Model-Specific Metadata for Enhancing Space Science Models

Jack Topper, Masha Kuznetsova, Mostafa El Alaoui, Maksym Petrenko, Lutz Rastaetter

Community Coordinated Modeling Center, NASA GSFC, Greenbelt, MD, USA

Runs-On-Request (ROR)

COMMUNITY COORDINATED MODELING CENTER

ccmc.gsfc.nasa.gov

AGU American Geophysical Union

Session: IN026

Abstract

The Space Weather and Heliophysics modeling community, supported by the Community Coordinated Modeling Center (CCMC, https://ccmc.gsfc.nasa.gov), provides a collaborative platform for space weather models and data. Flexible metadata is vital for advancing scientific research and fostering collaboration.

Our work in expressing complex simulations of the Space Weather Modeling Framework (SWMF), particularly Global Magnetosphere (GM) grid components, in terms of simple metadata records shows great promise in creating searchable and reusable units of knowledge. Such records can be readily utilized to support the process of scientific discovery, closely aligning with the goals outlined in the Open Science initiative.

Our primary goal is to show the scalability and benefits of metadata-focused methodologies. This presentation highlights the potential for applying metadata methodologies to other complex models, improving usability, supplying efficient documentation and fostering interdisciplinary research.

Metadata: Enhancing Model Usability

What is Metadata?
Metadata is a comprehensive list of external model drivers and internal settings for simulation conditions, fully detailing how a model is configured for each simulation run.

Clear and Accessible Format:
Transitioning to `.json` format for better structure and efficiency, making models easier to use.

Why It's Important:
Metadata allows users to understand how different inputs impact model behavior, making fine-tuning easier and ensuring accurate results.

Driving Open Science:
Metadata plays a pivotal role in advancing open science by enhancing **reproducibility** and **accessibility**, actively supporting the **FAIR principles** (Findable, Accessible, Interoperable, Reusable).

- **Metadata as a tool to simplify disorganized inputs into structured, usable configurations.**
- **Role of metadata in adhering to FAIR principles (Findable, Accessible, Interoperable, Reusable).**
- **Examples of metadata enabling reproducibility and fine-tuning models (below)):**

Simplifying Complexity:
Metadata not only simplifies complex inputs but also expands the range of options for advanced models that are rapidly becoming more intricate.

Sensitive to Inputs:
Models are like musical notes—played wrong, they create chaos; played right, they produce harmony.

CCMC Metadata Solution:
Metadata systematically organizes and groups key parameters, ensuring models are configured accurately and deliver scientifically reliable results.

SWMF - Global Magnetosphere Grid Metadata Documentation

General Metadata

Basic Information

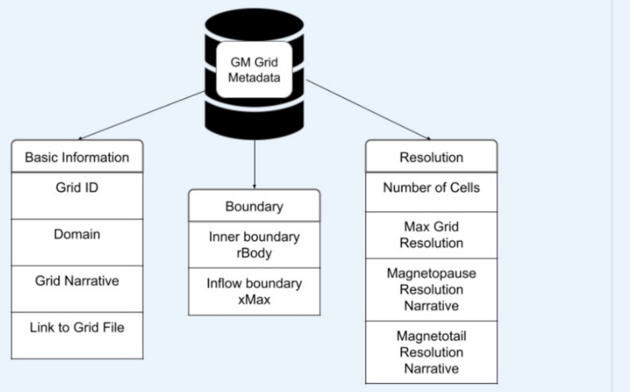
- Domain: Default GM
- Grid ID: Grid–1o8–2M_xMax64_01
- Main Description: Updated SWPC grid with tailward boundary –480
- Link to Grid File: Link to grid file

Boundary

- Inner Boundary rBody: Default 2.5 (Optional: r1.25)
- Inflow Boundary xMax: Default 32 (Options: xMax24, xMax64, xMax96, xMax128, xMax192)

Resolution

- Max Grid Resolution: 1o8 (1 over 8)
- Number of Cells: 2M (2 million cells)
- Magnetopause Resolution Narrative: High resolution near the magnetopause for detailed solar wind interactions
- Magnetotail Resolution Narrative: Enhanced resolution in the magnetotail to capture tail dynamics



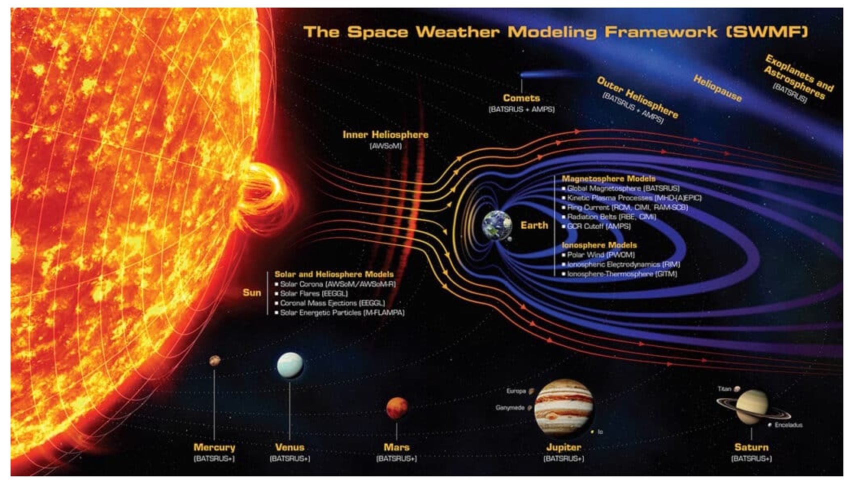
Space Science Models

What They Do

- **Simulate Space Weather**: Provide realistic depictions of solar wind, magnetosphere, and ionosphere interactions.
- **Test Various Scenarios**: Explore conditions like geomagnetic storms or solar eruptions.
- **Support Global Research**: Serve as tools for international collaboration in understanding space weather impacts.

Why CCMC Hosts Them

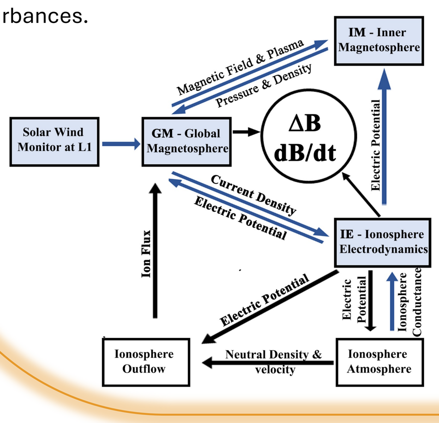
- **Complex Setup**: Managing these models requires advanced hardware, software, and expertise.
- **Cutting-Edge Techniques**: State-of-the-art methods ensure high precision and reliability.
- **Accessible and Customizable**: CCMC makes these powerful tools available to all, with tailored simulations for specific research needs.



Complexity

Interconnected Framework

The Space Weather Modeling Framework (SWMF) consists of multiple components that continuously exchange data during simulations. This interaction forms a cohesive system capable of modeling the intricate dynamics of space weather, from solar wind-magnetosphere interactions to geomagnetic disturbances.

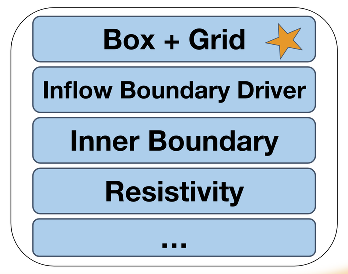


SWMF Documentation

The SWMF includes a vast array of tuners and input parameters, offering fine-grained control over model configurations. While this flexibility enables researchers to study unique phenomena, the extensive documentation and complexity of inputs can be **daunting to navigate.**

Simplifying the Complexity

At CCMC, we work to make the models more accessible by **abstracting its inputs into manageable building blocks.** This approach retains the framework's flexibility while allowing users to focus on their research goals without **being overwhelmed by the complexity of configurations.** By simplifying the setup process, we empower researchers of all expertise levels to leverage the SWMF's full potential for studying space weather phenomena.



Results and Applications

We've developed custom configurations for the **2023 SWMF version** and its **BATS-R-US component**, now hosted on the CCMC website. These configurations are designed to explore complex phenomena such as Kelvin-Helmholtz instabilities, thin magnetotail currents, solar wind-magnetosphere interactions, and more. By utilizing advanced resolution and extended boundaries, we've gained deeper insights into intricate dynamics and broader space weather systems. These tools are advancing open science, enabling detailed investigations, and driving new discoveries in space weather modeling.

To make these capabilities widely accessible, we introduced a **Custom Configuration Submission Page** that simplifies complex inputs into modular building blocks. This tool empowers users to create simulations suited to their specific needs, while detailed explanations and support ensure newcomers and experts alike can fully utilize the platform. By combining accessibility with cutting-edge configurations, this initiative drives open science and fosters the discovery of even more space weather phenomena.

For more information: ccmc.gsfc.nasa.gov/news/swmf/

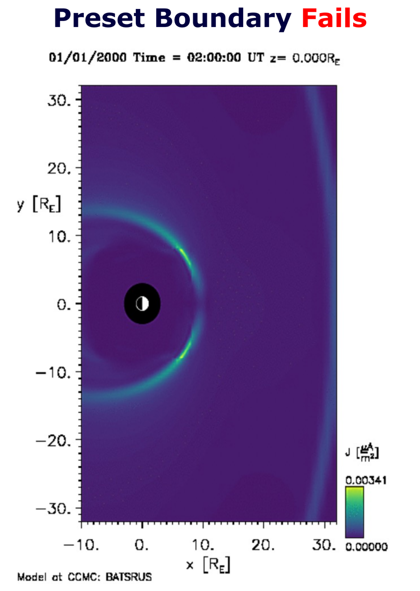
SCAN ME

Global Magnetosphere Boundary

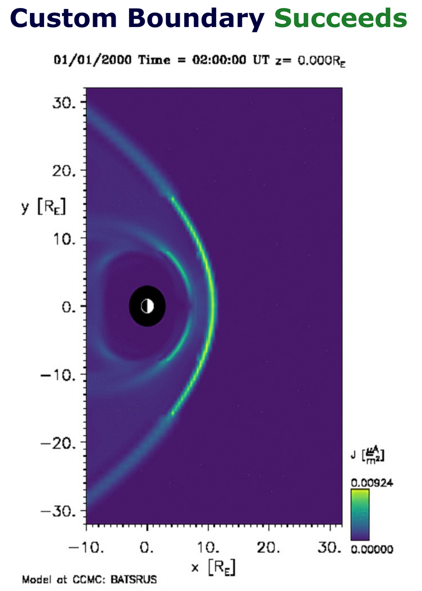
- **Why it Matters**: Boundary inputs define the starting conditions for simulations, including solar wind properties and inflow conditions. Expanding these boundaries allows models to capture a larger section of the space environment, providing a more complete picture of the solar wind's interaction with Earth's magnetosphere.
- **Applications**: Extended boundary inputs are crucial for:
  - Modeling upstream solar wind dynamics before they interact with the magnetosphere.
  - Capturing large-scale structures like Coronal Mass Ejections (CMEs) that impact Earth's space weather environment.

Impact: With extended boundaries, models can simulate events over a larger area, improving predictive capabilities and ensuring edge effects do not distort results.

Preset Boundary Fails



Custom Boundary Succeeds



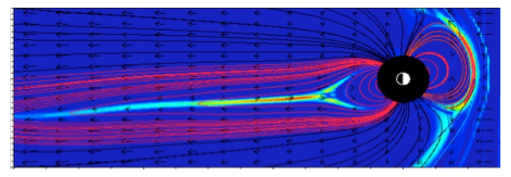
The images above illustrate the necessity for custom inflow boundary conditions under low Mach number scenarios. Accurate simulation of such flows requires tailored boundary conditions to ensure fidelity and stability

Resolution: Capturing Fine Details

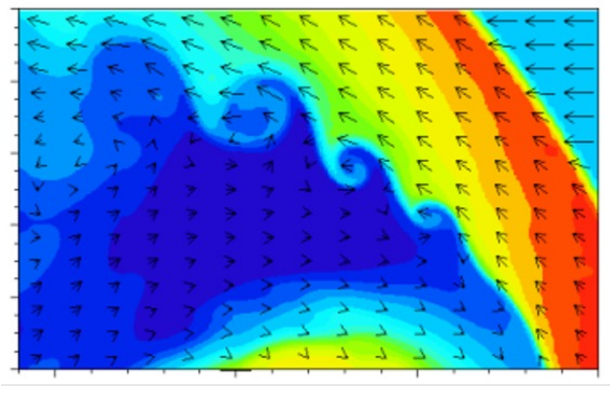
- **Why It Matters**: Resolution determines the level of detail captured in a simulation. Higher resolution breaks down large-scale features into smaller, more precise elements, uncovering subtle dynamics that lower resolutions cannot detect.
- **Applications**: Essential for studying:
  - **Kelvin-Helmholtz Instabilities**: Fine-scale surface waves at plasma boundaries.
  - **Thin Magnetotail Currents**: Narrow, localized current sheets.
  - **Magnetic Reconnection Sites**: Areas with high variability and energy transfer.

Impact: Higher resolution reveals small-scale phenomena, enriching our understanding of space weather and improving predictive accuracy.

Thin Magnetotail Current



KH Instability (Magnetopause surface Waves)



Documentation

The **GM Grid Metadata Documentation** explains key parameters like grid resolution and boundary inputs, helping users configure accurate and reproducible simulations in the Global Magnetosphere model. It's a vital resource for both research and open science.

Grid Naming Conventions

Format: Grid–MaxGridResolution–NumberOfCells–AdditionalParameter–NN

- MaxGridResolution Options:
  - 1o4 (1 over 4)
  - 1o8
  - 1o16
  - 1o32 (resolutions higher than 1/16 are not introduced for online submission for now)
- NumberOfCells: Approximate count in millions (mln)
- AdditionalParameter:

  If not introduced in the title, defaults are assumed (specified in metadata).

  Inflow Boundary (if other than default 32):
  - Options: xMax24, xMax64, xMax96, xMax128, xMax192

  Inner Boundary (if other than default 32):
  - Options: r1.25
- NN: A sequential number (01, 02, 03, ...) if several grids with the same parameters

Examples

- Grid–1o8–2M_01
  - Updated SWPC grid with tailward boundary –480
- Grid–1o8–2M_02
  - SWPC grid currently in use (tailward boundary –224)
- Grid–1o8–2M_xMax64_01
- Grid–1o8–2M_xMax96_01
- Grid–1o8–2M_xMax128_01
- Grid–1o8–2M_xMax192_01
  - Similar to Grid–1o8–2M_01 with different inflow boundaries for low Mach numbers in solar wind.
  - Note: Use a formula to calculate the bow shock stand-off position depending on the Mach number.
- Grid–1o8–5M_01
  - Michigan storm grid with increased resolution
- Grid–1o8–5M_02
  - Same as Grid–1o8–5M_01 with tailward boundary –224
- Grid–1o8–5M_xMax64_01
- Grid–1o8–5M_xMax96_01
- Grid–1o8–5M_xMax128_01
- Grid–1o8–5M_xMax192_01
  - Similar to Grid–1o8–5M_01 with different inflow boundaries for low Mach numbers in solar wind.
  - Note: Use a formula to calculate the bow shock stand-off position depending on the Mach number.
- Grid–1o16–6M_01
- Grid–1o16–6M_xMax64_01
- Grid–1o16–6M_xMax96_01
- Grid–1o16–6M_xMax128_01
- Grid–1o16–6M_xMax192_01
  - Similar to Grid–1o8–5M grids with 1/16 resolution near the inner boundary.
- Grid–1o16–6M_r1.25_01
  - Similar to Grid–1o16–6M_01 with inner boundary at 1.25
- Grid–1o16–10M_01
- Grid–1o16–10M_r1.25_01
- Grid–1o16–20M_01

Notes

- xMax24 is not introduced here. This grid is useful for simulating narrow pressure pulses where 1/8 or better resolution is needed up to the inflow boundary.
- For inner boundaries at 1.25, the resolution at the inner boundary should be 1/16 or better.
- When the number of grid cells exceeds 10M due to increased resolution in the tail, low Mach number grids will not be offered beyond xMax64.
- If the number of cells exceeds 20M, inflow boundaries will not be offered beyond 32.

Conclusion & Future

Conclusion

Metadata has become essential in managing the rising complexity of space science models. At CCMC, it ensures models remain accessible, reliable, and high-performing for users of all expertise levels. By simplifying intricate configurations, metadata balances complexity and usability, supporting both advanced experimentation and open science principles. As a result, CCMC is setting new standards in reproducibility, accessibility, and collaboration in space science research.

Future Applications

Metadata will continue to drive innovation by:
- Expanding customizable features to cover more configurations.
- Automating adjustments like resolution and boundary inputs for seamless optimization.
- Broadening accessibility, enabling researchers worldwide to explore and discover.

As space science evolves, metadata will remain a cornerstone of reproducible, impactful research.

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