SOURCES OF THE HIGH LATITUDE IONOSPHERE VARIABILITY DURING WINTER NIGHTTIME

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Solar wind impact on the ionosphere: from high-latitudes to global scale

Solar energy is dissipated into Earth in:

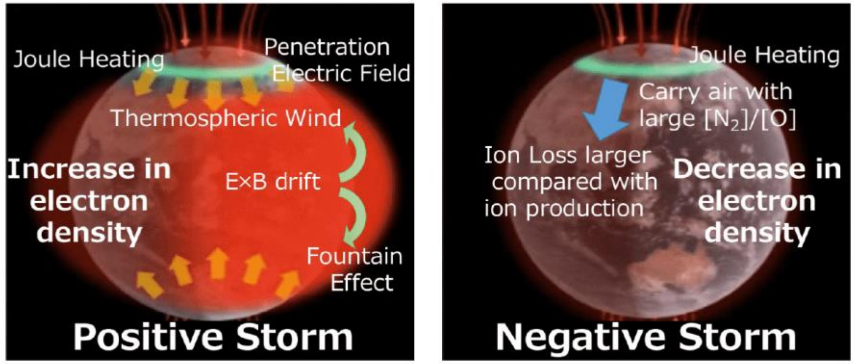
1) solar EUV radiation
2) solar wind kinetic energy (Prölss et al., 1988)

Source	Power (GW)	Energy flux ($mW\,m^{-2}$)	Altitude (km)
Solar EUV radiation (variation)	600 to 1400	1.5 to 4.5 (subsolar)	100 to 500 km
Precipitating particles			
– Magnetospheric protons	1–15	3–6	100–150 km
– Magnetospheric electrons	40 to 100	0 to 250	70 to 150 km
Joule heating	70–1000	0–100	100–250 km
Solar wind			
– Kinetic $1/2\rho v^3$	14 000	0.5	Magnetospheric cross section of 15 R_E
– Electromagnetic ExB/μ_0	800	0.03	

Credit: Sarris et al. (2020)

With M-I couples, part of solar wind energy is dissipated into Earth's ionosphere as:
1) electromagnetic energy
2) precipitation of energetic particles (Cai et al., 2014)

The electrodynamic conditions in high latitudes impact the T-I system on a global scale via:
1) heating in the polar zone,
2) increase in the thermospheric circulation,
3) delayed generation of disturbance dynamo electric field,
4) changes in the atmospheric composition (Kakoti et al., 2023).



Credit: *NICT*

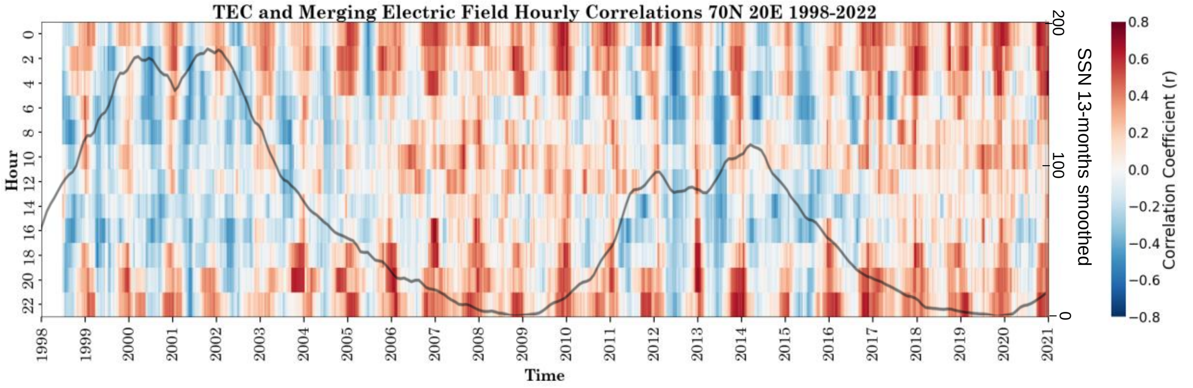
How does the high latitude thermosphere-ionosphere system respond to solar wind variation?

- **Solar wind forcing** causes a systematic and persistent response of the HL ionosphere, which varies depending on local time, season, and solar cycle (Borries et al., 2024).

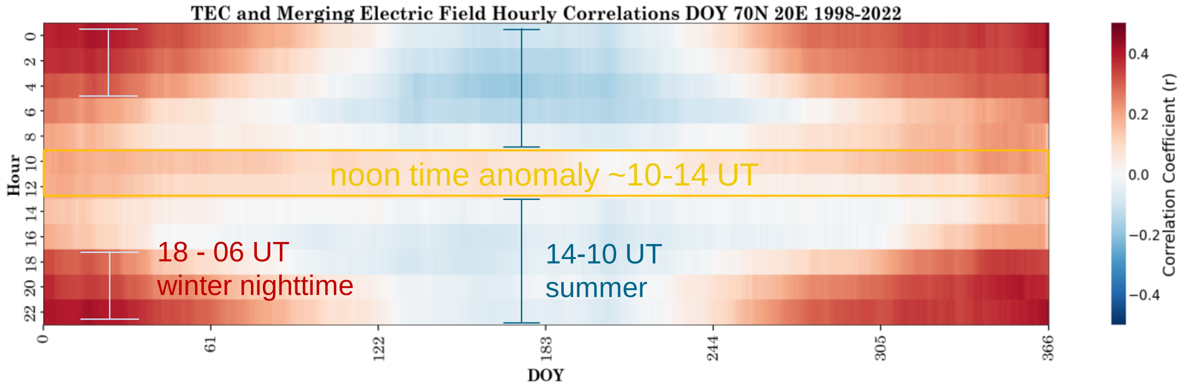
- This response is recently studied by analyzing different **ionospheric parameters and solar wind coupling function** with a cross correlation method of 90-days moving window at HL Tromsø location.

- Modification of the electron density at HL:
  1) polar cap plasma transport
  2) auroral particle precipitation
  3) Joule heating (Evans et al., 1972; Labelle et al., 1989; Sojka and Schunk, 1994; Consolini et al., 2021).

a) temporal evolution of TEC and E_m correlations



b) annual variation of TEC and E_m correlations



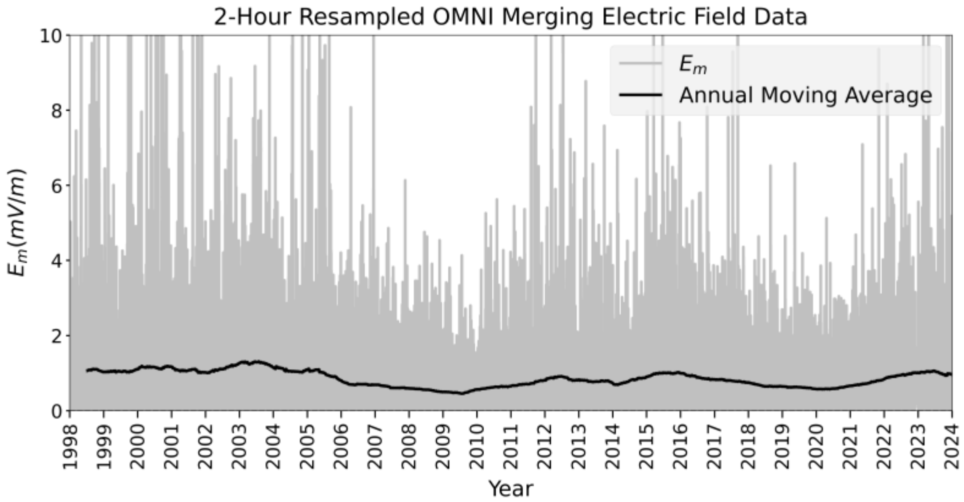
E_m: merging electric field

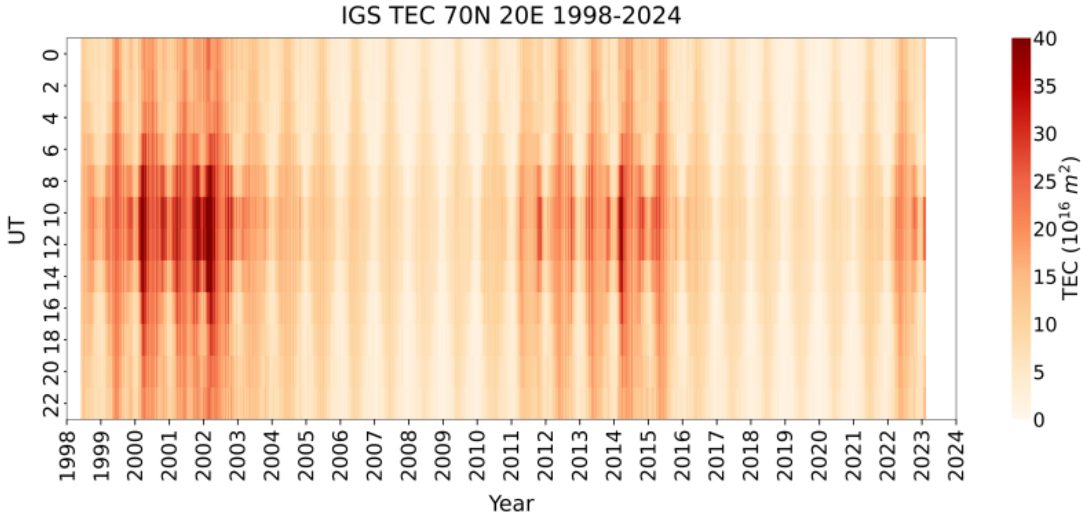
Motivation of the study

- High-latitude ionosphere persistently responds to the variation in the solar wind during winter nighttime.

- The sources of this response can be characterized by their difference in the response time to solar wind perturbations.

Solar wind forcing at Tromsø location and response time





$$E_\mathrm{m} = v_\mathrm{sw} B_\mathrm{t} \sin^2\left(\frac{\theta}{2}\right)$$

Kan & Lee (1979)

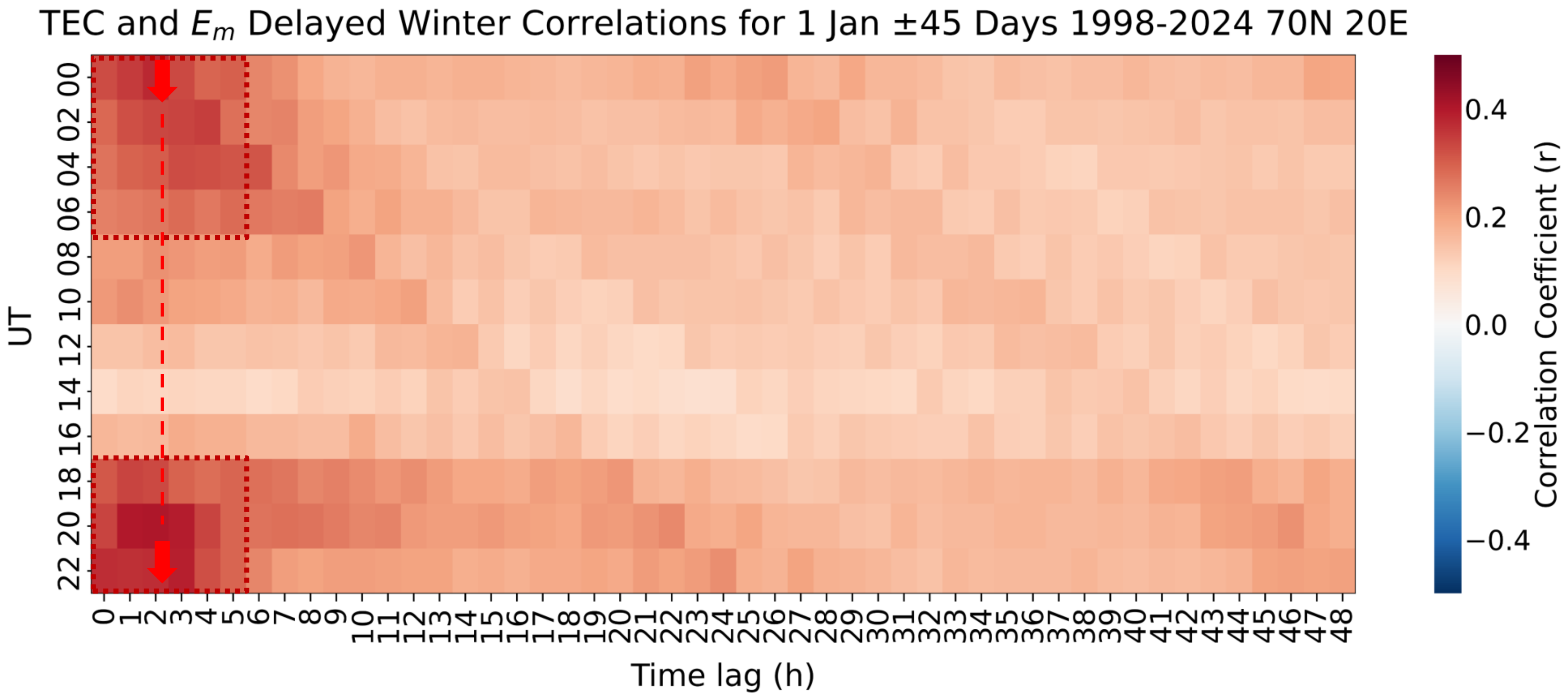
Lagged cross correlation

I. TEC and E_m datasets from 1998 to 2024 are separated into 12 UT groups.

II. A lag on the E_m is applied from 0 to 48 hours

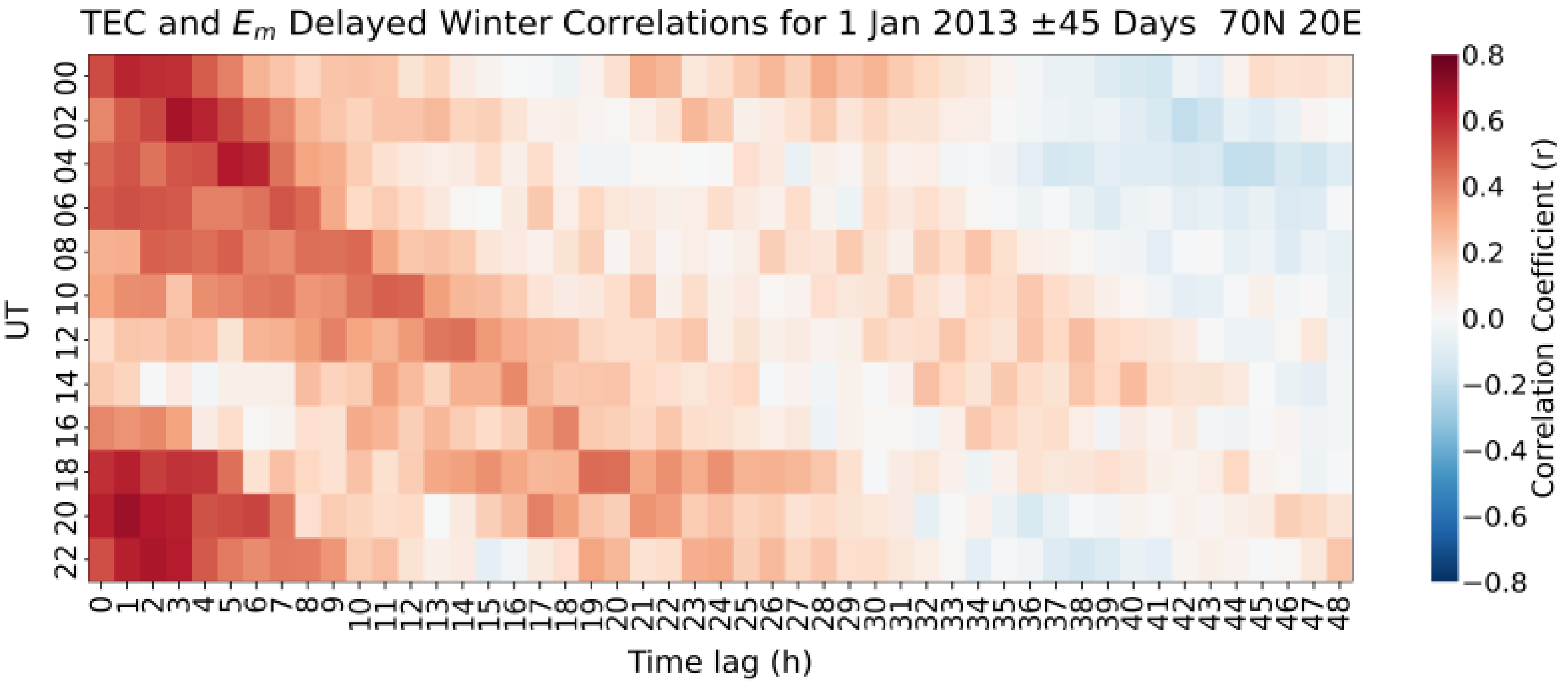
III. Pearson correlation between TEC and E_m during 90 winter days (1 Jan ± 45 days) is calculated for each lag hour.

Solar wind forcing at Tromsø location and response time: 1998-2024 winters averaged



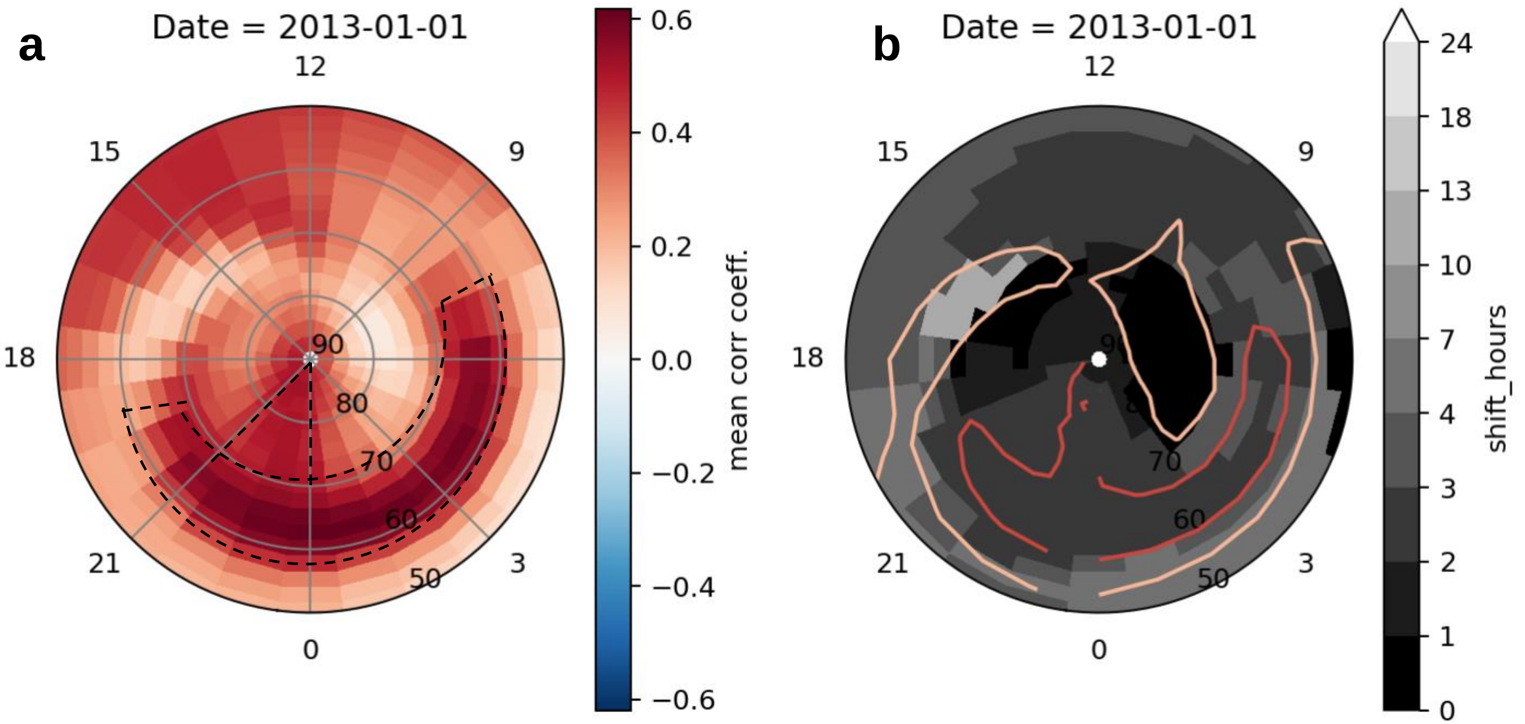
- TEC and E_m correlation values up to ≈ 0.5
- enhanced positive correlation → 18 UT to 06 UT
- time lag of the highest correlation ≈ 2 hour

Solar wind forcing at Tromsø location and response time: 15 November 2012 – 15 February 2013



- ➢ TEC and E_m correlation values up to ≈ 0.8
- ➢ enhanced positive correlation → 18 UT to 06 UT
- ➢ time lag of the highest correlation ≈ 2 hour

Solar wind forcing at high latitudes (NH) and response time: 15 November 2012 – 15 February 2013



a) Maximum correlation between IGS *TEC* and *Em* at each grid point of the IGS *TEC* maps in the time period of 01.01.2013 ± 45 days, computed for a shifted solar wind by lag hours ranging from 0 to 48 hours.

b) The corresponding lag for the maximum correlation between IGS *TEC* and *Em.*

- TEC and E_m high correlation values up to ≈ 0.8 (~21-06 MLT) in the auroral oval → auroral particle precipitation
- nightside polar cap (~21-00 MLT) enhanced correlation → polar cap plasma convection
- time lag ≈ 2 hour for highest correlations

EISCAT Tromsø UHF radar campaigns: particle precipitation

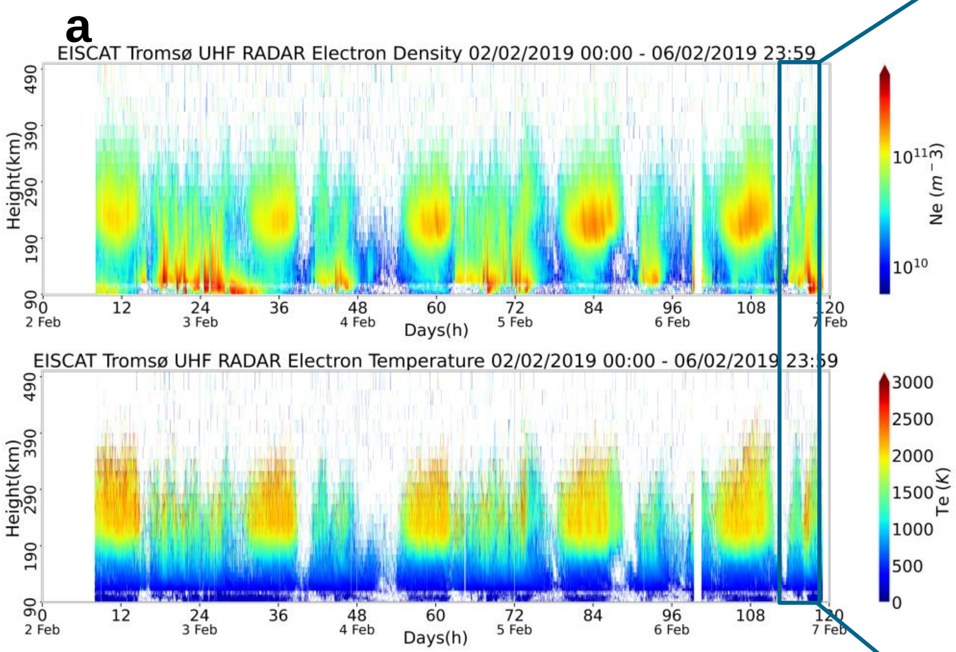
Campaign	Experiment Type	Experiment Date
1	beata (CP2)	9-12 January 2013
2 ☆	beata (CP2)	2-6 February 2019
3	beata (CP2)	19-29 January 2010
4	tau2pl (CP2)	6-9 February 2007

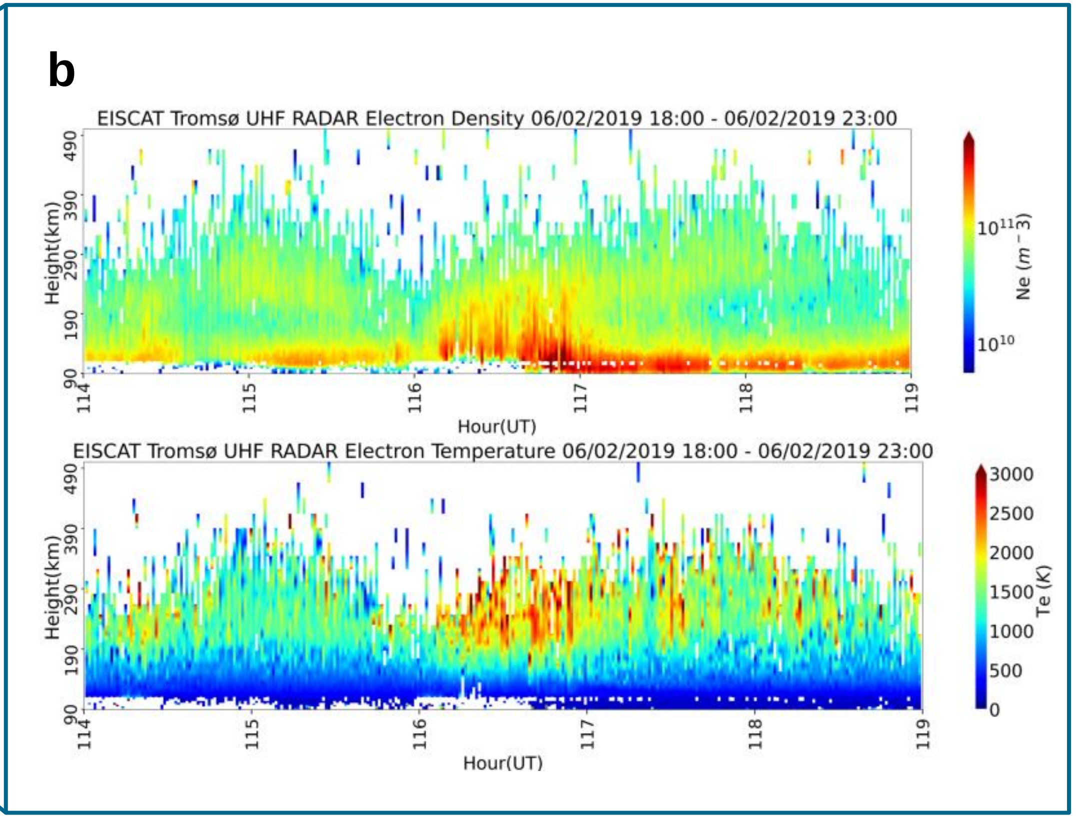
☆ : campaign shown in figures

Large peak at ~110 km of *Ne* in the E-region → **auroral electron precipitation (> keV).**

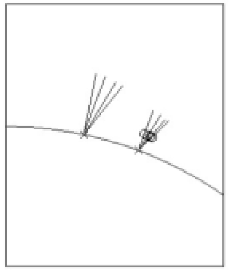
Weaker peak in the F-region → **soft-particle precipitation at ~250 km (few hundred of eV) and/or plasma patches/blobs (higher than ~ 250 km)**

Oyama et al., (2014)



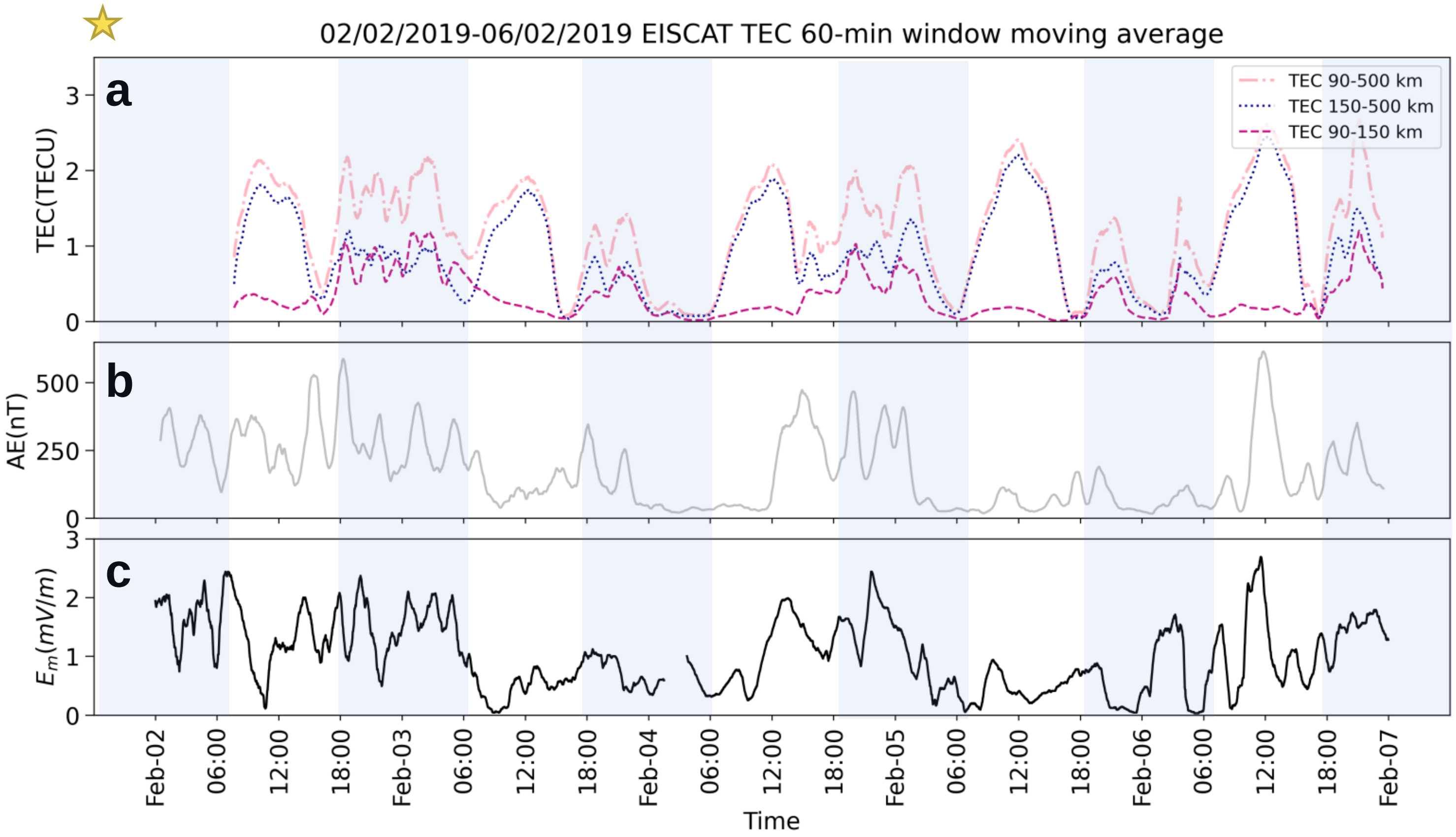


CP2 beata experiment
49-693 km range span



Credit: EISCAT

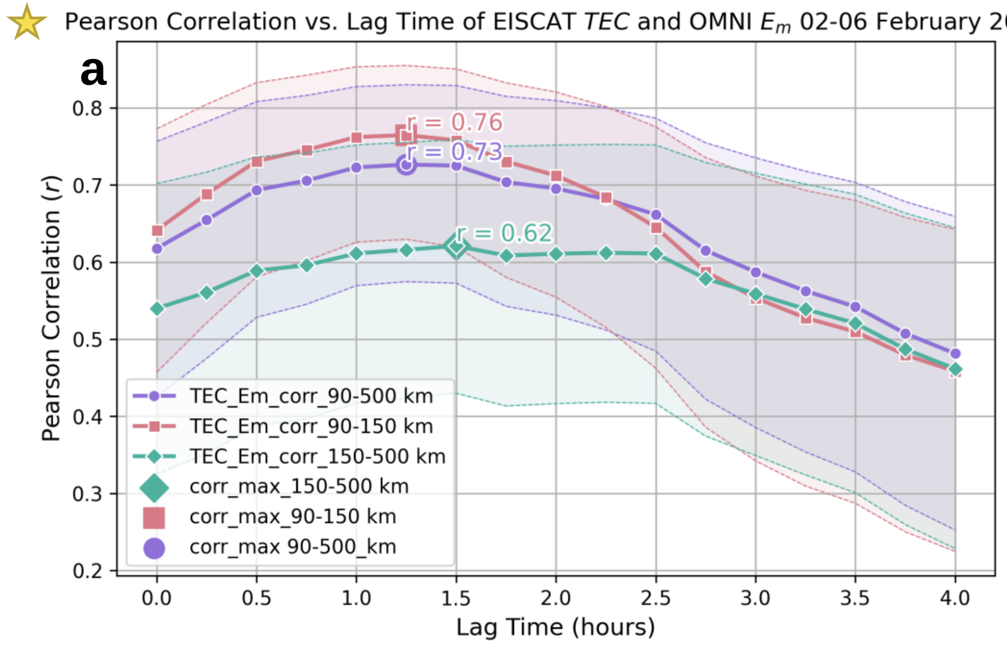
EISCAT Tromsø UHF Radar measurements: Campaign #2

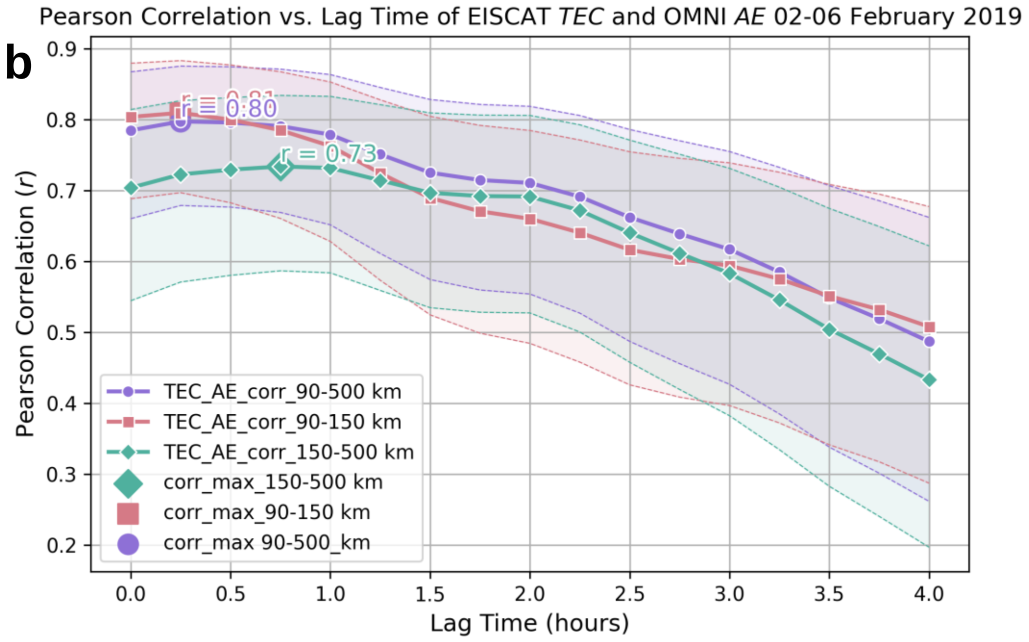


a) 60-min moving averages of EISCAT *TEC (E, F, combined regions)*
b) OMNI *AE* index and
c) OMNI merging electric field
in the time period of 2–6 February 2019

- enhanced *TEC* during nighttime (18–6 UT)
- higher E-region *TEC* during nighttime than during the daytime
- *TEC* on some nights as high as during daytime
- Substorm activity is identified → *AE* index > 250 nT

Correlation of EISCAT TEC with an offset applied to Em and AE: Campaign #2





Lagged Pearson correlation values between the time range of 18 and 6 UT on 2–6 February 2019 of:
a) 1-hour resampled EISCAT *TEC* and OMNI merging electric field *Em*
b) 1-hour resampled EISCAT *TEC and* OMNI AE

TEC & Em

- E-region: r = 0.76 when t =75 min
- F-region: r = 0.62 when t = 90 min
- Combined: r = 0.73 when t = 75 min

TEC & AE

- E-region: r = 0.81 when t =15 min
- F-region: r = 0.73 when t = 45 min
- Combined: r = 0.80 when t = 15 min

Results: ionospheric response observed at EISCAT Tromsø UHF radar

a

	90–150 km		150–500 km		90–500 km	
Campaign	Offset (min)	Max corr. (r_{max})	Offset (min)	Max corr. (r_{max})	Offset (min)	Max corr. (r_{max})
1	90	0.80	90	0.77	90	0.81
2 ★	75	0.76	90	0.62	75	0.73
3	75	0.60	135	0.75	135	0.74
4	45	0.69	90	0.58	90	0.63

b

	90–150 km		150–500 km		90–500 km	
Campaign	Offset (min)	Max corr. (r_{max})	Offset (min)	Max corr. (r_{max})	Offset (min)	Max corr. (r_{max})
1	45	0.81	60	0.62	60	0.68
2 ★	15	0.81	45	0.73	15	0.80
3	0	0.60	75	0.68	15	0.68
4	15	0.63	30	0.49	15	0.52

a) EISCAT TEC & OMNI Em

- shorter time lag (45-90 minutes) → E-region
- E-region response covers the time period from the arrival of the solar wind until it results in substorm activity (magnetospheric loading-unloading processes)
- longer time lag (90-135 minutes) → F-region
- F-region response is similar to the ≈120 min IGS TEC response

b) EISCAT TEC & OMNI AE

- 0-45 min time lag → E-region
- almost immediate/fast ionospheric response in the E-region to the substorm activity
- 30-75 min time lag → F-region
- response cannot be solely due to substorm activity in the F-region → polar cap plasma convection

★ : campaign shown in figures

Summary and conclusions

This study investigates the processes driving the high-latitude ionospheric response to the solar wind forcing during winter nighttime conditions.

1. There is a persistent ionospheric response to solar wind variability in the high-latitude ionosphere during winter nighttime with a lag of ≈ 2 hours.

2. Delay in the E-region *EISCAT TEC* and *Em max* correlations is ≈ 71.25 min → magnetospheric processes (loading and unloading) and particle precipitation

3. ≈101.25 min delay in the F-region *EISCAT TEC* and *Em max* correlations → plasma convection processes

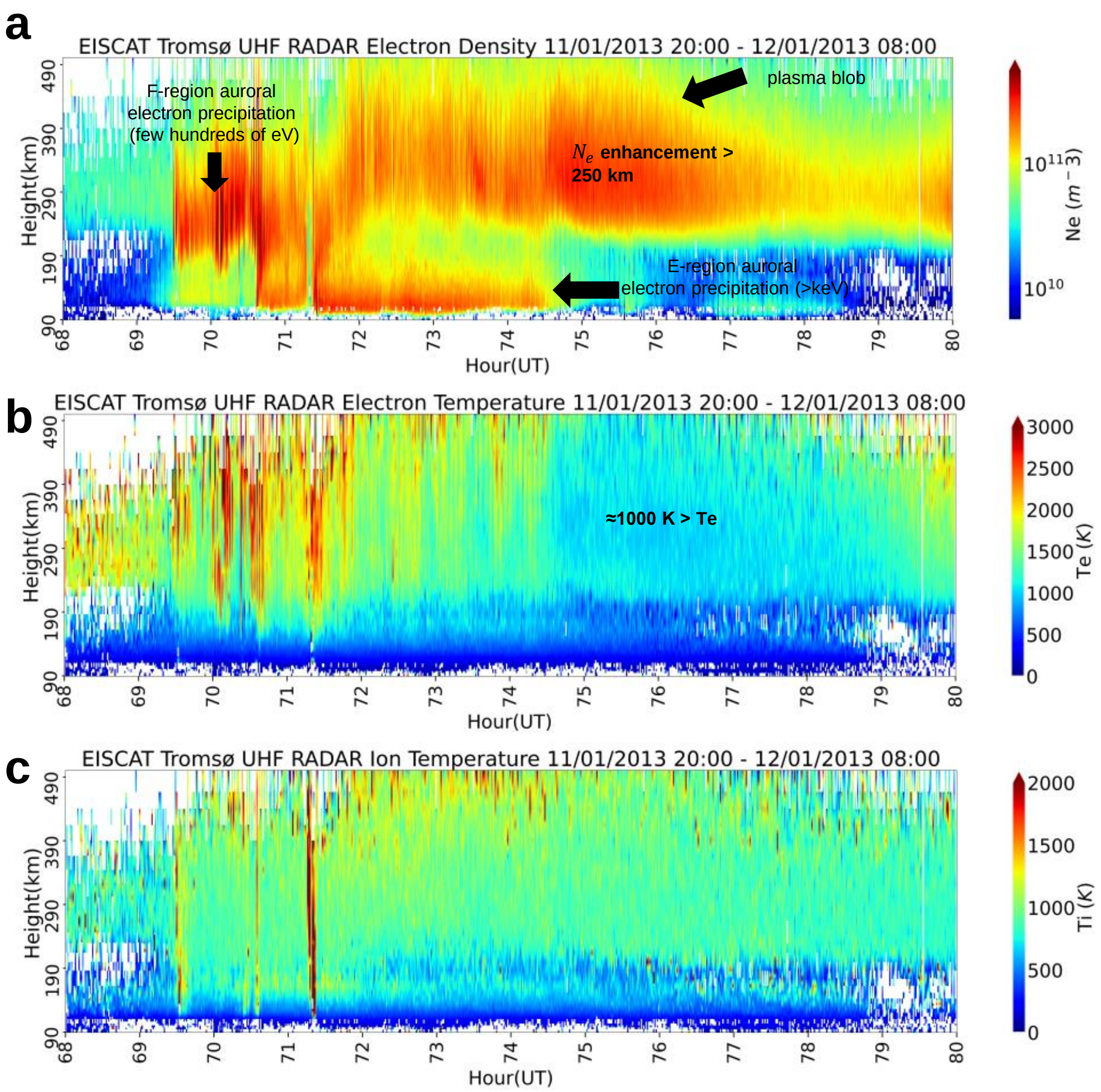
4. 120 minutes delay of the IGS TEC and *Em max* correlations during ≈ 25 years is driven mainly by the plasma convection processes in the F-region.

→ **Manuscript in review (Iochem et al., JSWSC)**

Thank you for your attention ☺

Extra slides

EISCAT Tromsø UHF radar campaigns: plasma blobs



EISCAT Tromsø UHF radar 1-min **a)** electron density, *Ne* , **b)** electron temperature, *Te* and **c)** ion temperature, *Ti* in the time period of 11–12 January 2013.

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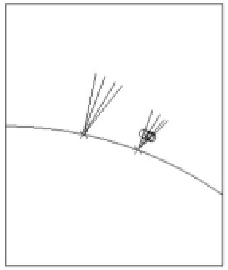
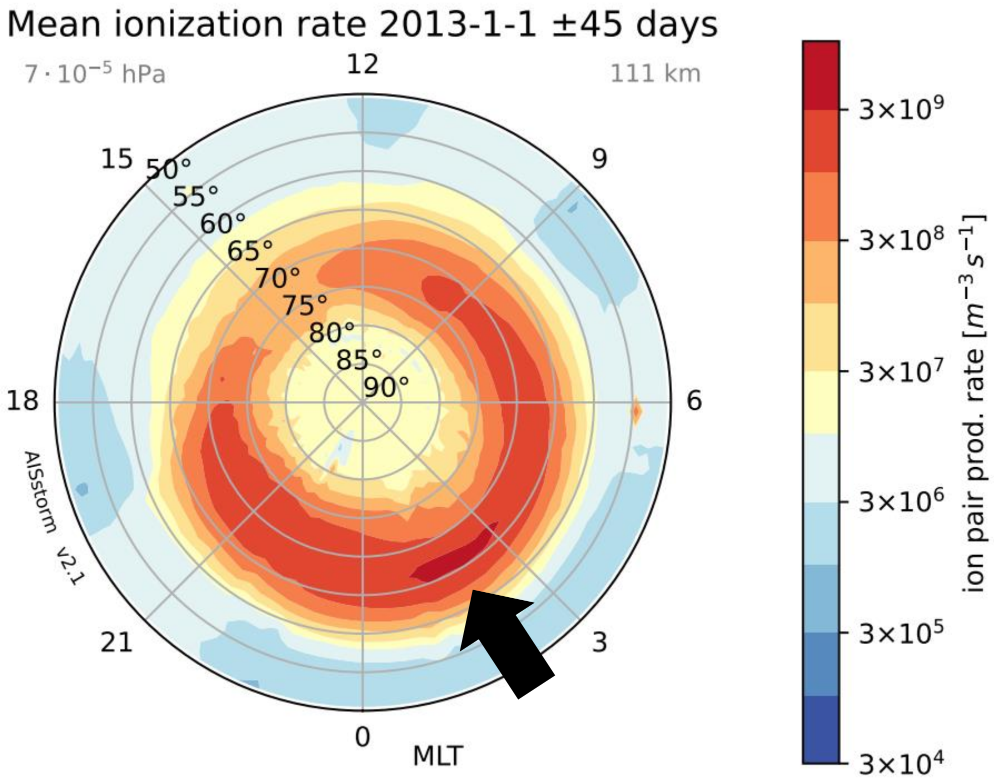
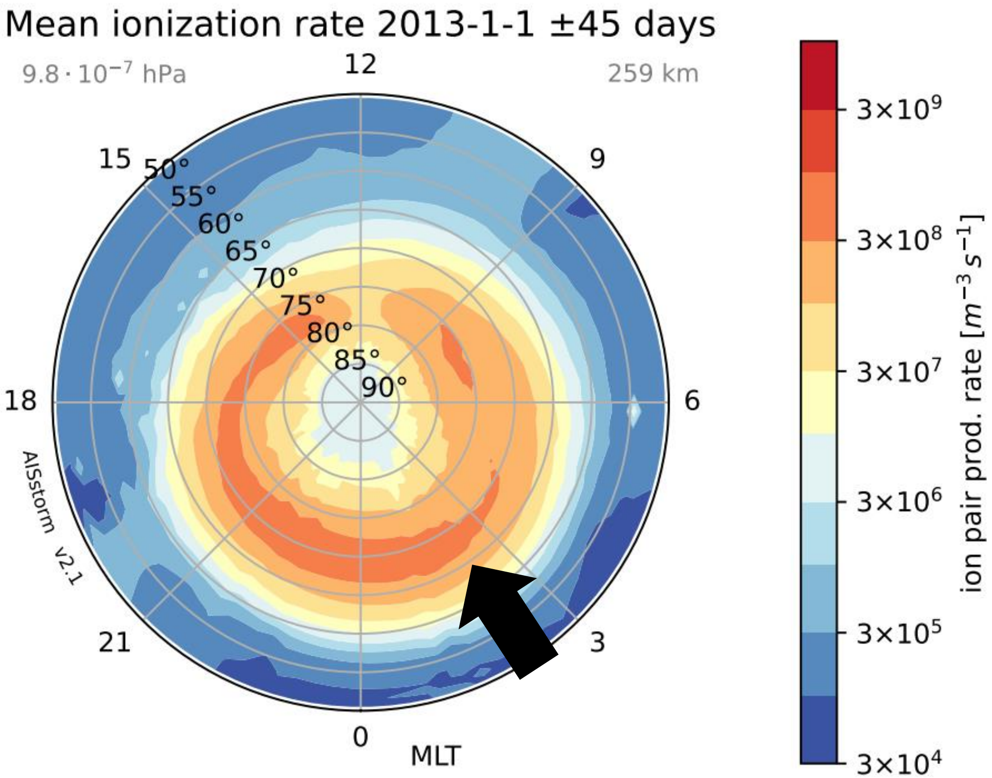


Credit: EISCAT

AISStorm ion pair production - AIMOS





Future work

- Define TIE-GCM model capabilities: Which TIE-GCM electric potential driver (T+AMGeO, T+Heelis, T+Weimer, T+AMIE, T+MAGE) performs the best to represent ionospheric response at winter nighttime HL? What is the offset of best model from real data? How it could be improved within the model?

Final goal of this task:

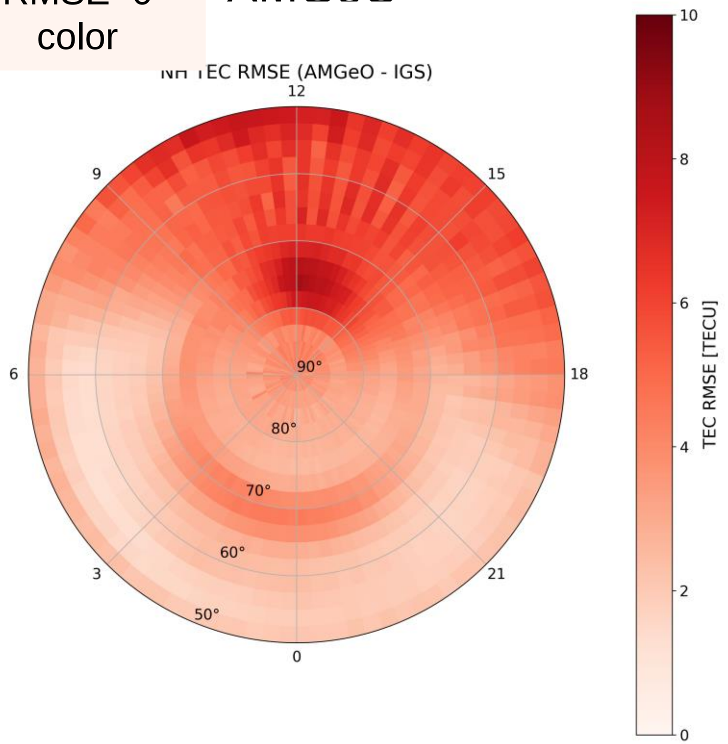
-TIEGCM run with the best electric potential driver during 90 days of winter, 1 Jan 2013 ± 45 days.

-Compare the observed ionospheric response.

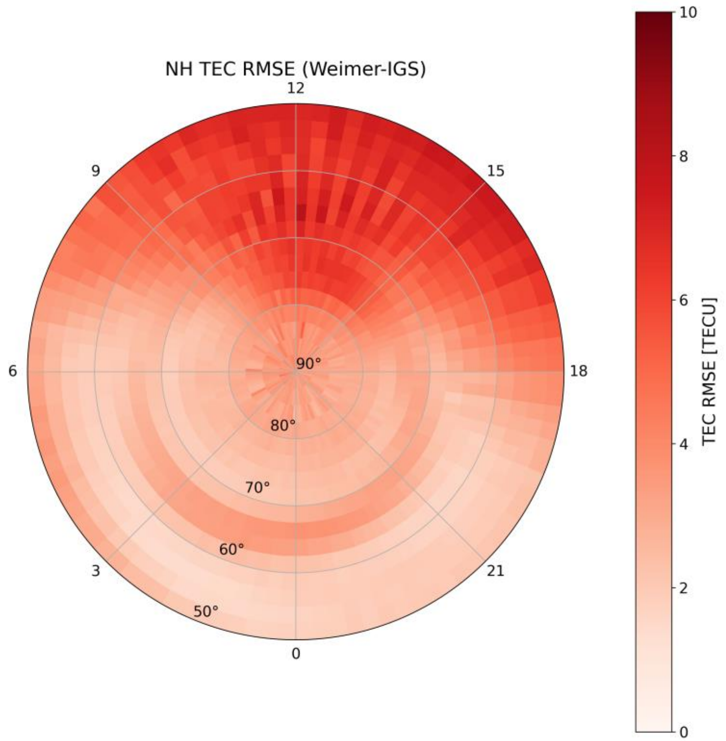
TIE-GCM+AMGeO // TIE-GCM+Weimer // TIE-GCM+Heelis RMSE from IGS TEC at NH 15.11.2012-15.02.2013

RMSE=0 color

AMGeO



Weimer



Heelis