Statistical estimates of auroral Pedersen conductance using Swarm measurements

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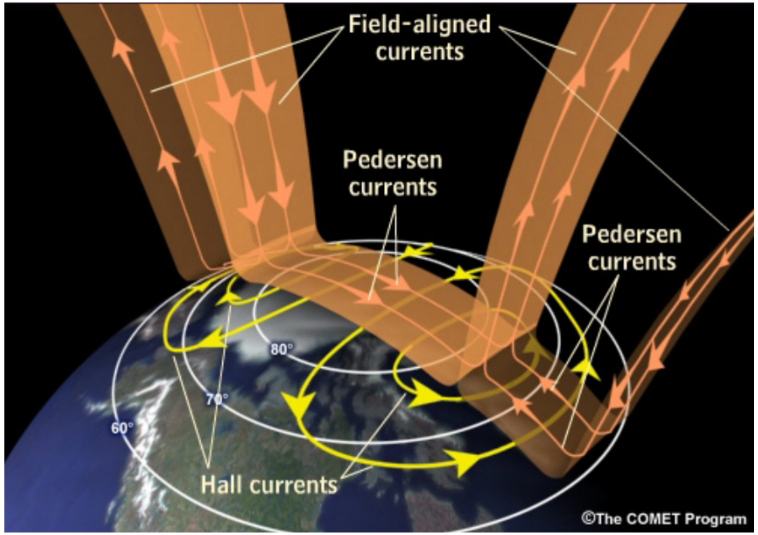
Background

- Ionospheric Pedersen conductance Σ_P plays an important role in MI-coupling
    - e.g. closure of FAC, Joule heating
- Conductance is difficult to measure directly, especially in hemispheric scales
- We try to estimate statistical maps from Swarm ion drift ($\boldsymbol{V}_{ion}$) and magnetic ($\boldsymbol{B}$) field data
- Same approach as in [Sugiura et al. (1982)]
    - Linear regression between $\boldsymbol{E}$ (or $\boldsymbol{V}_{ion}$) and $\Delta\boldsymbol{B}$ measured by a LEO satellite
    - Slope of the line gives Σ_P



Theory

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- **Case 1: Electrostatic situation**
  - Assume conductance gradients are everywhere parallel to $\boldsymbol{E}$
    ==> Pedersen current = curl-free,   Hall current = divergence-free
  - Relation for curl-free current and their magnetic field (e.g. Vanhamäki+Juusola, 2020)
    $\Delta \boldsymbol{B}_{cf} = \mu_0\, \hat{\mathbf{e}}_B \times \boldsymbol{J}_{cf} \approx \mu_0\, \Sigma_P\, \hat{\mathbf{e}}_B \times \boldsymbol{E}_{cf}$ [unit vector $\hat{\mathbf{e}}_B$ along main field]

- **Case 2: Alfven wave reflection**
  - Incident wave (↓) from magnetosphere, reflected wave (↑) from ionosphere
  - Wave fields $\Delta \boldsymbol{B}^{\downarrow} = -\boldsymbol{E}^{\downarrow} \times \hat{\mathbf{e}}_B / V_A$ and $\Delta \boldsymbol{B}^{\uparrow} = \boldsymbol{E}^{\uparrow} \times \hat{\mathbf{e}}_B / V_A$ [V_A = Alfven velocity]
  - Superposed wave fields $\Delta \boldsymbol{B}_w = \Delta \boldsymbol{B}^{\downarrow} - \Delta \boldsymbol{B}^{\uparrow}$ and $\boldsymbol{E}_w = \boldsymbol{E}^{\downarrow} + \boldsymbol{E}^{\uparrow}$
  - If conductance gradients are parallel to $\boldsymbol{E}_w$, we have $\boldsymbol{E}^{\uparrow} = R\boldsymbol{E}^{\downarrow}$ with $R = (\Sigma_A - \Sigma_P)/(\Sigma_A + \Sigma_P)$.
    [e.g. Glassmeier (1984) , Σ_A is the Alfven conductance]
  - This results in relation $\Delta \boldsymbol{B}_w = \mu_0\, \Sigma_P\, \hat{\mathbf{e}}_B \times \boldsymbol{E}_w$

- **Both cases give the same relation**
  - Get electric field from ion drift   ==> $\Sigma_P \boldsymbol{V}_{ion} = -k\, \Delta \boldsymbol{B}$ where $k = \mu_0\, |\boldsymbol{B}_{\text{main field}}|$
  - Need to assume that divergence-free currents (electrojets) do not affect measured $\Delta \boldsymbol{B}$.
    Most easily satisfied in 1D situation, e.g. a uniform electrojet.

Data & analysis

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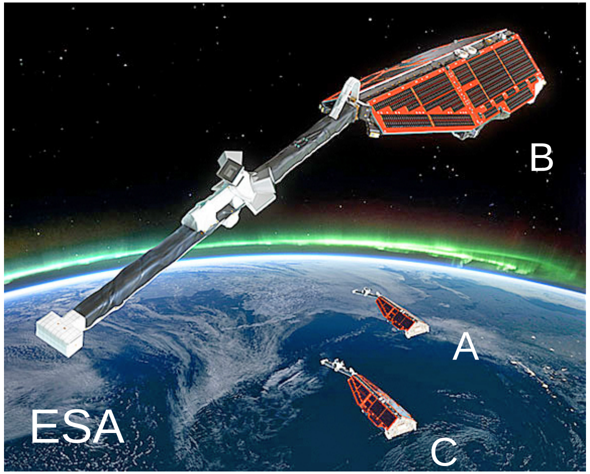
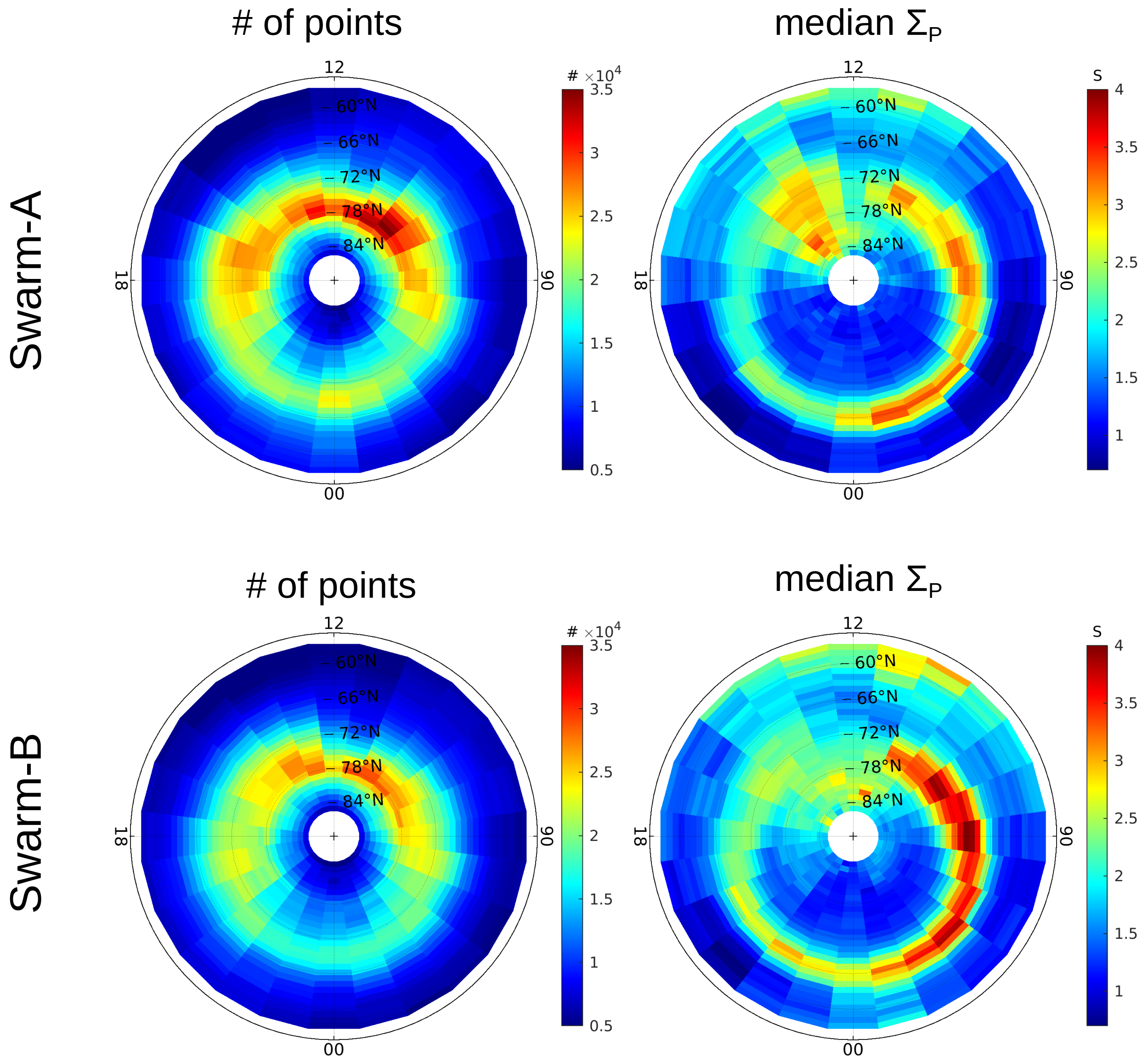


- **Swarm-A and -B**
  - 12/2013 – 04/2022
  - Thermal ion imager 2 Hz data (0302 version)
    - Only cross-track (ct) ion velocity $V_{ion,ct}$ is used
  - Remove CHAOS-7 from ***B*** to get ΔB_{ct}

- **Steps in conductance estimation**
  1) Remove $V_{ion,ct}$ with bad calibration flags
  2) Remove $|\Delta B_{ct}| > 5000$ nT or $|V_{ion,ct}| > 5000$ m/s
  3) Smooth with 13 point moving median (2 Hz data ==> about 45 km)
  4) Fit slope to ($V_{ion,ct}$, k ΔB_{ct}) in 13 point moving window
  5) Correlation ($V_{ion,ct}$, k ΔB_{ct}) in 13 point moving window ==> Remove if > -0.70
  6) Calculate angle of orbit wrt. constant magnetic latitudes ==> Remove if <45º
  7) Remove all data with $\Sigma_P < 0$

- **Grid data**
  - 1º mlat / 1h mlt, median in each grid cell



Raw statistics

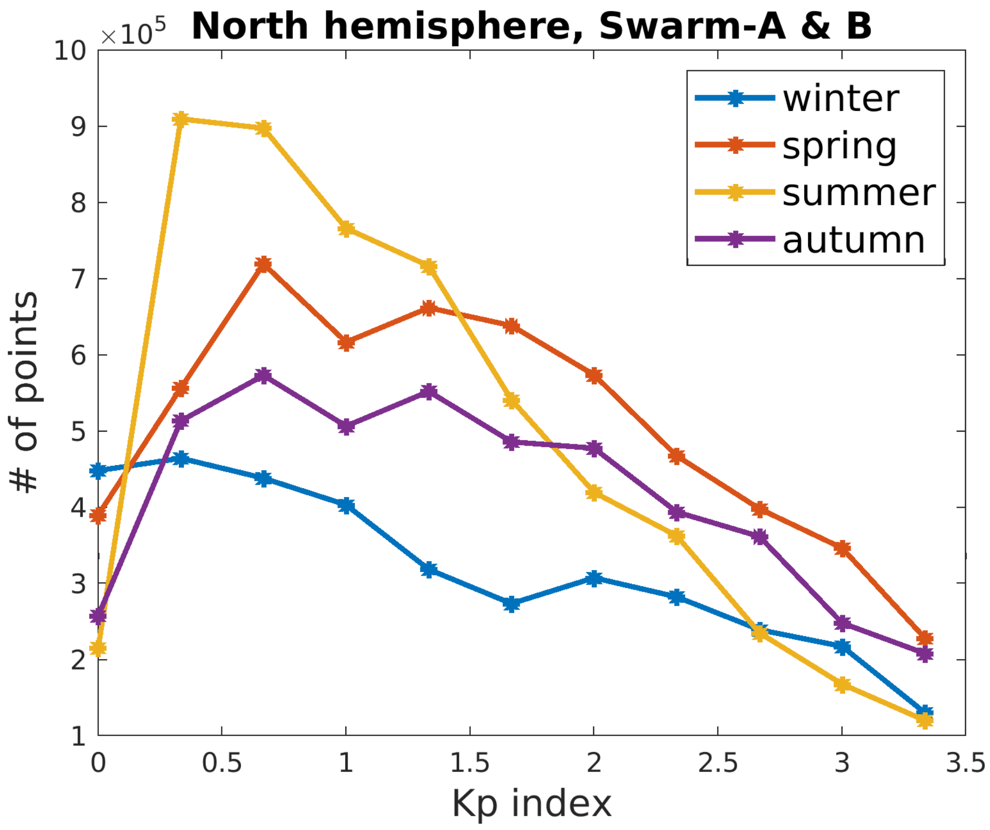
- North hemisphere, all seasons together
- Swarm-A and Swarm-B analyzed separately
- Different orbits ==> data to same mlat/mlt bin comes from different months
- Same overall pattern
- Result is not sensitive to details in analysis

Bootstrapping

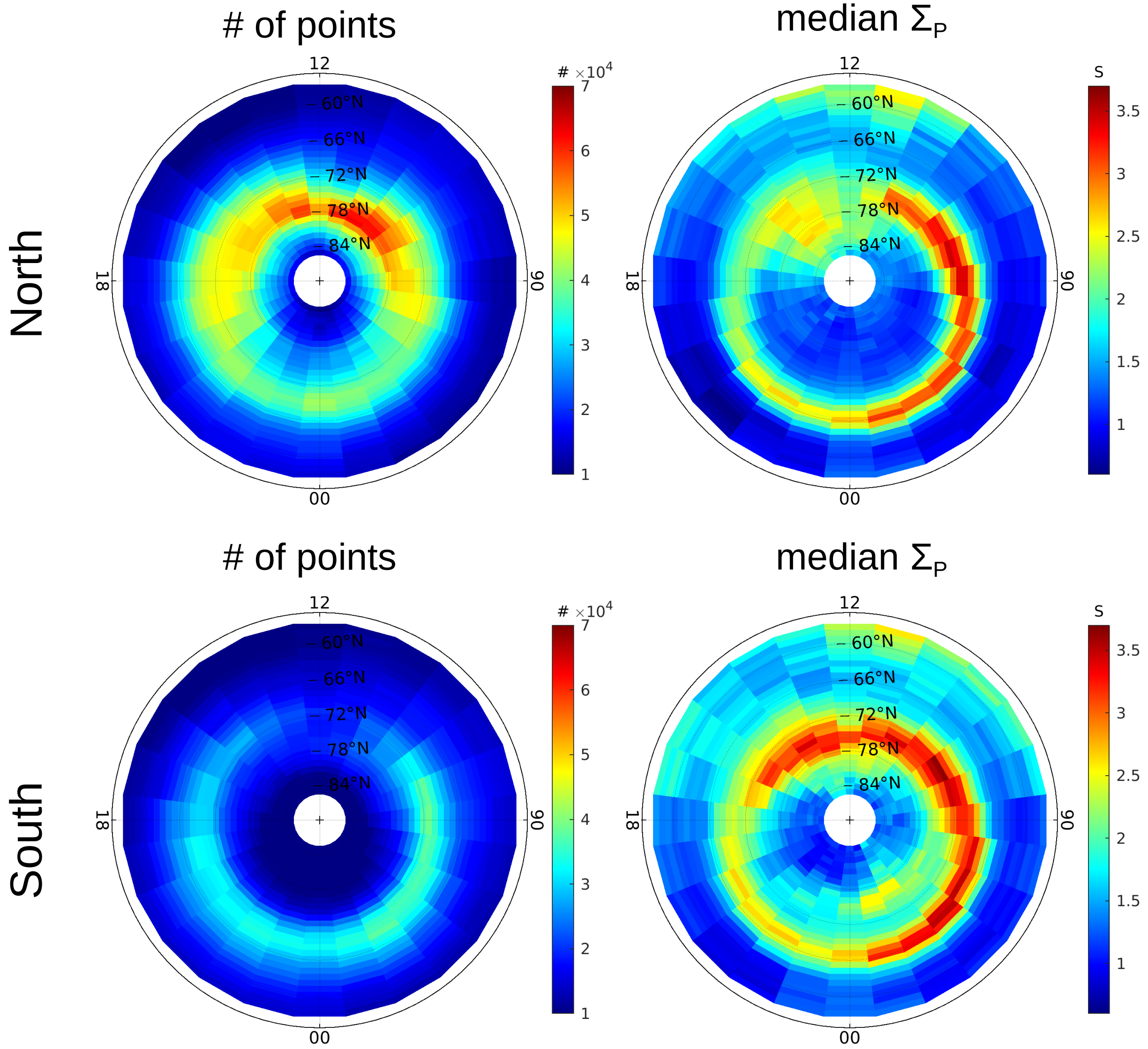
- **Unequal sampling of seasons and conditions**
  - Activity described by Kp index

- **Bootstrapping**
  - Each mlat/mlt grid cell separately
  - Random re-sampling with replacement
  - Each sample as big as the original
  - 1000 repetitions

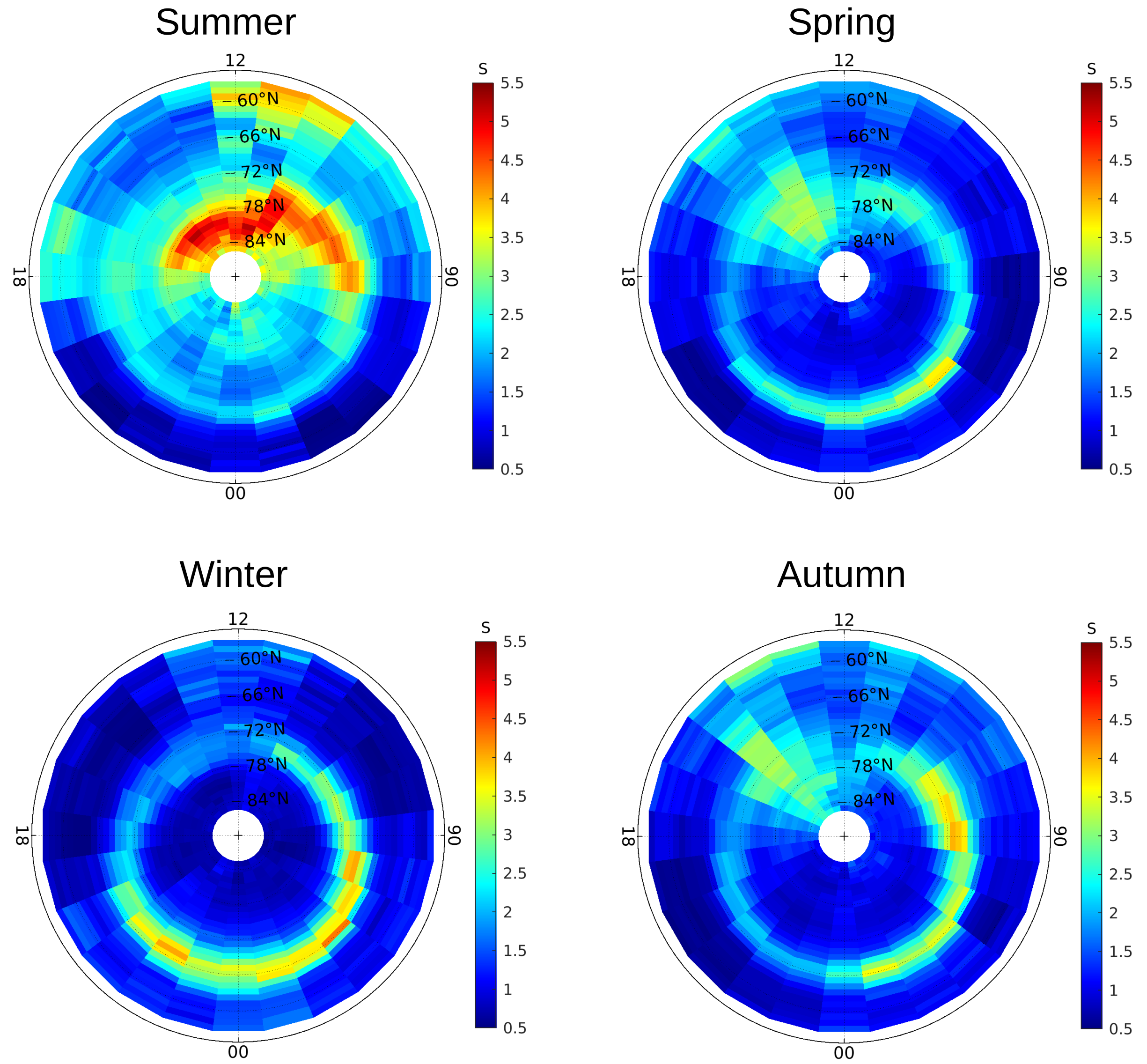
- **Remove biases by bootstrapping**
  - Force same Kp distribution in each grid cell & season
  - Draw equal # of points from each season
  - Use average Kp distribution (all seasons, Swarm-A & B, both hemispheres)



Hemispheres



- All seasons together, Swarm-A & B together, bootstrapped
- North and south hemispheres separately
- Our selection criteria remove more points in the south
- Overall quite similar
  - Differences in the afternoon sector
  - Larger latitude spread in south

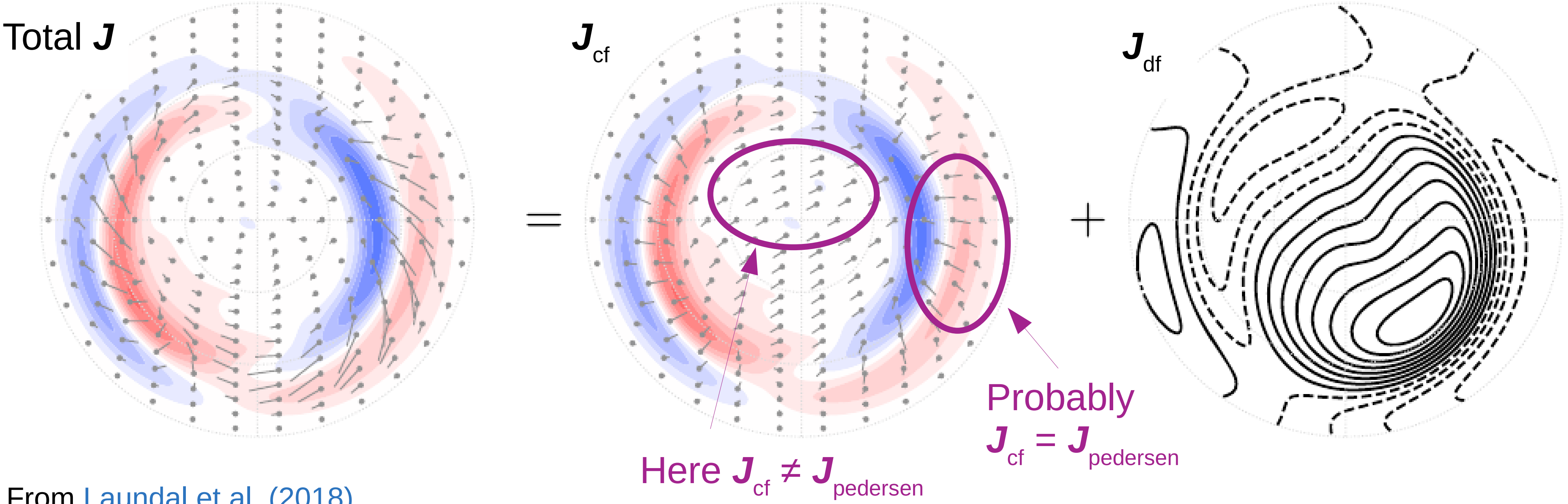


Seasons

- North hemisphere, Swarm-A & B together, bootstrapped
- Winter is as expected
- Autumn has larger Σ_P than spring in the morning side, bit weaker in evening.
- Summer Σ_P has some resemblance to particle flux in Newell et al. (2011)
- Why so weak dayside conductances?

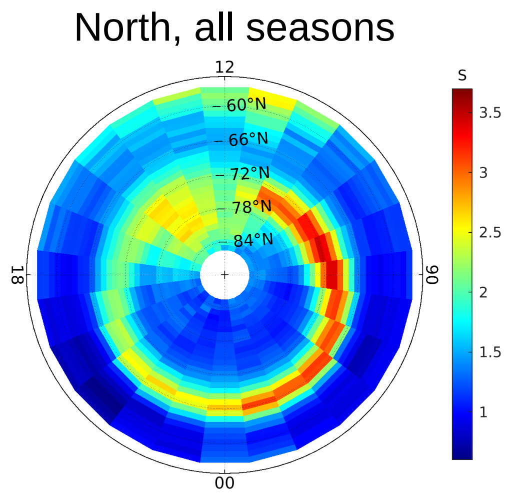
Issues?

- The total current system (FAC + horizontal $\boldsymbol{J}$) can be divided to
  - FAC + curl-free $\boldsymbol{J}_{cf}$
  - Divergence-free $\boldsymbol{J}_{df}$ (shown as streamlines)
- <u>We assume:</u> measured $\Delta\boldsymbol{B}$ corresponds to $\boldsymbol{J}_{cf}$, and furthermore $\boldsymbol{J}_{cf} \approx \boldsymbol{J}_{pedersen}$



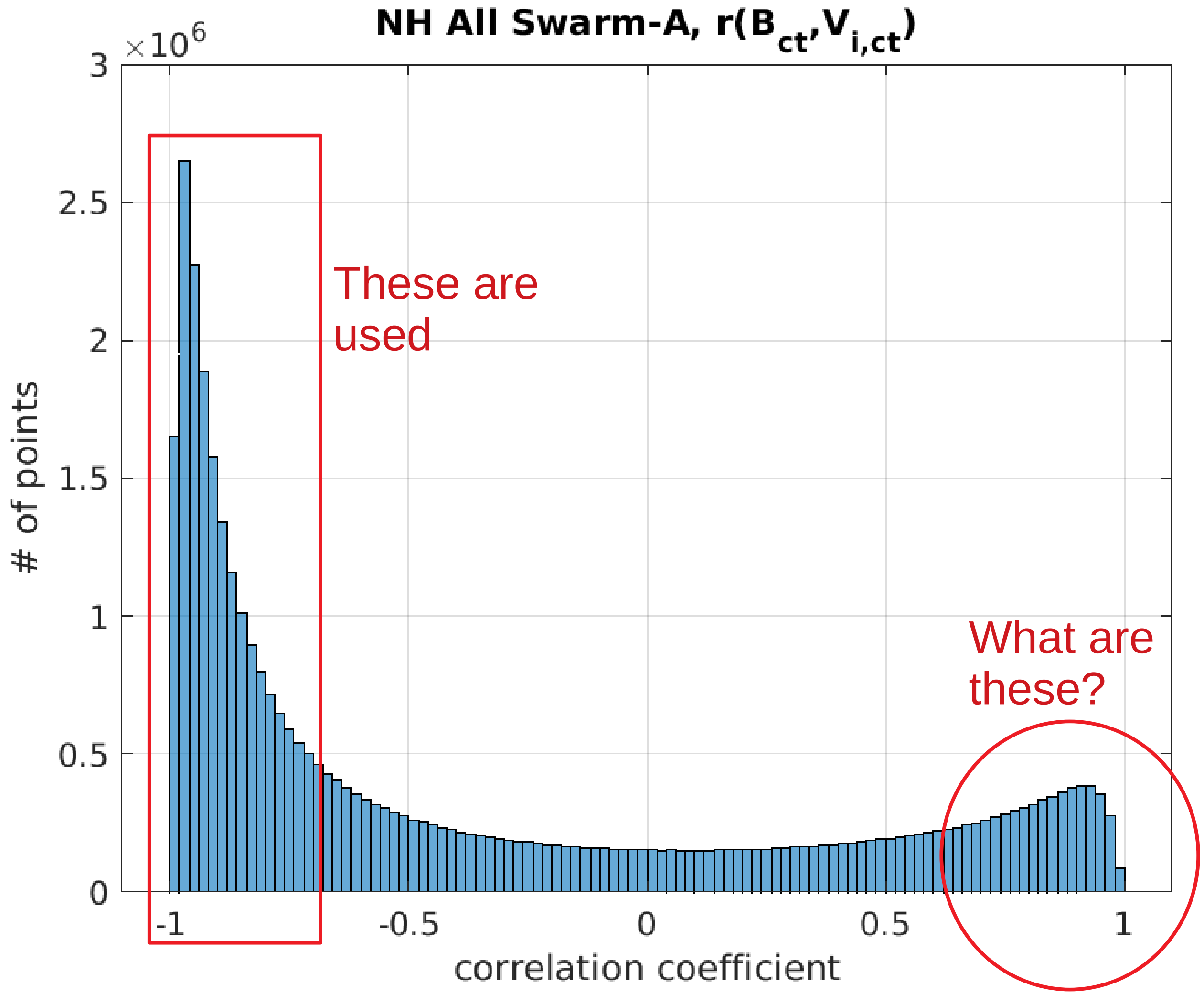
From [Laundal et al. (2018)]

Summary and Discussion

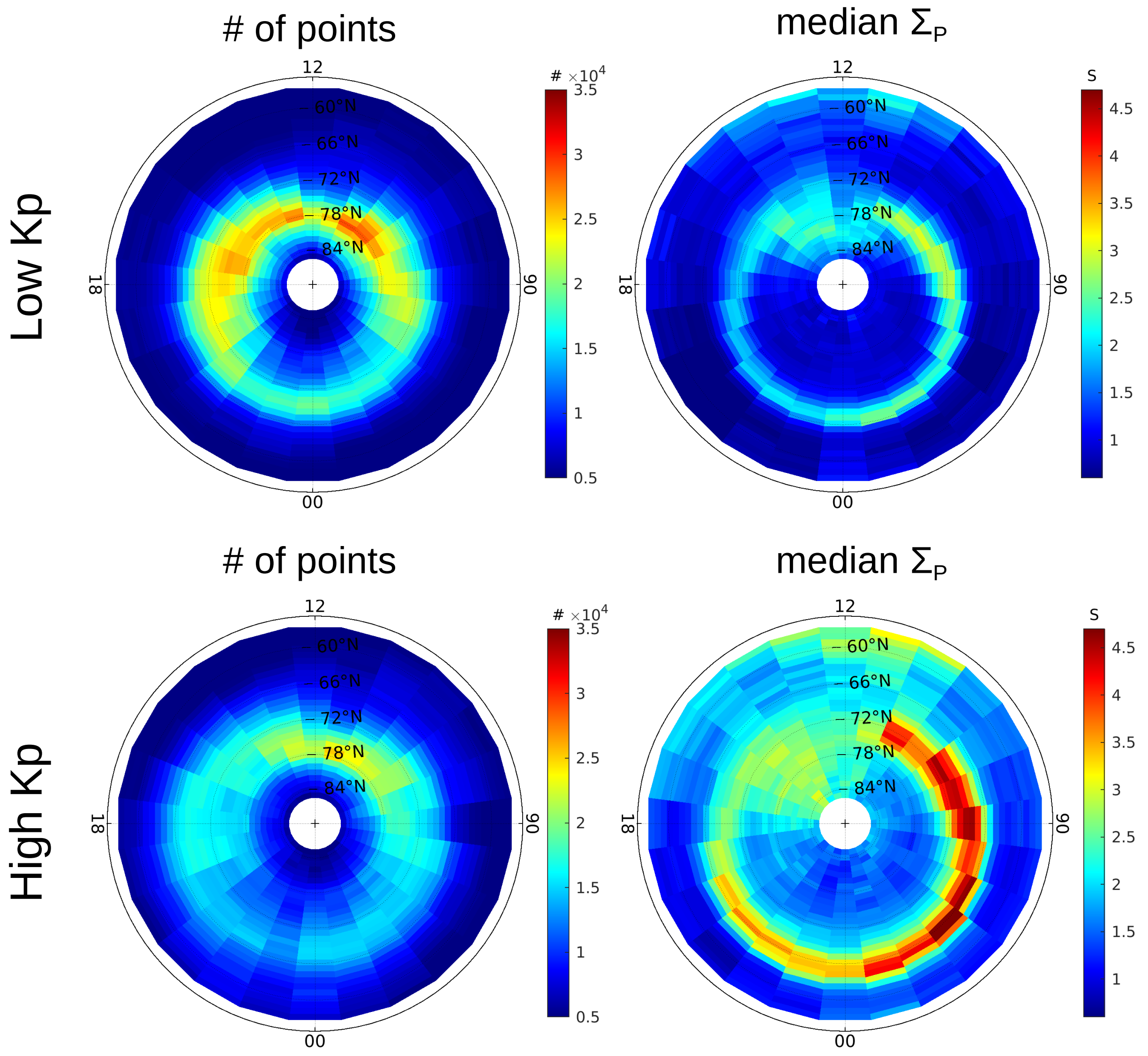


- Estimated Σ_P using ~8 years of Swarm data
- Results seem robust.
  - Main features are not sensitive to details in the analysis
- Bootstrapping is used to mitigate seasonal and Kp biases
  - Oval visible in all seasons, weakest in summer.
  - Dawn/Dusk asymmetry varies with season.
  - Equinoxes show early afternoon enhancement.
  - North hemisphere has sharper oval than south.
- Some points to keep in mind
  - Outside the oval divergence-free electrojet currents may distort the measured $\Delta \boldsymbol{B}_{ct}$
  - Also assumption $\boldsymbol{J}_{cf} \approx \boldsymbol{J}_{pedersen}$ may be invalid outside the oval
  - For Alfven waves the result $\Delta \boldsymbol{B}_w = \mu_0 \Sigma_P \hat{\mathbf{e}}_B \times \boldsymbol{E}_w$ is valid for all frequencies, but includes assumption of expt(iz/λ) altitude dependence

Correlations



- **North hemisphere, all seasons together**
- Swarm-A, 2013-2022
- Mostly negative correlation between Δ**B** and **V**$_{ion}$, as expected
- Filtering with correlation removes most $\Sigma_P < 0$ (not all)
- Why secondary peak at positive correlation? Upward Alfven waves?



Kp levels

- All seasons together, Swarm-A & B together, bootstrapped
- Low Kp [0 1] and high Kp [2- 3+] separately
- Overall as expected
  - High Kp has larger Σ_P and wider oval.