Statistical Comparison of Performance of Global MHD Models

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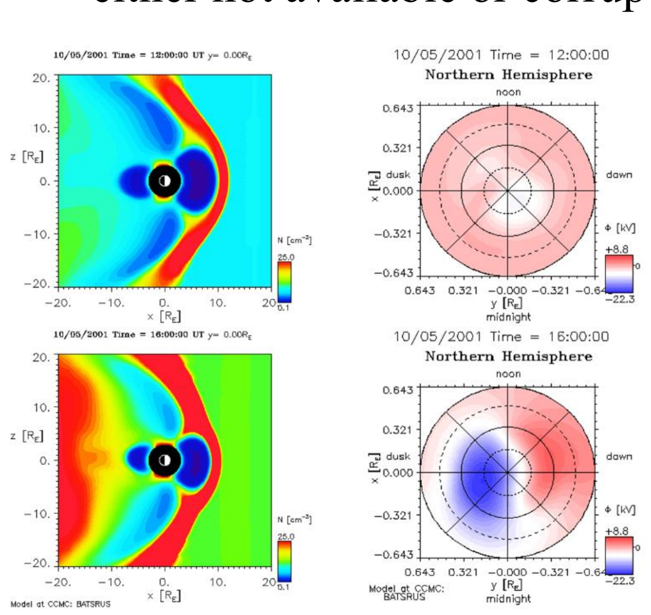
Abstract

The goal of this research is to compare the performance of three magnetohydrodynamic models - SWMF, LFM and OpenGGCM - in estimating the Earth's magnetopause location and the ionospheric cross polar cap potential (CPCP). Ten solar events of varying magnitudes have been considered to generate the MP standoff distance and CPCP from the global models and compare with six empirical MP models CPCP estimations from AMIE and SuperDARN. Four performance metrics are considered for comparison : RMS Error, Prediction Efficiency, Max Amplitude and Wrong Prediction. The global models were run using the Community Coordinated Modeling Center's Run-on-request system and extensive database on results of various magnetospheric scenario runs.

MHD Models Description

- The features and settings of global MHD models used in this study have been kept to as identical as possible.
- All models were run using the CCMC Run-on-Request option, and with additional information from the CCMC run database
- The **SWMF** 2014 version used for the study contained 2 million grid cells with a variable dipole tilt configuration. The Rice Convection Model was also incorporated.
- The **LFM** version 2_1_5 (with TIE-GCM ionosphere model) used contained (106x64x48) grid cells with a variable dipole tilt configuration.
- The **OpenGGCM** Version 4.0 contained 7 million cells with a variable dipole tilt configuration.
- The ionospheric conductance model driven by solar irradiance and FACs was used for SWMF. OpenGGCM used the auroral option (*Raeder et al, 2001*). LFM used the TIE-GCM conductance model option (*Wiltberger et al., 2009*).
- Most cases used WIND satellite data for the solar wind input. In some particular cases where WIND data was either not available or corrupted, ACE data was used.



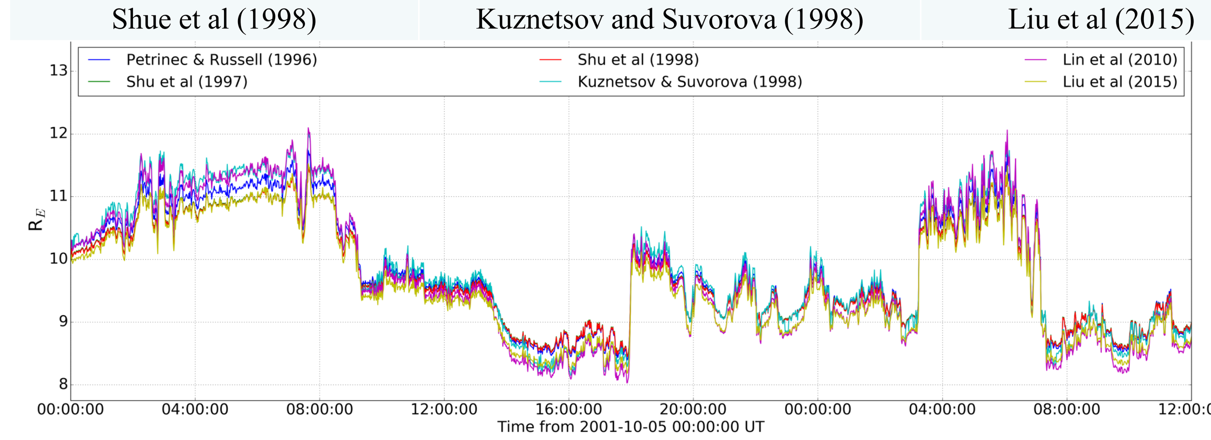
The global magnetosphere density in the *x-z* plane (a) and the ionospheric potential in the northern hemisphere (b) for the October 2001 storm case, generated by the SWMF model via CCMC at two different times.

MP Empirical Models Description

- Six MP Empirical Models were used. The most recent one of these is the *Liu et al (2015)* model.
- The empirical models included were based on the standard deviation study presented in *Lin et al (2010)*, where the proposed *Lin et al (2010)* model was compared with previously defined empirical models for an independent set of 2000 magnetopause crossings by satellites. The models with standard deviations less than 1 R_E in the above study were chosen for comparison in this study.
- Most of the models depend on the IMF Bz and the subsolar angle which was taken below 30 deg.

MP Empirical Models Used

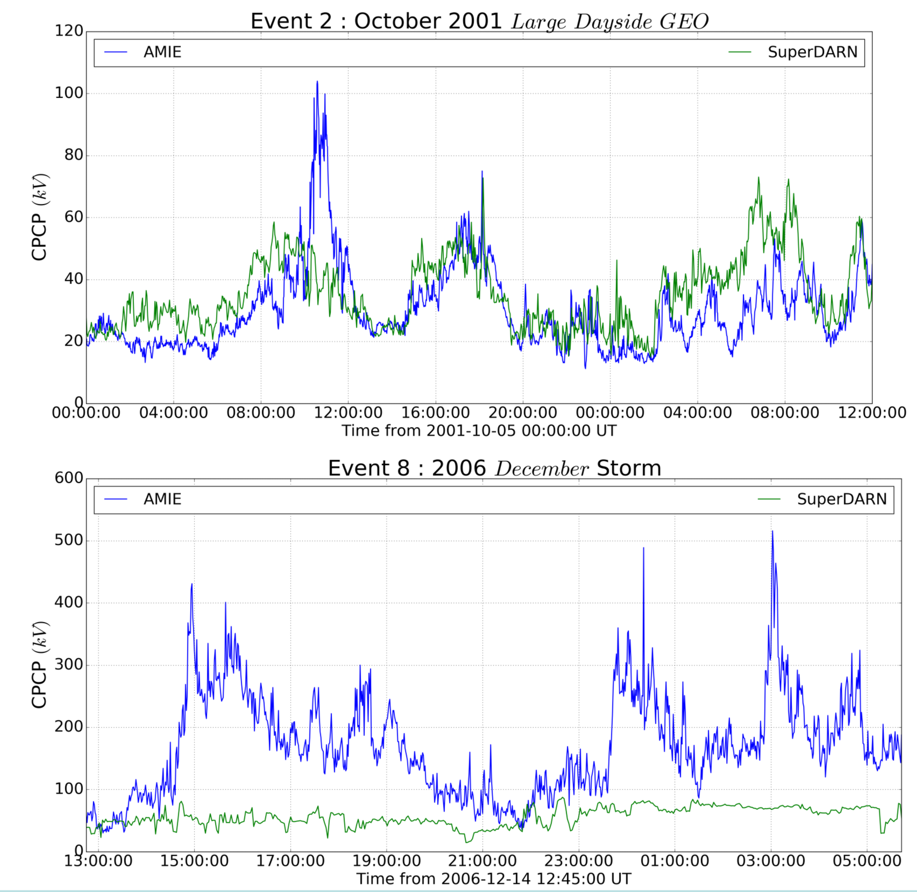
Petrinec and Russell (1996)	Shue et al (1997)	Lin et al (2010)
Shue et al (1998)	Kuznetsov and Suvorova (1998)	Liu et al (2015)



All Empirical Model data plotted for 5-6 October 2001 Event. The standard deviations were later added to conduct further analysis.

SuperDARN & AMIE

- Data from SuperDARN (VT) and AMIE (UMich) were used to compare the CPCP data.



Comparison of AMIE and SuperDARN data for the high *Kp* storms (5-6 October 2001 Event and 2006 December Storm).

- For the high *Kp* (December 2006 storm), the two techniques generate contradicting results. SuperDARN underestimates probably due to limited radar field of view.

Performance Metrics

1. Root Mean Square:
$$\mathrm{RMS} = \sqrt{\langle (x_{obs} - x_{mod})^2 \rangle_i}$$
2. Prediction Efficiency:
$$\mathrm{PE} = 1 - \frac{\langle (x_{obs} - x_{mod})^2 \rangle_i}{\langle (x_{obs} - \bar{x})^2 \rangle_i}$$
3. Max Amplitude (MA):
$$\text{Max Amp} = \frac{\max(|x_{mod}|_i)}{\max(|x_{obs}|_i)}$$
4. Wrong Prediction (WP):
$$x_{model} \notin x_{obs}(max, min) \pm \sigma_{obs}$$
Underprediction: $x_{model} < x_{obs}(max, min) \pm \sigma_{obs}$
Overprediction: $x_{model} > x_{obs}(max, min) \pm \sigma_{obs}$

Solar Events

- Ten solar events were considered, which were characterized on the basis of the maximum *Kp* value into low, medium and high intensity events.
- Low Intensity Event: $0 \le Kp < 4$
  Medium Intensity Event: $4 \le Kp < 7$
  High Intensity Event: $Kp \ge 7$
- While all 10 events were considered for the MP standoff distance comparison, only 8 events could be considered for the CPCP comparison due to lack of data.
- Simulation results available on CCMC database.

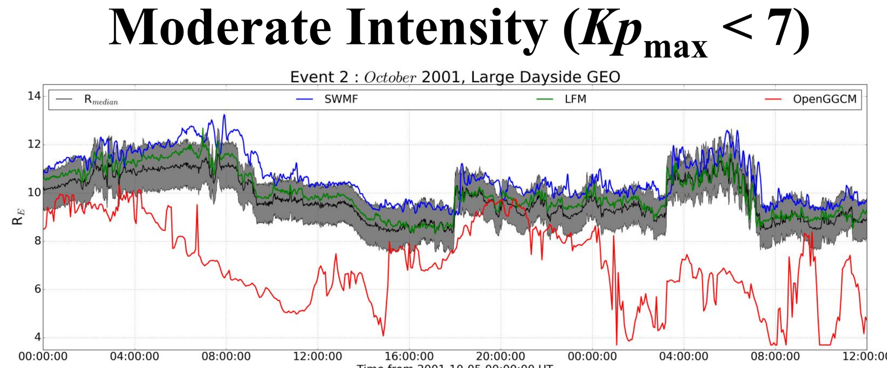
List of Solar Events

31 August – 1 September, 2001 (M)	19 – 20 November, 2004 (L)
5 – 6 October, 2001 (M)	31 August – 1 September 2005 (H)*
8 September, 2002 (M)	14 – 16 September, 2006 (H)
29 – 30 October, 2003 (H)	18 July, 2008 (L)
18 – 19 February, 2004 (L)	16 – 18 March, 2015 (H)*

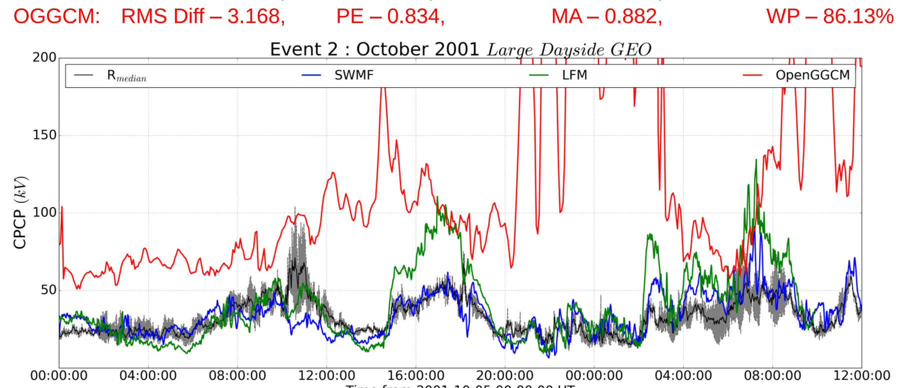
L – Low, M – Moderate, H – High Intensity Storms
* - Not included in CPCP study due to lack of data

Results & Analysis

Moderate Intensity ($Kp_{max} < 7$)



SWMF: RMS Diff – 0.873, PE – 0.977, MA – 1.132, WP – 51.03%
LFM: RMS Diff – 0.367, PE – 0.99, MA – 1.084, WP – 0.278%
OGGCM: RMS Diff – 3.168, PE – 0.834, MA – 0.882, WP – 86.13%

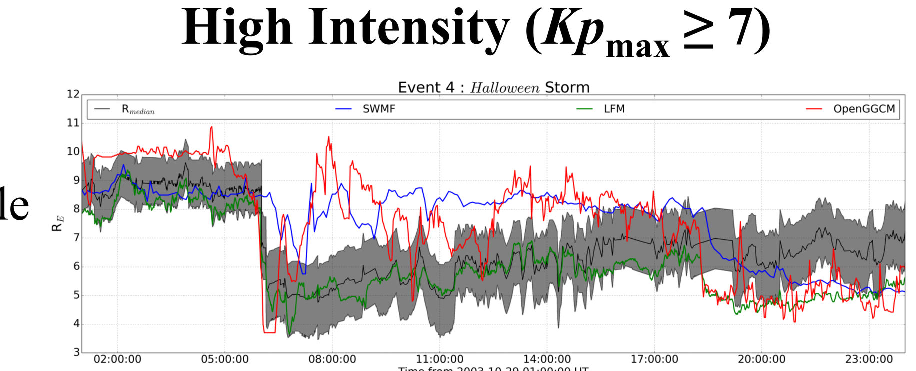


SWMF: RMS Diff – 10.59, PE – 0.083, MA – 1.283, WP – 62.26%
LFM: RMS Diff – 19.01, PE – -1.933, MA – 1.891, WP – 79.23%
OGGCM: RMS Diff – 164.1, PE – -213.7, MA – 8.613, WP – 99.69%

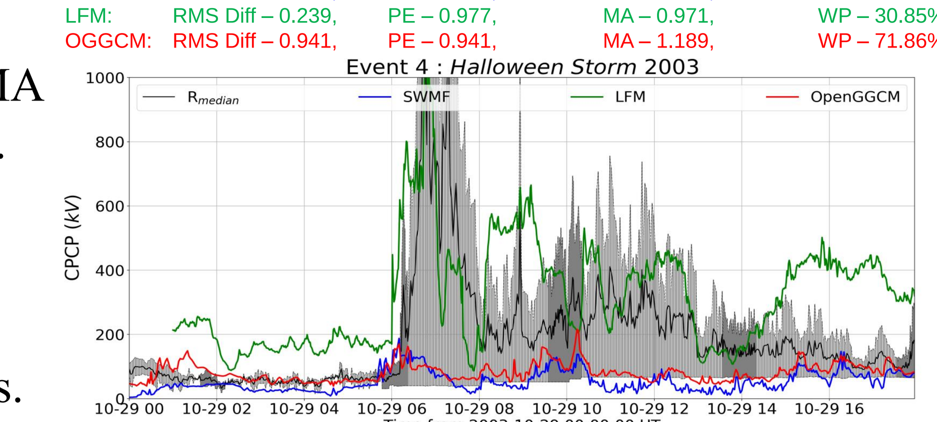
SOLAR PROPERTIES	Min	Median	Max
IMF Bz (nT)	-3.26	0.592	46.17
Solar Wind u_x (km/s)	-250.3	-396.75	-431.1
Dyn. Pressure (nPa)	0.1	6.597	15.5
Kp (Kyoto)	1	3.75	5

- MP Standoff Distances estimations near perfect for LFM.
- SWMF predicts commencement of storm well, however is not able to perfectly recover after decrease.
- Due to low comparable differences between empirical and MHD results, metrics PE and MA fail characterizing performance.
- CPCP estimations are comparatively unsatisfactory.
- Huge deviations by LFM and OpenGGCM for moderate cases.
- Due to lower σ in CPCP estimation, prediction errors increase.
- Huge deviations between AMIE and SuperDARN for both High intensity cases.

High Intensity ($Kp_{max} \ge 7$)



SWMF: RMS Diff – 0.228, PE – 0.958, MA – 1.464, WP – 45.83%
LFM: RMS Diff – 0.239, PE – 0.977, MA – 0.971, WP – 30.85%
OGGCM: RMS Diff – 0.941, PE – 0.941, MA – 1.189, WP – 71.86%



SWMF: RMS Diff – 224.1, PE – -0.374, MA – 0.171, WP – 44.01%
LFM: RMS Diff – 201.2, PE – -0.333, MA – 0.609, WP – 64.33%
OGGCM: RMS Diff – 217.6, PE – -0.296, MA – 0.201, WP – 25.34%

SOLAR PROPERTIES	Min	Median	Max
IMF Bz (nT)	-50.25	0.314	25.79
Solar Wind u_x (km/s)	-325.02	-911.85	-1202.4
Dyn Pressure (nPa)	0.102	0.34	2.41
Kp (Kyoto)	5	8.5	9

MP Standoff	RMS Error	Prediction Eff.	Max. Amplitude	Wrong Prediction
SWMF	***0.5977***	0.9198	***1.00005***	31%
LFM	0.6392	***0.9302***	1.019	***23%***
OpenGGCM	1.7491	0.8121	0.96519	51.7%
CPCP	RMS Error	Prediction Eff.	Max. Amplitude	Wrong Prediction
SWMF	***48.0127***	***-2.04205***	***0.8531***	70.68%
LFM	85.994	-8.9649	1.9294	79.493%
OpenGGCM	87.647	-37.5095	2.4282	***70.104%***

(top) Examples of a low/moderate and high intensity solar event (5-6 October 2001 & 29-30 October 2003) simulations for the magnetopause locations and CPCP estimation using the three MHD Models and comparisons along the empirical data. The grey region denotes the empirical data along with the addition of the standard deviation bounds. The black line signifies the median value from the empirical data, while the blue, green and red lines are data from SWMF, LFM and OpenGGCM respectively.

(left) Median values of the metrics used to compare the three MHD models for the MP Standoff Distances and CPCP.

Conclusions

- We conducted a comparison of three MHD models on their estimation performance of the MP locations and CPCP.
- We find that almost all the MHD models compare well with the empirical model during quiet time and moderate storm time for MP locations.
- CPCP predictions by MHD and empirical model are highly unreliable for high intensity storms. SWMF predicts best during quiet time.
- Some metrics might not work universally, and they should be optimized accordingly to cater the needs.

References

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3. Lin et al., JGR **115**, 207 (2010).
4. Pulkinnen et al., SW **9**, 35 (2011).
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