Sporadic E Behavior over Central Europe during a Geomagnetically Quiet Period in 2019

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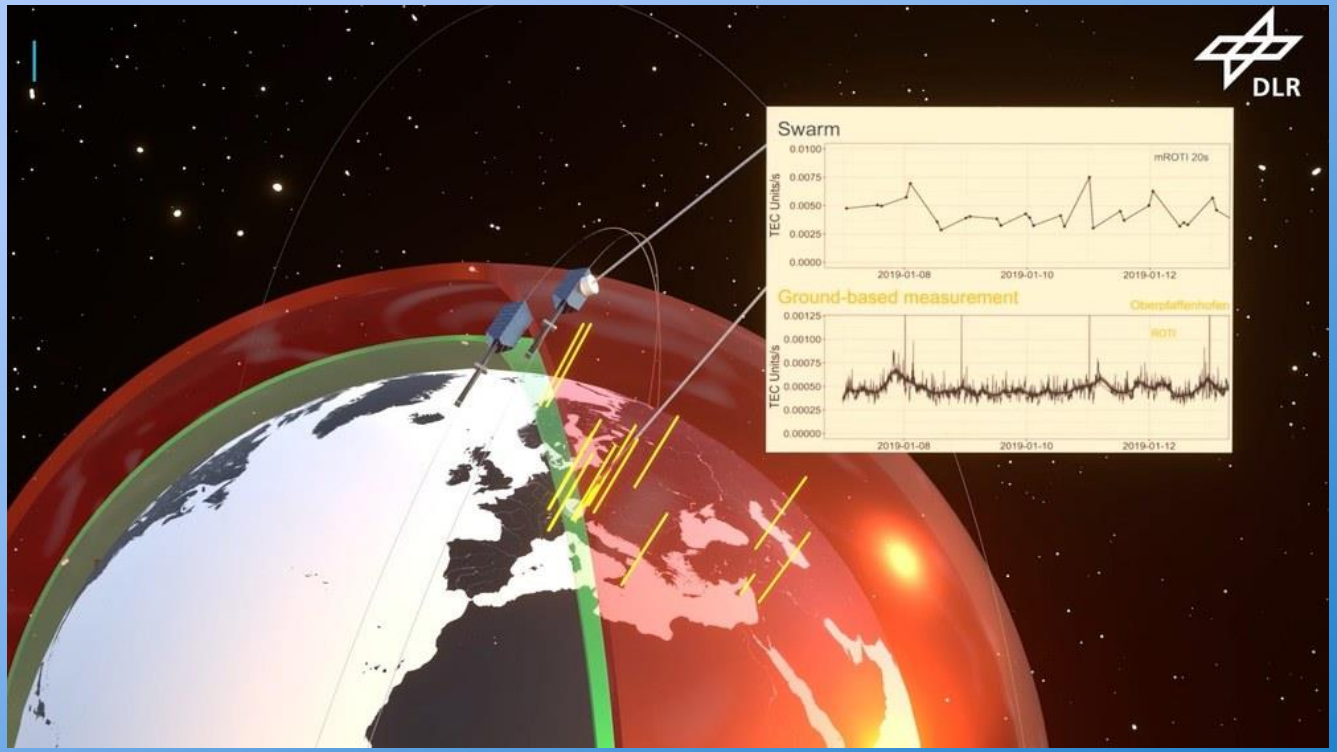
(6) Czech Hydrometeorological Institute

QUiet **I**onospheric **D**isturbances
REsearch based on **G**round-based mesospheric and **I**onospheric data with **S**warm data

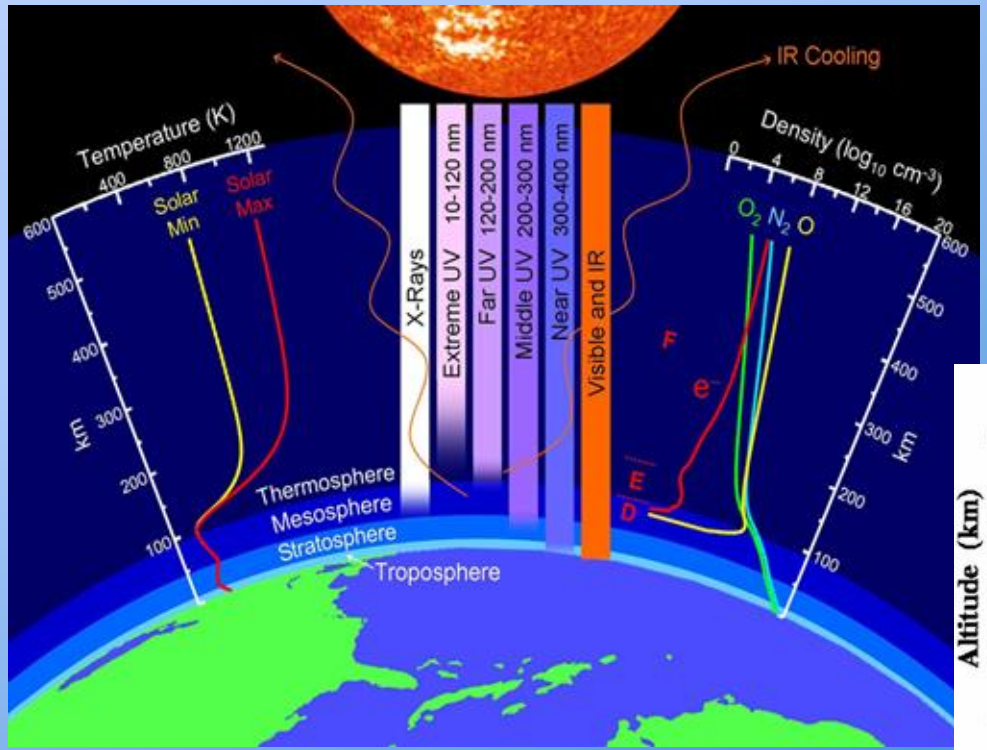


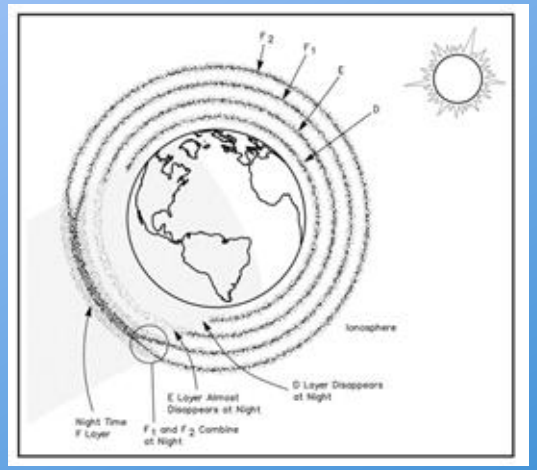
DLR – GERMAN AEROSPACE CENTER (DE)

CAS - INSTITUTE OF ATMOSPHERIC PHYSICS (CZ)

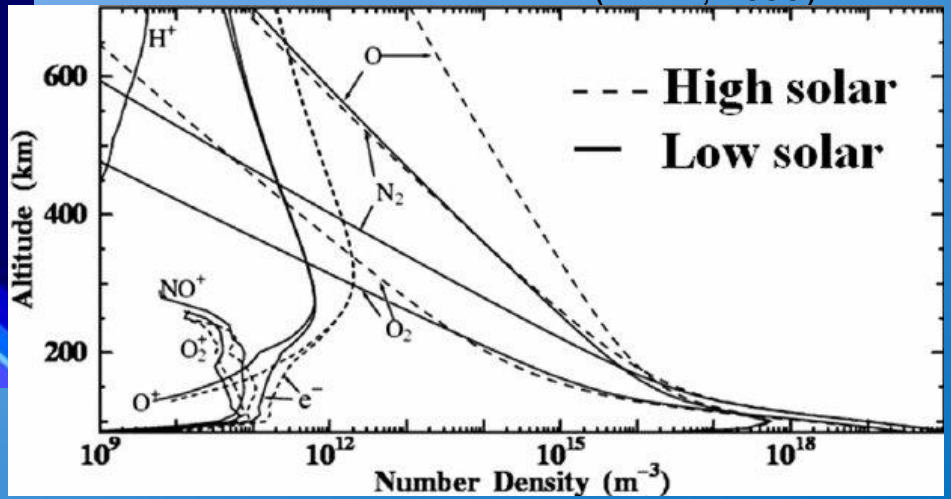
SAS - INSTITUTE OF EXPERIMENTAL PHYSICS

Ionosphere



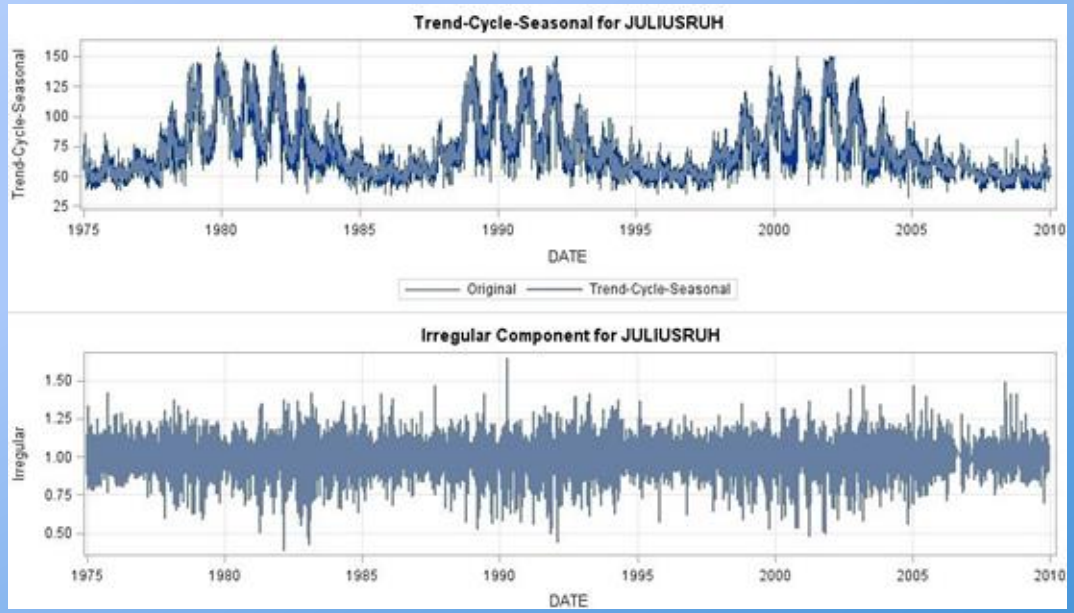


(Poole, 1999)



Thermospheric temperature and density variations, 10.1017/S1743921309992857

Ionospheric foF2 variability SC21-SC23



Long-period solar flux (Solar Cycle scale) - major source of ionospheric variability
Annual and semiannual variations important sources of variability, although small compared to long-term solar changes
Day-to-day solar flux variations, including that connected with the 27-day solar rotation (involves geomagnetic storms), is of comparable importance to the annual and semiannual variations.

Irregular variability component:
Varies within SC and from SC to SC

Solar variability description parameters

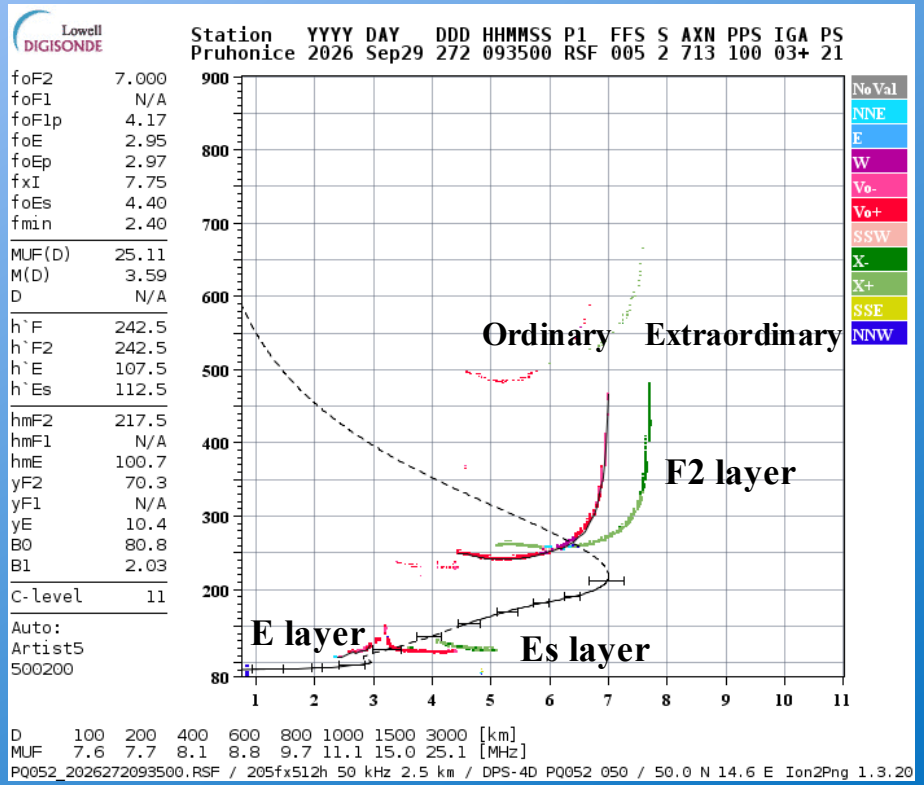
- **Standard approach - F10.7, sunspot numbers** - used for most studies and behavior forecast and modelling
- Other solar activity proxies, F10.7, sunspot numbers, F30, Mg II, He II, and solar H Lyman-α flux
- Trend studies (Laštovička and Burešová, 2023) - **Mg II and F30 are found to be the best solar proxies** – describes 99% of the total variance of yearly foF2 and the foF2 dependence on solar proxies is highly linear at middle latitudes.
- **The dependence of foF2 on F10.7 and sunspot numbers is significantly steeper in 1996–2014 than in 1976–1995, whereas for F30 both intervals provide the same dependence.**
- Structural changes in solar magnetic fields and the solar atmosphere during the decay of the **Modern Maximum (MM - maximum in SC19)** (Mursula et al., 2024) **- Decay of the Modern Maximum may not proceeded synchronously in different solar parameters.**
- Sunspot number fell faster than several measures of emission and activity higher in the solar atmosphere. F10.7 and F30 do not have identical long-term behaviour.

Ionospheric behavior description

- **Ionospheric Layers** – formation well described by Chapman funcion in 1931 - The level of **ionization simply depends on solar radiation and the loss is controlled by the recombination**

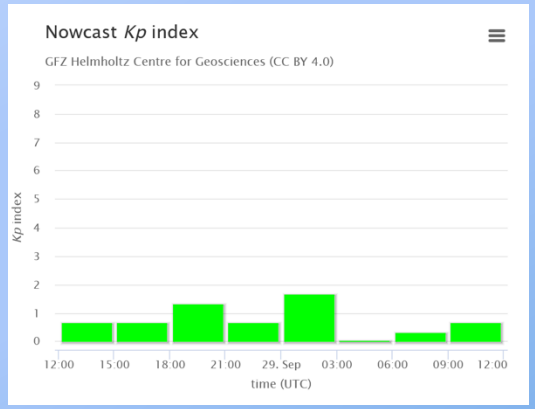
- Simple models describing the ionospheric behavior originate in the Chapman function with implementation of hmaxF2, NmaxF2 from ionograms.

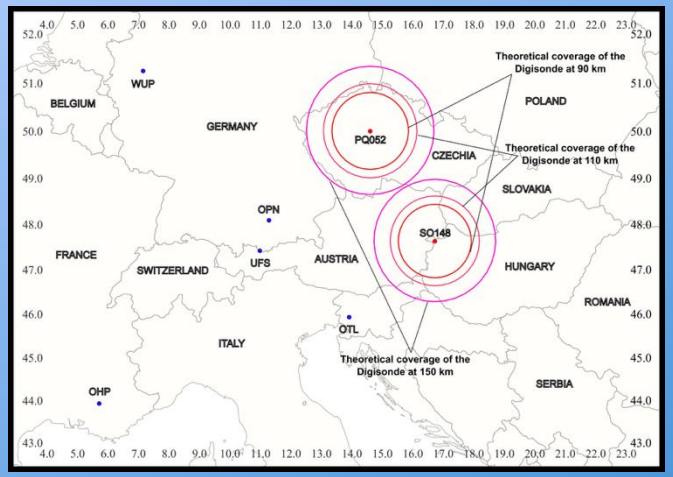
- Comparison with rocket measurements - to first order these simple approximations by Chapman layers and parabolic height profile approximation agree with measurements obtained during quit time conditions.

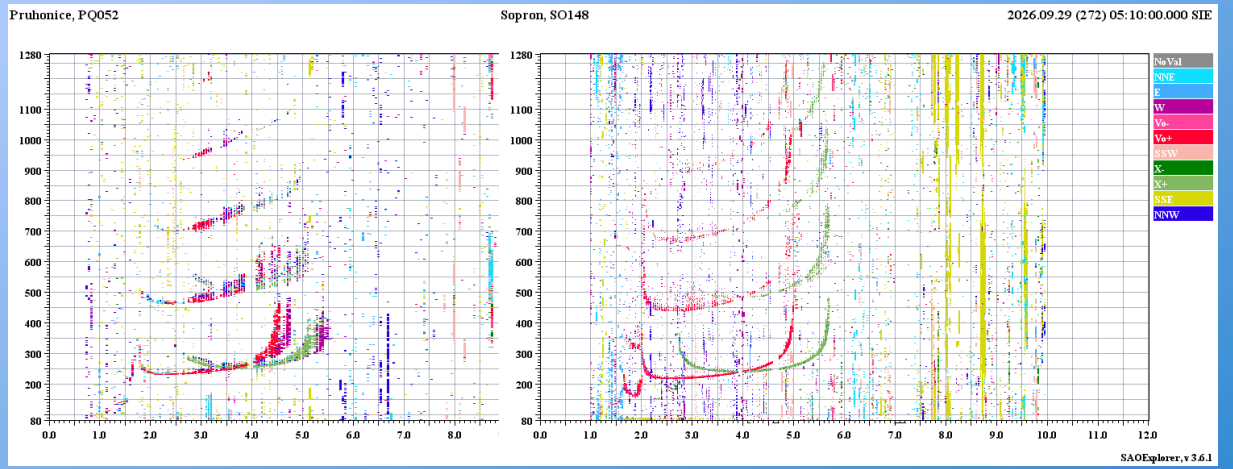


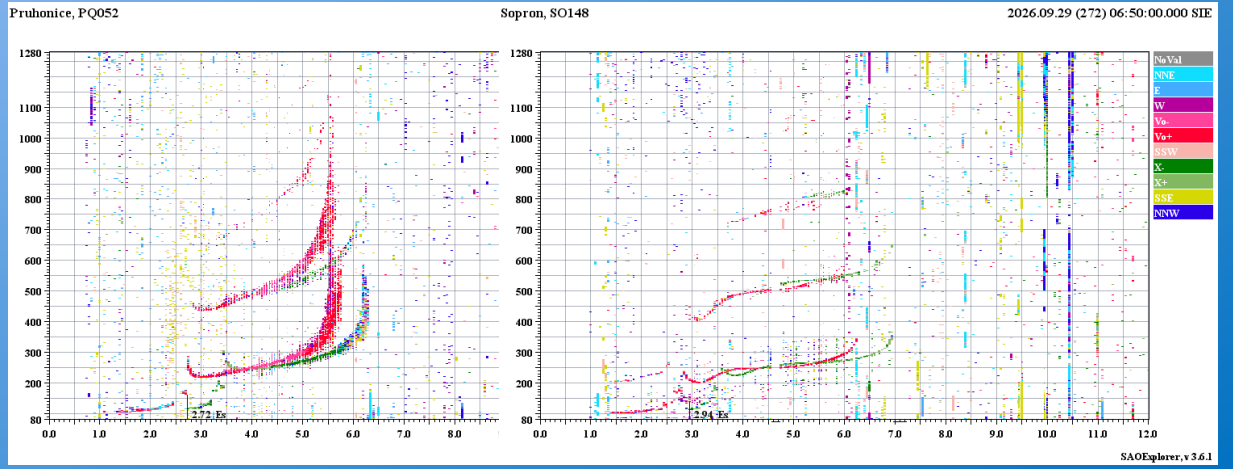
Closest Digisondes Průhonice – Sopron, Central Europe

Geomagnetic activity index









Quiet ionosphere – definition

Historical study:

MEAN ELECTRON DENSITY VARIATIONS OF THE QUIET IONOSPHERE, (Wright and Fine, 1959)

A. Averaging process. Each hour of each day is identified with its magnetic character figure, Kp. For each hour, those days for which Kp is less than 4+ are included in the "quiet" average. The other days are similarly combined to form a "disturbed" average;

- Mostly used quiet time definition **(Kp < 5) or (Kp < 4+)**!

Quiet ionosphere - definition

Historical study:

The quiet ionosphere over Singapore during 1962 - Clarke and Hammond, JASTP, 1965

…The median values for which ***Kp, was 5*** or more were eliminated. The parameter shows a considerable day-to-day scatter and rejection of "disturbed" times had an appreciable effect, the difference between the quiet only and the all-data monthly medians being up to **11** % for some hours…

…The quartile range scatter for all data varied from 20 to 70 per cent of the median values; **the diurnal pattern of the scatter was confused but tended to a maximum around sunrise and a minimum in the evening…**

(Suggest the effects of morning and evening Solar Terminator)

Quiet ionosphere – definition

Forbes et al., 2000 - Strict restrictions for quiet time Kp **(Kp < 1)** compare to usual **(Kp < 5)**

Quiet time reference - the hourly values from the three magnetically quietest days of the month are utilized to form the reference for that month.

Data are divided into the 25% least active (`low activity'), 25% most active (`high activity') and intermediate (`medium activity') levels of magnetic disturbance.

Resulting in Average estimate of ionospheric variability mainly due to „meteorological influences" : Under **quiet geomagnetic conditions (Kp < 1),** variability of Nmax about the mean is approx. 25±35% at `high frequencies' (periods of a few hours to 1±2 days)

0 < Kp < 3 "nearly quiet" level occurred more than 60% of the time across the four solar cycles

Quiet conditions?

Geomagnetic activity during SC20 – SC23

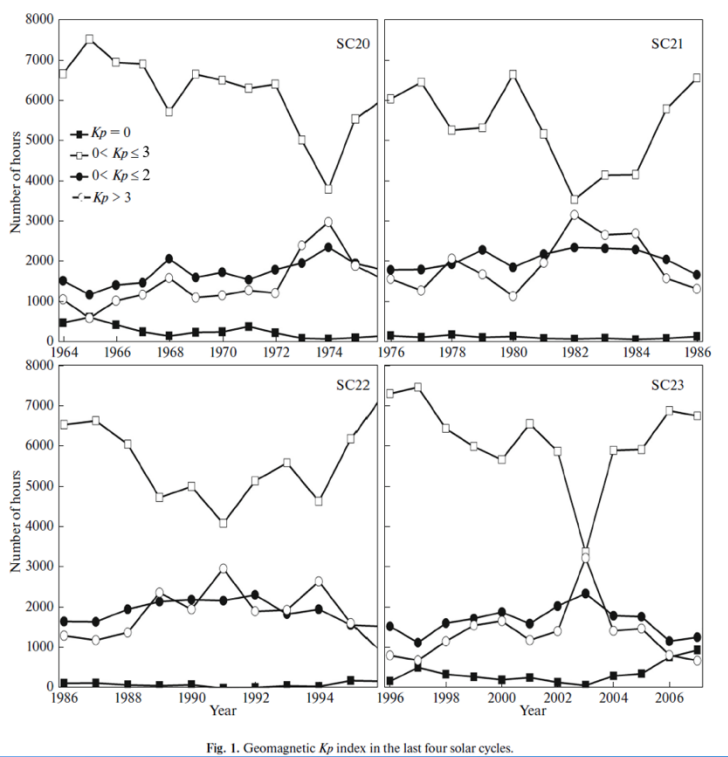


Fig. 1. Geomagnetic *Kp* index in the last four solar cycles.

Peak of Modern Maximum around 1957

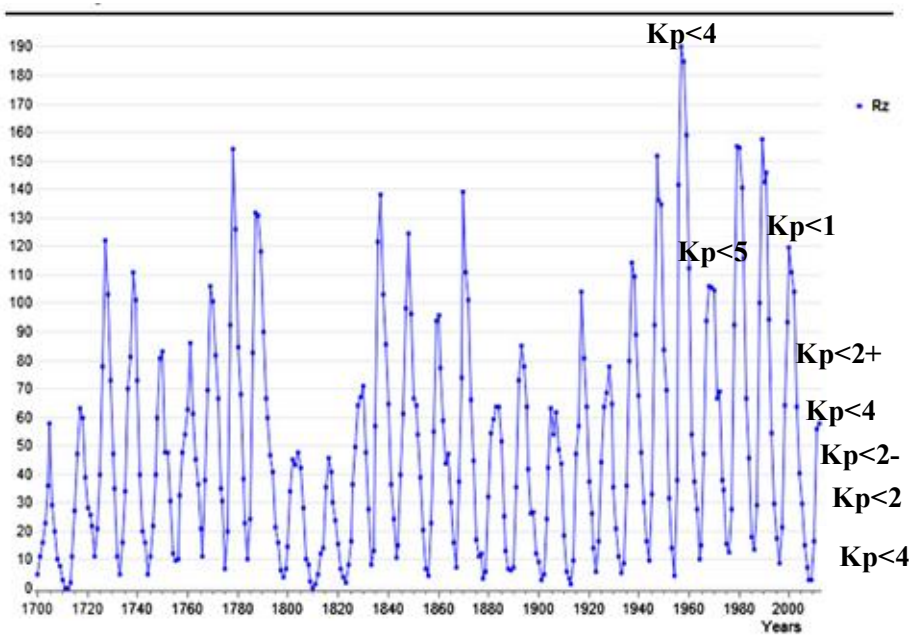
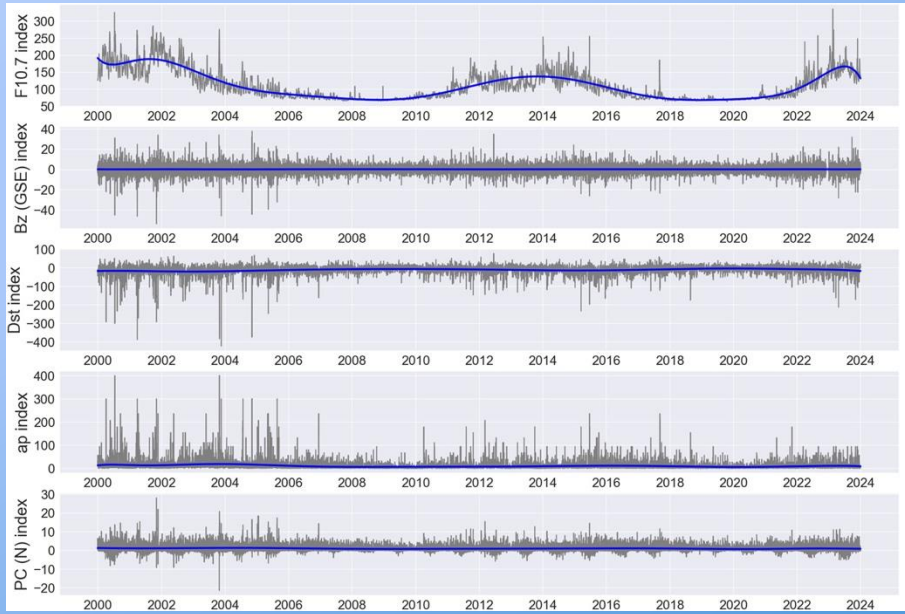
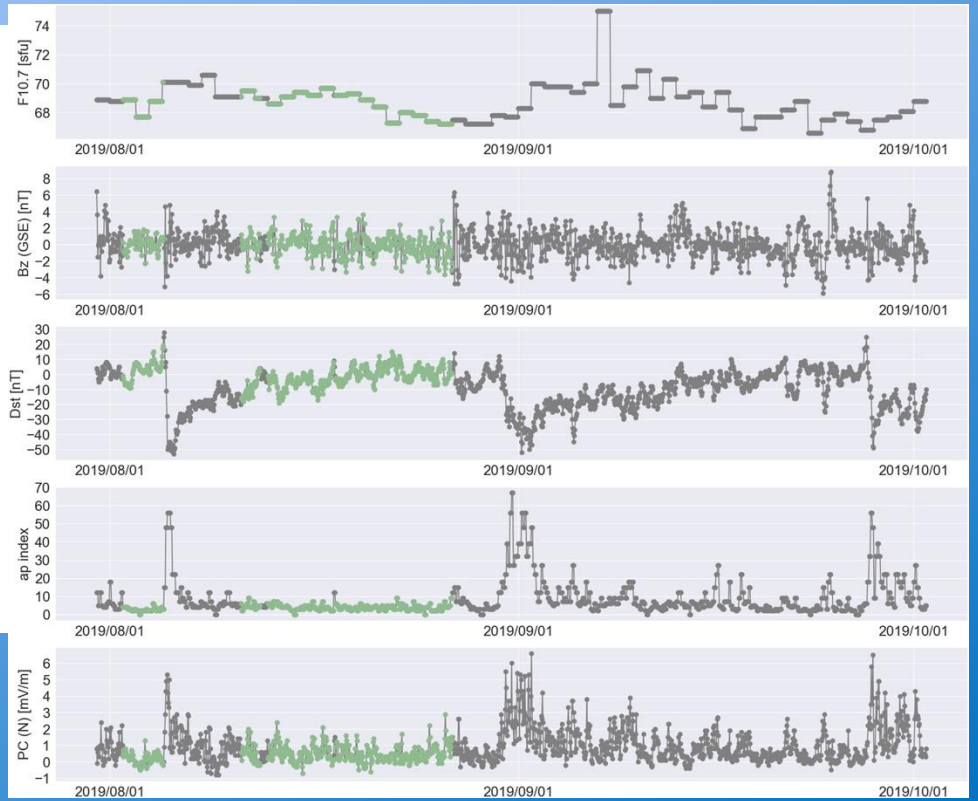


Figure 1 The time series of the yearly Zürich SSN [R_z] for the past 313 years (1700–2012).

Asenovski, 2017 https://doi.org/10.1134/S0016793217080035

Dataset of Quiet Space Weather Periods for Ionospheric Studies



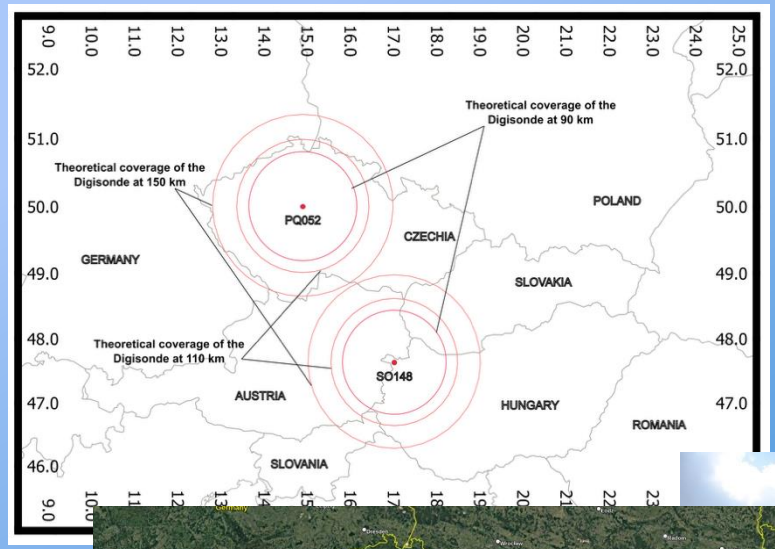


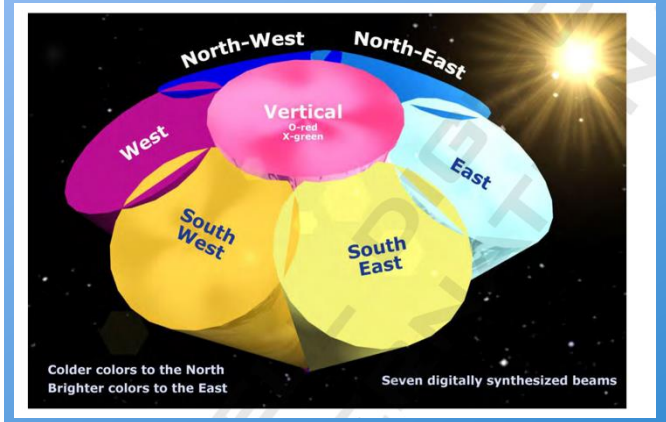
Mackovjak et al., 2026

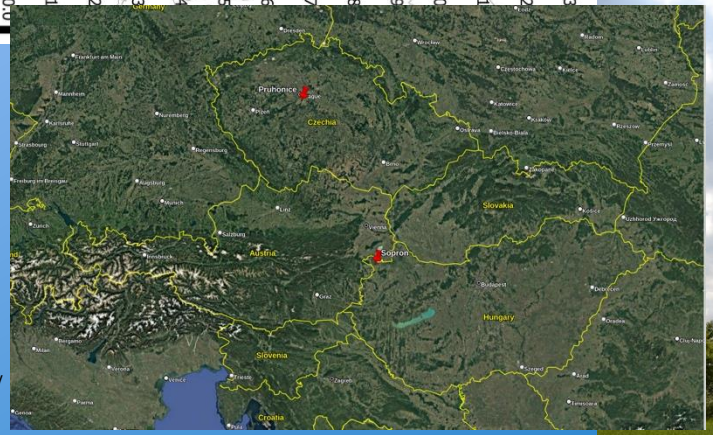
Dataset of Quiet Space Weather Periods for Ionospheric Studies, **10.1029/2025EA004537**

Central Europe stations – ionospheric vertical sounding DPS 4D





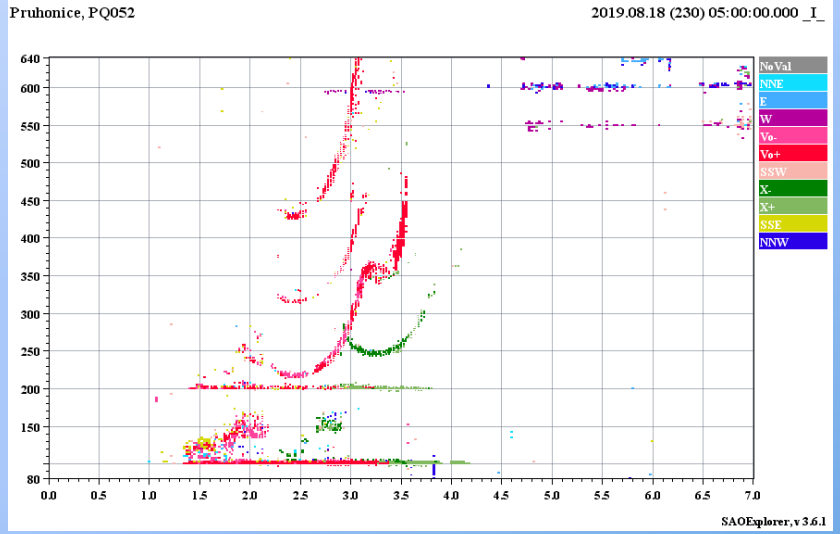






Průhonice (49.98°N, 14.55°E)
Sopron (47.63°N, 16.72°E)

Closest ionospheric observatories!
Data available: https://giro.uml.edu/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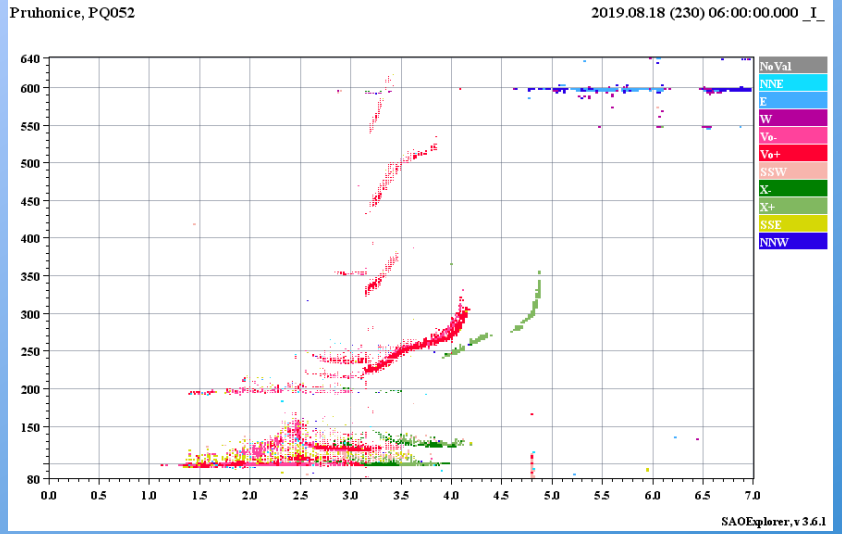
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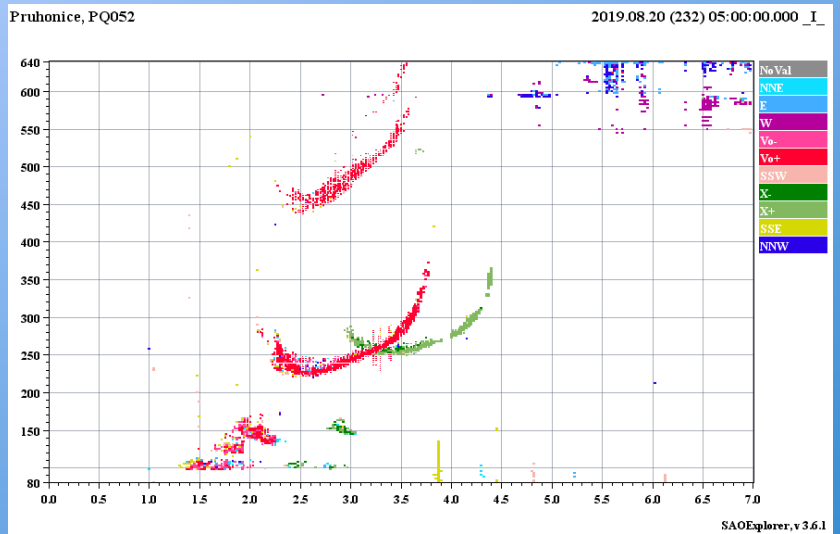
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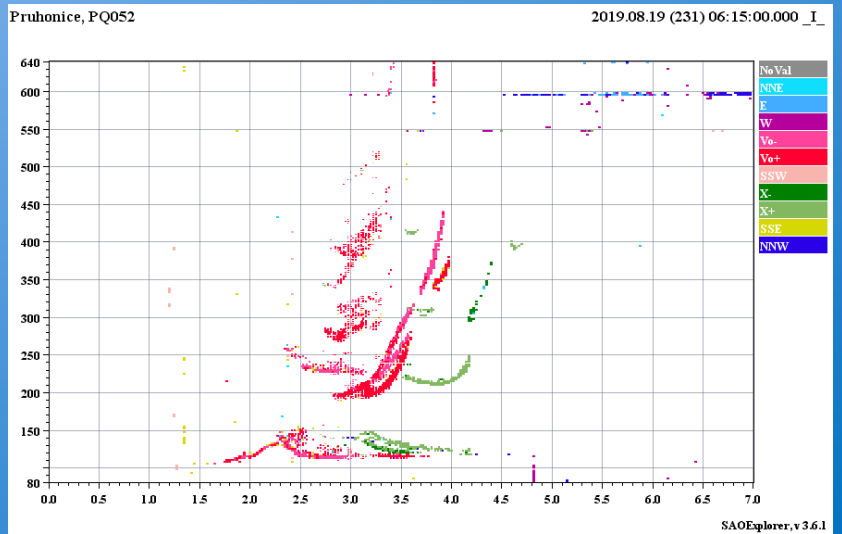
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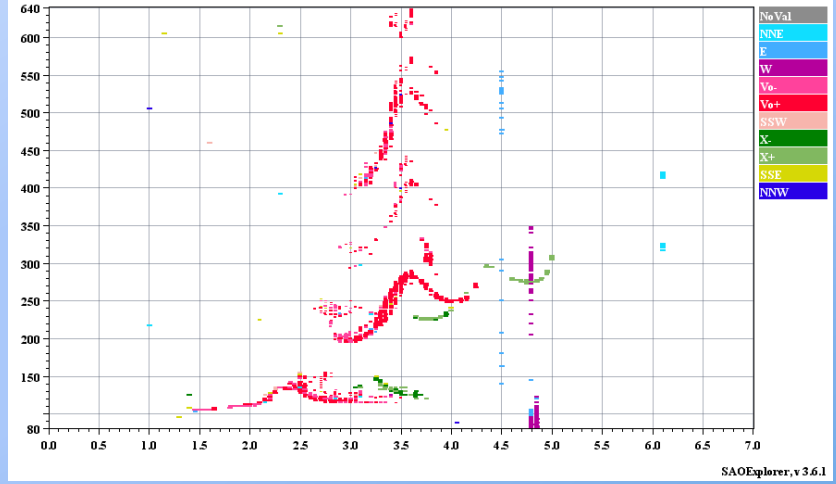

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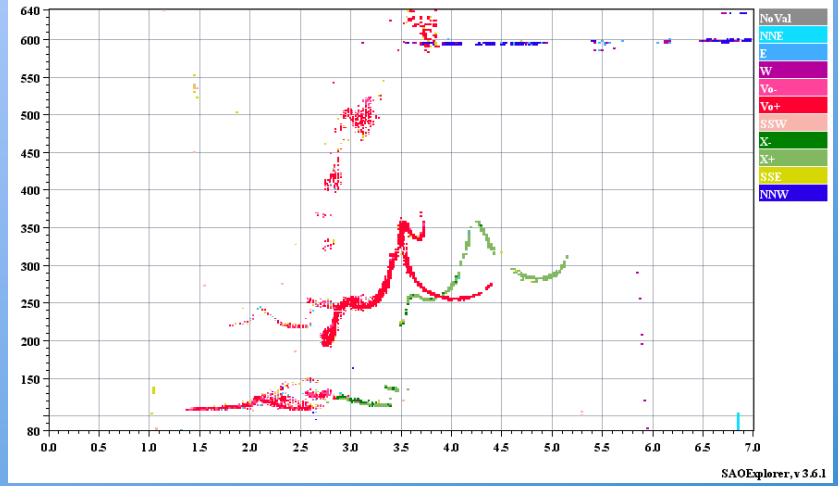

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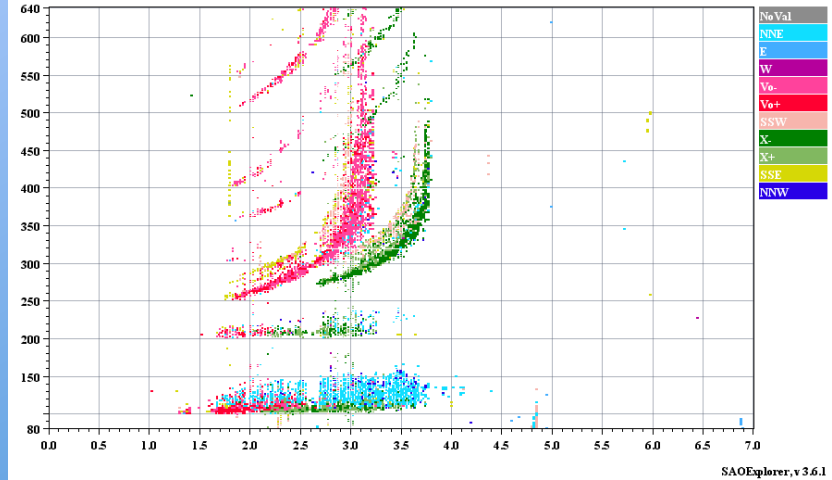

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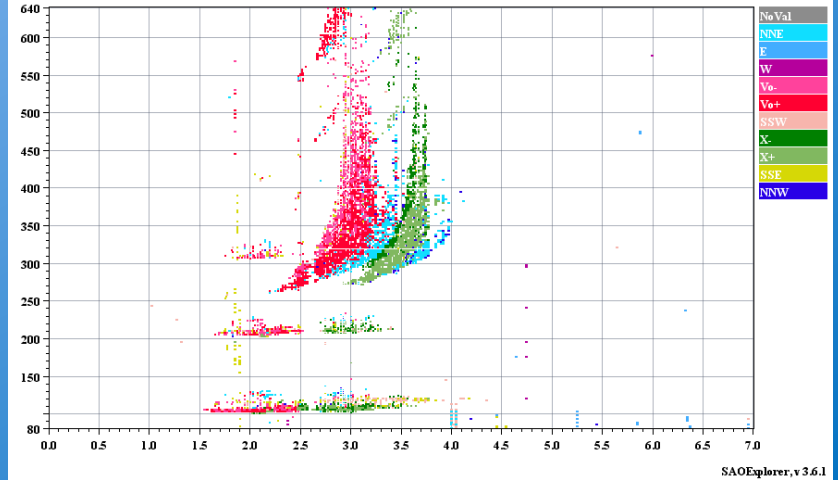

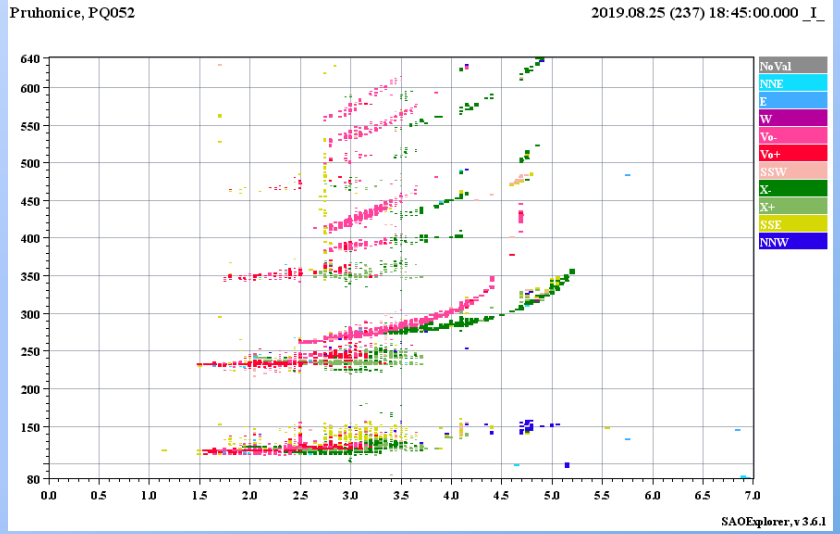
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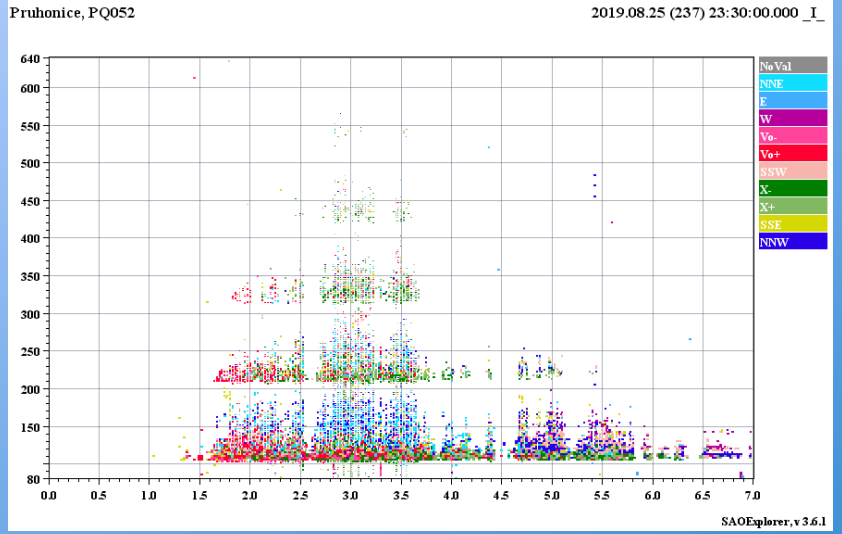
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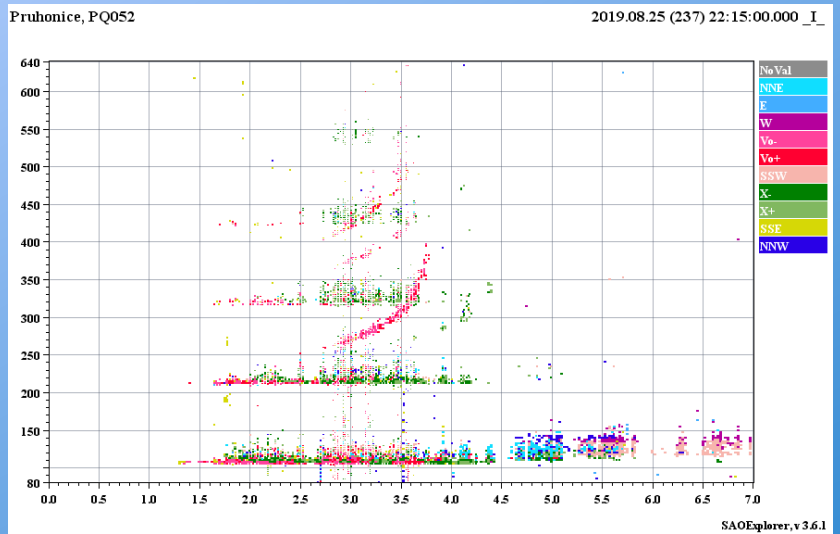
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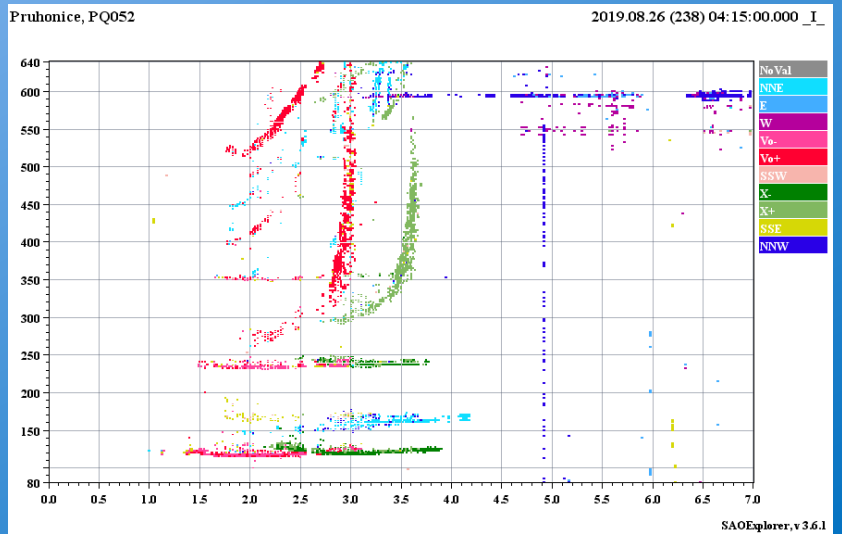
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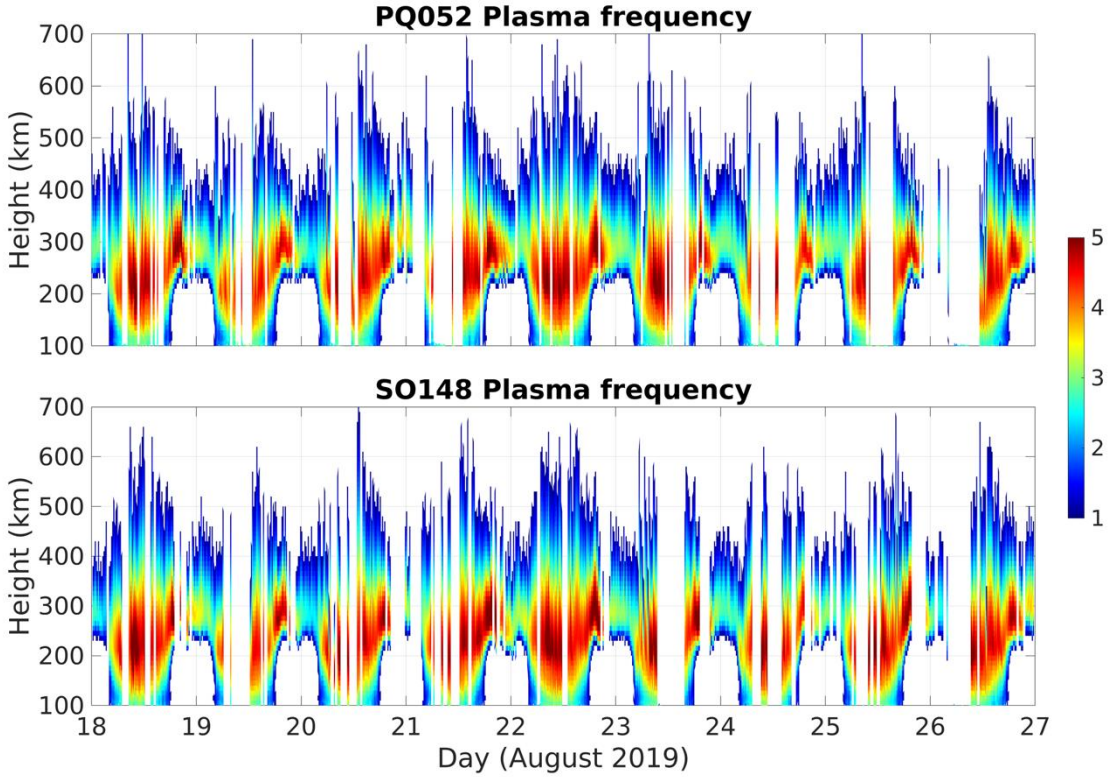
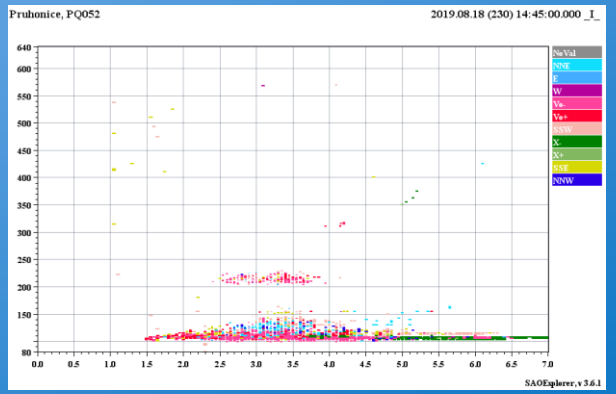
Electron concentration profiles



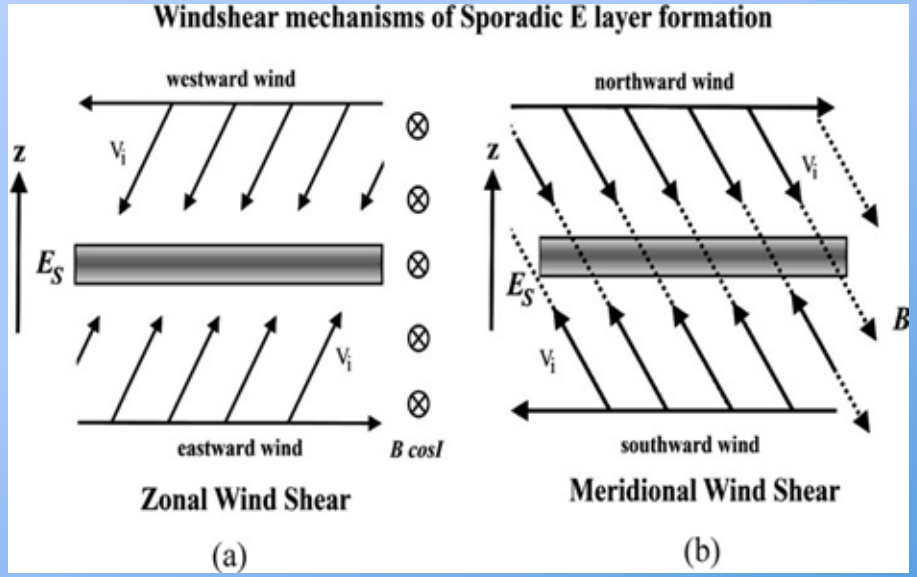
Day-to-day variability

N(h) profile – NHPC algorithm

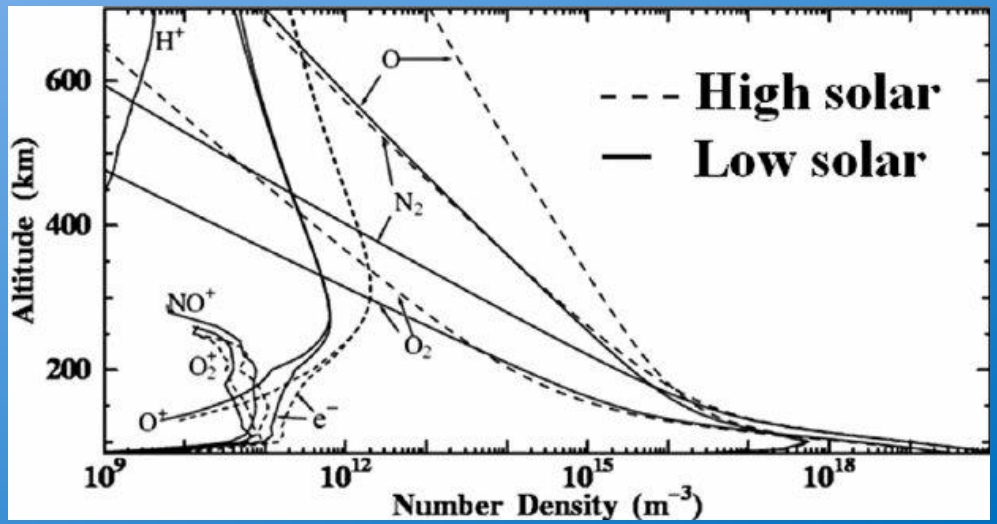
Gaps – strong Es structures blanketing F region



Ionospheric Sporadic E



- Summer phonomenon
- Solar and geomagnetic activity
- electric fields, lightning
- particle precipitation
- atmospheric gravity waves, tides and planetary waves
- Coupling with lower-lying atmosphere
- (Interhemispheric coupling)



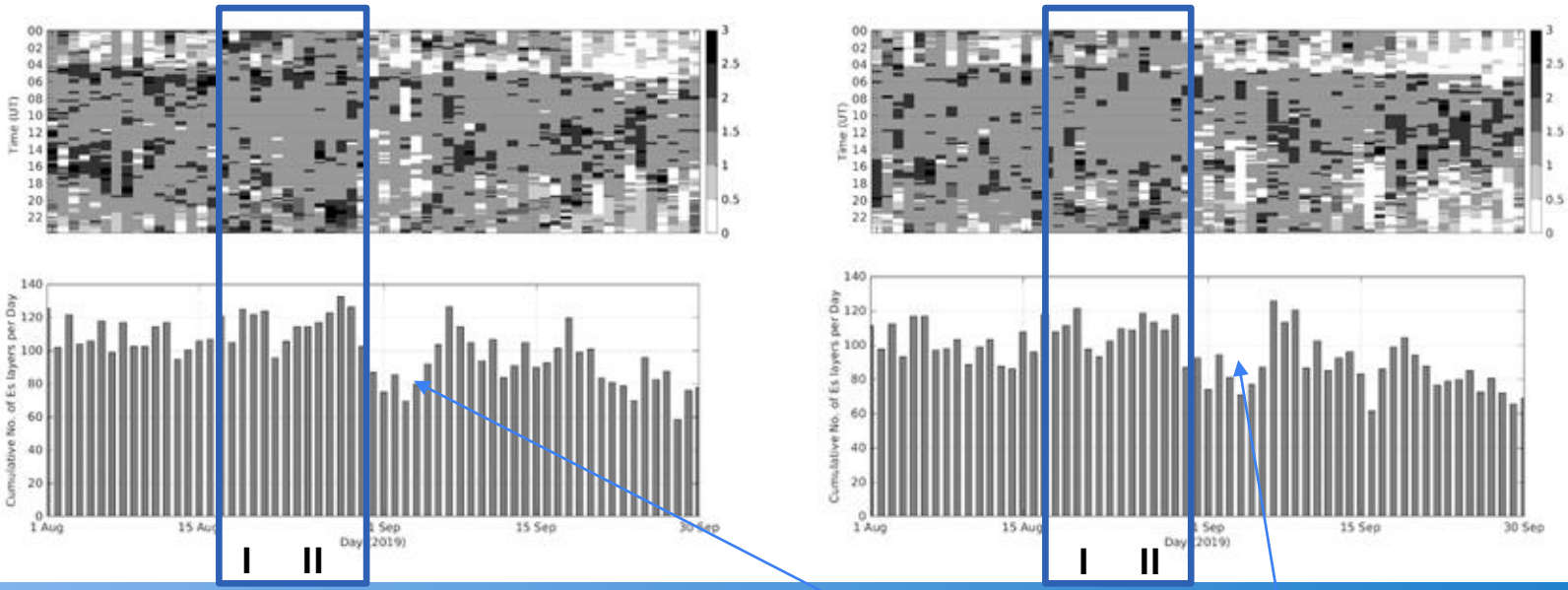
Haldoupis, Space Sci Rev (2012) 168:441–461DOI 10.1007/s11214-011-9786-8

Influence the GNSS!!!

Sporadic E occurence

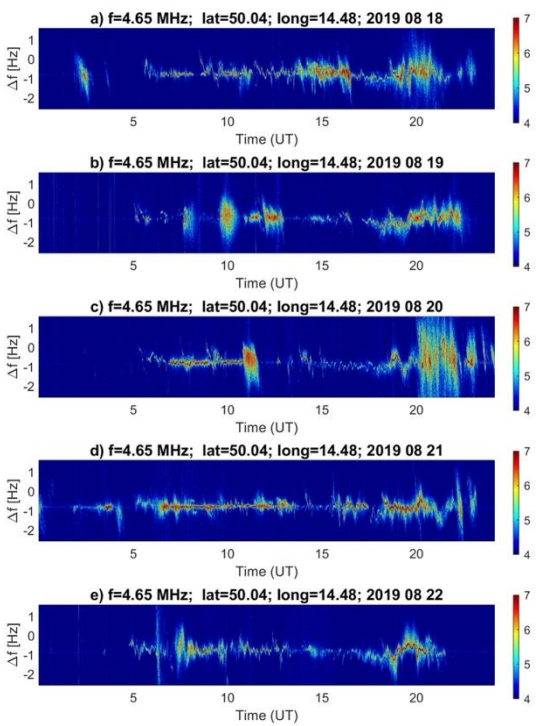
Průhonice

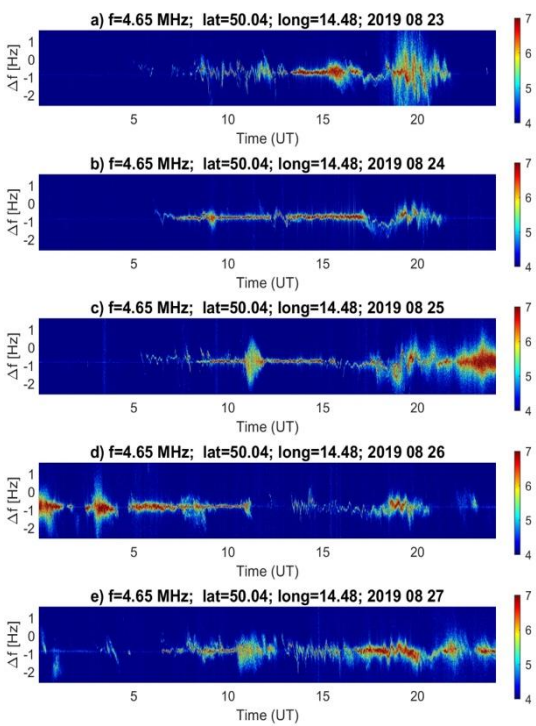
Sopron



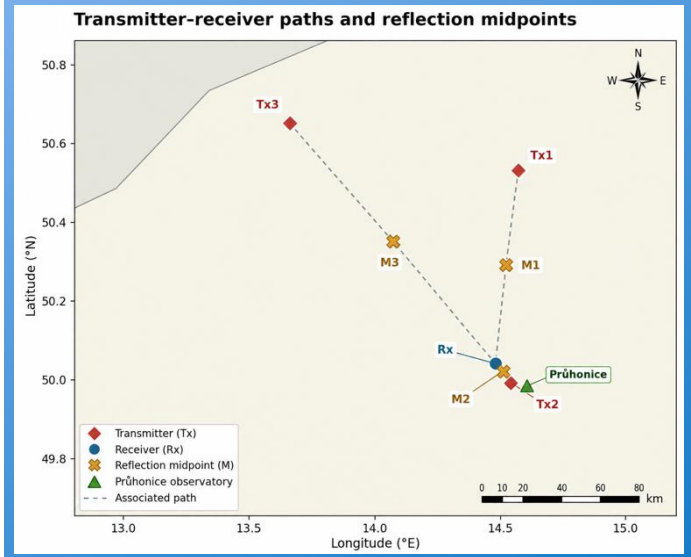
Es structures occurence decrease Geomagnetic disturbance caused by Corrotating Interaction Regions on 31 August

Continuous Doppler Sounding 4.65 MHz





Strong GW activity with periods of 15–40 min



Troposphere

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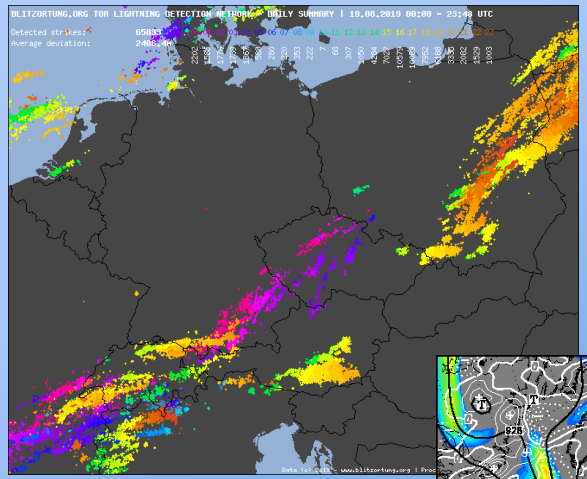

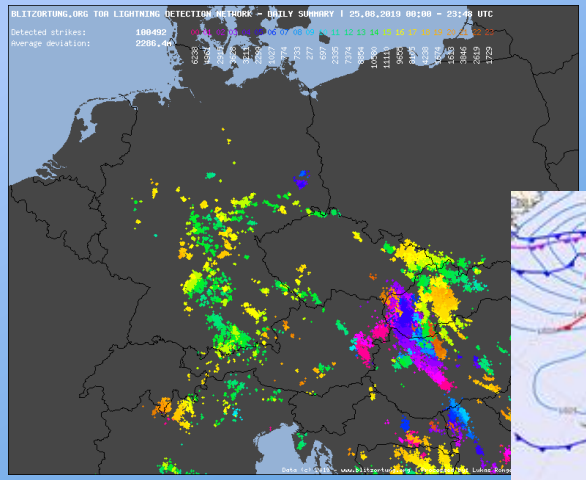

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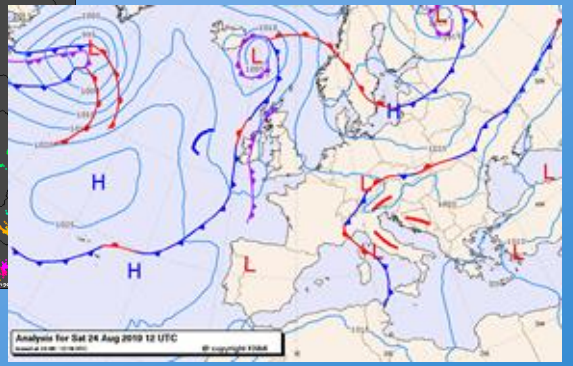
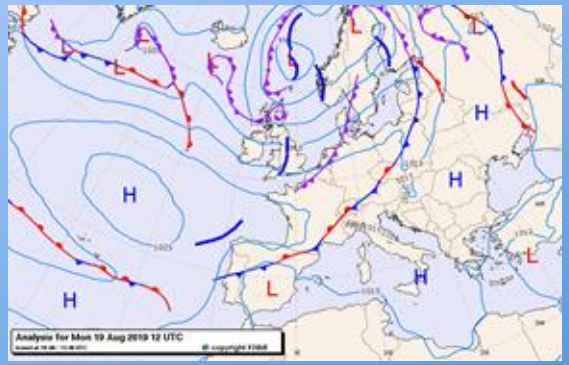
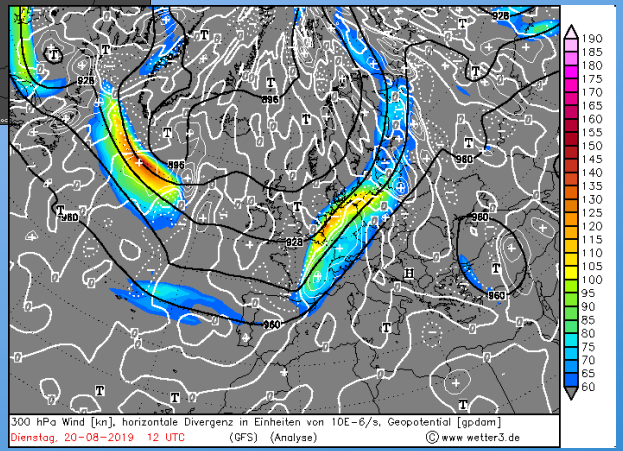
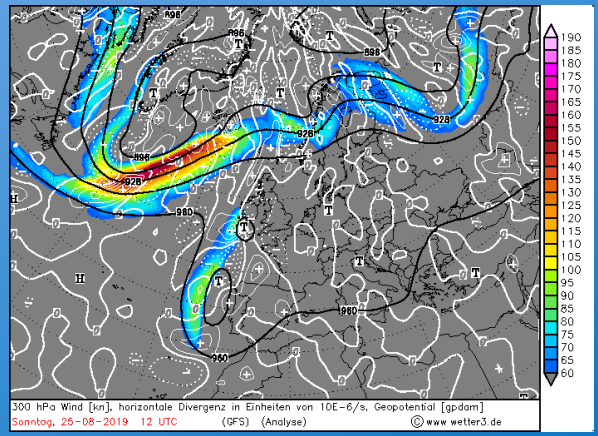






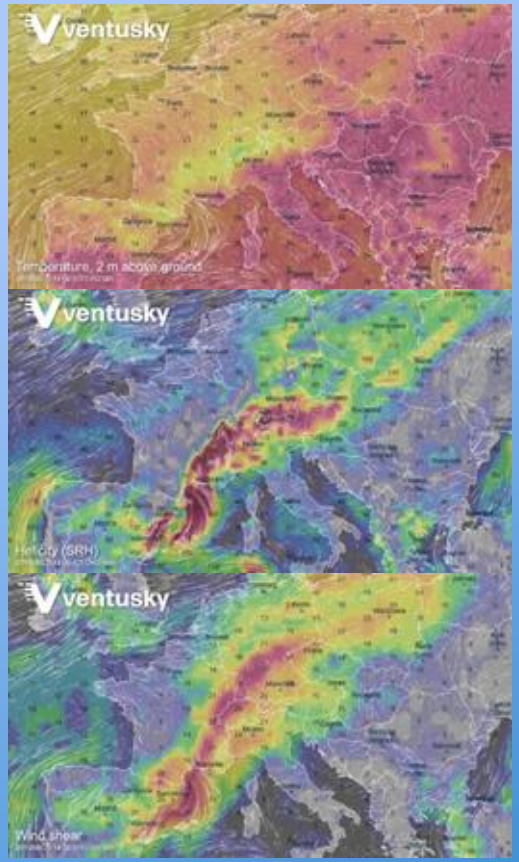


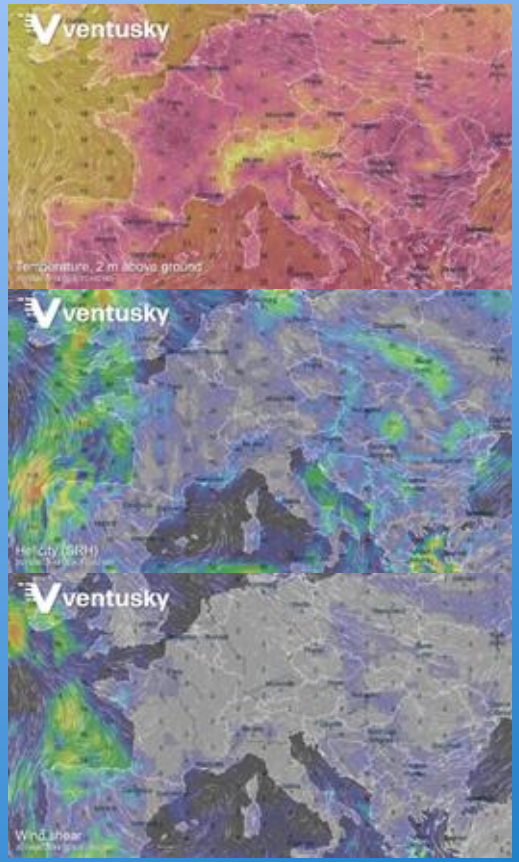
Troposphere – two different situations

Temperature – significant divison of warm and cold airmass

Helicity – high values above divison of warm and cold airmass

Windshear – strong above divison of warm and cold airmass



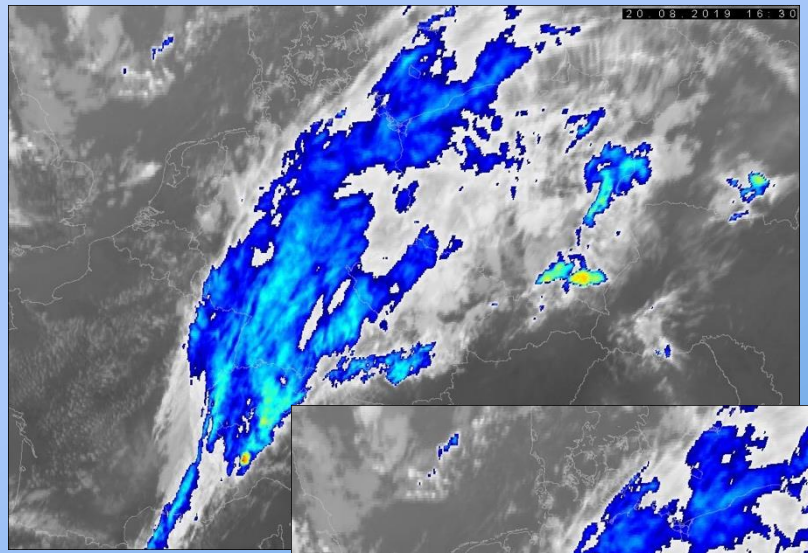


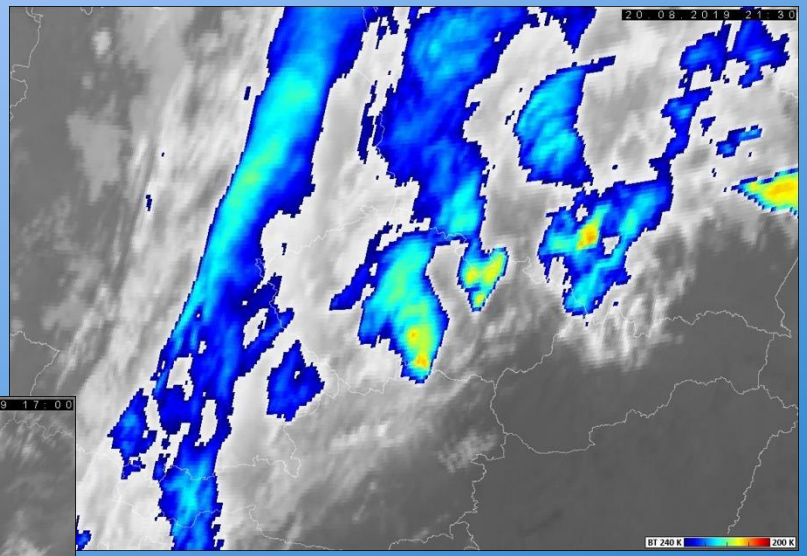
Temperature – uniform distribution of warm airmass

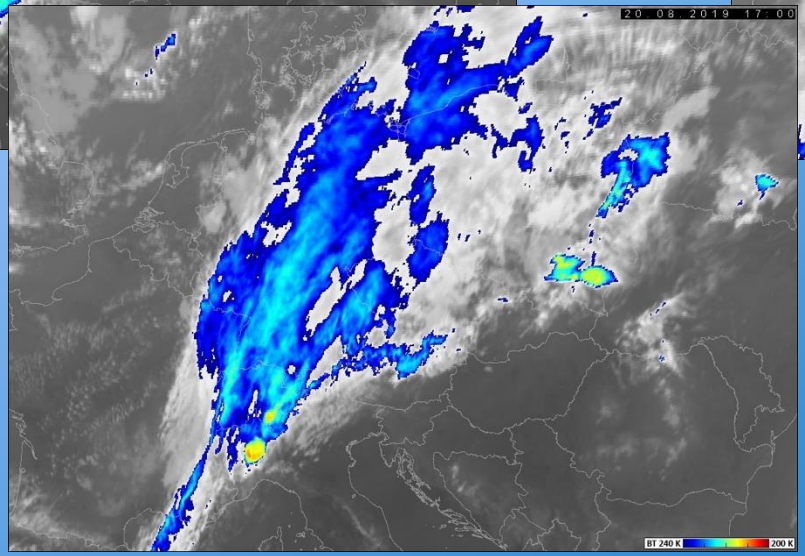
Helicity – rather low values above Europe

Windshear – rather low values above Europe

Eumetsat – 20 August, 2019 – IR and WV channels

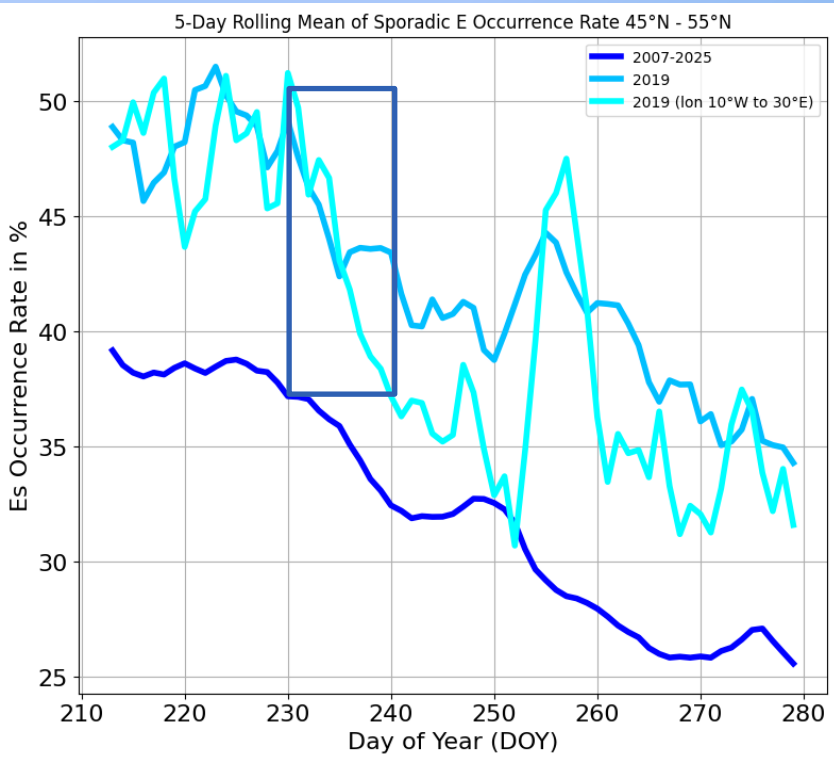


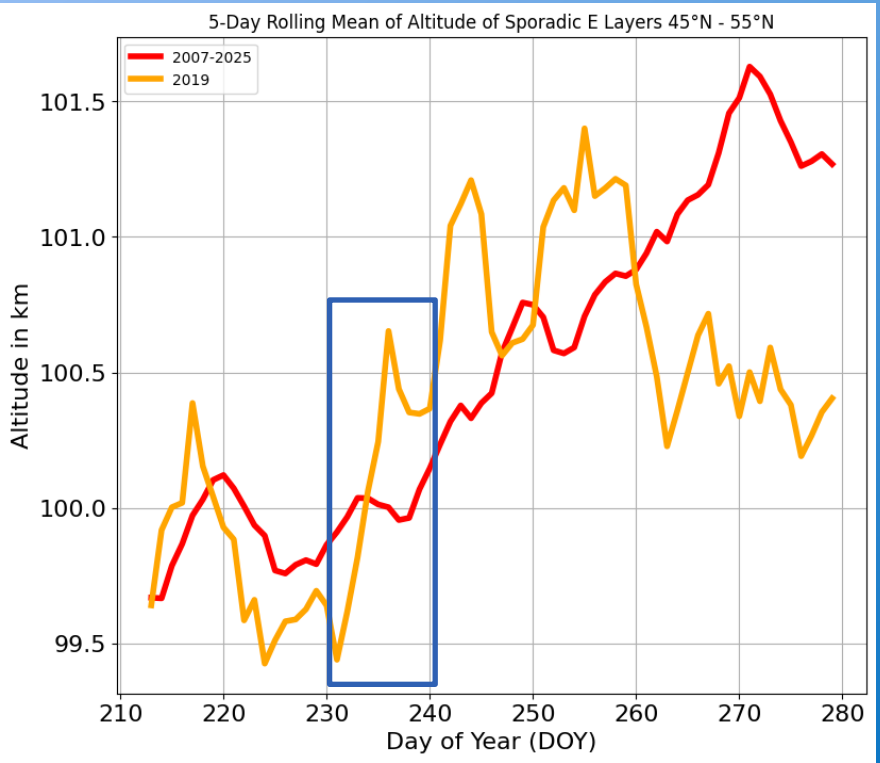




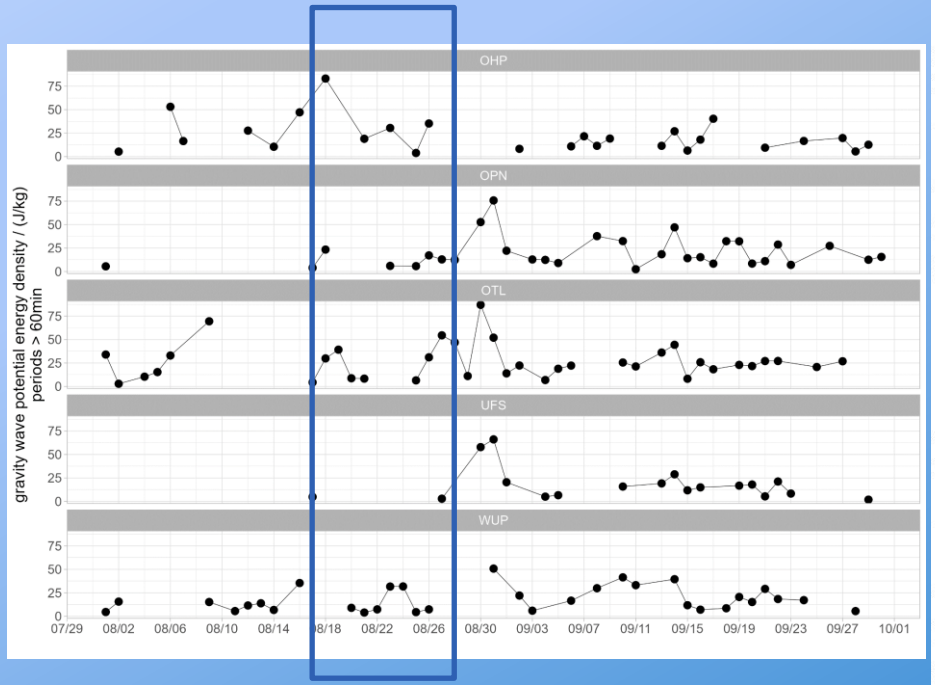


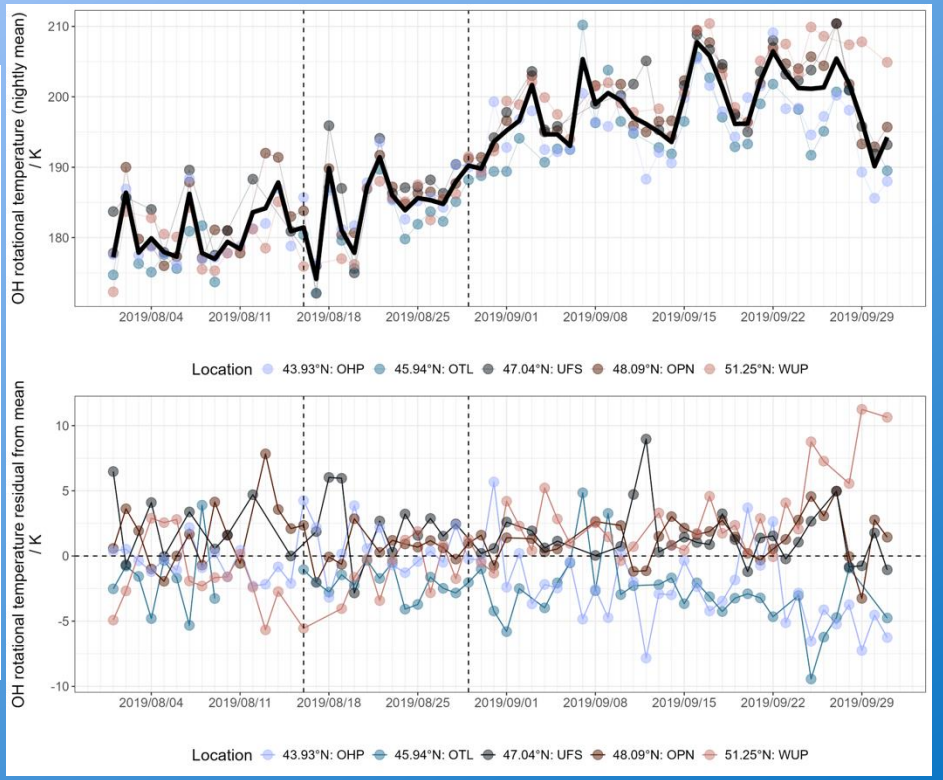
Es occurrence from GNSS radio occultation



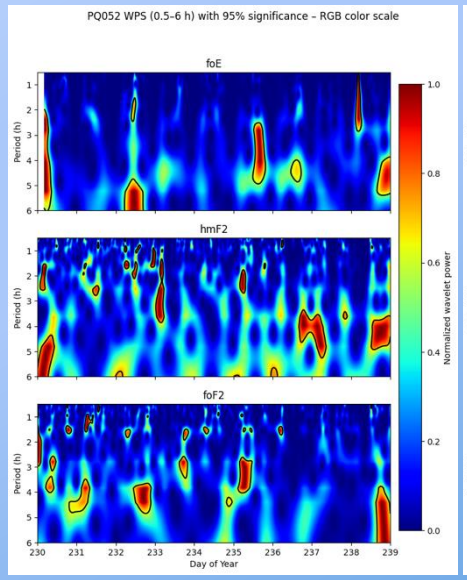


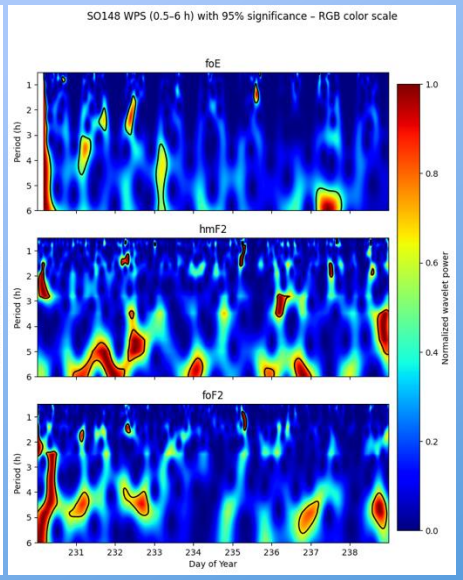
Mesosphere – FAIM2 (Fast Airglow IMager2)

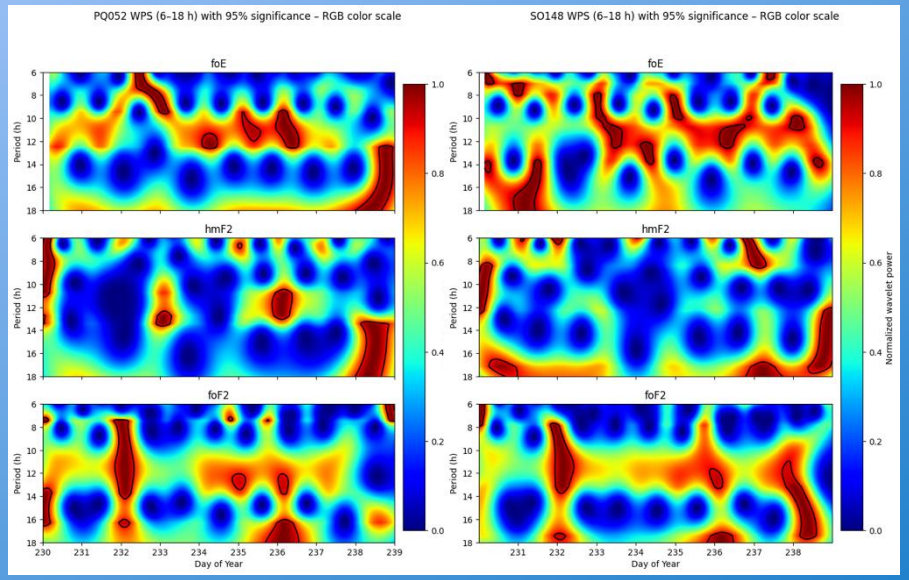




Ionosphere – foE, hmF2, foF2







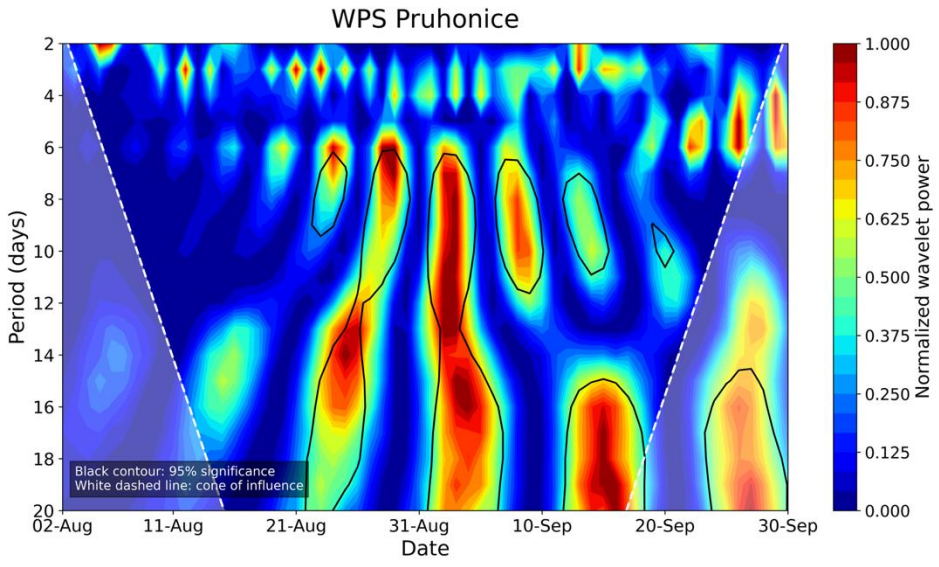
Limitation – gaps due to Es blanketing

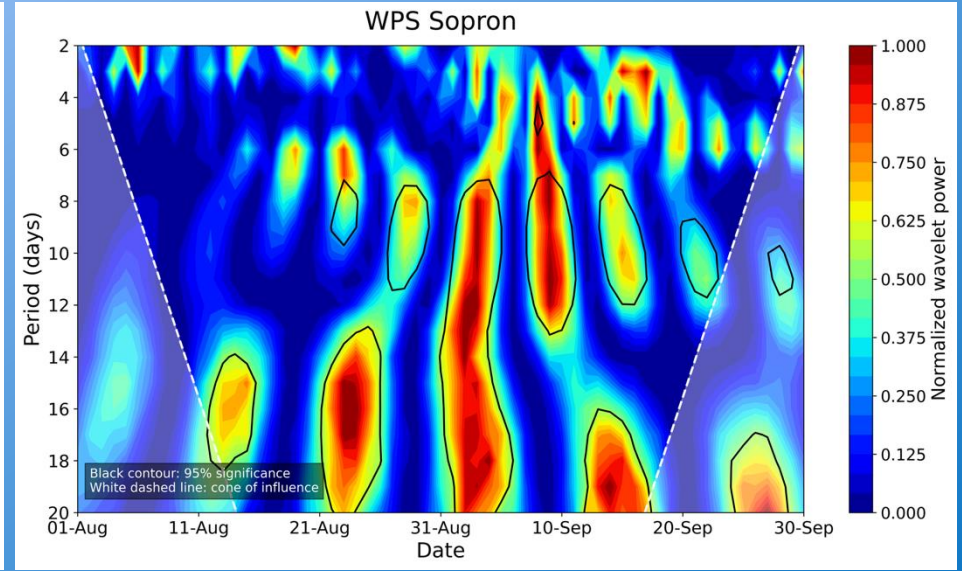
A clear difference between the two stations is evident

~8–14 h period range, indicating the presence of **tidal influences**. The wave activity is clearly intermittent, appearing as localized packets rather than continuous oscillations.

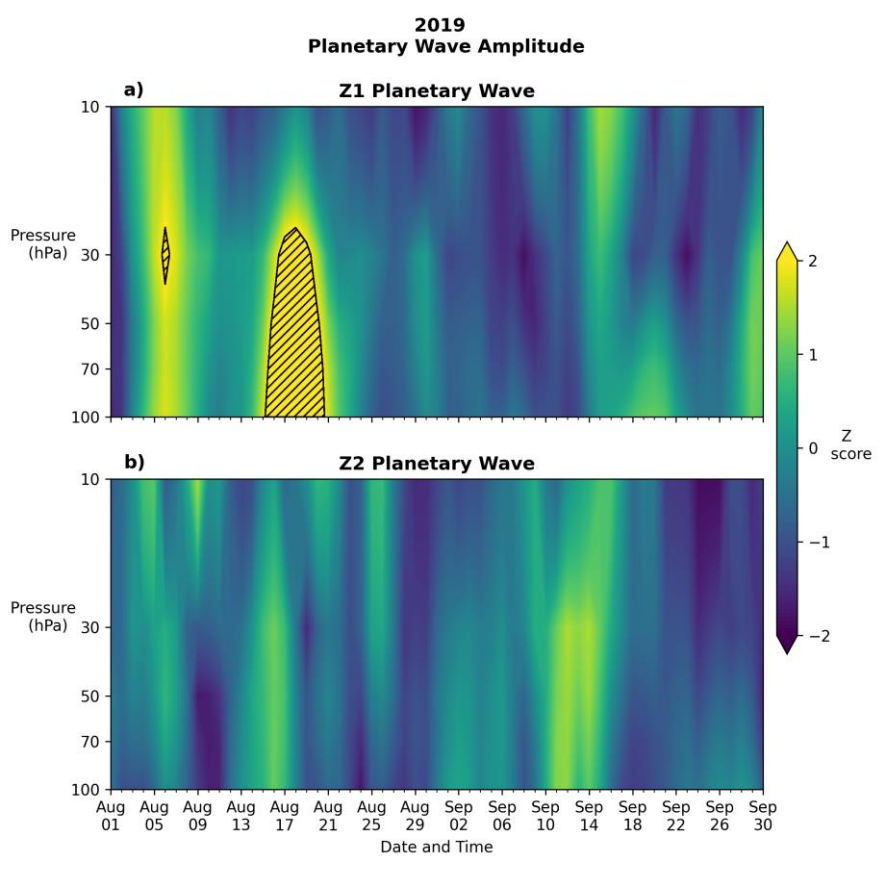
Průhonice shows **stronger, more structured, and longer-lasting wave packets**, particularly in the **~10–14 h band**, indicating enhanced tidal

Planetary wave activity





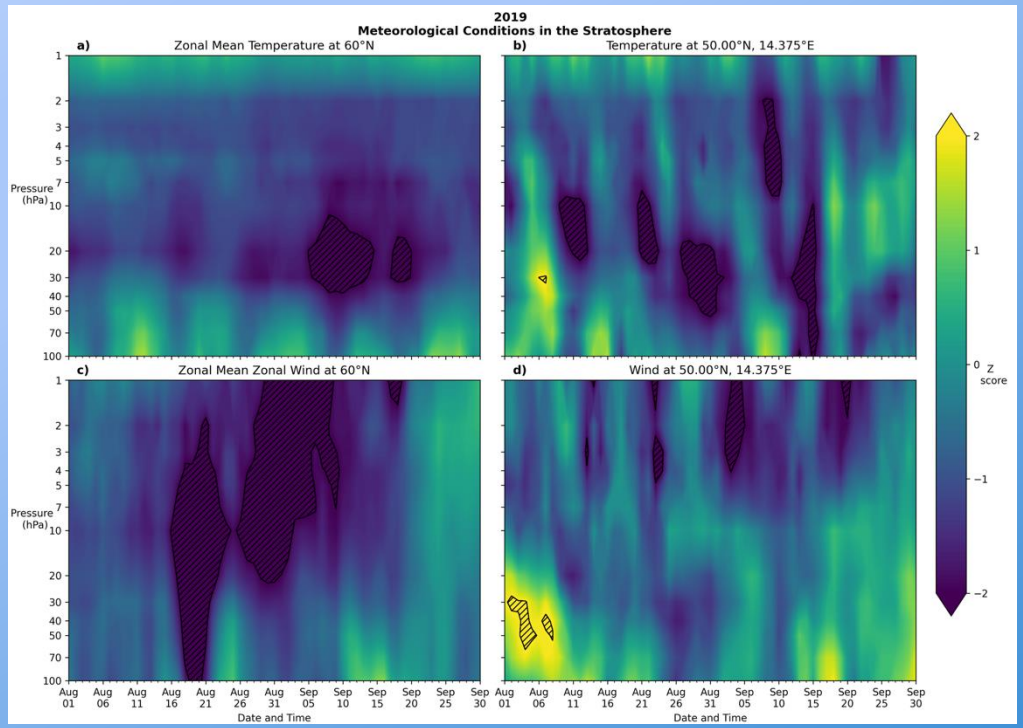
Stratosphere - MERRA 2 reanalysis - PW activity Z1 score



Positive anomalies with respect to the climatology in amplitudes of PW Z1 at 60 ºN between approximately 15-20 August 2019 across the 30-100 hPa region.

Enhanced planetary wave activity during mid-August 2019 was followed by substantial weakening of the stratospheric zonal circulation. This behavior is consistent with wave-mean flow interaction.

Stratosphere – MERRA 2 reanalysis



mid-August (18-24 August 2019), significant negative anomalies in the ZMZW at 60 ºN

indicative of a weakened zonal circulation, observed throughout the 2-100 hPa layer.
The most pronounced anomalies (Z-scores below -3) were concentrated within the 7-30 hPa region.

26 August to 9 September 2019 - negative anomalies developed within the 1-20 hPa layer, with minimum Z-scores below -3 occurring at 1 and 10 hPa.

Local weakening of the zonal wind at 50°N, 14.375°E upper stratosphere from 13 August 2019.

South Hemisphere Major Sudden Stratospheric Warming 2019

- A **major sudden stratospheric warming (SSW)** is a rapid disruption of the winter stratospheric polar vortex, accompanied by strong warming over the polar region and a reversal of the prevailing winds.
- **Defining criterion:** In the Northern Hemisphere, the daily zonal-mean zonal wind at **60°N and 10 hPa**—approximately **30 km altitude**—reverses from **westerly to easterly**.
- The traditional definition also requires reversal of the poleward temperature gradient, so the polar stratosphere becomes warmer than lower latitudes. A temperature rise alone does not establish a major SSW.
- **Mechanism:** Upward-propagating planetary waves interact with the stratospheric circulation and break, slowing the polar vortex. The resulting enhanced descent of polar air produces **adiabatic warming**, while the vortex may become displaced or split.
- **Effects:** The disturbance can influence lower-atmospheric circulation and winter weather, and also modify the mesosphere, thermosphere, and ionosphere through changes in atmospheric waves and circulation.

Sporadic-E response to the 2019 Antarctic SSW
Fontes et al. (2025)

- **Enhanced Es intensity:** ftEs exceeded 10 MHz, with peaks reaching approximately **20 MHz**.
- **Multi-day variability:** Dominant **2–8-day oscillations**, particularly **4–6 days** in the Southern Hemisphere.
- **Coupling with tidal winds:** Common periodicities in ftEs and neutral winds support **planetary-wave–tide modulation of Es-forming wind shear**.
- **Interhemispheric effects:** Signatures appeared in both hemispheres, with a stronger Southern Hemisphere response.
- **Supporting comparison:** Pronounced multi-day oscillations were absent at selected stations during the corresponding **2018 non-SSW period**.

Interhemispheric coupling: a possible driver of enhanced Es

- **Southern Hemisphere precursor:** Enhanced planetary-wave activity and weakening stratospheric winds in mid-August preceded the Antarctic SSW.
- **Coupling pathway:** Changes in the cross-equatorial residual circulation may transmit the disturbance to the Northern Hemisphere summer mesosphere.
- **Central European signatures:** Enhanced Es occurrence during **18–28 August 2019** coincided with planetary-wave variability, increased mesospheric gravity-wave activity, and warming.
- **Possible Es response:** Modified background winds and gravity-wave propagation may alter **neutral wind shear and metallic-ion convergence**, favoring Es formation.

Conclusion

High ionospheric variability during interval of stable low and geomagnetic forcing over Central Europe during August–September 2019

Pronounced variability was detected in ionospheric parameters: Icreased rate of enhanced Es occurrence, fluctuations in foE, foF2, and hmF2.

Widespread wave-like structures were also detected in the E and F regions. WPS revealed significant oscillations in the gravity-wave (~1.5–6 h), semidiurnal (~8–14 h), and planetary-wave (~6–18 days) ranges. Continuous Doppler Sounding Sobservation showed enhanced Doppler fluctuations and spread echoes on 20, 23, and 25 August, confirming strong gravity-wave (GW) activity with periods of 15–40 min.

Radio occultation measurements further showed Es occurrence rates significantly exceeding climatological values during DOY 230–240, together with enhanced Es altitude variability.

Mesospheric observations revealed intensified GW activity and persistent warming during late August and early September 2019.

Enhanced GW potential energy density and increasing OH rotational temperatures coincided with strengthened planetary-wave (PW) activity and weakening of the zonal-mean zonal wind associated with the developing 2019 Southern Hemisphere sudden stratospheric warming (SSW).

Enhanced vertical and interhemispheric coupling during the study period. Neutral atmospheric dynamics played a dominant role in modulating Es occurrence during geomagnetically quiet conditions.

Two possible forcing mechanisms are proposed: (1) GW generation by frontal and convective activity over Central Europe, and (2) PW modulation associated with interhemispheric coupling during the SSW.

The combined observations provide strong evidence that GW, tides, and PW propagated upward through the atmosphere and significantly influenced ionospheric variability over Central Europe during late summer 2019.

He, et al. (2020) https://doi.org/10.1029/2020GL091453
Jinee Gogoi - Evaluation of the Relative Contributions of Solar, Geomagnetic, and Sudden Stratospheric Warming (SSW) induced forcing on Ionospheric Variability

Quiet ionosphere is an illusion!