Global Driving of Auroral Conductance - Balance of Sources & Numerical Considerations

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November 24, 2022

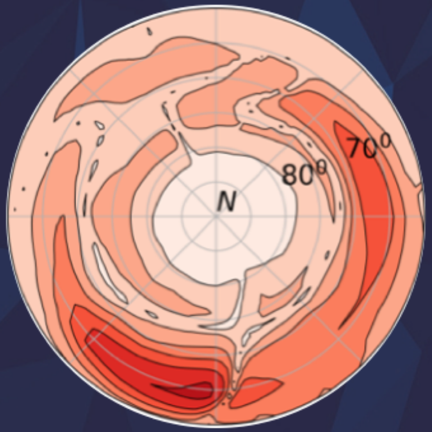
Abstract

We present latest results from the Conductance Model for Extreme Events (CMEE) and the Magnetosphere-Ionosphere-Thermosphere (MAGNIT) Conductance Model. Both models have been integrated into the Space Weather Modeling Framework (SWMF) to couple dynamically with the BATS-R-US MHD model, the Rice Convection Model (RCM) of the ring current & the Ridley Ionosphere Model (RIM) to simulate the April 2010 “Galaxy15” Event. The model is used with three grid configurations: the low-resolution configuration currently employed by NOAA’s Space Weather Prediction Center and two additional configurations that decrease the minimum grid resolution from $\frac{1}{4}$ RE to 1/8 and 1/16 RE. In addition, the simulation is driven with and without the dynamic coupling with RCM to study the impact of the ring current’s pressure correction in the inner magnetospheric domain. Using this model setup for a Maxwellian distribution, aforementioned precipitation sources are progressively applied and compared against the DMSP SSUSI observations. Finally, data-model comparisons against AMPERE Field-Aligned Currents, geomagnetic indices & magnetometer measurements are shown, with additional comparison against the existing conductance model in RIM. Results show remarkable progress in auroral precipitation modeling & MI coupling layouts in global models.

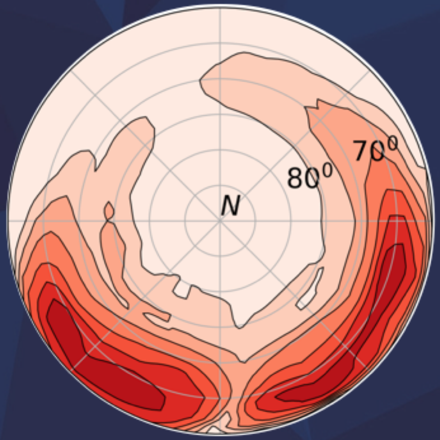
Global Driving of Auroral Conductance

Development of Advanced Auroral Precipitation Modules in the SWMF

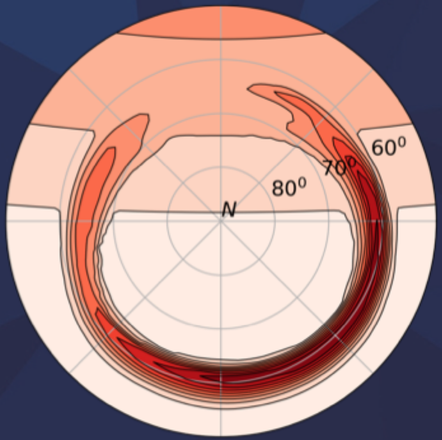
RLM
(Ridley et al. 2004, *AnnGeo*)



CMEE
(Mukhopadhyay et al. 2020, *SpWeather* submtd)



MAGNIT
(Mukhopadhyay et al., in prep)



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Global Driving of Auroral Conductance

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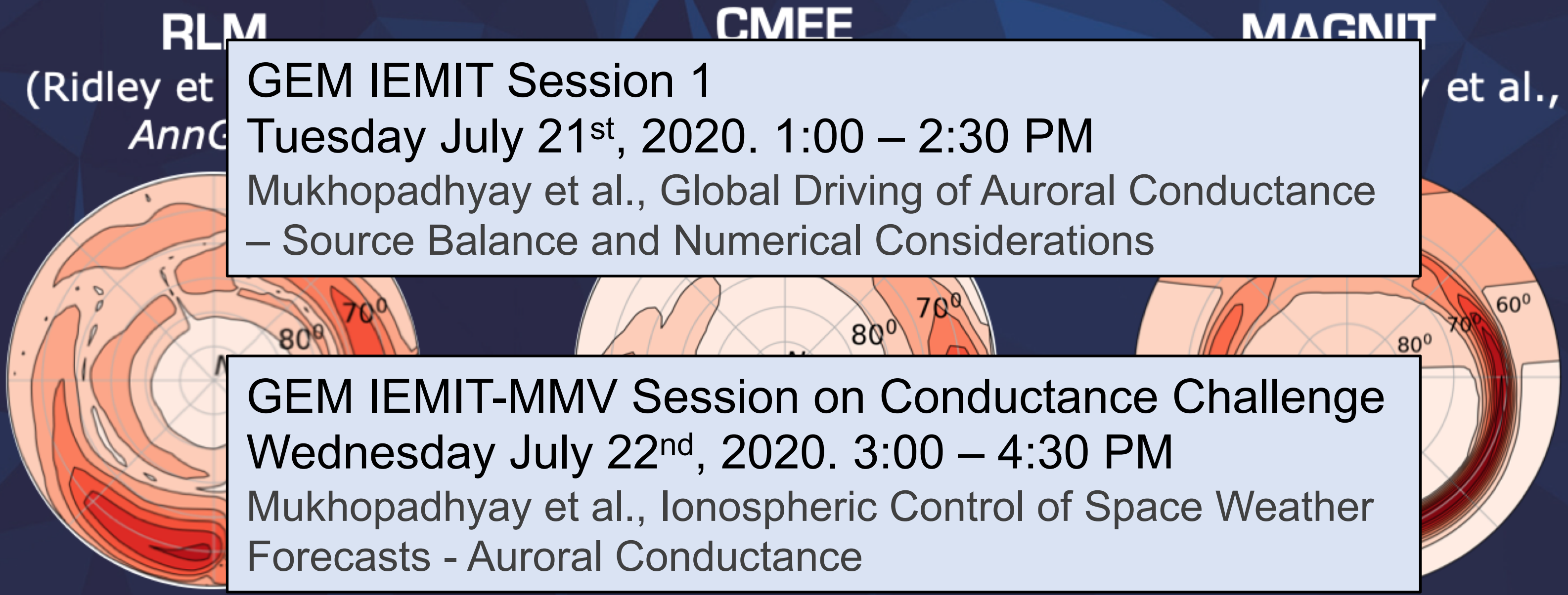

GEM IEMIT Session 1
Tuesday July 21st, 2020. 1:00 – 2:30 PM
Mukhopadhyay et al., Global Driving of Auroral Conductance – Source Balance and Numerical Considerations

GEM IEMIT-MMV Session on Conductance Challenge
Wednesday July 22nd, 2020. 3:00 – 4:30 PM
Mukhopadhyay et al., Ionospheric Control of Space Weather Forecasts - Auroral Conductance

Agnit Mukhopadhyay[1], Daniel Welling[2], Meghan Burleigh[1,3], Michael Liemohn[1], Aaron Ridley[1], Shasha Zou[1], Brian Anderson[4], Elizabeth Vandegriff[2], Hyunju Connor[5], Jesper Gjerloev[4]

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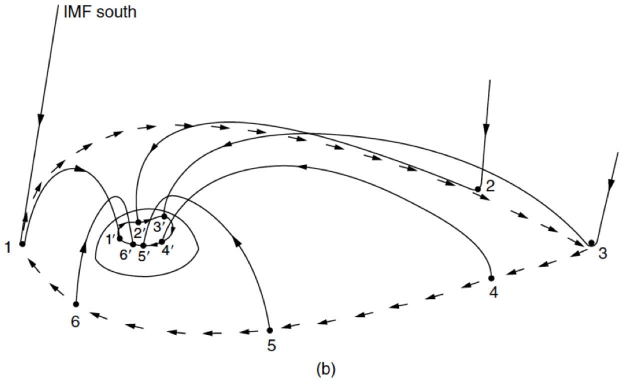
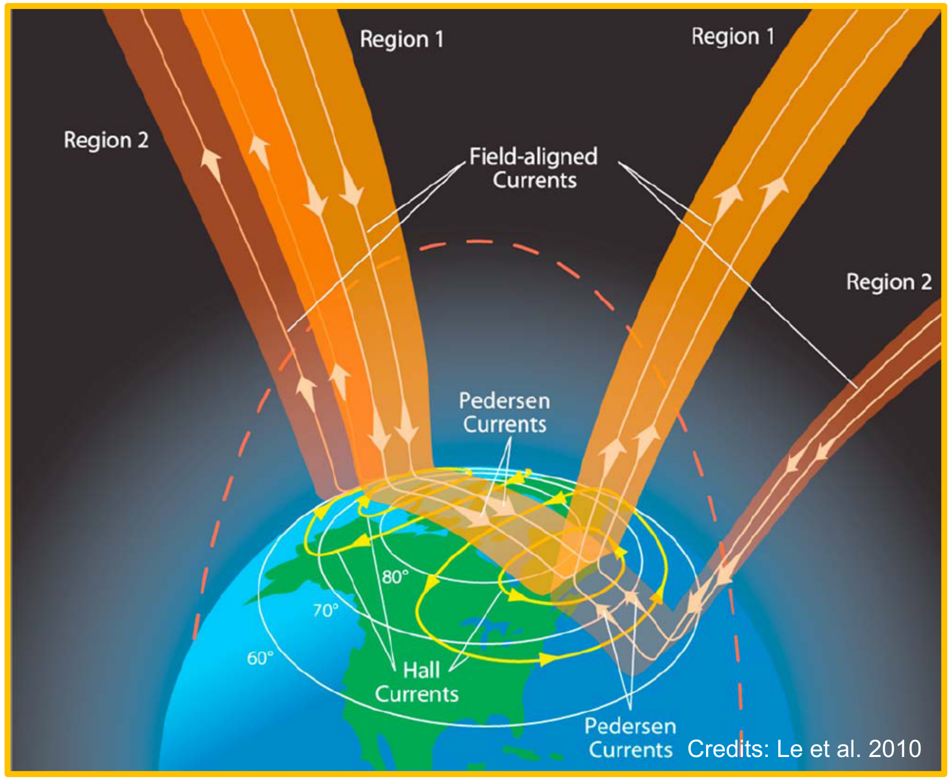
Magnetosphere – Ionosphere (M-I) Coupling

- Magnetospheric motion maps back to the Ionosphere. Field aligned current closure.
  [e.g. Dungey, 1963; Axford and Hines, 1961]

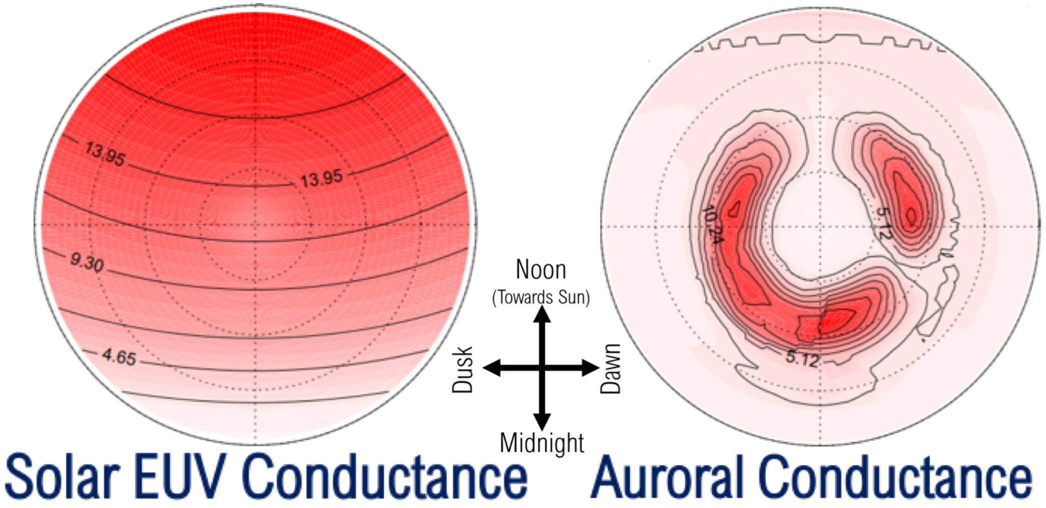


- Estimating the coupling of magnetosphere and ionosphere help predict GICs (*dB/dt*) accurately. *[e.g. Yu et al. 2010]*

- Ionospheric conductance is a major player in estimating this coupling.
  [e.g. Ridley et al. 2004; Merkin et al. 2003, 2005a,b; Wiltberger et al. 2009, 2017; Zhang et al. 2015; Yu et al. 2016; Perlongo et al. 2017]



Modeling M-I Coupling in Global Models - Review



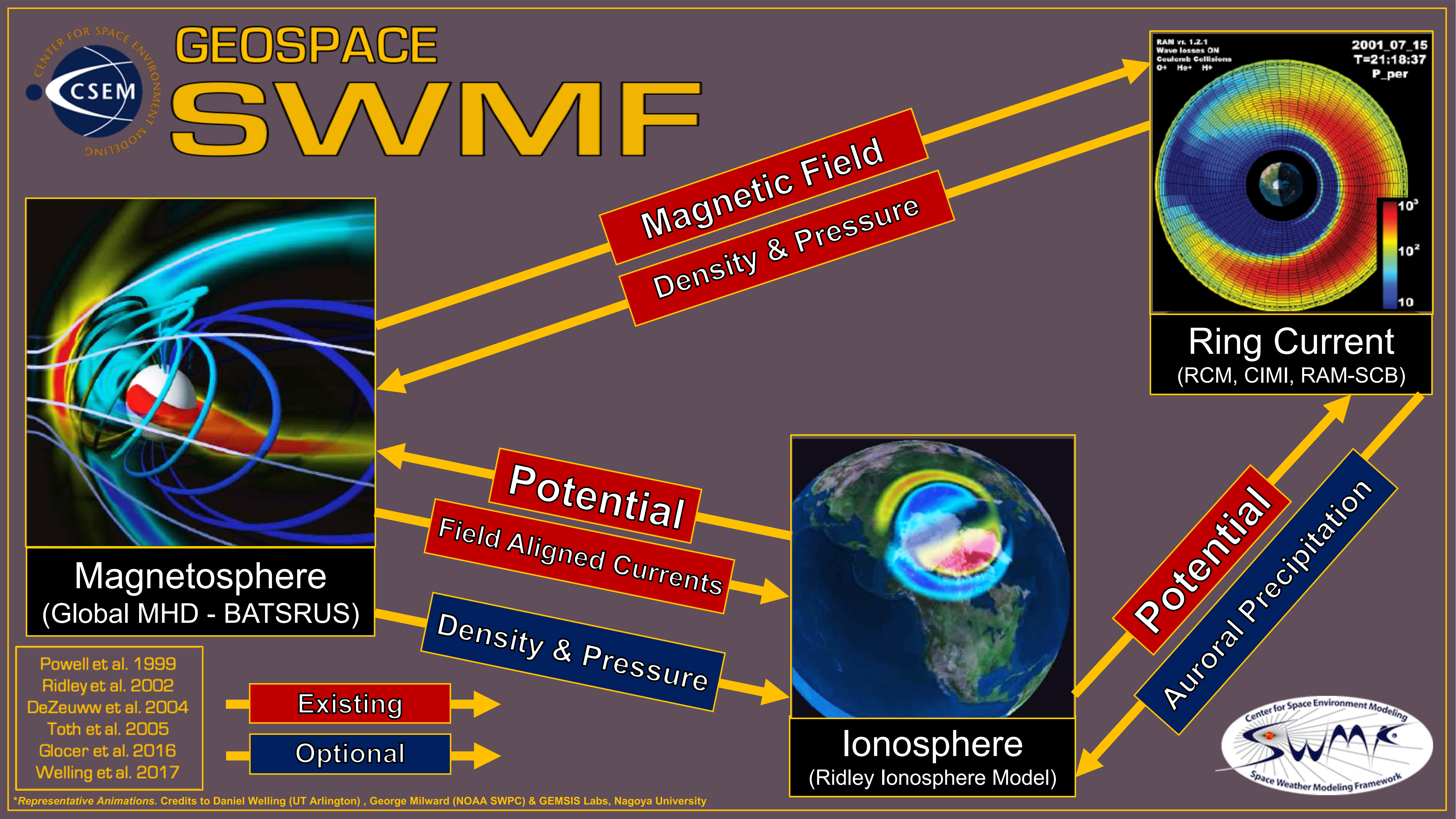
Ohm's Law

Field-aligned current — Conductance — Potential

$$j_R(R_I) = [\nabla_\perp \cdot (\Sigma \cdot \nabla \psi)_\perp]_{R=R_I}$$

If the field-aligned current is constant, & the conductance increases, then the potential must go down.

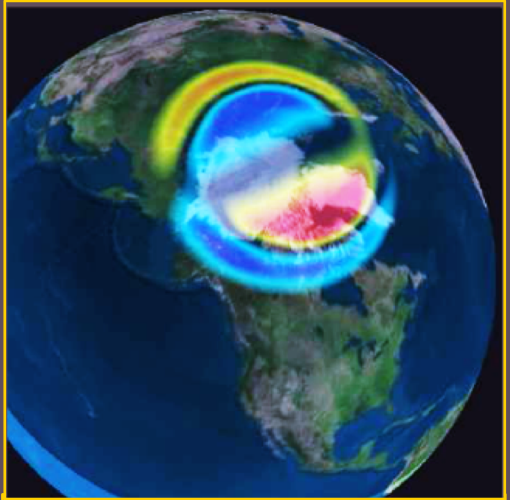
- Most global MHD models use a two-dimensional 'shell' Poisson solver to model the ionosphere *[e.g. Raeder et al. 1991; Ridley et al. 2002]*
- Field Aligned Currents (FACs) from MHD domain are passed to ionosphere, & electrostatic potential is passed back. Conductance must be known *a priori*. *[e.g. Goodman, 1995]*
- Two dominant sources of conductance: **Solar EUV** and **Auroral Precipitation**.


GEOSPACE
SWMF
CSEM
CENTER FOR SPACE ENVIRONMENT MODELING
Wave losses ON
Coulomb Collisions
O+ He+ H+
2001_07_15
T=21:18:37
P_per
10^3
10^2
10
Ring Current
(RCM, CIMI, RAM-SCB)
Magnetic Field
Density & Pressure
Magnetosphere
(Global MHD - BATSRUS)
Potential
Field Aligned Currents
Density & Pressure
Ionosphere
(Ridley Ionosphere Model)
Potential
Auroral Precipitation
Powell et al. 1999
Ridley et al. 2002
DeZeuww et al. 2004
Toth et al. 2005
Glocer et al. 2016
Welling et al. 2017
Existing
Optional
Center for Space Environment Modeling
SWMF
Space Weather Modeling Framework
*Representative Animations. Credits to Daniel Welling (UT Arlington) , George Milward (NOAA SWPC) & GEMSIS Labs, Nagoya University

GEOSPACE

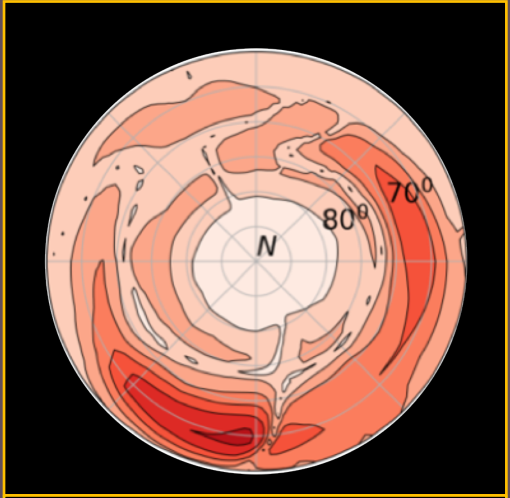
SWMF

Ionospheric CONDUCTANCE



Ionosphere

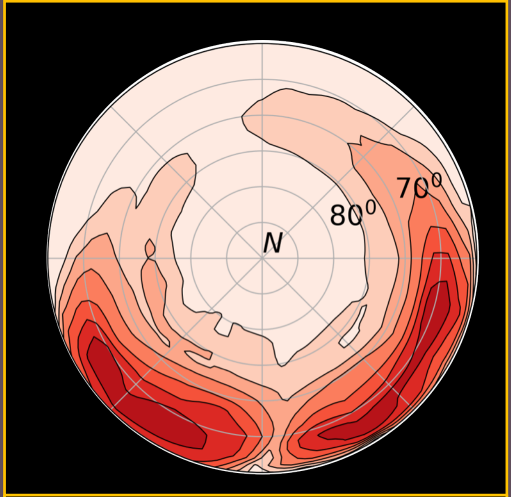
(Ridley Ionosphere Model)



Ridley Legacy Model | **RLM**

Ridley et al. 2004

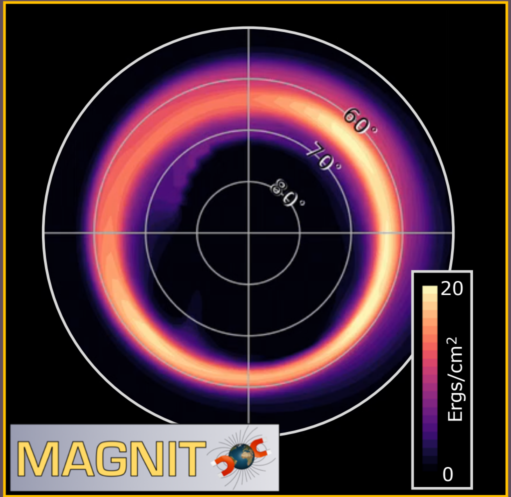
- Dominant contributors – Solar EUV + Aurora
- Default model for the last ~2 decades
- Moen & Brekke (1992) solar EUV conductance
- AMIE-derived empirical model for aurora



Conductance Model for Extreme Events | **CMEE**

Mukhopadhyay et al. 2020*

- Improved empirical aurora
- AMIE data from extreme events used for fitting
- Increases conductance ceiling during extreme driving
- Improves Space Weather Forecasts



Magnetosphere - Ionosphere -Thermosphere Conductance Model for the Aurora | **MAGNIT**

Mukhopadhyay et al. *in prep*

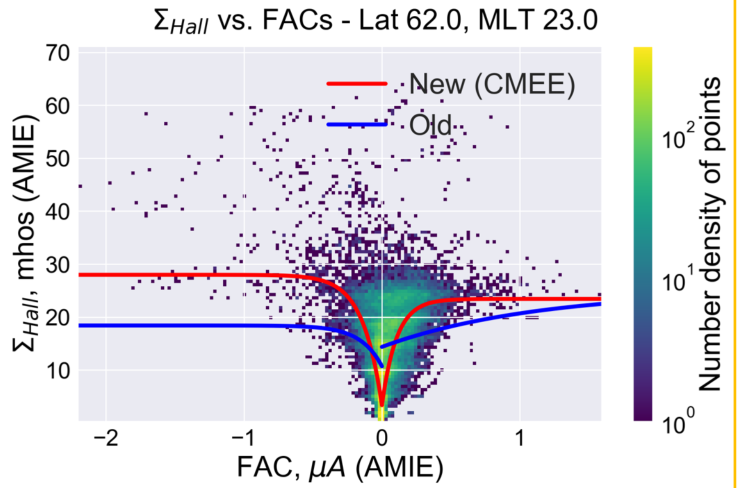
- Physics-driven aurora
- Precipitation derived from MHD and/or ring current
- Different sources of precipitation (e^- and ion)
- Designed to estimate conductance for multiple dist. functions

Conductance Model for Extreme Events

Mukhopadhyay et al. 2020, SpWthr (und. review)

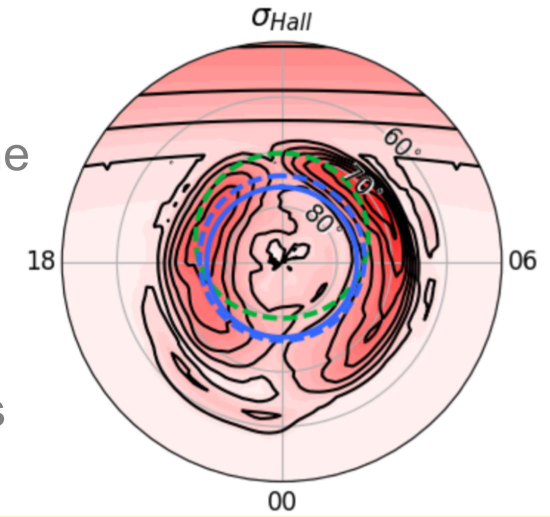
Increased Dataset + Advanced Fitting

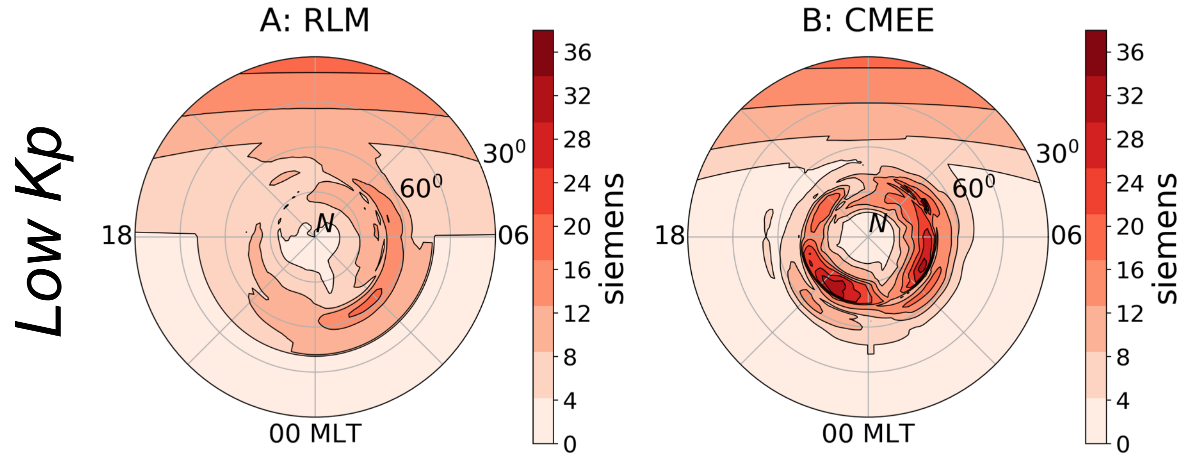
- Empirical fitting between auroral conductance and field aligned currents were improved.
- Minute-res data from the year of 2003 was used. Nonlinear Regression used to incld extremes.

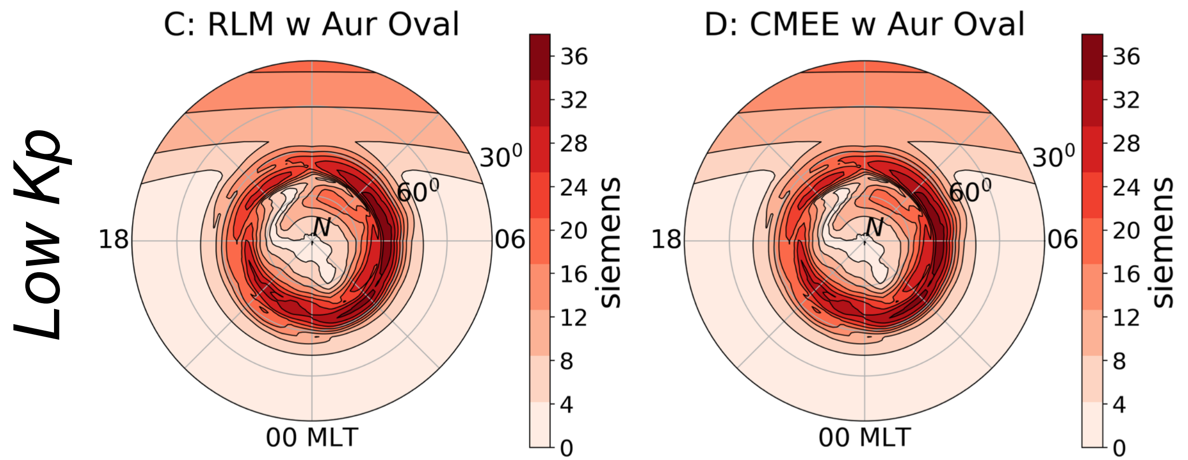


Auroral Oval Adjustment

- Artificial oval fitted to strengthen the auroral electrojet and tighten the oval.
- Upward FACs used to mimic mono-energetic aurora. Baseline values for nonzero values







Conductance Model for Extreme Events

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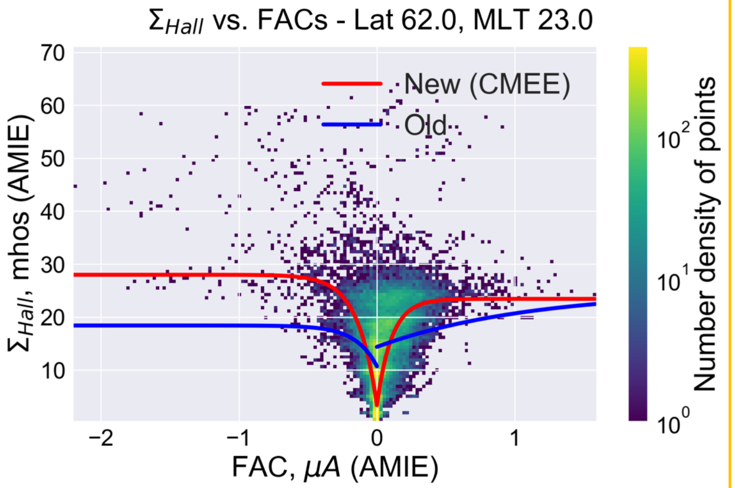

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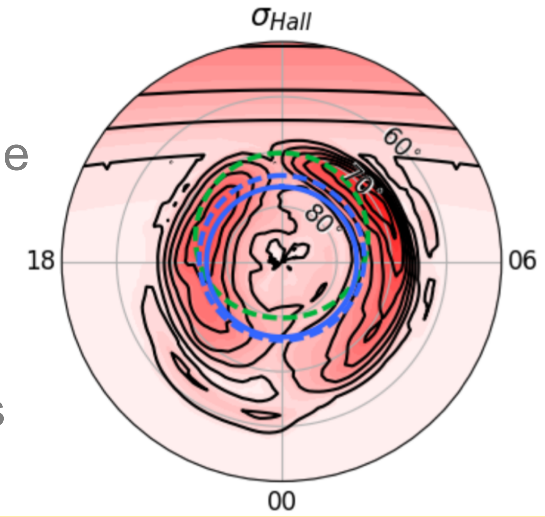
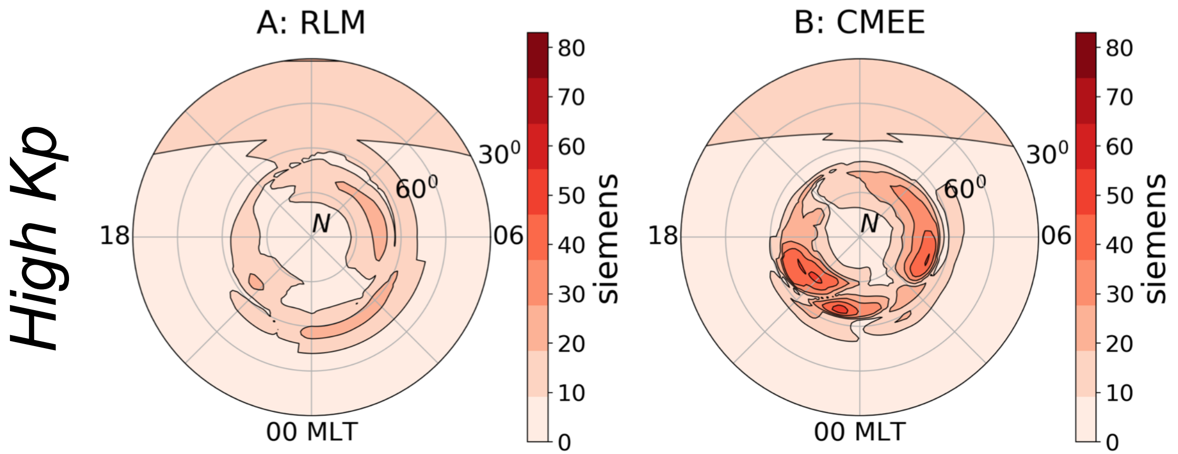
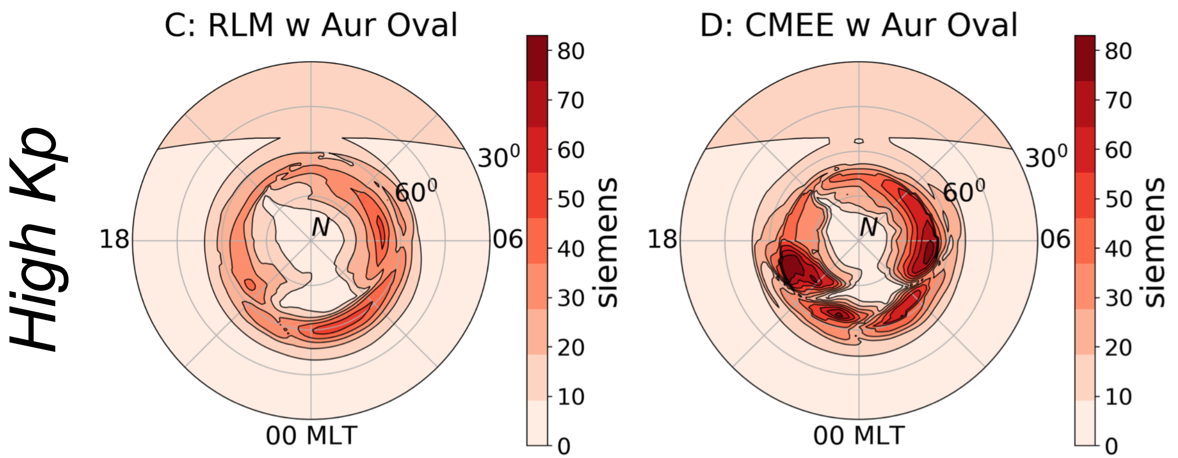


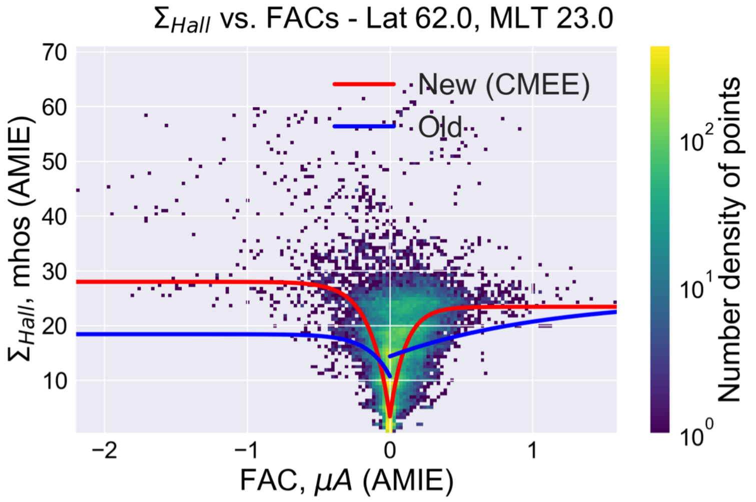




Data Question - Is one month of data enough to model extreme events?

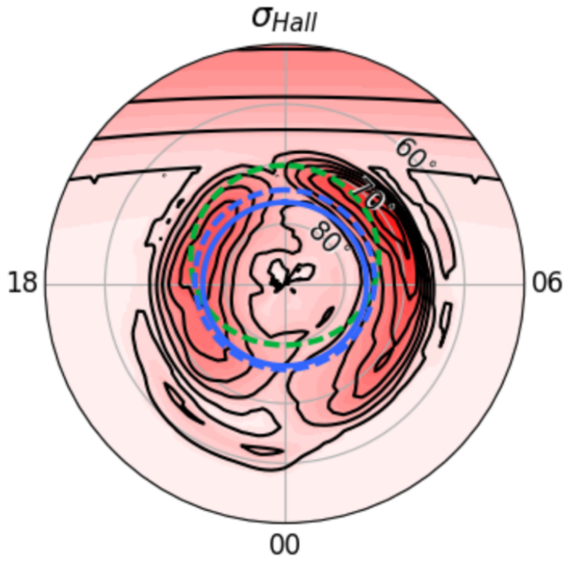
Question 1

Does expanding the dataset help improve Space Weather predictions?



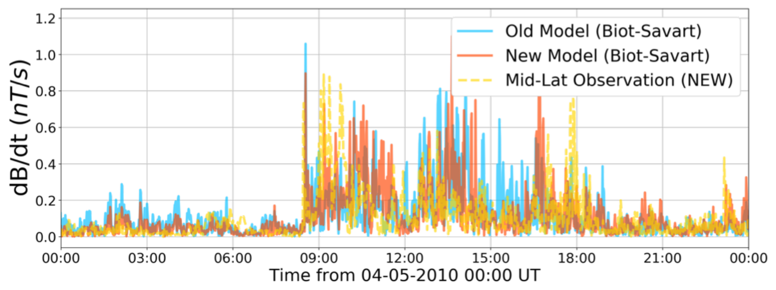
Question 2

How significant is the effect of the artificial auroral oval in improving SW predictions?



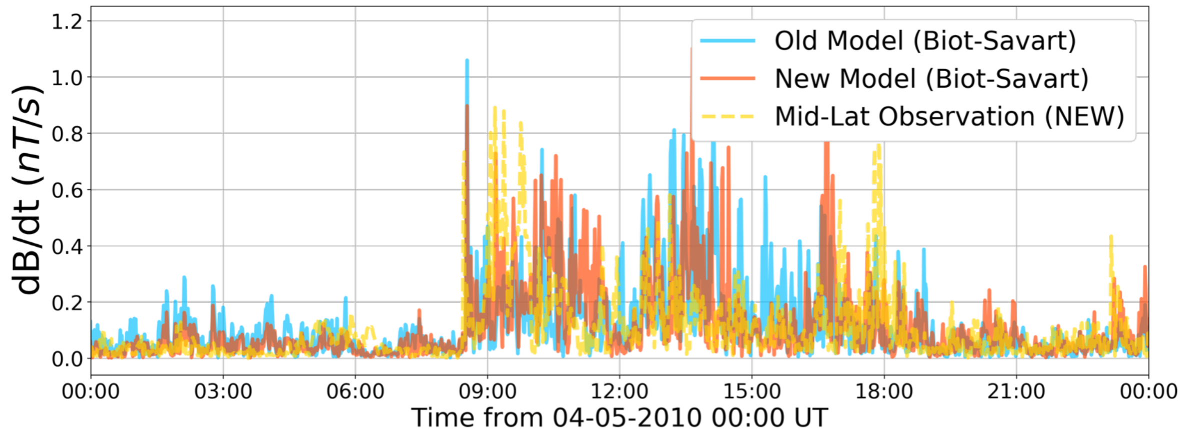
Question 3

Does the enhanced combo of dataset expansion and artificial auroral oval improve SW predictions?



Simulation Setup

SWMF - CMEE



6 Space Weather Events
12 Magnetometers

Heidke Skill Score (HSS)

$$\frac{(\text{Hits} + \text{False Negative}) - (\text{Expected Correct})}{(\text{Perfect Score}) - (\text{Expected Correct})}$$

Threshold	*SWPC* Configuration RLM	CMEE	Difference
0.3 nT/s	0.521	0.554	+0.033
0.7 nT/s	0.445	0.478	+0.033
1.1 nT/s	0.353	0.394	+0.040
1.5 nT/s	0.285	0.312	+0.027

Based on *Pulkinnen et al. [2013]* study on dB/dt predictions

		OBSERVATION Yes	No
FORECAST	Yes	Hit	False Alarm
	No	Miss	False Negative

Probability of Detection (POD)

$$= \frac{\text{Hits}}{\text{Hits} + \text{Misses}}$$

Probability of False Detection (POFD)

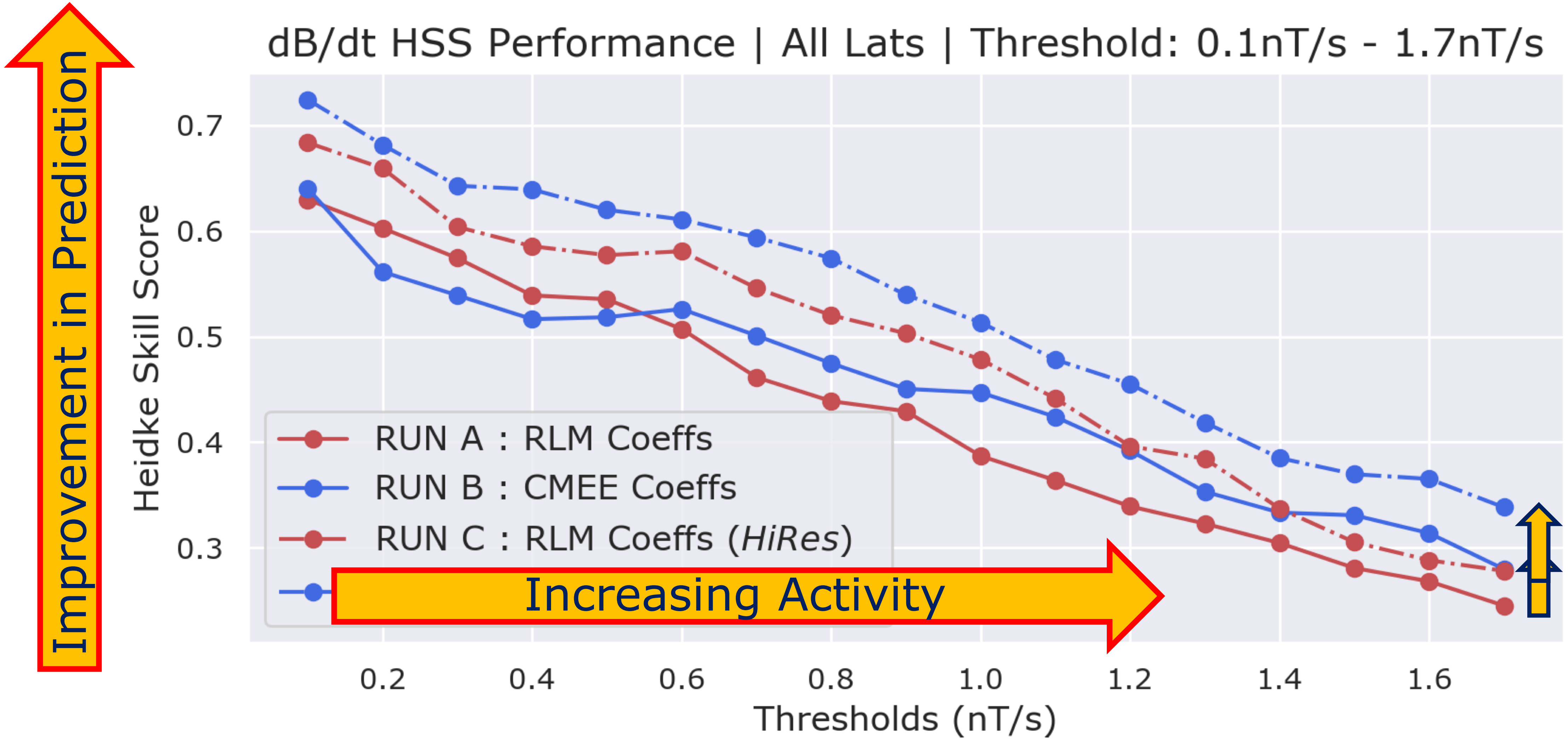
$$= \frac{\text{False Alarms}}{\text{False Alarms} + \text{False Negatives}}$$

Heidke Skill Score (HSS)

$$= \frac{(\text{Hits} + \text{False Negative}) - (\text{Expected Correct})}{(\text{Perfect Score}) - (\text{Expected Correct})}$$

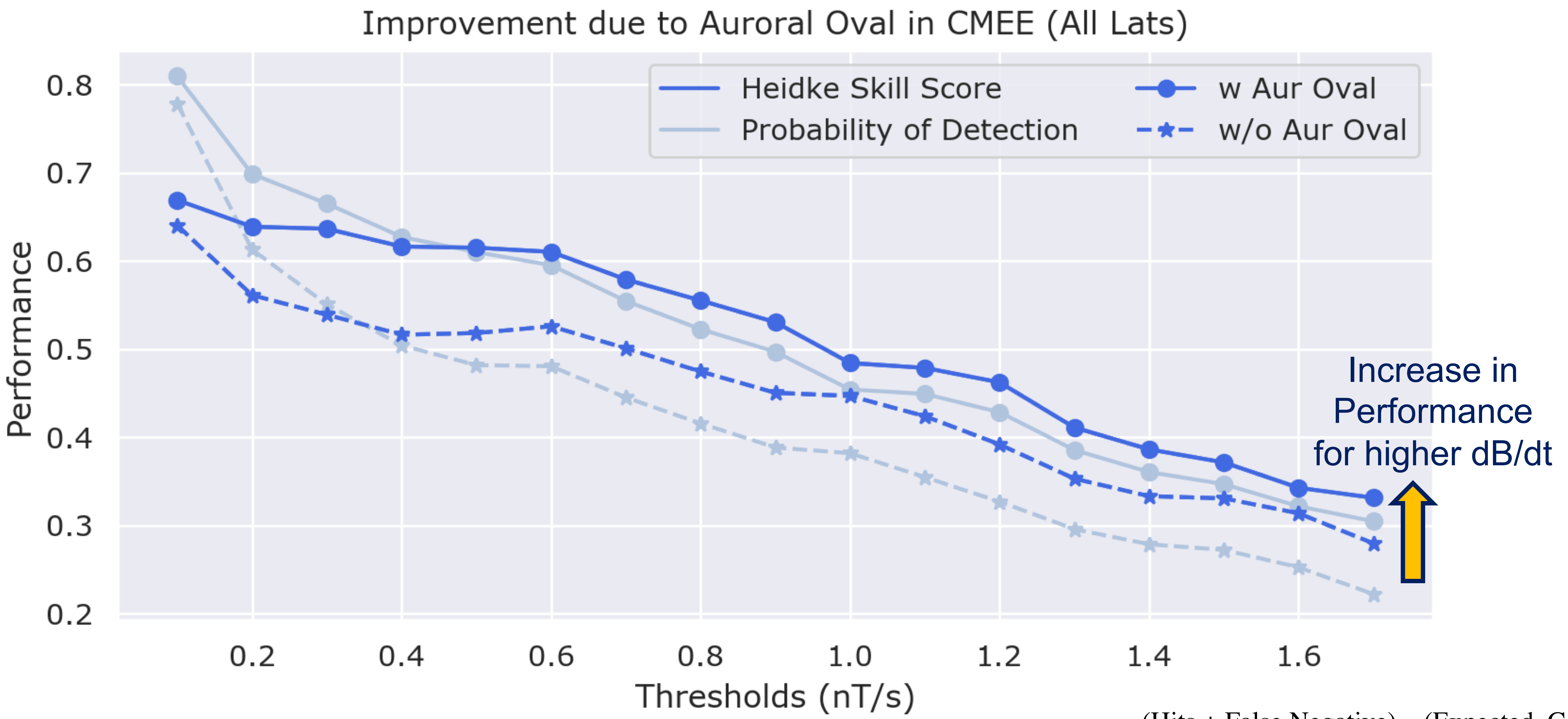
Changing Coefficients Only

SWMF - CMEE



Addition of an Auroral Oval Enhancement

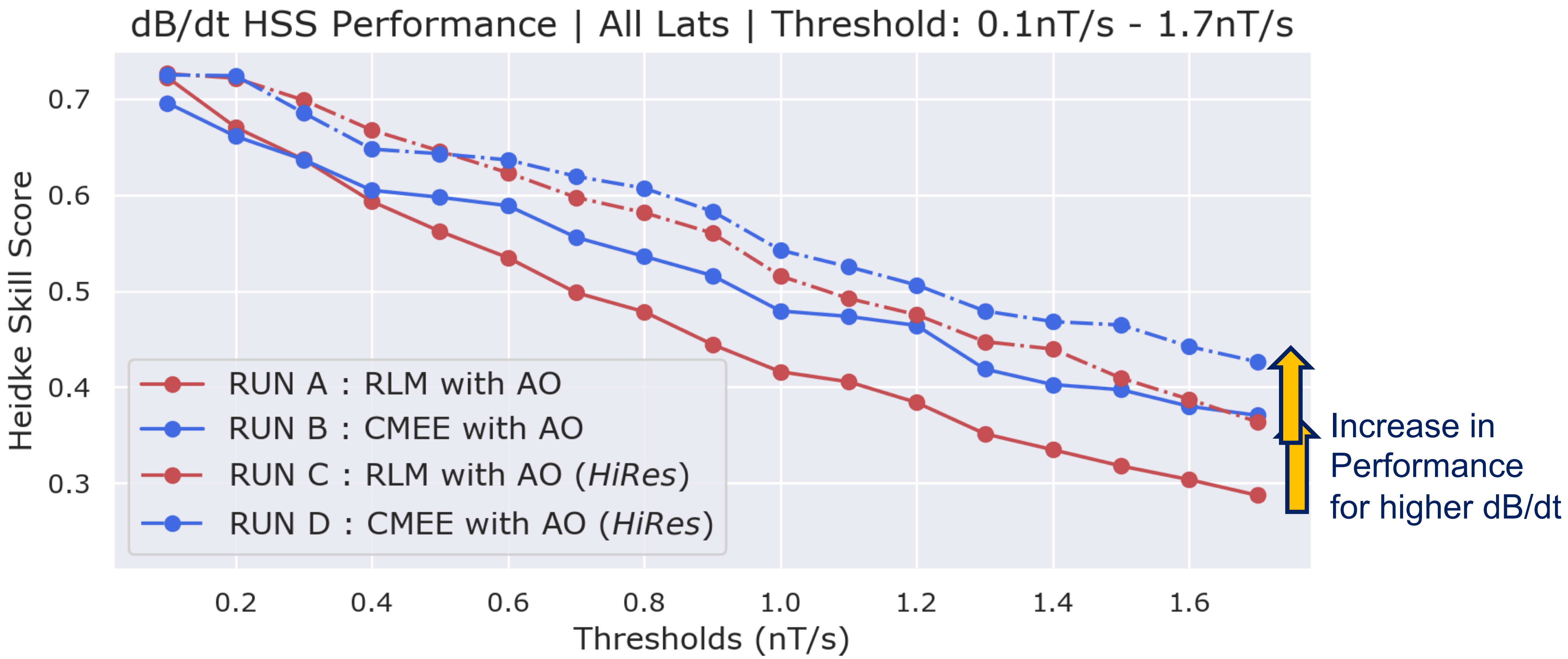
SWMF - CMEE



$$\text{Heidke Skill Score (HSS)} = \frac{\text{(Hits + False Negative)} - \text{(Expected Correct)}}{\text{(Perfect Score)} - \text{(Expected Correct)}}$$

Combining Models...

SWMF - CMEE



$$\text{Heidke Skill Score (HSS)} = \frac{\text{(Hits + False Negative)} - \text{(Expected Correct)}}{\text{(Perfect Score)} - \text{(Expected Correct)}}$$

Mukhopadhyay et al. (2020*)

MAGNIT | MAGNetosphere-Ionosphere-Thermosphere Conductance Model

1. Auroral Precipitation Derived Directly From Global Quantities

Pressure and density from MHD mapped onto aurora to provide isotropic temperature, in order to find first and third order moments, with direct flux transfer available from ring current

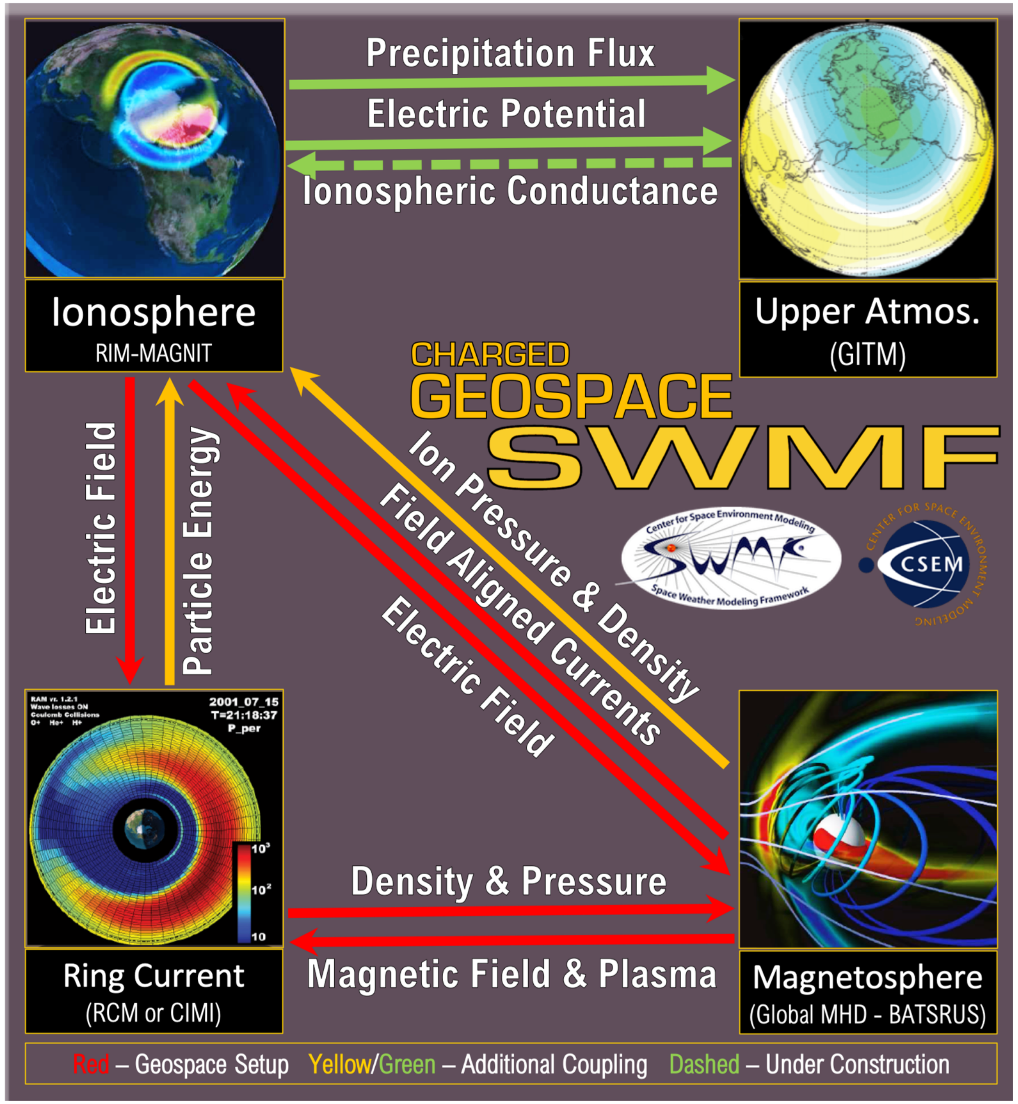
(e.g. *Fedder et al. 1995, Wiltberger et al. 2009, Gilson et al. 2012, Zhang et al. 2015*. Within SWMF by *Yu et al. 2016, Perlongo et al. 2017*)

2. Dynamic Boundary Conditions

Mapping of fluxes conducted through the field-line tracing program used for coupling between ring current and global MHD model. Dynamic open-closed FL and equatorward boundary.

3. Source Balance + Impact of Surrounding

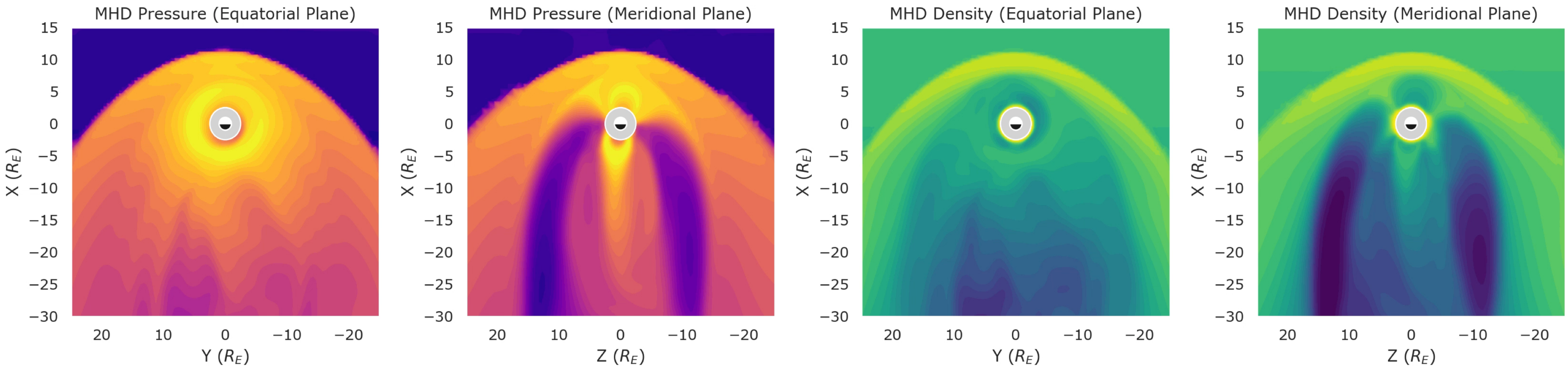
Present configuration allows a variety of auroral sources of precipitation (diffuse, monoenergetic, broadband, etc.) for different distribution functions (Maxwellian, Lorentzian) with direct/indirect contribution by ring current and numerical resolution.



Mukhopadhyay et al. 2018, 2019, AGUFM

MAGNIT

Dynamic Boundaries

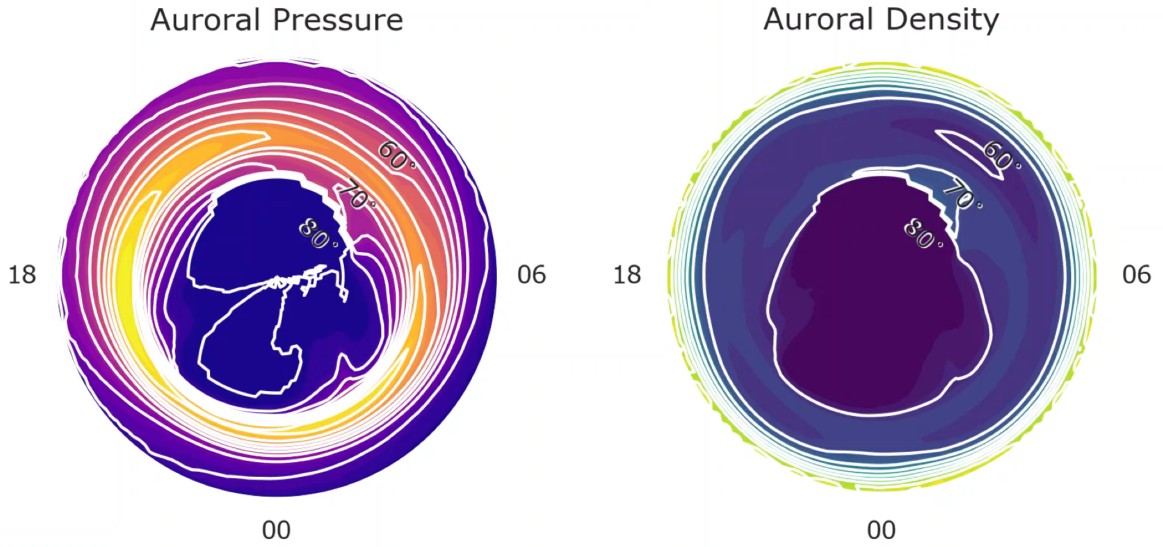


➢ Fieldline Tracing

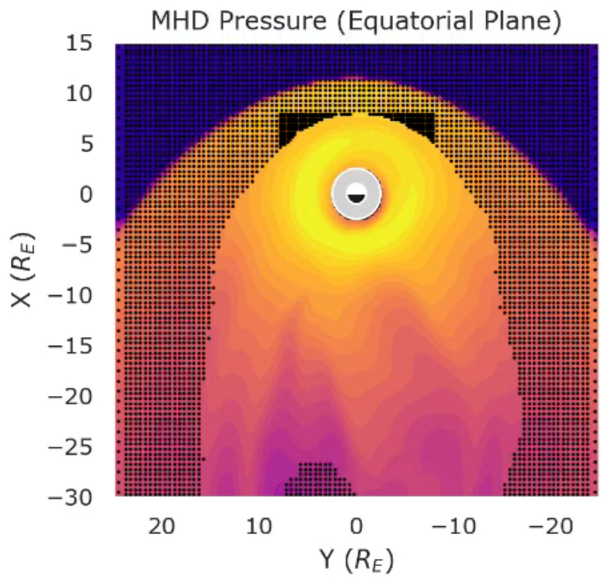
Both equatorward and poleward boundaries are defined using knowledge of open and closed magnetic fieldlines throughout MHD domain (DeZeeuw et al. 2004).

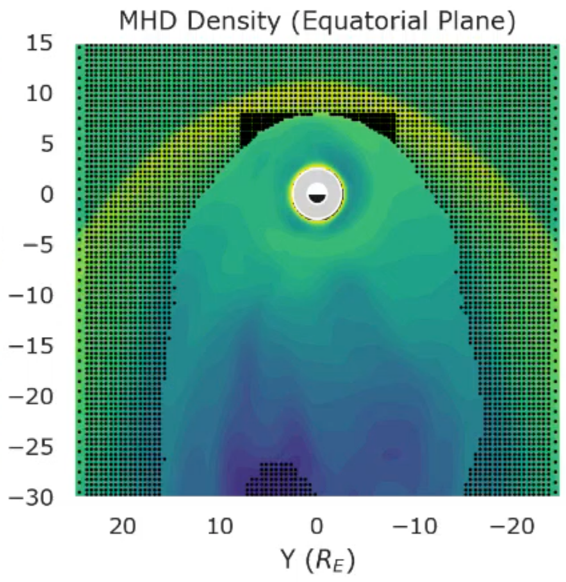
➢ Poleward OCFLB

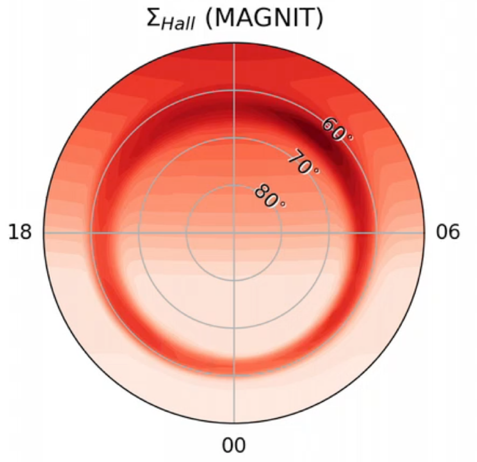
Poleward boundary is specifically defined as the boundary between open and closed field lines. This boundary is dynamic in nature and changes rapidly with time and activity.

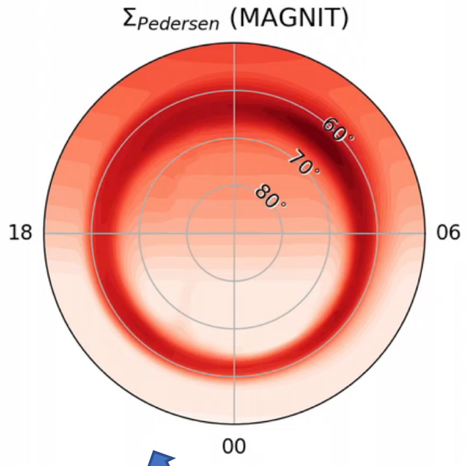


Fluxes & Conductances

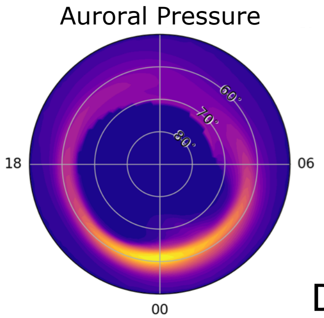




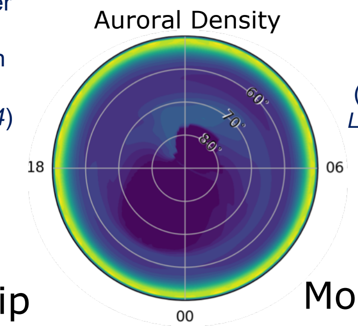




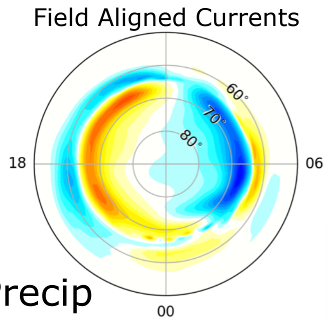
As input to other models: UA, PW. [Burleigh et al. 2019 AGUFM]



First and Third Order Moment of Temperature-driven M-B Distribution (e.g. *Gombosi, 1994*)



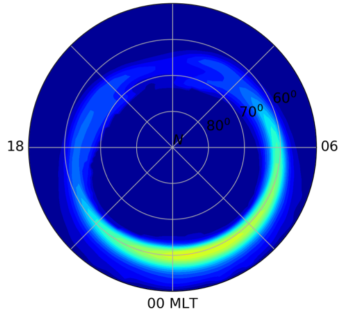
First and Third Order Moment, with parallel field acceleration (*Knight, 1973; Fridman & Lemaire, 1980; Liemohn & Khazanov, 1998*)



Within Ridley Ionosphere Model

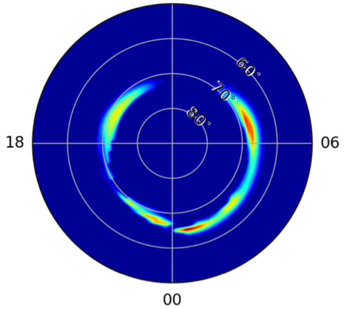
Conversion of fluxes into conductances (*Robinson et al. 1987, Galand and Richmond, 2001 Kaeppler et al. 2015*)

Diffuse Precip



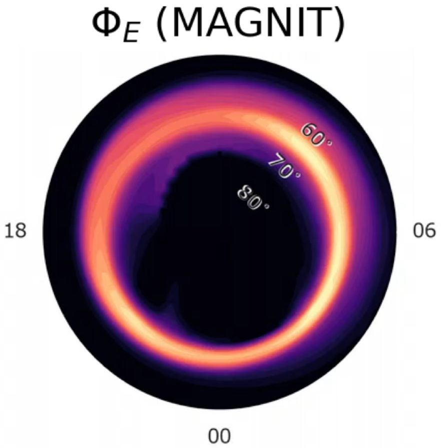
Both source of precipitation are combined.

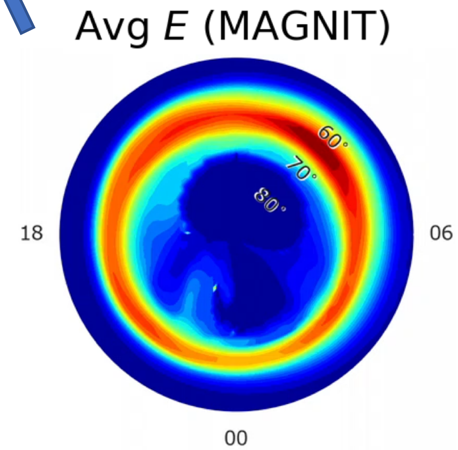
Monoenergetic Precip



Total precipitation is computed

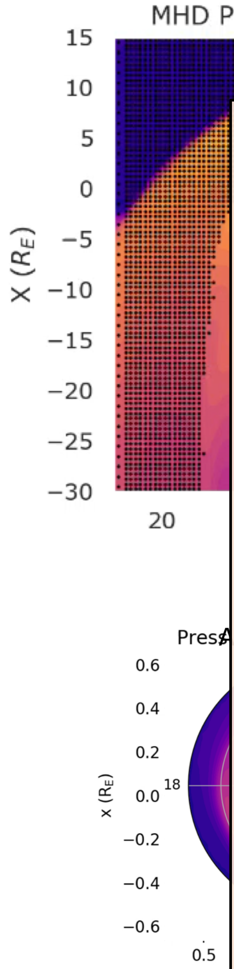
Ring Current Precipitation may be added here.





MAGNIT

Fluxes & Conductances



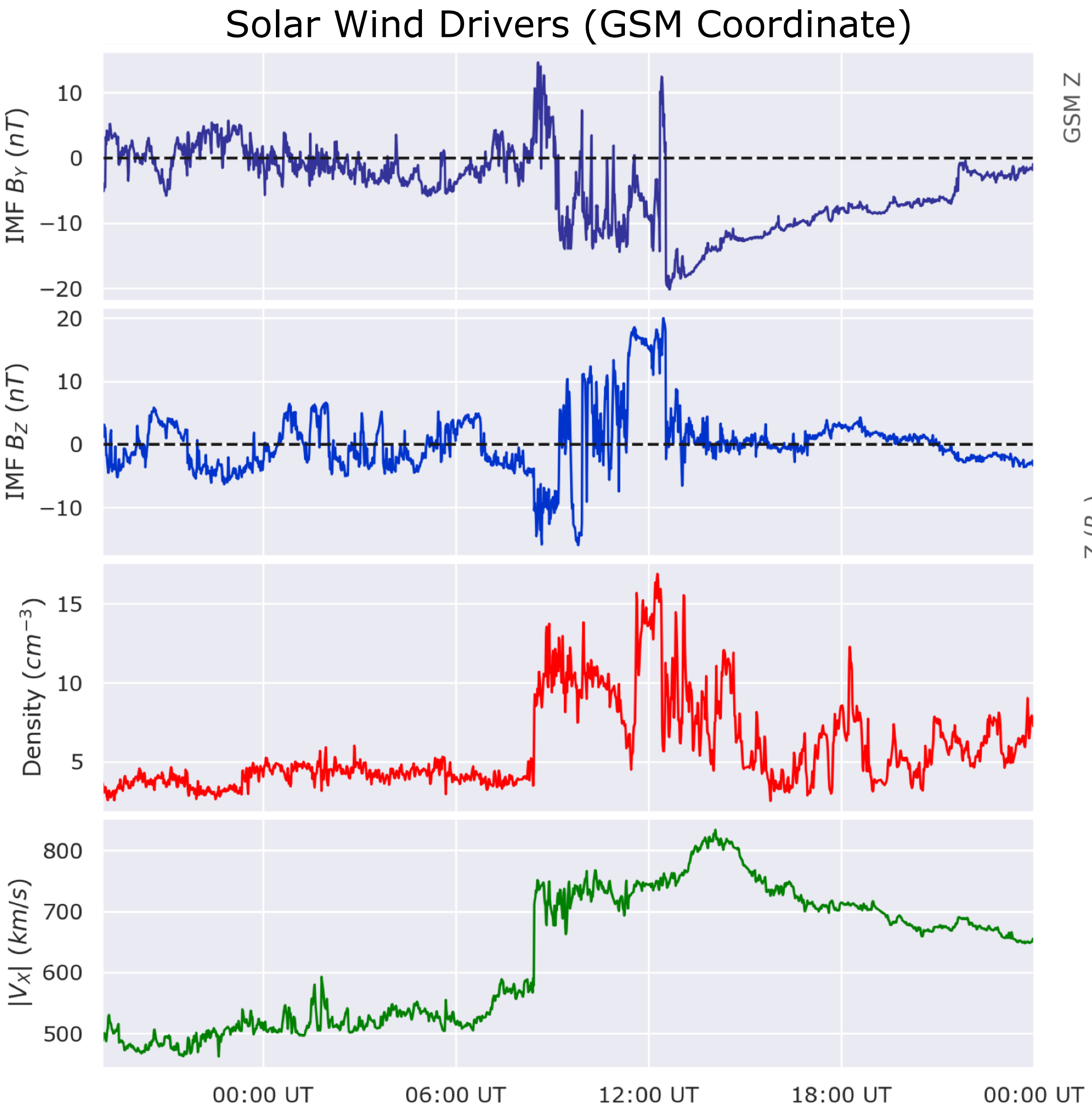
As input to other models: UA, PW. [Burleigh et al. 2019 AGUFM]

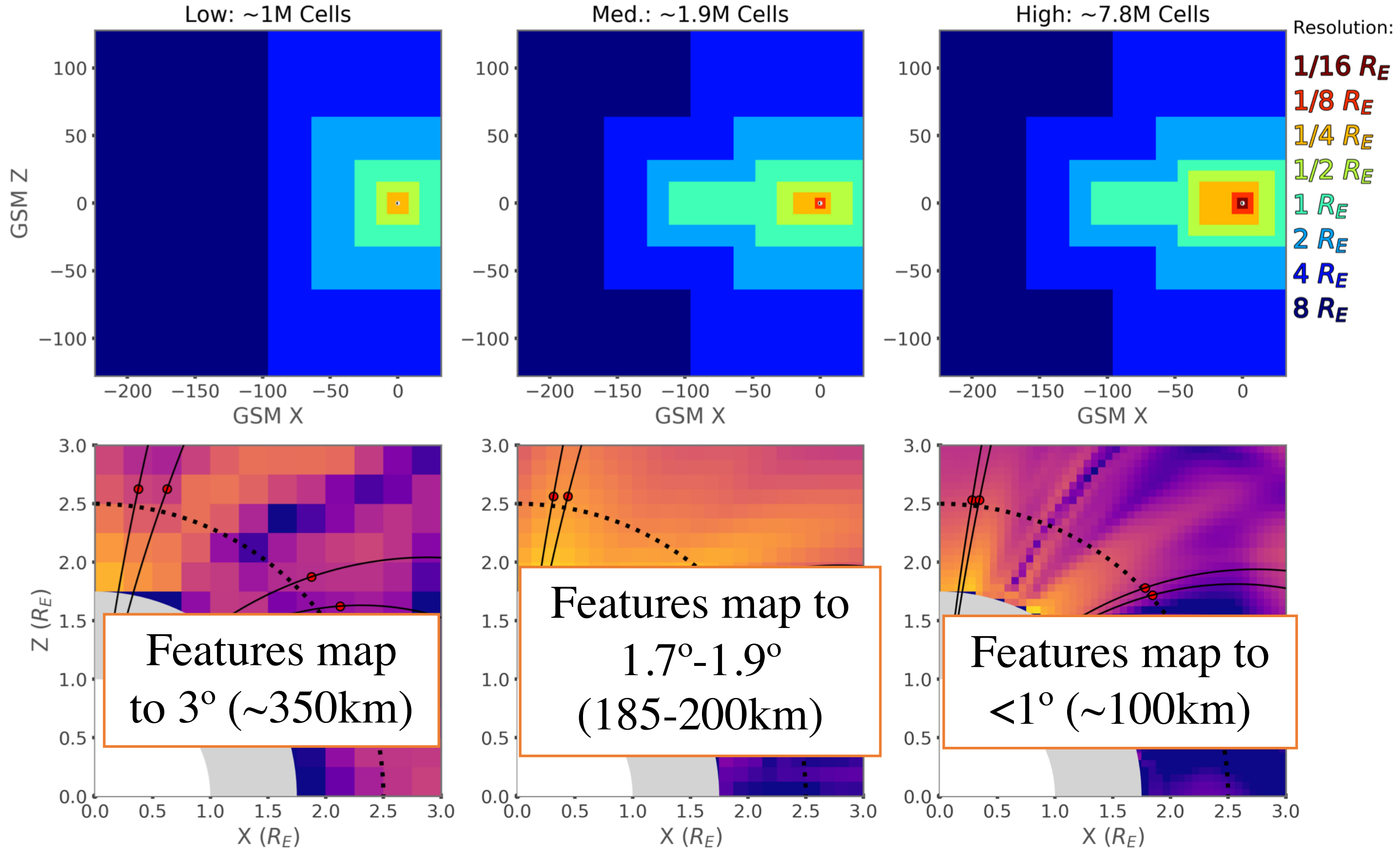
Summary:

- MAGNIT drives precipitation from global MHD and (optional) ring current model to derive auroral conductance.
- Unlike RLM and CMEE, the model is ***not*** empirically-driven and is able to calculate precipitation from multiple sources.
- Boundaries are *not* hard-set or empirically-set. Instead uses additional information from global models for assignment.
- **Spatial Resolution** of both global domain and ionospheric domain would play a role in the *strength* of precipitative flux
- **Ring current** pressure tweaking + flux loss would play a role in defining auroral pattern and strength

MAGNIT

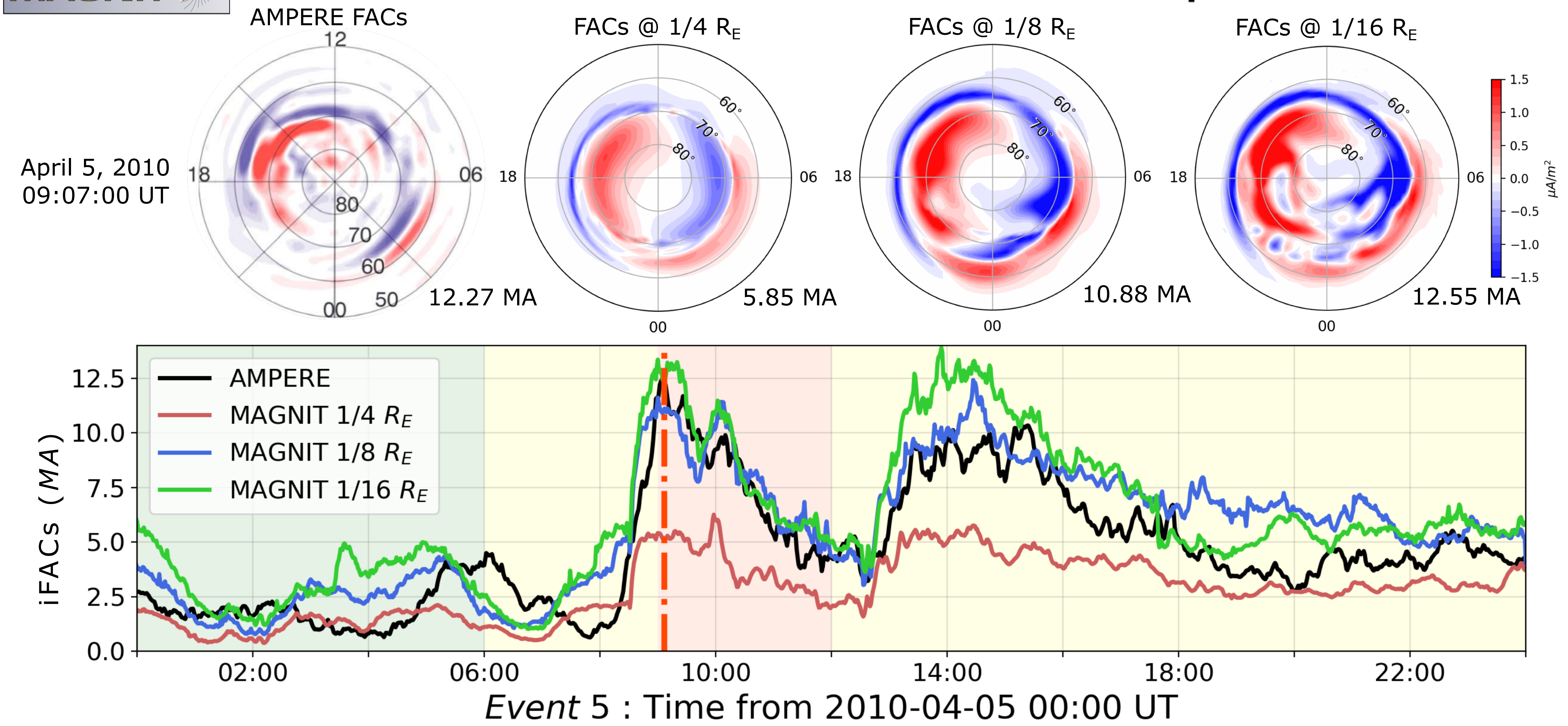
Galaxy15 - April 2010 Event





- **3 Resolutions:** 1/4 (Operational Version), 1/8 and 1/16 R_E. IE resolution kept at $2^0 \times 2^0$
- **Decouple IM:** Simulate with and without using RCM.
- **Electron Precipitation only:** Diffuse + Discrete Precipitation. Loss Cone assumes 100% precipitation.

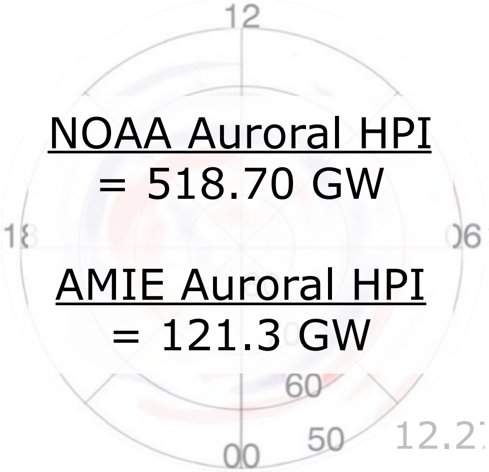
Impact of Resolution



Impact of Resolution

April 5, 2010
09:07:00 UT

AMPERE FACs

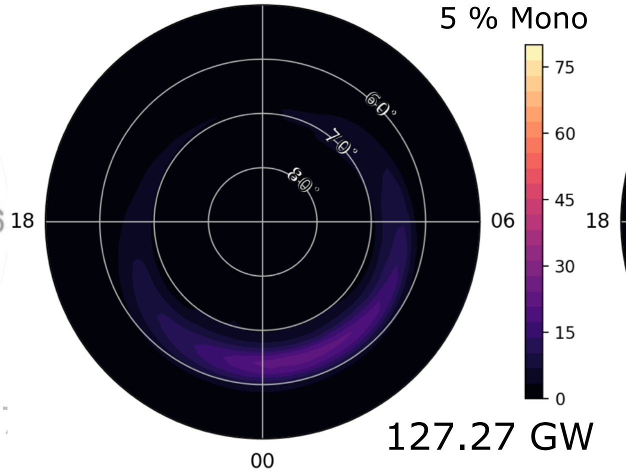


NOAA Auroral HPI
= 518.70 GW

AMIE Auroral HPI
= 121.3 GW

EFlux @ 1/4 R_E

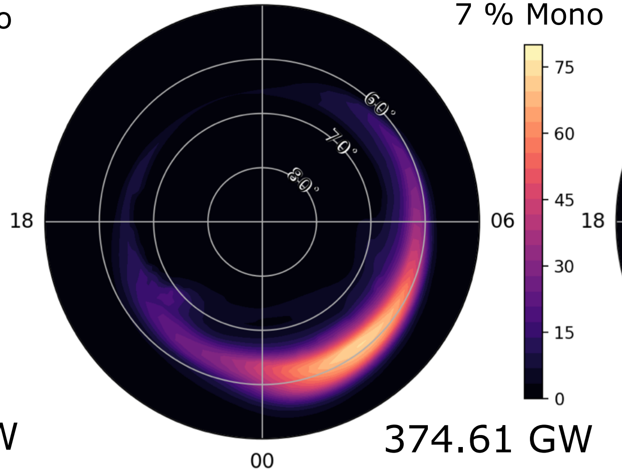
95% Diffuse
5 % Mono



127.27 GW

EFlux @ 1/8 R_E

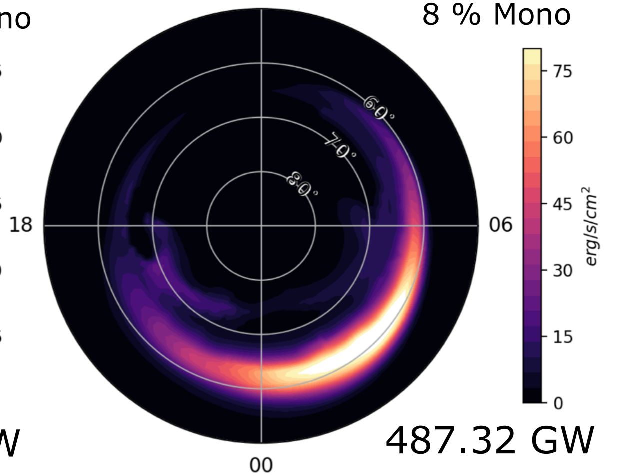
93% Diffuse
7 % Mono



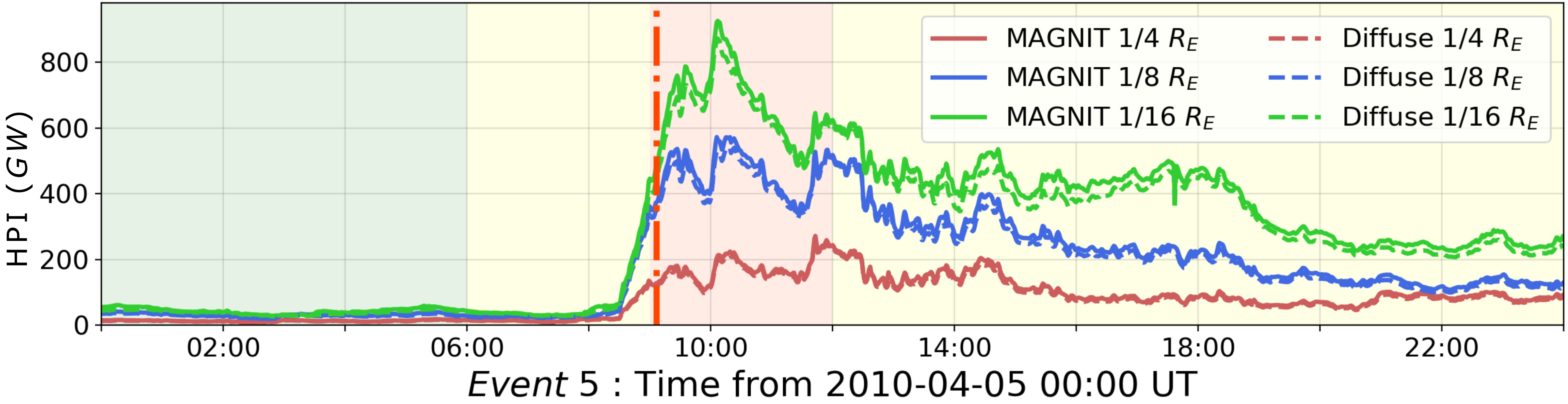
374.61 GW

EFlux @ 1/16 R_E

92% Diffuse
8 % Mono



487.32 GW



MAGNIT

Impact of Resolution

April 5, 2010
09:07:00 UT

In general, increasing spatial resolution leads to:

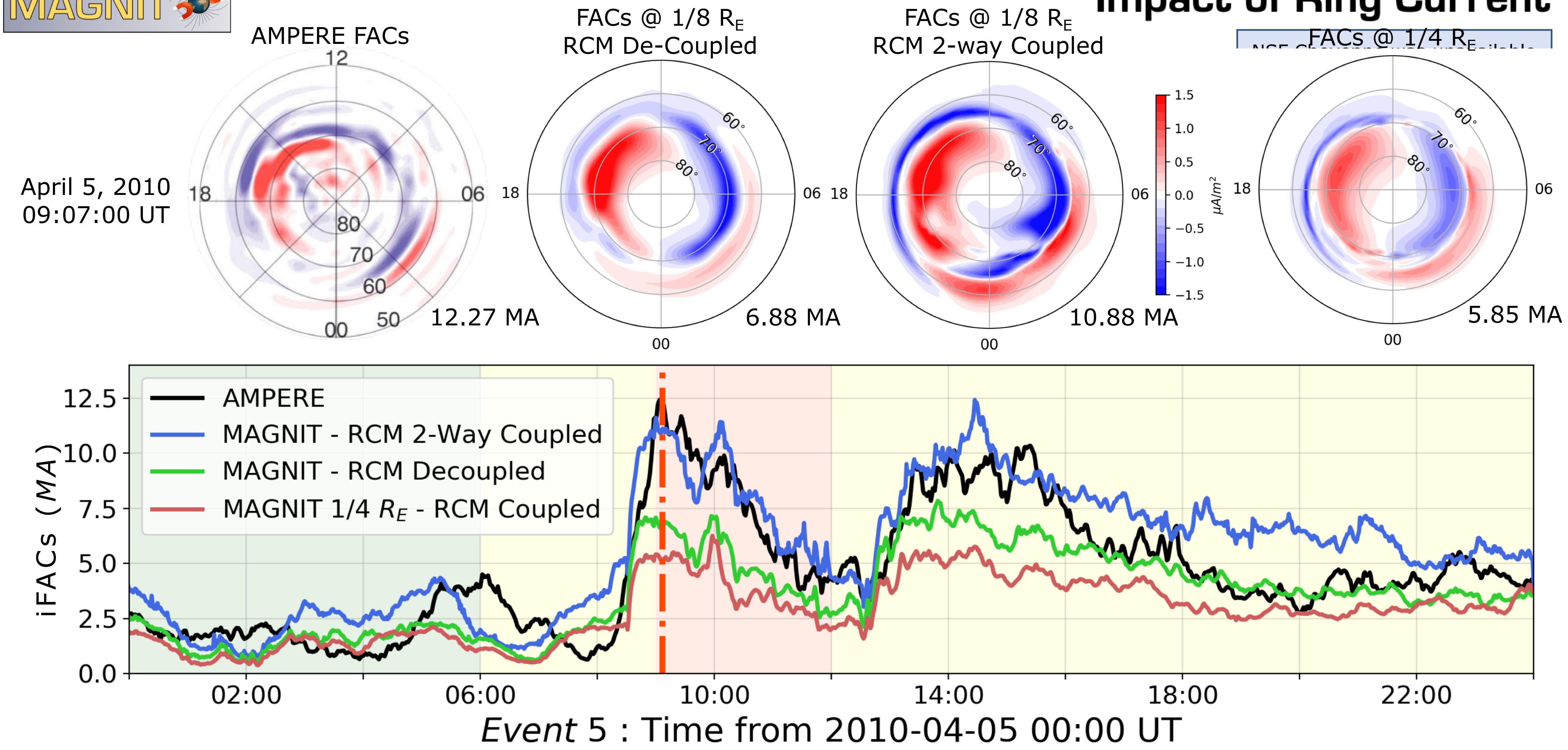
- Stronger and sharper features of currents & conductance
- Increased nightside pressure, which allows for higher diffuse precipitation.
- Higher discrete flux due to stronger currents.
  (As expected from results by Wiltberger et al. 2017, Welling et al. 2019 AGUFM)
- No substantial change in ionospheric potential.

Critical Lesson: *Variation of Loss Cone Factor is key for accurate conductance over increasing resolution.*

HPI (GW)

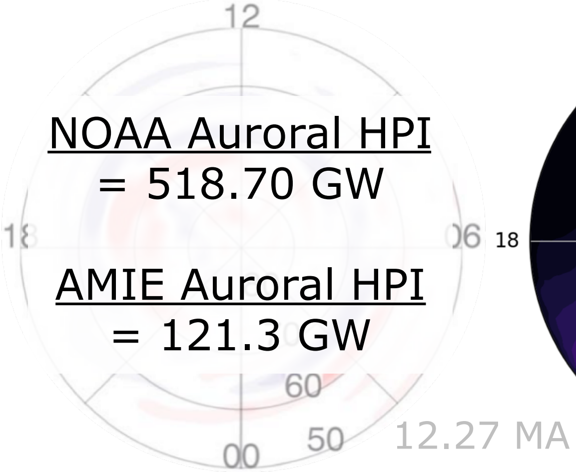
Event 5 : Time from 2010-04-05 00:00 UT

Impact of Ring Current



Impact of Ring Current

April 5, 2010
09:07:00 UT

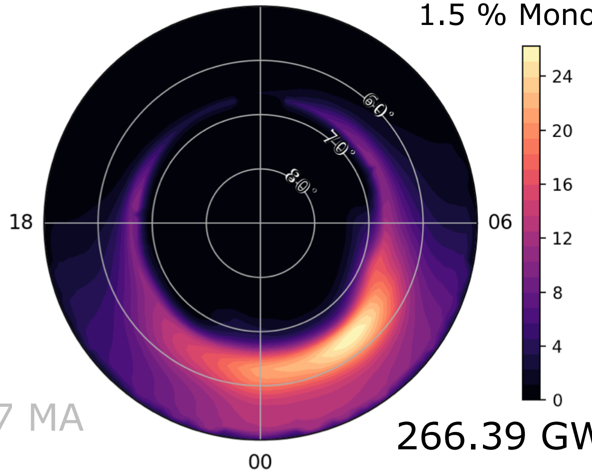


NOAA Auroral HPI
= 518.70 GW

AMIE Auroral HPI
= 121.3 GW

EFlux @ 1/8 R_E
RCM De-Coupled

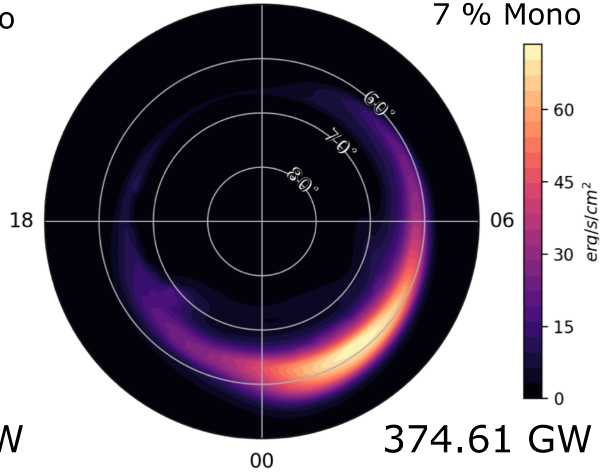
98.5% Diffuse
1.5 % Mono



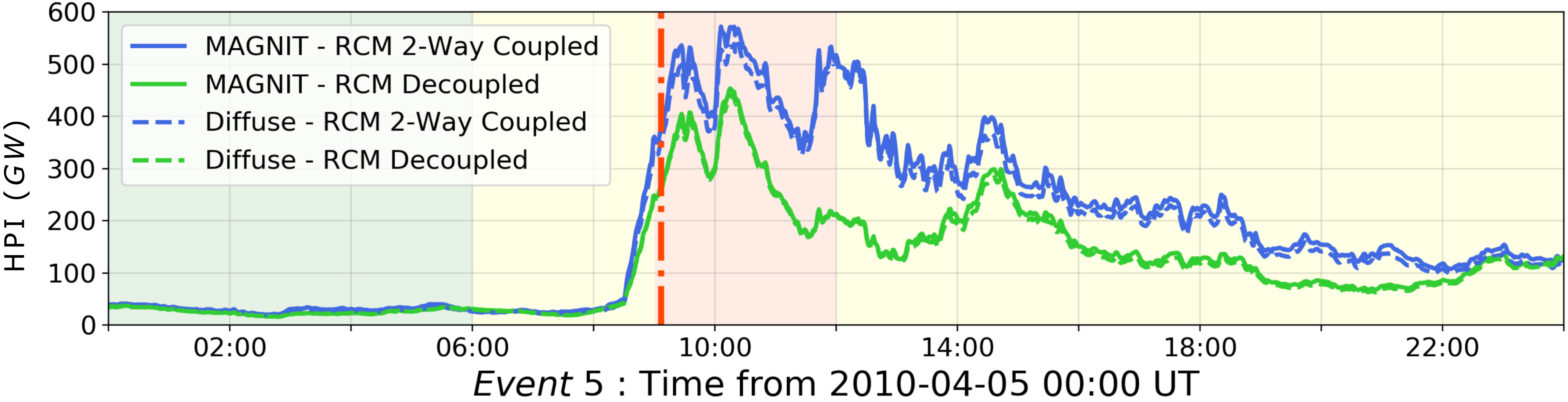
266.39 GW

EFlux @ 1/8 R_E
RCM 2-way Coupled

93% Diffuse
7 % Mono

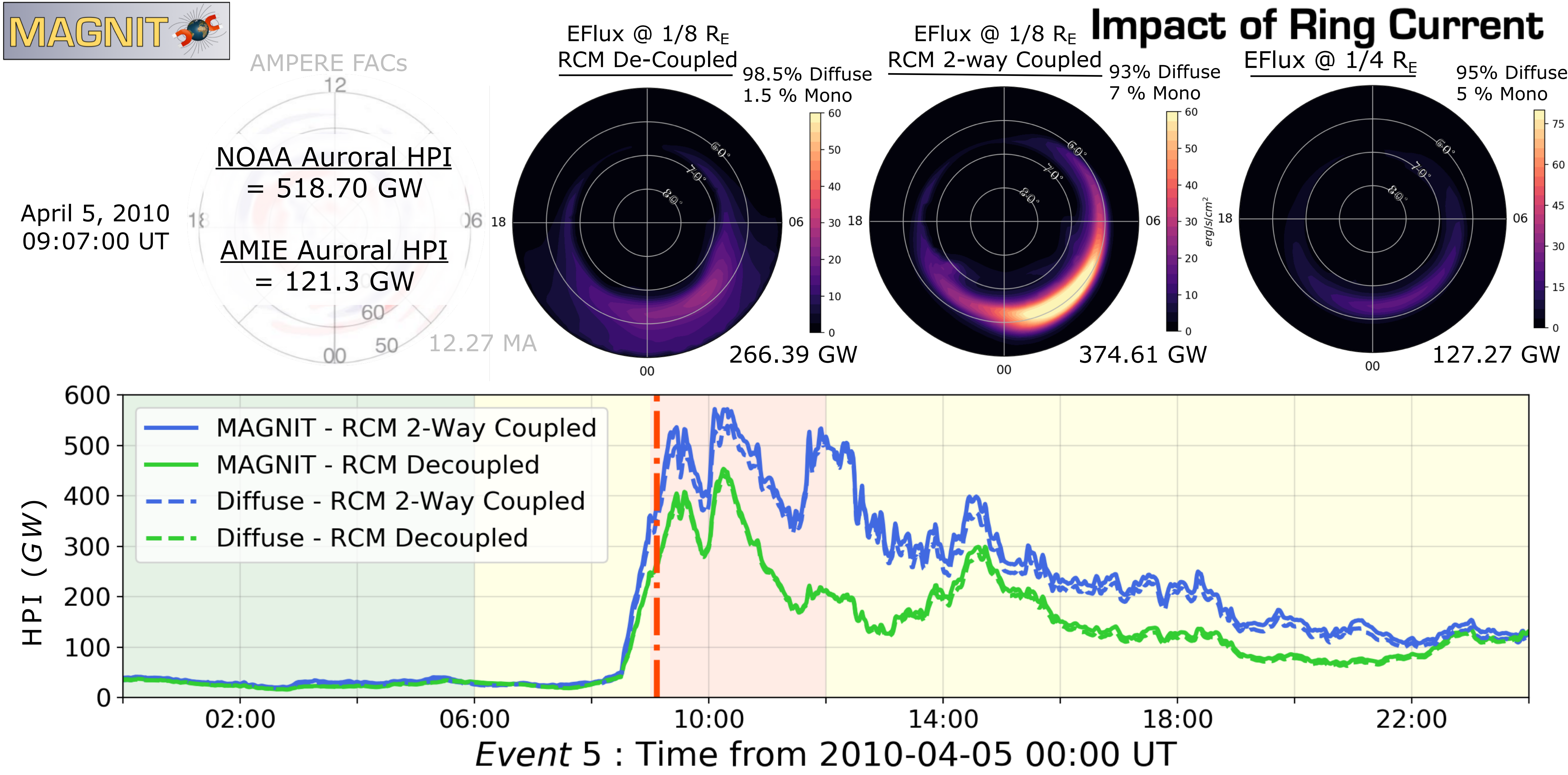


374.61 GW

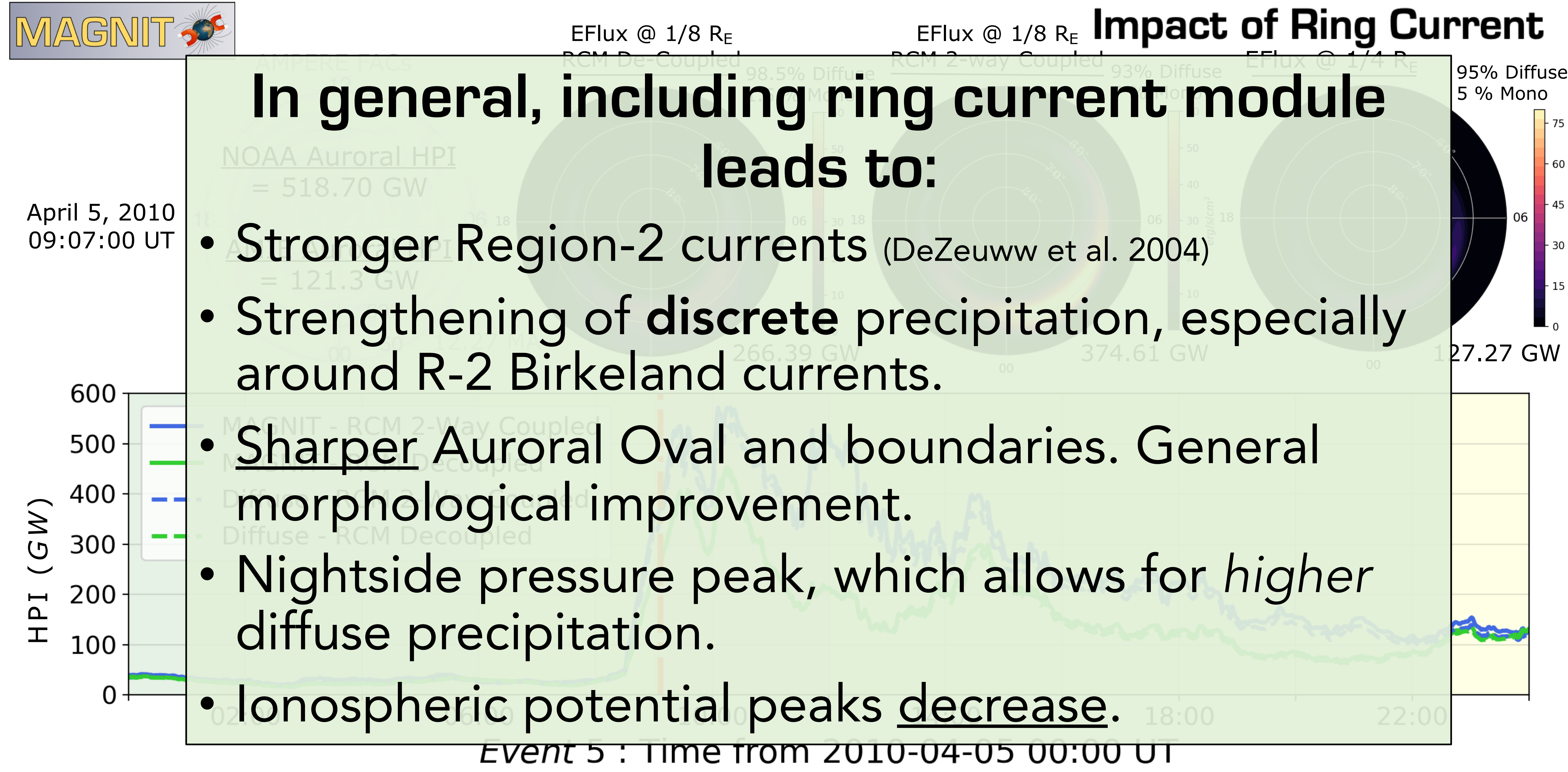


Impact of Ring Current

April 5, 2010
09:07:00 UT



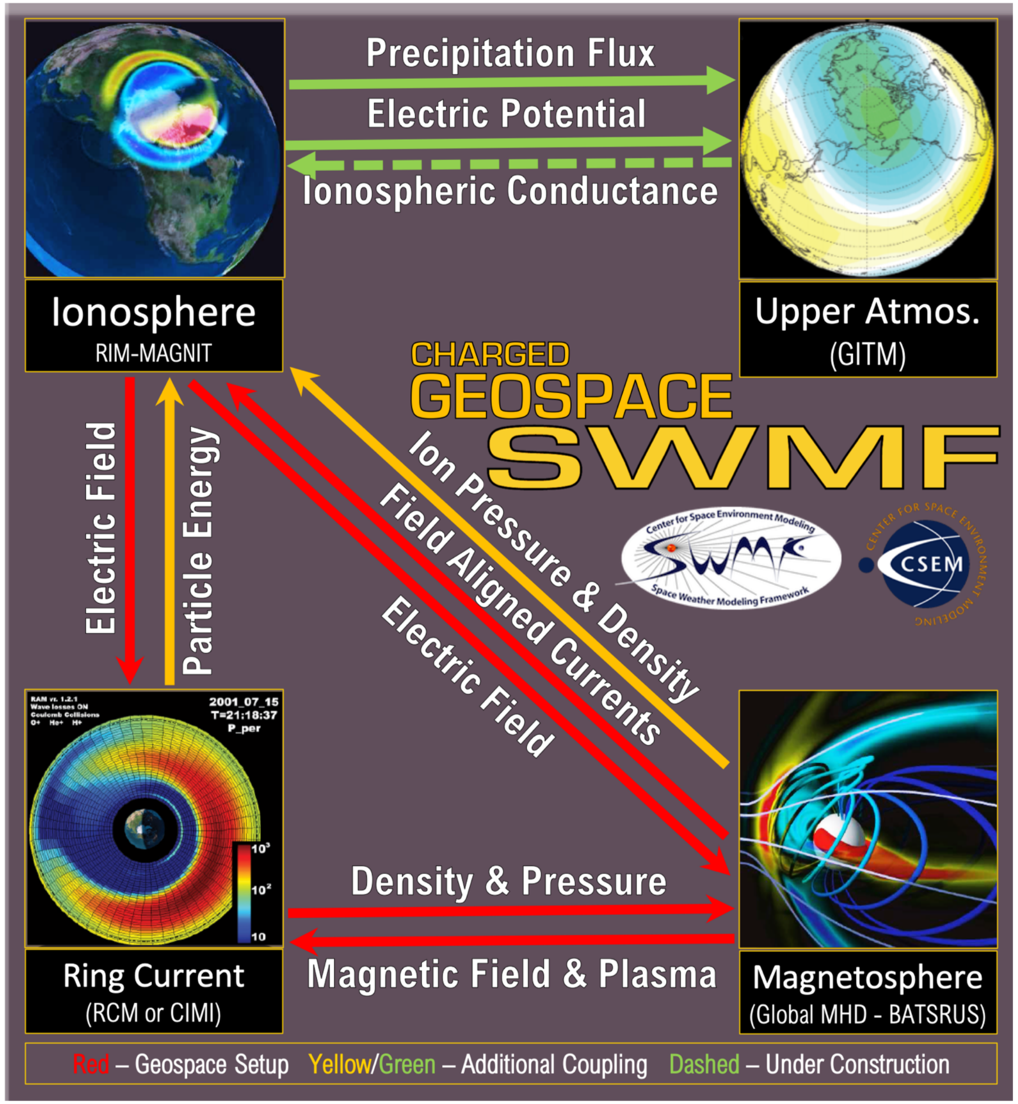
Impact of Ring Current



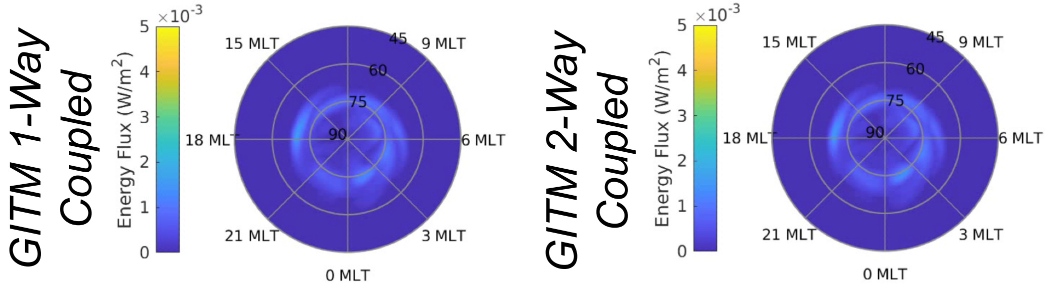
In general, including ring current module leads to:

- Stronger Region-2 currents (DeZeuww et al. 2004)
- Strengthening of **discrete** precipitation, especially around R-2 Birkeland currents.
- Sharper Auroral Oval and boundaries. General morphological improvement.
- Nightside pressure peak, which allows for *higher* diffuse precipitation.
- Ionospheric potential peaks decrease.

Near - Future Developments

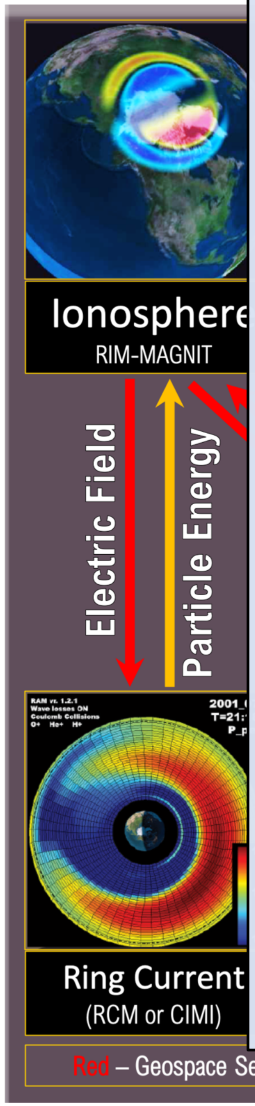


- Add <u>more sources</u> that impact auroral precip:
  - **Distribution Functions** – Deriving the precipitation using Lorentzian-κ distribution functions (*Liemohn & Khazanov, 1998*). Accounts for 37% of total flux (*McIntosh & Anderson, 2014; Connor et al. 2016*)
  - **Broadband precipitation** – Accounts for 30% of total precip [*Zhang et al. 2015*], can be derived from the Alfvenic Poynting Flux (*Yu et al. 2011, Zhang et al. 2012a,b, 2015*)
  - **Anomalous resistivity** – Localized pockets of high electric fields causes superheating of electrons, and increases conductance (*Wiltberger et al. 2017*).
- <u>**2-way coupling with GITM**</u> to receive realistic ionospheric conductance (*Burleigh et al., AGUFM 2019; CEDAR 2020; manuscript in prep*) while providing realistic auroral precipitation from MHD-driven simulation.



Burleigh et al. 2020, CEDAR

Near - Future Developments



AGU Session SA016

AGU FALL MEETING
Online Everywhere | 1–17 December 2020

Recent Advances in Characterizing the Ionospheric Conductance

Convener – *Meghan Burleigh*
Co-Convener(s) – *Agnit Mukhopadhyay, Doga can su Ozturk*

The characterization of the ionospheric conductance is fundamental for understanding the electrodynamics of the coupled magnetosphere-ionosphere-thermosphere system. It is not possible to directly quantify the ionospheric conductance, therefore its characterization relies on numerical models and measurements of parameters, that drive the changes in the conductance patterns. This session aims to bring together experts in different disciplines to address how ionospheric conductance and its drivers vary (1) across different spatial and temporal scales, and (2) with different levels of geomagnetic activity. The session encourages presentations on novel methodologies that include but are not limited to modeling experiments, data-model comparisons, multi-platform data analyses of in-situ or remote-sensing measurements, and increased instrument capabilities to answer the aforementioned questions.

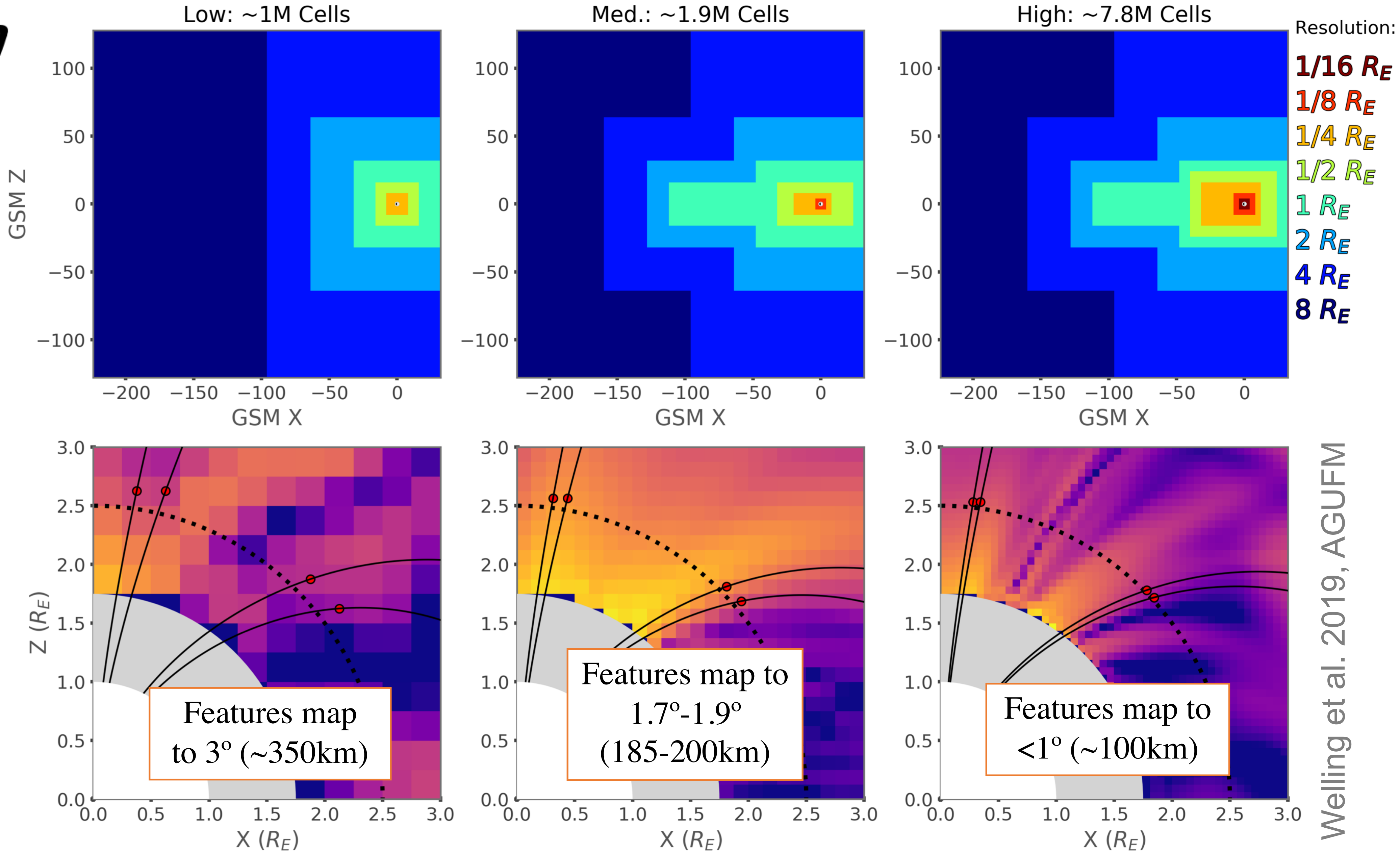
Thank You

Special Thanks to *Dr. Doga Ozturk, Dr. Gabor Toth, Dr. Steve Morley, Dr. Robert Robinson, Dr. James Slavin, Dr. Tuija Pulkkinen, Dr. Tamas Gombosi, Dr. Abigail Azari, Mr. Brian Swiger, Mr. Christopher Bert, Dr. Natalia Ganjushkina & Dr. Lutz Rastaetter* for their advice and support.

This work is being funded by the *NASA Earth and Space Sciences Fellowship (NESSF) Program*, the *NSF PREEVENTS Program* and the *LANL LDRD Program*.

Resolution

- Low 1M cells (LoRes – 1/4 RE) Operationally used at SWPC.
- Med 2M cells (HiRes – 1/8 RE) To be used soon in operations; workhorse sim domain in this study.
- High ~8M cells (SuperHiRes – 1/16 RE) Highest resolution being used.
- Two IE resolut-ions available – $2^0 \times 2^0$ & $1^0 \times 1^0$



Galaxy15 - April 2010 Event - FACs