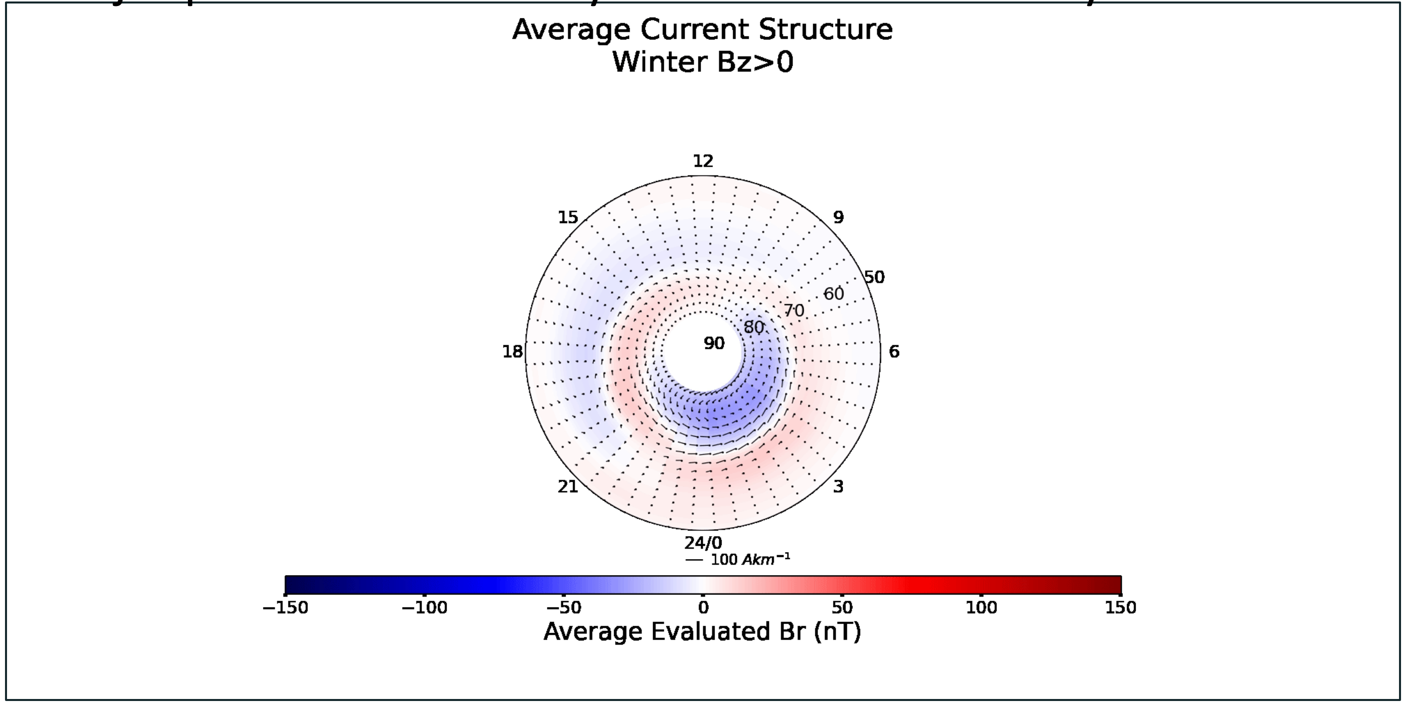
Electrojet poleward boundary variations with IMF By and season



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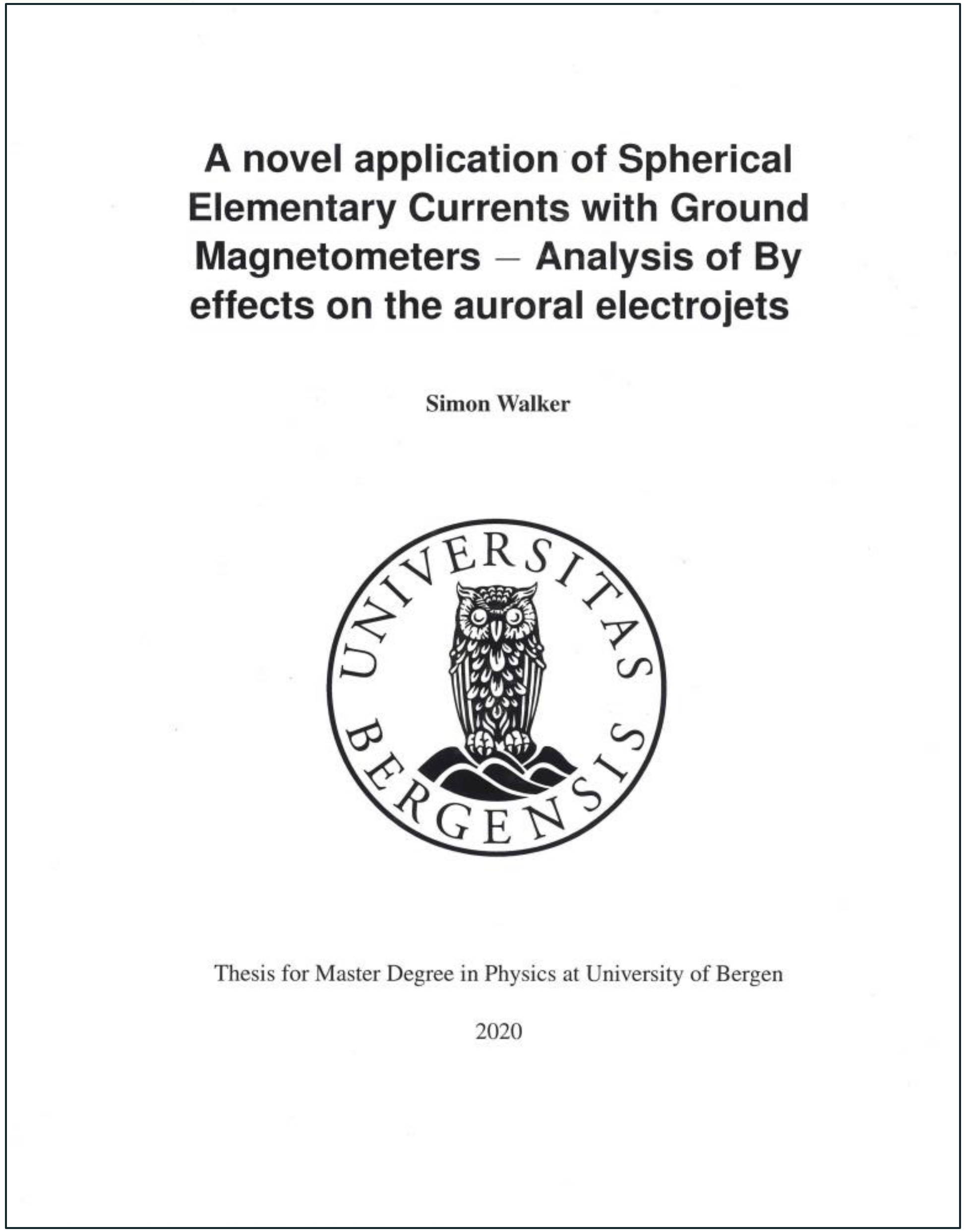

A novel application of Spherical Elementary Currents with Ground Magnetometers – Analysis of By effects on the auroral electrojets

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Thesis for Master Degree in Physics at University of Bergen

2020

- This presentation is based on work within my recent masters thesis:

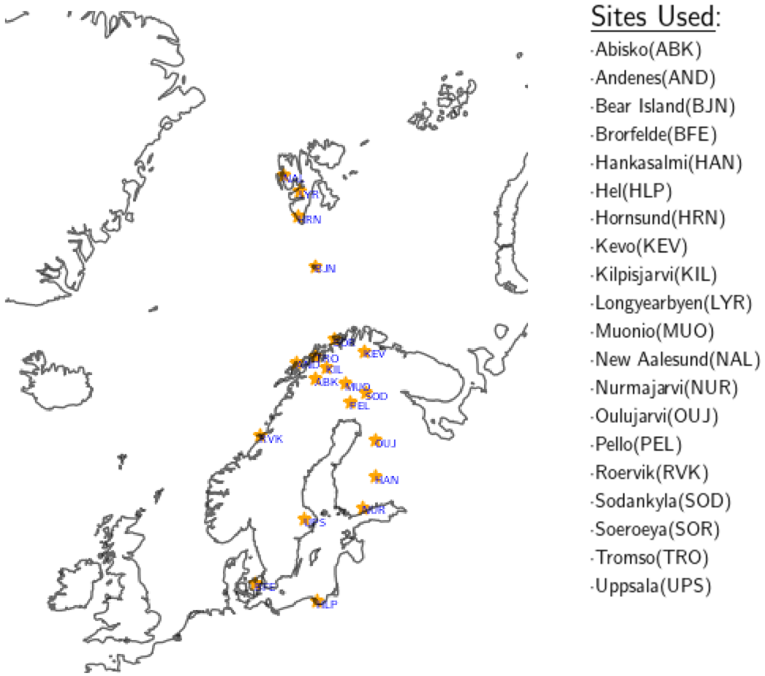
https://bora.uib.no/bora-xmlui/handle/11250/2716829

- Code written for modelling ionospheric currents using SECS is available in a public Github repository:

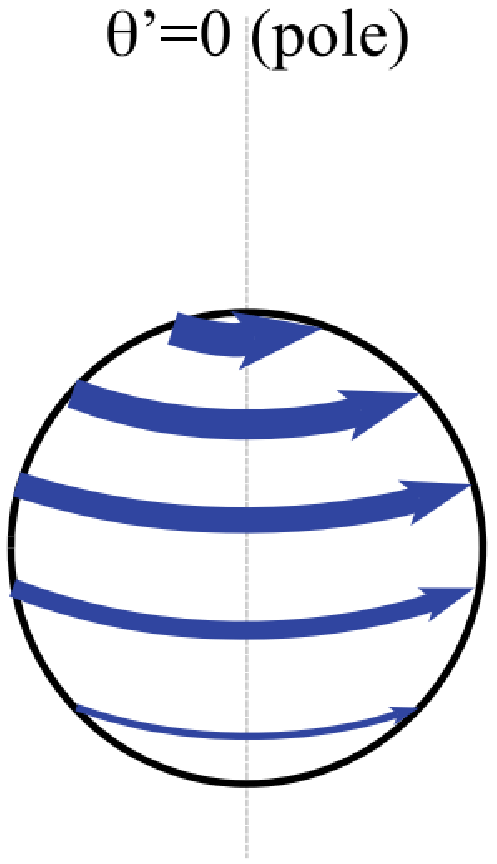
https://github.com/08walkersj/SECpy

Spherical Elementary Currents (SECS)

- This study utilises **divergence-free** (df) SECS to model the divergence-free currents that produce the magnetic perturbations seen on the ground.
- Due to the **longivity of data** coverage and **density of magnetometers, Fennoscandia** was the chosen region for this study



DF SECS



Divergence-free elementary system

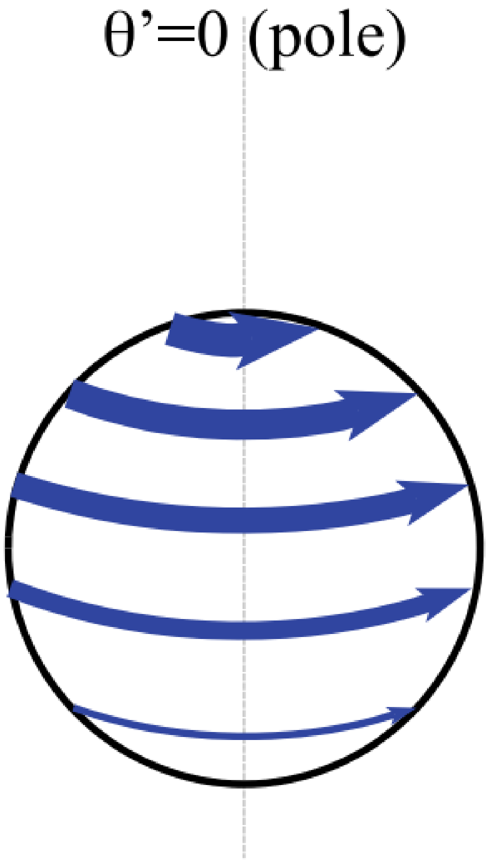
- A **divergence-free spherical elementary current system (SECS)** consists of a pole with a series of **closed circulating currents** (J_{df}) that **decrease** in **strength** with increasing co-latitude from the pole
- This system can then be **scaled by** an **amplitude** (I_0), adjusting the amplitude of the surrounding currents.

$$\mathbf{J}_{df}(\mathbf{r}') = \frac{I_{0,df}}{4\pi R_I} cot(\frac{\theta'}{2})\hat{\mathbf{e}}_{\phi'}$$

R_I: Radial position of the SECS pole (Usually the ionospheric current layer)
Θ': Co-latitude of the point of evaluation of the current from the SECS pole

Vanhamäki, H., & Juusola, L. (2020). Introduction to Spherical Elementary Current Systems. In *Ionospheric Multi-Spacecraft Analysis Tools* (pp. 5–33). Springer International Publishing. https://doi.org/10.1007/978-3-030-26732-2_2

DF SECS



Divergence-free elementary system

The **magnetic field** from the **divergence-free currents** surrounding a **SECS pole** can be found, again in terms of the pole:

$$\mathbf{B}_r^{DF}(r,\theta',\phi') = \frac{\mu_0 I_{0,df}}{4\pi r_m}\begin{cases} \frac{1}{\sqrt{1+(\frac{r_m}{R_I})^2-2(\frac{r_m}{R_I})cos(\theta')}} - 1, & r_m < R_I \\ \frac{\frac{R_I}{r_m}}{\sqrt{1+(\frac{R_I}{r_m})^2-2(\frac{R_I}{r_m})cos(\theta')}} - \frac{R_I}{r_m}, & r_m > R_I \end{cases}$$

$$\mathbf{B}_\theta^{DF}(r,\theta',\phi') = \frac{-\mu_0 I_{0,df}}{4\pi r_m sin(\theta')}\begin{cases} \frac{\frac{r_m}{R_I} - cos(\theta')}{\sqrt{1+(\frac{r_m}{R_I})^2-2(\frac{r_m}{R_I})cos(\theta')}} + cos(\theta'), & r_m < R_I \\ \frac{1-\frac{R_I}{r_m}cos(\theta')}{\sqrt{1+(\frac{R_I}{r_m})^2-2(\frac{R_I}{r_m})cos(\theta')}} - 1, & r_m > R_I \end{cases}$$

The **magnetic field** is **scaled by** the **amplitude** (I_0) the same as the currents.

r_m: radial position of the evaluation of the magnetic field

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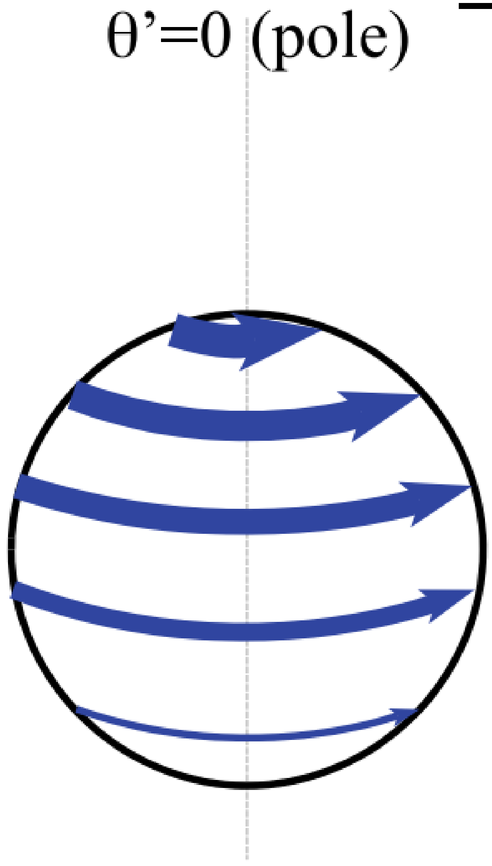
Superposition of SECS Poles



Divergence-free elementary system

- Using **multiple SECS poles** and the **superposition** of their currents, a complex current structure can be created by **varying the amplitudes** of each pole.
- The **superposition** can also be applied to the **magnetic field** of the SECS poles.
- This allows a current system created by the superposition of SECS poles to be **constrained by magnetic field measurements**

1. The currents and magnetic field of each pole must be converted into a global system (e.g. Geodetic)
2. The SEC pole amplitudes must be **related** to the **magnetic field** perturbations **measured** on the ground
3. The inversion must be **encouraged** towards a solution that creates **currents** that are **justified** by expectations from **theory**

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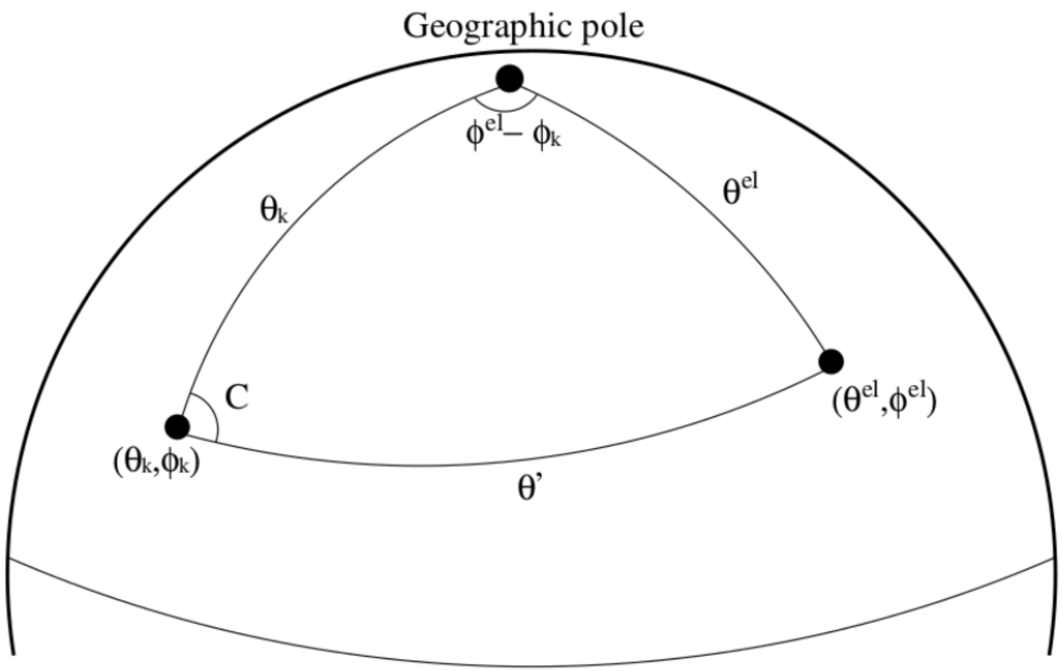
Conversion from Local to Global System



$$cos(\theta') = cos(\theta_k)cos(\theta^{el}) + sin(\theta_k)sin(\theta^{el})cos(\phi^{el} - \phi_k)$$

$$cos(C) = \frac{cos(\theta^{el}) - cos(\theta)cos(\theta')}{sin(\theta)sin(\theta')}$$

$$sin(C) = \frac{sin(\theta^{el})sin(\phi^{el} - \phi)}{sin(\theta')}$$

$$\hat{\mathbf{e}}_{\theta'} = \hat{\mathbf{e}}_{\theta}cos(C) - \hat{\mathbf{e}}_{\phi}sin(C)$$

$$\hat{\mathbf{e}}_{\phi'} = \hat{\mathbf{e}}_{\theta}sin(C) + \hat{\mathbf{e}}_{\phi}cos(C)$$

θ^{el} and ϕ^{el} are the global co-ordinates of the SEC pole, θ_k and ϕ_k are the global co-ordinates of the evaluated point and θ' is the colatitude of the evaluated point in terms of the SECS system co-ordinates

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Inversion

- The SECS pole amplitudes can be factorised out of the equations
- The remaining variables describe the geometry of the system
- The remaining variables are evaluated at the **location of the magnetometers** and **converted to a global system** (converting from being in a system relative to each SECS pole into a geographic system)
- This allows the problem to be set up to be described in terms of **matrices**

$$\boldsymbol{G}\mathbf{m} = \mathbf{d}$$

$$G = \begin{vmatrix} Ge_{11} & Ge_{12} & \Longrightarrow & Ge_{1p} \\ Ge_{21} & Ge_{22} & \Longrightarrow & Ge_{2p} \\ \Downarrow & \Downarrow & & \Downarrow \\ Ge_{m1} & Ge_{m2} & \Longrightarrow & Ge_{mp} \\ Gn_{11} & Gn_{12} & \Longrightarrow & Gn_{1p} \\ Gn_{21} & Gr_{22} & \Longrightarrow & Gn_{2p} \\ \Downarrow & \Downarrow & & \Downarrow \\ Gn_{m1} & Gn_{m2} & \Longrightarrow & Gn_{mp} \\ Gr_{11} & Gr_{12} & \Longrightarrow & Gr_{1p} \\ Gr_{21} & Gr_{22} & \Longrightarrow & Gr_{2p} \\ \Downarrow & \Downarrow & & \Downarrow \\ Gr_{m1} & Gr_{m2} & \Longrightarrow & Gr_{mp} \end{vmatrix}$$

Gx_{mp} contains the geometric information of magnetometer **m** in terms of pole **p** that will scale the effect of the magnetic perurtabation measured in the direction **x** on the amplitude of **p**

- Matrix **G** contains the geometry of the system (converted to produce geographic vectors)
- Vector **m** contains the amplitudes of each SECS pole (I_0 for each pole)
- **d** contains the measurements at each magnetometer station

By finding the **inverse of G**, the **SECS pole amplitudes can be found**. Therefore, the corresponding **divergence-free ionospheric current** that can produce the perturbations seen **can be found**

Helping the Inversion

- The nature of this type of modelling is that we have **more unknowns than knowns**
- This means that there are many current systems that could create the magnetic perturbations we see on the ground and, therefore, **many combinations of SECS pole amplitudes**
- The goal is to pick the combination of amplitudes that create a current that is closest to the **expected behaviour**
- Most studies use **truncated singular value decomposition**, this method will use an adjustable condition which controls how structured the currents will be
- Ground magnetometers are long distance from the ionospheric currents (typically 110km in altitude) and have a large seperation. This means that they are **unlikely to be able see small scale current structures**.
- **Encouraging currents to be less structured** is, therefore, justifiable

This study uses **regularisation** that both encourages the solution to be **less structured** but also **discourages variations in the magnetic east-west direction**

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Regularisation

- Inversions rely on a **cost function**, f_0, that must minimised to find the best solution.

$$f_0 = (\mathbf{d} - G\mathbf{m})^T(\mathbf{d} - G\mathbf{m})$$

- This standard cost function will minimise the **difference** between the **data** and the **model** (therefore finding the solution that matches the data most closely)
- On its own this will create **highly structured currents** in order match the magnetic perturbations as closely as possible

$$f = f_0 + \lambda_1 ||I\mathbf{m}||_2 + \lambda_2 ||L_e\mathbf{m}||_2$$

- This new cost function, f, contains the original cost function but adds two extra parameters to be minimised:

$\lambda_1 ||I\mathbf{m}||_2$ Has a scaling parameter λ_1 that controls how much it should be minimised. $||Im||_2$ is the euclidean norm of the pole amplitudes.

- By increasing λ_1, variations in the amplitudes over small spatial distances are discourage (**reducing the overall structure** of the currents)

$\lambda_2 ||L_e\mathbf{m}||_2$ Has a scaling parameter λ_2. $||Lem||_2$ is the euclidean norm of the gradient of the pole amplitudes in the magnetic east-west direction.

- By increasing λ_2, variations in the amplitudes in east to west are discouraged (**encouraging smooth currents** in the magnetic **east-west** direction)

Electrojet poleward boundary variations with IMF By and season- Regional Example

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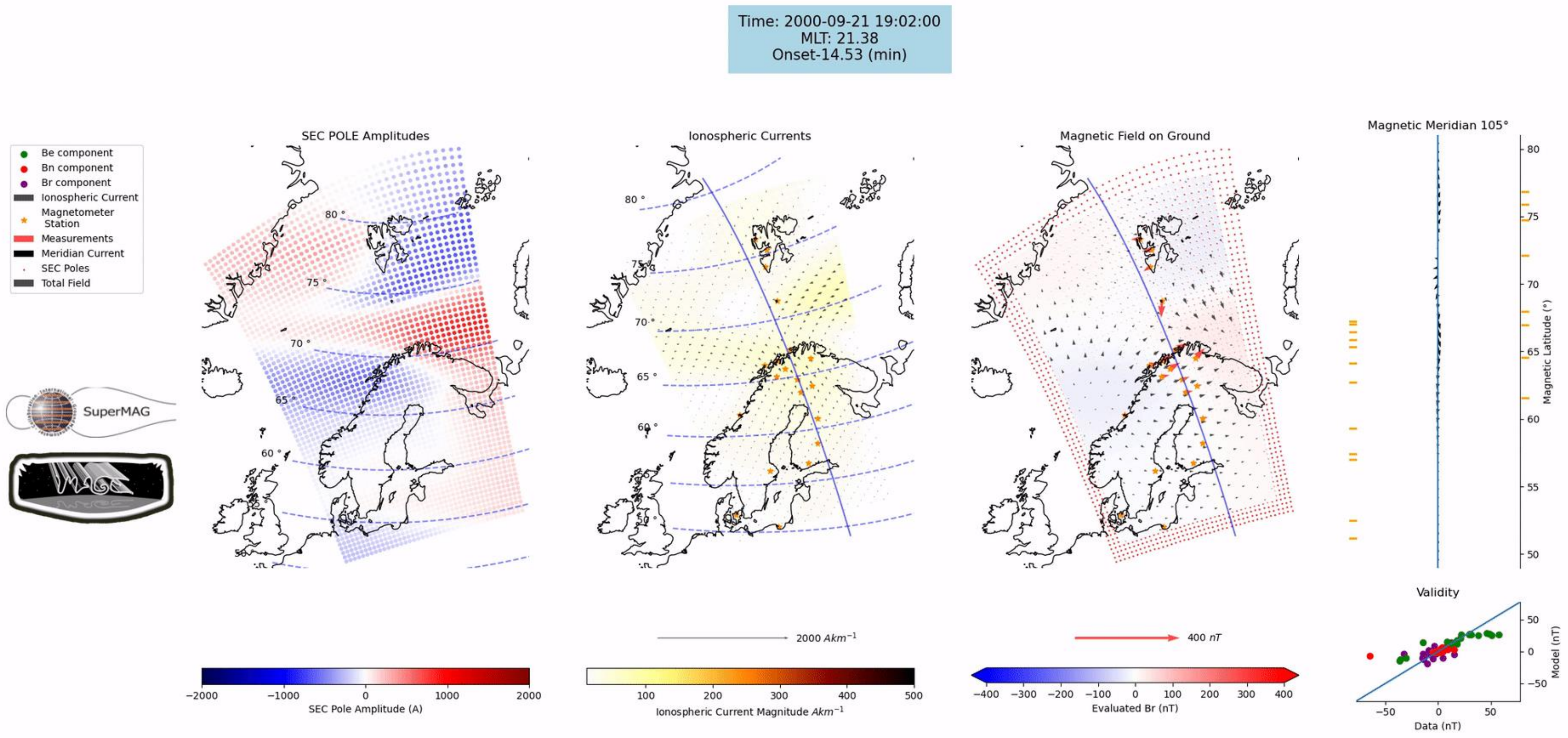

- This is a **substorm** occuring within the region of analysis.
- The currents in the magnetic east and north direction and radial component of the magnetic field (**B_r**) are evaluated along a magnetic meridian of **105^o mlon** for **each minute** when all chosen magnetometers are available which covers the period **2000-2019**.

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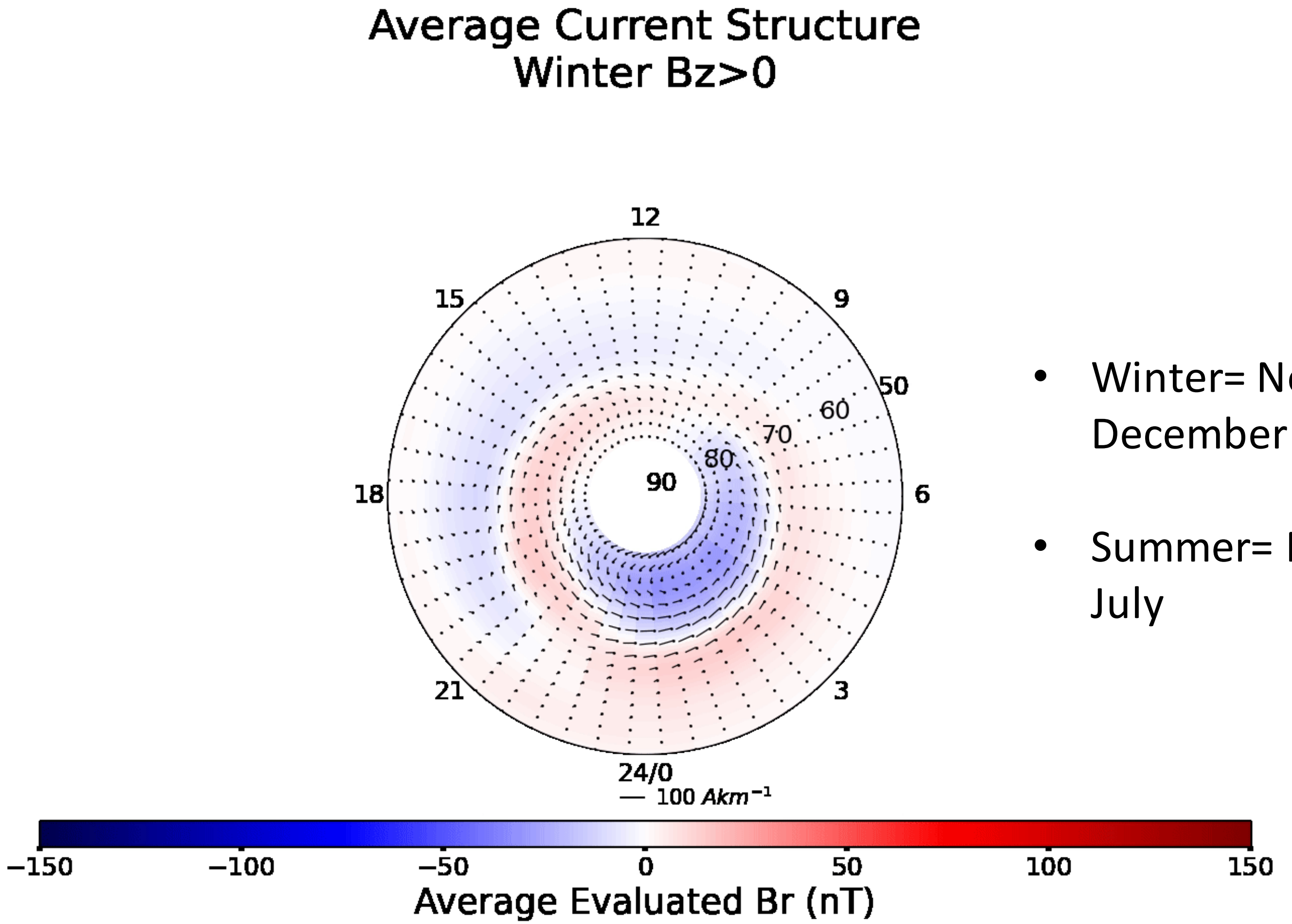
Using the magnetic meridian **all MLTs are scanned** and can produce a **statistical description** of the **divergence-free ionospheric currents** in the northern hemisphere



- Winter= November, December and January
- Summer= May, June and July

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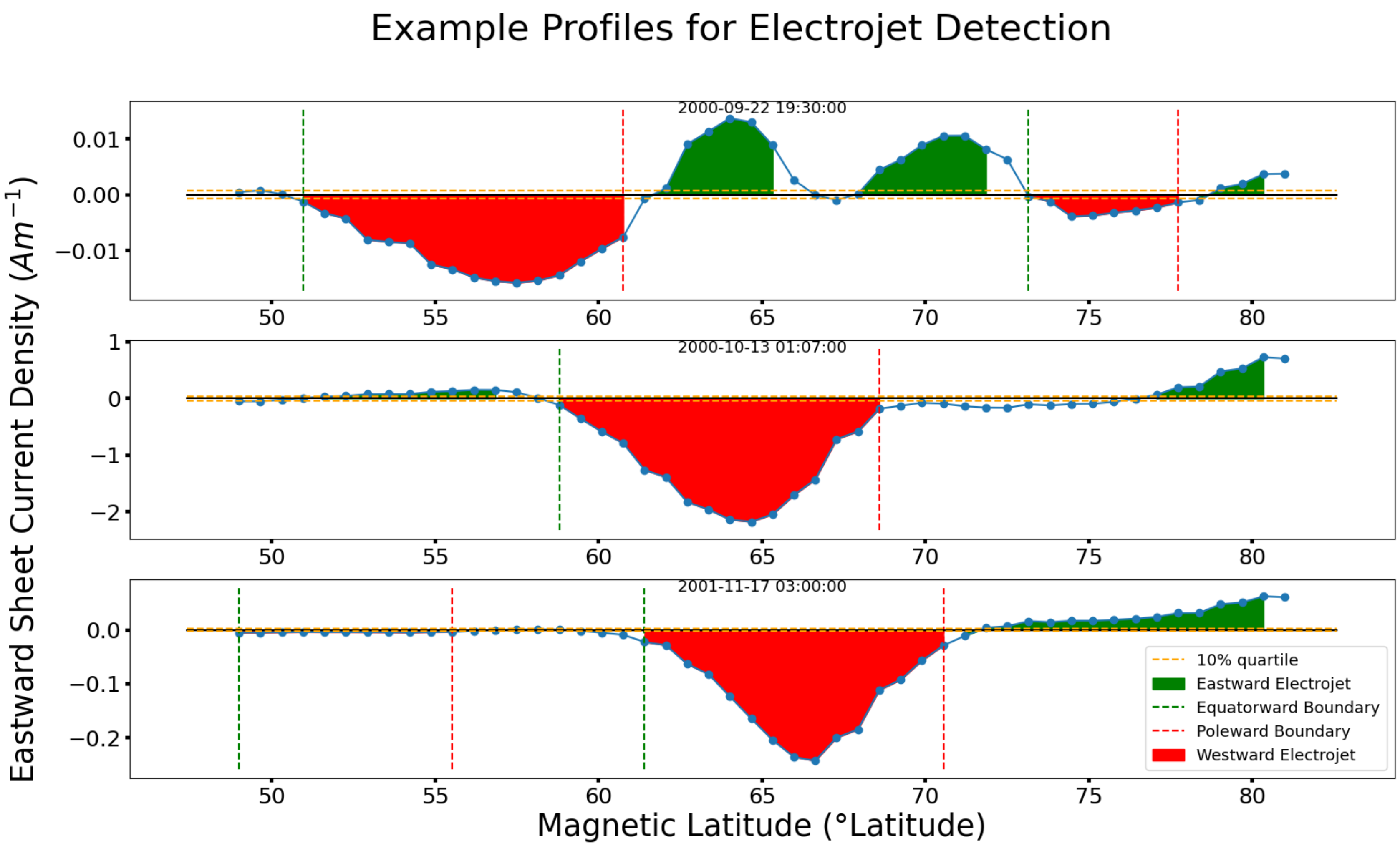

- From **each minute** of meridian currents, information on the **auroral electrojets** are extracted
- The electrojets are identified using a combination of **profile peak**, the **quantiles** and **gradients** within the profile.

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Properties found

The **three strongest** (indentified by peak sheet current value) **westward** and three strongest **eastward** electrojets in each profile have the following **properties** recorded:

- **Boundaries**:
  - The magnetic latitude of the **poleward** and **equatorward** boundaries of each electrojet are found using the electrojet detection algorithm
  - Units: $^{o}mlat$
- **Width**:
  - The width of each electrojet in magnetic latitude is recorded by finding the **difference** in the poleward and equatorward boundaries
  - Units: $^{o}mlat$
- **Peak**:
  - The peak of the profile between the boundaries (**peak sheet current density**) is found for each electrojet
  - Units: Am^{-1}
- **Total Current**
  - The total current of each electrojet is found by **integrating the profile** between the boundaries
  - Units: $^{o}mlatAm^{-1}$ (Is converted to just Amps when plotted)

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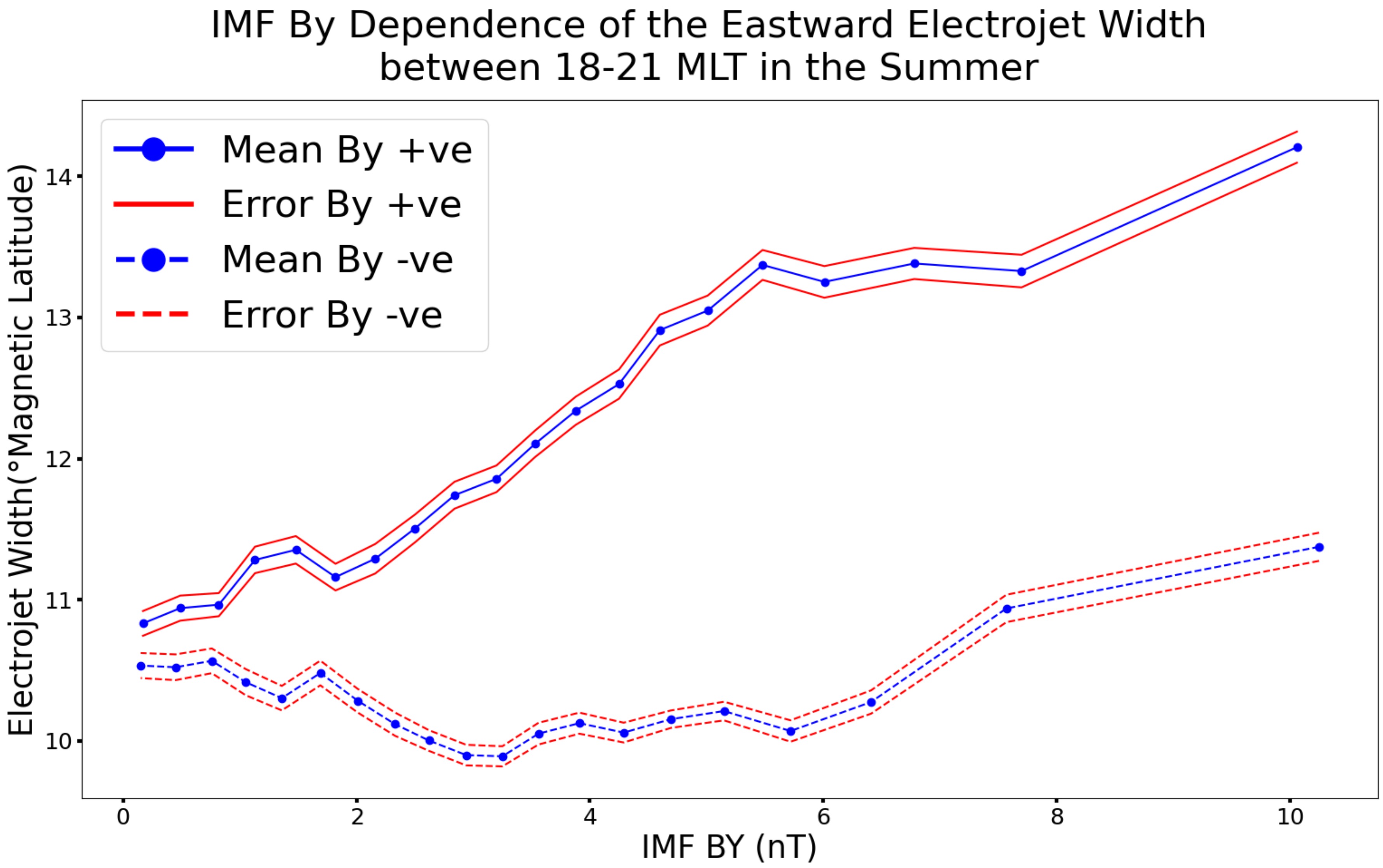
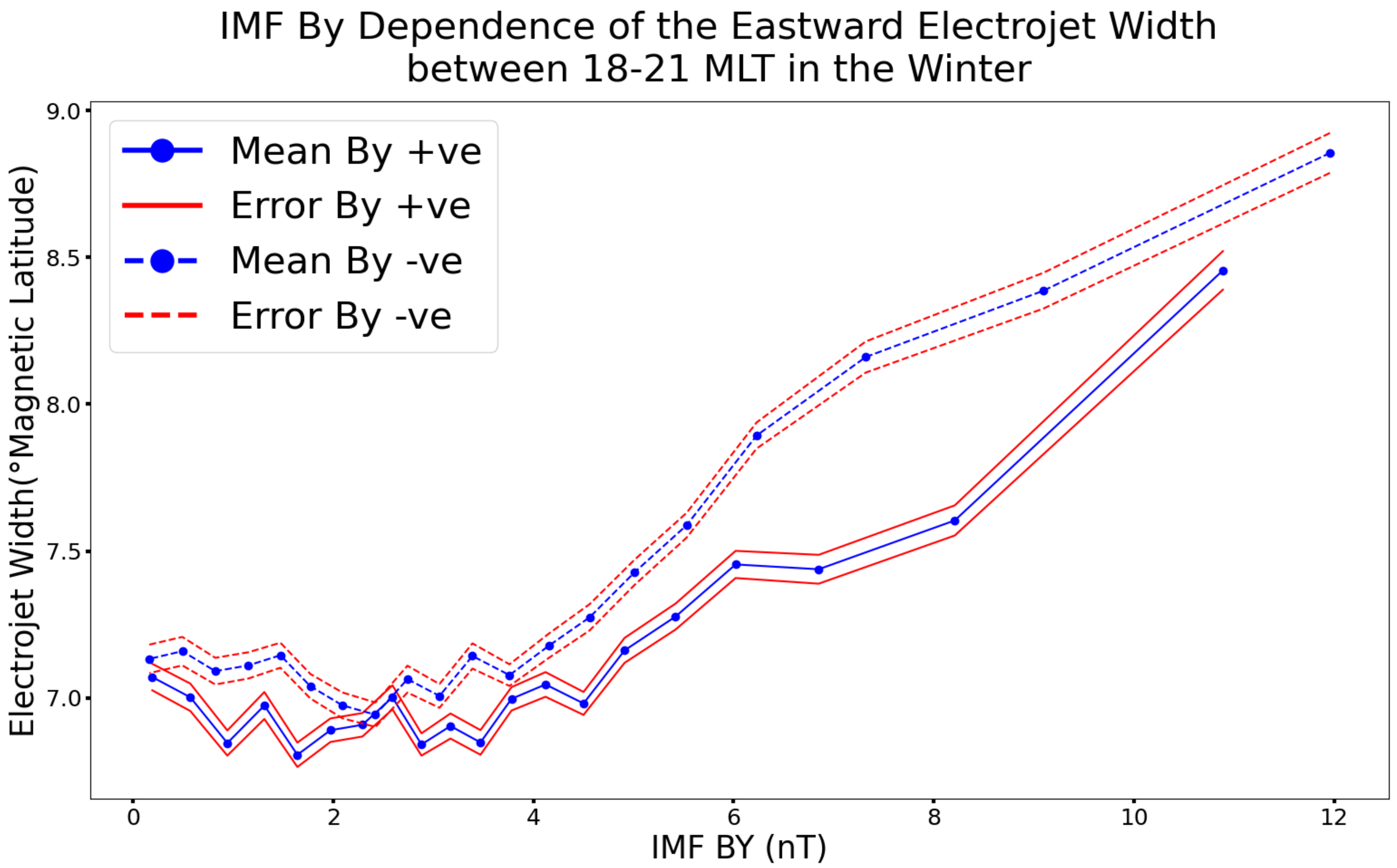
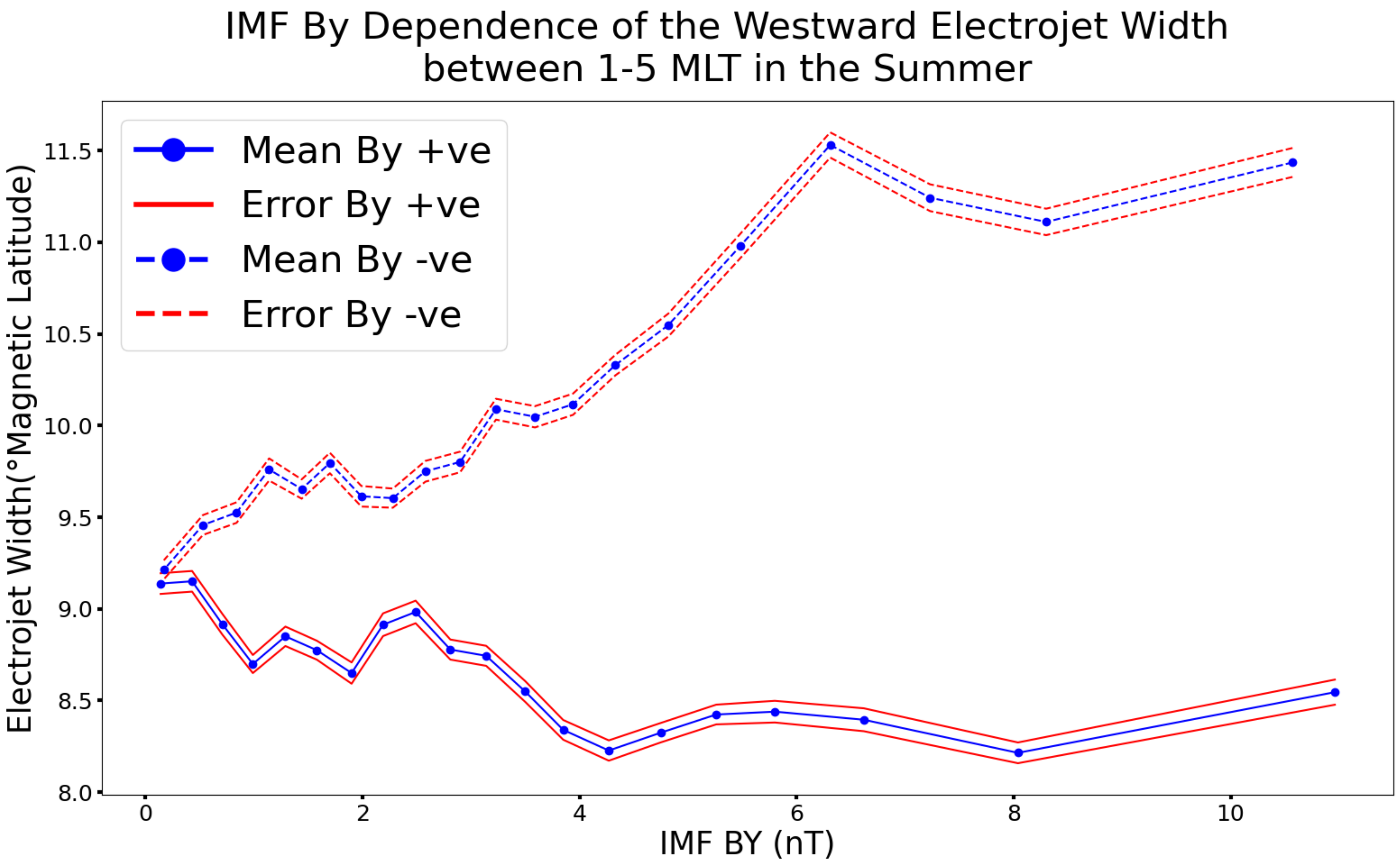
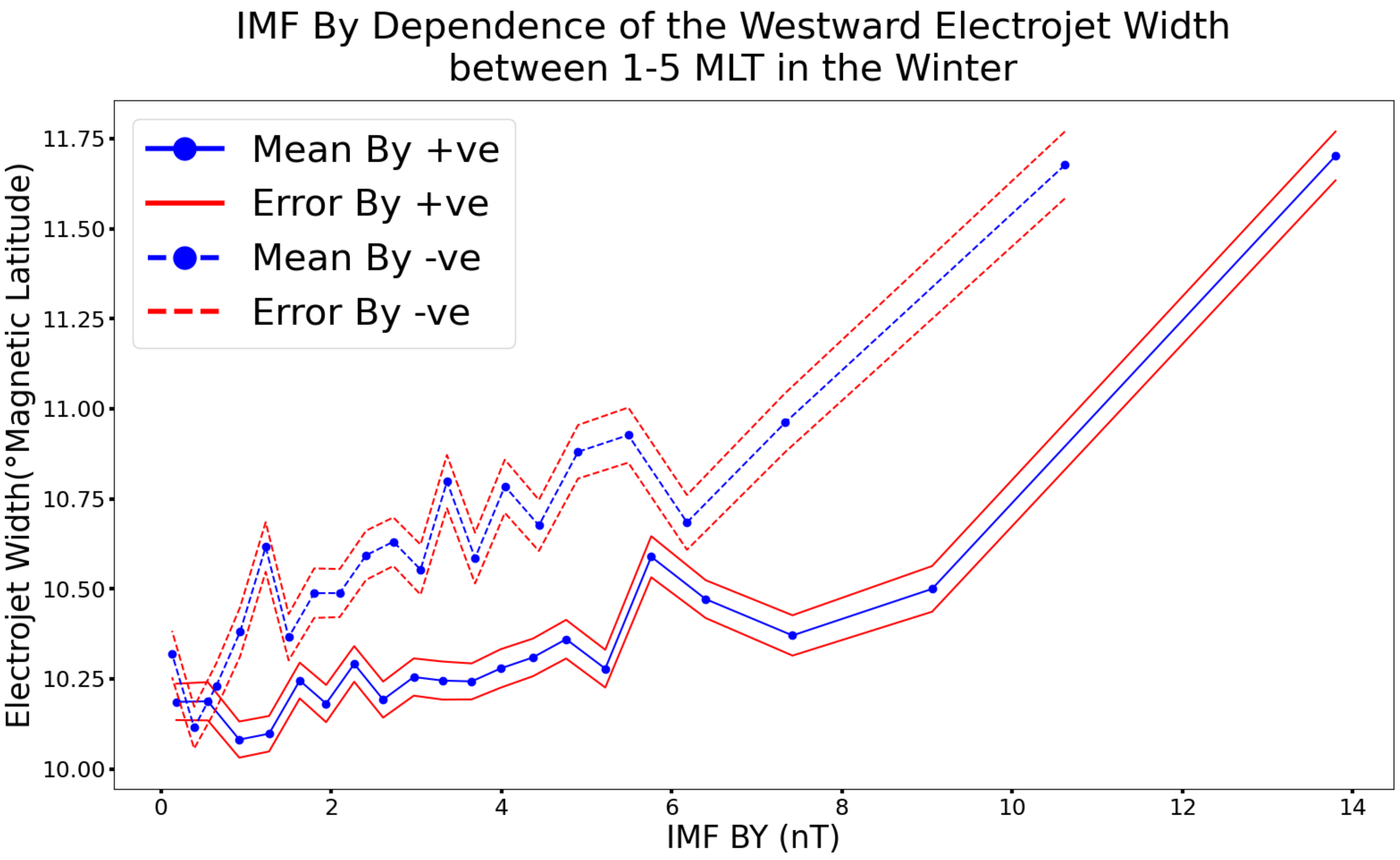
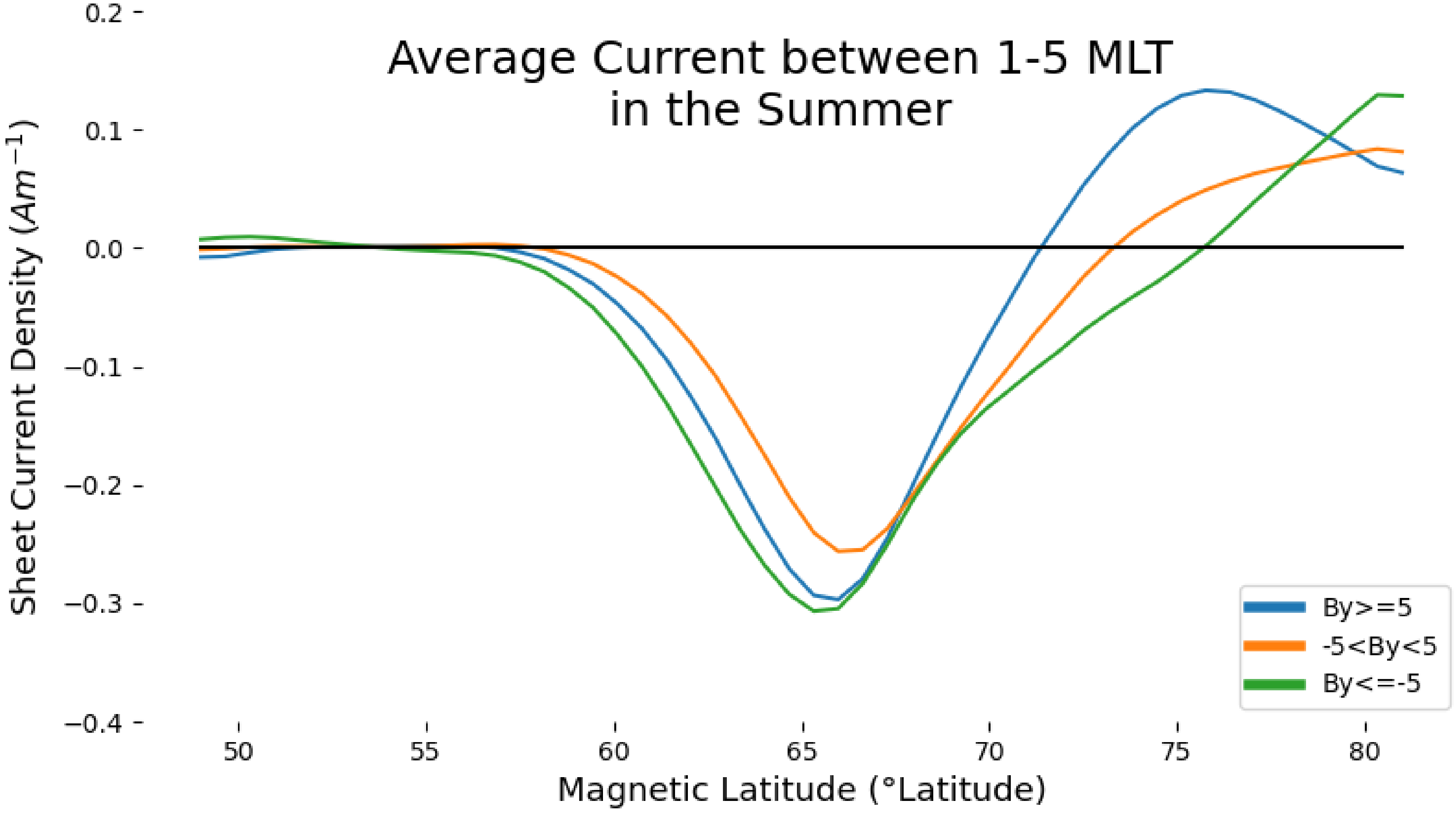


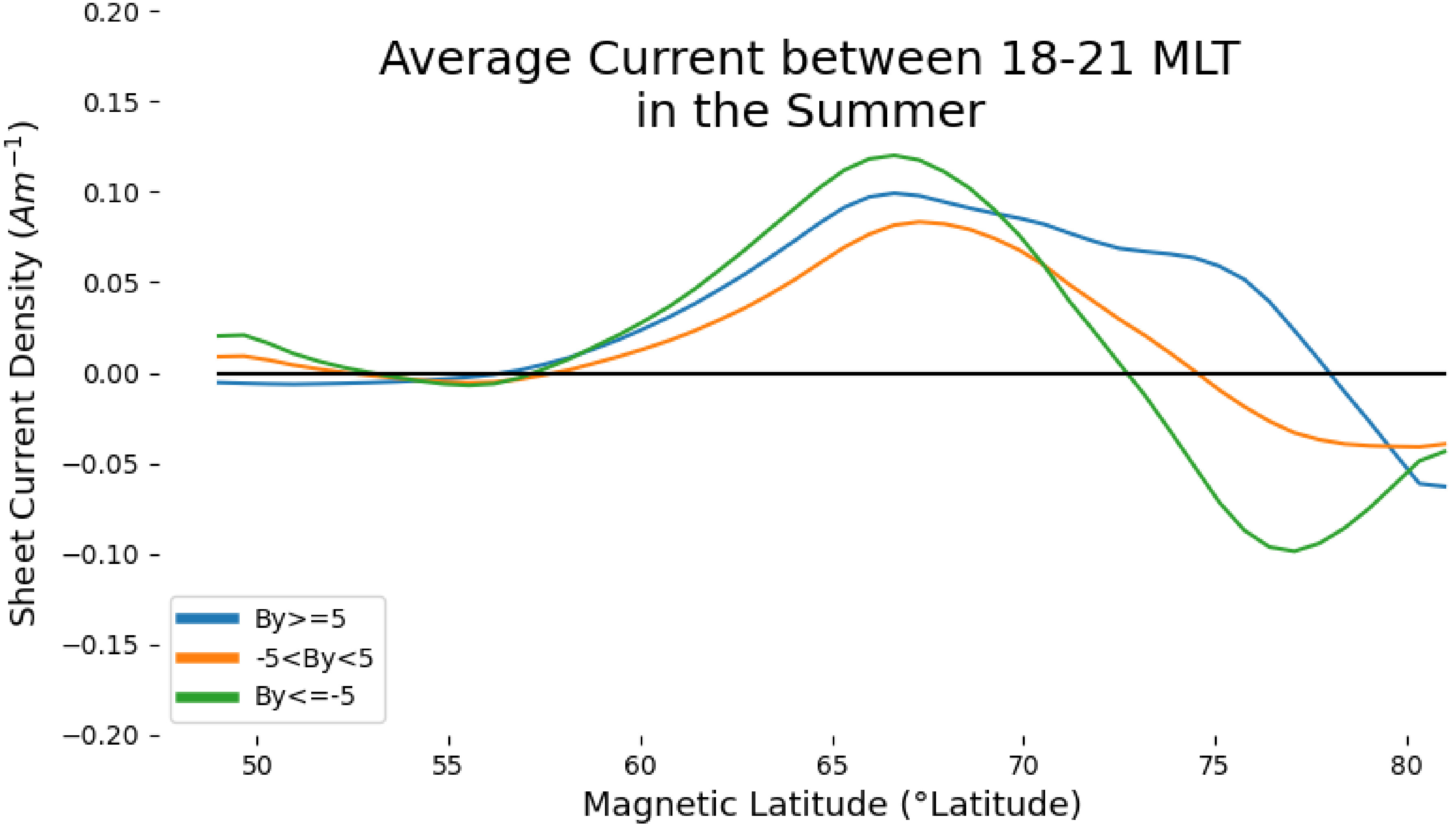

IMF By Dependence of the Eastward Electrojet Width
between 18-21 MLT in the Winter
Mean By +ve
Error By +ve
Mean By -ve
Error By -ve
Electrojet Width(°Magnetic Latitude)
9.0
8.5
8.0
7.5
7.0
0
2
4
6
8
10
12
IMF BY (nT)


IMF By Dependence of the Westward Electrojet Width
between 1-5 MLT in the Summer
Mean By +ve
Error By +ve
Mean By -ve
Error By -ve
Electrojet Width(°Magnetic Latitude)
11.5
11.0
10.5
10.0
9.5
9.0
8.5
8.0
0
2
4
6
8
10
IMF BY (nT)

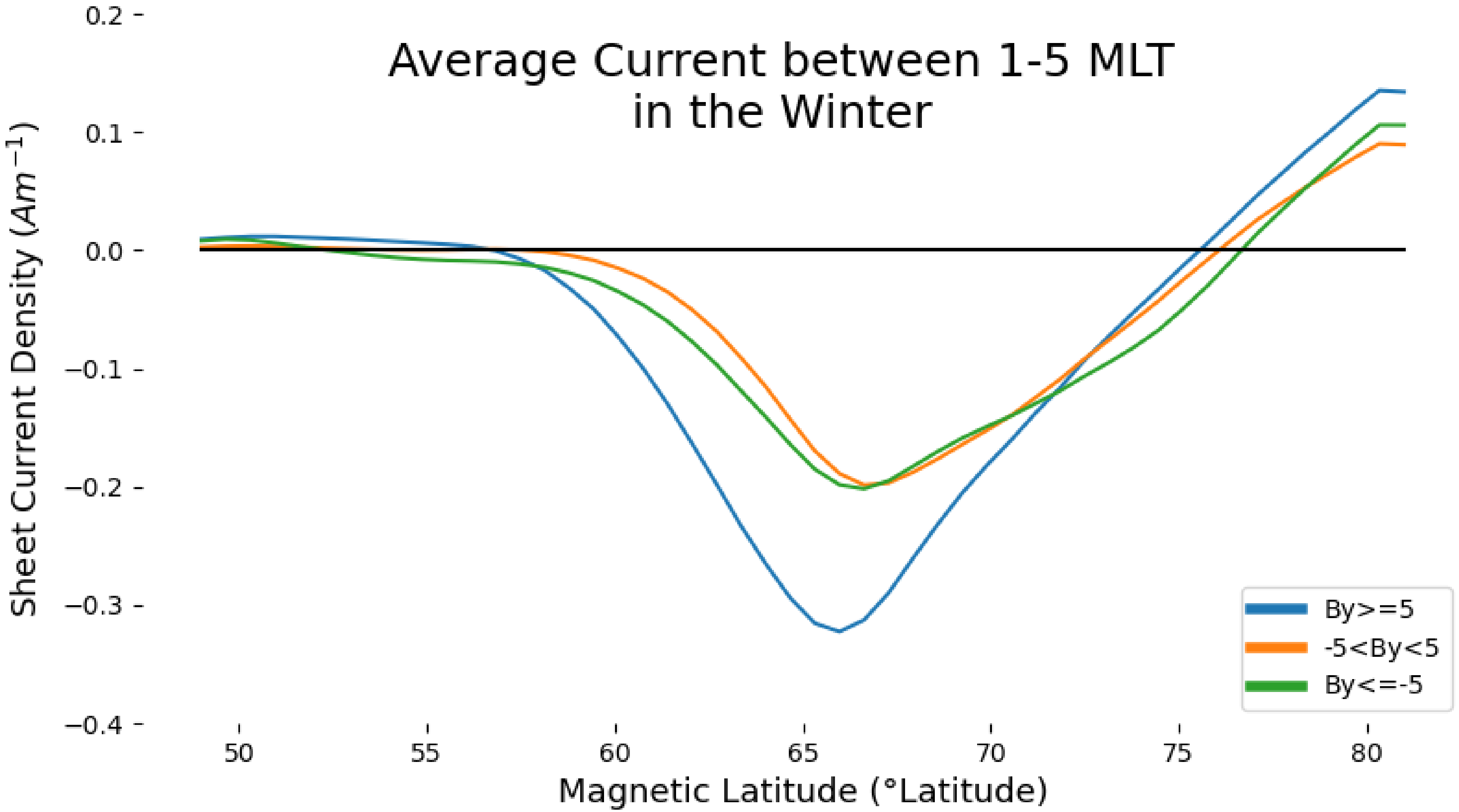

IMF By Dependence of the Westward Electrojet Width
between 1-5 MLT in the Winter
Mean By +ve
Error By +ve
Mean By -ve
Error By -ve
Electrojet Width(°Magnetic Latitude)
11.75
11.50
11.25
11.00
10.75
10.50
10.25
10.00
0
2
4
6
8
10
12
14
IMF BY (nT)

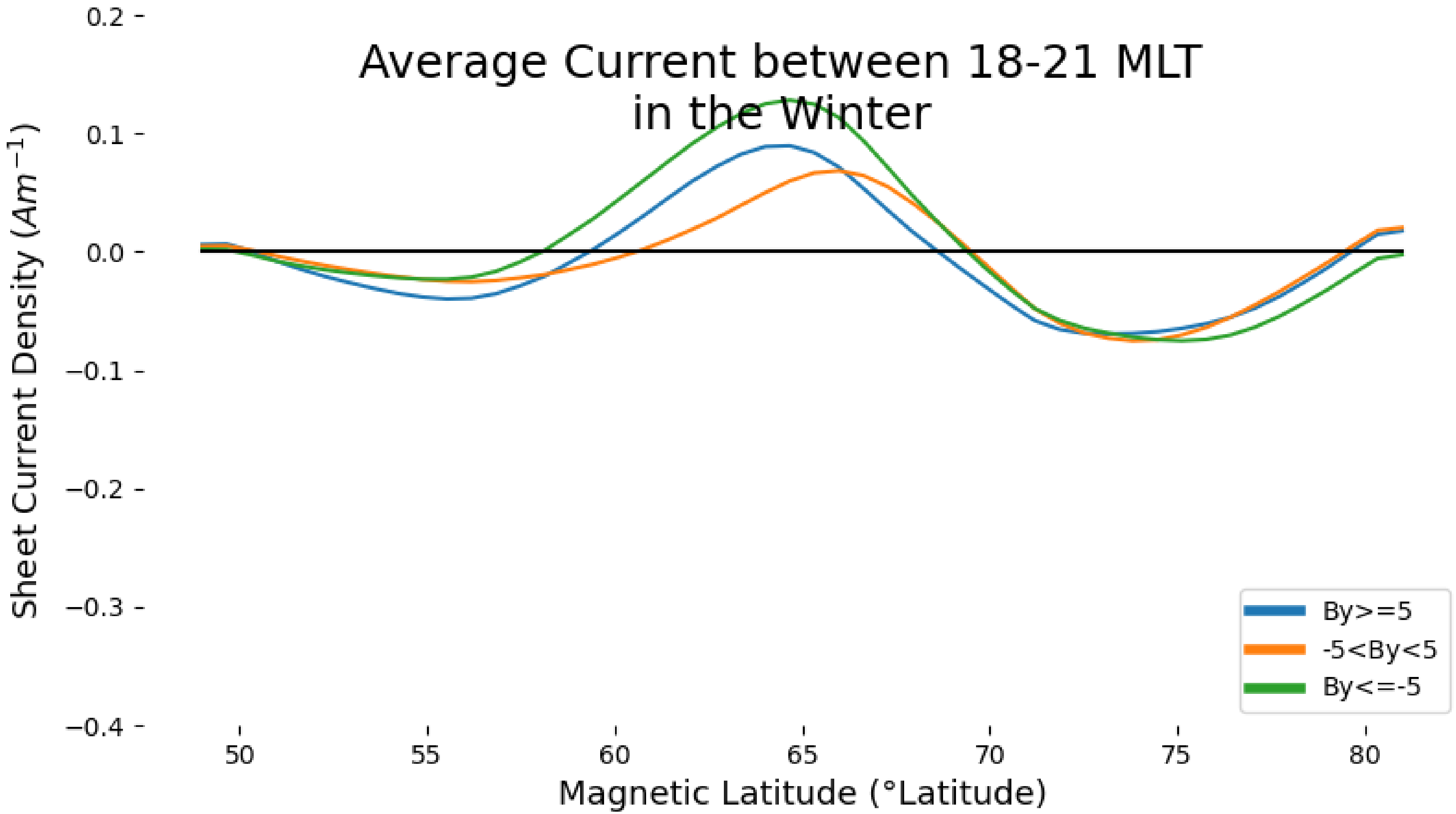
- There is a clear **By trend** for both electrojets during the **Summer** but **not during the Winter**
- To investigate this further the s**heet current density profiles,** that contribute to the properties being analysed, are **plotted**.


Average Current between 1-5 MLT
in the Summer
Sheet Current Density (Am^{-1})
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
50
55
60
65
70
75
80
Magnetic Latitude (°Latitude)
By>=5
-5<By<5
By<=-5



Average Current between 18-21 MLT
in the Summer
Sheet Current Density (Am^{-1})
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
−0.15
−0.20
50
55
60
65
70
75
80
Magnetic Latitude (°Latitude)
By>=5
-5<By<5
By<=-5


Average Current between 1-5 MLT
in the Winter
Sheet Current Density (Am^{-1})
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
50
55
60
65
70
75
80
Magnetic Latitude (°Latitude)
By>=5
-5<By<5
By<=-5


Average Current between 18-21 MLT in the Winter
Sheet Current Density (Am^{-1})
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
50
55
60
65
70
75
80
Magnetic Latitude (°Latitude)
By>=5
-5<By<5
By<=-5

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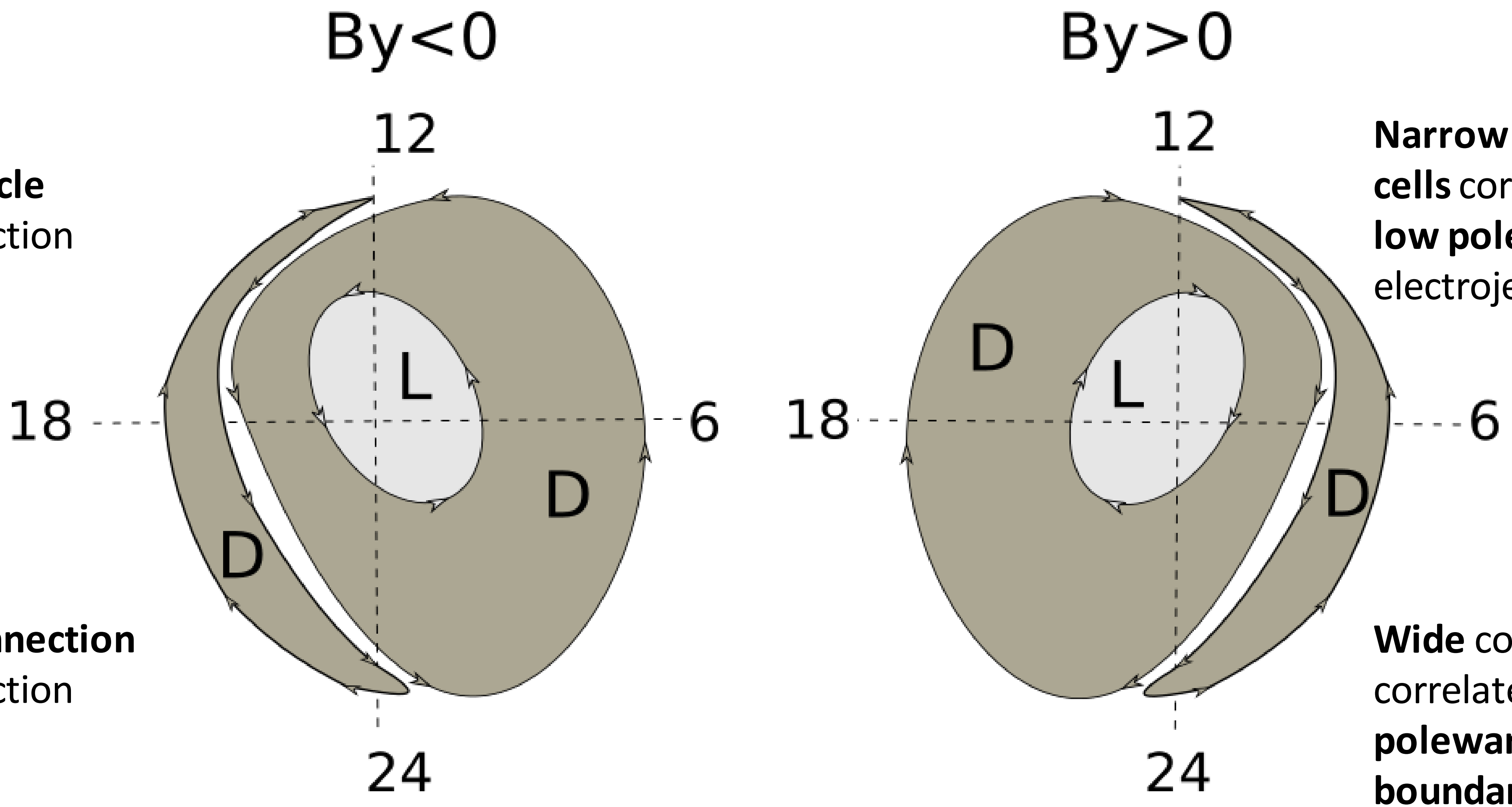
Results

- In the profile plots the **poleward edge** of the electrojet **shifts** due to **B_y** during the **Summer**
- This trend is **not** visible during the **Winter**.
- This **B_y** trend is **opposite** for the **eastward** and **westward** electrojets
- This leads to the idea that it may be a result of **convection patterns**
- The **seasonal trend** suggests the influence of **lobe reconection**
- A process that is more **dominant during the Summer** (+ve dipole tilt)

Lobe Reconnection Convection Cells

D: **Dungey cycle** driven convection cell

L: **Lobe reconnection** driven convection cell



Narrow convection **cells** correlate with a **low poleward** electrojet **boundary**

Wide convection **cells** correlate with a **higher poleward** electrojet **boundary**