Analysis of the Seasonal and Solar Effect on the Vertical Magnetic Transfer Function at Eskdalemuir Observatory

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AUTUMN MIST 2024

Magnetosphere, Ionosphere and Solar-Terrestrial

ABSTRACT In deep electromagnetic sounding, the vertical magnetic transfer function, or "tipper", relate the variations in the induced vertical magnetic field to the horizontal field components. They are sensitive to lateral contrasts in the subsurface electrical conductivity. The source of these fields are large-scale current systems in the ionosphere assumed to cause uniform magnetic field variations at mid-latitude. However, non-uniform source effects, e.g. related to increased geomagnetic activity due to strong solar winds, challenge this assumption and can bias tipper estimates. What do we do if this assumption breaks down? Taking advantage of the availability of high-quality geomagnetic observations at Eskdalemuir observatory in the Scottish borders (see Fig. 1), we attempt to investigate.

We analysed 1s and 1min magnetic field data from 2001-2019 and observed seasonal differences at Eskdalemuir for signal periods between 1000s and 10000s. In order to quantify the variations, we determined that the tipper estimate from 2016 winter data (during a period of minimal solar activity) forms a suitable baseline. To quantify daily tipper variability relative to this baseline we applied a simple empirical model dependent on either daily F10.7cm solar flux or daily geomagnetic index, A_p. Neither model fits to expected error, but the model parameterised by A_p produced a better fit to data. We observed dominant peaks in tipper deviations between summer and winter observations, indicating that long-period magnetotelluric (LMT) surveys collected over many months may be affected by seasonal field variations. We propose a correction based on our model using the daily A_p.

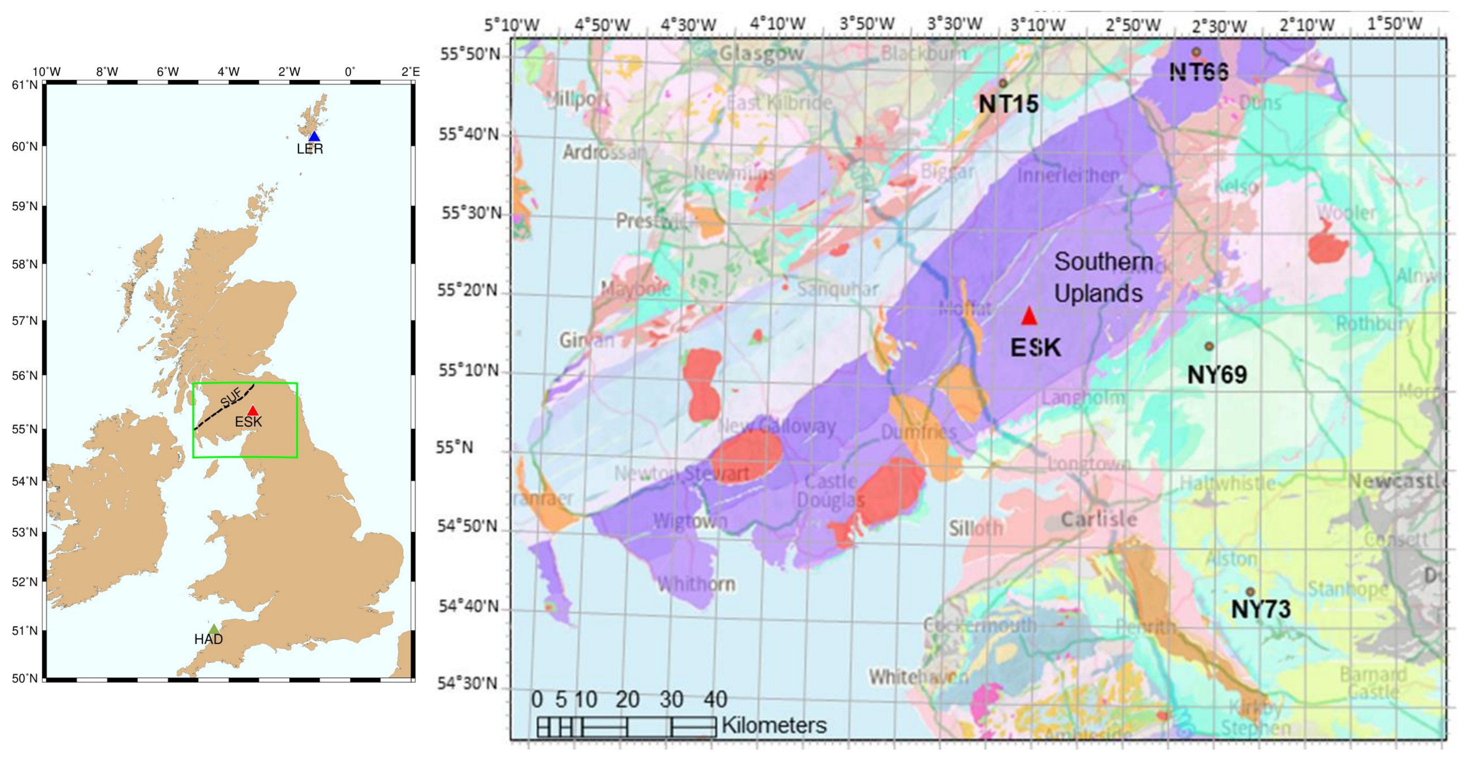

Figure 1. Location of ESK observatory, LMT sites and bedrock geology of the Southern Uplands, adapted from maps produced by the British Geological Survey. Inset shows the location of geomagnetic observatories at Lerwick (LER), ESK and Hartland (HAD) managed by BGS. LMT data were recorded for the SWIMMR-SAGE field campaign during 4-6 weeks in 2021-23 (Hübert et al., 2024). For geological legend check the BGS online store at https://www.bgs.ac.uk/map-viewers/bgs-geology-viewer/

1. The Vertical Magnetic Transfer Function 'Tipper'

The tipper is estimated from observations of the magnetic field variations and describes the ratio of the induced vertical component B_z to the variations in the horizontal magnetic field (B_x, B_y):

$$B_z(\omega) = T_x B_x(\omega) + T_y B_y(\omega) \qquad (1)$$

With $\omega = 2\pi T$. It is used to model subsurface electrical conductivity distributions. We use the magnetotelluric time series processing code by Smirnov (2008).

2.1 Stable Tipper Baseline at ESK

We want to study the seasonal changes of the tipper and therefore need to find a suitable baseline estimate.

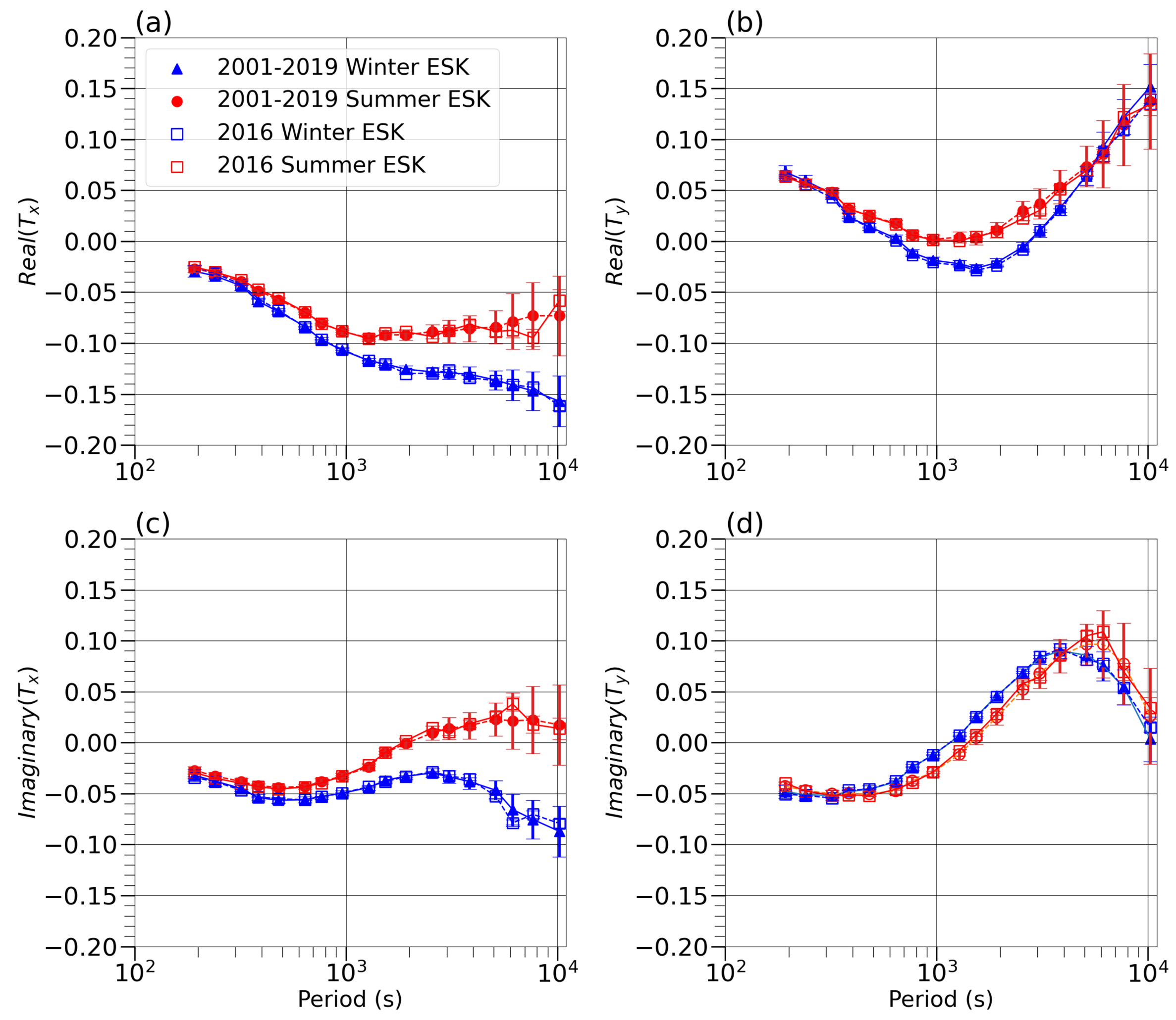

Figure 2. Real and imaginary components of the tipper estimated for 2001-2019 separately for summer (red circles connected by solid line) and winter (blue triangles connected by solid line). Results for 2016 are marked with open squares connected by dashed lines. We selected the winter 2016 estimate as our baseline.

2.2 Empirical Modelling Describing the Seasonal Changes of the Tipper in Relation to Solar Wind Activity

Next, we attempted to model the temporal variation of the tipper using a function with dependence on the day of the year (DOY) and the daily F10.7 flux (Vargas & Ritter, 2016) to analyse the long-term variability of the tipper relative to the stable baseline. The empirical contains 6 coefficients to be determined:

$$T_{source\ effect}(DOY, F10.7) = C_1 + C_2\left(\frac{2\pi \cdot DOY}{N} + C_3\right) + C_4\left(\frac{4\pi \cdot DOY}{N} + C_5\right) + C_6[F10.7] \qquad (2)$$

Equation (1) is adapted so that source effect is dependent on a geomagnetic index (daily definitive A_p) instead of F10.7 flux, so the fourth term in eq. (1) becomes $C_6[A_p]$.

2.3 Predicting the Seasonal Changes in the Tipper at ESK Observatory

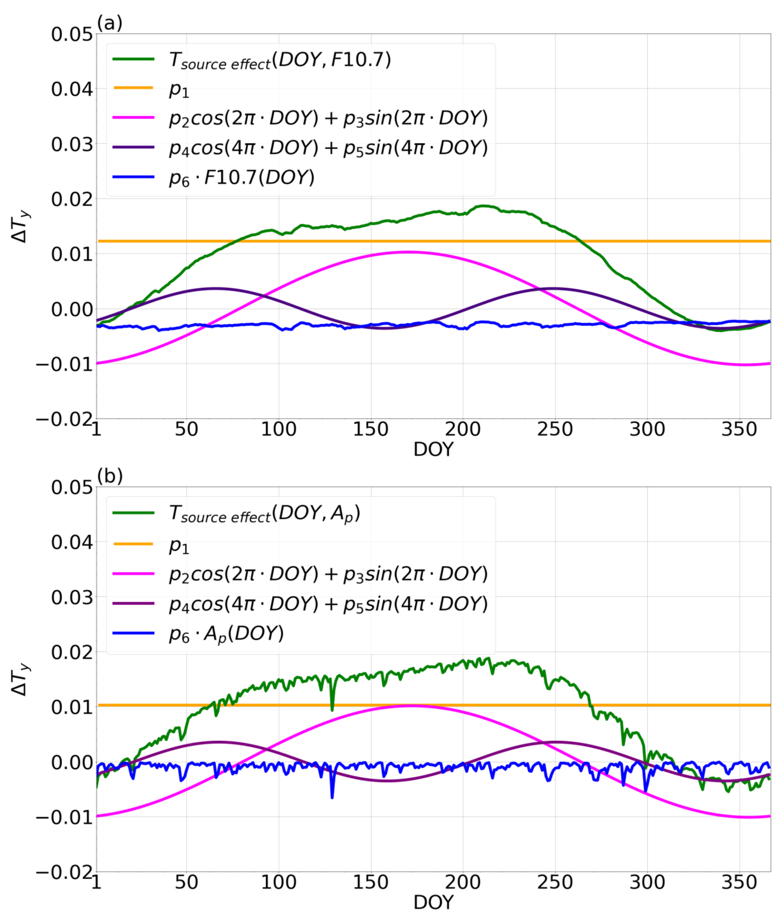

Figure 3. (a) The $Re(T_y)$ source effect prediction at T = 682s of modelled annual and semi-annual contributions, in addition to the offset (red) and the solar wind terms in equation (1). Daily tipper deviations are relative to the 2016 winter baseline using F10.7 . (b) Same as part (a) but using A_p index as per equation (2).

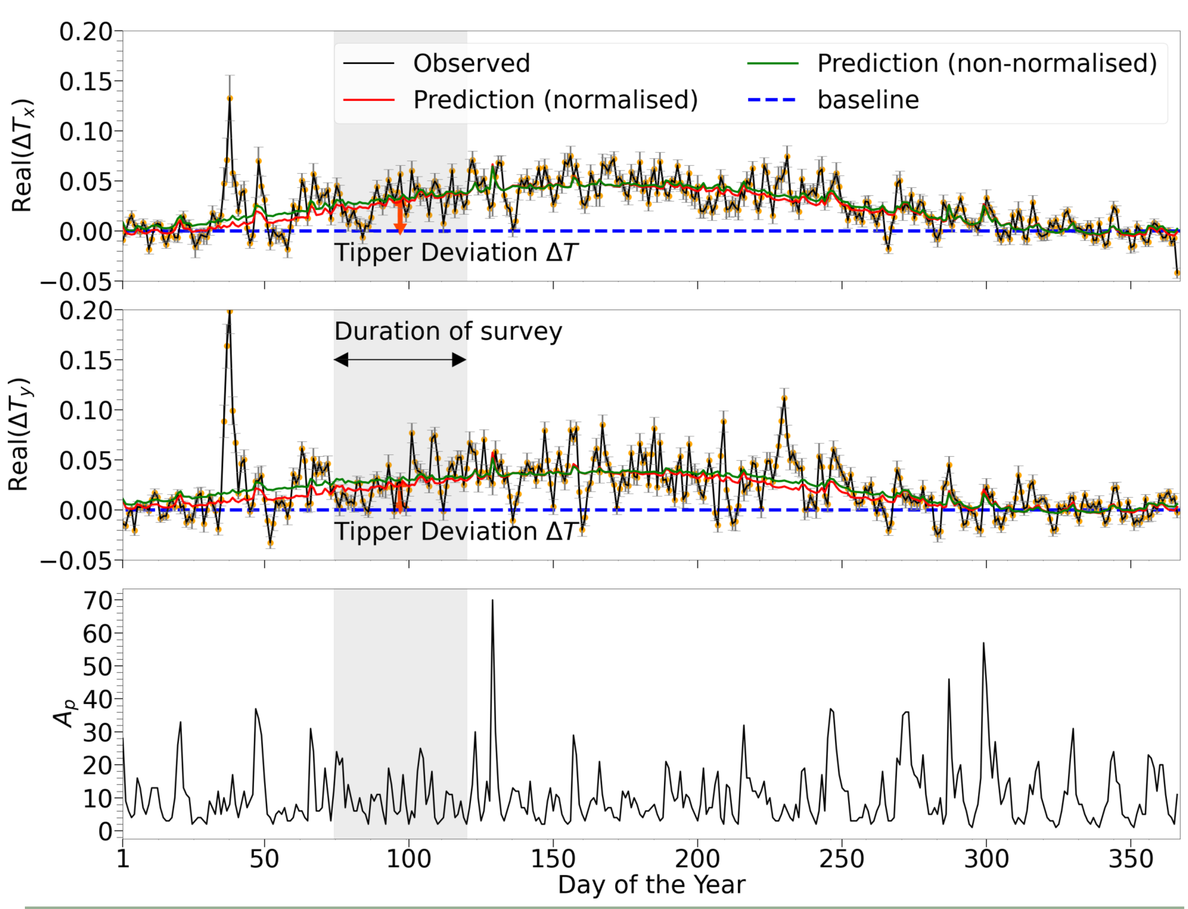

Figure 4. Prediction generated from the normalised and non-normalised solutions of the daily tipper deviation relative to the 2016 winter baseline at 2048s.

Modelling tipper changes throughout the year helps identify weeks with minimal external field influence on vertical magnetic field variations, allowing tipper to better represent subsurface electrical conductivity. We predicted tipper deviation produced for 2016 (Fig. 4).

3.1 Correcting the Seasonal Effect in SAGE data

This model was applied to LMT data collected at sites surrounding ESK (see Fig. 1), with the intention to correct for the seasonal effects. We chose the mid date of each survey period as the correction time (Fig.4.). To illustrate the results, Fig.5 shows the original and corrected tipper for T=2048s estimates as induction arrows (Parkinson convention: Real induction arrows point towards the conductors). Fig.6 shows the data fit of both the model using F10.7 and the daily A_p. Data are fitted better using daily A_p better, especially during geomagnetic storms.

3.2 SAGE LMT Data

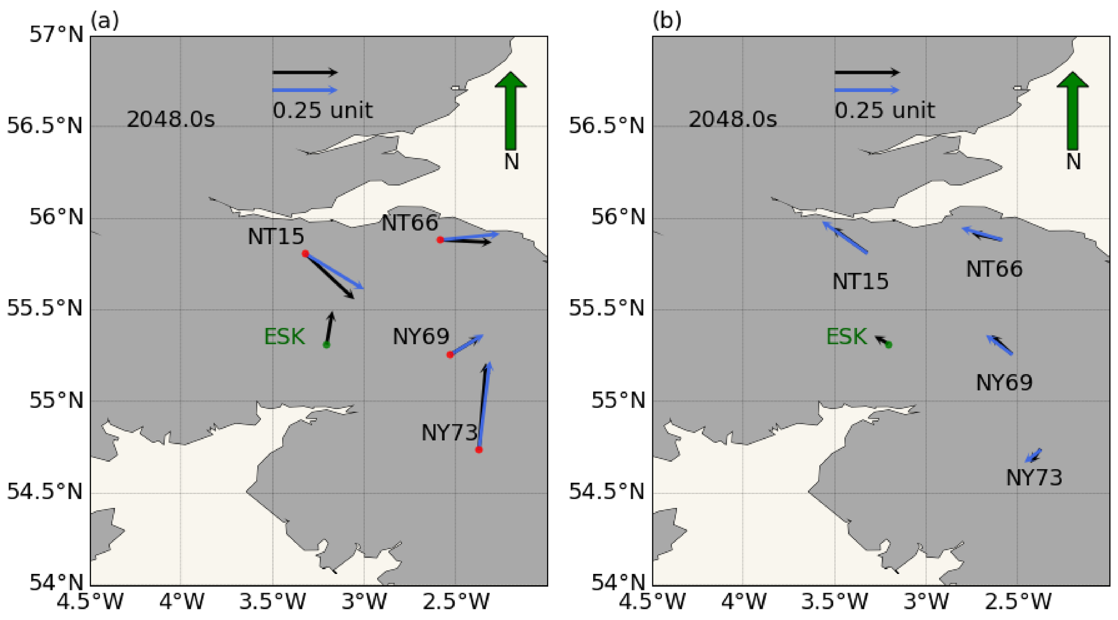

Figure 5. Tipper estimates for T = 2048s displayed as induction arrows (Parkinson convention pointing towards conductor) at ESK and nearby LMT sites, corrected arrows are in black, uncorrected are in blue. ESK arrows are not corrected (a) Real (b). Imaginary.

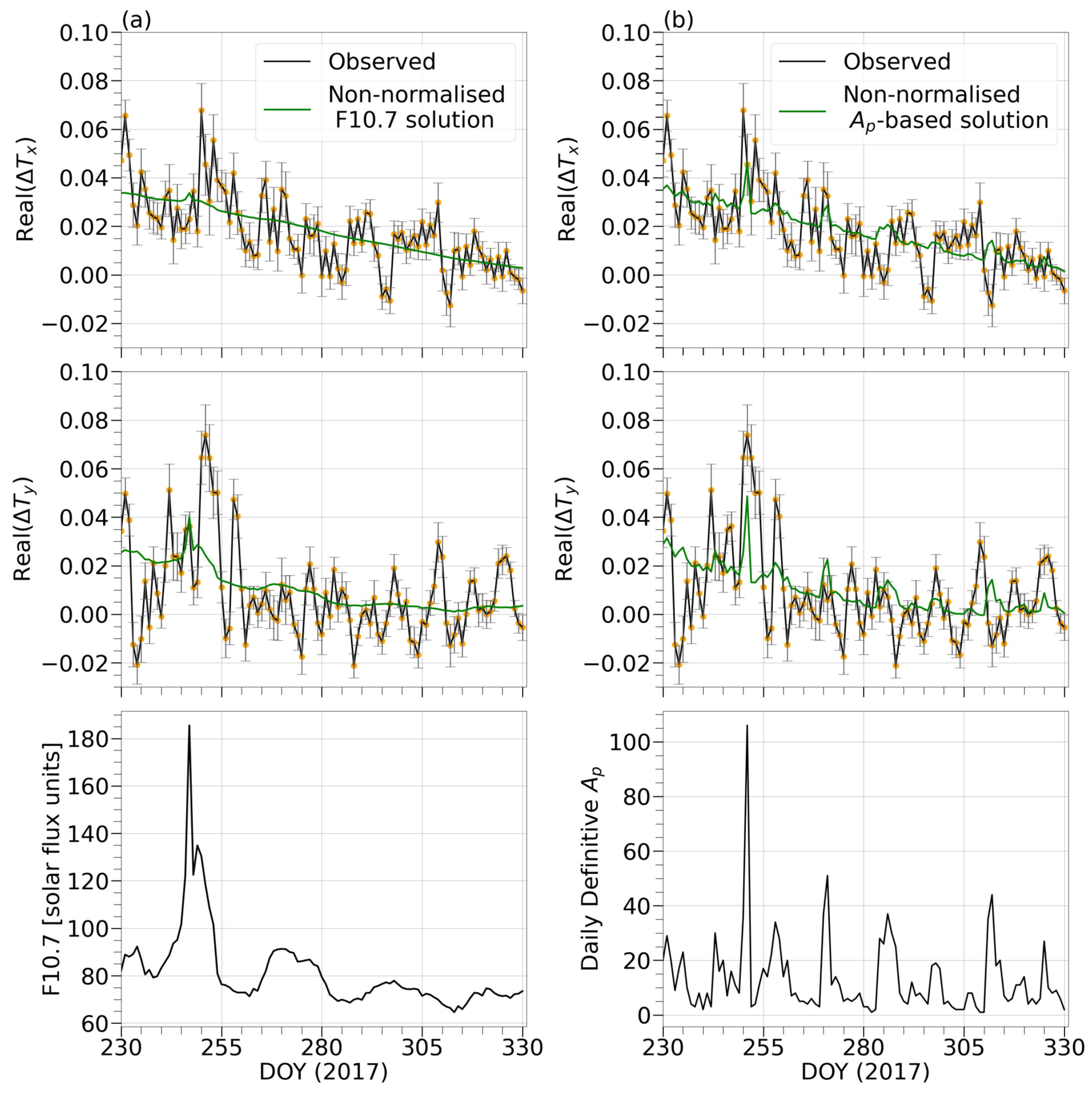

Figure 6. Modelled seasonal variation of the tipper (ΔT_i) for $Re(T_x)$ and $Re(T_y)$ at ESK for T=2048s. (a) Upper panels show a close-up of non-normalised solutions fitted to period around the September 2017 geomagnetic storm. ΔT_i is relative to the 2016 winter baseline using daily F10.7 (bottom panel) in the prediction. (b) Same as (a), with the solution computed using daily A_p.

References

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