MODEL-BASED ANALYSIS OF IONOSPHERIC REACTION TO 27-DAY SOLAR EUV VARIABILITY

A LONG-TERM STUDY

Hanna Dühnen[1], Rajesh Vaishnav[2], Erik Schmölter[1], Christoph Jacobi[2]

[1] German Aerospace Center (DLR) – Institute for Solar-Terrestrial Physics

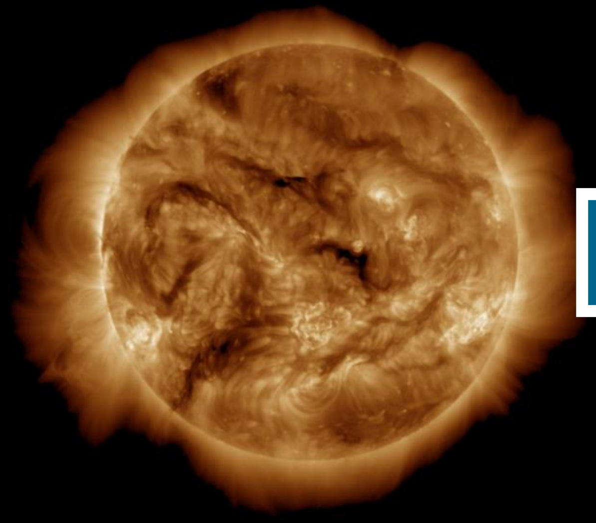
[2] Leipzig University – Institute for Meteorology

Table of Contents

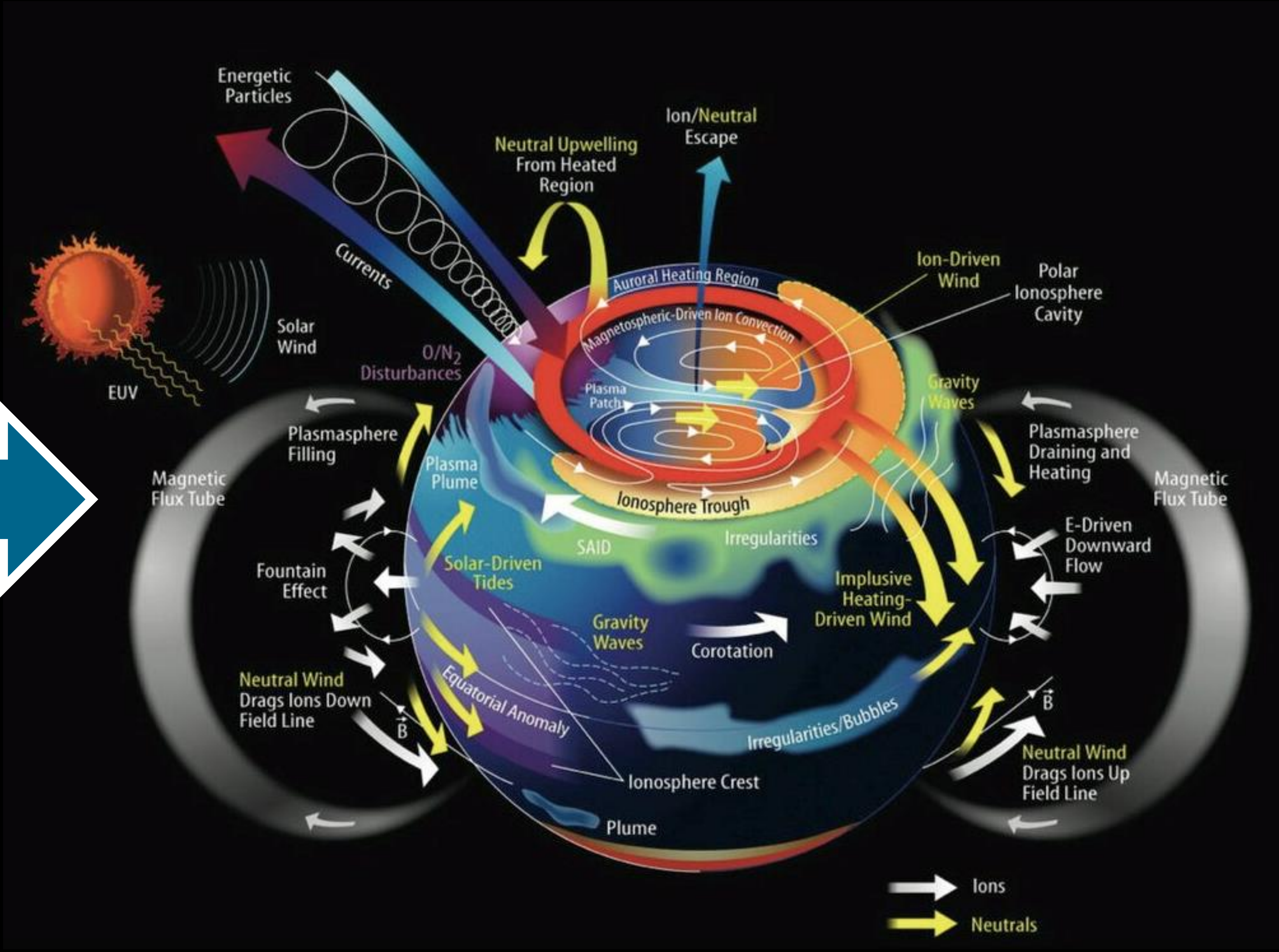
- Introduction
- Previous studies
- Data
- Methods
- Results
- Summary

INTRODUCTION

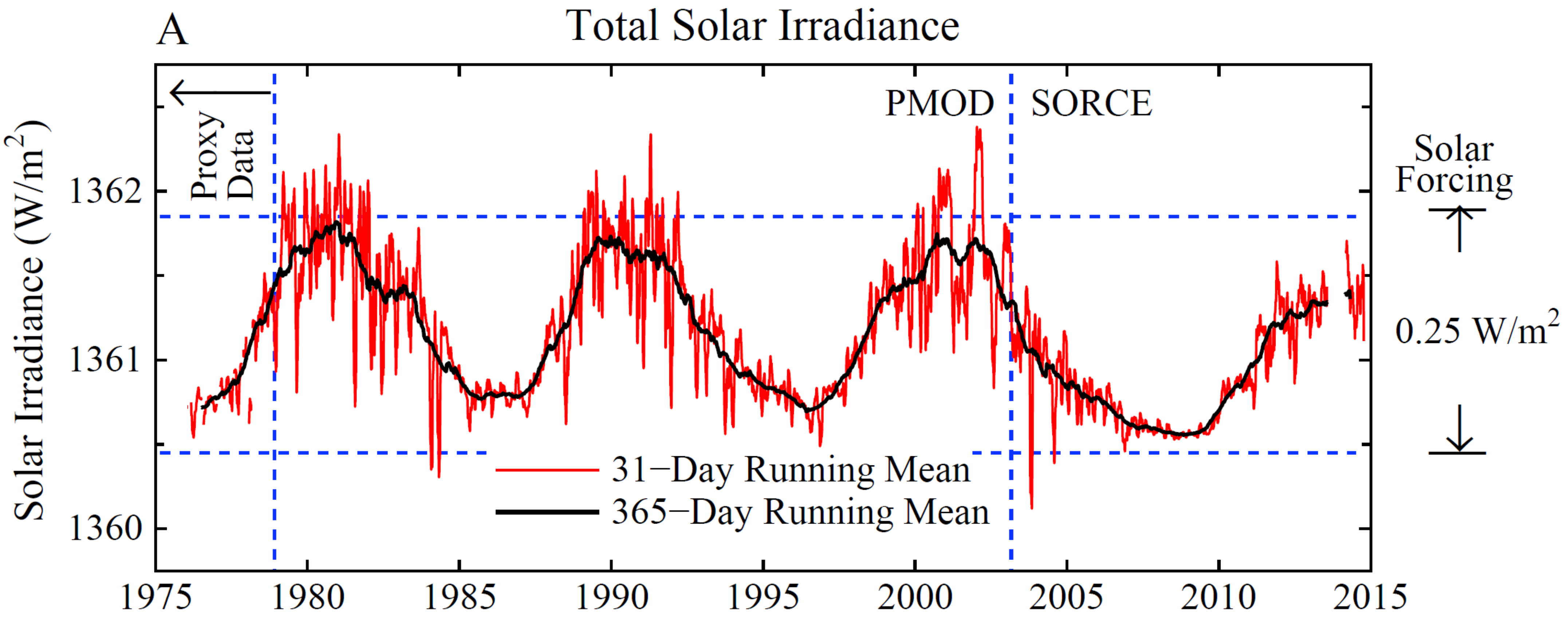
Solar activity dominates ionospheric processes



GOES-16 SUVI Composite 195 Angstroms 2024-09-22 16:36:35

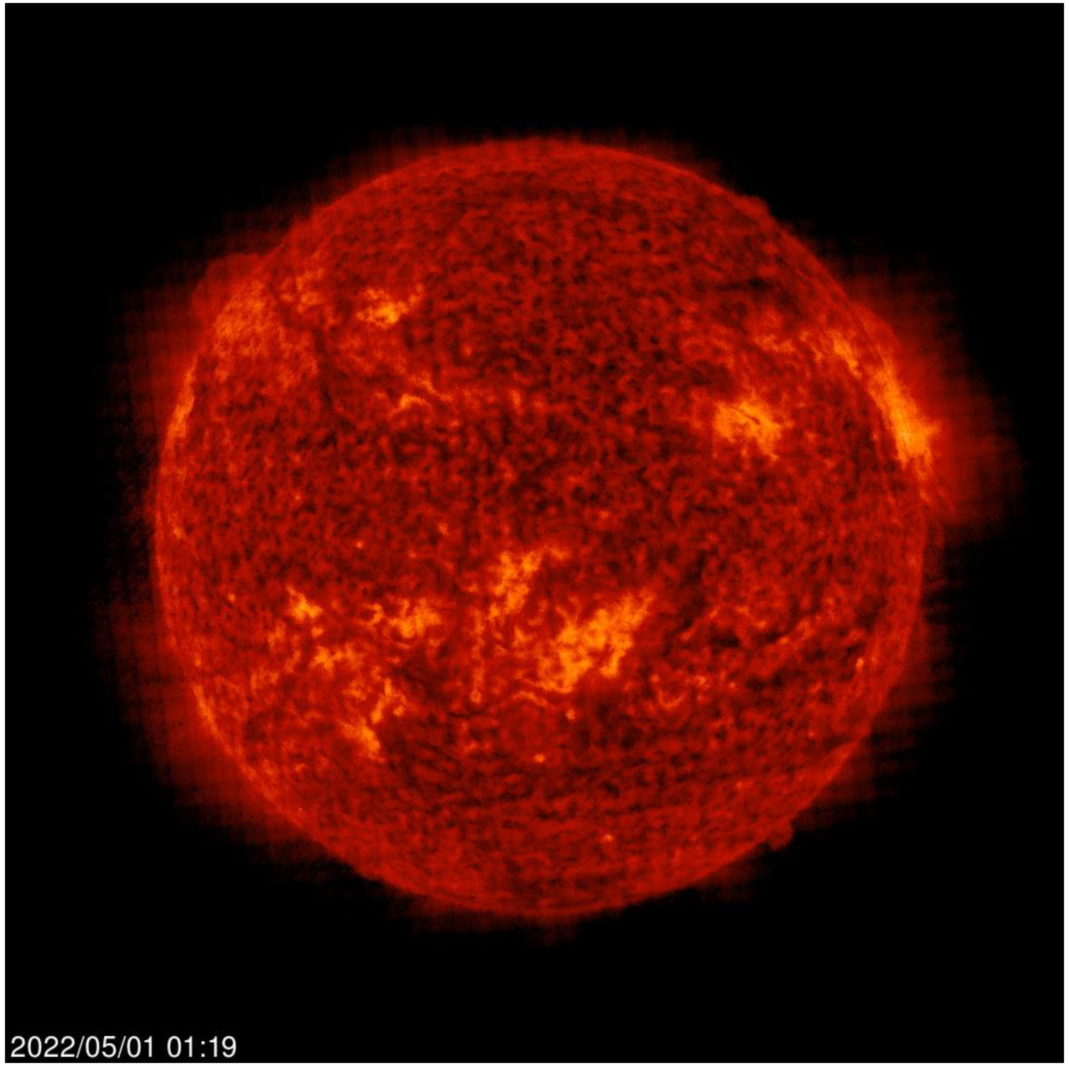


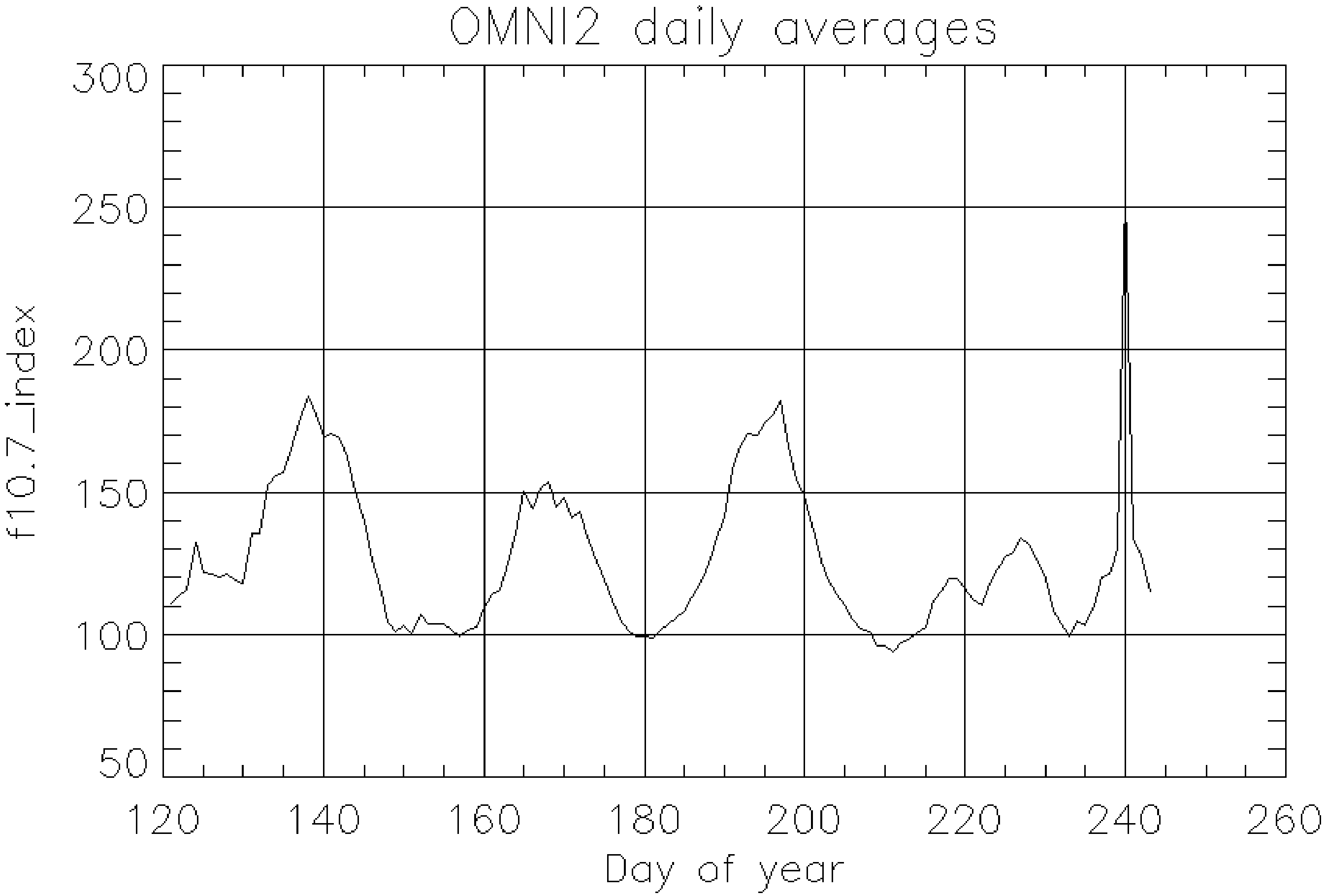
Solar variability



11-Year solar cycle is one of the important time scales in solar activity

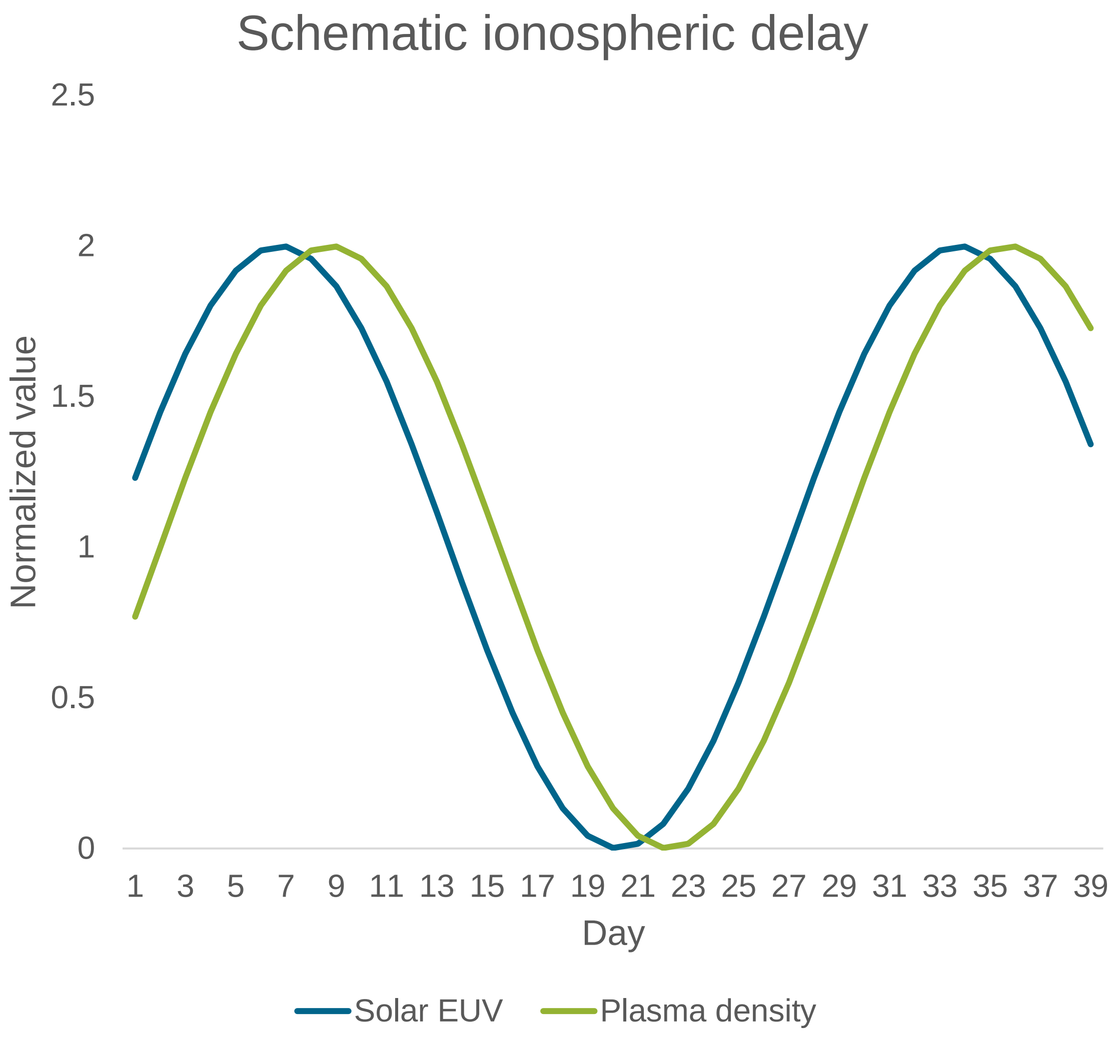
27-day solar rotation period





Solar variability due to 27-day solar rotation

Ionospheric reaction to 27-day solar rotation period



- Absorption (ionization, dissociation, heating), transport and recombination determine the ionospheric plasma
- Ionization (fast) vs. recombination (slow)

  ➔ **Delay**

- Ionospheric delay changes with different solar and geomagnetic activity levels

[1] Ren et al. 2018; doi: 10.1029/ 2018JA025835
[2] Schmölter et al.; 2020; doi: 10.5194/angeo-38-149-2020
[3] Vaishnav et al.; 2021; doi: 10.106/j.asr.2021.12.041

PREVIOUS STUDIES

Previous studies – initial delay estimations

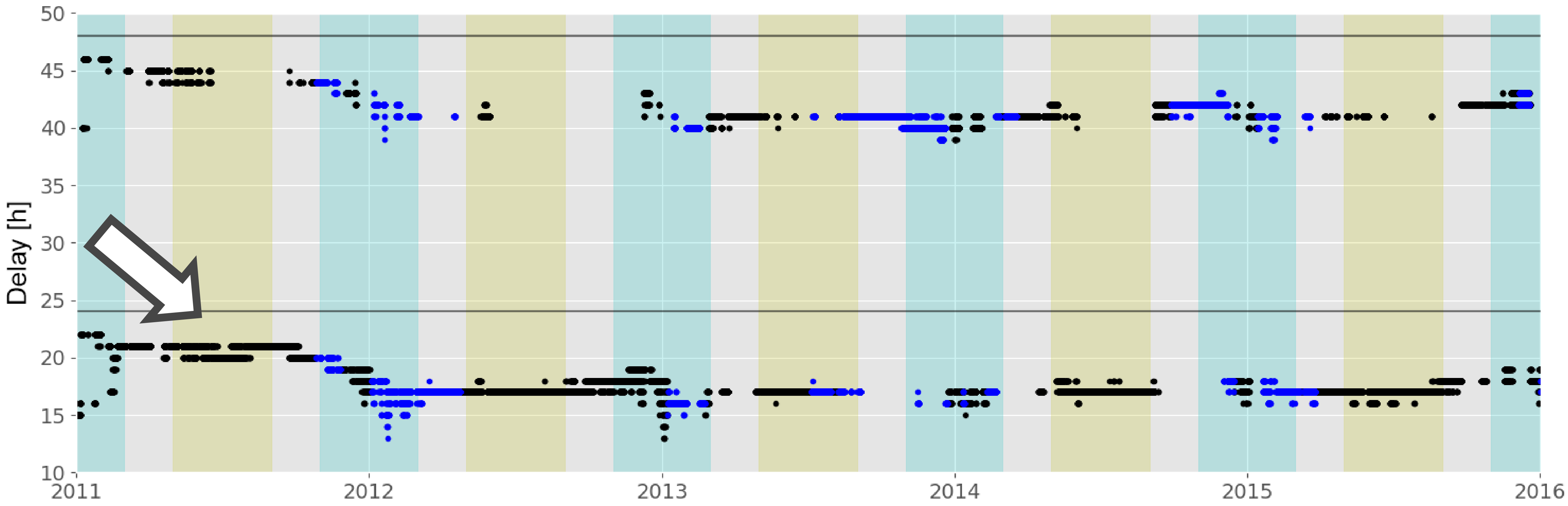
- Global TEC and NmF2 generally show delay of 1-2 days to 27-day period

Features:

  - Variations with latitude and season [1,2]
  - Shorter delays in northern hemisphere [1,2]
  - Altitude dependence of delay [3,4]

[1]Lee et al. 2012; doi: 10.1016/j.jastp.2012.01.010
[2] Schmölter et al.; 2020; doi: 10.5194/angeo-38-149-2020
[3] Schmölter et al.; 2022; doi: 10.1029/2021JA030118
[4] Ren et al.; 2018; doi: 10.1029/2018JA025835

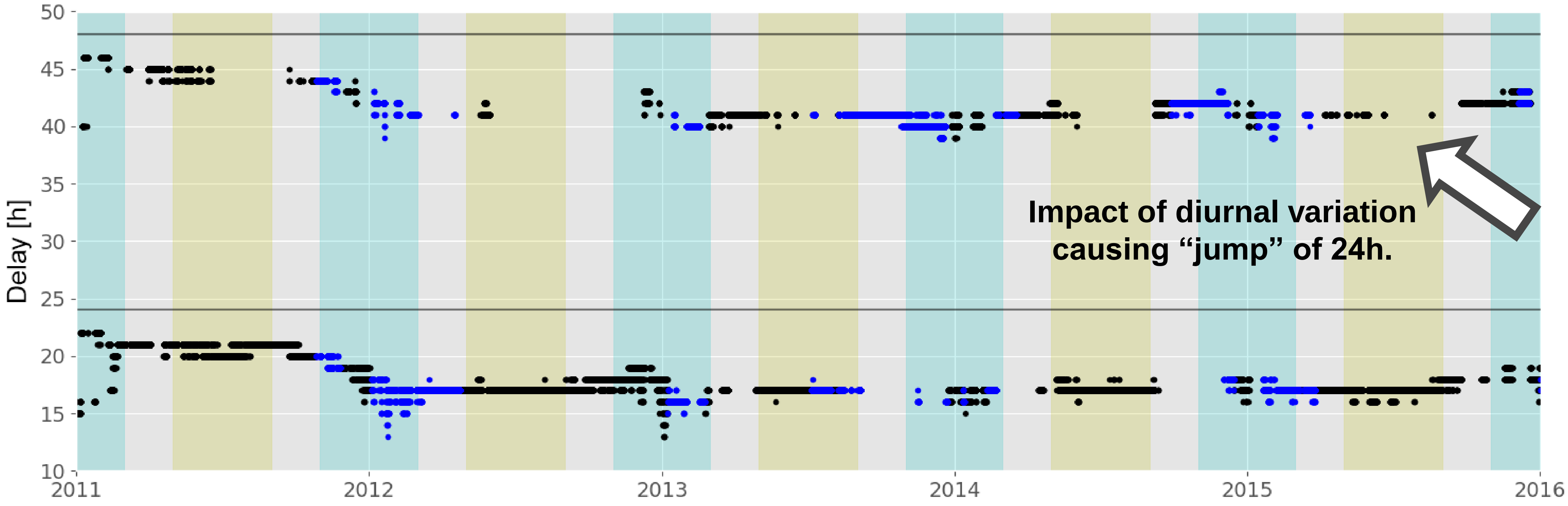
Previous studies – initial delay estimations



Delay of EUV (GOES E from 115 to 130 nm) and TEC (for grid point 50N, 10E). The blue dots represent delays which are related to negative correlations. Summer and winter months are shaded in yellow and blue.

[1] Schmölter et al.; 2018; doi:10.5194/ars-16-149-2018

Previous studies – initial delay estimations



Delay of EUV (GOES E from 115 to 130 nm) and TEC (for grid point 50N, 10E). The blue dots represent delays which are related to negative correlations. Summer and winter months are shaded in yellow and blue.

[1] Schmölter et al.; 2018; doi:10.5194/ars-16-149-2018

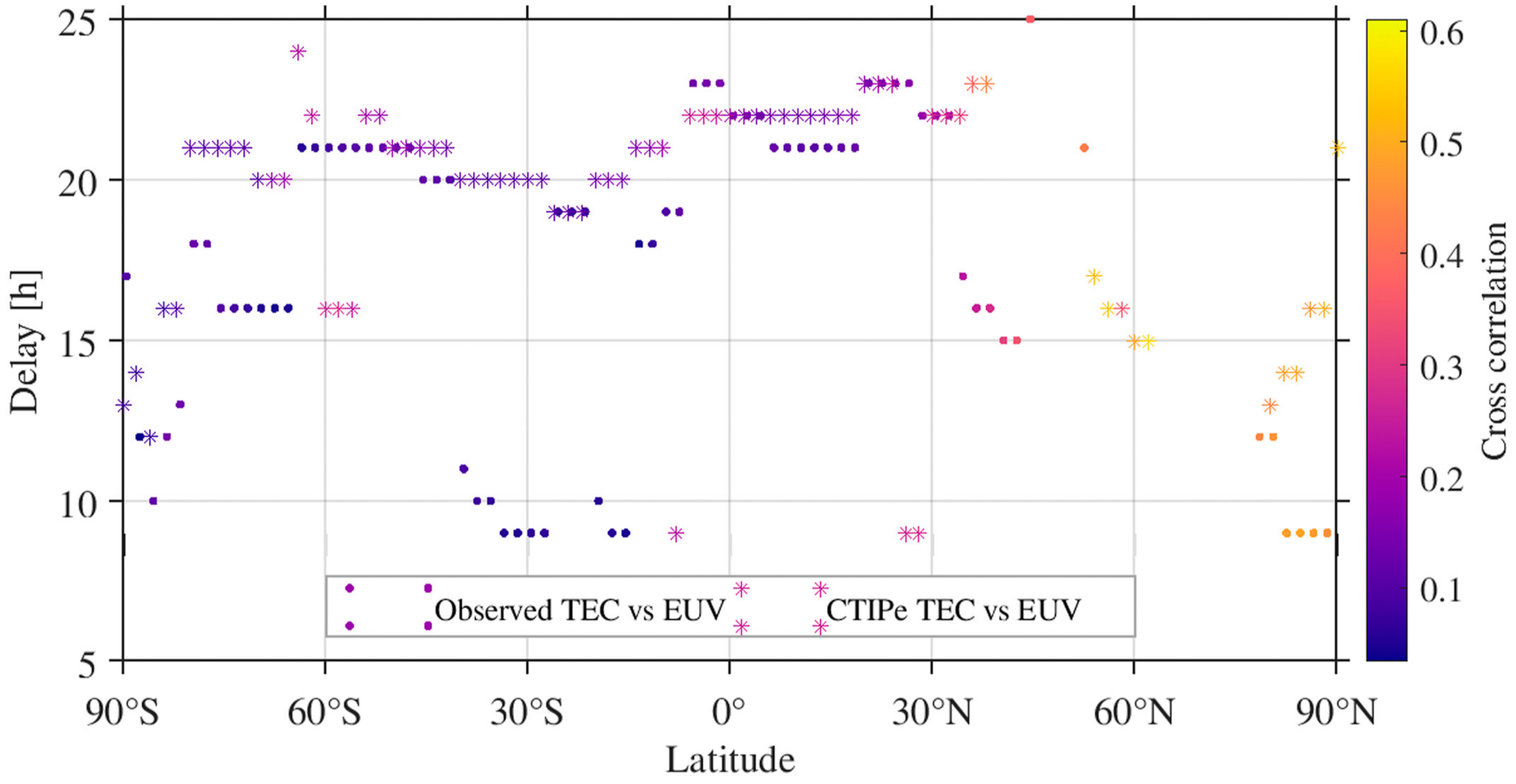
DRIVAR II Project

Delayed Response of the Ionosphere to solar EUV VARiability

What is the role of thermospheric (photo-) chemistry and neutral dynamics on the global distribution of the delay?

How can we use the knowledge on processes affecting the ionospheric delay to improve both numerical and empirical models?

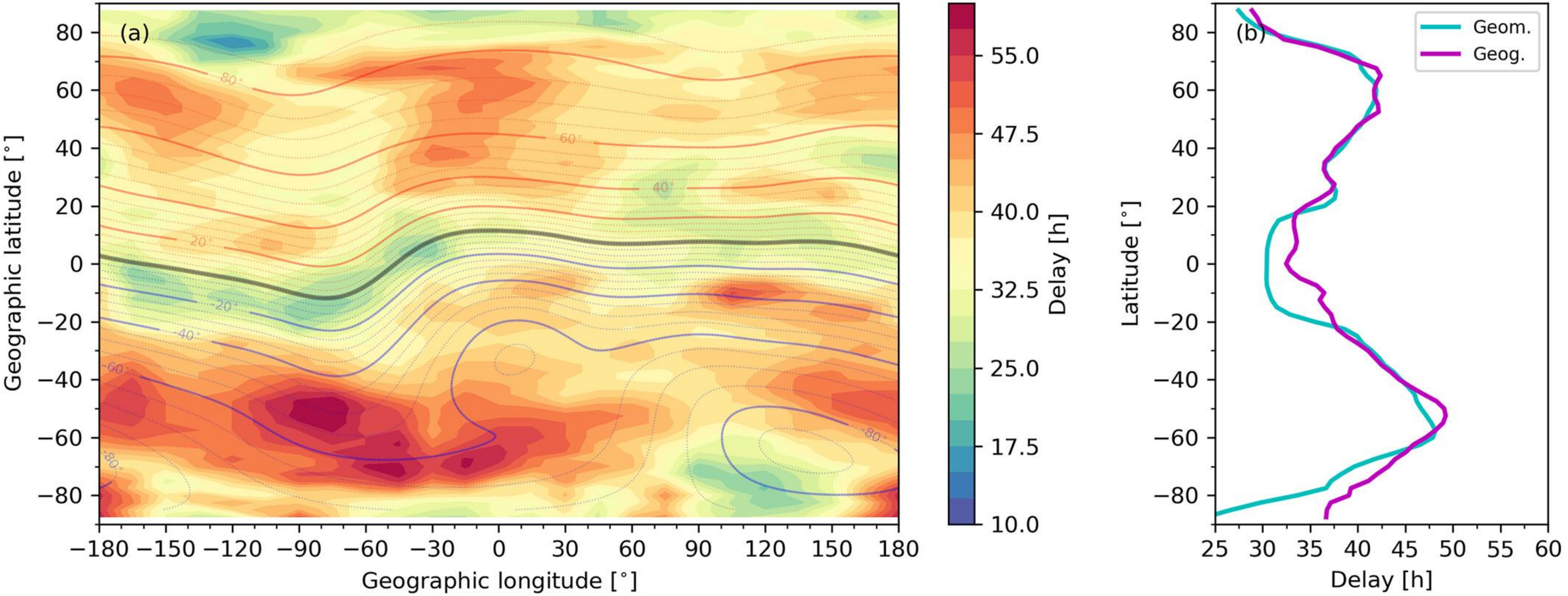
DRIVAR II
Latitudinal structure of the delay



Latitudinal variations of the delayed ionospheric response and cross-correlations for observed (dots) and modeled (asterisks) TEC with the EUV flux during 16 November–12 December 2020 at 80°W longitude.

[1] Vaishnav et al.; 2023; doi: 10.1029/2022JA030887

DRIVAR II
Latitudinal structure of the delay



Cross-correlation lag (delay) via the SEA method for all epochs and World Magnetic Model (WMM) inclination (red and blue lines) are shown (a). The latitude-dependent mean is given for geographic and geomagnetic latitude (b).

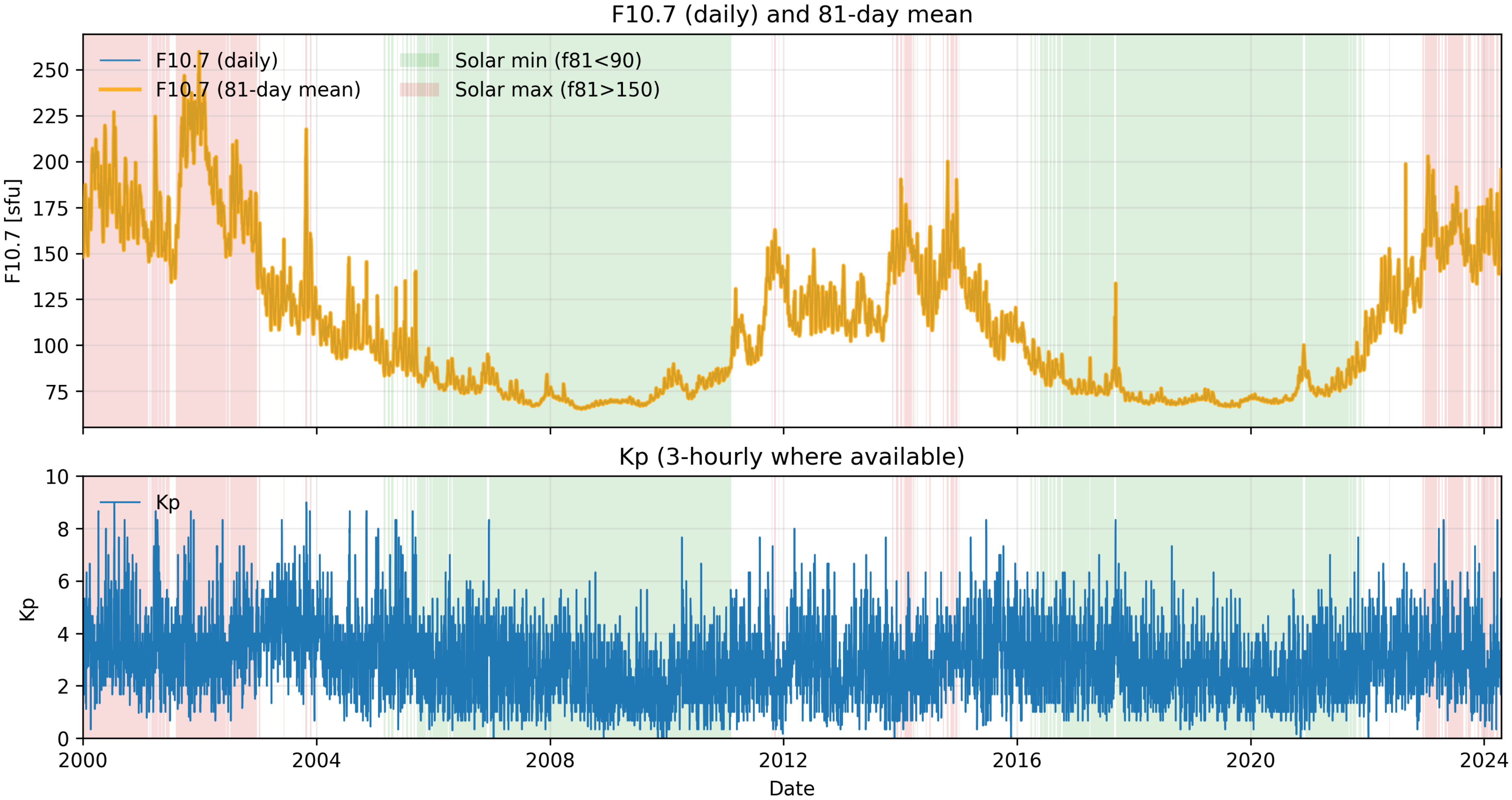
[1] Schmölter et al.; 2024; doi:10.1029/2024JA032672

What are the **key processes of the ionospheric delay**?

How can we identify them using a **3D (+ time) analysis of the delay**?

DATA

Solar and geomagnetic forcing from 2000 to 2024



TIE-GCM

Thermosphere Ionosphere Electrodynamics General Circulation Model

- First-principles, 3D global general circulation model
- Solves continuity, momentum and energy equation

External forcing:

- Solar: via F10.7 index
- Geomagnetic: Heelis convection model

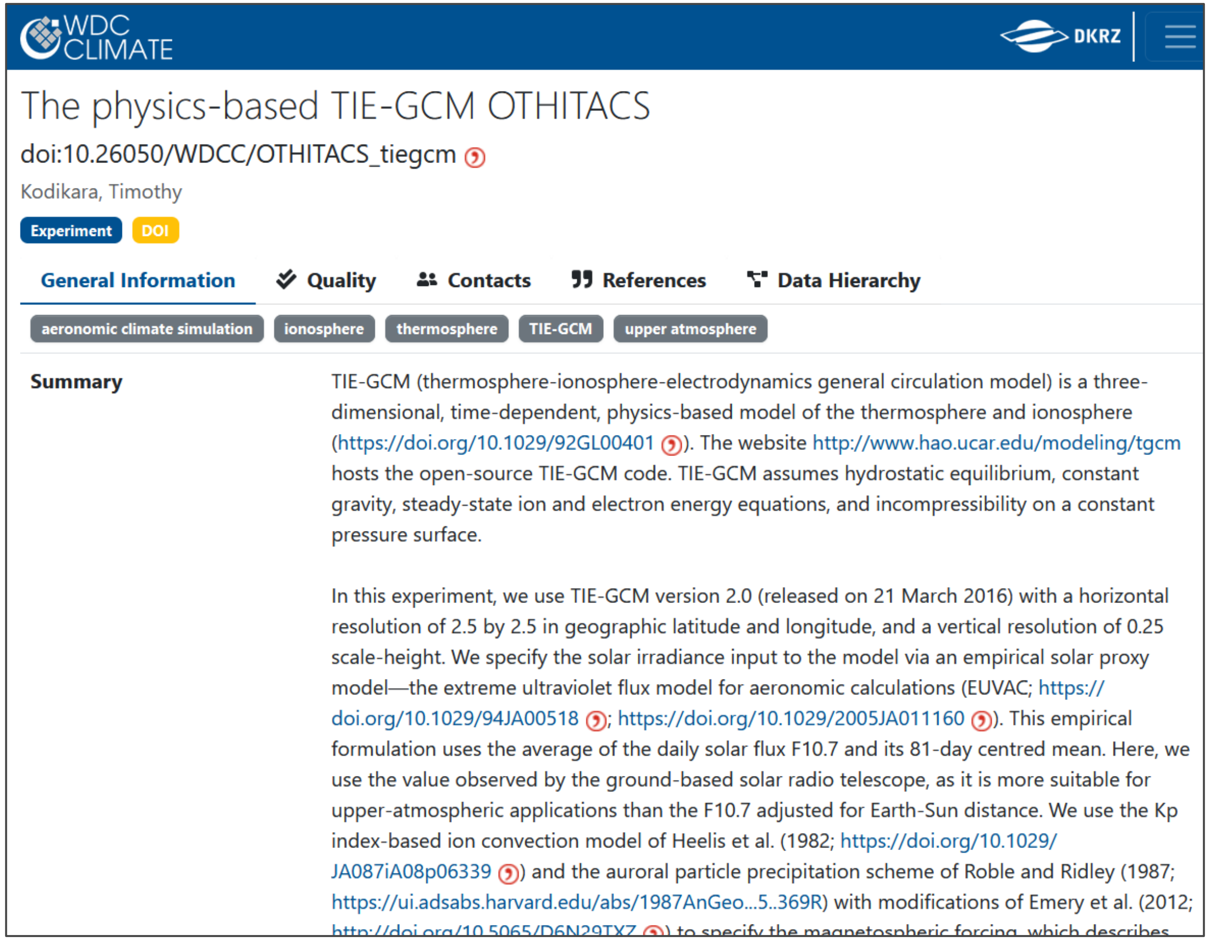
[1] Qian et al.; 2014; doi:10.1002/9781118704417.ch7

OTHITACS

- Open Time-series of the High-resolution Ionos.-Thermos. Aeronomic Climate Simulation

Features:

  - Long-term TIE-GCM simulation
  - 2.5 deg. resolution
  - 10 Minute cadence
  - From 2000 to 2024


WDC CLIMATE DKRZ

The physics-based TIE-GCM OTHITACS

doi:10.26050/WDCC/OTHITACS_tiegcm

Kodikara, Timothy

Experiment DOI

General Information | Quality | Contacts | References | Data Hierarchy

aeronomic climate simulation | ionosphere | thermosphere | TIE-GCM | upper atmosphere

Summary

TIE-GCM (thermosphere-ionosphere-electrodynamics general circulation model) is a three-dimensional, time-dependent, physics-based model of the thermosphere and ionosphere (https://doi.org/10.1029/92GL00401). The website http://www.hao.ucar.edu/modeling/tgcm hosts the open-source TIE-GCM code. TIE-GCM assumes hydrostatic equilibrium, constant gravity, steady-state ion and electron energy equations, and incompressibility on a constant pressure surface.

In this experiment, we use TIE-GCM version 2.0 (released on 21 March 2016) with a horizontal resolution of 2.5 by 2.5 in geographic latitude and longitude, and a vertical resolution of 0.25 scale-height. We specify the solar irradiance input to the model via an empirical solar proxy model—the extreme ultraviolet flux model for aeronomic calculations (EUVAC; https://doi.org/10.1029/94JA00518; https://doi.org/10.1029/2005JA011160). This empirical formulation uses the average of the daily solar flux F10.7 and its 81-day centred mean. Here, we use the value observed by the ground-based solar radio telescope, as it is more suitable for upper-atmospheric applications than the F10.7 adjusted for Earth-Sun distance. We use the Kp index-based ion convection model of Heelis et al. (1982; https://doi.org/10.1029/JA087iA08p06339) and the auroral particle precipitation scheme of Roble and Ridley (1987; https://ui.adsabs.harvard.edu/abs/1987AnGeo...5..369R) with modifications of Emery et al. (2012; http://doi.org/10.5065/D6N29TXZ) to specify the magnetospheric forcing, which describes

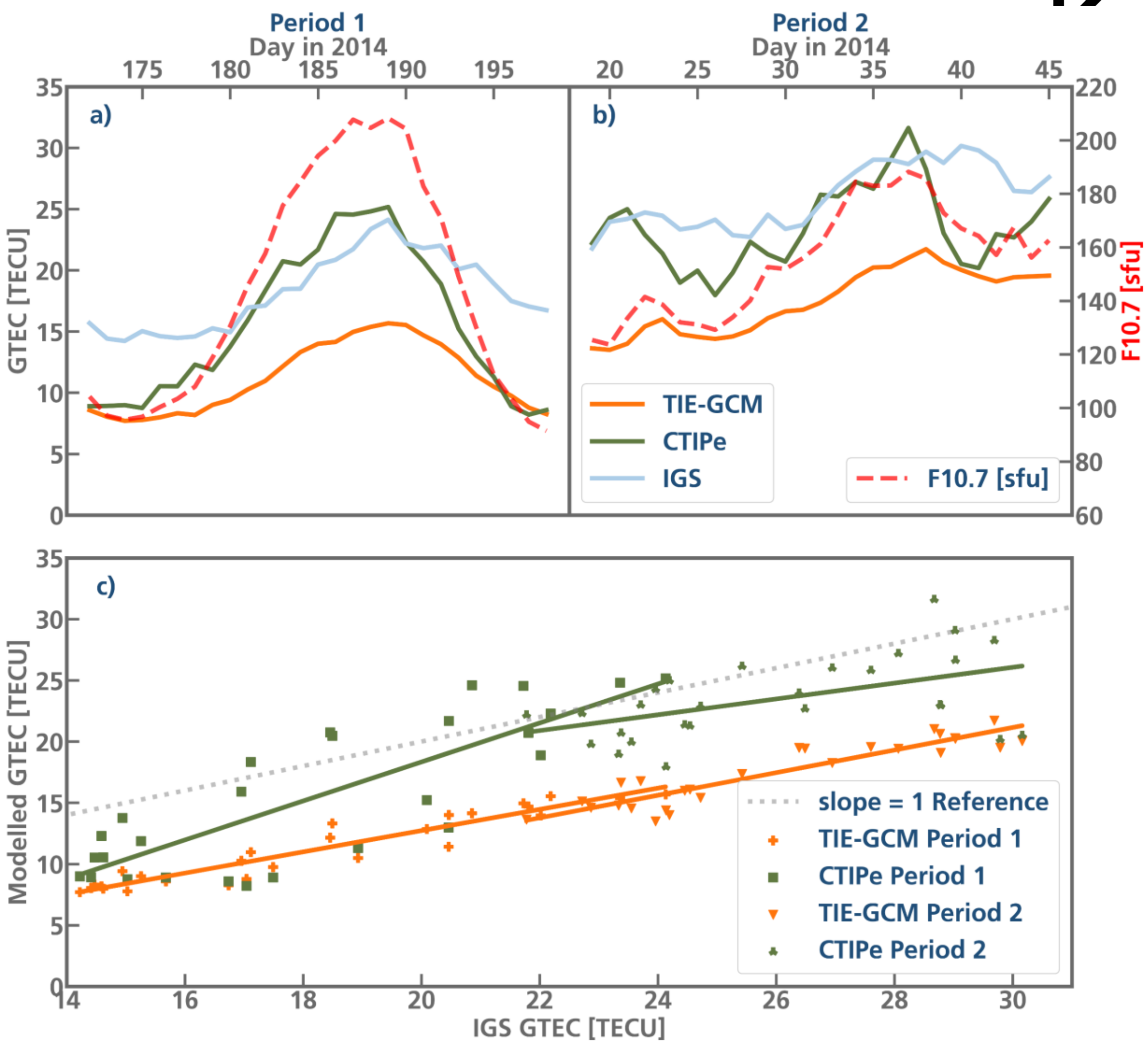
[1] Kodikara; 2023; doi:10.26050/WDCC/OTHITACS_tiegcm

Comparison TIE-GCM to other models and observations

- Comparison of global and local TEC for two physics based models + TEC observations

TIE-GCM results:

- Good correlation with obs.
- But, constant offset to obs.



[1] Dühnen; 2024; doi:10.1016/j.asr.2024.12.004

METHODS

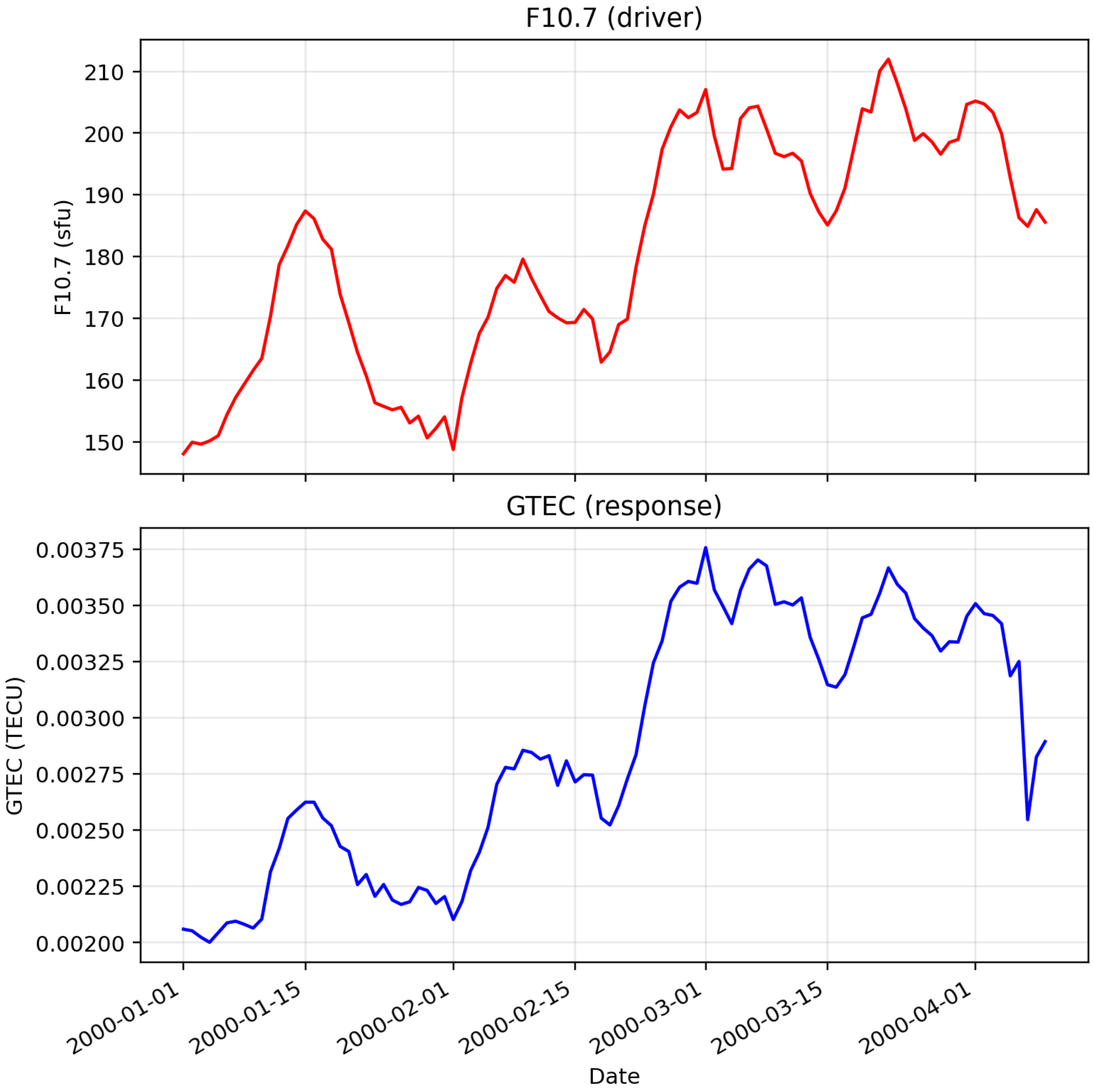
Delay estimation using correlation coefficients

1. Bandpass-filter

2. Pearson-Correlation

3. Time-shift

4. Delay at max. correlation



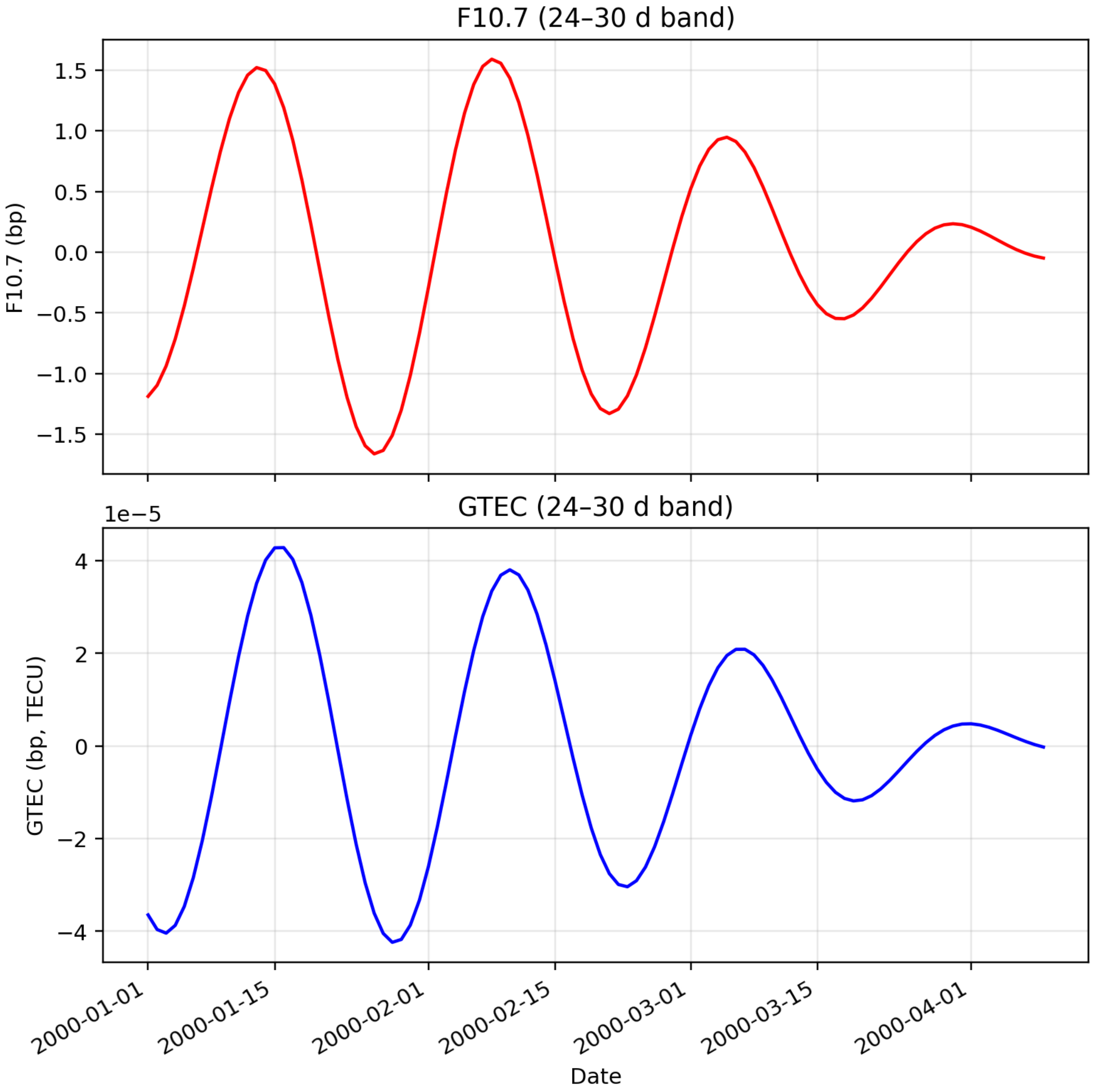
Delay estimation using correlation coefficients

1. Bandpass-filter

2. Pearson-Correlation

3. Time-shift

4. Delay at max. correlation



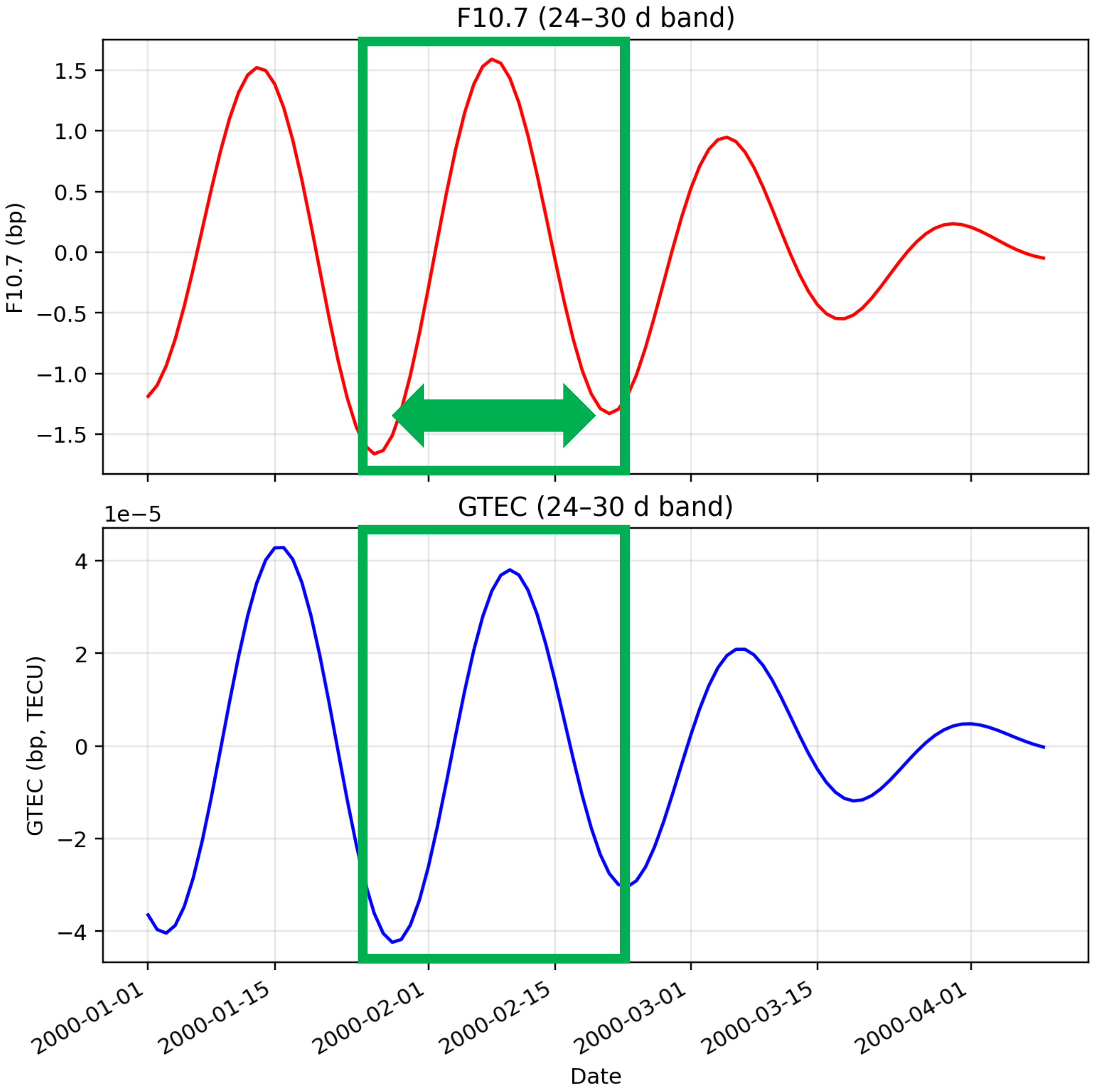
Delay estimation using correlation coefficients

1. Bandpass-filter

2. Pearson-Correlation

3. Time-shift

4. Delay at max. correlation



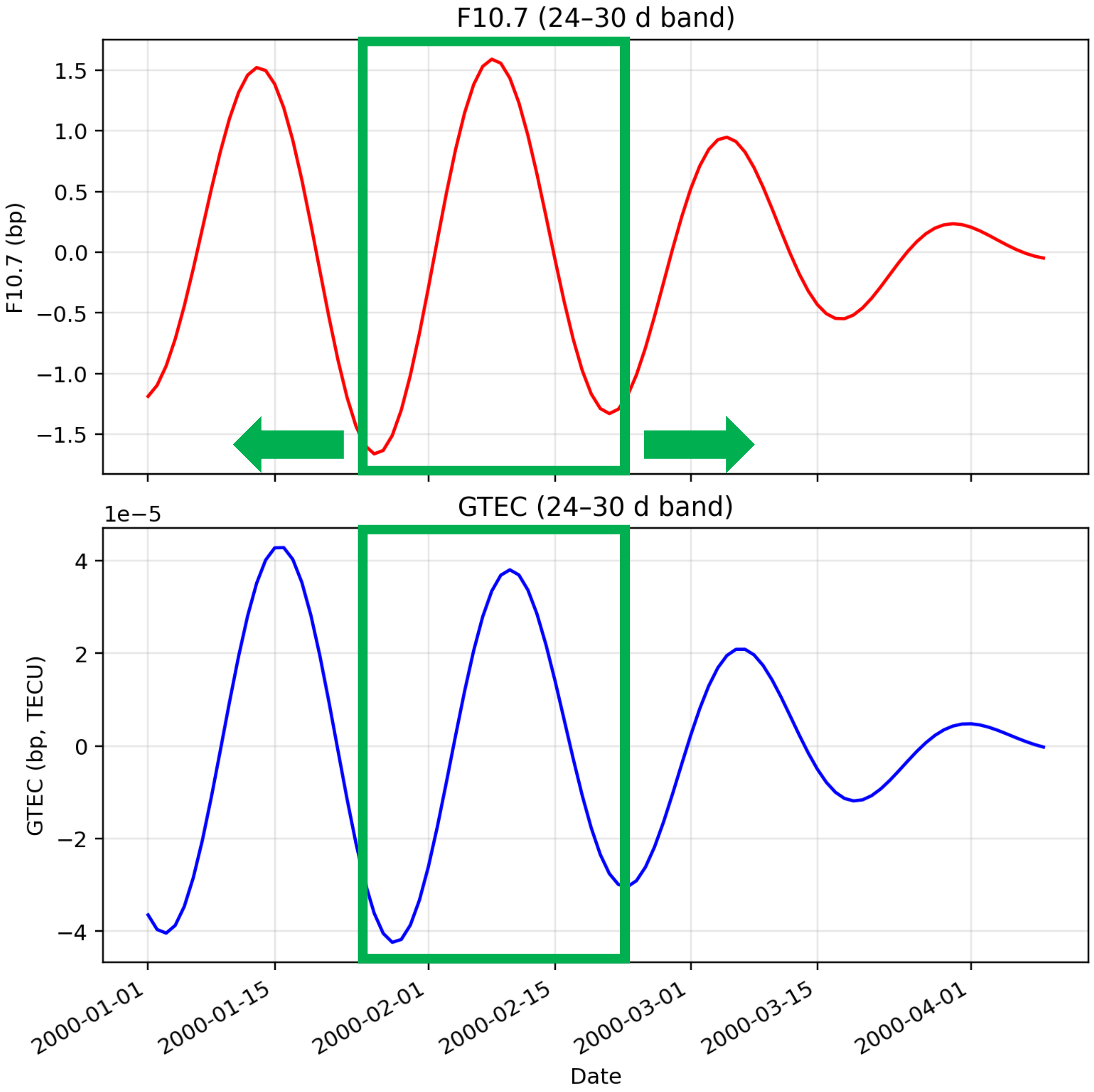
Delay estimation using correlation coefficients

1. Bandpass-filter

2. Pearson-Correlation

3. Time-shift

4. Delay at max. correlation



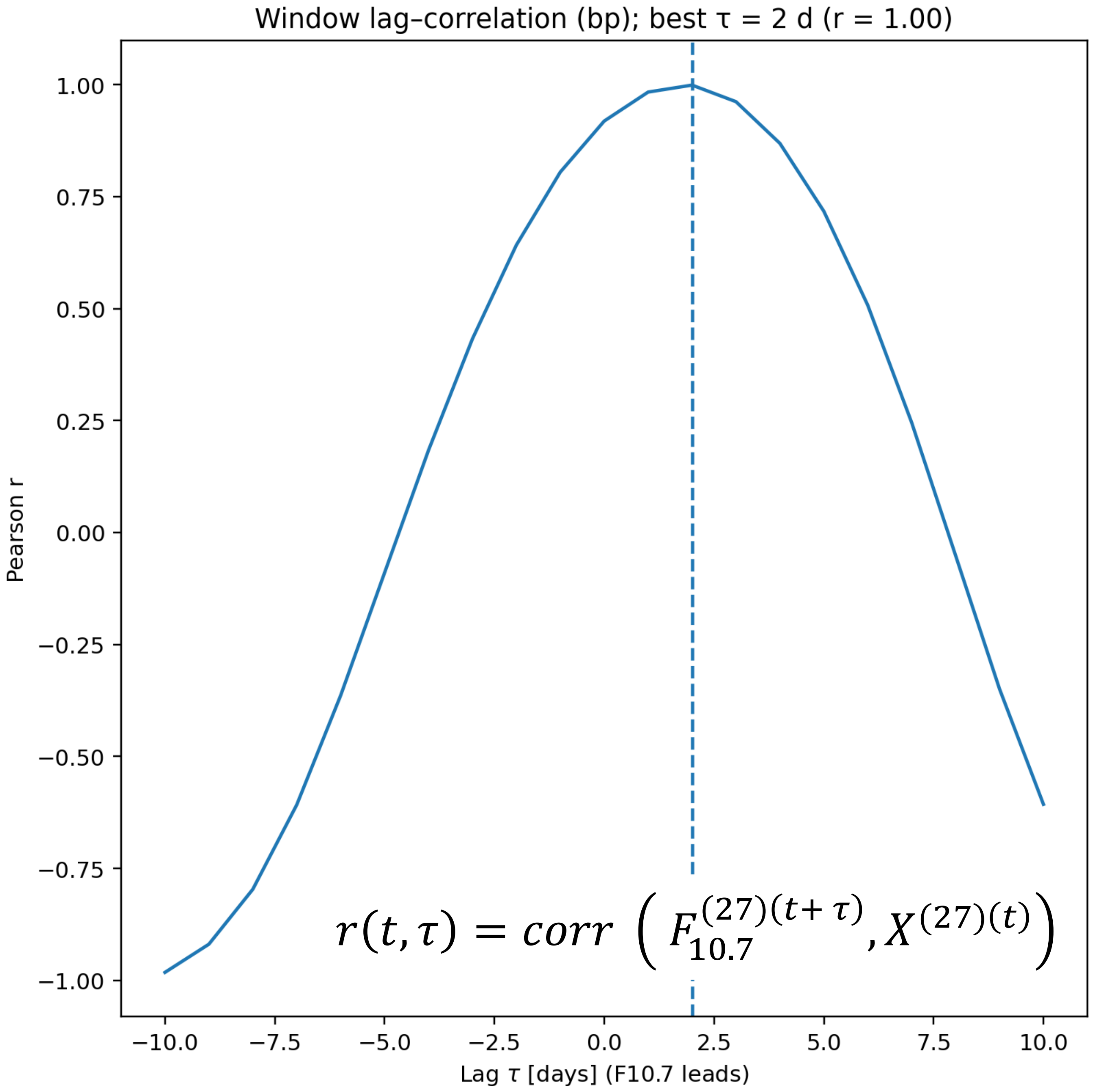
Delay estimation using correlation coefficients

1. Bandpass-filter

2. Pearson-Correlation

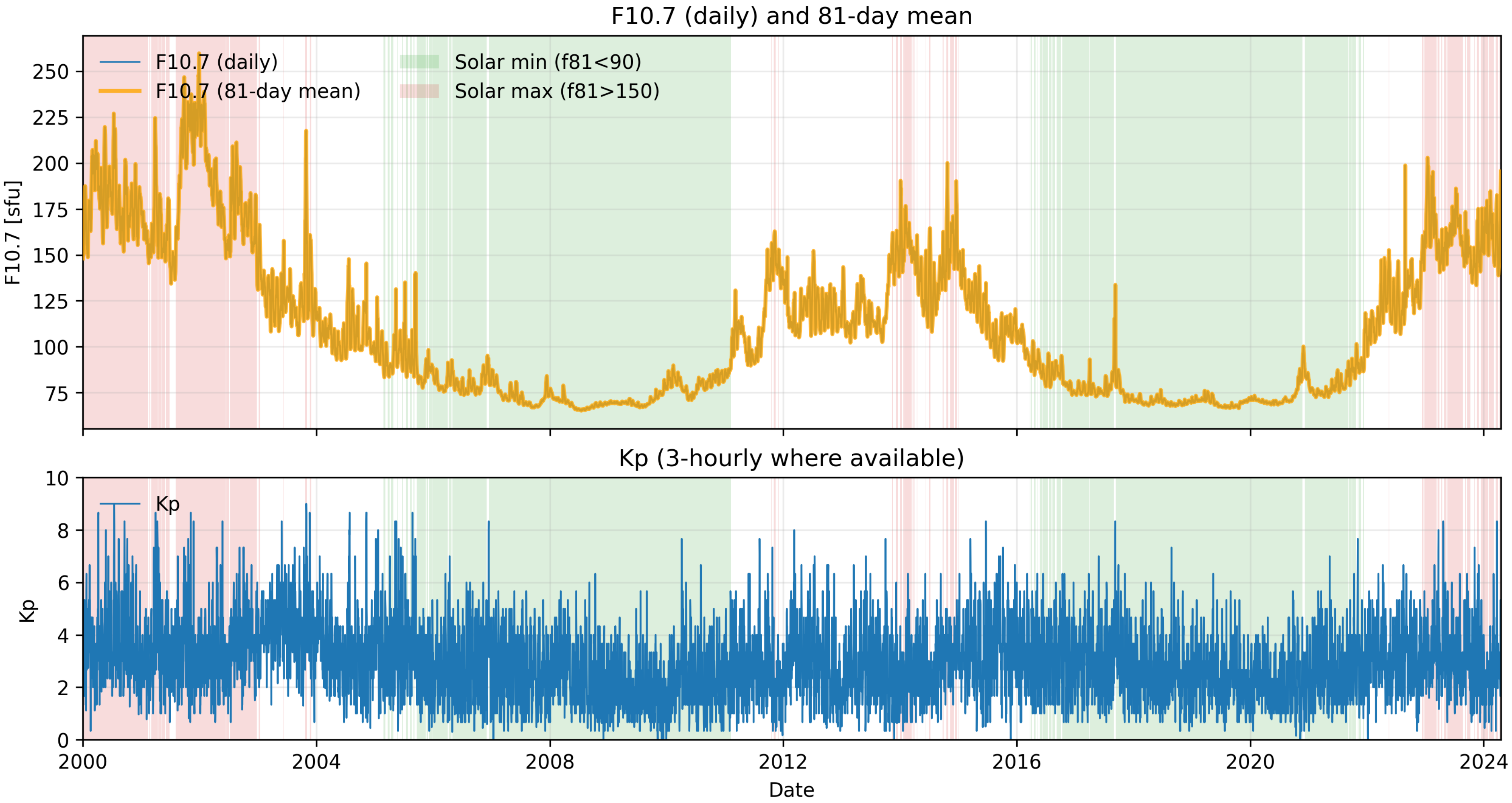
3. Time-shift

4. Delay at max. correlation



RESULTS

Dependence of delay on solar activity

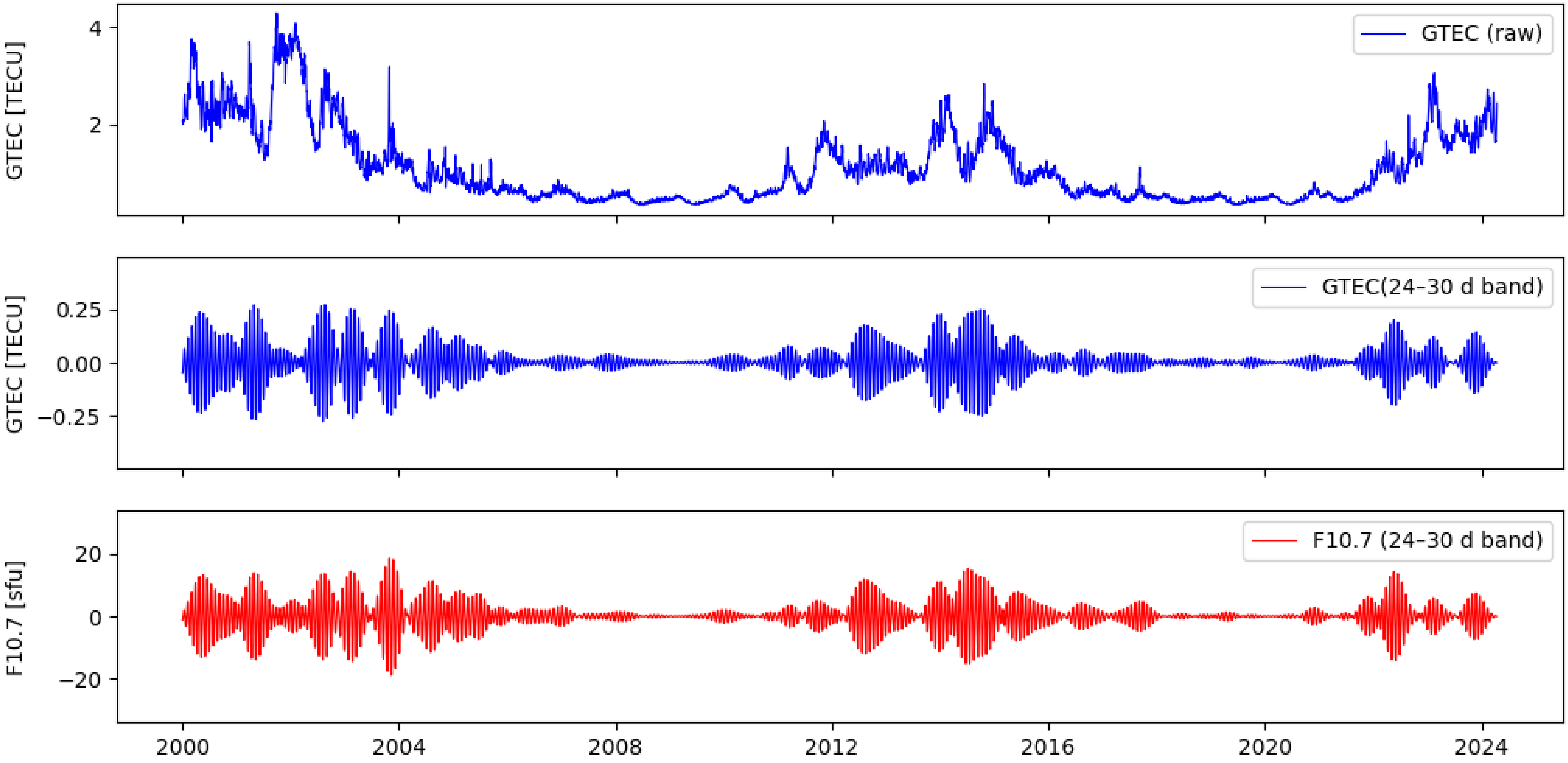


Filtered times:

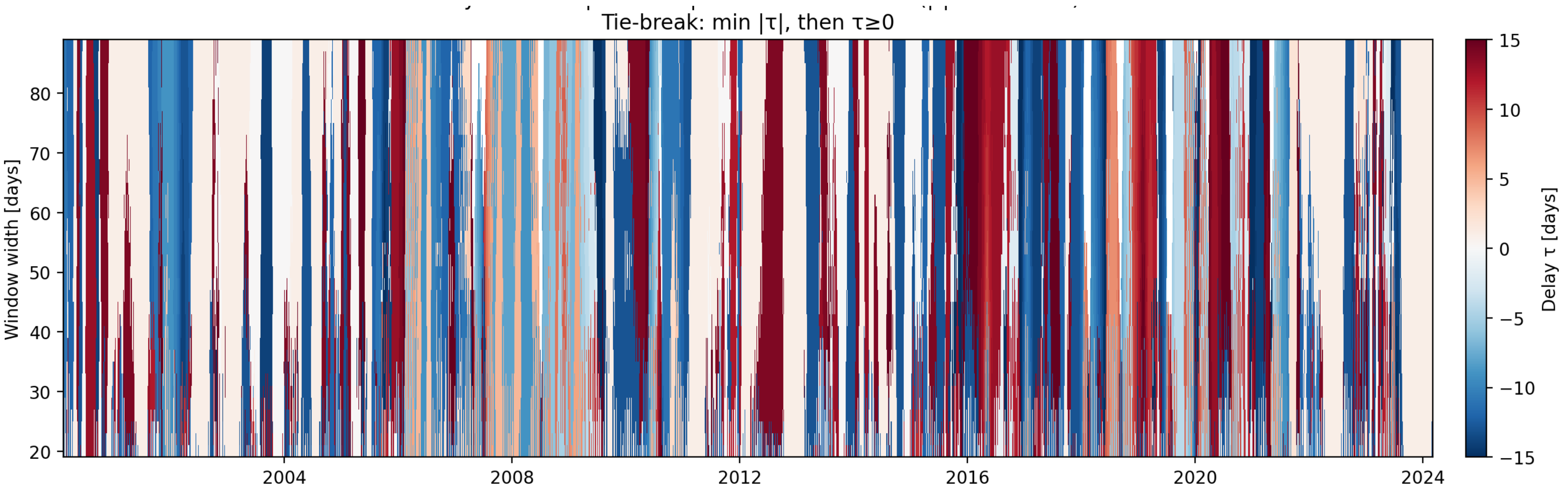
High solar activity = 81-day average F10.7 index > 150 sfu

Low solar activity = 81-day average F10.7 index < 90 sfu

Filtered data



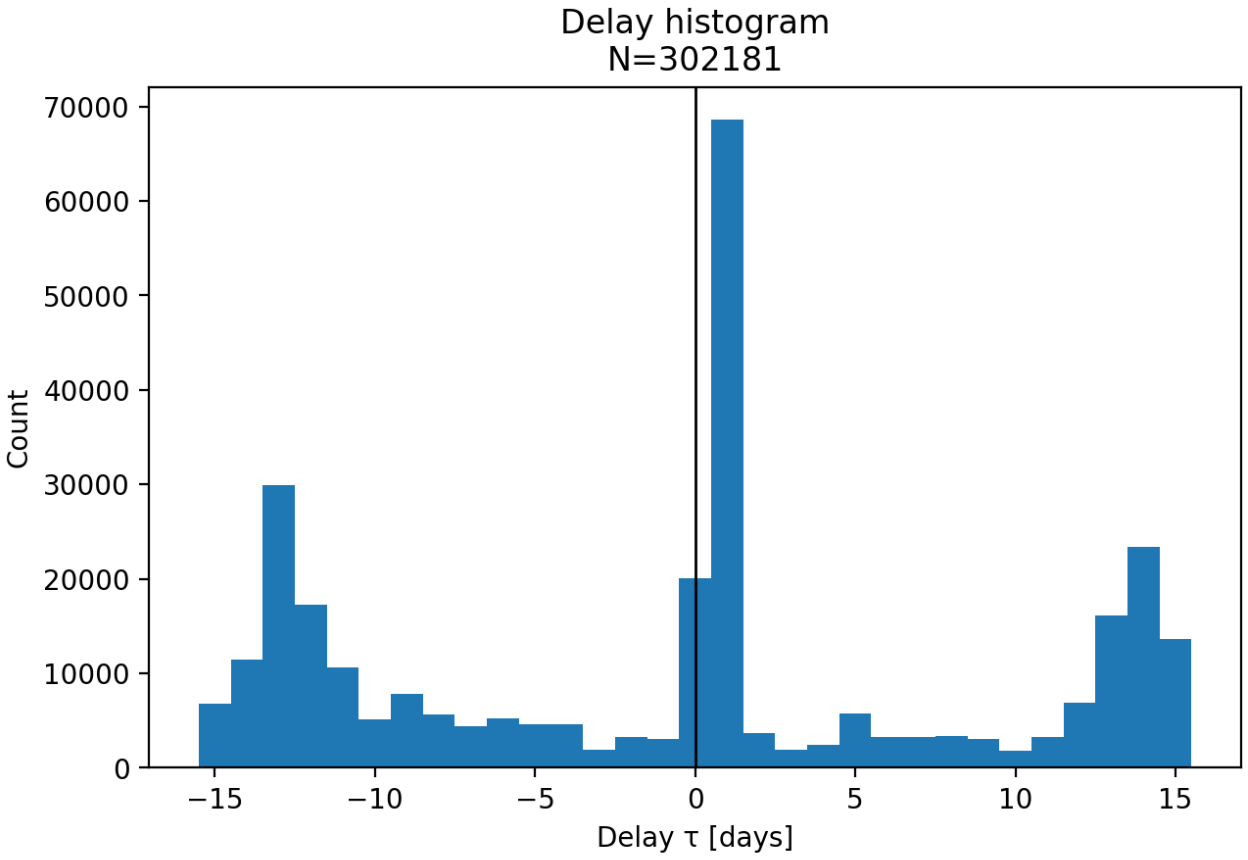
GTEC delay from 2000 to 2024

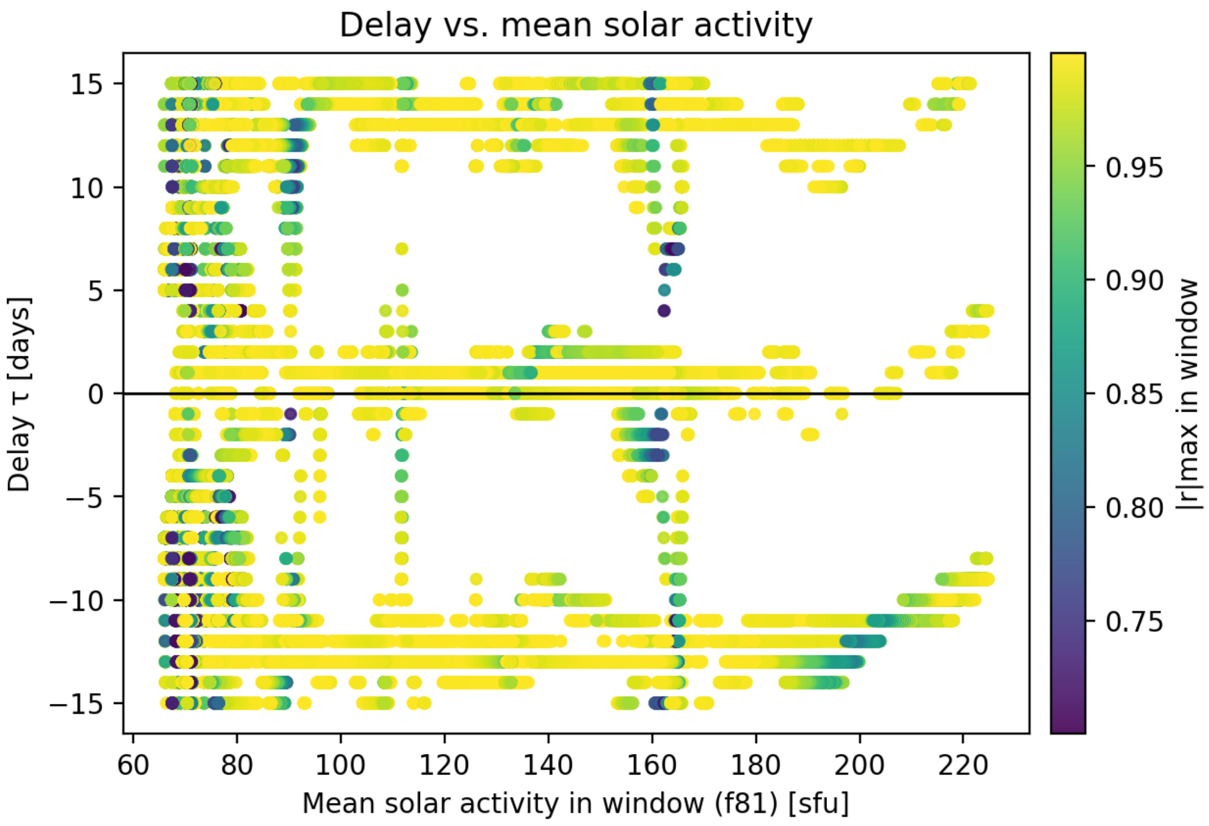


Requirements:

- Correlation is strong (greater than 0.7) in 24-30 day window
- First positive lag favored

Histogram of windowed delays





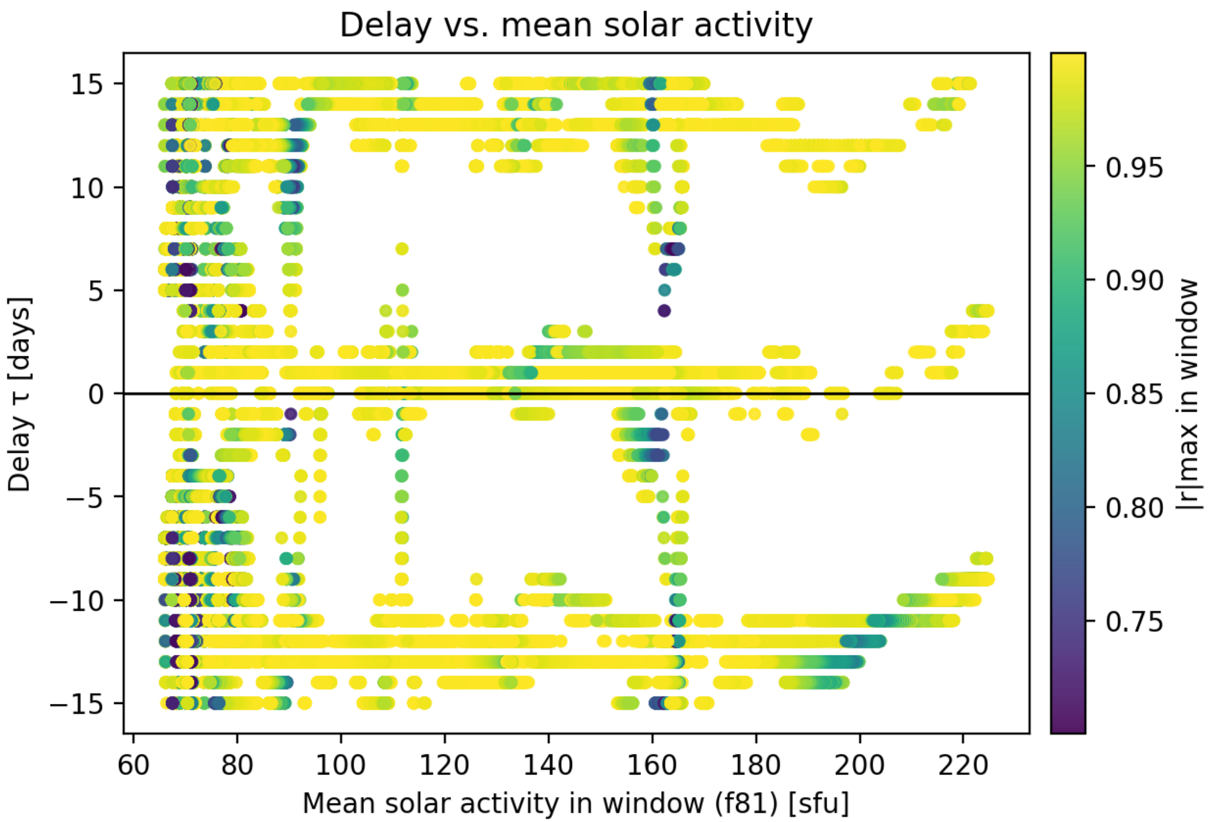
Histogram of windowed delays

- Complex relation with solar activity
- No straightforward interpretation

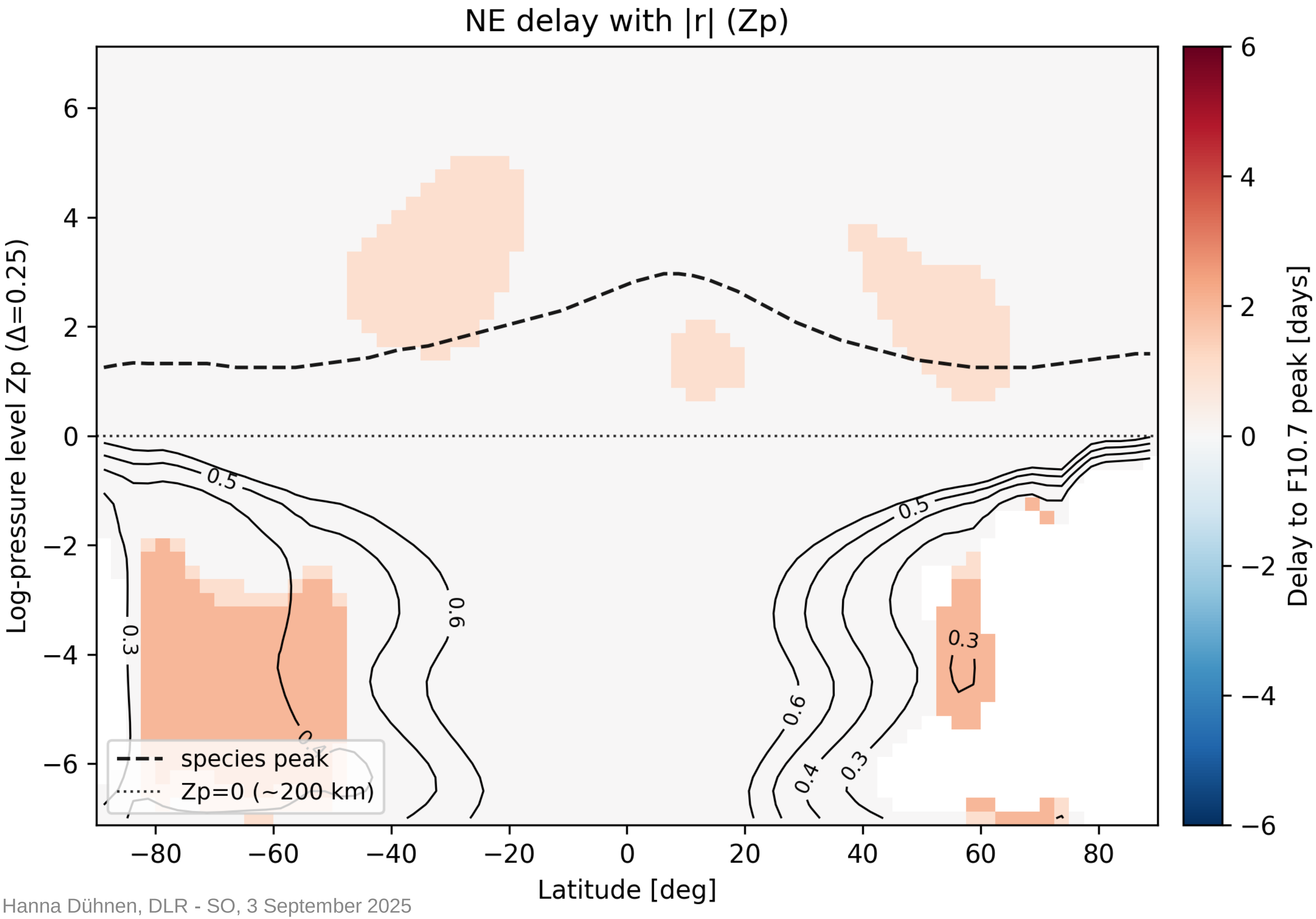
Open questions:

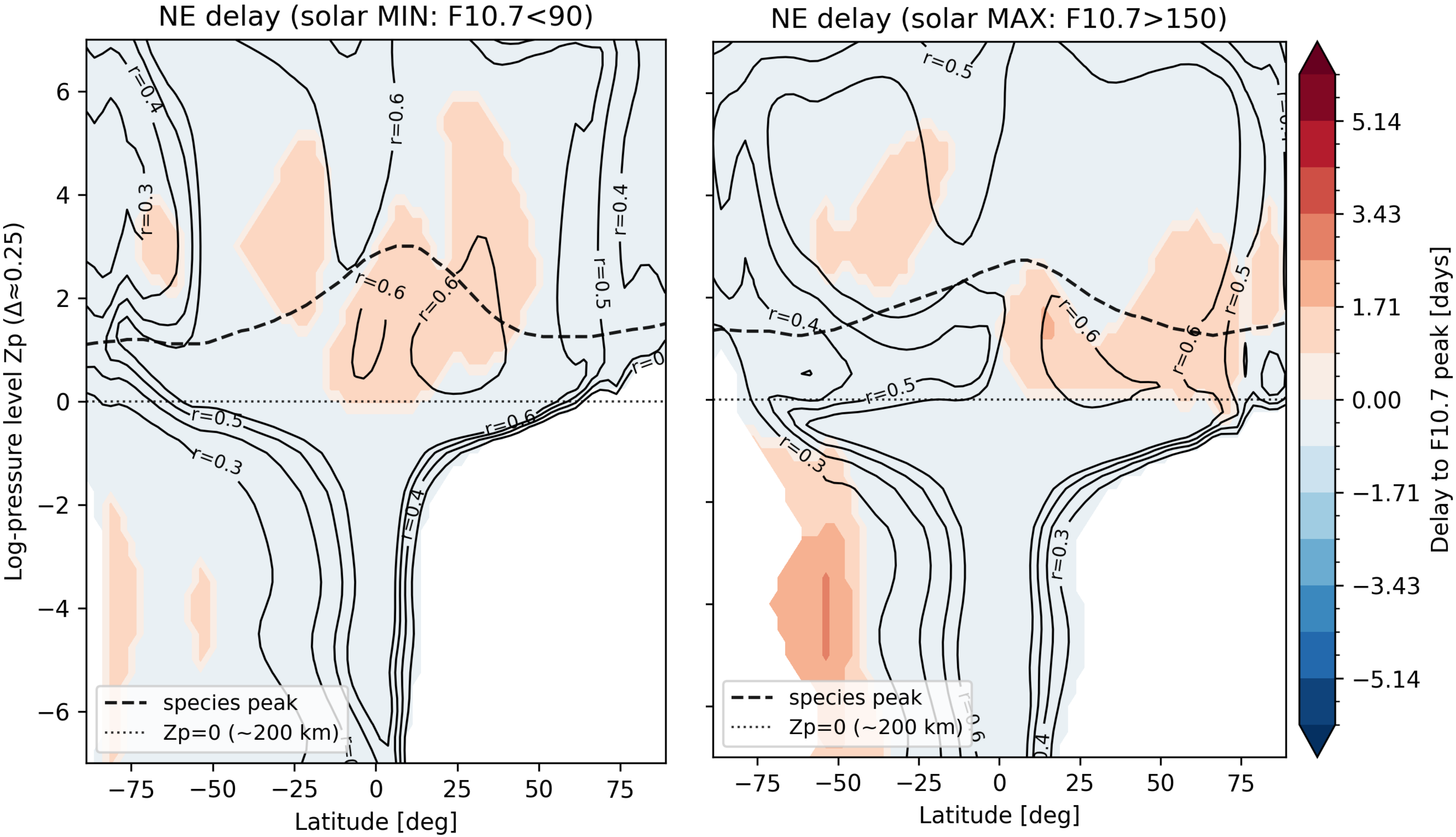
- What do negative delays imply?
- Clustered distribution at high sol. activity?
- “Random” distribution at low sol. activity?

➔ Is there still information about ionospheric processes?



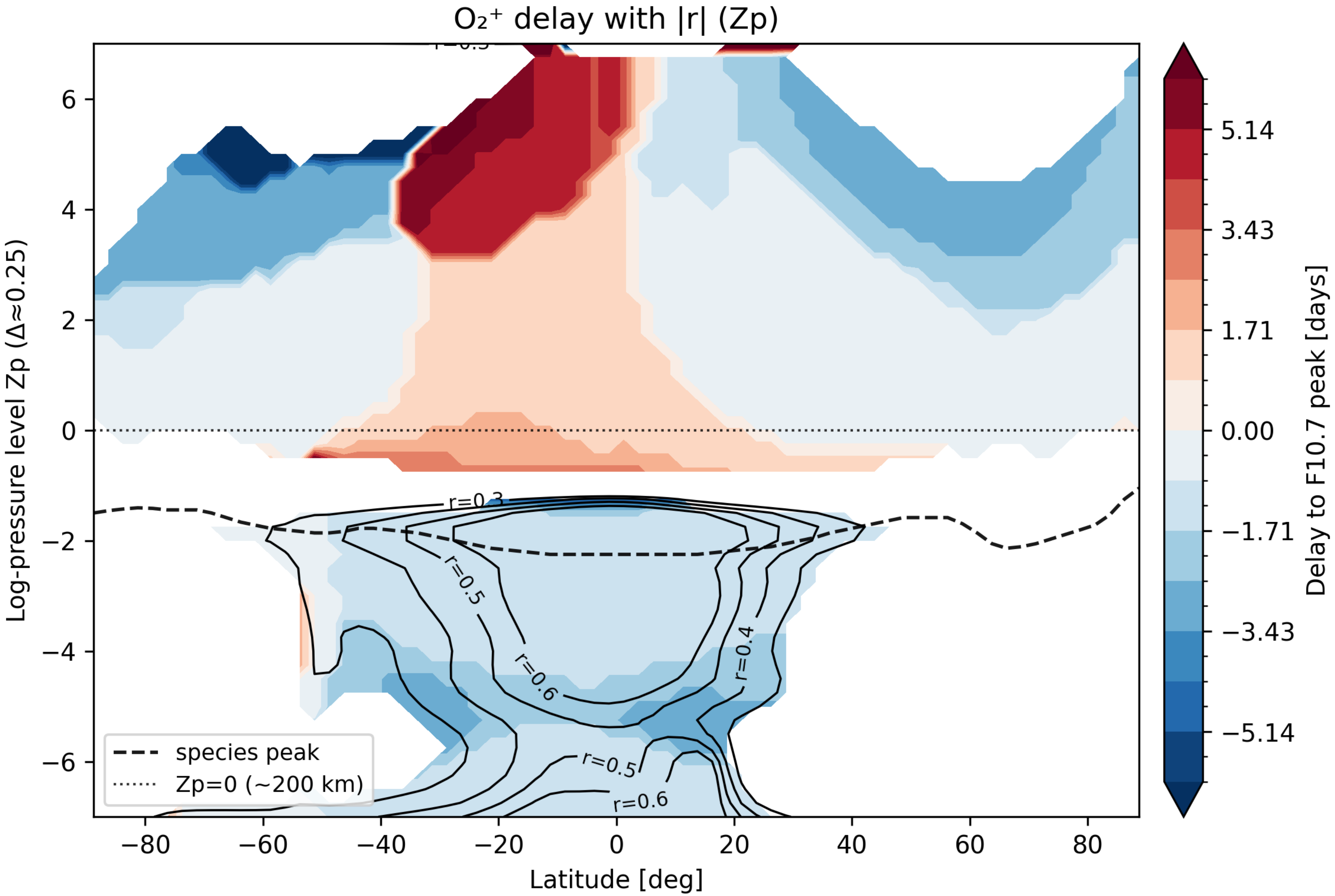
Altitude dependence based on species

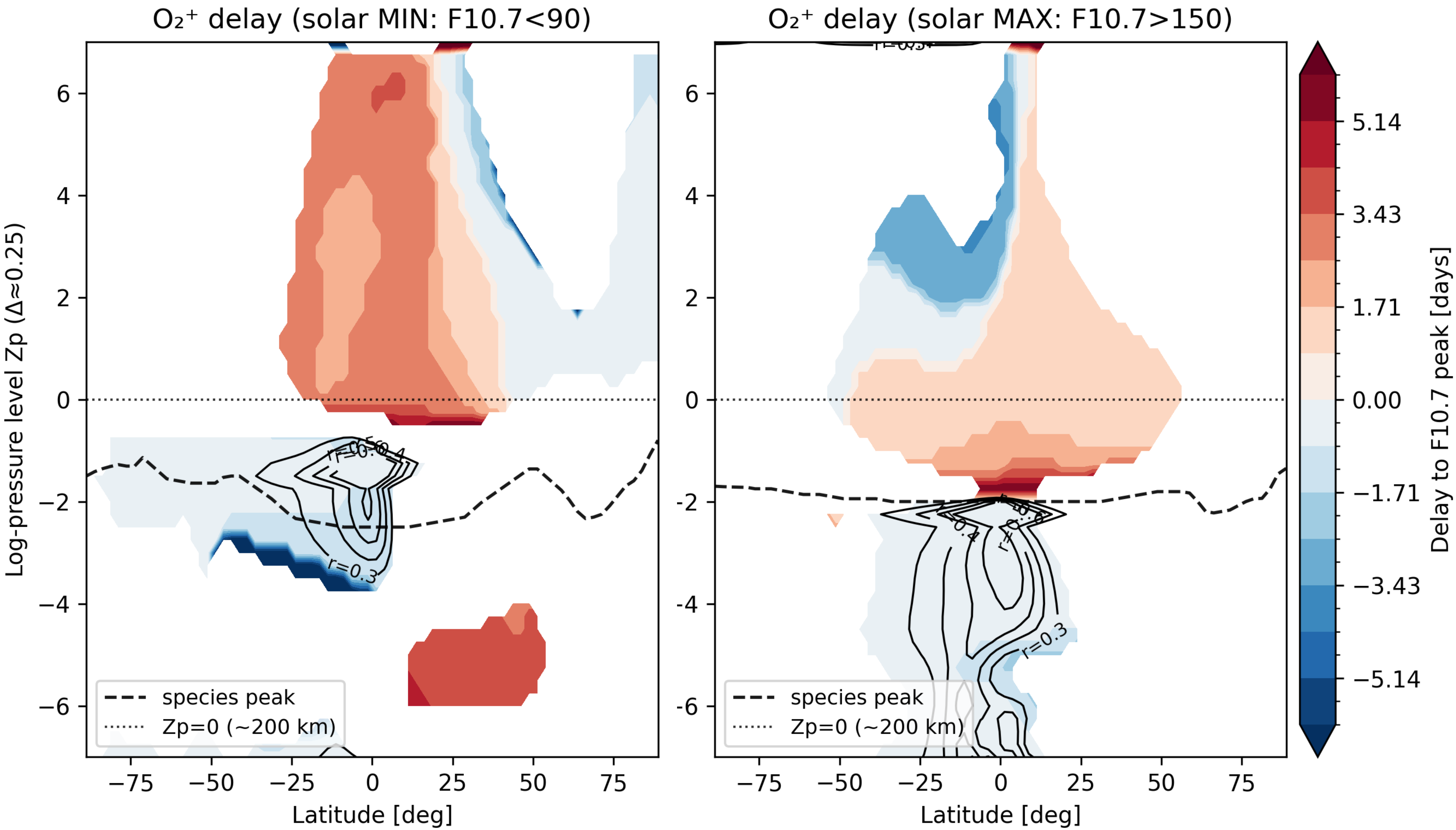




NE delay (solar MIN: F10.7<90)
NE delay (solar MAX: F10.7>150)
Log-pressure level Zp (Δ≈0.25)
Latitude [deg]
Delay to F10.7 peak [days]
species peak
Zp=0 (~200 km)
r=0.3
r=0.4
r=0.5
r=0.6
5.14
3.43
1.71
0.00
−1.71
−3.43
−5.14

Altitude dependence based on species





O₂⁺ delay (solar MIN: F10.7<90)
O₂⁺ delay (solar MAX: F10.7>150)
Log-pressure level Zp (Δ≈0.25)
Latitude [deg]
Delay to F10.7 peak [days]
5.14
3.43
1.71
0.00
−1.71
−3.43
−5.14
r=0.3
species peak
Zp=0 (~200 km)

SUMMARY

Summary

- Solar 27-day variations drives upper atmosphere ionization

➔ **“simple” delay**

- T/I interactions (spatial, temporal, solar and geomag. levels, etc.)

➔ **complex delay**

- O_2^+ and lower ionosphere is governed by slow trends
- NE and O^+ react directly to variations in solar activity

Thank you for your attention!

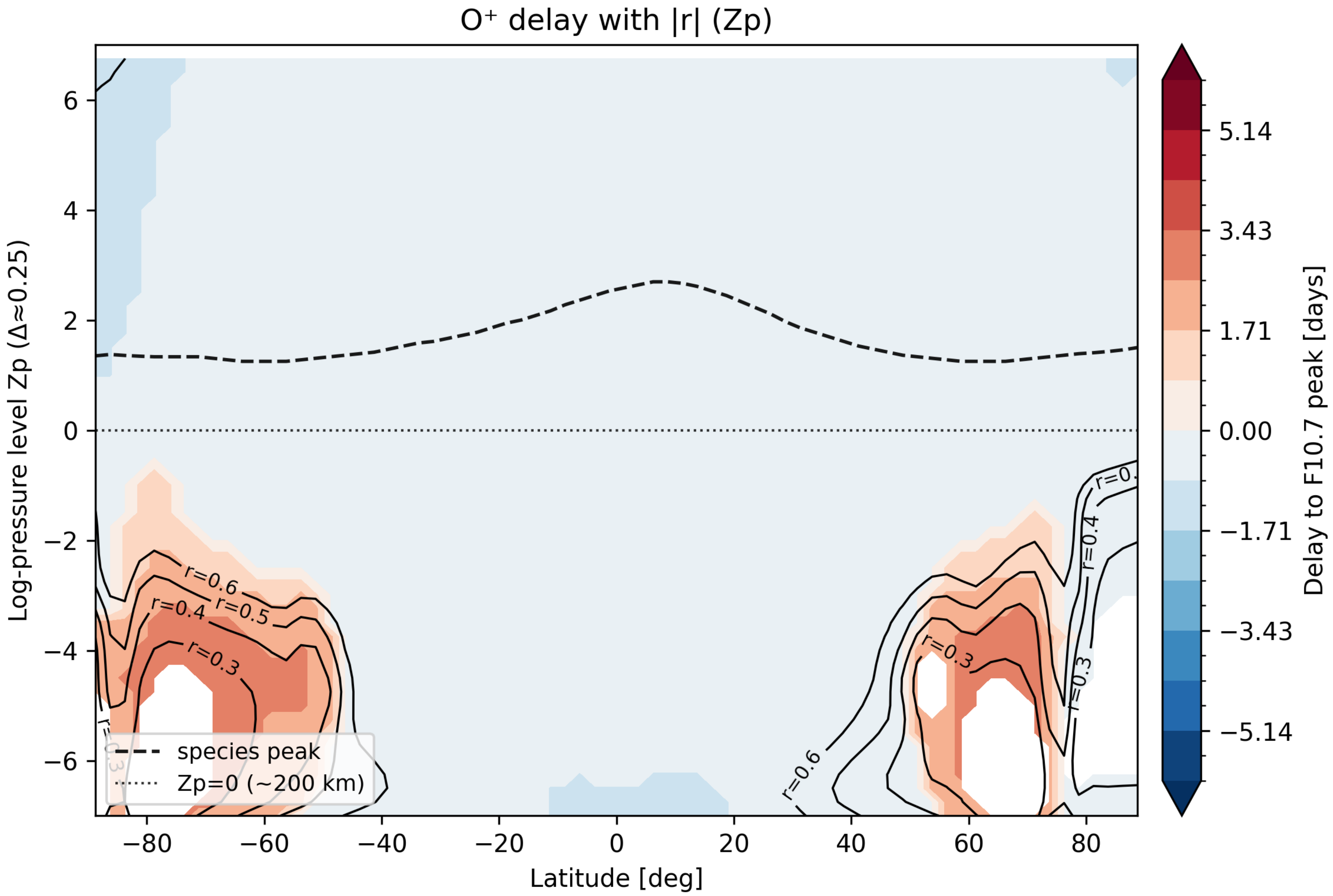
This research is supported by Deutsche Forschungsgemeinschaft (DFG) - Nos. JA 836/48-1 and SCHM 3761/1-1.

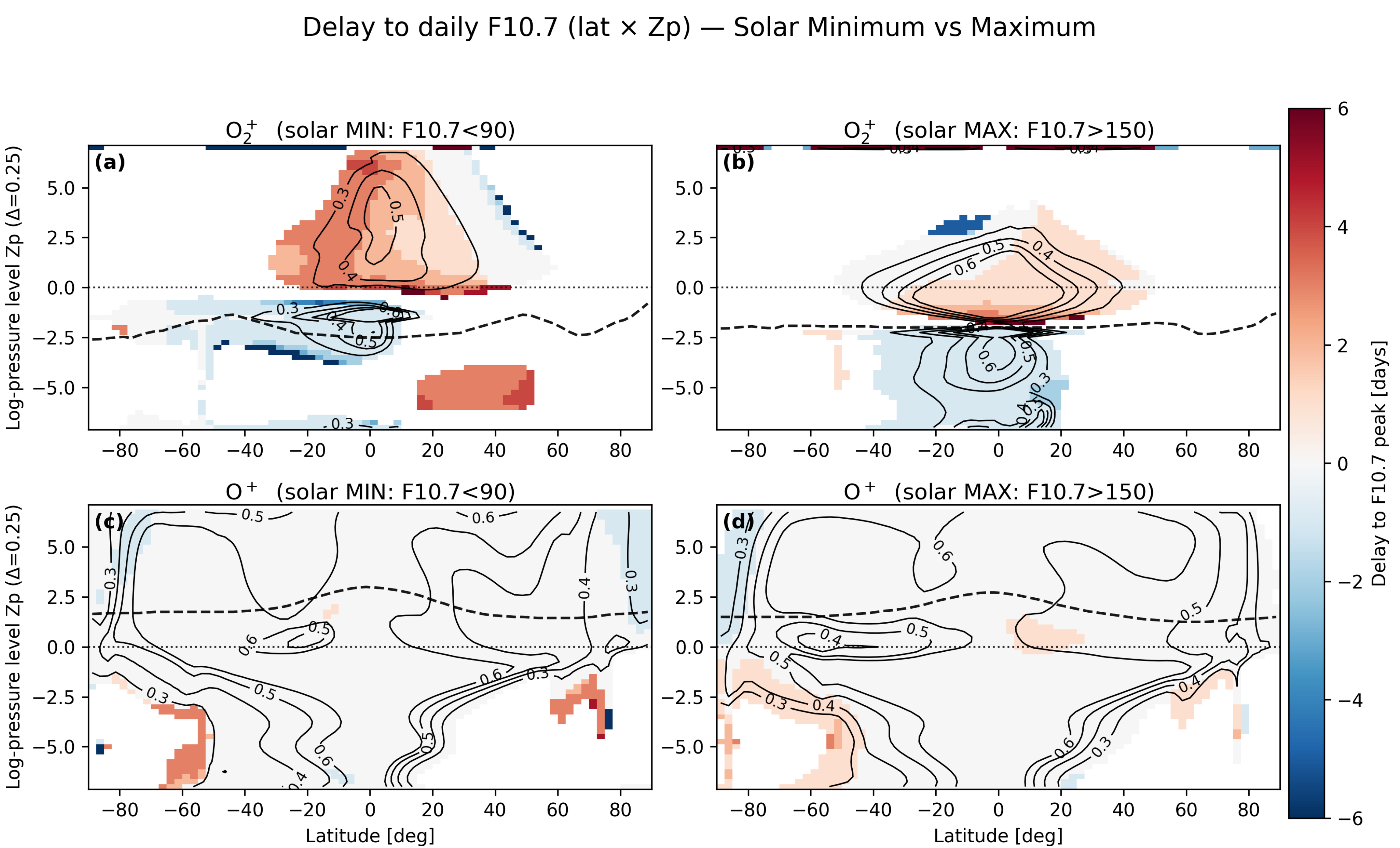
References:

- Dühnen; 2024; doi: 10.1016/j.asr.2024.12.004
- Lee et al.; 2012; doi: 10.1016/j.jastp.2012.01.010
- Qian et al.; 2014; doi: 10.1002/9781118704417.ch7
- Ren et al.; 2018; doi: 10.1029/2018JA025835
- Schmölter et al.; 2018; doi: 10.5194/ars-16-149-2018
- Schmölter et al.; 2020; doi: 10.5194/angeo-38-149-2020
- Schmölter et al.; 2022; doi: 10.1029/2021JA030118
- Schmölter et al.; 2024; doi: 10.1029/2024JA032672
- Vaishnav et al.; 2021; doi: 10.1016/j.asr.2021.12.041
- Vaishnav et al.; 2023; doi: 10.1029/2022JA030887

BACKUP SLIDES

Altitude dependence based on species





Delay to daily F10.7 (lat × Zp) — Solar Minimum vs Maximum
O2+ (solar MIN: F10.7<90)
O2+ (solar MAX: F10.7>150)
O+ (solar MIN: F10.7<90)
O+ (solar MAX: F10.7>150)
(a)
(b)
(c)
(d)
Log-pressure level Zp (Δ=0.25)
Latitude [deg]
Delay to F10.7 peak [days]