A climatological model of the Equatorial Electrojet derived from Swarm satellite magnetic data

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Introduction

The Equatorial Electrojet (EEJ) is a strong horizontal electric current in the ionospheric dynamo region (about 115 km altitude), located on the dayside hemisphere above the magnetic dip equator. Latitudinal profiles of the electric sheet current density between $\pm 20^\circ$ magnetic (QD) latitude are provided as the *Swarm* Level-2 EEF data product for each of the three *Swarm* satellites. In this study we use an extended EEF data set for *Swarm* Alpha and Bravo spanning nine years, to derive a climatological model of the EEJ. This extended data set includes EEJ profiles not only during daytime (as in the operational EEF product) but for all Local Times. Our model includes dependencies on UT, longitude, season, EUVAC solar flux and lunar phase and is validated with independent data from *Swarm* Charlie and the CSES satellite.

Data

Profile measurements of satellite scalar magnetic data near the magnetic equator can be converted to latitudinal profiles of height-integrated EEJ sheet current densities **J** by applying the *Swarm DISC / SCARF* algorithm. Each of the resulting sheet current density profiles consists of 81 values spanning the QD-latitudes $-20.0^\circ, -19.5^\circ, -19.0^\circ, \ldots, -0.5^\circ, 0.0^\circ, +0.5^\circ, \ldots, +19.5^\circ, +20.0^\circ$. This algorithm has been applied to data collected by the:

- *Swarm* satellites (25 Nov 2013 – 25 Nov 2022): 32 equatorial crossings per day and satellite spanning all Local Times (LT);
- Chinese Seismo-Electromagnetic Satellite (CSES-01) (12 Jul 2018 – 30 Apr 2022): limited local time coverage (02/14 LT)

Model estimation is based on *Swarm* A and C EEJ current density estimates for all LT (extended dataset). **Model validation** is based on daytime *Swarm* B (operational L2 product) and CSES-01 estimates.

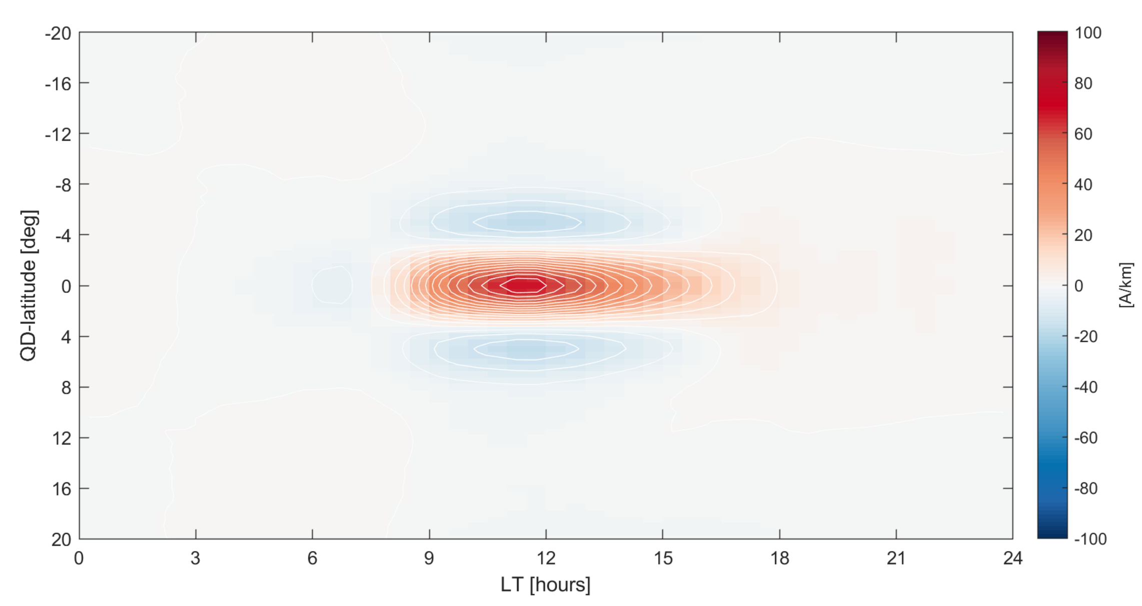

Figure 1: Mean EEJ sheet current density as a function of quasi-dipole latitude and Local Time T based on 9 years of magnetic data from *Swarm* A and B.

- Eastward 'main body' peaking at the dip equator (0° QD latitude) around local noontime
- 'Counter equatorial electrojet' during the morning hours (around 06 LT) and occasionally in the afternoon
- Reverse (westward) currents at $\pm 5^\circ$ QD latitude

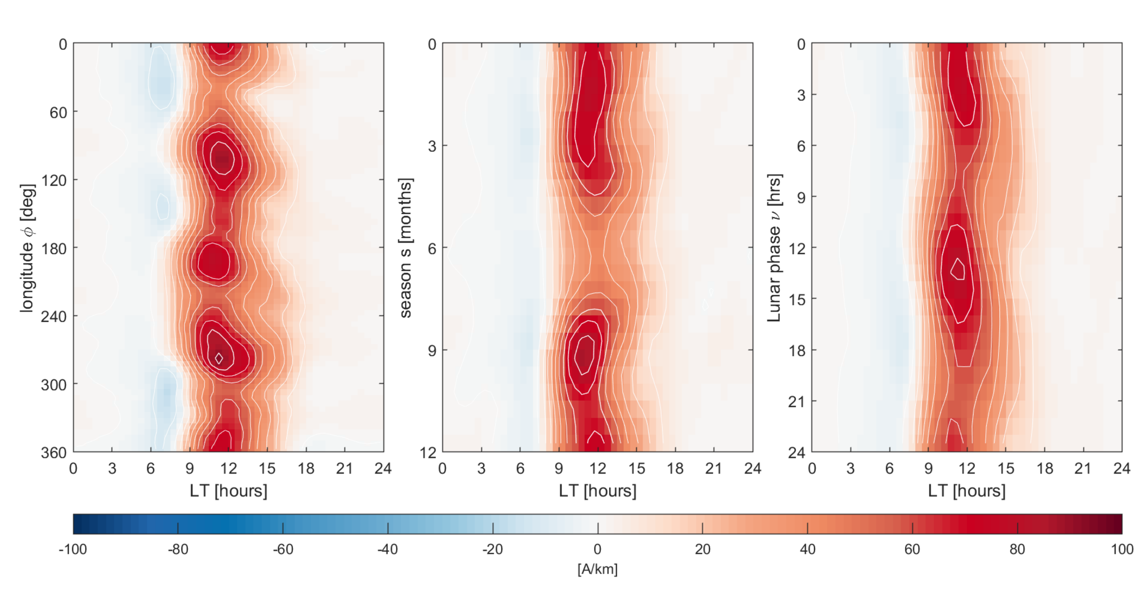

Figure 2: Left: Mean EEJ sheet current density at the dip-equator (0° QD latitude) as a function of Local Time T and longitude ϕ (left), season s (middle), and lunar phase ν, respectively.

- Wavenumber four longitudinal dependence
- Seasonal maxima around the equinoxes with secondary maximum during winter
- Maxima around New and Full Moon

Model parameterisation and model estimation

For a given (fixed) QD-latitude, the ionospheric sheet current density is expanded according to:

$$J(t, \phi, s, \nu, F_{10.7}) = (1 + R\, F_s) \times \sum_{p=0}^{n_t} \sum_{m=-n_\phi}^{n_\phi} \sum_{k=-n_s}^{n_s} \sum_{l \in I_{sel}} \Big[a_{p,m,k,l} \cos(pt + m\phi + ks + l\nu) + b_{p,m,k,l} \sin(pt + m\phi + ks + l\nu) \Big]$$

- t: Universal Time (UT) in radians
- ϕ: geographic longitude in radians
- s: season in radians, counted from 20 March ($s = 0$)
- ν: lunar phase in radians, where $\nu = 0$ corresponds to New Moon and $\nu = \pi$ is Full Moon
- F_s: solar flux proxy EUVAC in s.f.u. (solar flux units), defined as $F_s = (F_{10.7} + F_{10.7A})/2$, where $F_{10.7}$ is the 10.7 cm wavelengths daily solar flux and $F_{10.7A}$ is its 81-day running mean
- $n_t = n_s = n_\phi = 4$ and $I_{sel} = [0, -2]$

Disregarding invalid parameter combinations for p, m, k, l results in 1539 model parameters $a_{p,m,k,l}$, $b_{p,m,k,l}$ and R.

An iteratively-reweighted robust least-squares approach with Huber weights is used to estimate separate models for each of the 81 QD latitudes between -20° and $+20^\circ$.
Because of the co-estimation of the solar flux regression coefficient R and the Huber weighting, the inversion problem becomes slightly non-linear and is therefore solved iteratively.

Modelled EEJ sheet current densities

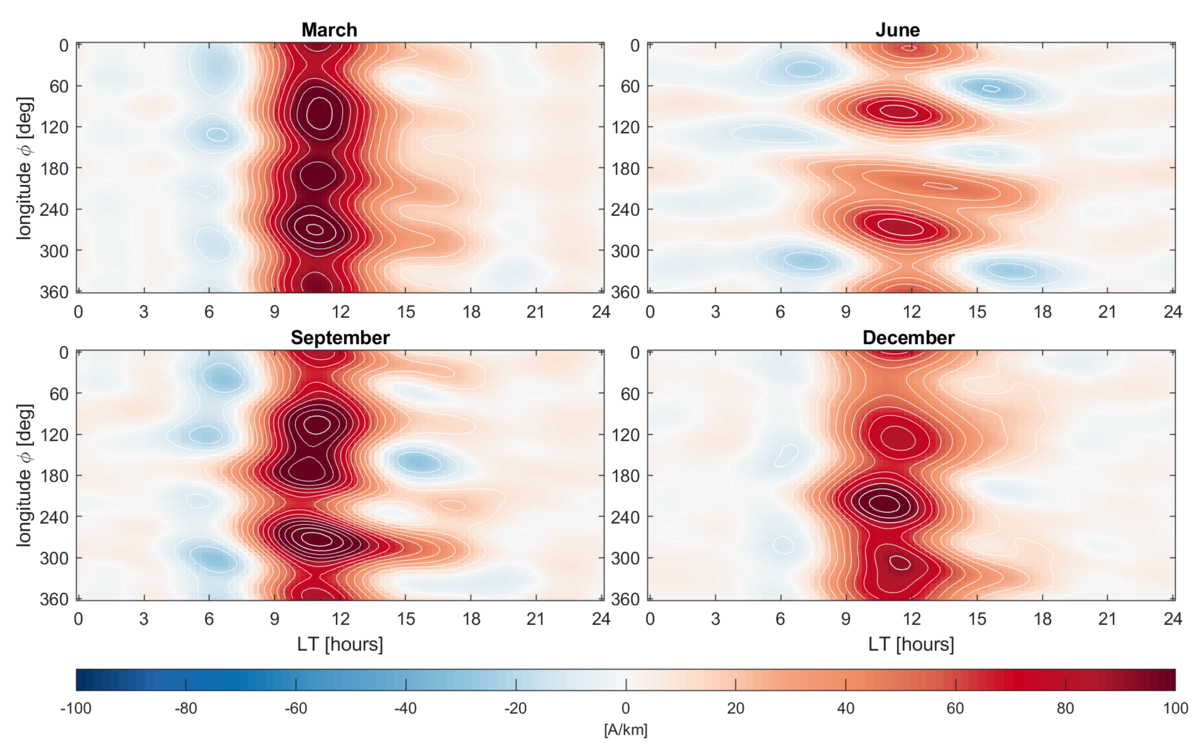

Figure 3: Model EEJ sheet current density at the dip-equator (QD-latitude = 0°) as a function of longitude ϕ and Local Time T, for different seasons and a mean solar flux of $\overline{F_s} = 100$ s.f.u.

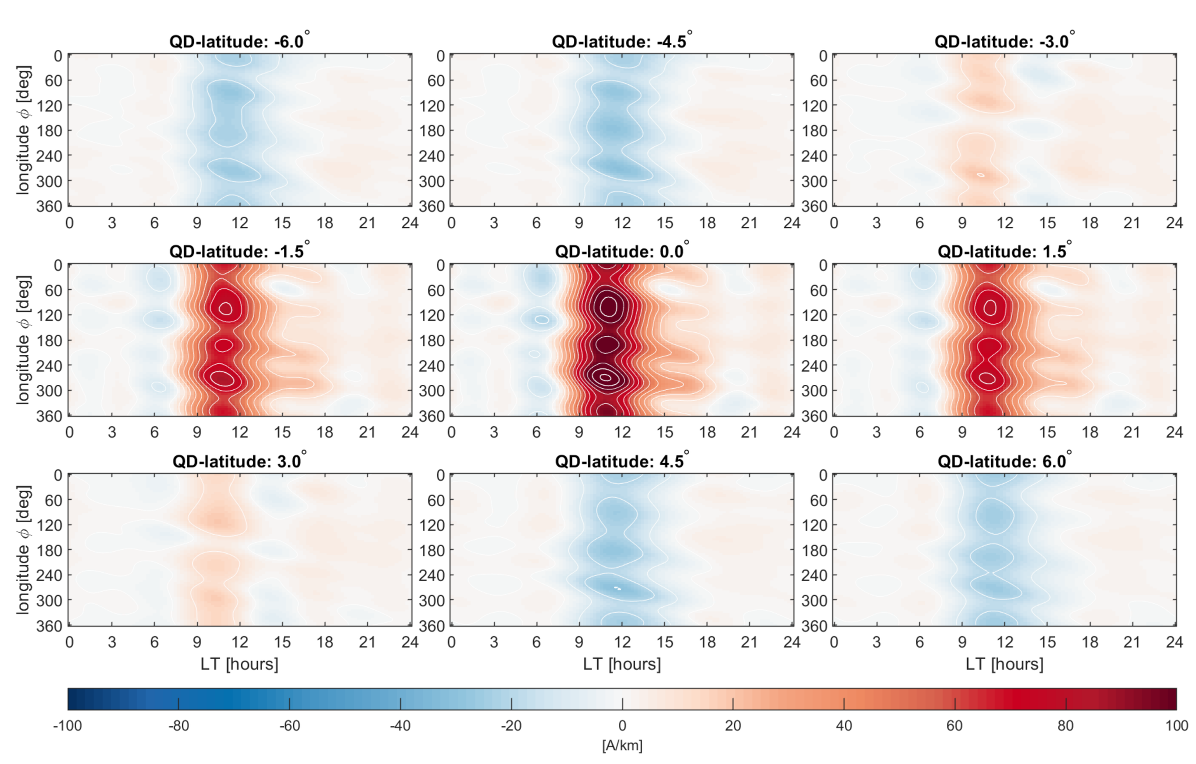

Figure 4: Model EEJ sheet current density as a function of longitude ϕ and Local Time T, for different QD-latitudes and a mean solar flux of $\overline{F_s} = 100$ s.f.u.

Model availability

Model coefficients and Matlab forward code available at `www.spacecenter.dk/files/magnetic-models/EEJ/` .

Model assessment

Fig. 5 shows the **M**ean **A**bsolute **D**eviation,

$$\mathrm{MAD} = \mathrm{median}\left\{ \sum_{i=1}^{N_{\mathrm{data}}} |r_i| \right\}$$

of the difference $\mathbf{r} = \mathbf{d} - \mathbf{d}^{\mathrm{mod}}$ between the N_{data} data points (the individual sheet current densities as given in the EEF data product), collected in **d**, and model predictions $\mathbf{d}^{\mathrm{mod}}$ for various data sets.
Compare with model predictions using EEJM-2.0 model (`https://geomag.org/models/EEJ.html`) based on CHAMP, Ørsted, and SAC-C satellite magnetic data.

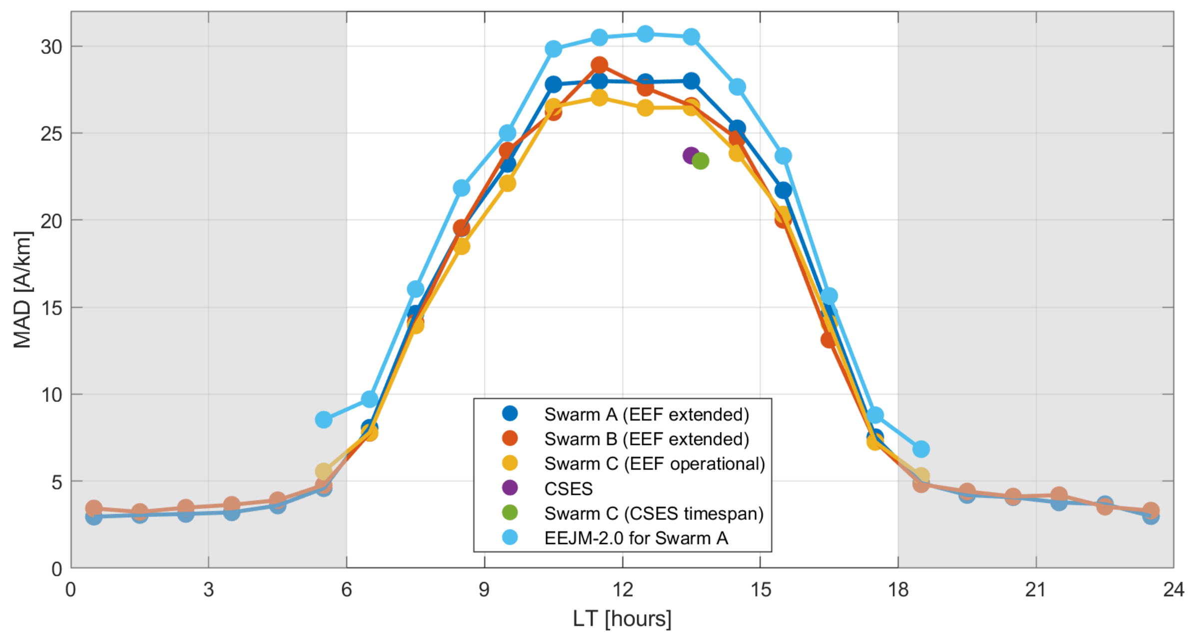

Figure 5: **M**ean **A**bsolute **D**eviation (MAD) of observations minus model predictions for the various data sets, as a function of Local Time.

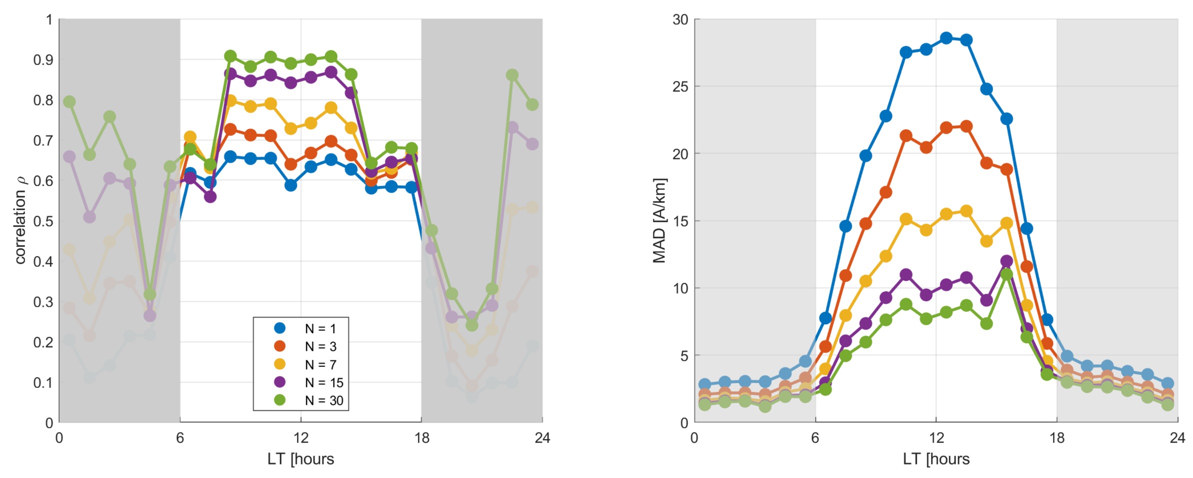

Figure 6: Model EEJ sheet current density as a function of longitude ϕ and Local Time T, for different QD-latitudes and a mean solar flux of $\overline{F_s} = 100$ s.f.u.

- Moving average over N values of observed as well as modelled time series (either ascending or descending tracks)
- Extract those parts of the time series that belong to a certain LT window and calculate *MAD* and correlations

Note that:

- Correlation of un-averaged time series around 0.6 at noon, with a *MAD* of approximately 27 A/km,
- Correlation increases and *MAD* decreases quite significantly when taking averages over neighbouring tracks,
- Low correlation for dusk, night and dawn,

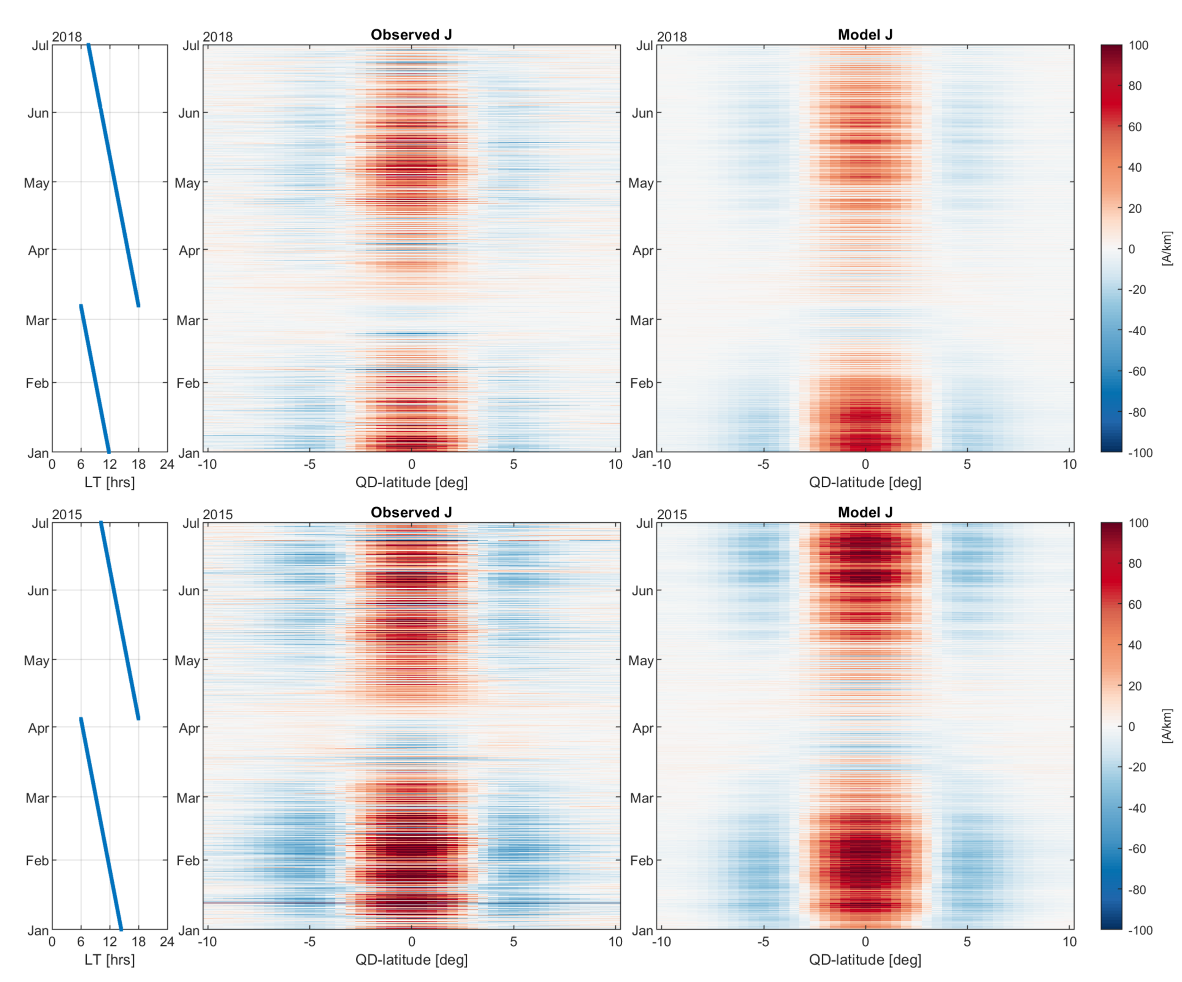

Figure 7: Observed and modelled current density for the first half of 2018 (solar minimum, average solar flux $\overline{F_s} = 71$ s.f.u., top), respectively 2015 (solar maximum, $\overline{F_s} = 128$ s.f.u., bottom).