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Developing an Empirical Model of Auroral Boundaries

Angeline G. Burrell[1]
Gareth Chisham[2] , Bruce Fritz[1], Kate Zawdie[1]

1: Naval Research Laboratory, Space Science Division, DC USA
2: British Antarctic Survey, Cambridge UK

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Outline

- Motivation
  - Background
  - Objective
- Boundary Data
  - Potential Observations
  - Individual Data Sets
- Boundary Model Construction
  - Data selection and weighting
  - Driver selection
  - Model formulation
- Products
  - Improved Gridding Data Sets
  - Boundary Identification Tool
- Conclusions
- Current and Future Work
- Acknowledgements

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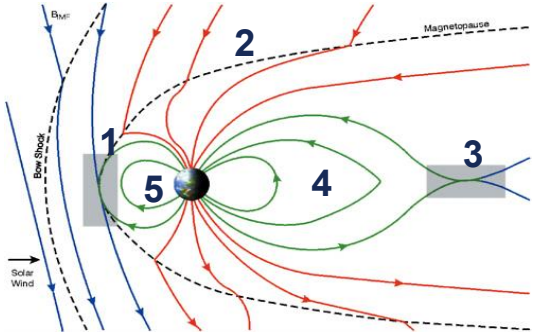
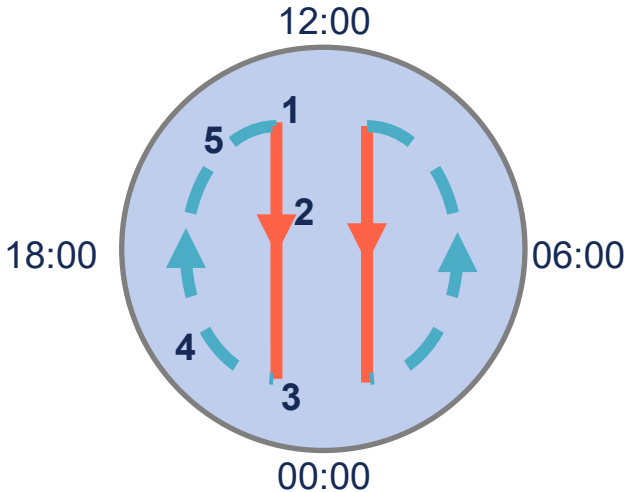
Motivation

- High latitude M-I coupling varies based on region:
  - Open field lines in the polar cap
  - Closed field lines in the auroral oval, high L-shells
  - Closed field lines below the auroral oval, low L-shells
- Magnetic coordinates can't accurately separate these regions, as they change based on changes in the Interplanetary Magnetic Field (IMF)
- Gridding relative to the polar cap (Open-Closed field line Boundary, OCB) and auroral oval (Equatorward Auroral Boundary, EAB) can improve modelling and statistical studies
- Providing EAB and OCB locations to ionospheric models can improve our high latitude specifications and magnetospheric coupling

Top: Plasma Physics of the Local Cosmos (2004)





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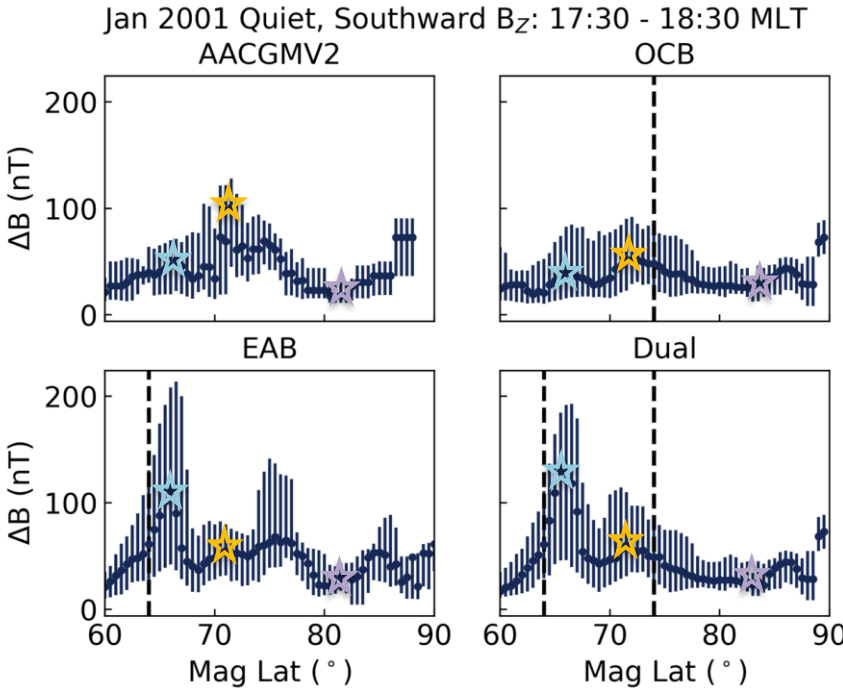
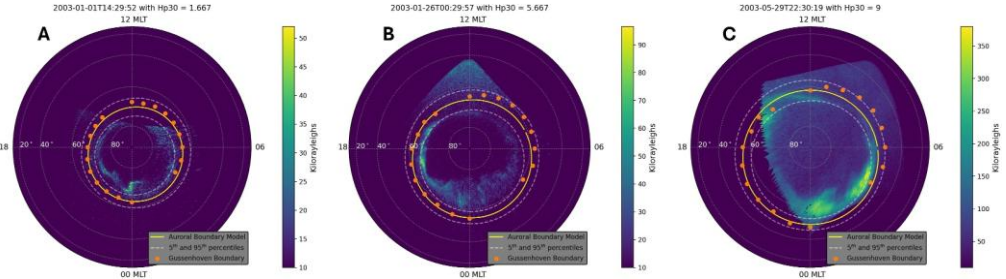
Adaptive Coordinate Systems

- The high latitudes at Earth consist of three physically distinct regions:
  - Polar cap
  - Auroral oval
  - Sub-auroral region
- Location of these regions change based on interactions between the solar wind and magnetosphere
- Treating the locations as static causes excessive smoothing and incorrect Atmosphere-Ionosphere-Magnetosphere (AIM) coupling
- Considering only one boundary is sufficient when in the polar cap or sub-auroral region

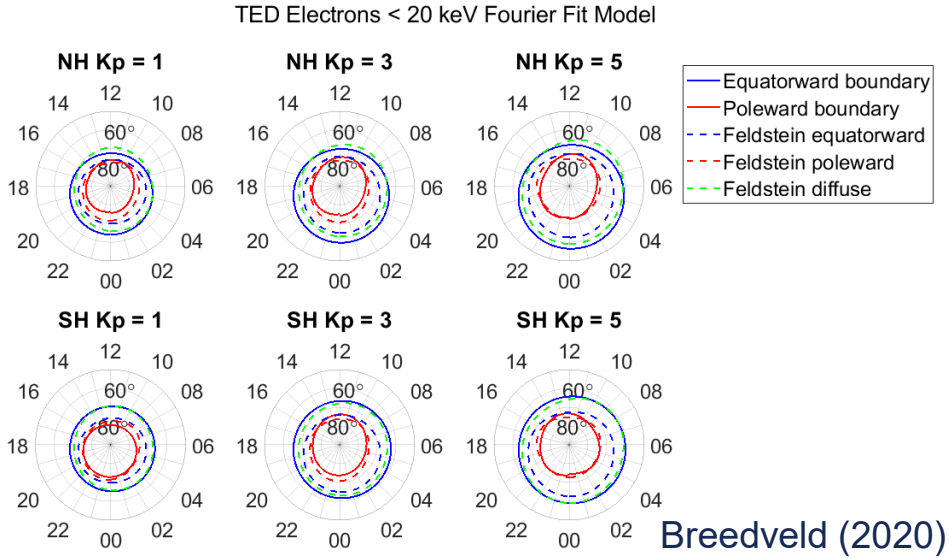


Goal: Model the OCB and EAB

- Requirements:
  - Available for public use
  - Specification of OCB and EAB in geodetic coordinates across all local times
  - Separate treatment for Northern and Southern hemispheres
  - Driven by appropriate solar and geomagnetic state specifications
  - Potentially provide an alternative version that can be driven by less-appropriate solar and geomagnetic state specifications that can be forecasted
- Current Options:
  - Models of auroral energy and probability
  - Models of particle precipitation
  - Private models of boundaries
  - Models of one boundary



Troyer et al. (2025)



Breedveld (2020)

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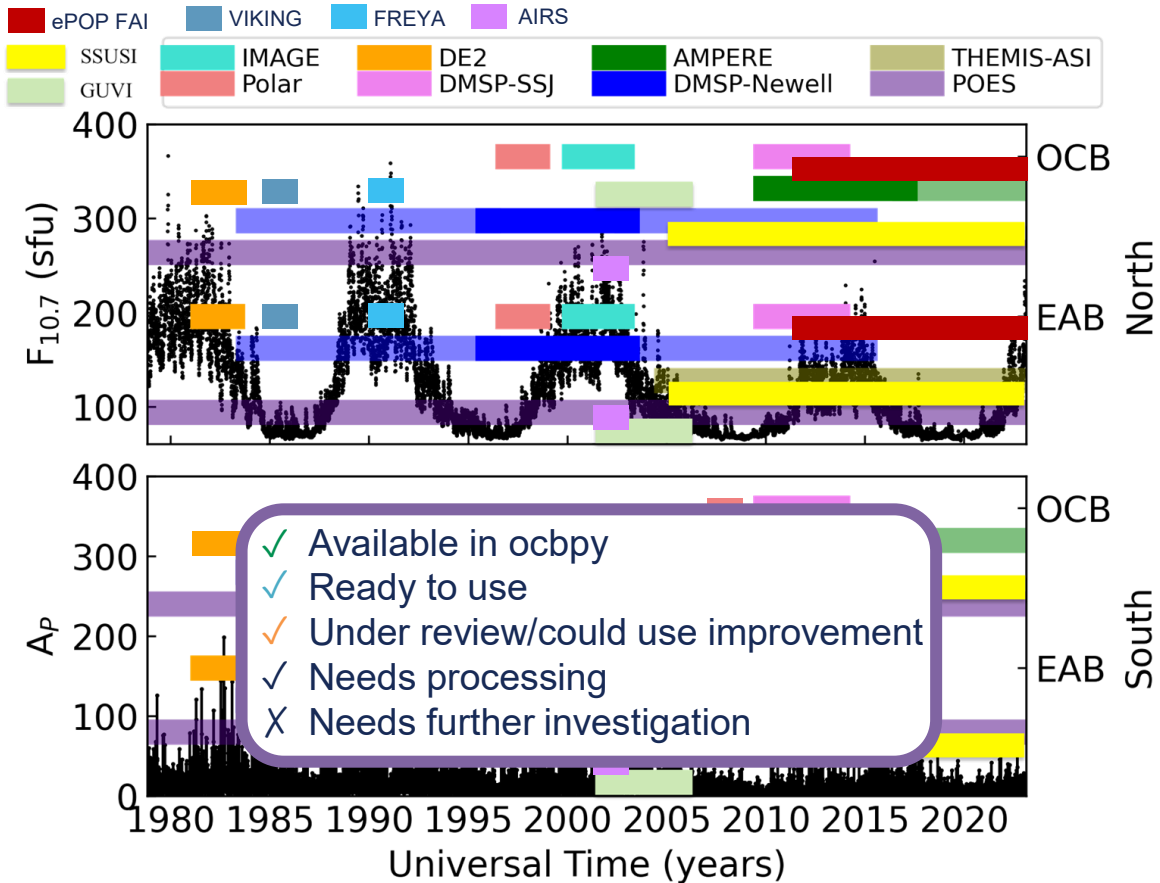
Potential Data for Boundary Model

High latitude boundary measurements

- ☑ DMSP: OCB and EAB from SSJ (Newell boundaries, Kilcommons boundaries)
- ☑ DMSP: IVM measures Convection Reversal Boundary (CRB) along satellite track
- ☑ DMSP: SSUSI measures the auroral luminosity boundaries (ALBs)
- ☑ TIMED: GUVI measures the ALBs
- ☑ DE-2: particle precipitation boundaries (EAB and OCB)
- ☒ POES: have been used to get OCB/EAB
- ☑ AMPERE: R1/R2 current boundaries or R1peak (related to OCB), R2 peak, Heppner-Maynard Boundary (HMB) proxy
- ☑ IMAGE: ALBs in three wavelengths
- ☑ POLAR: ALBs
- ☑ Ground-based All Sky Imagers (ASIs): ALBs
- ☒ SuperDARN: CRB, HMB
- ☒ SuperMAG: can identify magnetic fluctuations associated with FACs
- ☒ AIRS: CO_2 imaging identified auroral boundaries
- ☑ VIKING (Swedish): ALBs
- ☑ FREYA: ALBs
- ☑ ePOP FAI: ALBs



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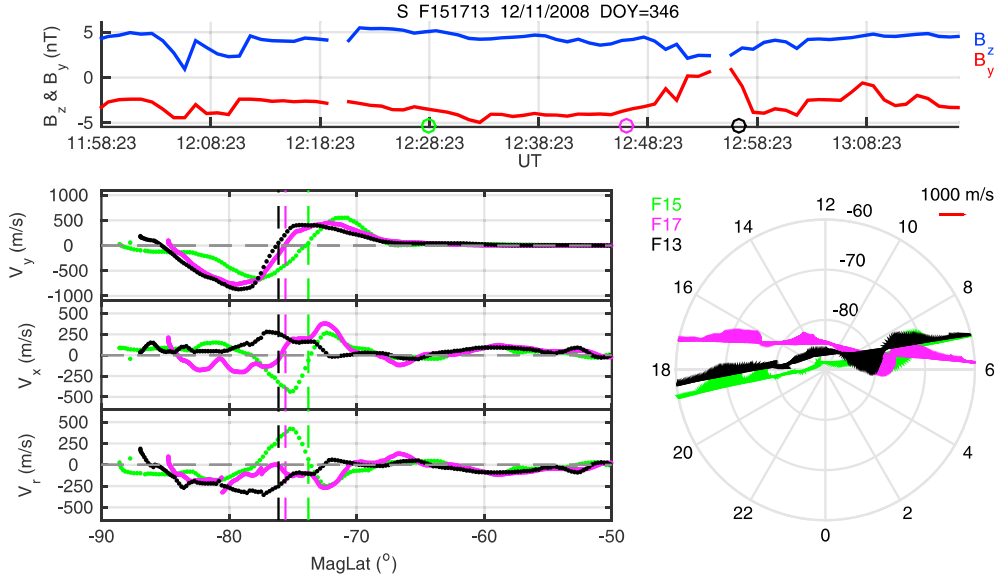
Boundary Data from DMSP IVM

- ✓ DMSP IVM (1998 – 2012)
  - Use the Ion Velocity Meter (IVM) to measure the cross-track drift and along-track in situ ion drift
  - Chen and Heelis (2017) describe the methodology used to produce this data set [source of figure]
  - Further work has produced an expanded data set that encompasses F11 – F18
  - *Useful for validating OCB near dawn and dusk MLT, where the two boundaries should move together*



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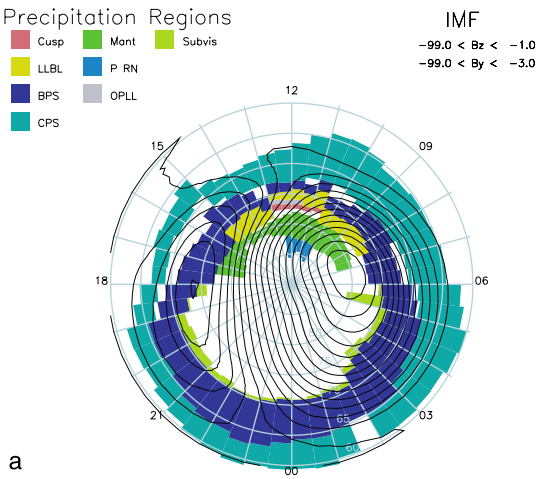
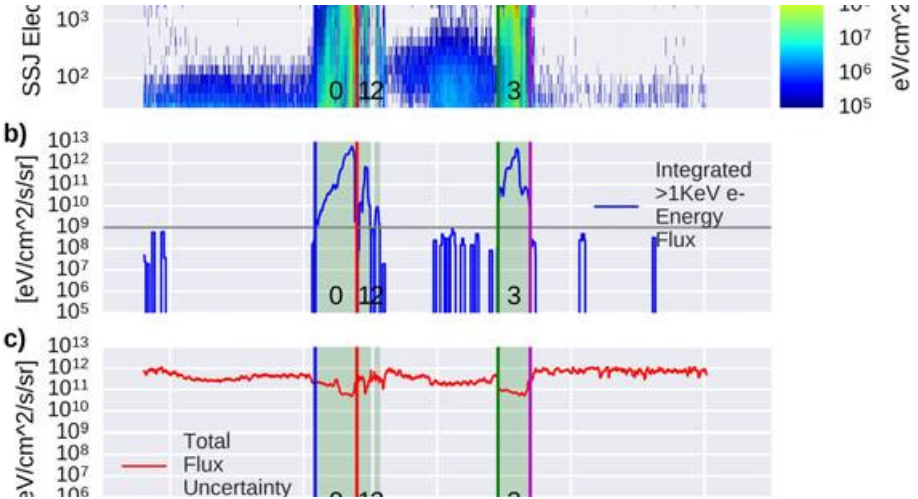
Boundary Data from DMSP SSJ

Newell Particle Precipitation Regions



Killcommons Particle Precipitation Boundaries



- ✓ DMSP SSJ (Newell: 1997 – 1998; Killcommons: 2010-2014)
  - SSJ4 and SSJ5 measure the particle precipitation
  - Newell et al. (2004) used SSJ to identify several different types of particle precipitation boundaries
  - Killcommons et al. (2017) used SSJ with updated ephemera to identify poleward and equatorward auroral boundaries based on particle precipitation
  - *Useful for calibrating auroral luminosity boundaries and for model creation*

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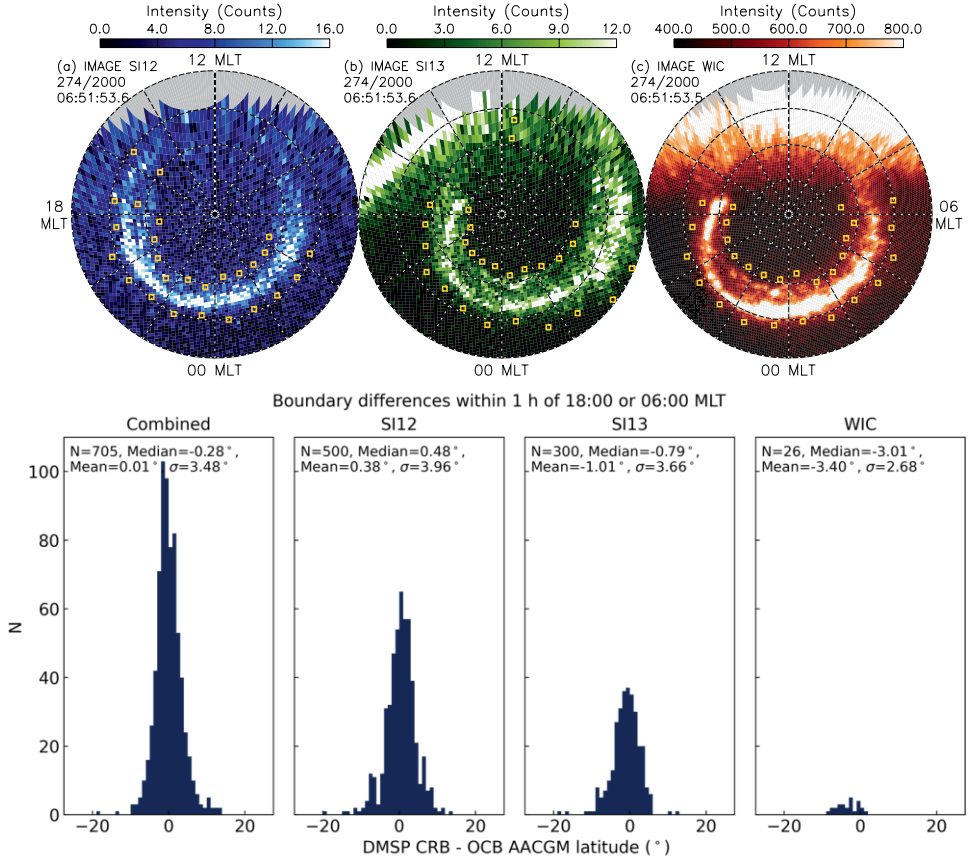
Boundary Data from IMAGE

- ✓ IMAGE (2000 – 2002)
  - SI12, SI13, and WIC measured Ly-α, O, and LBH emission bands in the Northern hemisphere
  - Chisham et al., 2022 found the polar and equatorward ALBs and used Newell DMSP boundaries to determine the offset between the luminosity and precipitation boundaries
  - Fits to the offset boundaries agree well with the DMSP CRB locations
  - *Useful for model creation*



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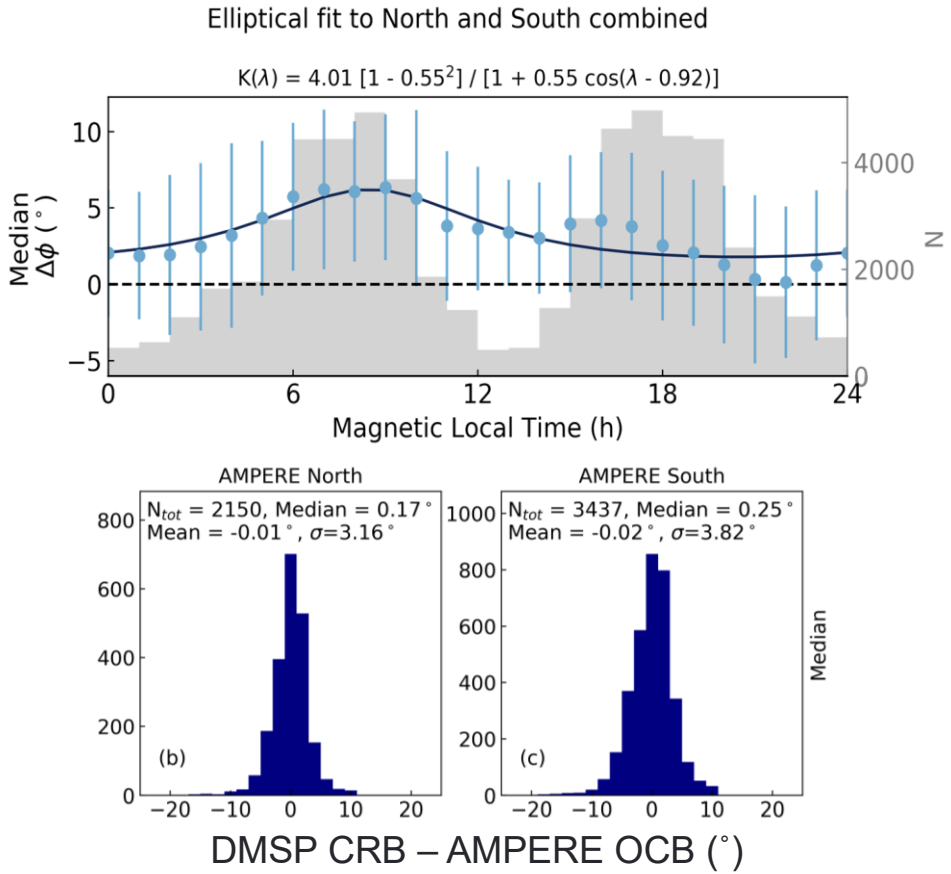
Boundary Data from AMPERE

- ✓ AMPERE (2010 – 2021)
  - AMPERE assimilates magnetic perturbation measurements to provide information about field-aligned currents (FACs) at the high latitudes
  - Milan et al. (2015) used principle component analysis to identify different FAC boundaries
  - Burrell et al. (2020) used the Killcommons SSJ boundaries to determine the offset between the OCB and R1/R2 current boundary
  - Validated against DMSP CRBs
  - *Useful for model creation*



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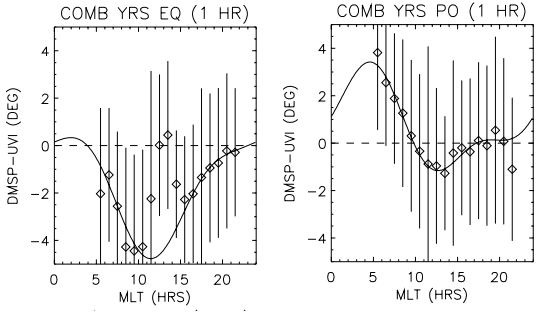
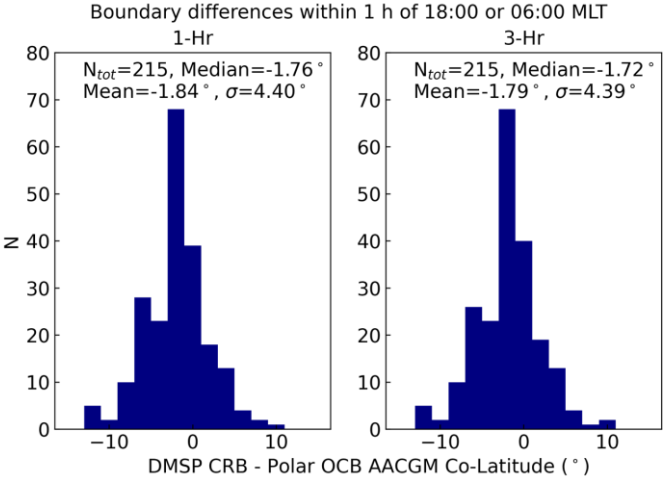
Boundary Data from POLAR

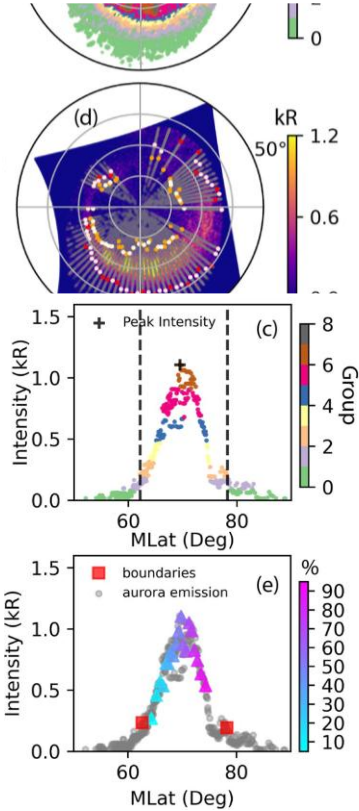
- ✓ POLAR (1997 – 1998)
  - UVI measured LBHL and LBHS bands in the Northern hemisphere
  - Carbary et al., (2003) used LBHL ALBs and Newell DMSP boundaries to determine the offset
  - Wu et al. (2021) provided ALBs for both LBHL and LBHS
  - Validation of fits to adjusted boundaries using DMSP CRBs shows a higher error than IMAGE
  - *Useful for model creation*

Carbary Offsets





Wu ALBs



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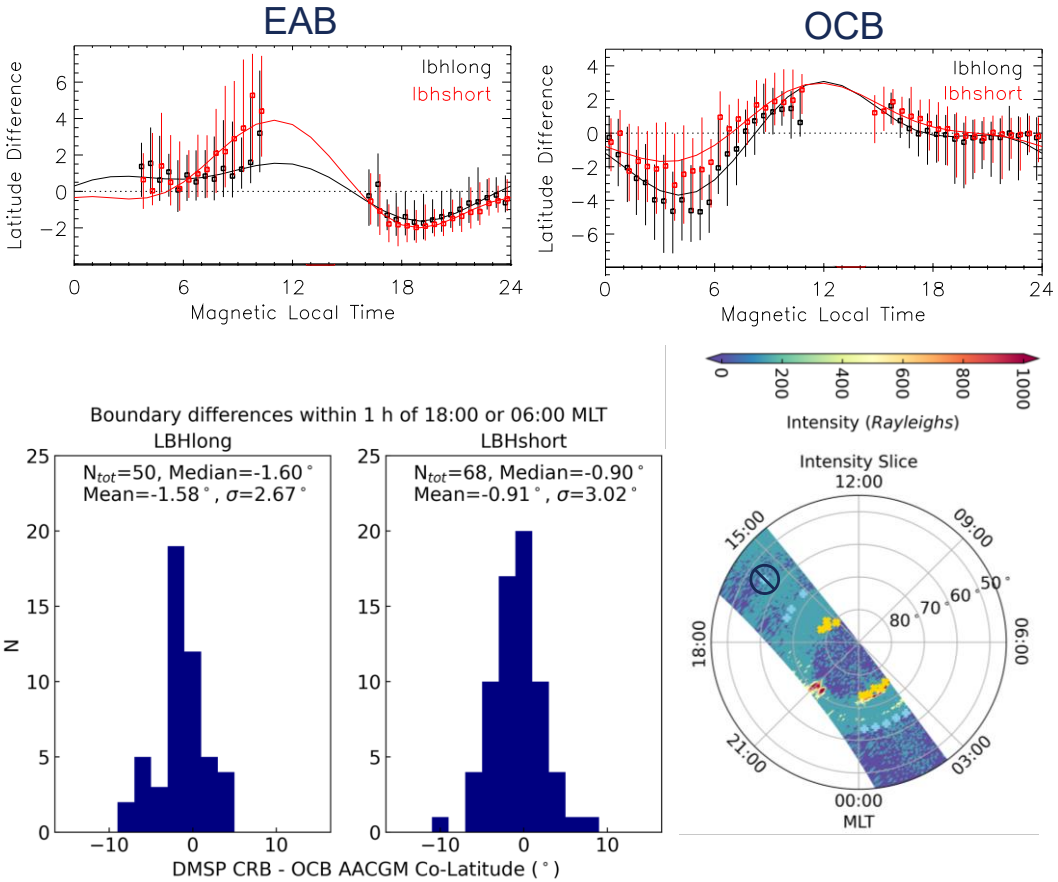
Boundary Data from GUVI

- ✓ TIMED GUVI (2002 – 2007)
  - Measured LBHL and LBHS bands in both hemispheres
  - NASA files provide auroral boundary identifications, but these boundaries do not match the intensity data well
  - Adapted the code described in Longden et al. (2009), into a new Python package `pyIntensityFeatures`
  - Paired with Newell boundaries to determine offset to particle boundaries
  - Validation performs better than POLAR, but worse than IMAGE
  - *Useful for model creation*



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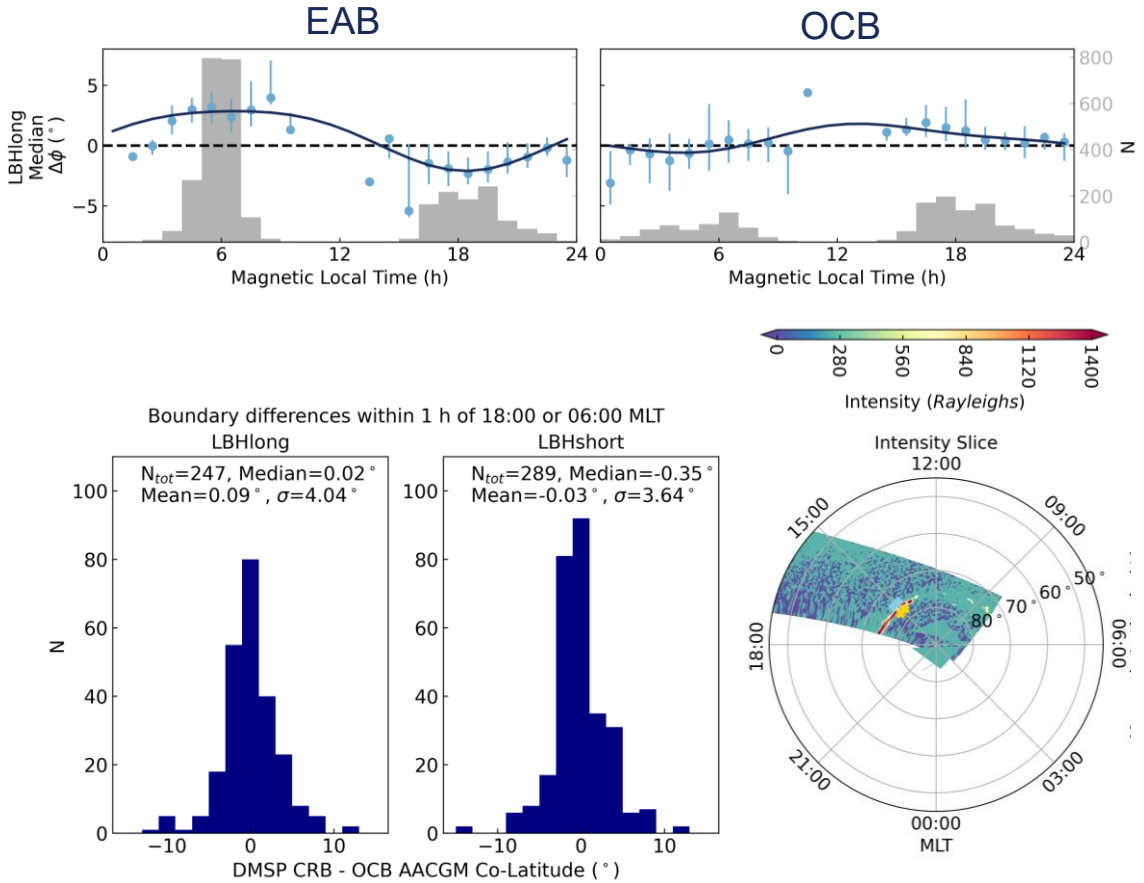
Boundary Data from SSUSI

- ✓ SSUSI (2005 – 2024)
  - Measured LBHL and LBHS bands in both hemispheres on F16, F17, F18, and F19
  - Similar format and issues as TIMED GUVI, used `pyIntensityFeatures` to identify ALBs
  - Paired ALBs with Kilcommons SSJ boundaries to determine EABs and OCBs in both hemispheres
  - Boundary validation shows similar accuracy as GUVI
  - *Useful for model creation*



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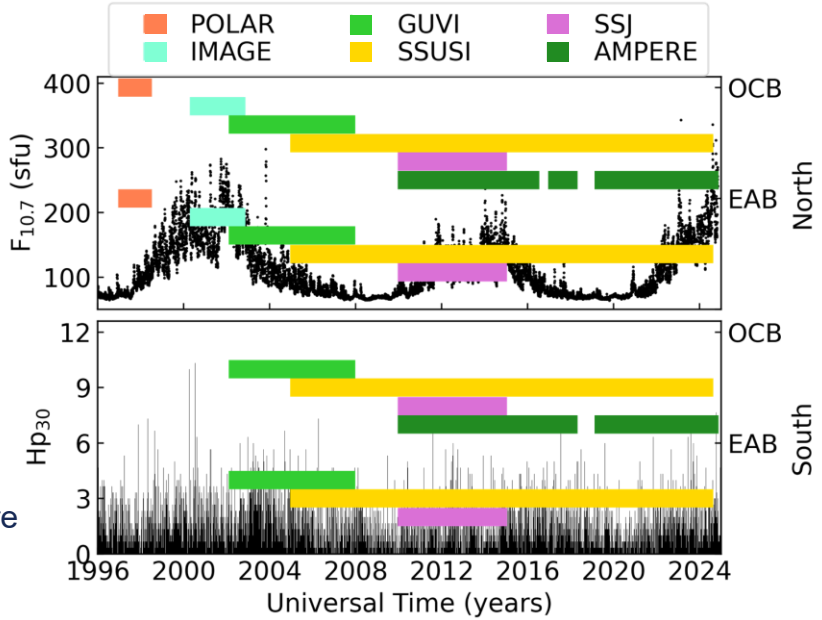
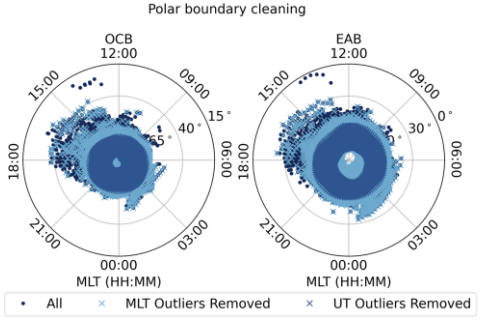
Gathered Boundaries and Drivers

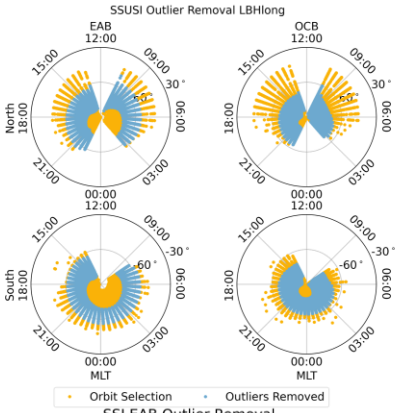
- Boundary Data
  - Start with DMSP SSJ, AMPERE, IMAGE, POLAR, GUVI, and SSUSI
    - Covers about 2.5 solar cycles
    - Both EAB and OCB in both hemispheres
    - Calculate weight for each boundary using available quality metrics for the different data sets
  - Retain Newell boundaries for model validation
- Potential Model Drivers
  - Considering accuracy and forecastability
  - Solar:
    - Day of year
    - Time of day
    - $F_{10.7}$
    - Cosmic ray counts
  - Geomagnetic:
    - Hp_{30}
    - AE
    - SMU
    - SML
    - SMR
    - IMF X, Y, and Z
    - IMF Clock Angle
    - Solar Wind Speed
    - Solar Wind Pressure
    - Solar Wind Density
    - Newell Coupling Function
    - Dipole moment

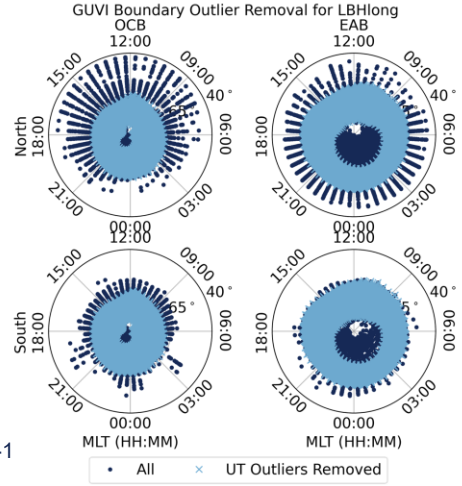


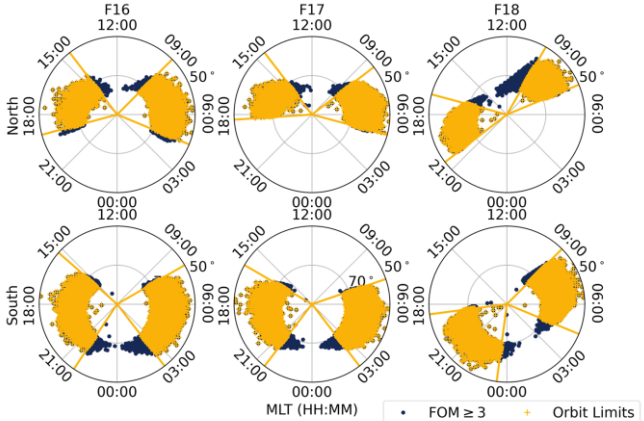
Outlier removal by Data Set

- POLAR
  - Remove outliers at each UT
  - Remove outliers at each MLT
- IMAGE
  - Outliers removed as described in Chisham et al. (2021)
- GUVI
  - Defined outlier quartiles and IQR using southern hemisphere data for each channel
  - Removed outliers at each MLT
- SSUSI
  - Removed boundaries in regions with a low occurrence, due to orbit
  - Removed outliers at each MLT and hemisphere
- SSJ
  - Removed boundaries with a FOM < 3
  - Removed boundaries in regions with low occurrence, due to orbit
- AMPERE
  - Removed boundaries with $\Delta J < 0.15$ mA m^{-1}









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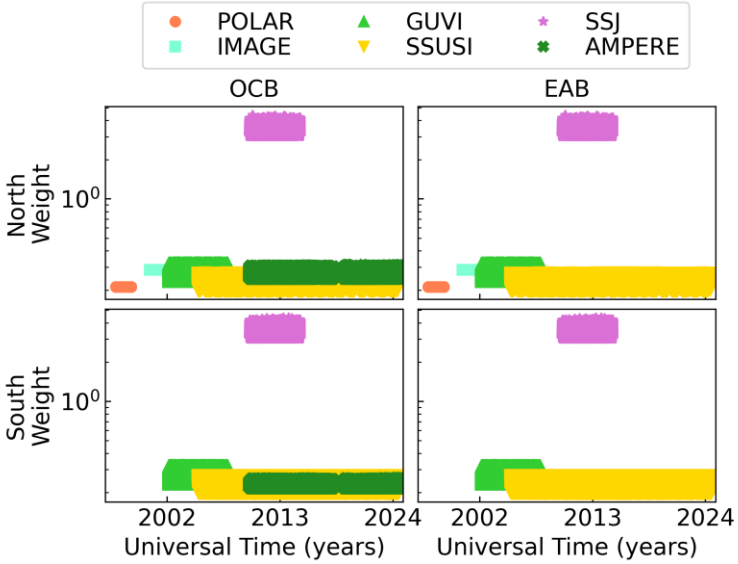
Weights by Data Set

- Boundary weights should have higher values when data is more reliable
  - SSJ has a figure of merit for each boundary that is already appropriate as a weight
  - IMAGE and POLAR boundaries do not have individual uncertainties, so the weight was calculated using the median (q_2) and standard deviation (σ) from the CRB validation (1)
  - GUVI and SSUSI boundaries have individual uncertainties (ε), so their weight includes these along with the CRB validation (2)
  - AMPERE fits have current values that are used for quality control, with $\varepsilon^2 = \Delta J^{-1}$, so these are combined with the CRB validation (2)



$$w = \frac{1}{\sqrt{q_{2_{CRB}}^2 + \sigma_{CRB}^2}} \quad (1)$$

$$w = \frac{1}{\sqrt{q_{2_{CRB}}^2 + \sigma_{CRB}^2 + \epsilon^2}} \quad (2)$$

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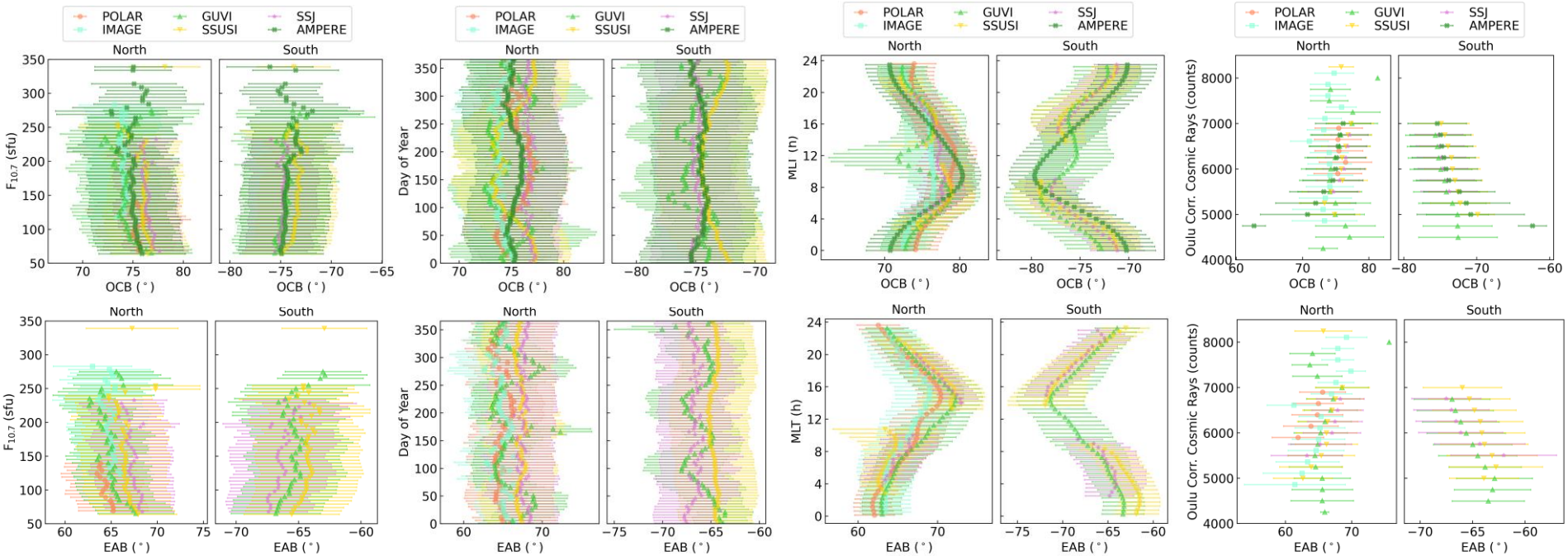
Driving Parameter Correlation: Solar



- Solar Variations are not key factors in determining the particle precipitation boundary locations
- MLT has a strong diurnal variation

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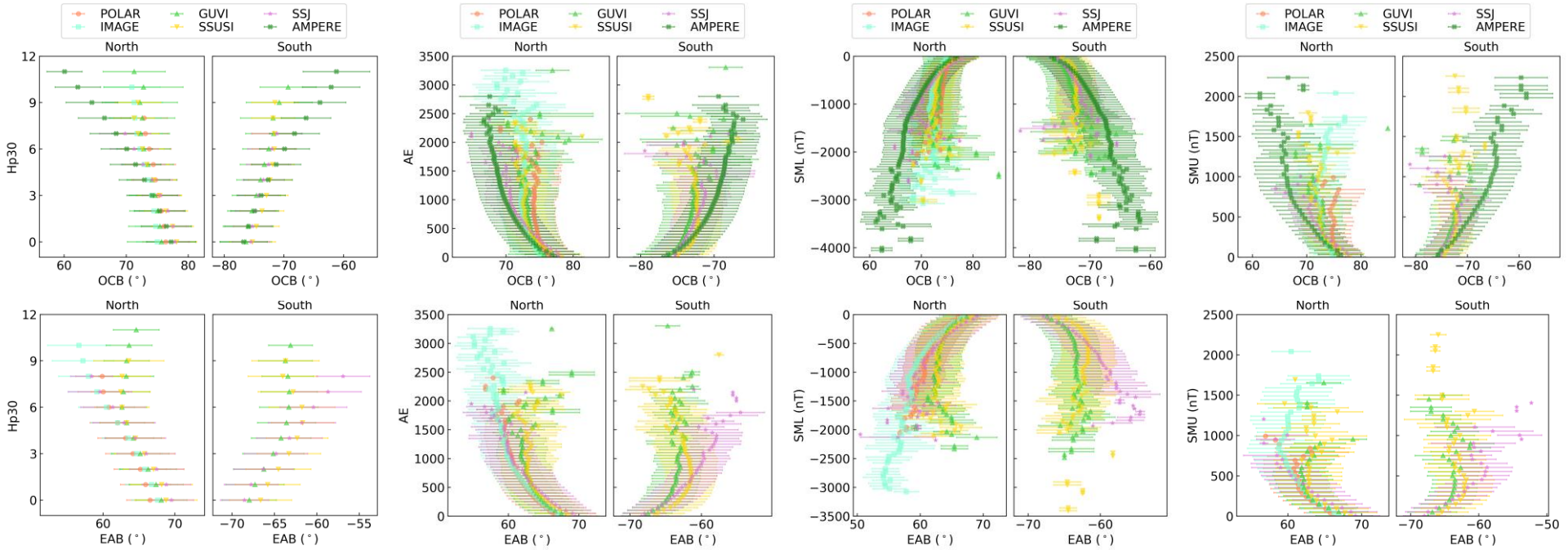
Driving Parameter Correlation: Geomagnetic



- Multiple geomagnetic parameters are correlated with particle precipitation boundary locations
- Northern and southern hemispheres respond similarly to the different magnetic drivers

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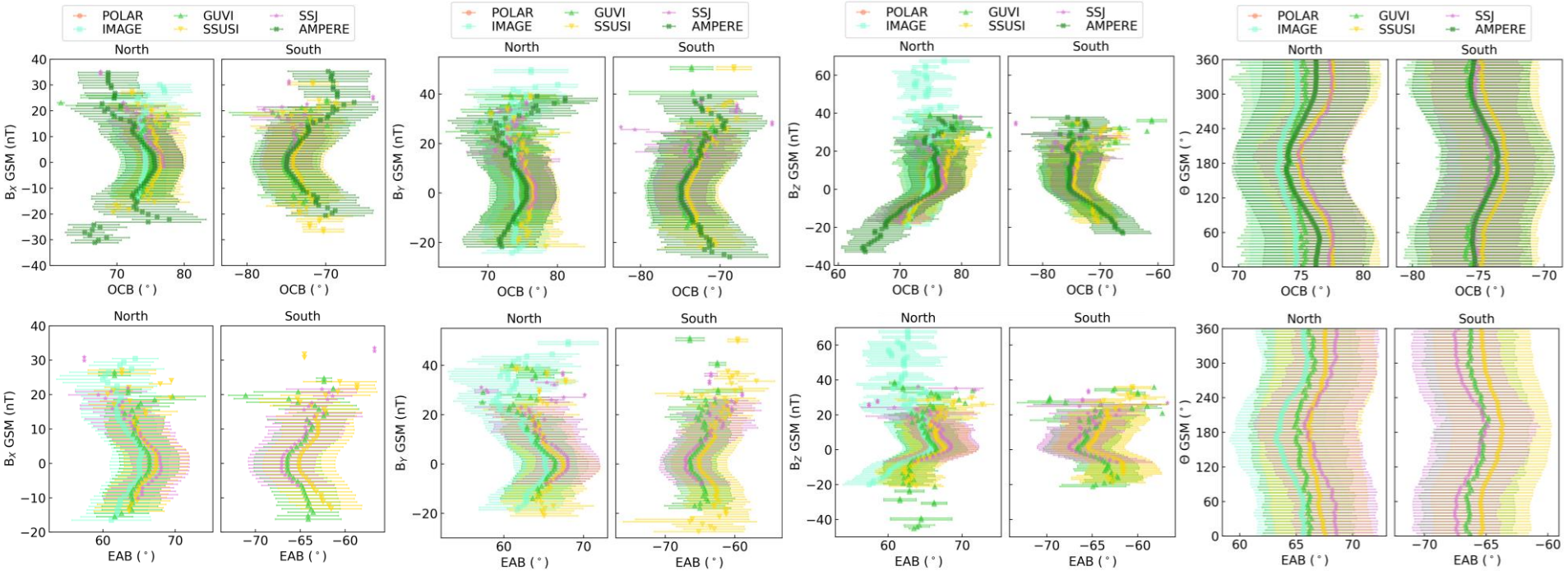
Driving Parameter Correlation: IMF



- IMF B_X and B_Y response is well behaved about zero, while B_Z shows a correlation with OCB for negative values
  - The clock angle (θ) shows a consistent correlation for OCB and EAB

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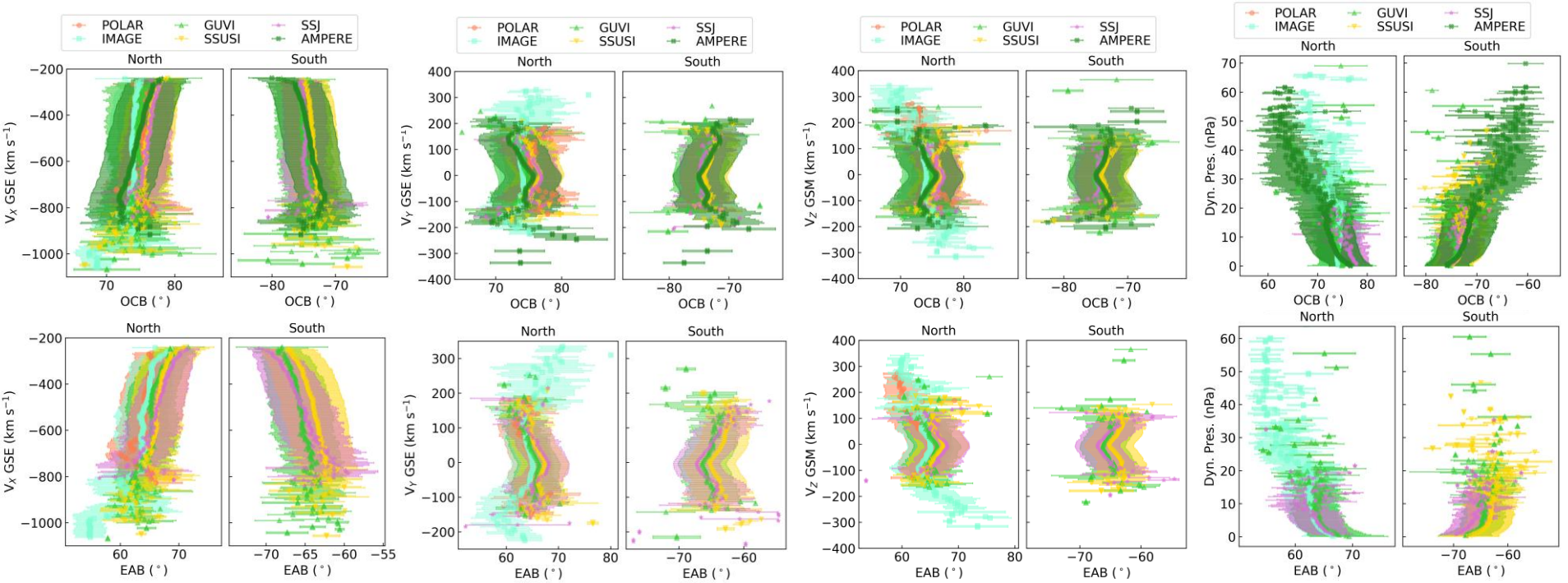
Driving Parameter Correlation: Solar Wind



- V_X and dynamic pressure show the strongest correlation with OCB and EAB locations

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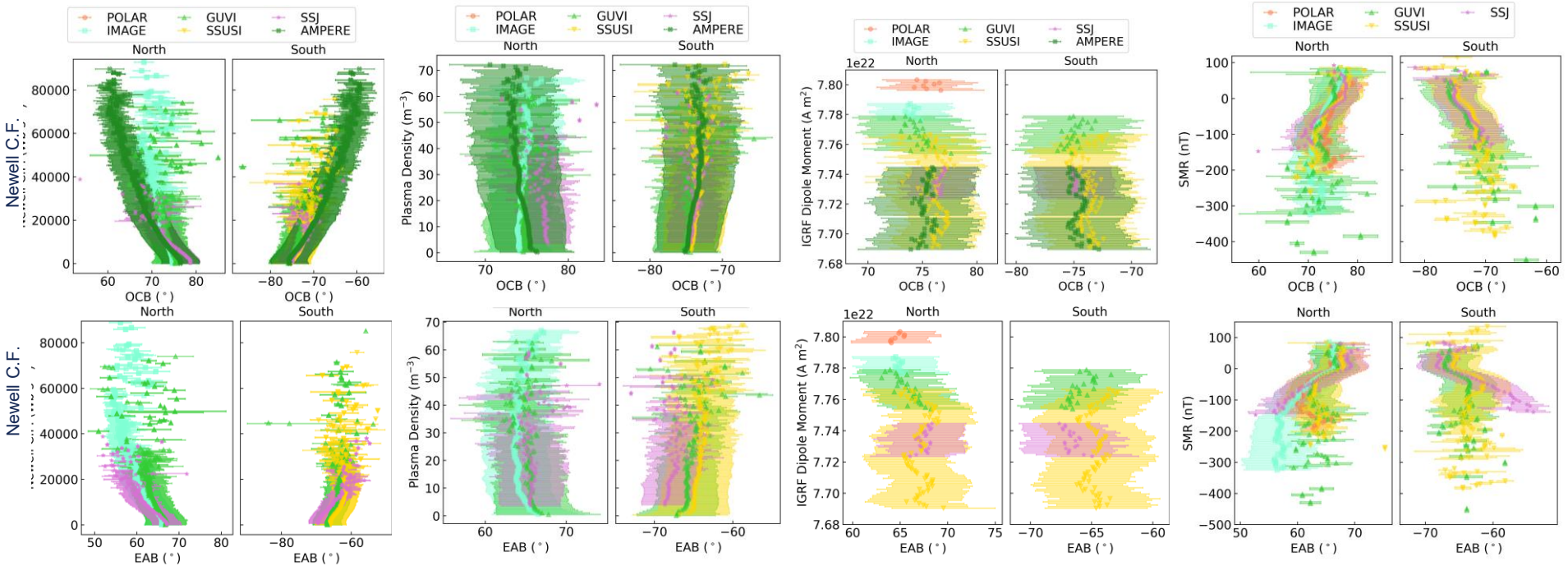
Driving Parameter Correlation: More!



- The Newell Coupling Function ($d\Phi_{MP}/dt = C_{MP} v^{4/3} B_T^{2/3} sin^{8/3}(\theta_c/2)$) shows the strongest correlation
- The main field's magnetic dipole moment, m_e, shows little variation with boundary location over this time period

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Potential Model Formulations

Potential Methods

- Spherical harmonics

$$\phi_X = \prod_{i=0}^{N} \sum_{j=0}^{M} (a_{i,j} \cos j\omega_i + b_{i,j} \sin j\omega_i)$$

  - ω_i initially includes:
    - MLT, Hp30, AE, θ, V_X, Dynamic Pressure, and Newell Coupling Function
  - φ_X is the boundary latitude, where X is OCB or EAB
- Machine learning tools
  - Need to investigate potential options

Potential Formulations

- Analyse impact of contributions from selected independent variables
  - Start with PCA
  - Manually add additional variables to determine impact
- Test formulations with hemispheres combined, separate, and as an independent variable
- Test formulation with magnetic and geodetic coordinates

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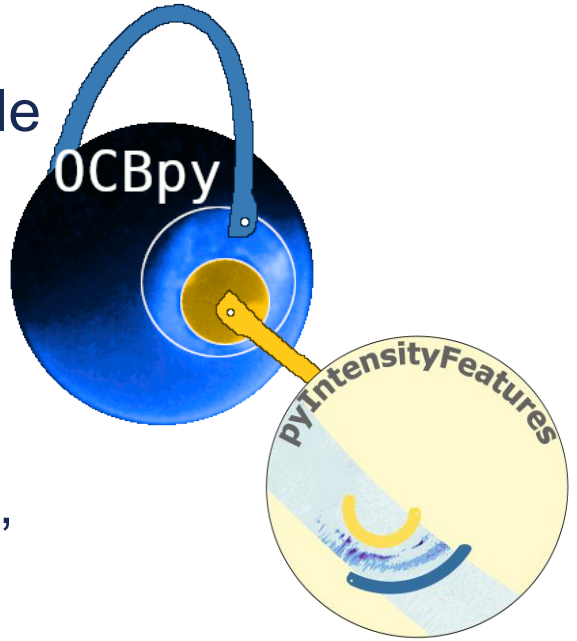
Published Products

- Improved gridding data sets
  - Expanded OCBpy to grid in dual-boundary coordinates
  - Updated AMPERE boundaries in OCBpy
- Formalized Longden boundary detection code
  - Generalized methodology
    - Allow any number of multi-Gaussian fits
    - Added adaptive limits for partial-aurora scans
    - Added test for MLT consistency in boundary IDs
  - Developed a unit test suite
  - Available as a pip-installable Python package, pyIntensityFeatures



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Conclusions

- Implementing adaptive, high latitude coordinates would improve research efforts for terrestrial atmospheric, ionospheric, and magnetospheric physics
  - Standard magnetic coordinates combine data from the polar cap and auroral regions, even for a narrow selection of solar and geomagnetic conditions
  - Considering only one boundary is sufficient when examining the region well-defined by that boundary
  - Dual-boundary gridding does the best job of fully specifying the high-latitude features
  - An open-source model of the polar cap and equatorward auroral oval will improve high latitude statistical studies, empirical model construction, and energy boundaries in first-principles models

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Current and Future Work

- Publish Results
  - New boundaries and boundary validations
    - POLAR, GUVI, SSUSI
    - Make appropriate data sets available on OCBpy
  - pyIntensityFeatures manuscript under review
- Creating an empirical boundary model
  - Combining DMSP SSJ, AMPERE, IMAGE, POLAR, GUVI, and SSUSI
    - Covers about 2.5 solar cycles
    - Both EAB and OCB in both hemispheres
  - Retaining DMSP Newell boundaries for validation
  - Selected a subset of geomagnetic parameters to consider in model formulation
  - Considering different empirical model construction methods

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OMNI Solar Wind data are courtesy of OMNI and are the 1-min-averaged, field/plasma data sets shifted to the Earth's bow shock nose (BSN). This "High Resolution OMNI" (HRO) data set involves an interspersal of BSN-shifted ACE, Wind, IMP 8 and Geotail data. See https://omniweb.sci.gsfc.nasa.gov/ow_min.html, Dr. Natalia Papitashvili, Mail Code 672, NASA/Goddard Space Flight Center, Greenbelt, MD 20771.

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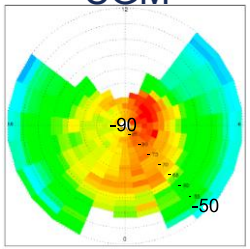
angeline.g.burrell.civ@us.navy.mil

Adaptive Coordinate Approaches

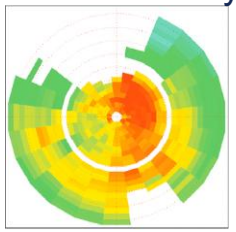
- Single Instrument or Platform
  - Grid data from the same instrument or other instruments on the same platform relative to an appropriate boundary observed at that time
- Multi Instrument
  - Grid data observed at the same time and region as another observation of an appropriate boundary
- OCBpy
  - Tool to grid data in adaptive coordinates (OCB, EAB, or Dual Boundary)
  - Provides access to multiple boundary data sets
  - A model of OCB and EAB locations would allow greater usage of adaptive coordinates

DMSP Southern O^+ Downflow: Redmon et al. (2010)

CGM



Dual-Boundary



Reistad et al. (2021): Seasonal Electric Potential for $B_Z \cong 0$ in OCB coordinates, with Lobe region identified