:

None (yet).

Upstream Boundary Conditions: Solar Wind & IMF



Obtaining Upstream Boundary Conditions

Get Solar Wind & IMF Values



Propagate Values to Mag'Sphere



Adapt to MHD
code
& Run

- L1 observations (ACE, DSCOVR): CDAWeb or OMNIWeb
- Near-bowshock values (e.g., Cluster, THEMIS, Geotail, etc): CDAWeb or mission websites
- ...or just make'em up!

- The solar wind must travel from point of observation to nose of bowshock.
- Several methods: ballistic, phase-front-angles, 1D MHD, etc. OMNI uses PFAs.

- Rotate to desired coordinate system.
- Upstream inputs are usually interpolated in time as MHD timesteps can be sub-second.

Obtaining Upstream Boundary Conditions

Get Solar Wind &
IMF Values

```
graph TD; A[Get Solar Wind & IMF Values] --> B[Propagate Values to Mag'Sphere]; B --> C[Adapt to MHD code & Run];
```

Are there data gaps?
What is the time resolution?
Did we measure what hit Earth?

Propagate Values to
Mag'Sphere

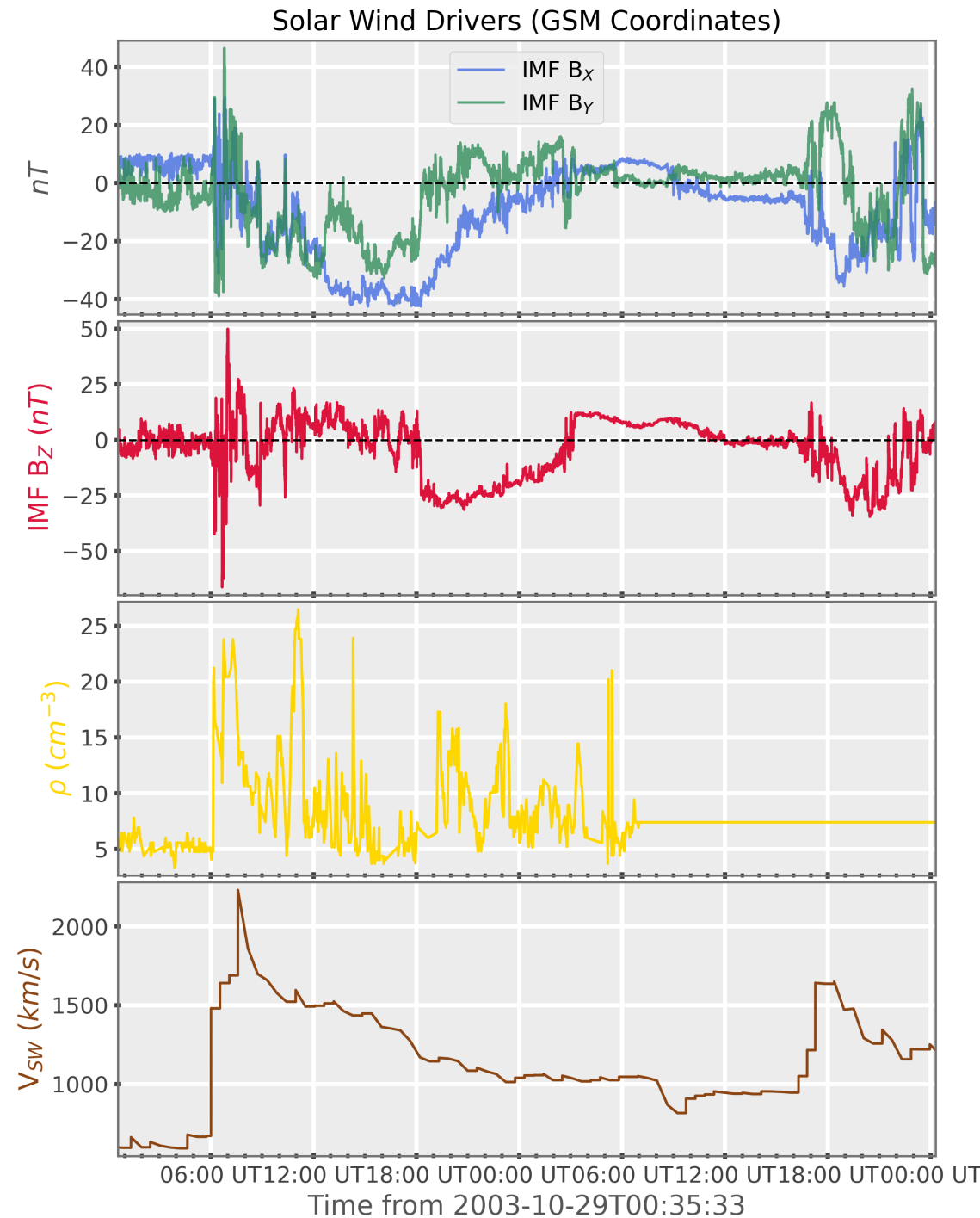
Is the propagation high quality?
Did values *evolve* from L1 to
Earth?

Adapt to MHD
code
& Run

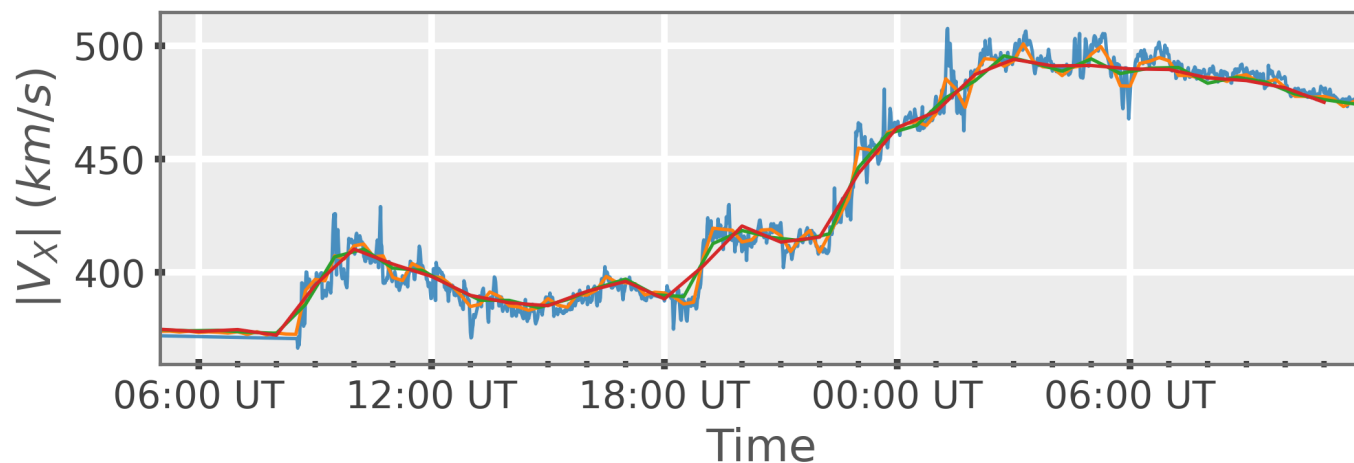
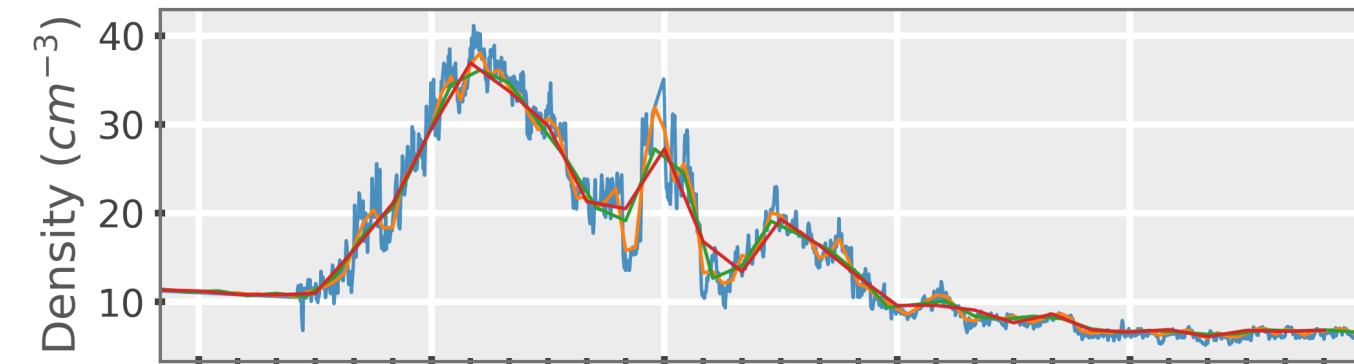
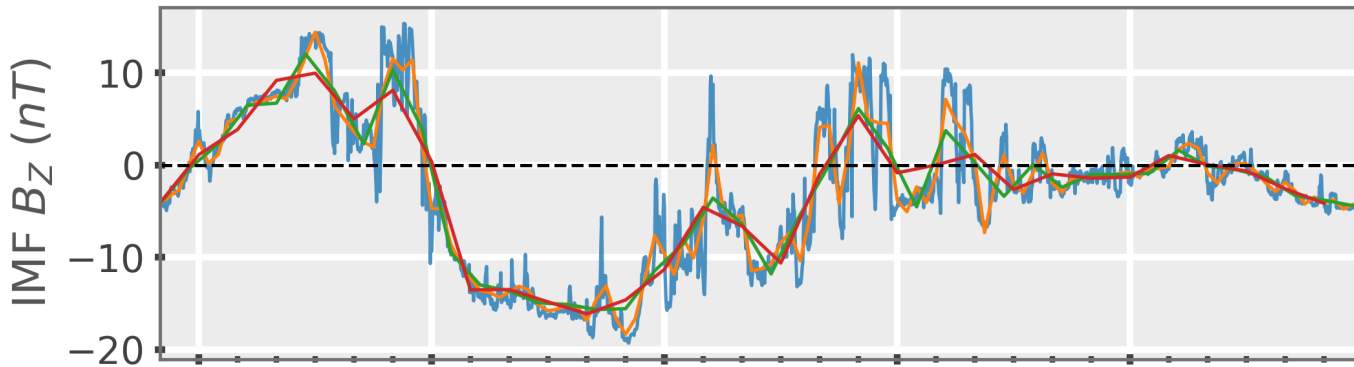
Is the model configuration
appropriate for the input data
set?

Data Quality Challenges

- L1 observations are often riddled with data gaps.
- During active times, instrument contamination (e.g., ACE SWEPPAM) can invalidate large periods
- Famous example: Oct. 2003 “Halloween Event”
- Mitigating strategies:
 - Do not rely purely on OMNIWeb
 - Consider multiple data sources
 - Talk to instrument PIs
- Do these data gaps matter?
 - Depends on your use case!



Small Scale Features: Do the wiggles matter?



Data gaps can be solved by interpolation, but this removes structure.

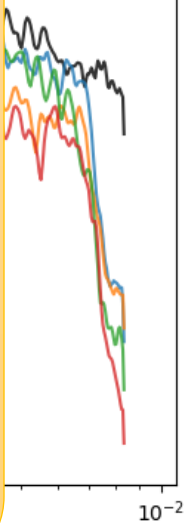
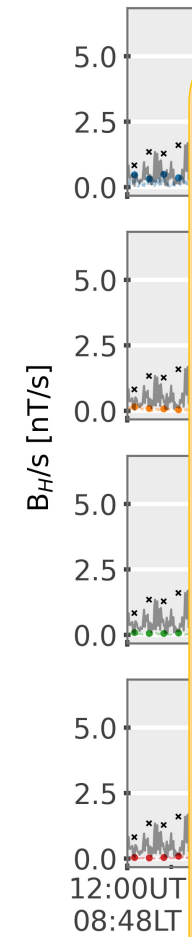
How much does *down sampling* or smoothing affect results? Let's test:

- Repeat SWPC/CCMC validation challenge, increase number of magnetometers
- For each storm, down sample **1min** solar values to **15**, **30**, and **60** minutes
- Simulate storms, compare forecasts to observations, calculate metrics

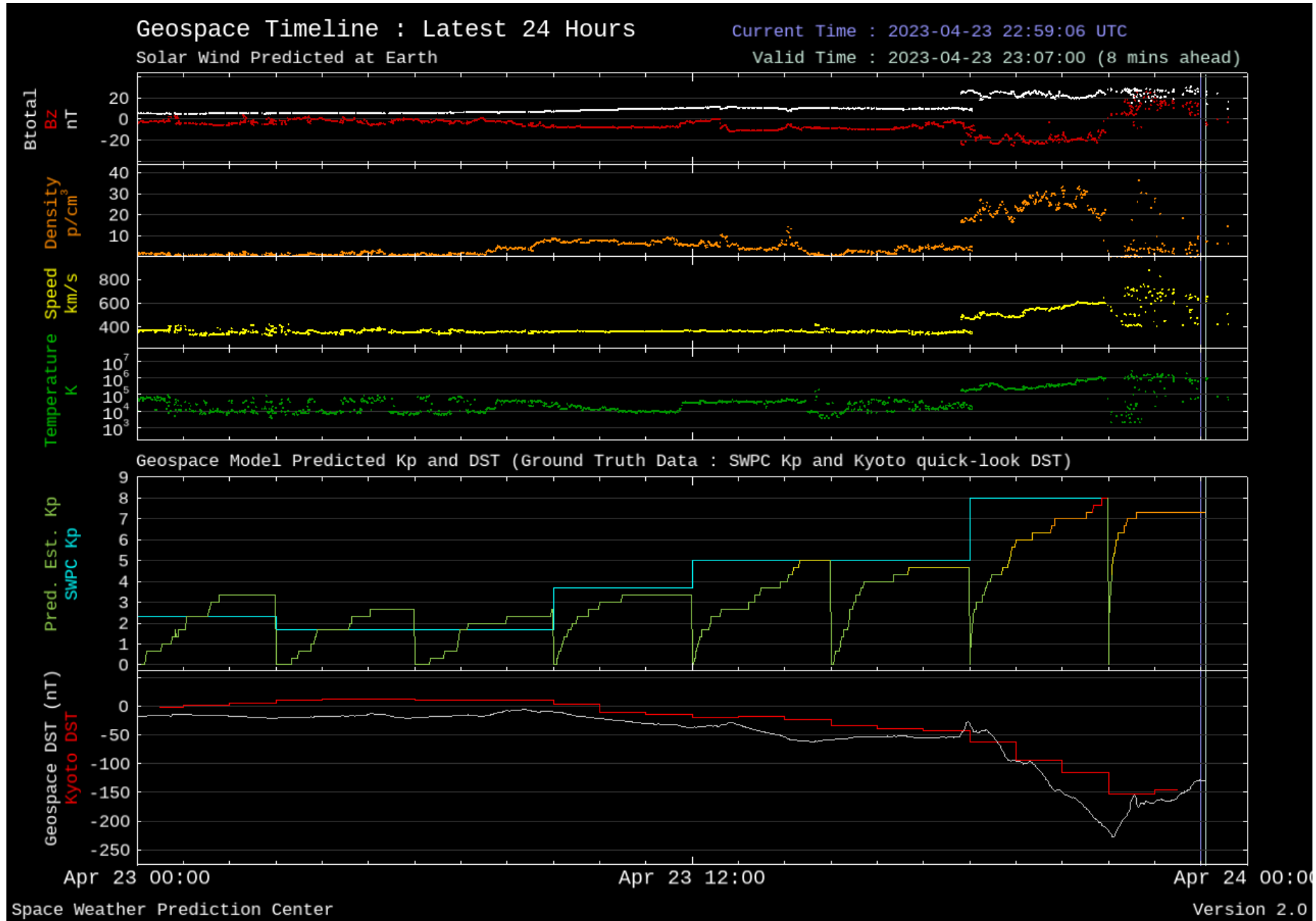


Small Scale Structure *Really* Matters

- Skill scores fall monotonically as down sampling period grows
- Skill scores more stable on nightside, indicating *internal* processes not tied to small scale solar wind structures
- Be aware of impact of interpolating over data gaps



More on Instrument Limitations

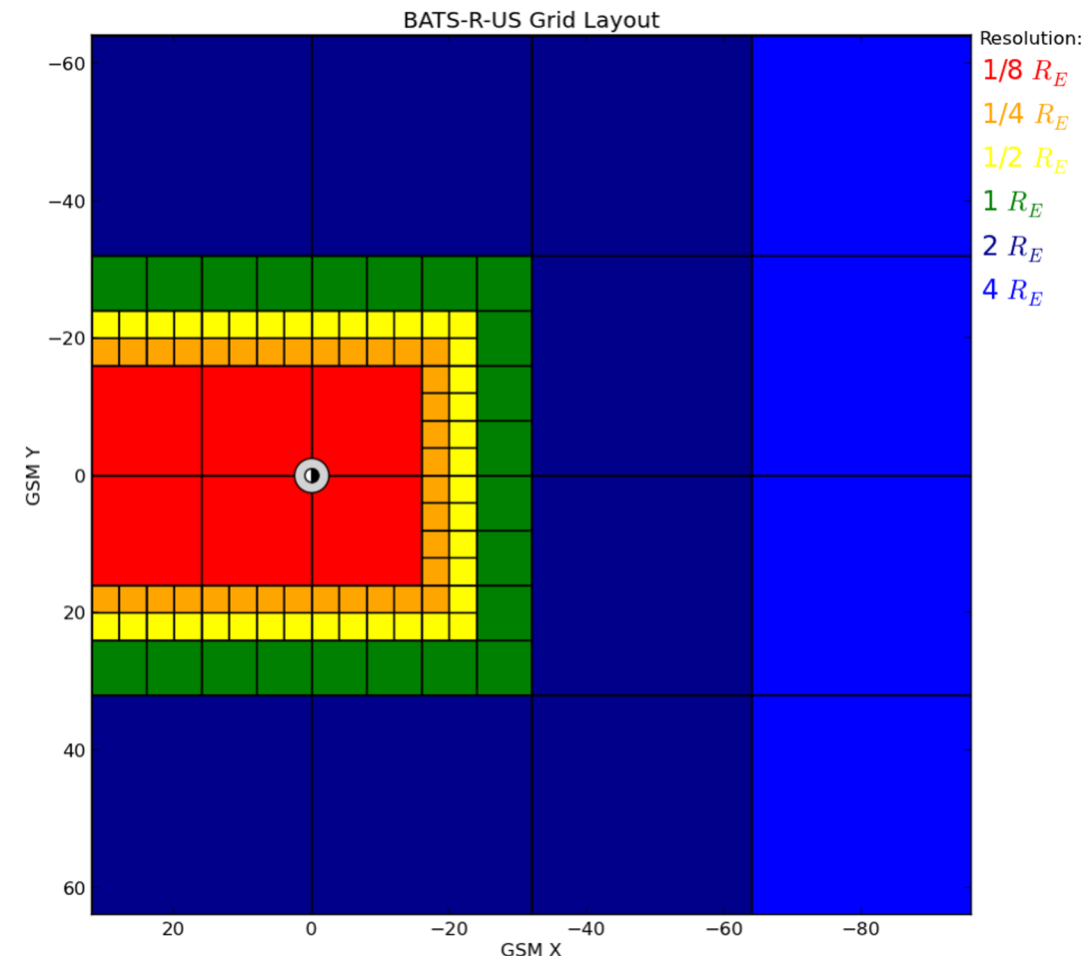
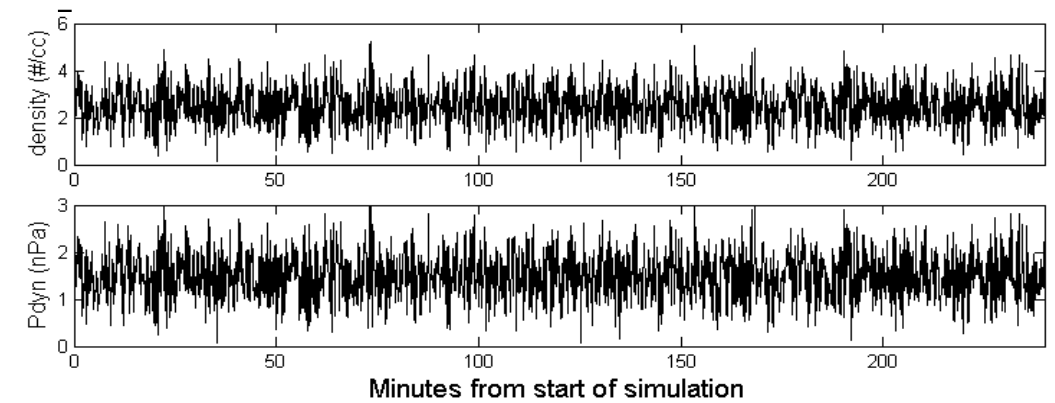


Model Considerations - An Anecd

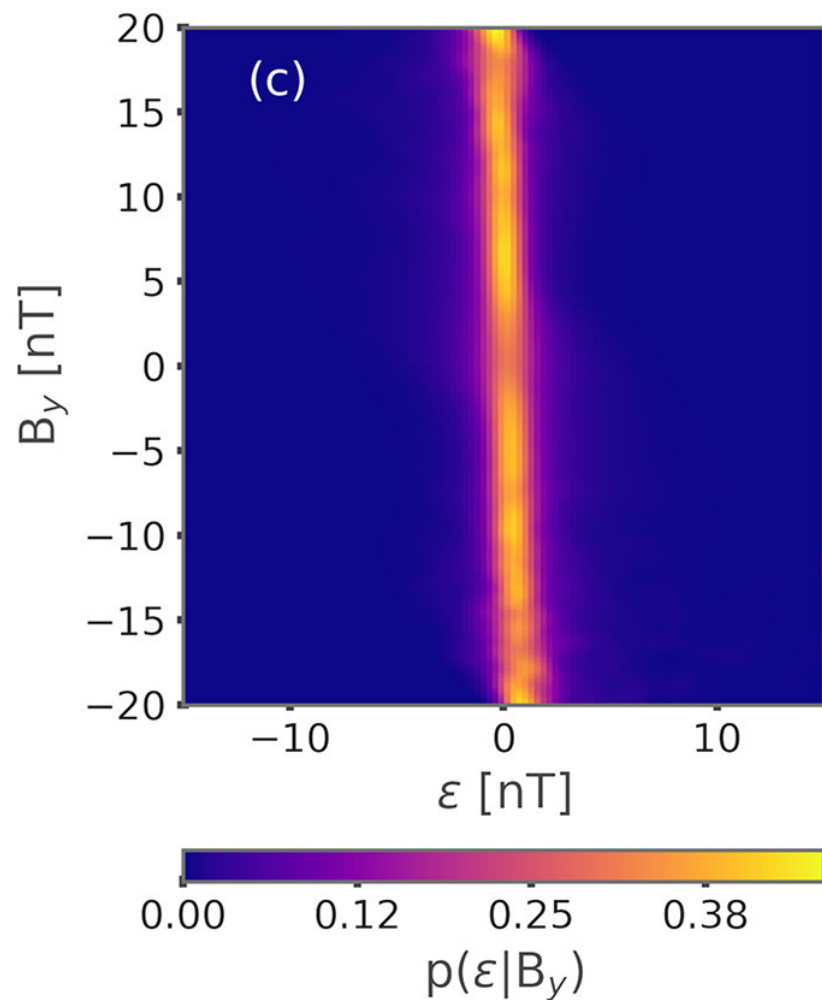
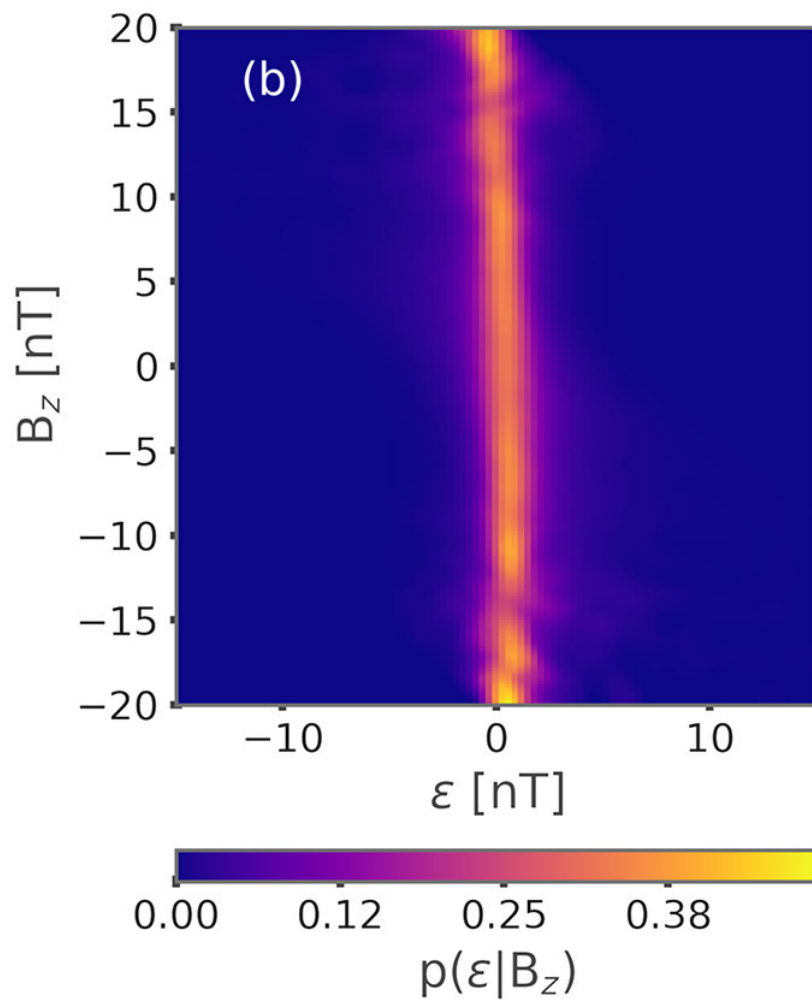
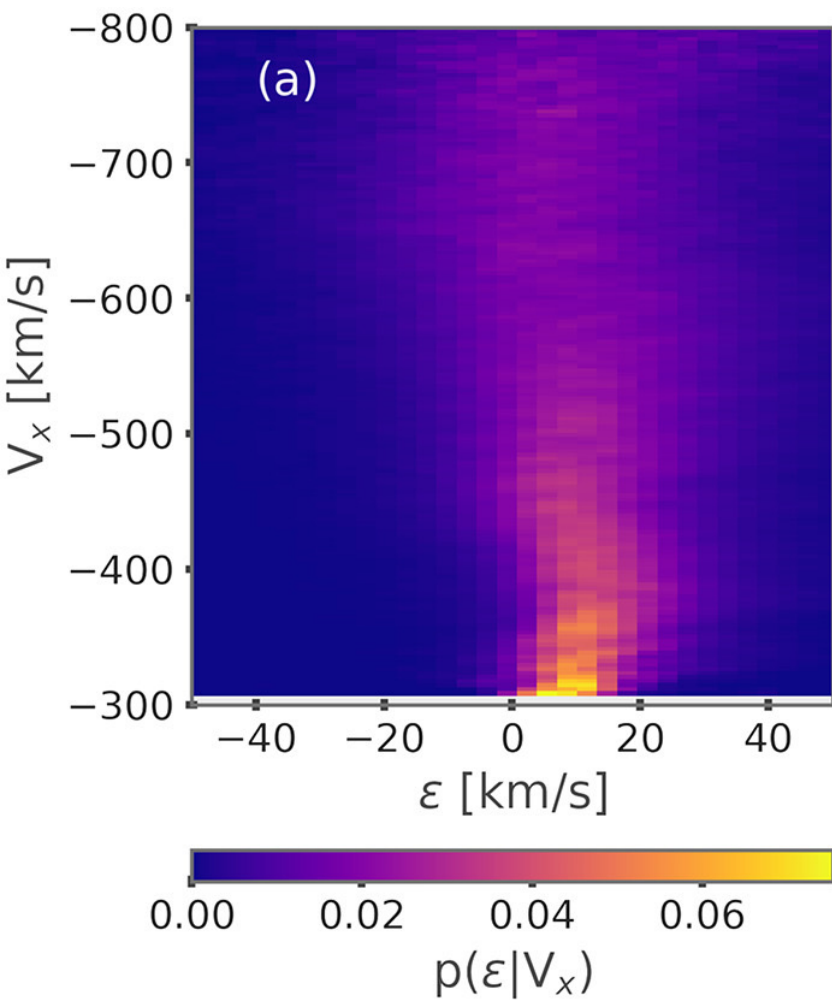
- Mike Hartinger & I wanted to simulate ULF waves and reproduce *Claudepierre et al., 2009*.
- BATS-R-US would not produce ULF waves using the same inputs.
- Problem was the grid!
- Spacing must meet Nyquist requirement for input wavelengths.

Other common considerations:

- Can model handle significant IMF BX?
- Are all state variables included (e.g., multifluid or anisotropic MHD)?



Propagation & Observational Limitations



Morley et al., 2018

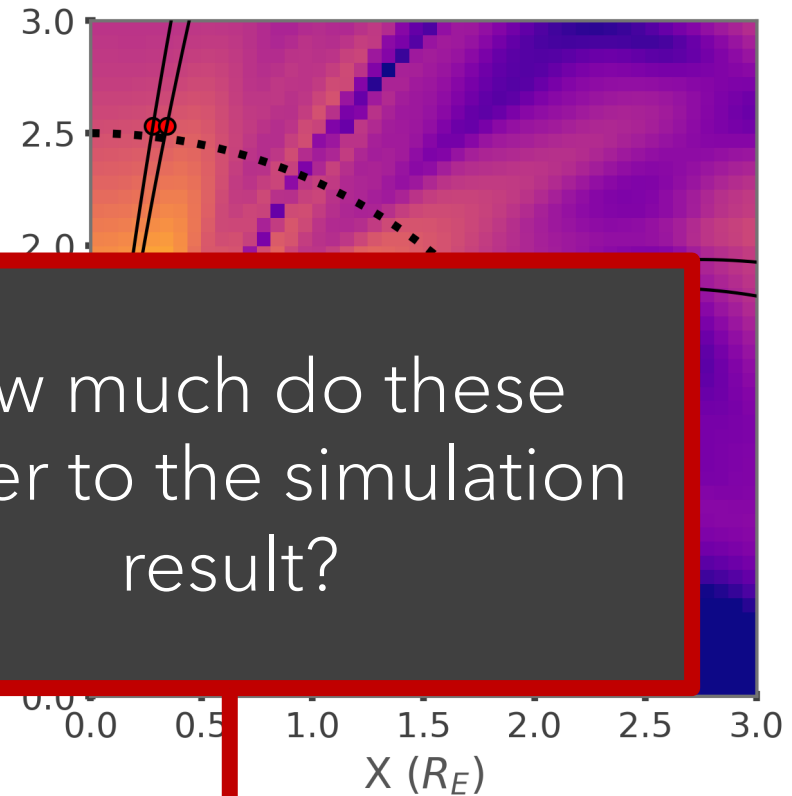
Upstream Boundary Conditions: Key Takeaways

- Keep in mind the goals of your study: what types of features or processes are important to you?
- Assess upstream data thoroughly – look for gaps or poor-quality values.
- Consider different sources than just OMNIweb.
- Be honest in your presentations and publications: what are the limitations of the upstream data?
- Seek a domain expert (e.g., an instrument PI or model developer) to help

Inner Boundary Conditions

MHD inner boundaries for geospace are typically spheres of radius 2-3 RE

Sometimes known as the “gap region” between mag’sphere & ionosphere.



Along the I.B. we need to set values

Variable

Mass Density & Pressure (ρ , p)

Magnetic Field ($\bar{B}$)

Radial Velocity (c)

Tangential Velocity ($\bar{u}_{\perp}$)

Typical Approach

Either set constant values or “hard wall” boundary

Dipole magnetic field (with or without tilt!)

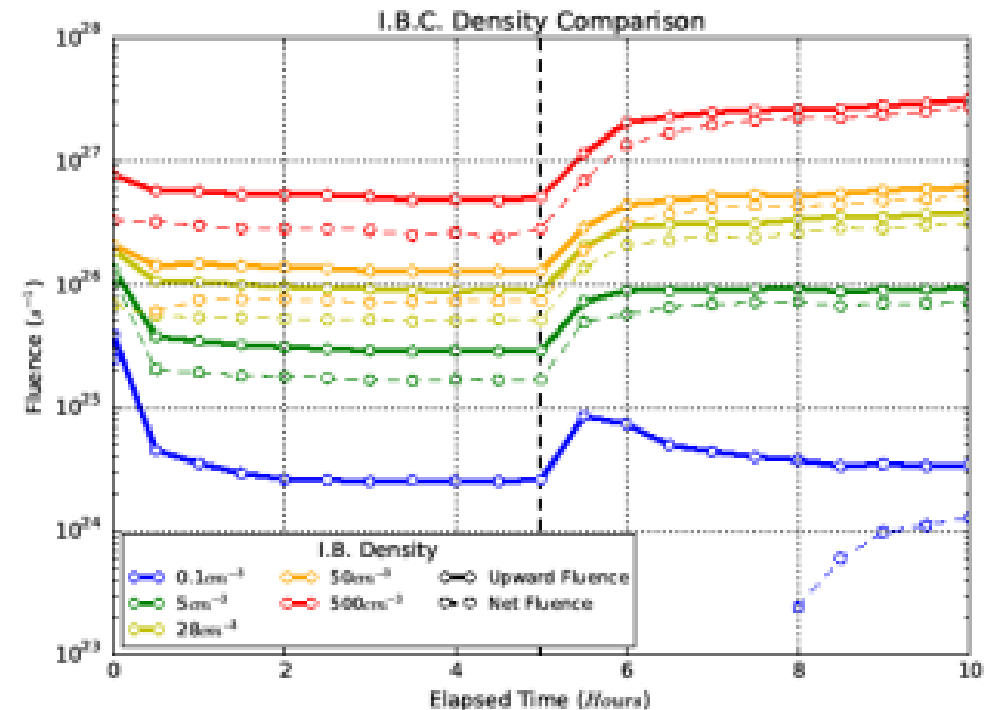
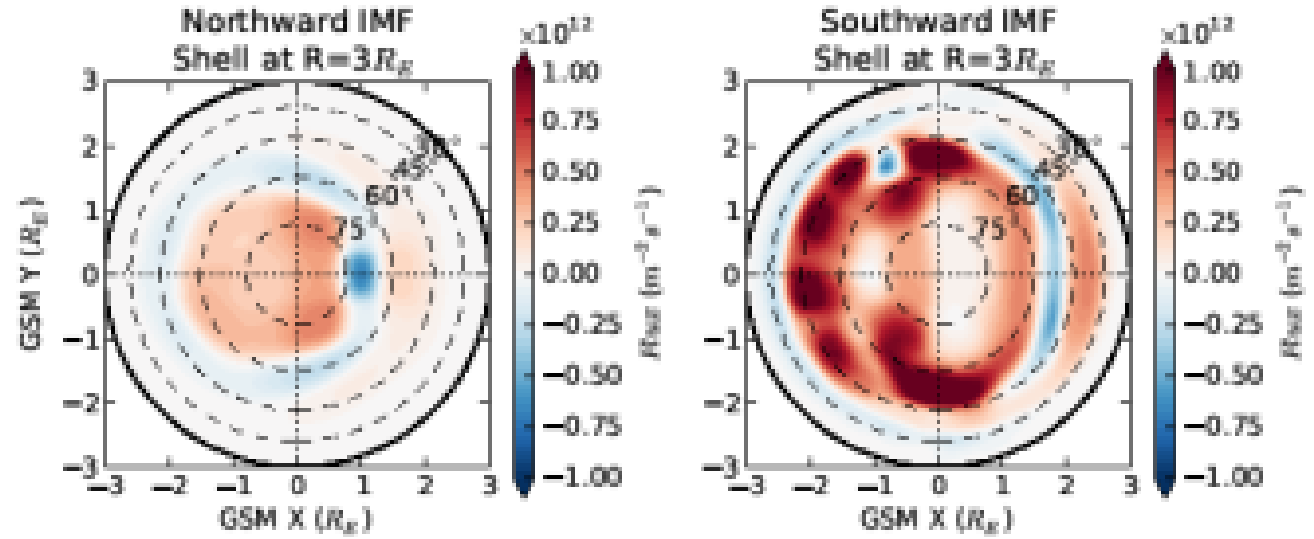
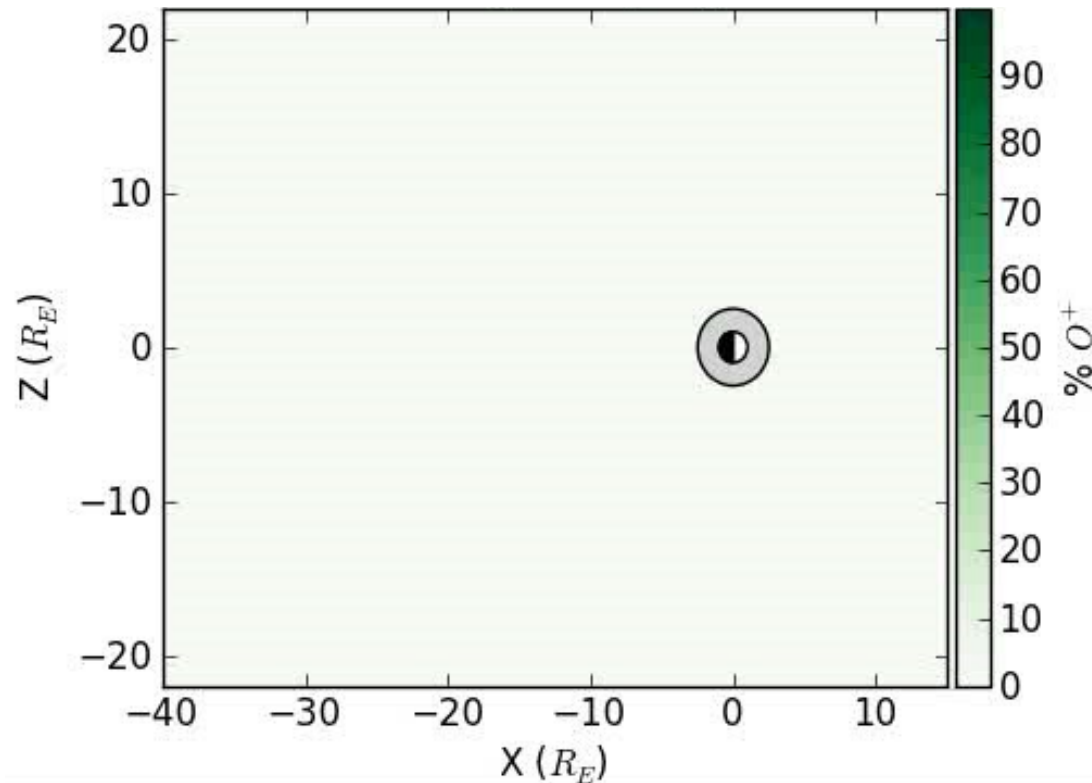
Set to zero.

Set to match ionosphere convection velocity

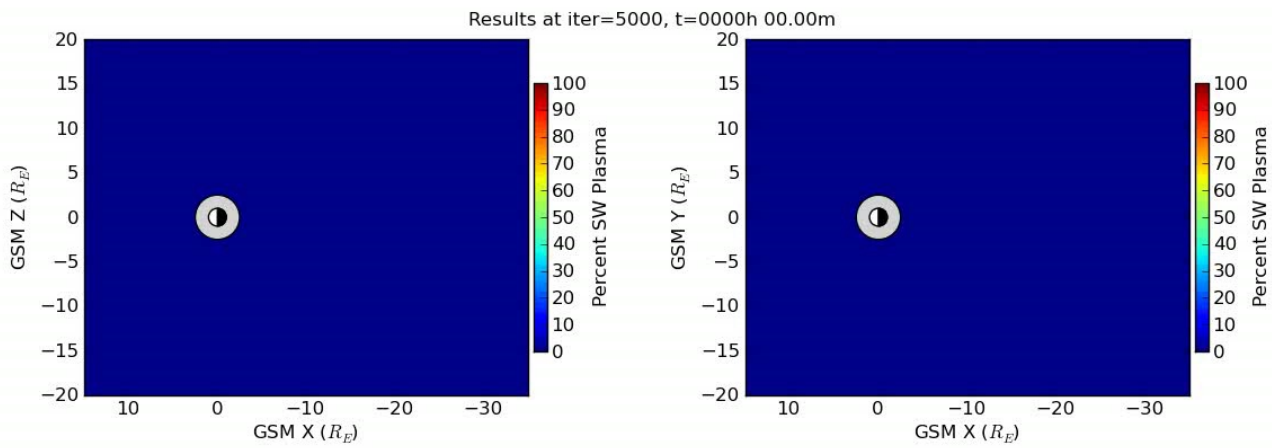
Inner Boundary Conditions: Mass Density

Even if $u_r = 0$, Dirichlet IBCs in ρ_{IB} yields *dynamic* plasma outflow...

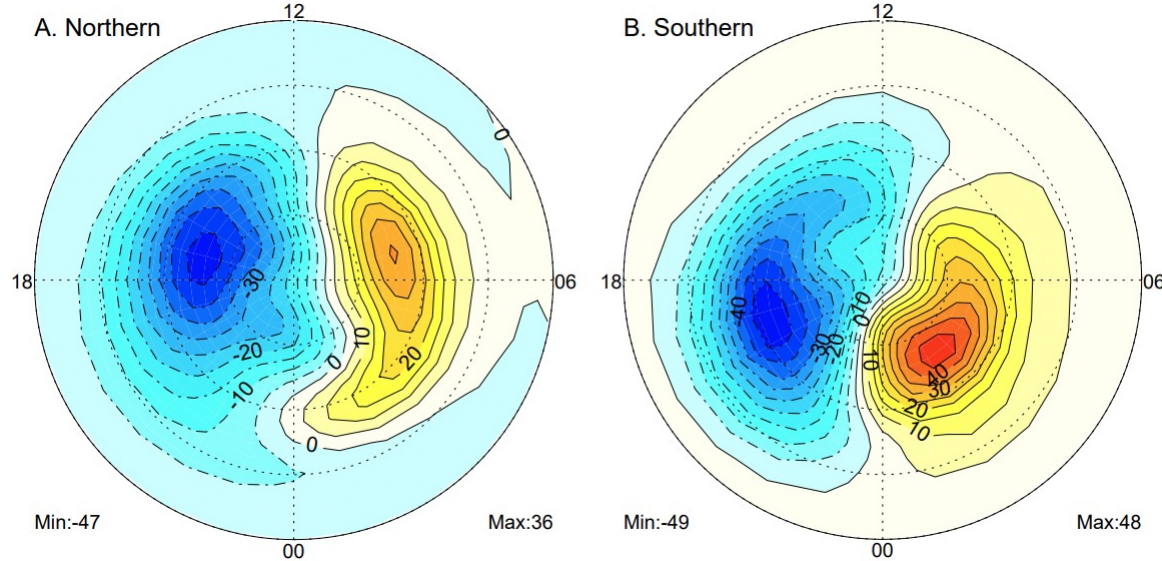
...that scales with ρ_{IB} and activity...



Consequences of ρ_{IB}



Case Study: Ionospheric Electrodynamics Solvers



Electric potential (kV)

$$J_R = \nabla_{\perp}(\bar{\bar{\Sigma}} \cdot \nabla_{\perp} \Phi)$$

Field-Aligned Currents (A/m^2)

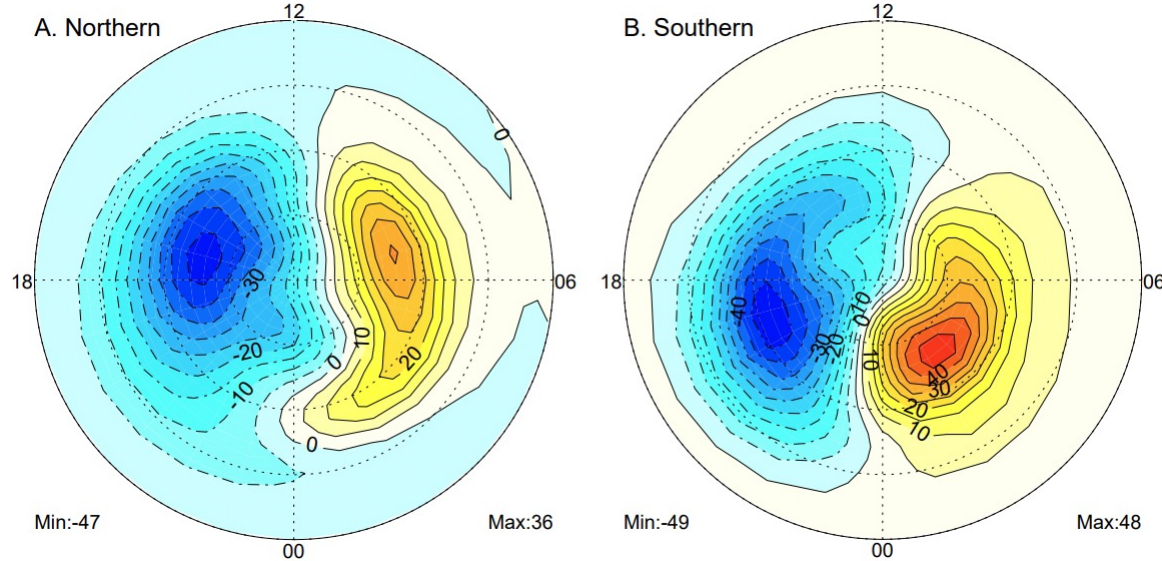
Conductance (S)

Ionospheric Electrostatic Solvers obtain the ionospheric potential given FACs and conductance.

- Given FAC pattern (J_R) and ionospheric conductance ($\bar{\bar{\Sigma}}$), solves a Poisson-like equation for the ionospheric potential, Φ
- An iterative minimal residual method to converge to a solution.
- Coupled to MHD to set the $\bar{u}_{\perp}$ inner boundary conditions

What are the inputs to this model?

Case Study: Ionospheric Electrodynamics Solvers



$$J_R = \nabla_{\perp}(\bar{\Sigma} \cdot \nabla_{\perp} \Phi)$$

What are the inputs to this model?

Initial conditions:

Iterative model/not time dynamic

Boundary conditions:

Zero Φ at the equator

Source & Loss Terms:

None.

Variables not solved for:

J_R from global MHD

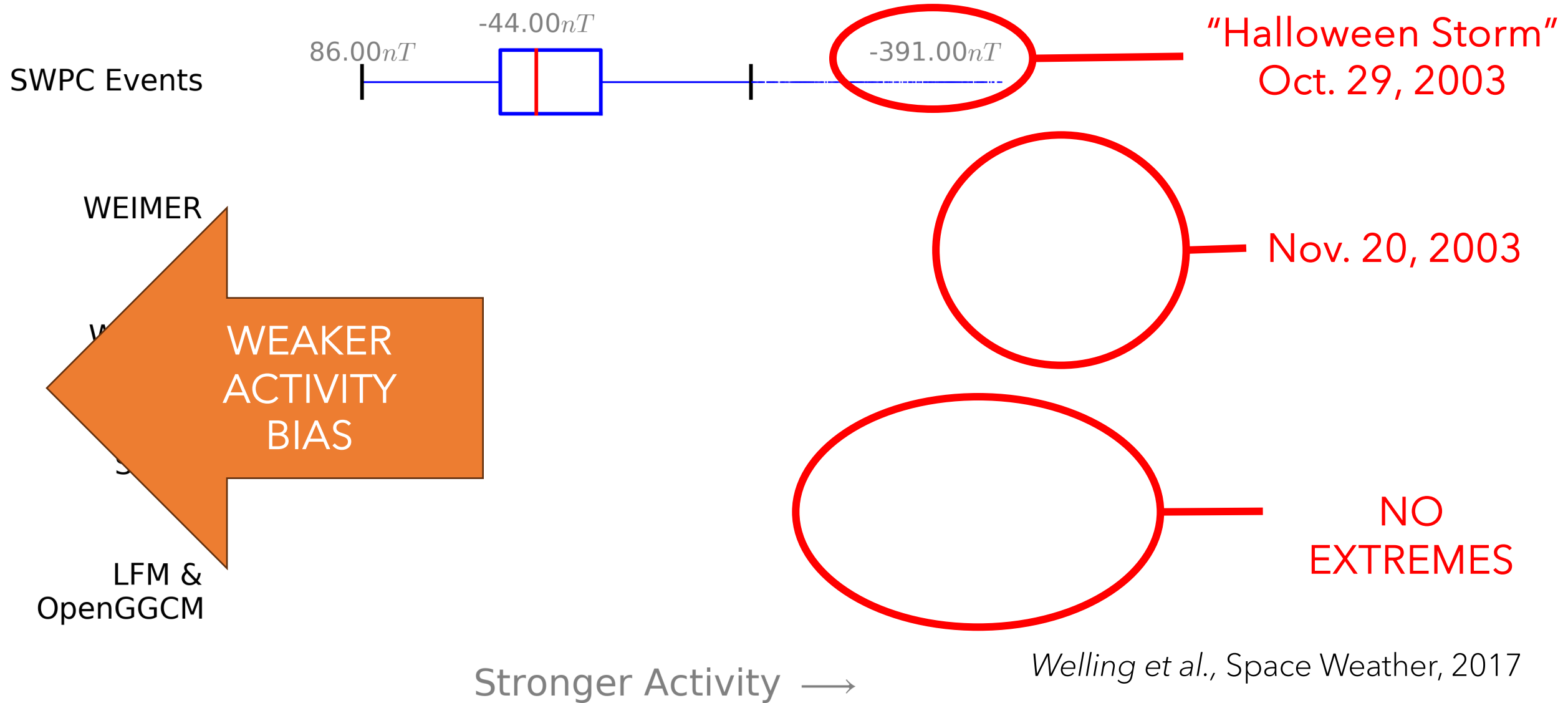
$\bar{\Sigma}$ from ✨🎩

Input data for relationships:

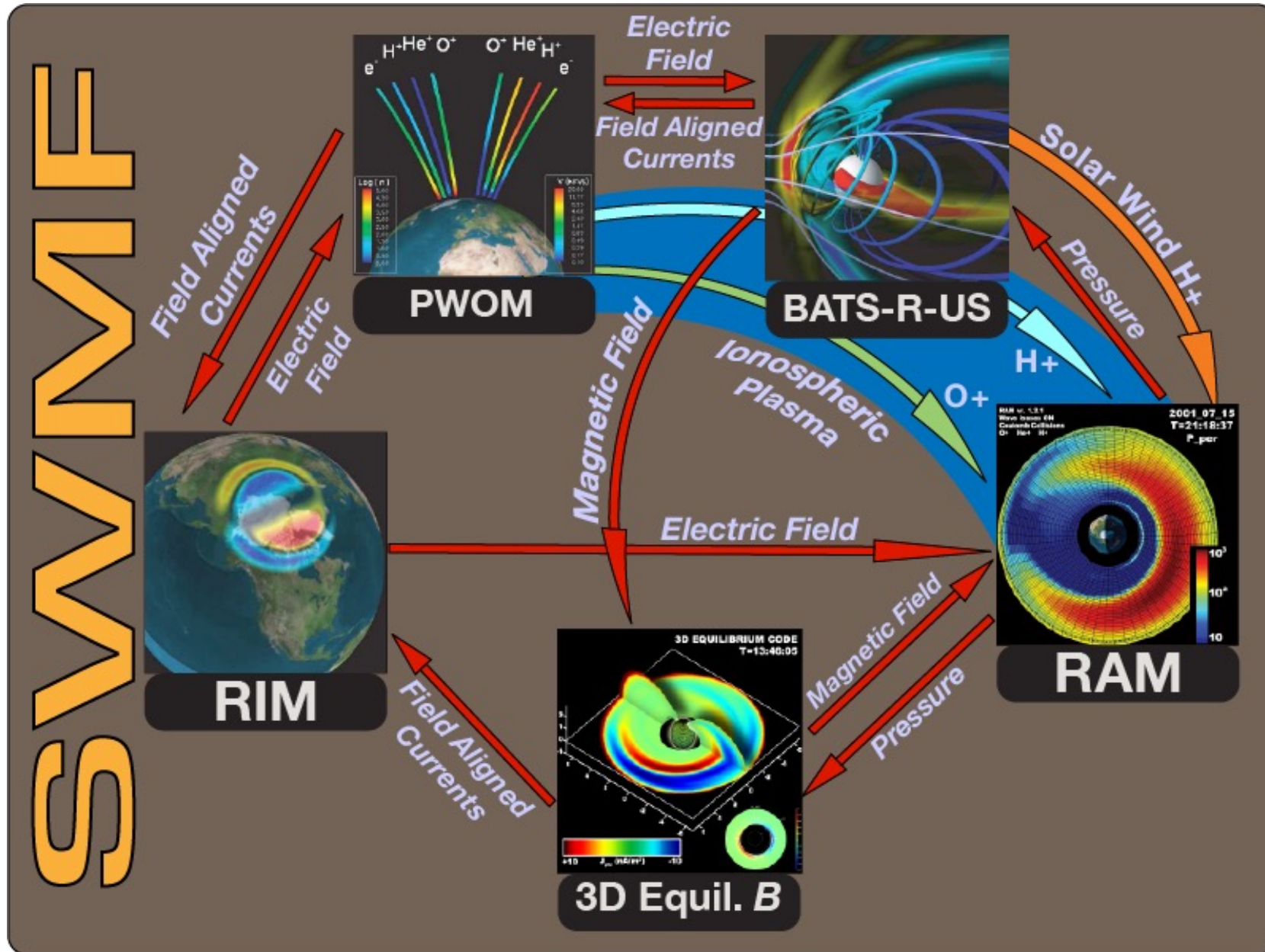
$\bar{\Sigma}$, based on empirical relationships

Range of Empirical Inputs

Input Conditions: Sym-H



Model Coupling



Final Take-Aways

Model inputs are any values or data sets required to run a simulation or build an empirical/ML relationship

These can include upstream values, boundary conditions, *anything* the code doesn't explicitly solve for.

Think beyond solar wind and upstream values! Codes have MANY inputs!

All inputs have consequences on model results

Critically consider the role each choice may have.

When reporting results, be open and honest about input limitations.

Evaluate everything with respect to the goal of the study

Is a limitation of a given input likely to be a 1st order effect?

Is a given limitation relevant to the processes being studied?