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ISTITUTO NAZIONALE DI GEOFISICA E VULCANOLOGIA

New dynamics of ionospheric electron temperature overshoot uncovered by neural networks

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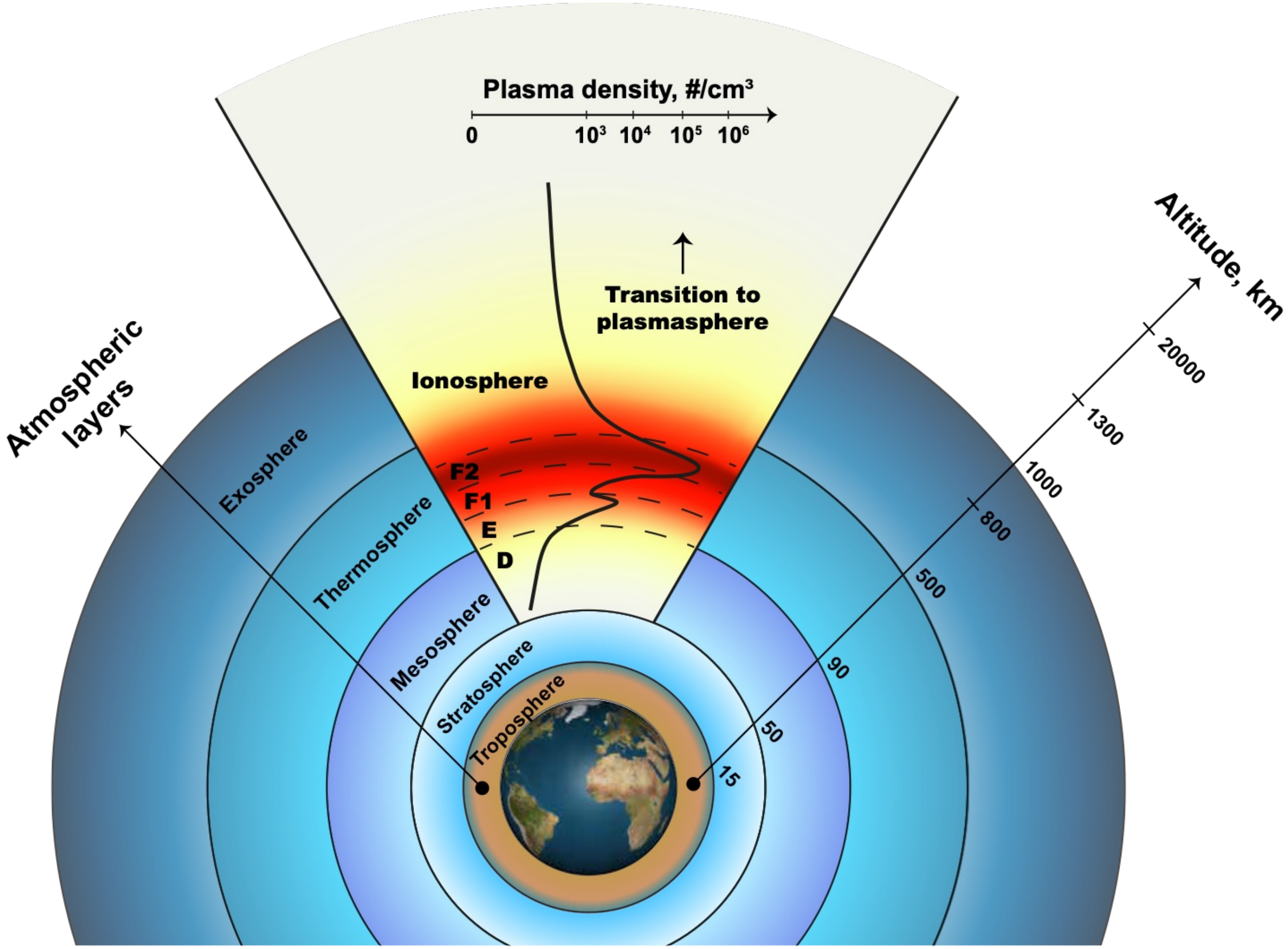
25 March 2026, ISWI Webinar

Earth's atmosphere and ionosphere



Adapted from Limberger (2015)

Ionosphere is a partially ionized region of the upper atmosphere, spanning from 60 to ~800 km in altitude

Numerous processes contribute to its dynamics and morphology:

- ✓**Source (q)** : photo- and impact ionization
- ✓**Loss (l)**: ion recombination or attachment
- ✓**Transport**: Vertical (**E**x**B** drift, diffusion), and horizontal (winds)

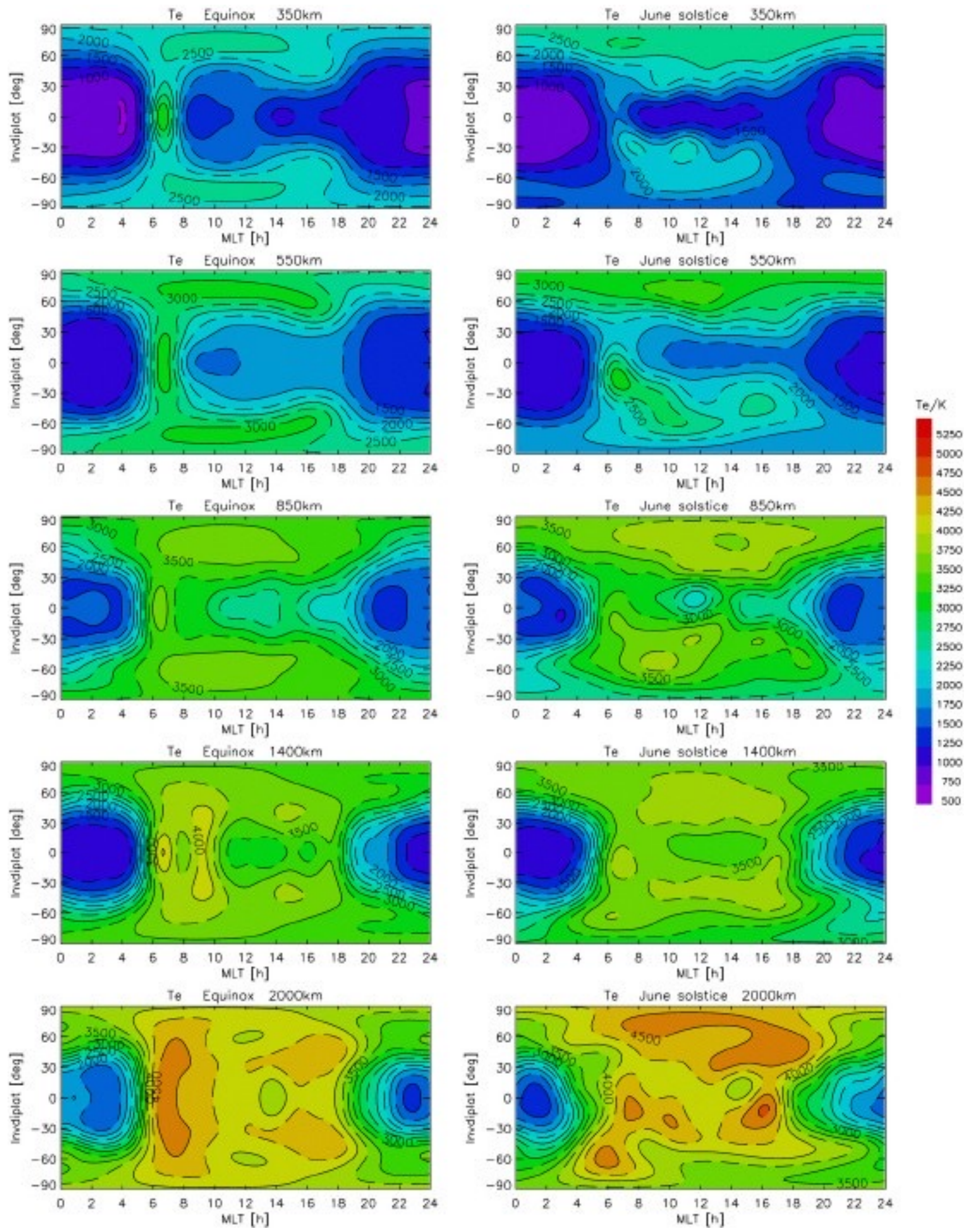
The continuity equation:

$$\frac{\partial N}{\partial t} = q - l - \nabla \cdot (n\boldsymbol{v})$$

Key ionospheric parameters

- Plasma density
- Plasma temperature
- Plasma composition

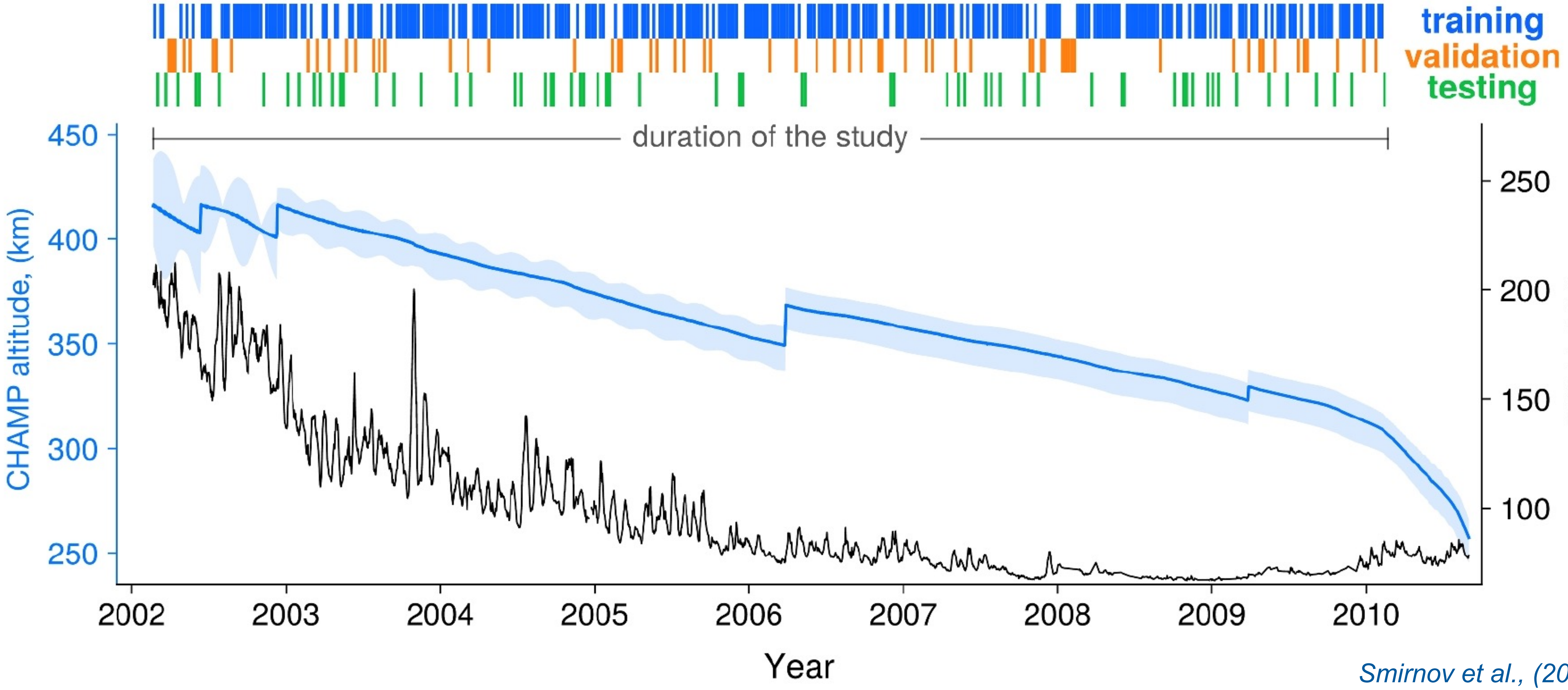
None of the previous Te models included geomagnetic activity



Truhlik et al., (2012)

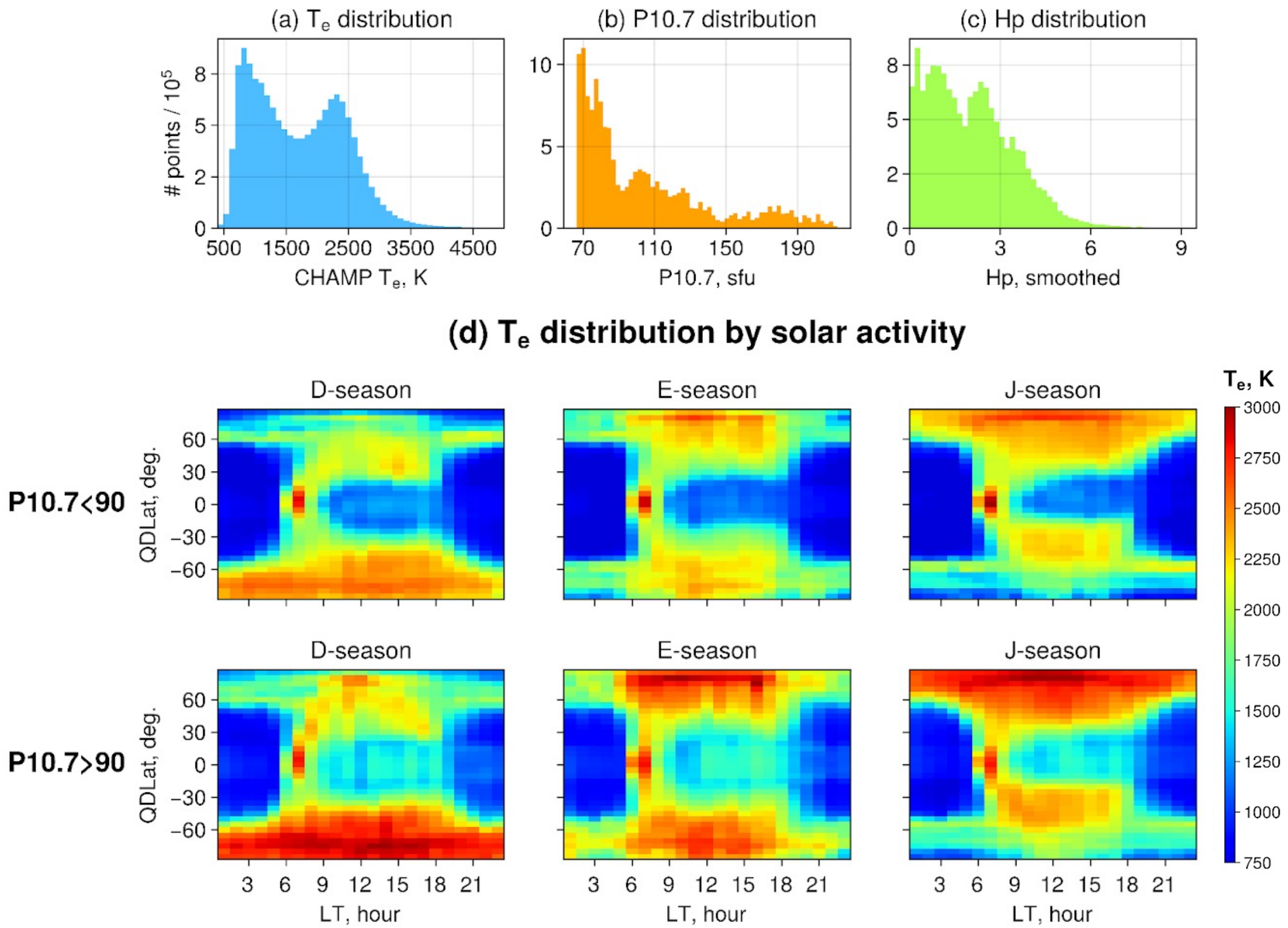
The CHAMP mission

CHAMP provided a high-quality data set of electron temperatures in 2002-2010

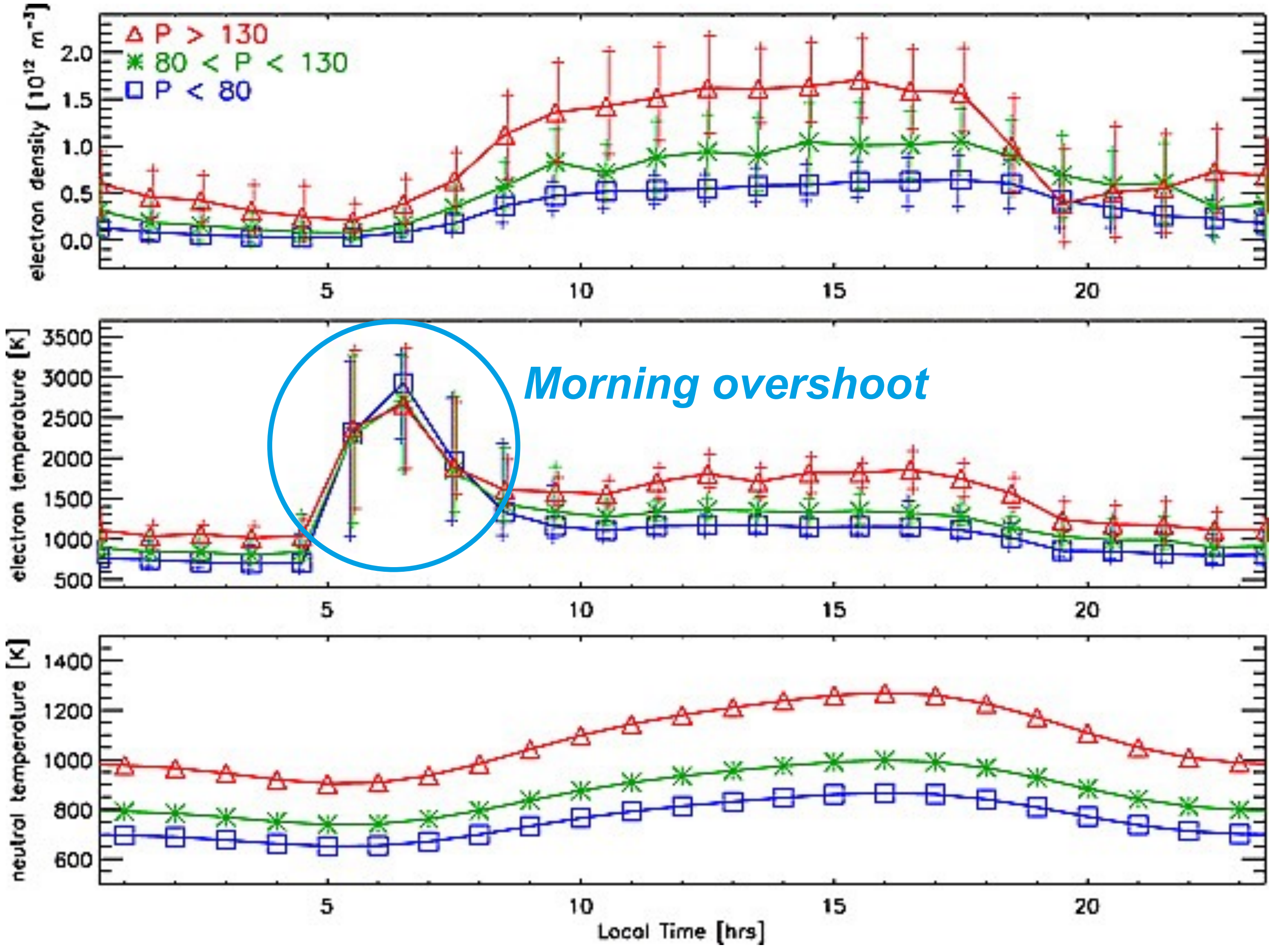


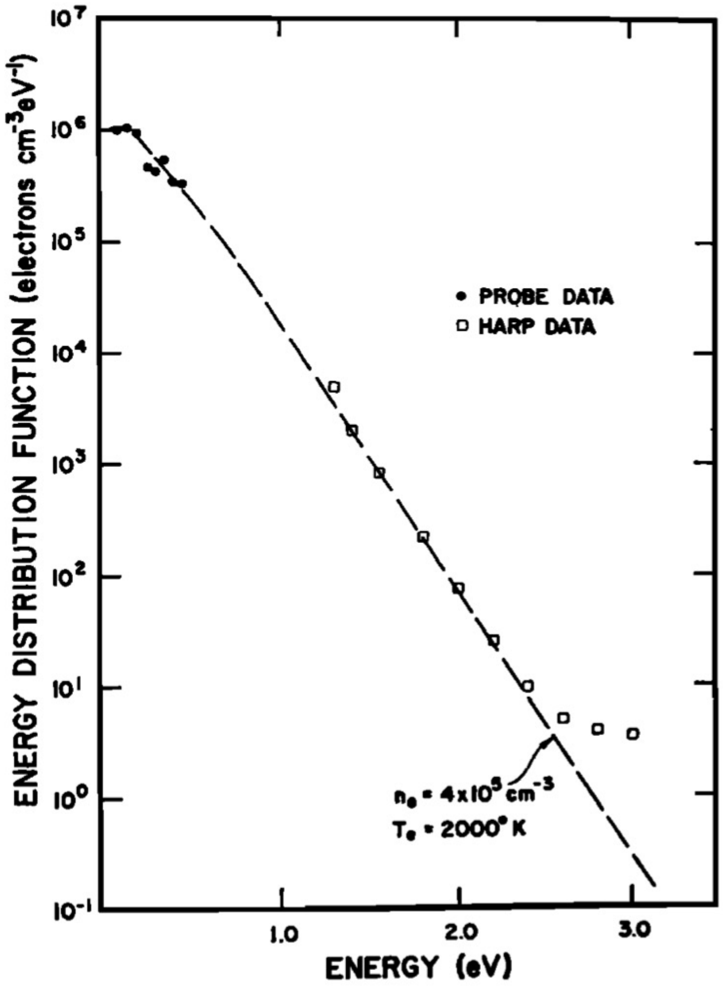
Smirnov et al., (2025)

Data exploration: relation to solar activity



Morning overshoot of electron temperature

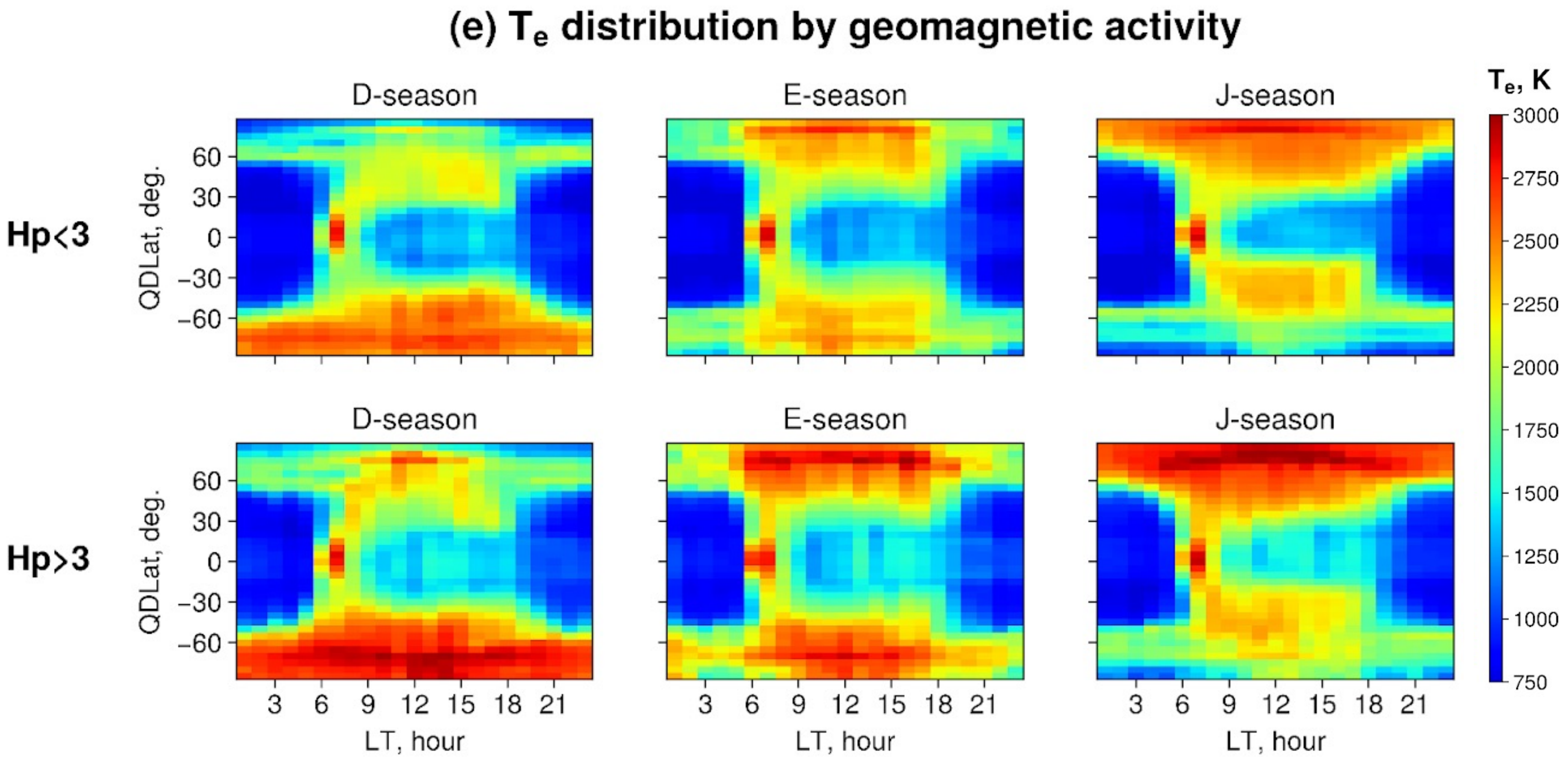




[Stolle et al., 2011]

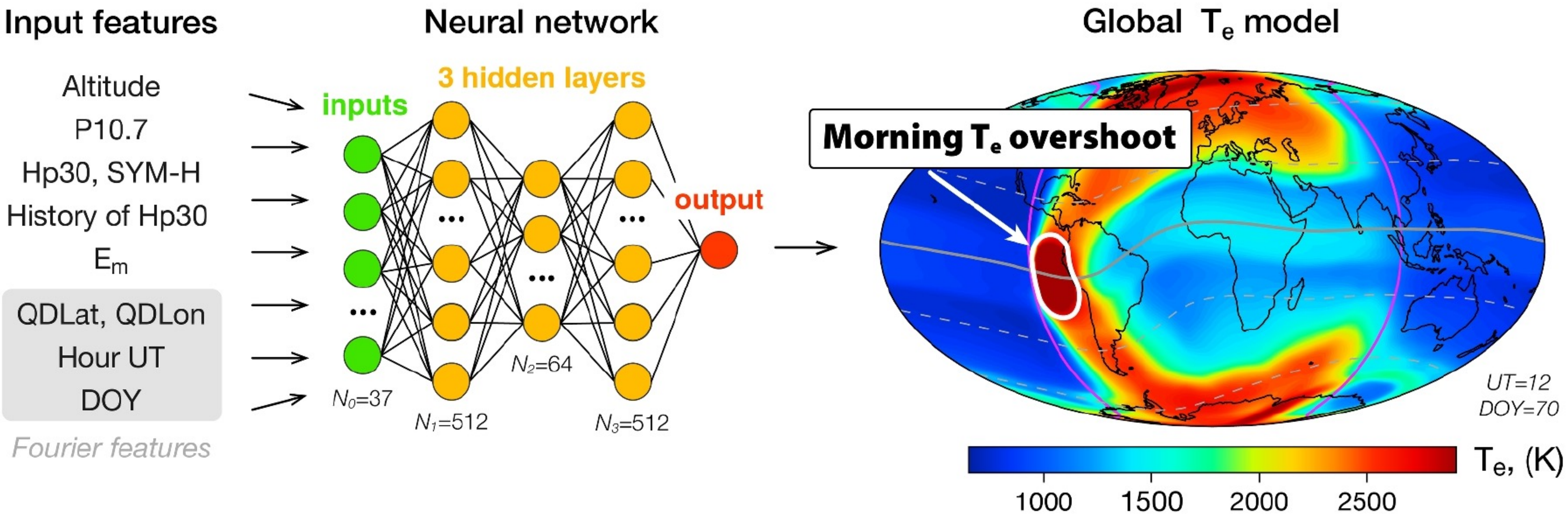
[Schunk, 1978]

Geomagnetic activity dependence in the data



Model workflow

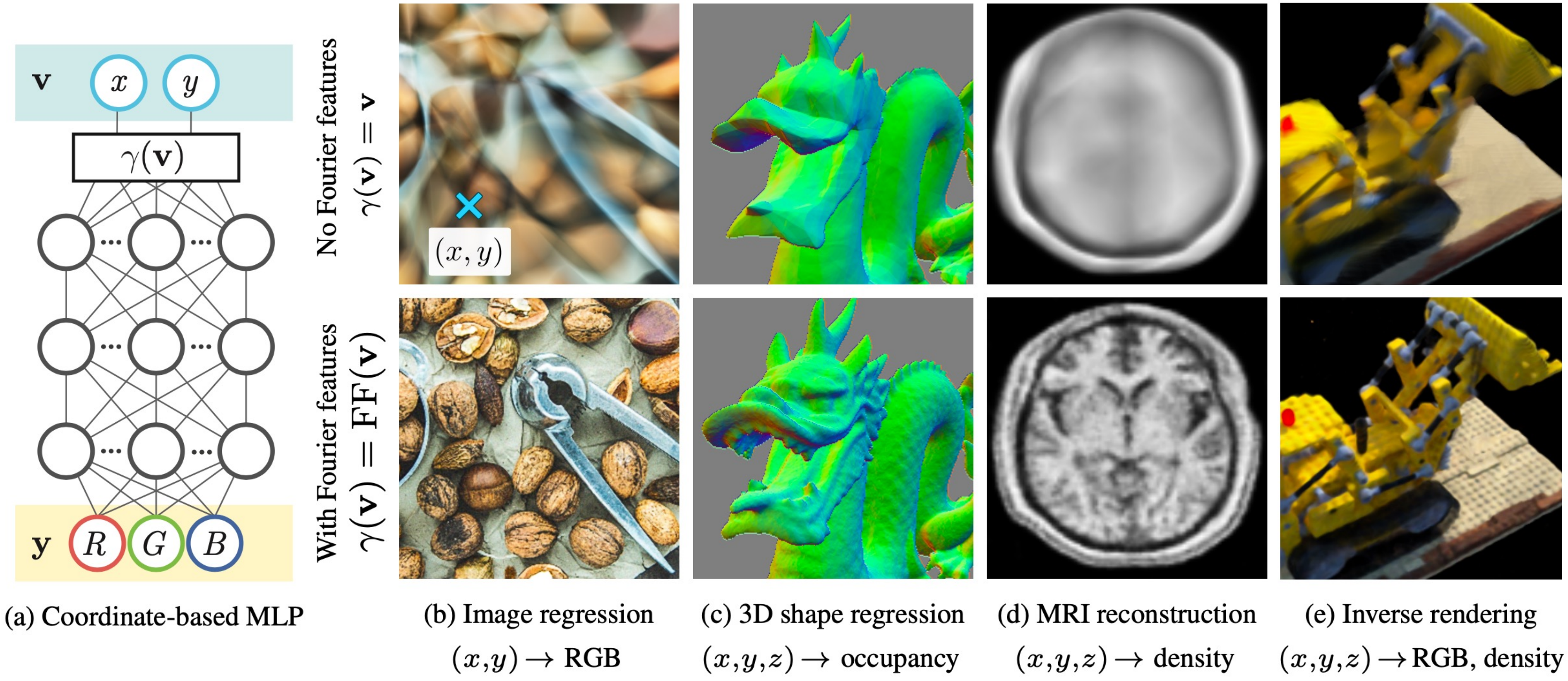
Using 8 years of CHAMP data, we developed a global model of electron temperatures



Smirnov et al., (2025)

Fourier features

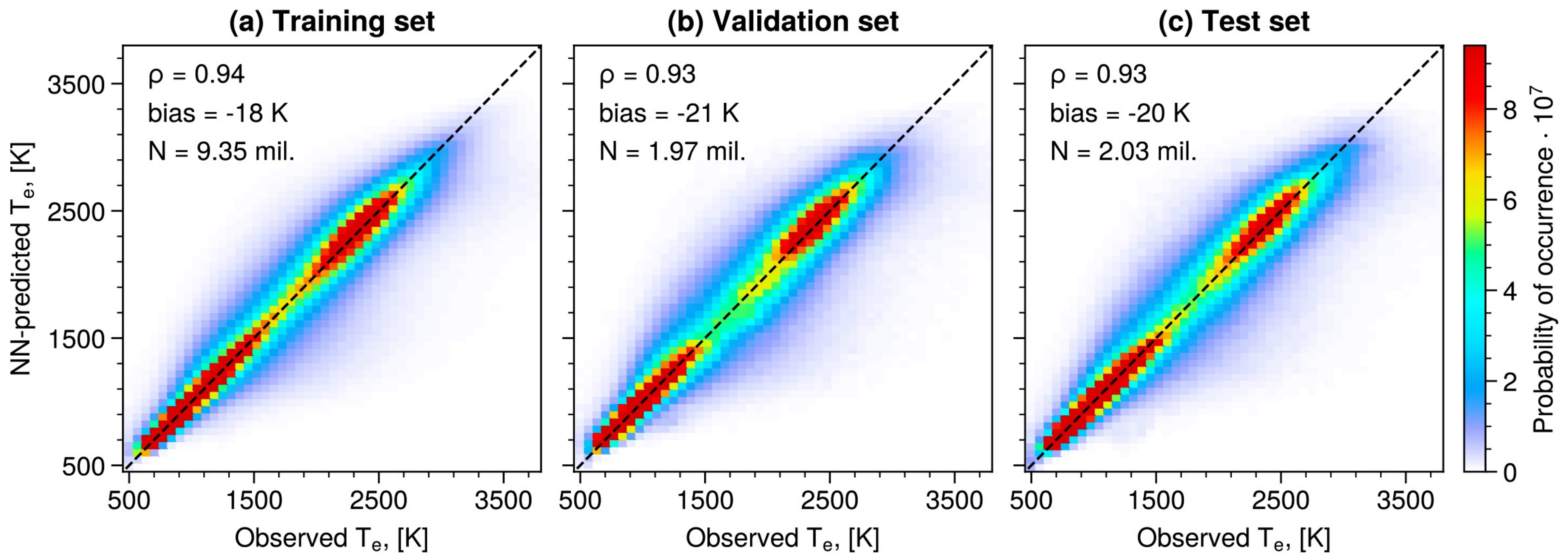
Replacing position with sin/cos transformations helps reproduce small structures



[Tancik et al., 2020]

Model results

The model can reproduce CHAMP observations very well. The performance is similar on training and independent test sets



Independent validation by the ISRs

MIT Haystack radar at Millstone Hill

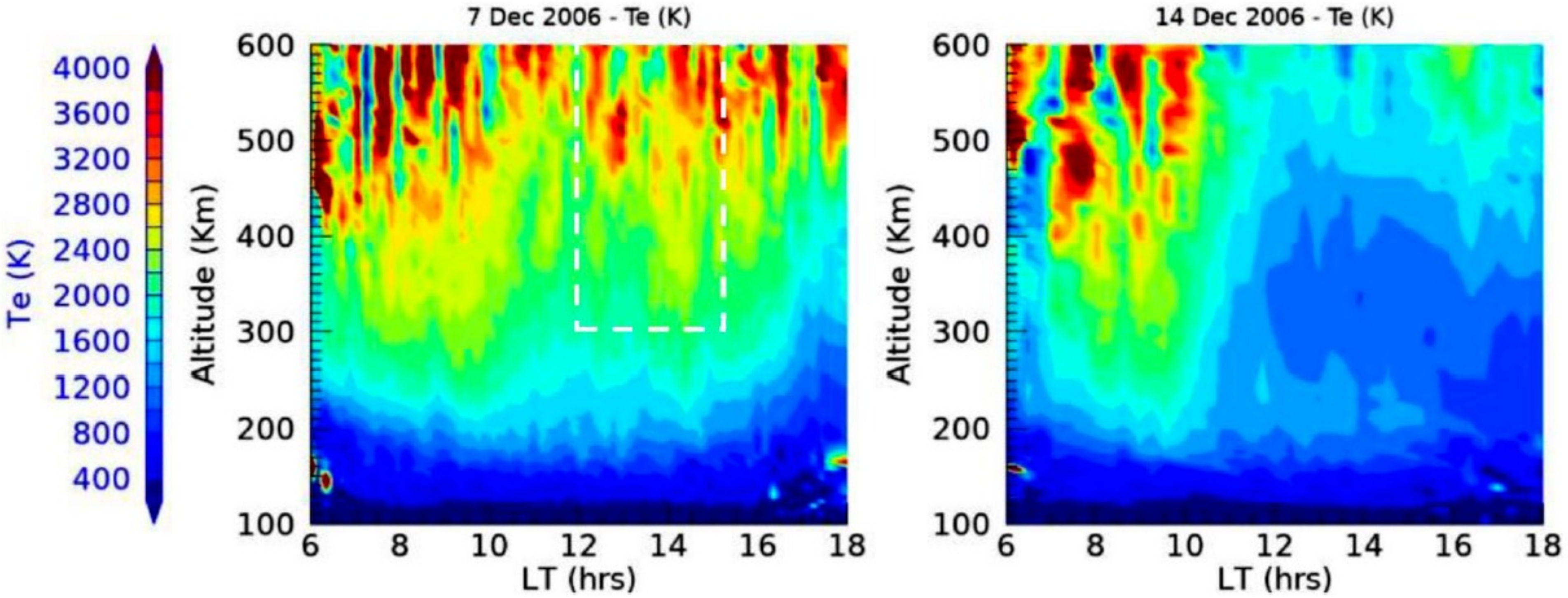
Independent validation by the ISRs

Arecibo ISR

Jicamarca ISR

Examples of electron temperatures at Millstone Hill

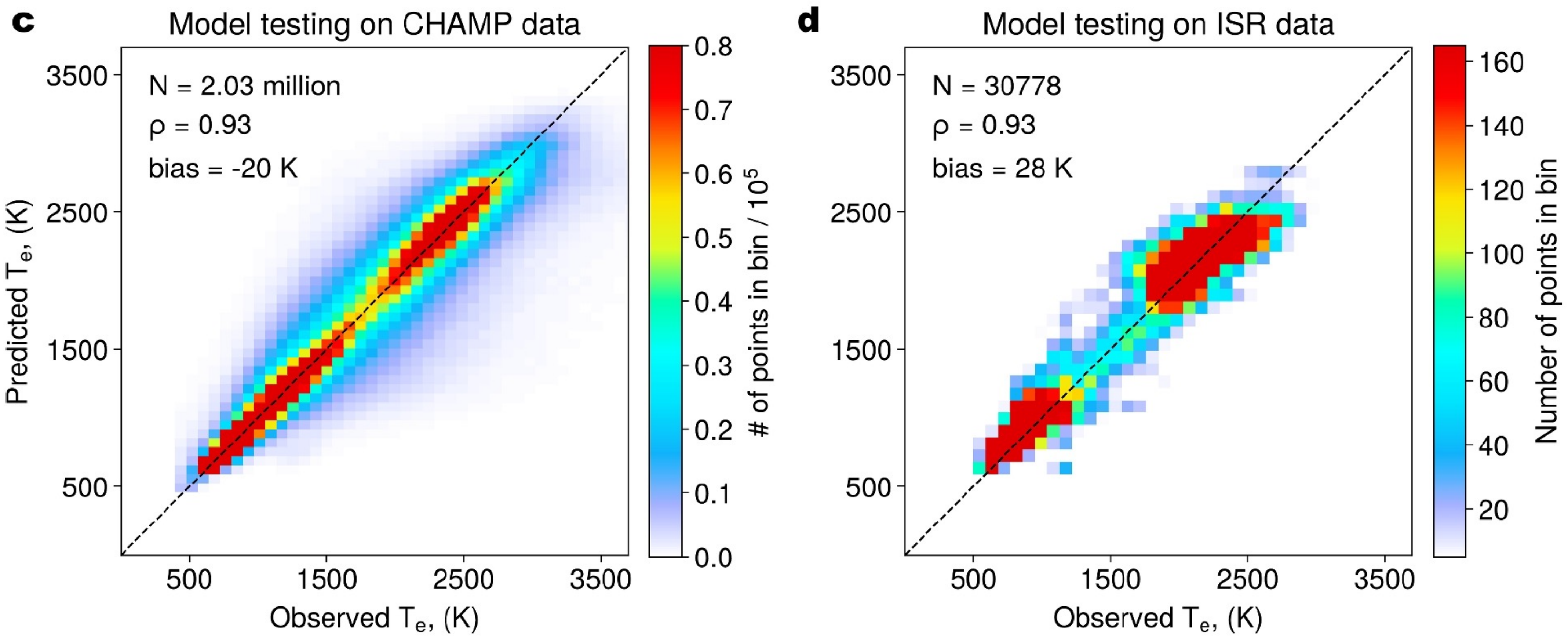
ISRs provide vertical profiles of several key parameters, including Te.
These data are ideal for testing the developed NN model



[Upadhyay and Pallamraju, 2024, GRL]

Model testing on ISR data

The model performance is very similar on CHAMP and ISR datasets

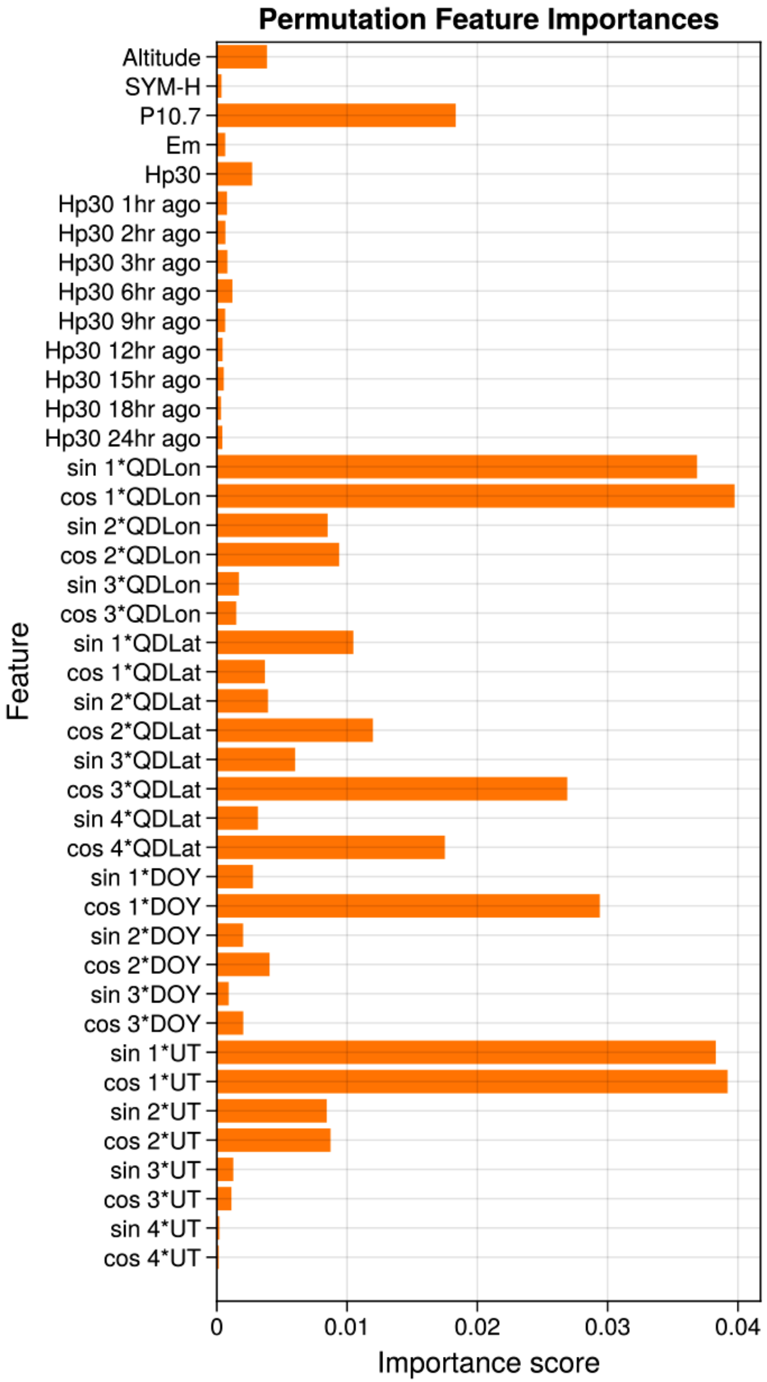


Smirnov et al., (2025)

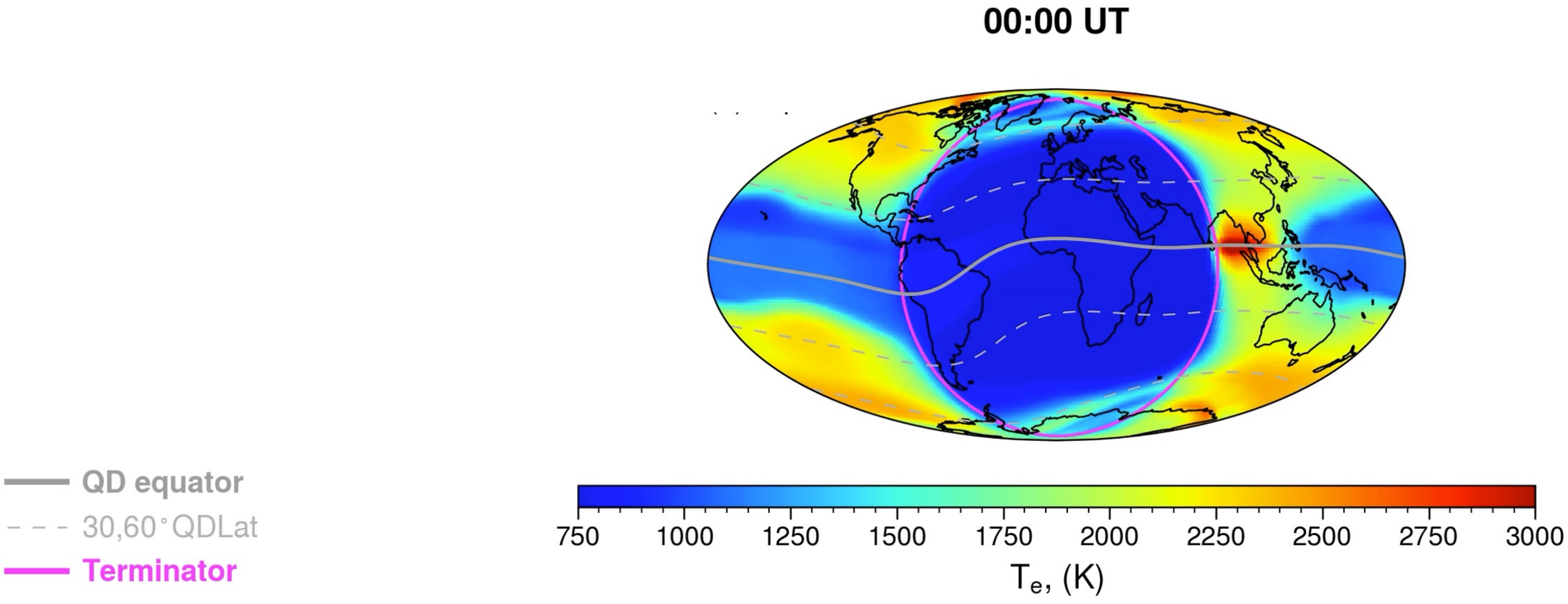
Feature importances

After the model is trained, we can shuffle each input column and evaluate the reduction of performance. This gives the permutation feature importance

- Altitude is not very important
- Most important features are the position and UT
- Merging electric field is locally important at high latitudes

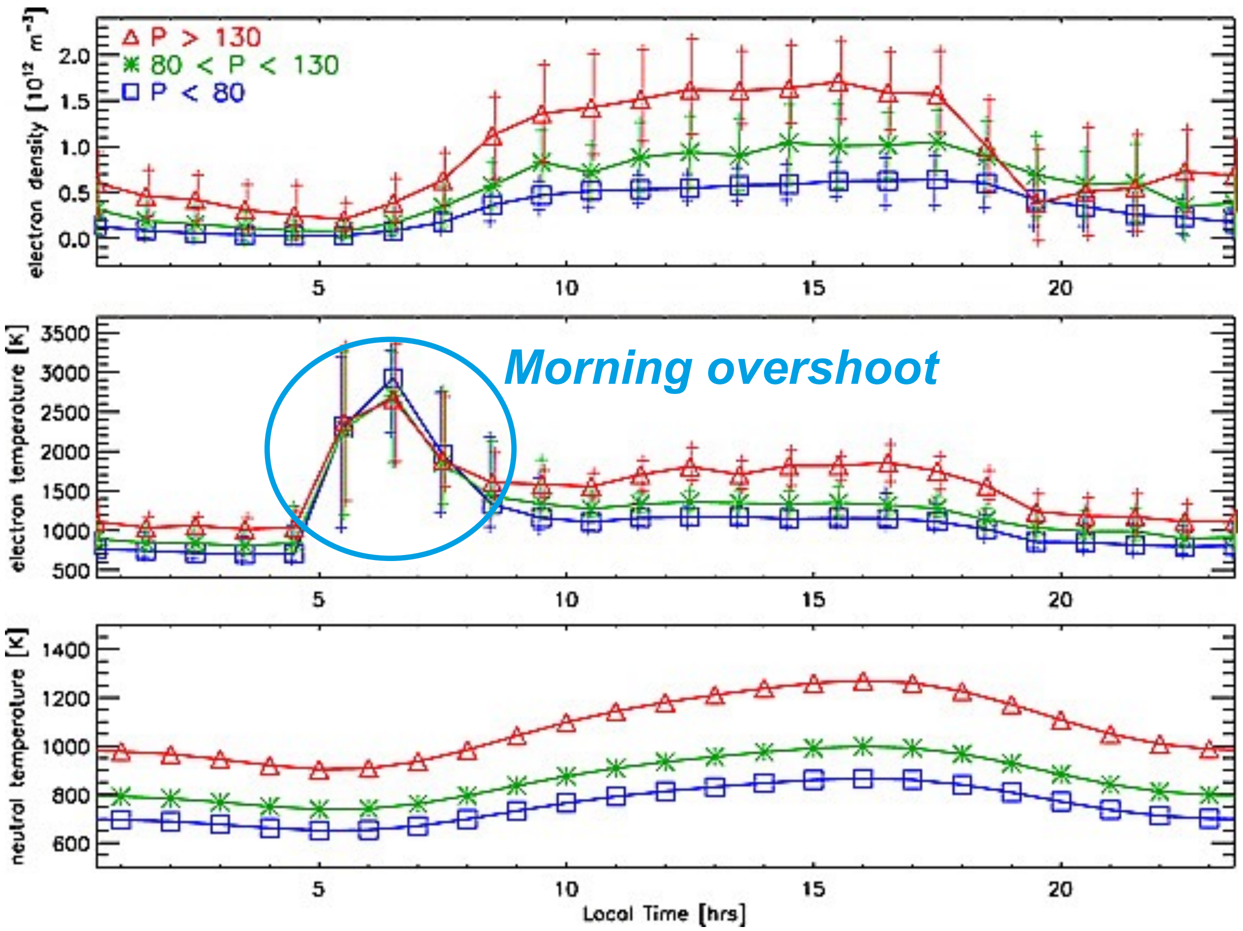


Diurnal T_e evolution

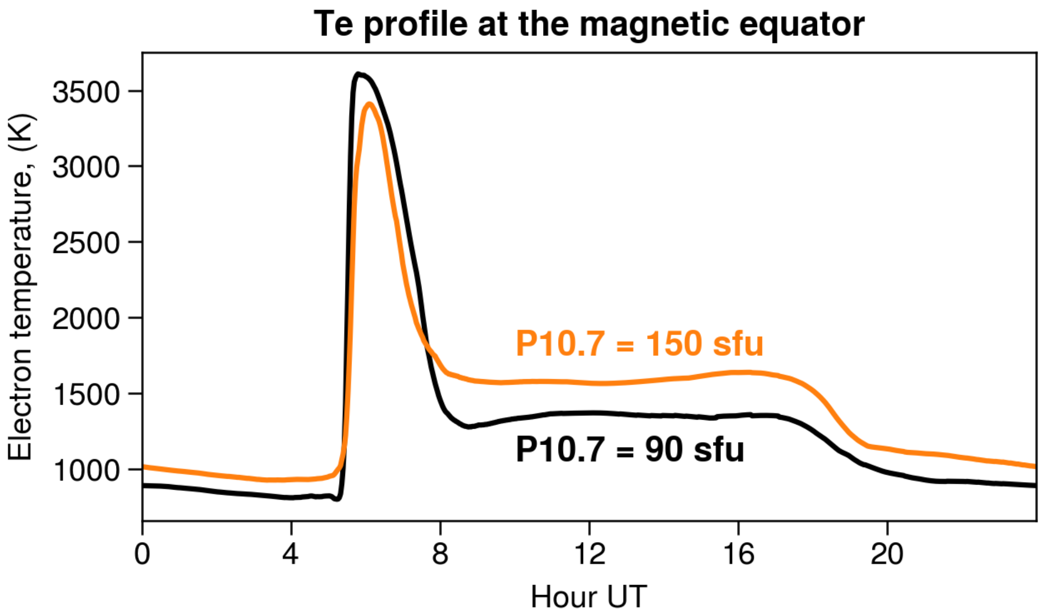


Morning overshoot of electron temperature

Morning overshoot becomes less pronounced with higher solar activity



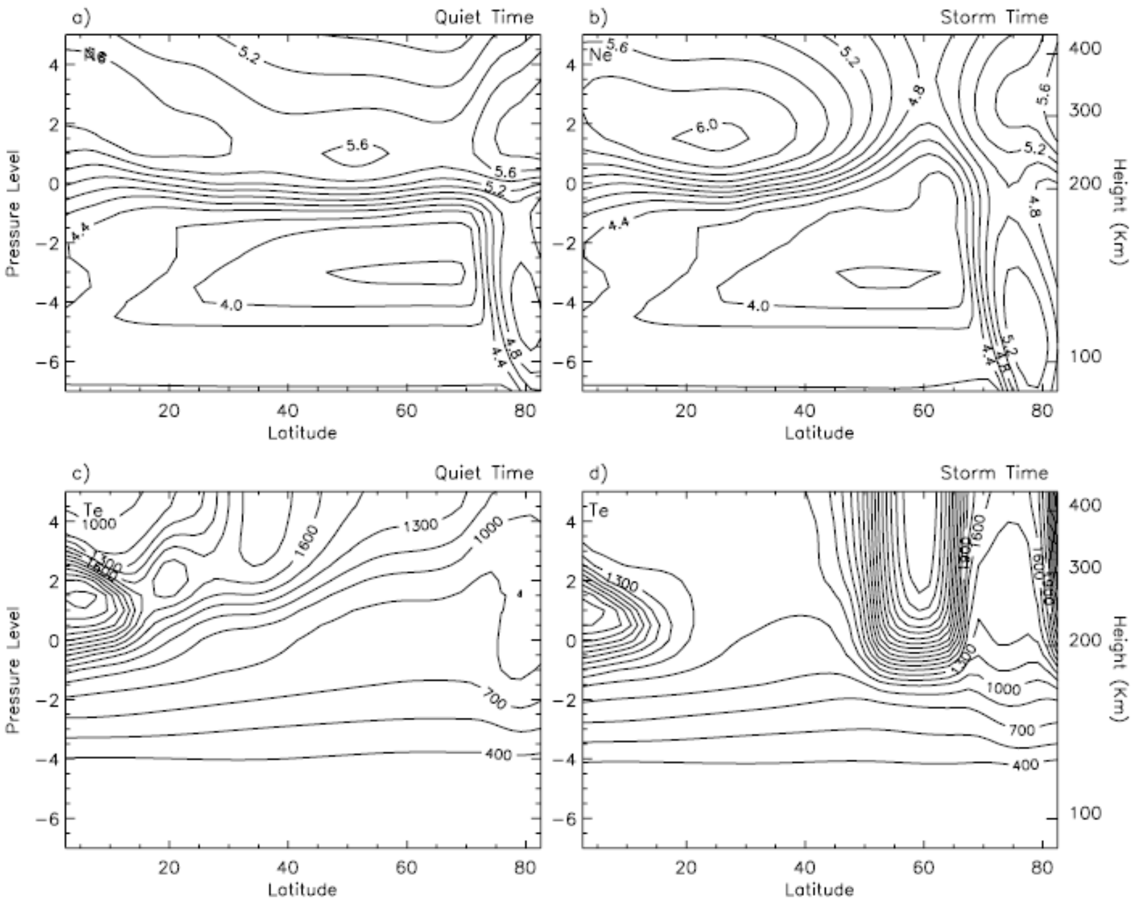
[Stolle et al., 2011]



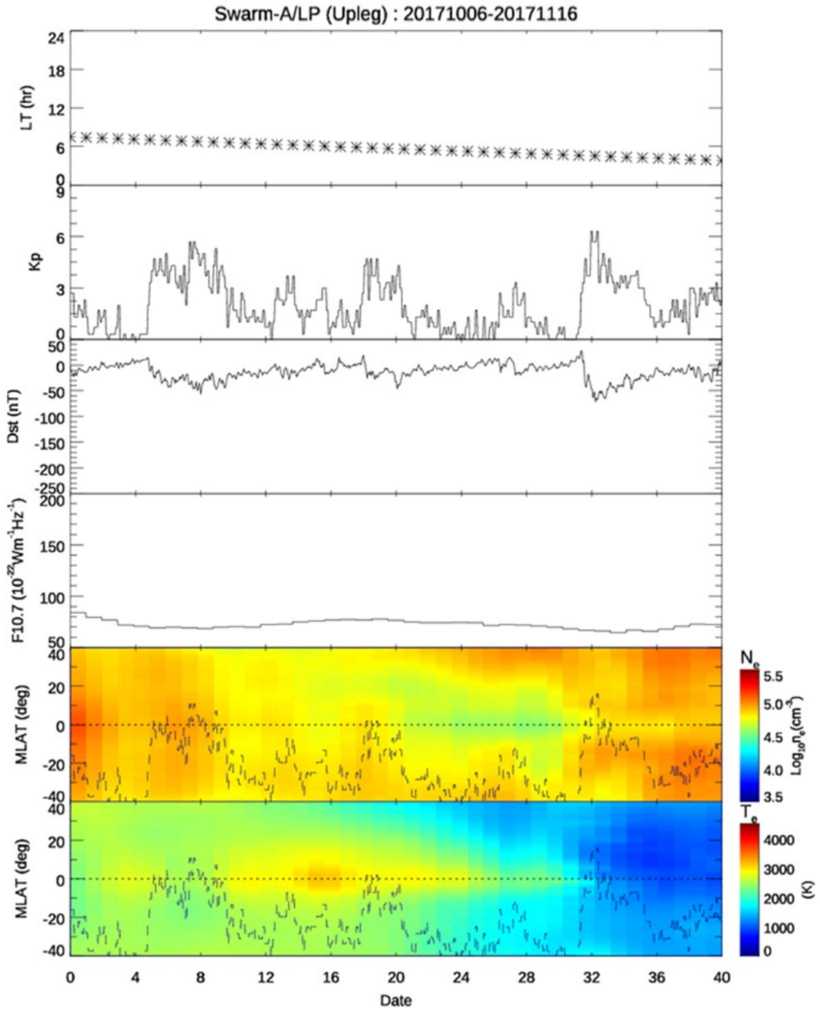
[Smirnov et al., 2025]

Previous results

Previous studies suggested an inverse relationship of Te with the Kp index



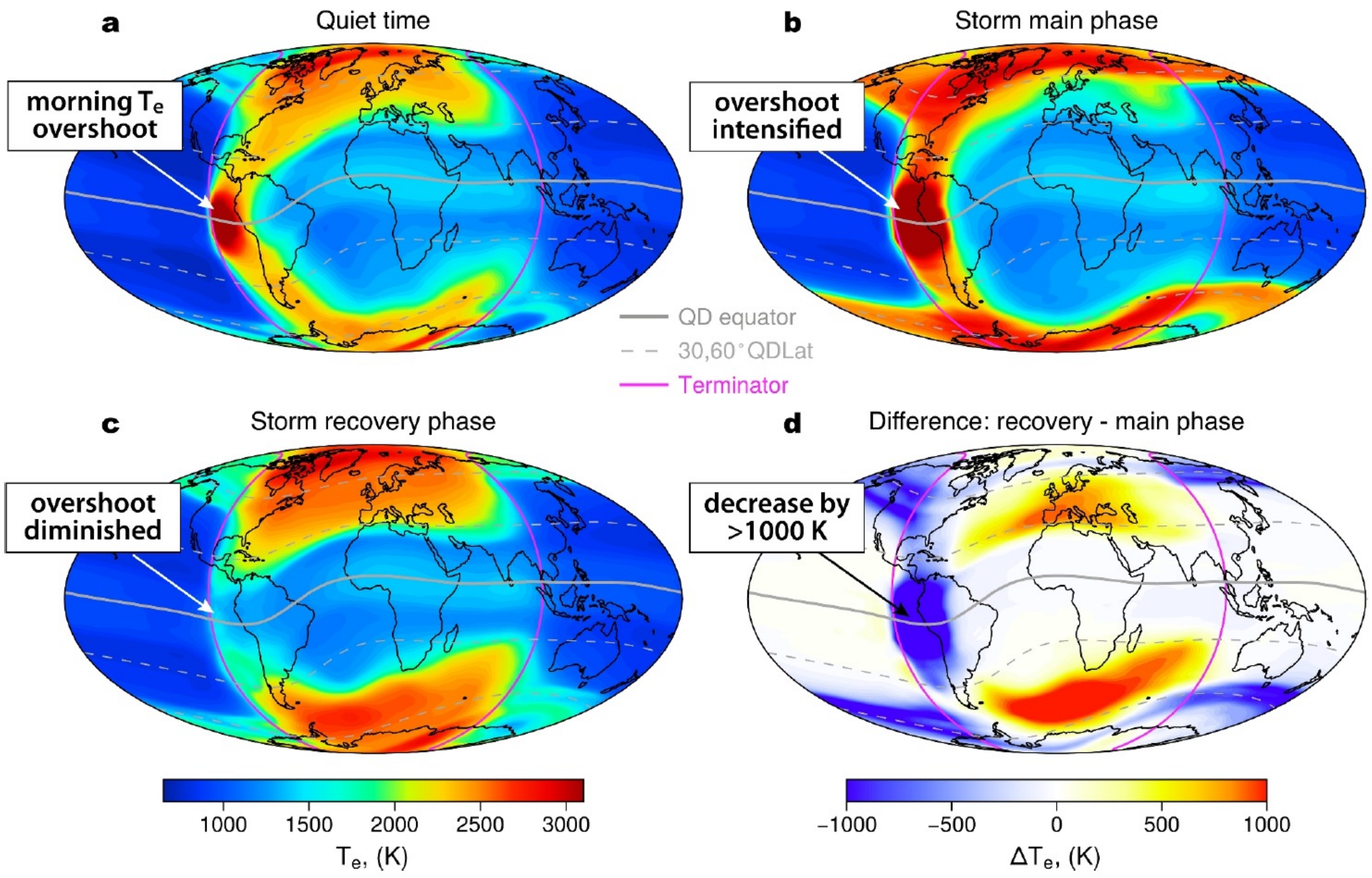
Wang et al., (2006)



Yang et al., (2021)

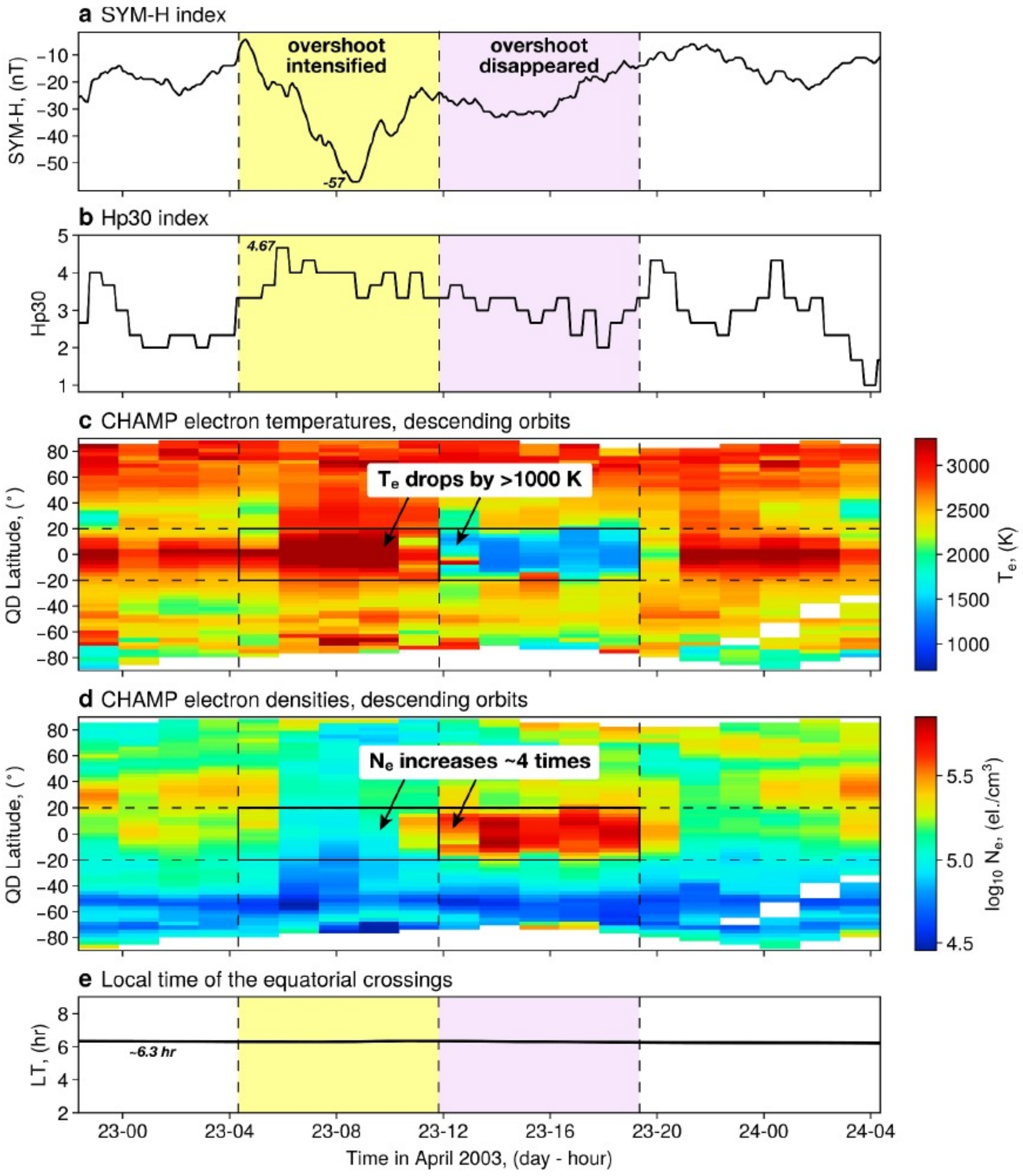
New insights into the morning overshoot

The model uncovered a 2-step response of the morning overshoot during storms



Smirnov et al., (2025)

Case study: 23 April 2003



The same 2-step pattern can be seen in the case study of the 23 April 2003 geomagnetic storm

- Electron temperatures are anti-correlated with densities

- Heating rate ~ N_e
- Cooling rate ~N_e^2

Key ionospheric parameters

Relevant processes can be summarized in the electron energy conservation equation:

$$\frac{3}{2} N_e k_B \frac{\partial T_e}{\partial t} = \sin^2 I \frac{\partial}{\partial z}\left(K_e \frac{\partial T_e}{\partial z}\right) + \sum Q_e - \sum L_e + \{\text{FAC terms}\}$$

transport along field lines

heating rate $\sim N_e$

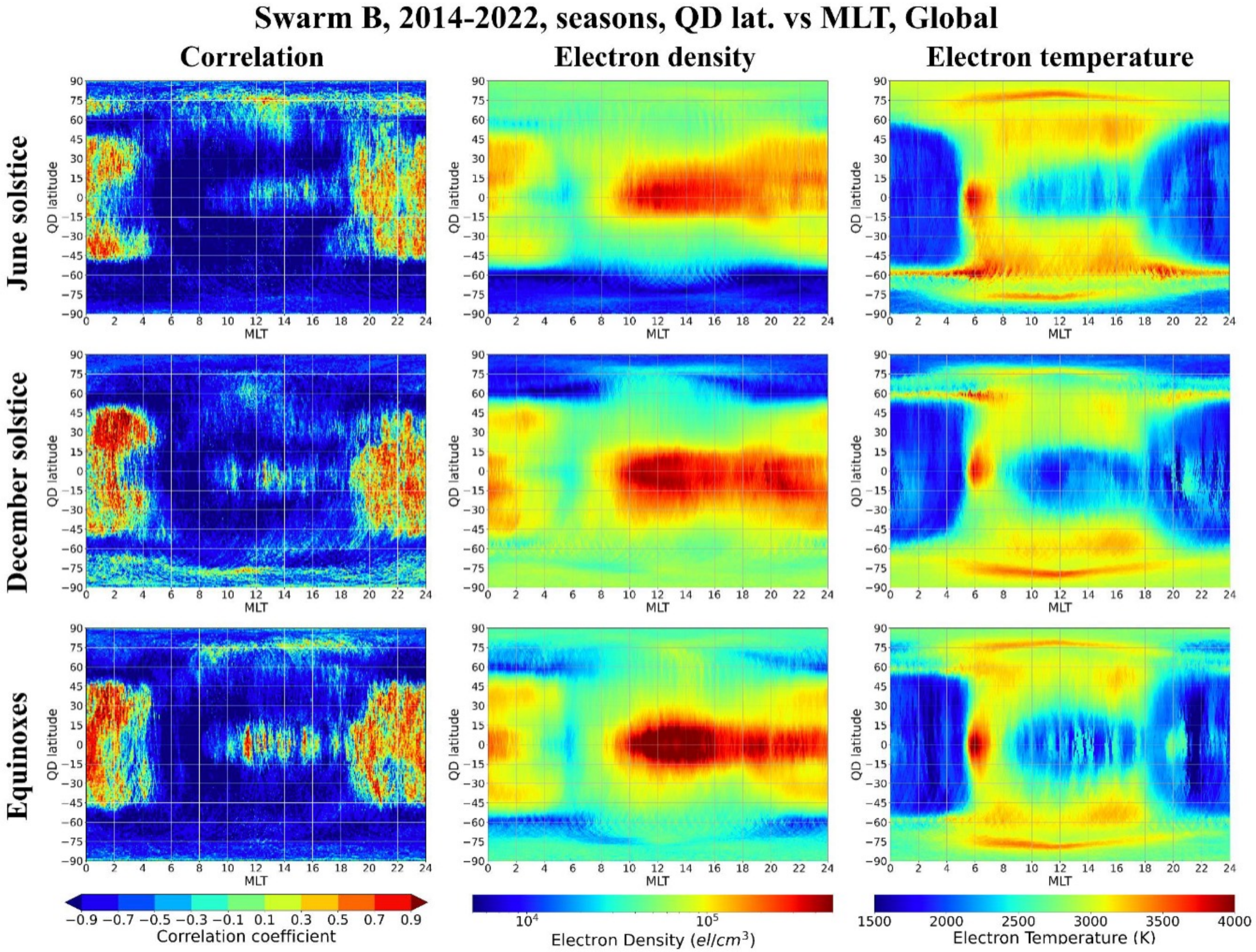
cooling rate $\sim N_e^2$

[Schunk and Nagy, 1978]

The terms correspond to:

- Transport of energy along geomagnetic field lines
- Increase of T_e due to photoionized electrons exchanging energy with ambient plasma (and more complex processes at high latitudes)
- Decrease of T_e due to Coulomb collisions in the topside ionosphere

Correlation between Ne and Te



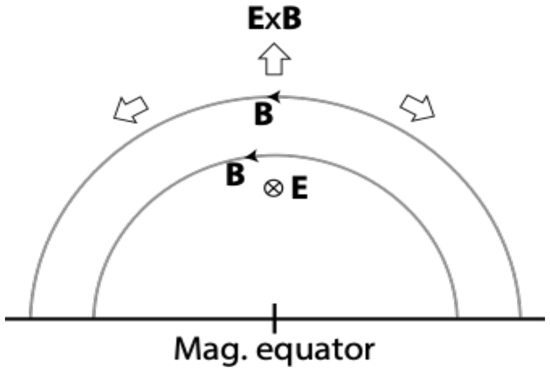
- |QD lat.| ≤ 50°:
  - anti-correlation during sunlit hours (Bilitza et al. 1975);
  - no-correlation to positive correlation during night-time hours (Su et al. 2015).
- No-correlation around the geomagnetic equator from 09:00 MLT onwards (Kakinami et al. 2011).
- |QD lat.| ≥ 50°: anti-correlation with the exception of the local Summer season around ± 75° QD lat.

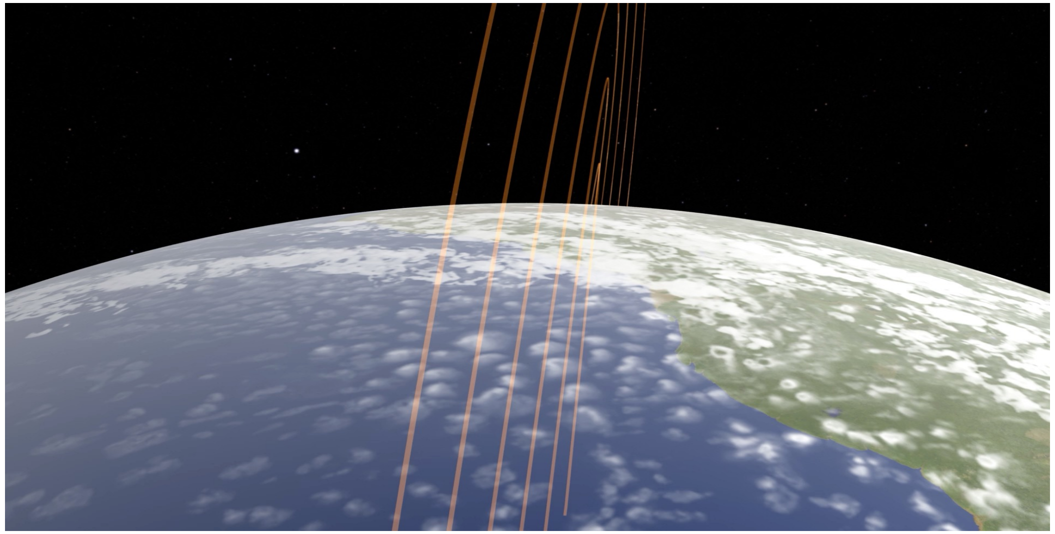
[Pignalberi et al., 2024]

What changes electron densities?

Vertical transport:

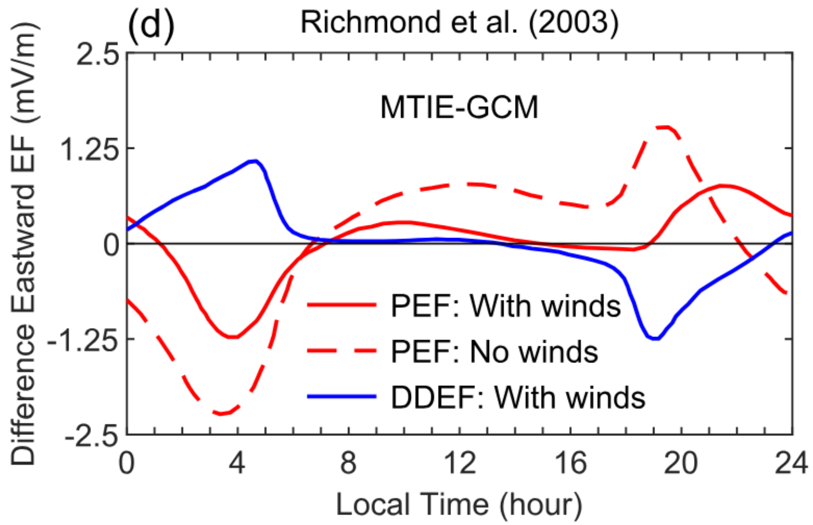
$$\boldsymbol{v}_{E\times B} = \frac{\boldsymbol{E}\times\boldsymbol{B}}{B^2}$$





Animation from NASA GSFC

Initially, PPEFs cause downward ExB drift, while subsequent DDEF lead to upwelling of ambient electrons into the topside



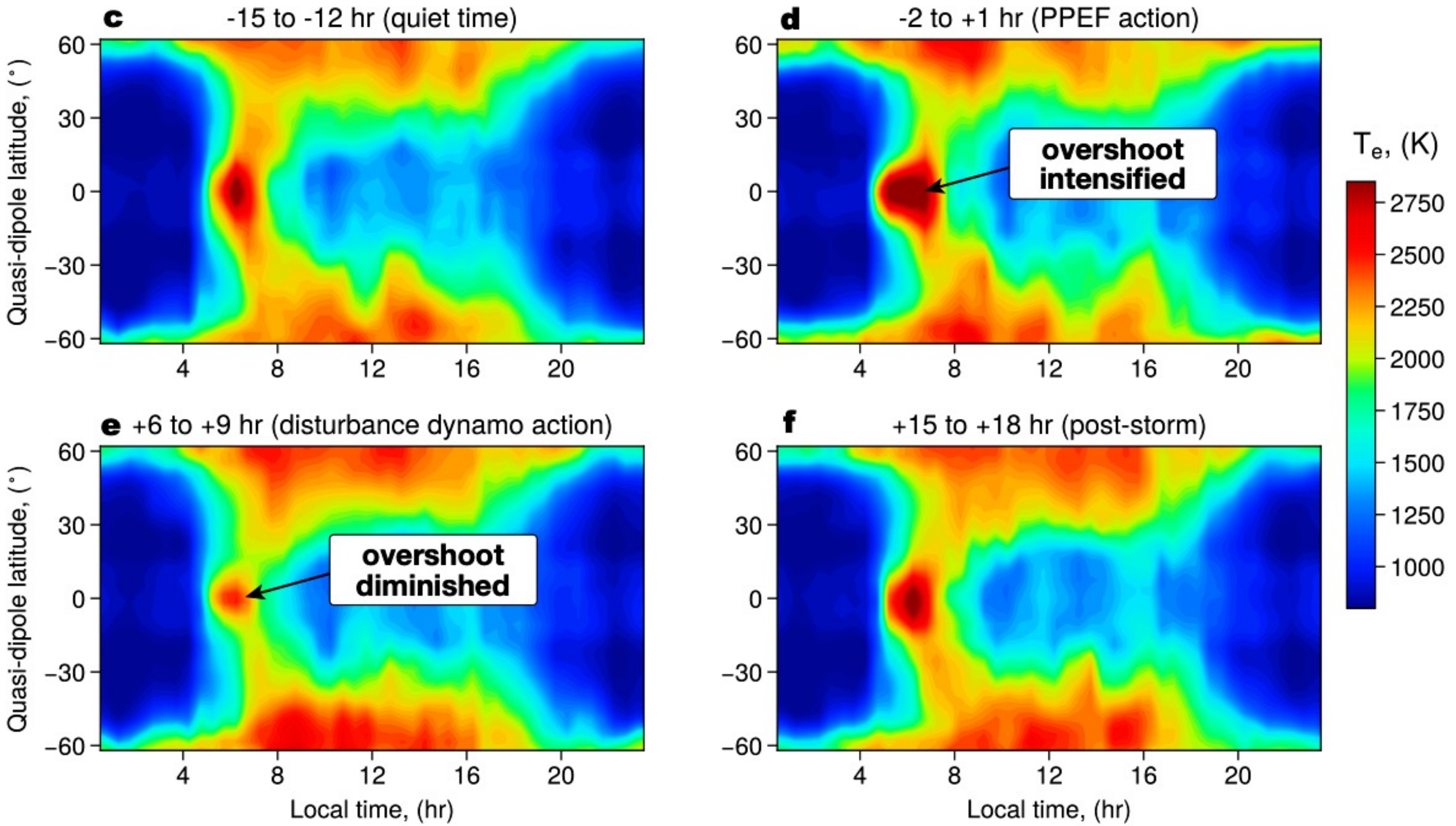
Electron energy conservation equation (Schunk and Nagy 1978) in simplified form:

$$\frac{3}{2}N_e k_B \frac{\partial T_e}{\partial t} = \underbrace{\sin^2 I \frac{\partial}{\partial z}\left(K_e \frac{\partial T_e}{\partial z}\right)}_{\text{Transport along geomagnetic field lines}} + \underbrace{\sum Q_e}_{\text{Heating rate} \propto N_e} - \underbrace{\sum L_e}_{\text{Cooling rate} \propto N_e^2}$$

[from Alessio Pignalberi's presentation]

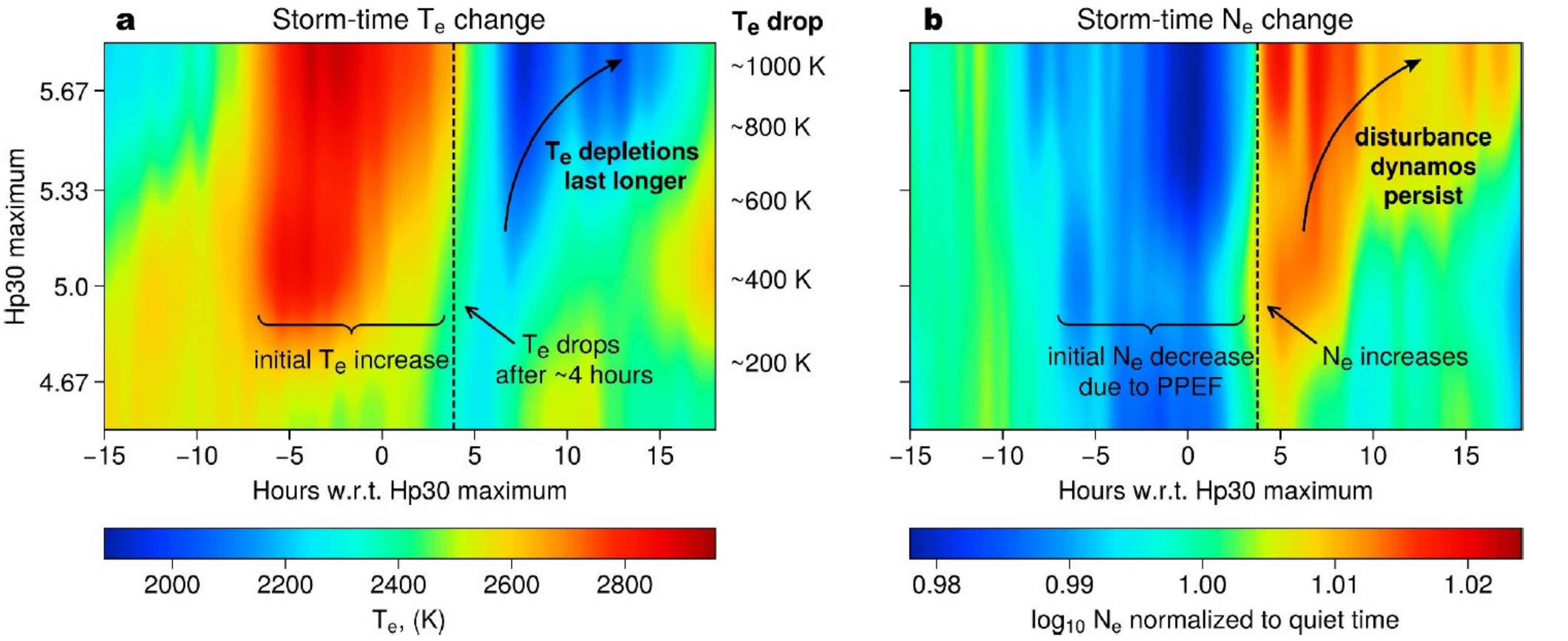
Superposed epoch analysis of Te and Ne

Superposed epoch analysis also shows similar storm-related changes around the overshoot region



Statistical behaviour during storms

The two-step overshoot change is more pronounced for stronger storms



Smirnov et al., (2025)

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Extreme two-phase change of ionospheric electron temperature overshoot during geomagnetic storms

Artem Smirnov[1,2], Yuri Shprits[2,3], Hermann Lühr[2], Alessio Pignalberi[4], Elena Kronberg[1], Fabricio Prol[5,6] & Chao Xiong[7]

An intense surge in the equatorial electron temperature (T_e) at sunrise, known as the morning T_e overshoot, has been one of the defining ionospheric features since its discovery early in the Space Age. Despite decades of study, the behavior of the morning overshoot during geomagnetic storms remains poorly understood. We report a two-stage response of the morning T_e overshoot to geomagnetic activity, uncovered by a neural network model. Electron temperatures show an initial enhancement during the storm's main phase, followed by a drastic depletion exceeding 1000 K and disappearance of the overshoot in the recovery phase. This two-phase change aligns with the early influence of westward prompt penetration electric field, overtaken by the development of the eastward disturbance dynamo later in the storm. These electric field changes affect vertical plasma drifts that redistribute electron densities, modifying ionospheric cooling rates. Our findings provide new insights into the dynamics of one of the most widely studied ionospheric features and showcase the

Conclusions

Advanced NN models can lead to finding new patterns even for the most commonly studied phenomena

1. We developed a new NN-based model of ionospheric electron temperatures
2. This is the first model based on global observations that includes geomagnetic activity
3. The model shows excellent performance on independent observations
4. The model helped uncover the 2-step change of the morning Te overshoot during geomagnetic storms
5. This pattern appears very robust both in individual events and in statistics