Comparison of Time-dependent Boundary-driven Heliospheric MHD models

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OVERVIEW

Heliospheric magnetohydrodynamic models are essential tools for space weather research and forecasting, providing the framework to understand solar-heliospheric coupling, forecast space weather conditions and interpret observations. Traditional approaches rely on quasi-steady-state solar wind boundary conditions, but capturing the heliosphere's dynamic evolution requires time-dependent boundary driving. Multiple heliospheric models are now available that can run such simulations, some of them only recently obtaining this capability. Here, we explore validating several independent models, by comparing their results driven by the same time-dependent boundary conditions. We compare five models and drive them using empirical solar wind boundary conditions derived from the Wang-Sheeley-Arge model applied to a sequence of full-Sun magnetic maps generated by the Open Flux Transport model. Our comparisons focus on in-situ plasma and magnetic field quantities at a static reference point near 1 au, incorporating uncertainty quantification via nearby in-situ points. Qualitative and quantitative metrics reveal generally strong agreement among the models in key variables and that differences can largely be attributable to implementation choices. The model comparisons highlight the critical importance of cross-model validation among independent teams, fostering transparency and reproducibility. They also enhances confidence in boundary-driven heliospheric modeling, with implications for ensemble forecasting and CME propagation studies.

MODELS

	MAS	Icarus	GAMERA	MS-FLUKSS	HelioCubed
Integration variables	$\vec{A}, \vec{v}, \rho, T$	$\vec{B}, \vec{p}, \rho, e$	$\vec{B}, \vec{p}, \rho, e$	$\vec{B}, \vec{p}, \rho, e$	$\vec{B}, \vec{p}, \rho, e$
$\nabla \cdot \vec{B} = 0$ method	Staggered grid with $\vec{B} = \nabla \times \vec{A}$ (intrinsic)	Parabolic cleaning	Constrained transport	Powell Method	Powell Method
Grid	Uniform* or Logically rectangular non-uniform	Uniform*, Radially stretched, or AMR	Uniform	Uniform	Uniform* or AMR
Domain includes poles	Yes	Yes or No* ($\pm 60^\circ$)	No ($\pm 72^\circ$)	Yes	Yes
Frame	Inertial* or Co-rotating	Co-rotating	Inertial	Inertial	Inertial
Order of accuracy	1^{st} & 2^{nd}	2^{nd}	7^{th}	2^{nd}	4^{th}
Shock Handling	Upwinding	TVDLF with Woodward Limiter	Partial Donor Cell Method (PDM)	Minmod Limiter	High-order Limiter (McCorquodale & Colella 2011)
Code Language	Fortran 2018	Fortran 2018	Fortran 2018	C++	C++
Parallelism	CPU | GPU MPI + StdPar +OpenACC	CPU MPI	CPU MPI + OpenMP	CPU MPI	CPU | GPU Proto (MPI +CUDA backends)
Open status	Open source, RoR	Open source	Open source*, RoR	RoR	Open source

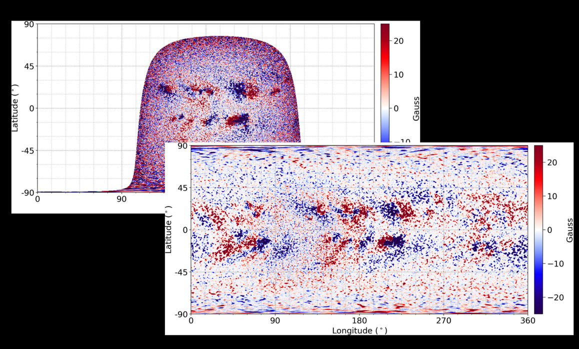
Performance on 4 CPU Nodes (1-day Simulation):

	MAS	Icarus	GAMERA	MS-FLUKSS	HelioCubed
Average Wall Clock (seconds)	831.8	609.1	852.0	554.5	7280.8
Standard Deviation (seconds)	2.5	2.3	11.47	1.3	9.3
Times Faster than Real Time	6232×	8510×	6084×	9348×	712×

EVOLVING BOUNDARY CONDITIONS

Synchronic Br Maps

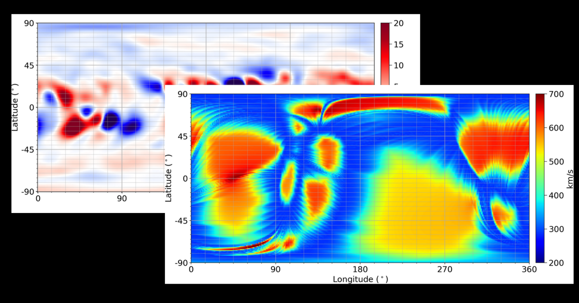
- Need evolving Br solar surface maps, but observations typically along Earth-Sun line
- Flux transport models "fill the gaps" using differential rotation, meridional flows, diffusion, convective flows, random flux emergence, etc.
- We use the open-source OFT model



OFT
github.com/predsci/OFT

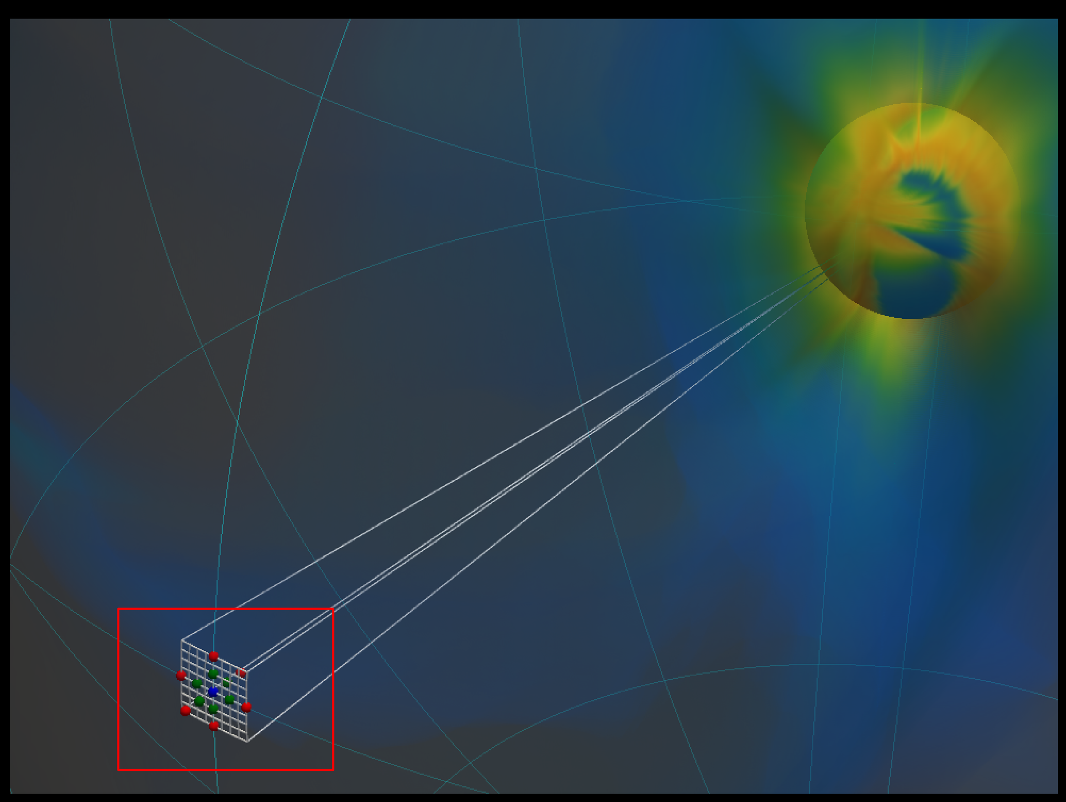
Lower Heliospheric Boundaries

- Can use MHD or PFSS+CS to model coronal field
- Can then use MHD or an empirical prescription (like WSA) for solar wind boundaries
- Empirical has 0-valued transverse fields (easier for models)
- Here, we use PFSS+CS+WSA (rss = 2.5 Rs) on maps after smoothing using the open-source SWiG tool



SWiG
github.com/predsci/SWiG

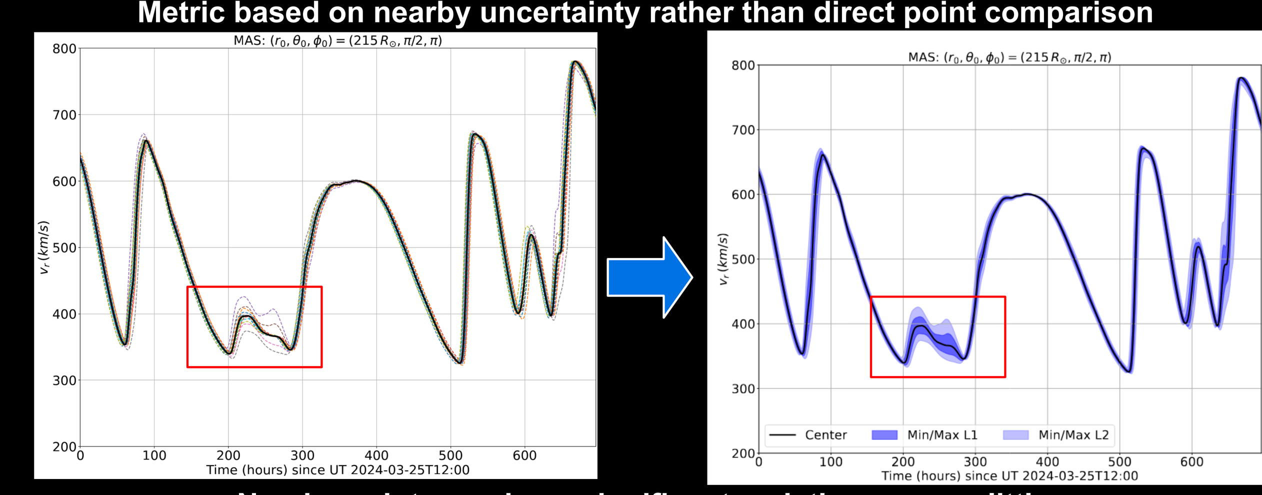
UNCERTAINTY COMPARISON METRIC



Stencil of points around in-situ point used for uncertainty quantification

Condition	Description	Value
$\lvert C^a - C^b \rvert \leq 0.01 \lvert C^a \rvert$	Center values within 1% (normalized to a)	6
$C^a \in L1^b$ and $C^b \in L1^a$	Center values within L1 stencil values	5
$L1^a \cap L1^b \neq \emptyset$	L1 stencil values overlap	4
$C^a \in L2^b$ and $C^b \in L2^a$	Center values within L2 stencil values	3
$(L1^a \cap L2^b \neq \emptyset)$ or $(L2^a \cap L1^b \neq \emptyset)$	L1 stencil values overlap L2 stencil values	2
$L2^a \cap L2^b \neq \emptyset$	L2 stencil values overlap	1
$L2^a \cap L2^b = \emptyset$	No values within stencils overlap	0

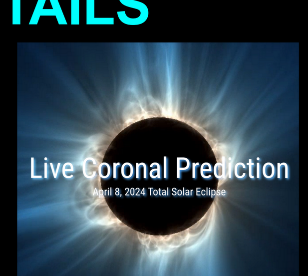
Metric based on nearby uncertainty rather than direct point comparison



Nearby points can have significant variation, or very little

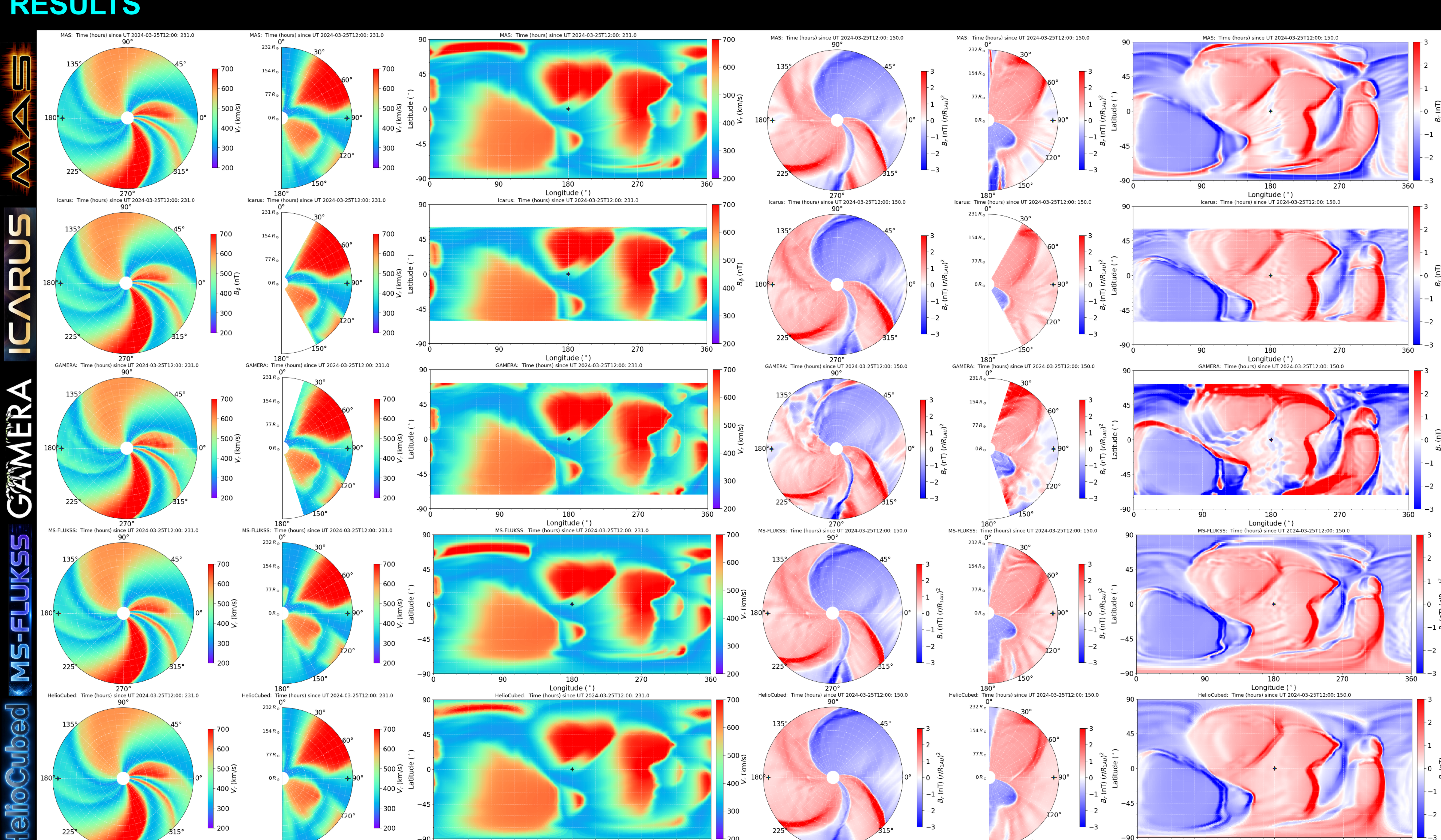
SIMULATION DETAILS

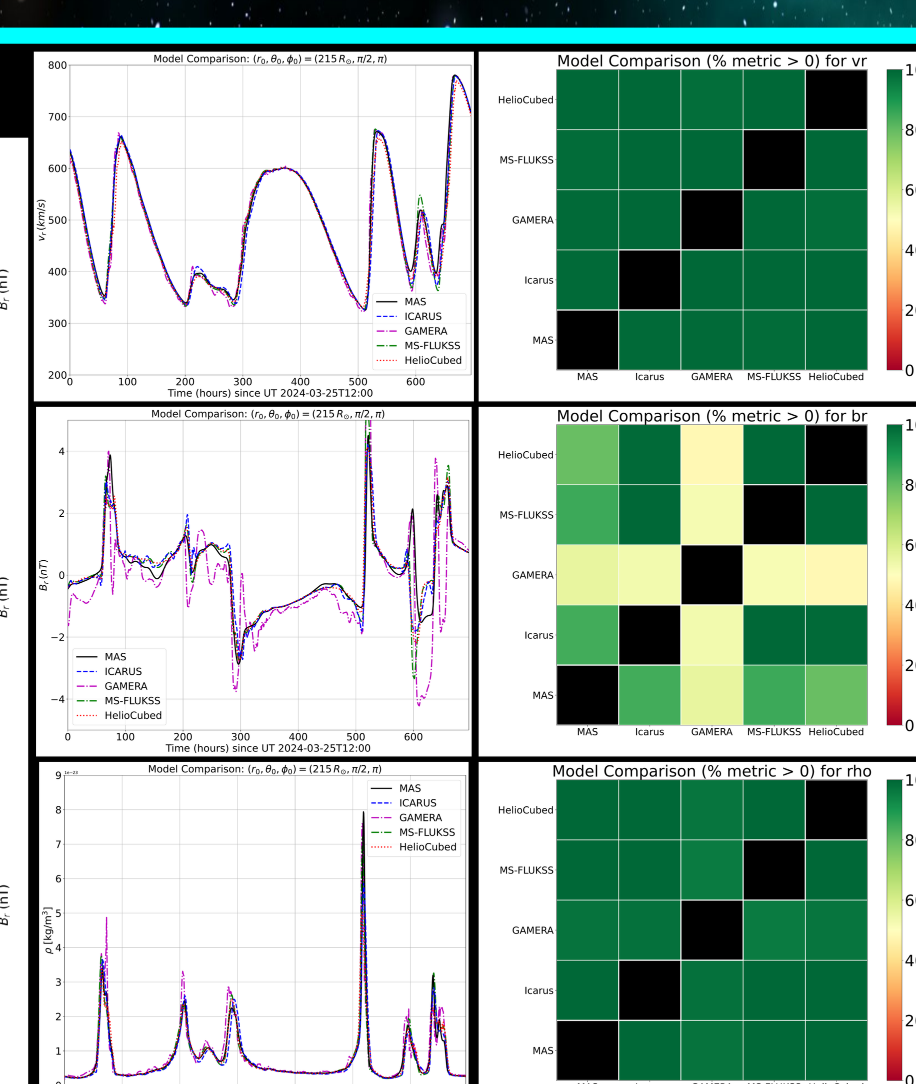
- We use the OFT maps utilized in [Downs, et. al. 2025] for their solar eclipse prediction run: zenodo.org/records/14889337



- Models run with maps spanning 32.3 days from 2024-03-16T12:00 to 2024-04-17T19:00 at 1 hr cadence
- Model comparisons start at 2024-03-25T12:00 (allowing the heliosphere to become "filled" first)
- Models run until 2024-04-23T12:00 (174 hours after last map) creating a "relaxation" at the end
- Heliospheric domain spans r=21.5Rs to r=231.5Rs with 528 cells, and 1-degree resolution in lat/long
- Some models run without polar regions, others are run fully global
- In-situ stencil cloud has two layers, each 1-degree (3.75Rs) apart in long/lat (radius)
- Physics used in each model are synchronized as much as possible

RESULTS





Discussion

- Overall good agreement between models
- Heliocubed slow run time being optimized
- Gamera is higher order than other models, which preserves strong Br boundary changes into domain
- MAS uses special boundary potential solvers – may be cause of Br mismatch
- Paper submission coming soon!
- Want to join? If you have an open-source/RoR heliospheric MHD model that can be driven with time-evolving boundary files, we welcome participaton in the next comparion study – full component MHD and/or CMEs!