

High-Latitude Ionospheric Irregularities

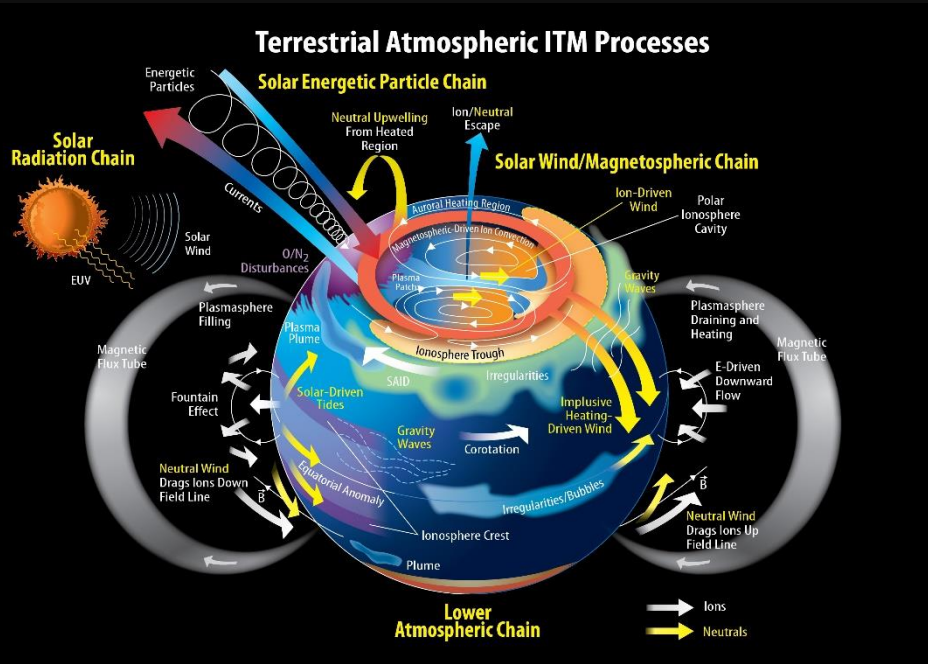
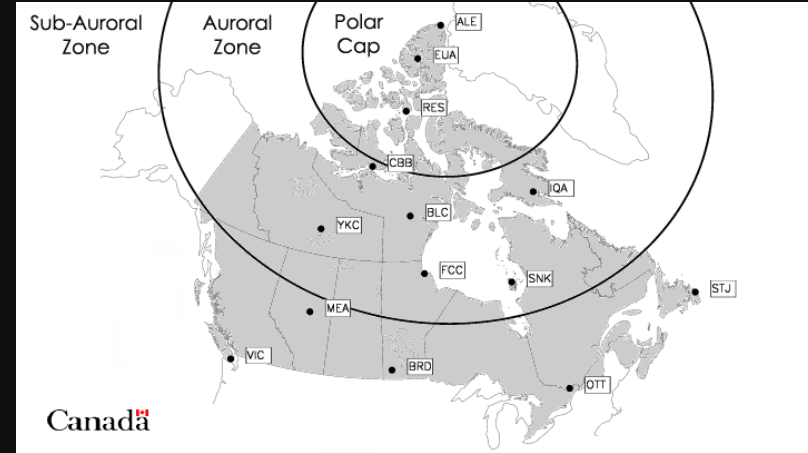


Figure courtesy - NASA

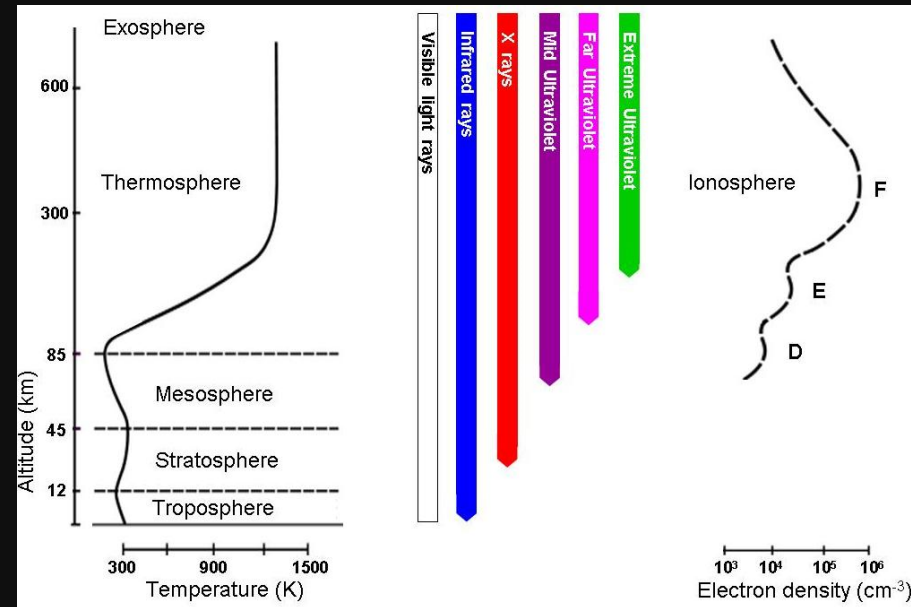


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The ionosphere

- Region of ionized plasma above 60 km from the Earth's surface
- Primarily produced by the solar EUV and particle precipitation (polar regions)
- Temporal variation scales from “milliseconds” to solar cycle
- Spatial variations from cm to a few thousand km
- Affects the propagation of radio waves
- Significant impact on communication and PNT systems
- Effect on systems is scale-dependent



The ionosphere – Effect on radio systems

- Effect on PNT Systems
 - Degrade the quality/precision of reference station measurements
 - Degrade the quality/precision of user measurements
- Disrupt HF and satellite communications
- Effect data links
- Effect radio astronomical and remote sensing measurements and applications

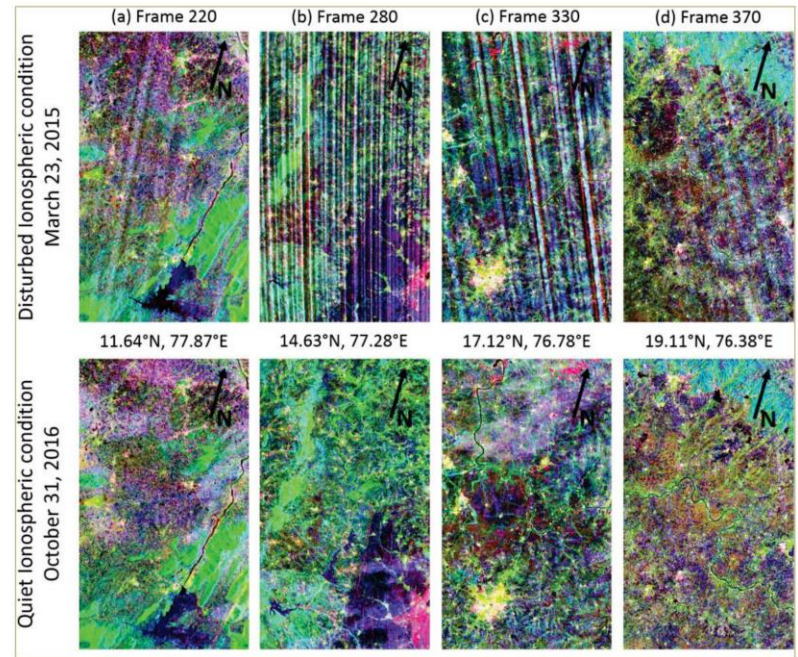
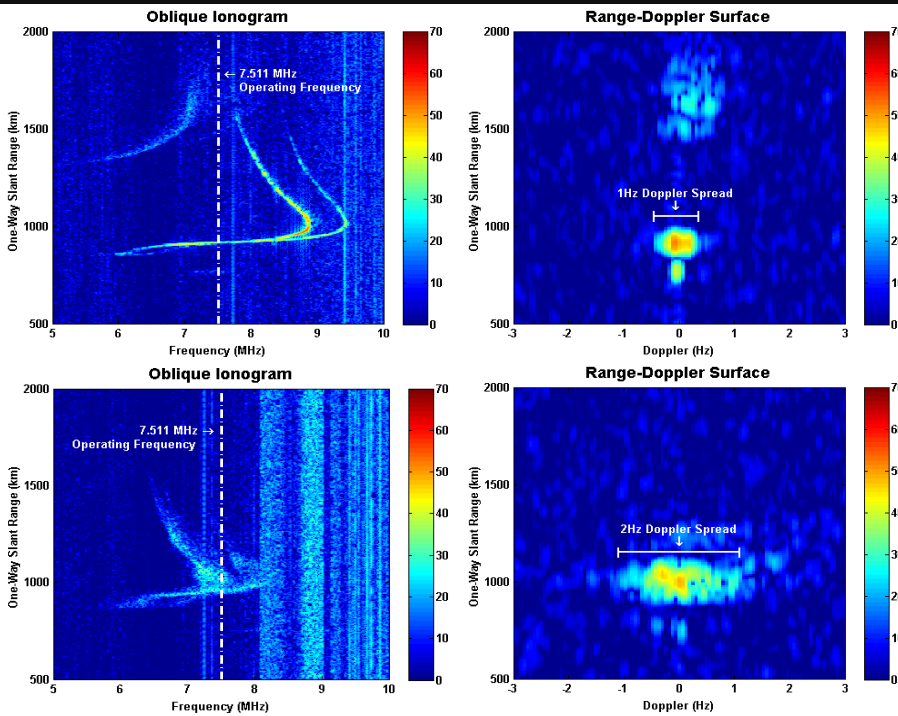
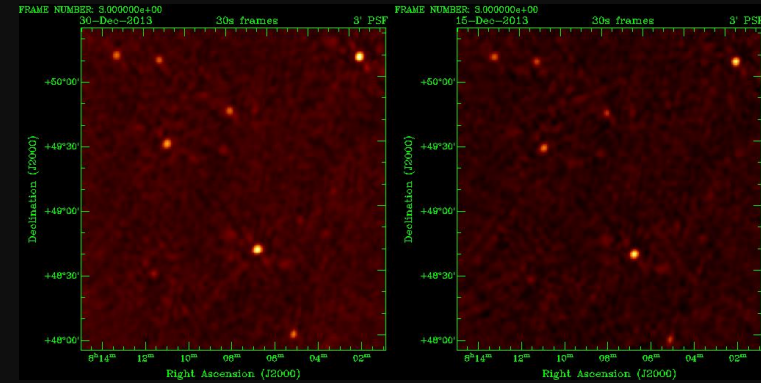
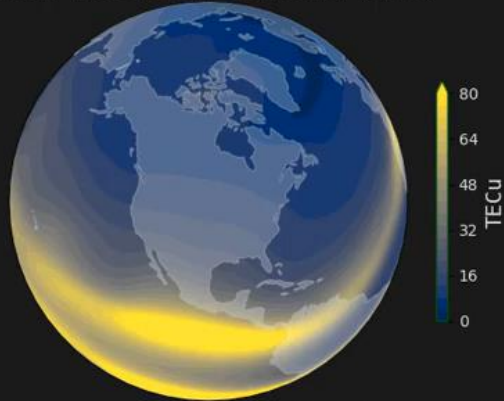


Figure 1. G4U color composite RGB images (Red: double-bounce scattering, Green: volume scattering, and Blue: surface scattering) of ALOS-2/PALSAR-2 data acquired on nights with different ionospheric activity: (top row) disturbed, and (bottom) quiet. The radar look

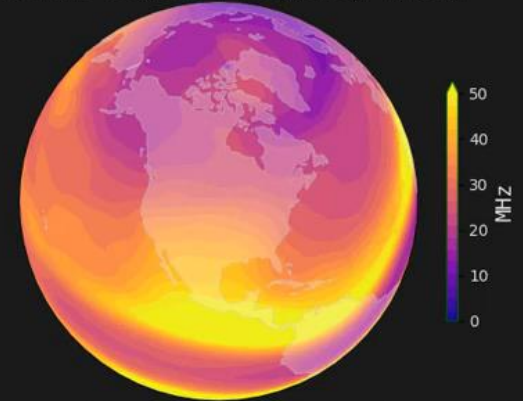
Global ionosphere

Global Ionosphere Valid at: Mar 17 2015 00:00 UTC

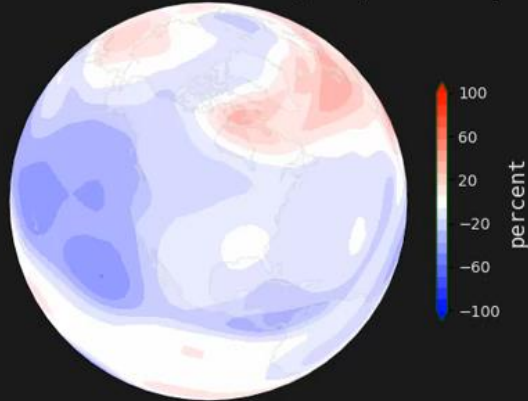
Total Electron Content (TEC)



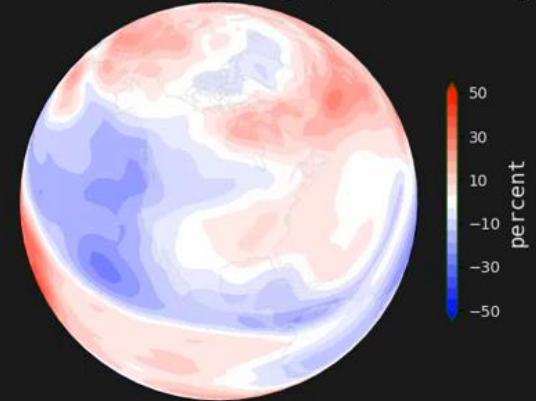
Maximum Usable Frequency (MUF)



Total Electron Content (TEC) Anomaly

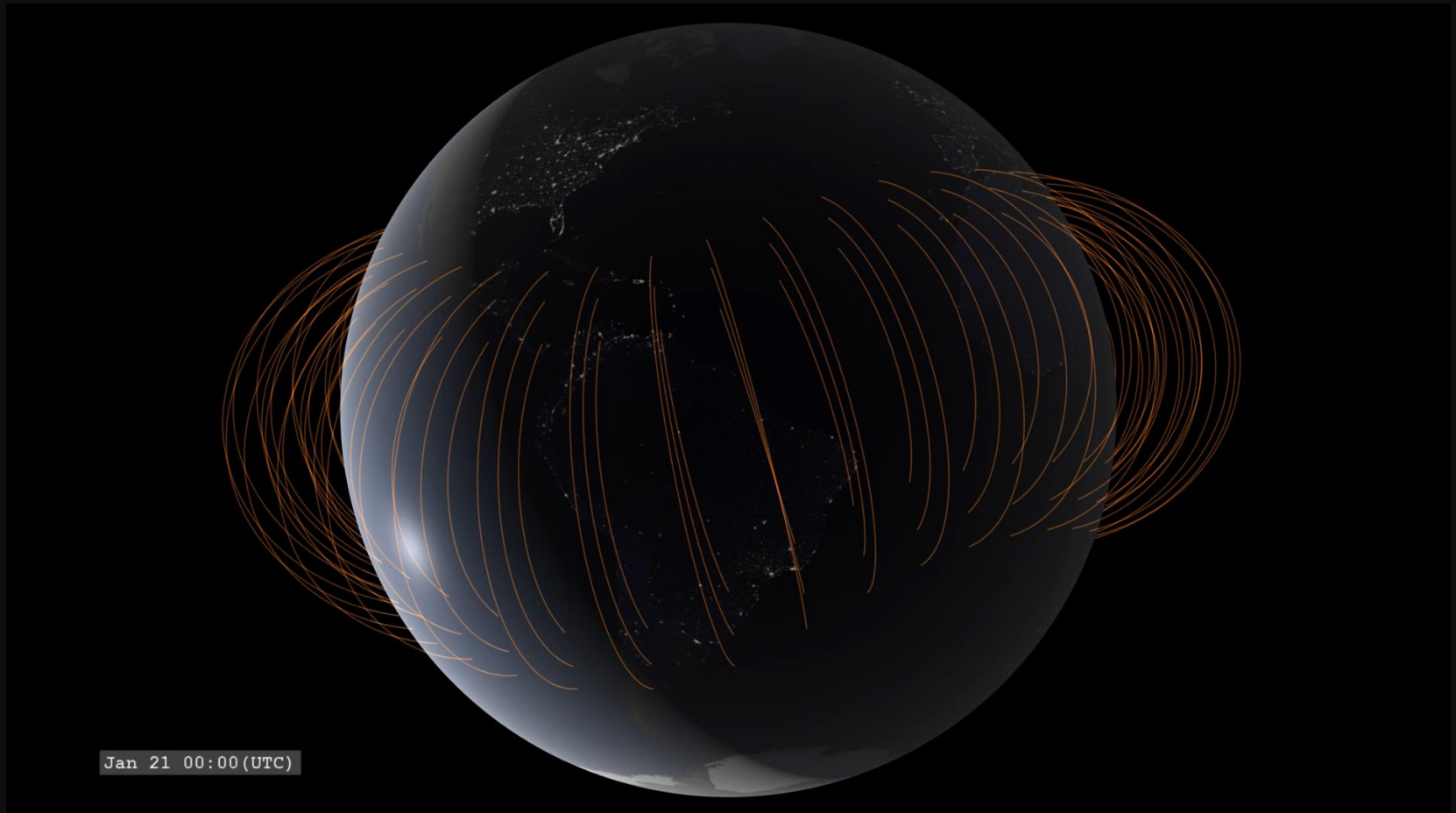


Maximum Usable Frequency (MUF) Anomaly

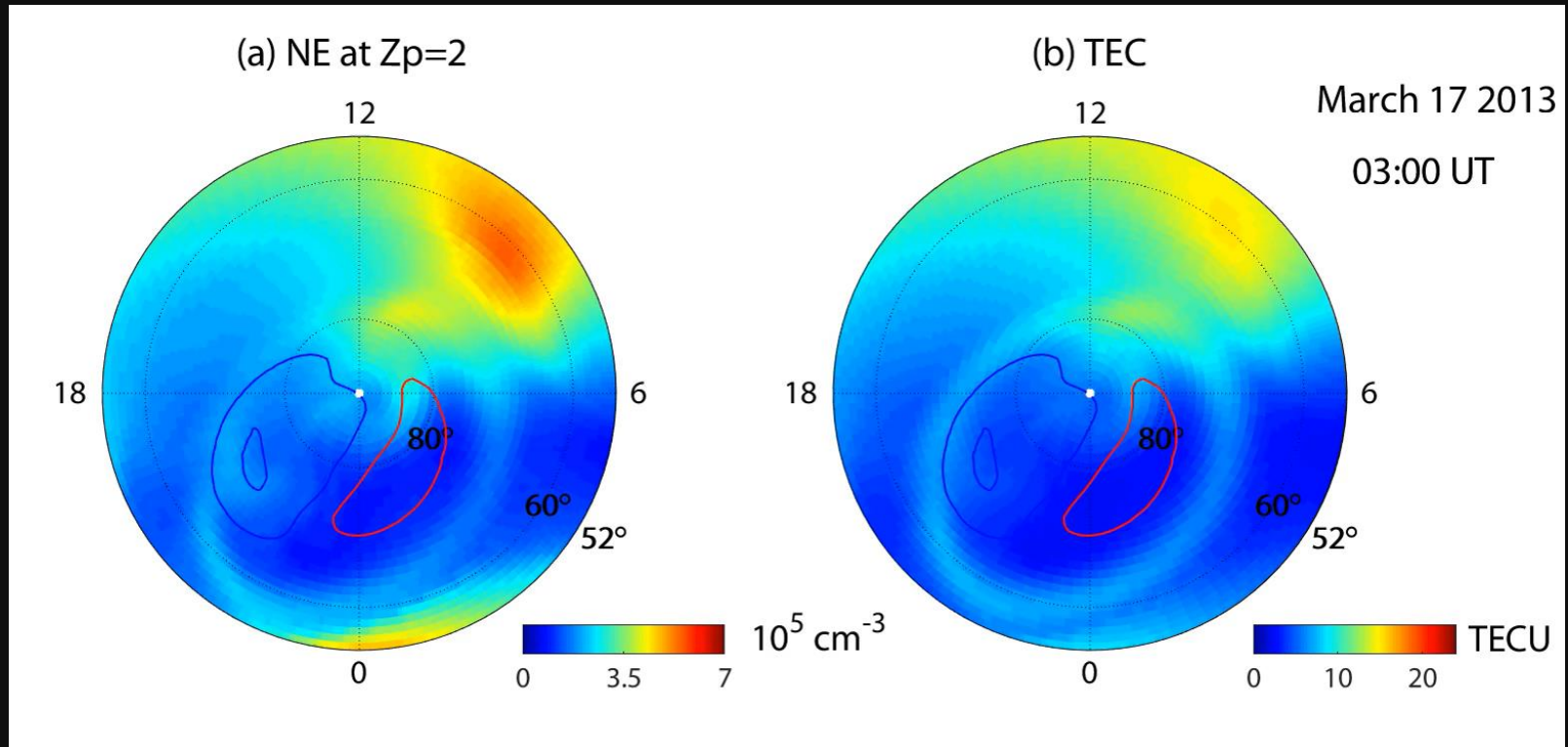


Space Weather Prediction Center

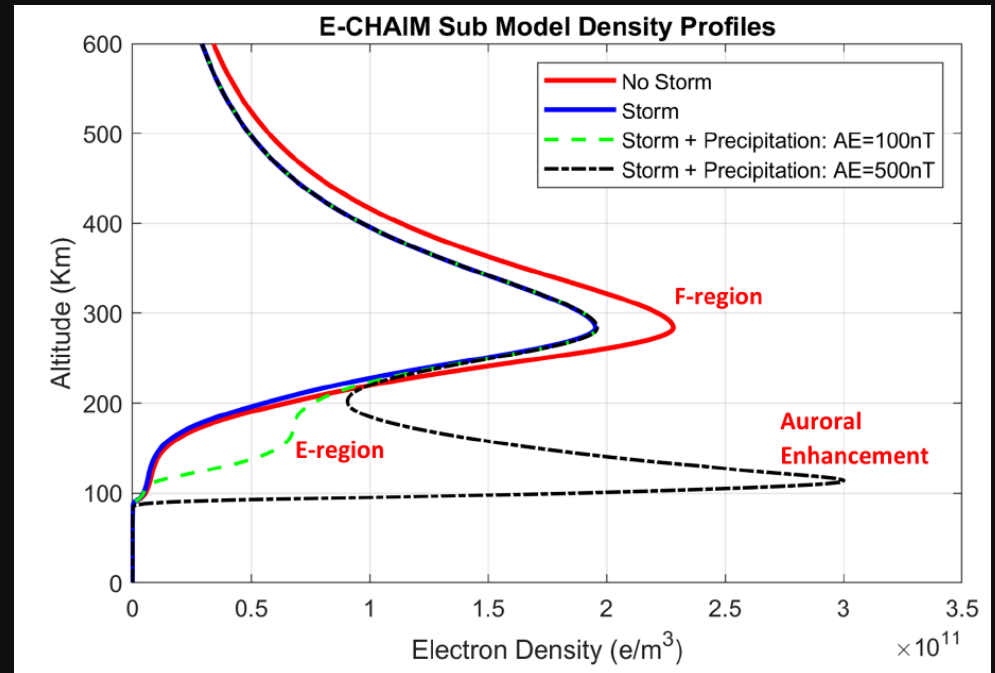
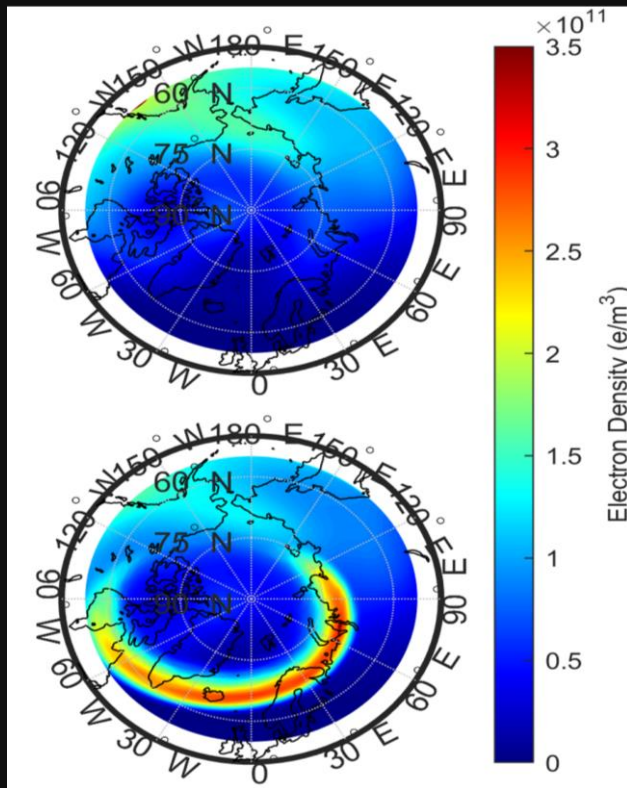
The ionosphere at low latitudes



High-latitude ionosphere



High latitude: Particle precipitation



High-latitude Vs Low-latitude

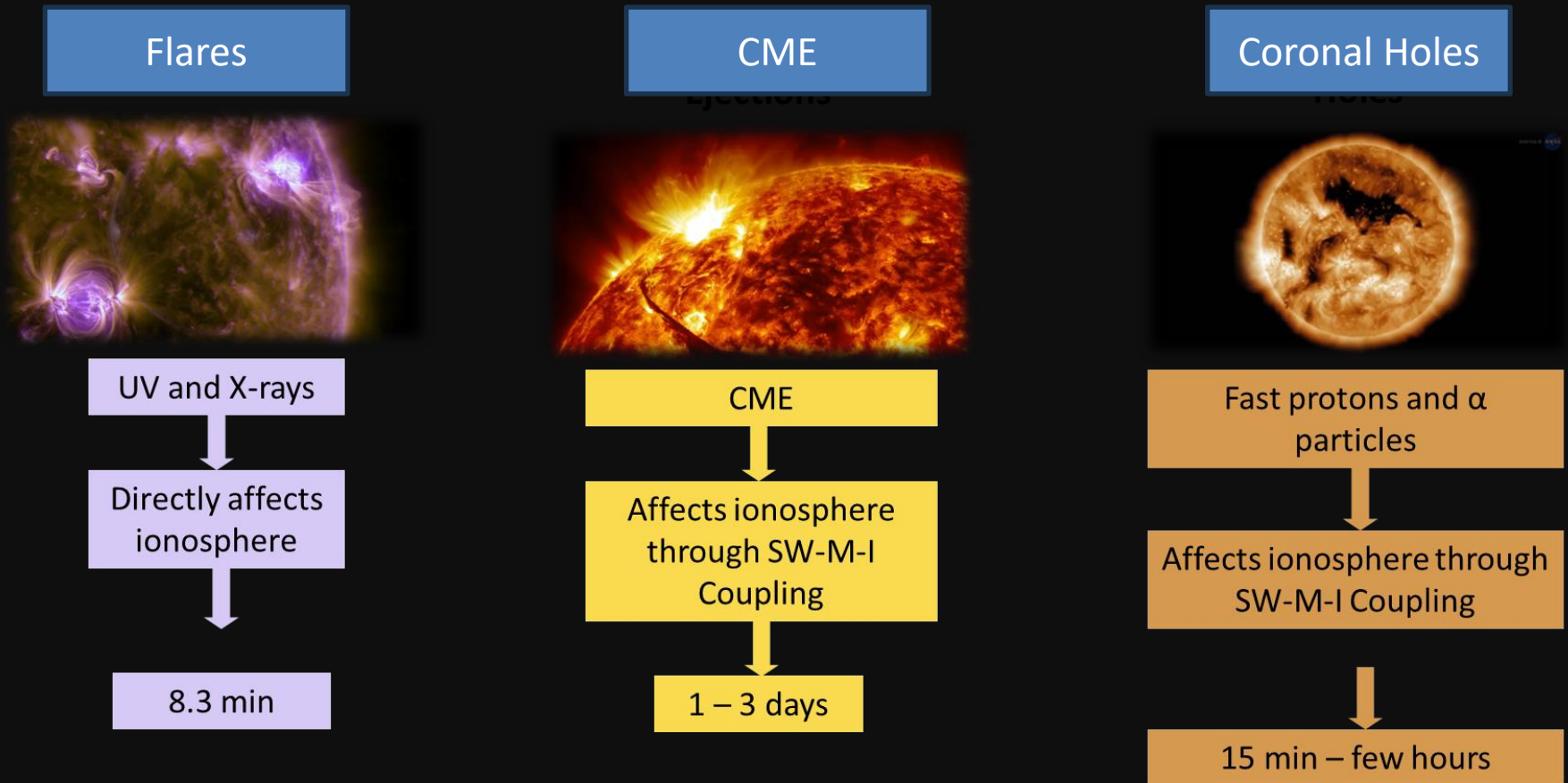
High-latitude

- External
 - Sun and Solar Wind
 - Interplanetary Magnetic Field
- Additional source of ionization in the form of particle precipitation
- Dominant variability is due to SW-M-I interaction
- Internal
 - Electrodynamics
 - Neutral dynamics
 - Ion-neutral coupling
- Variability is “stochastic”

Low-latitude

- Dominant variability is due to internal processes
- Internal
 - Atmospheric dynamo
 - Electrodynamics
 - Ion-neutral coupling
- Occasional influence of the SW-M-I coupling process
- Variability is “predictable”

Ionospheric irregular variations – Externally driven



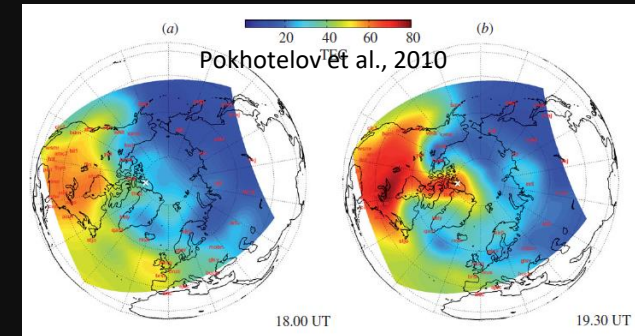
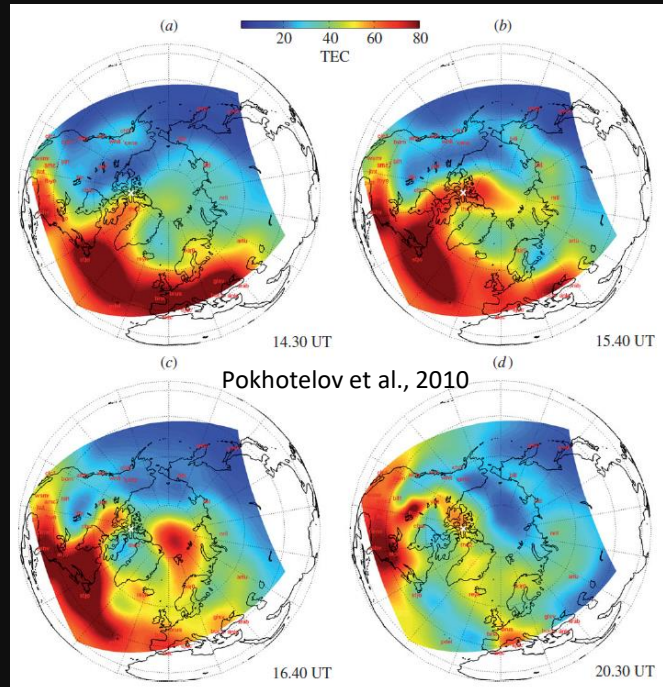
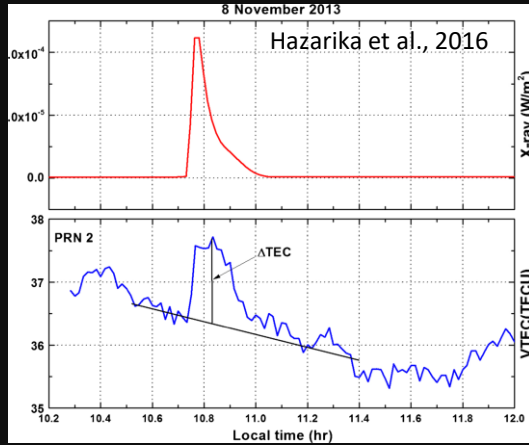
Slide courtesy – Dr. Claudio Ceseroni, INGV, Italy

Ionospheric irregular variations – Externally driven

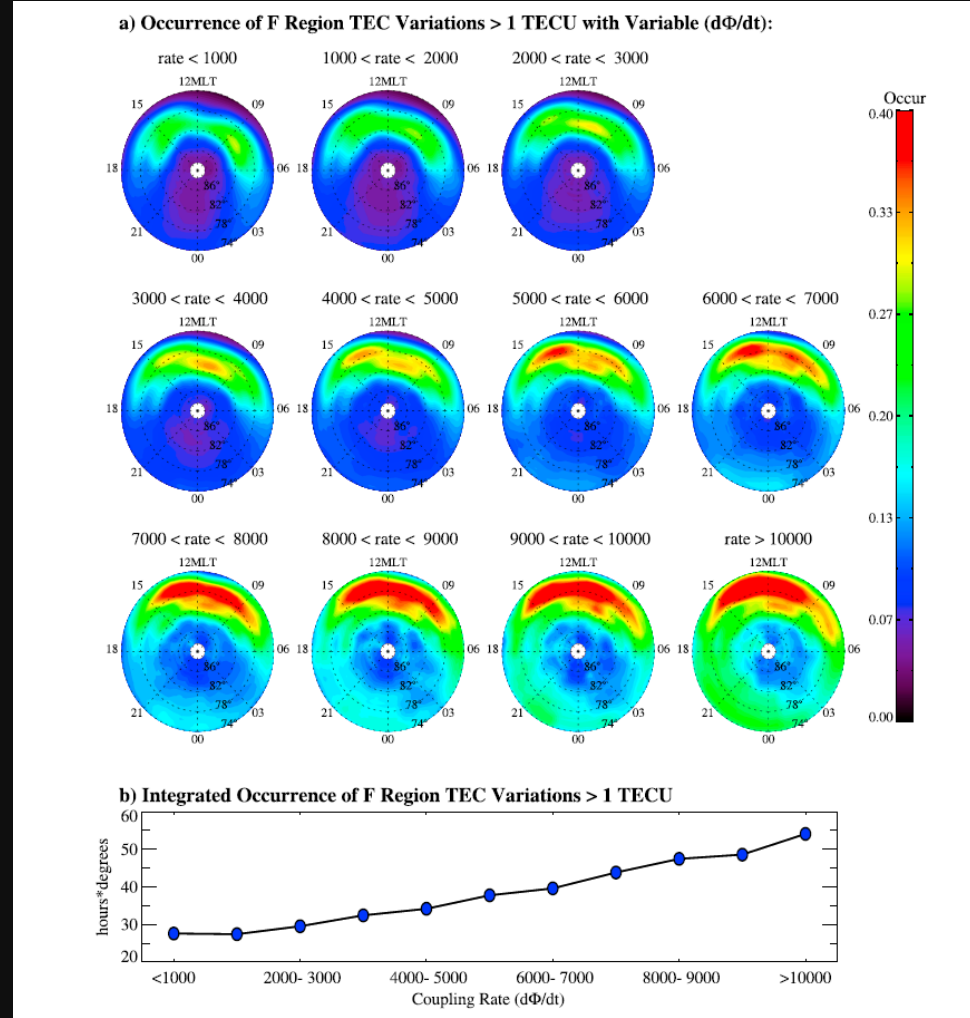
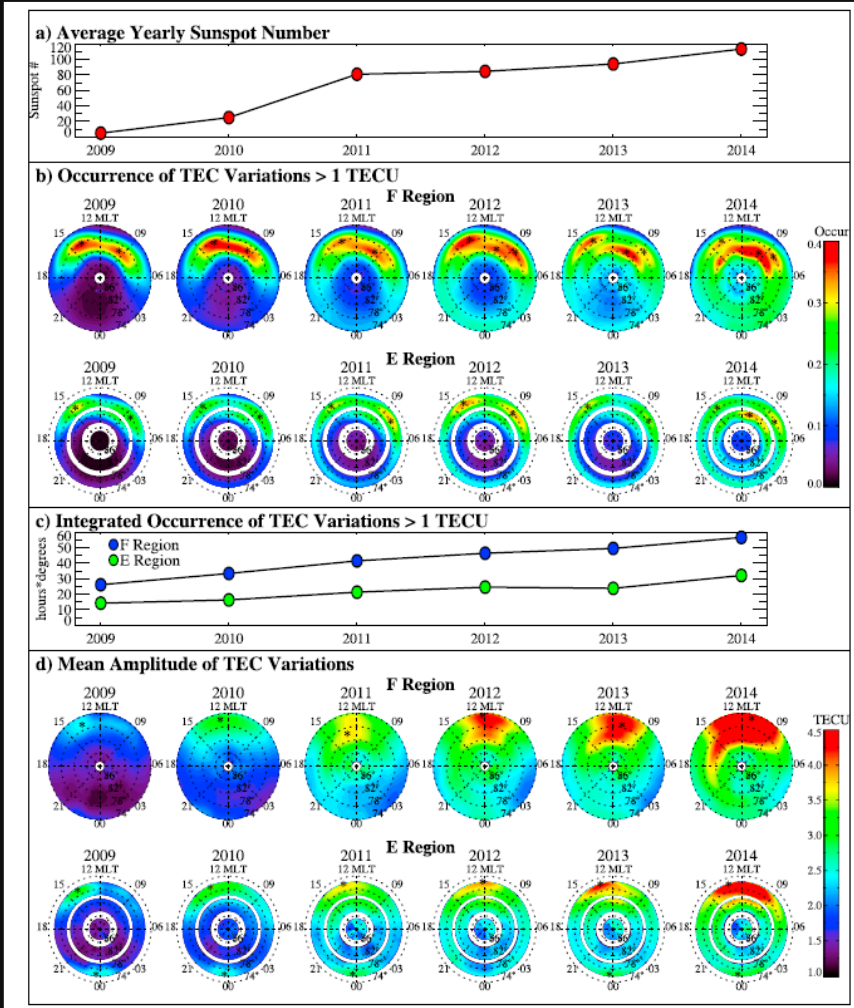
Flares

CME

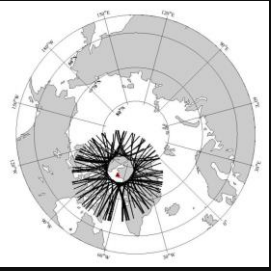
Coronal Holes



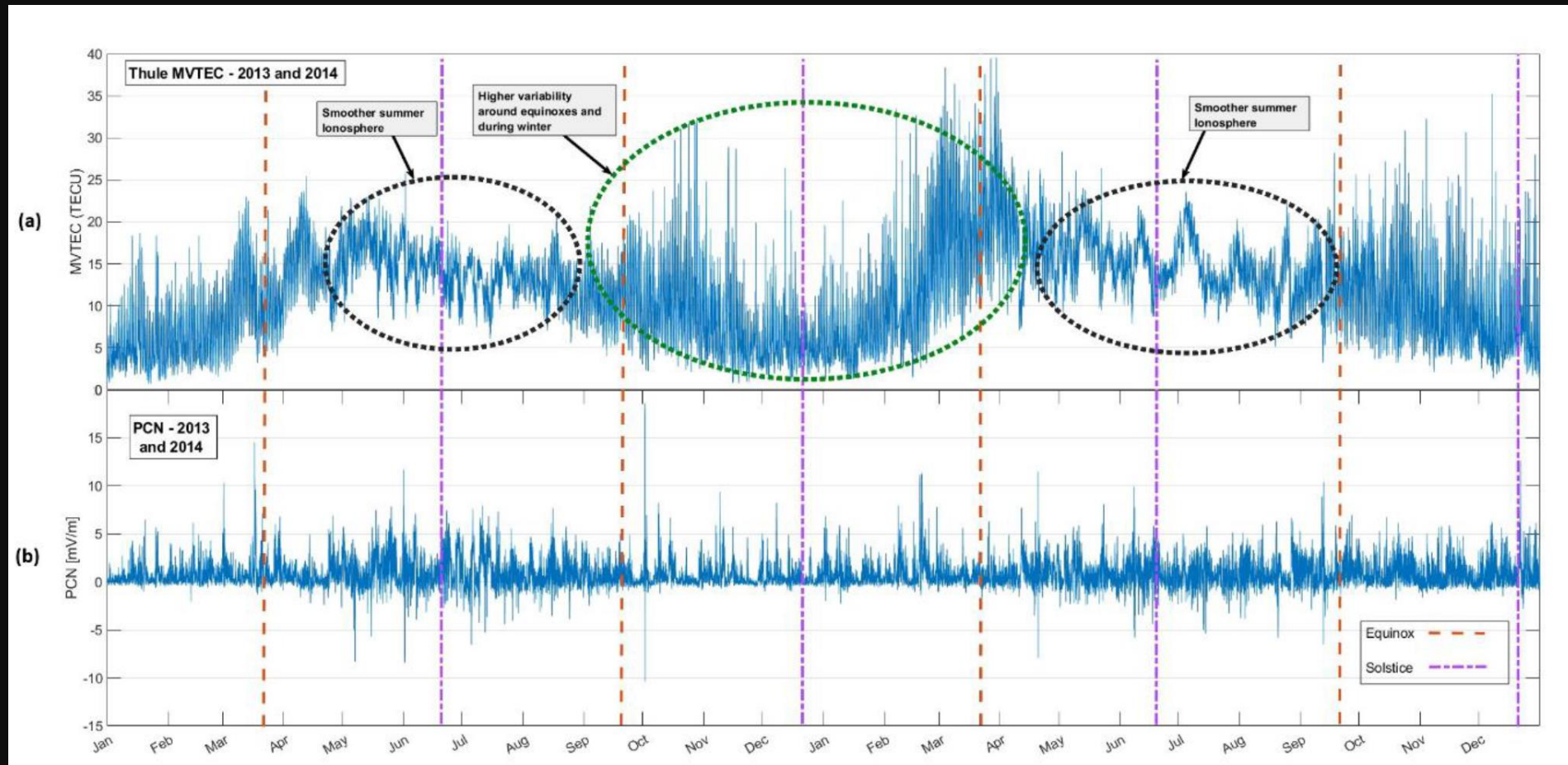
High-latitude ionosphere



Watson et al., 2016



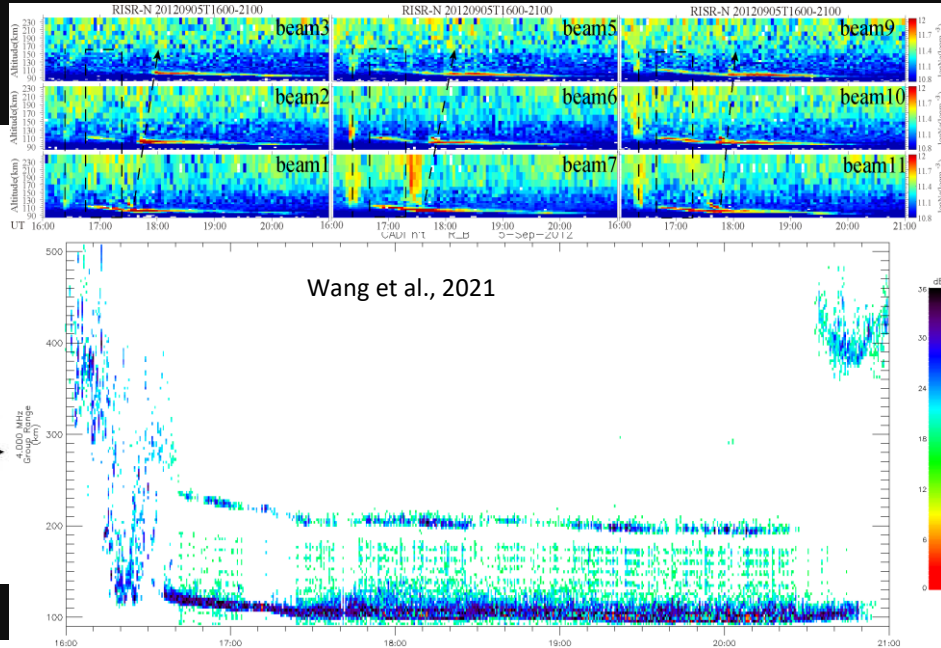
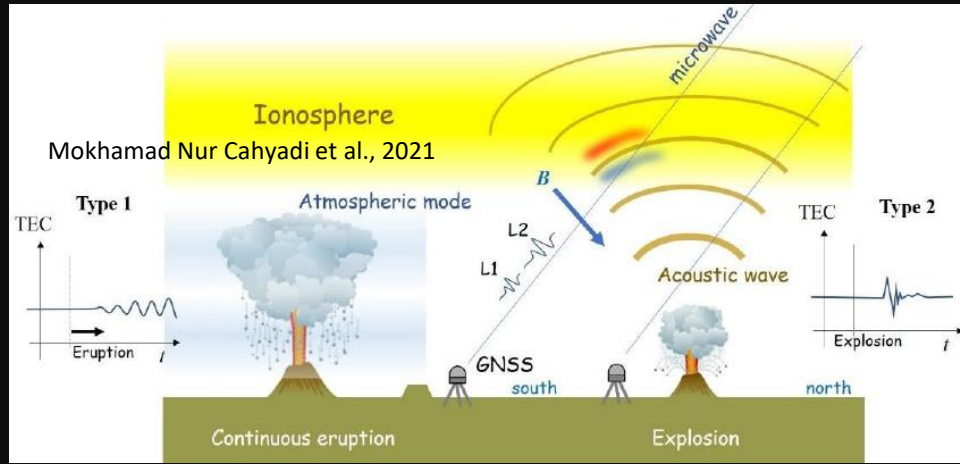
Polar Cap ionosphere



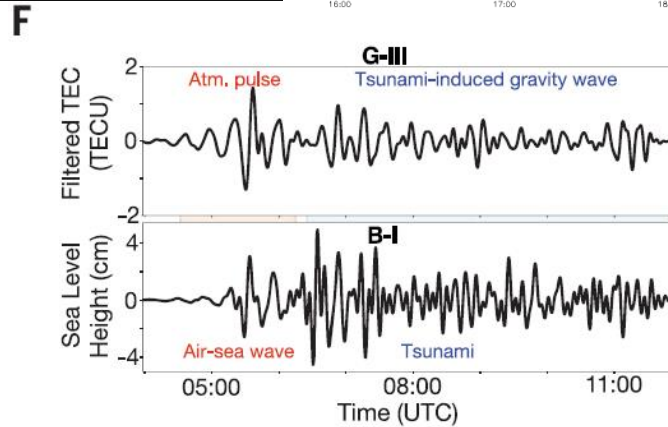
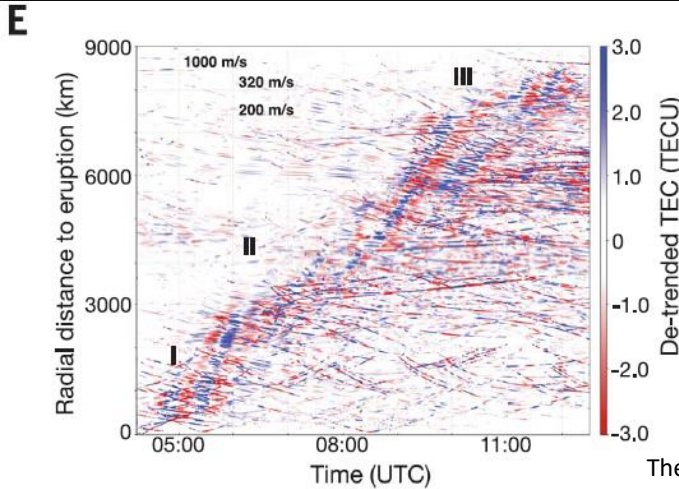
Durgonics et al., 2024

Ionospheric irregular variations – Internally driven

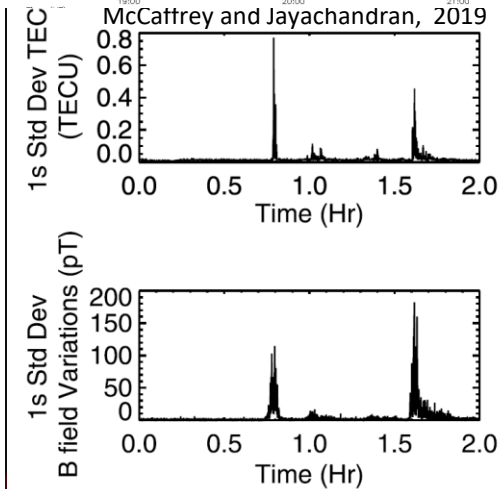
Mokhammad Nur Cahyadi et al., 2021



Wang et al., 2021



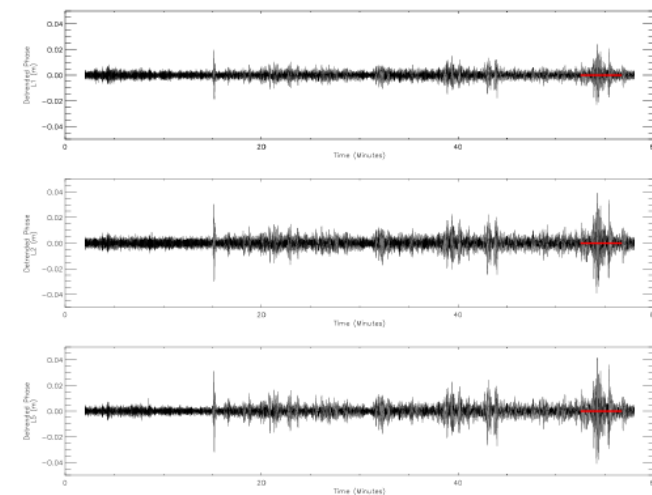
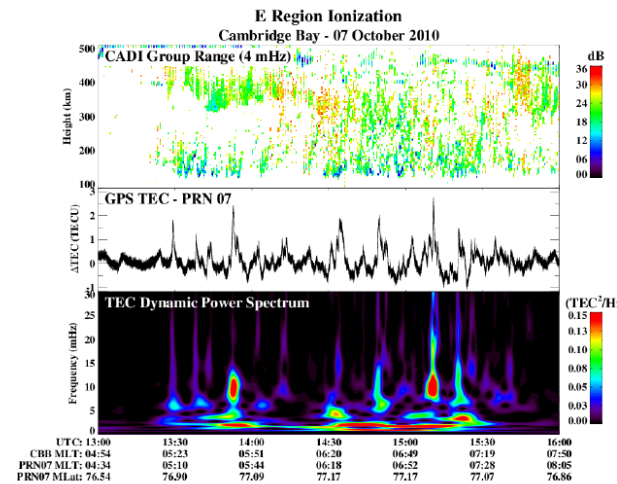
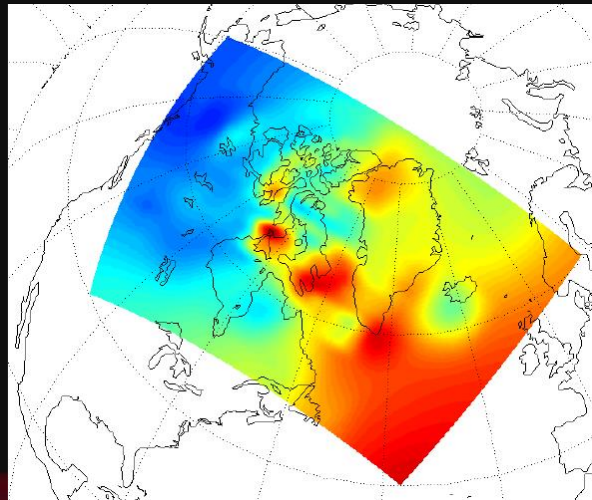
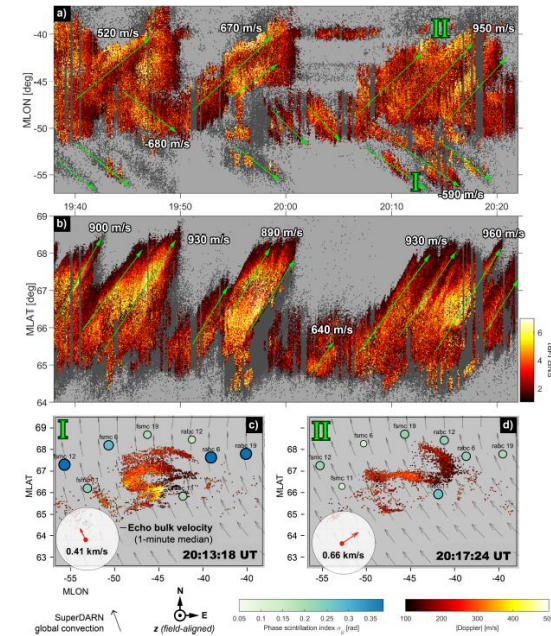
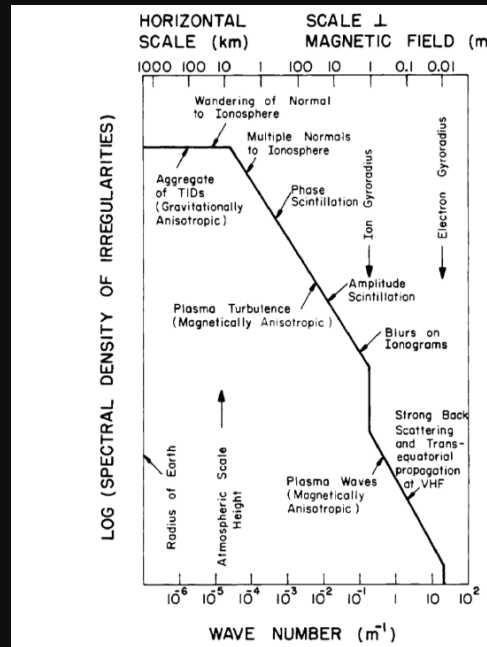
Themens et al., 2022



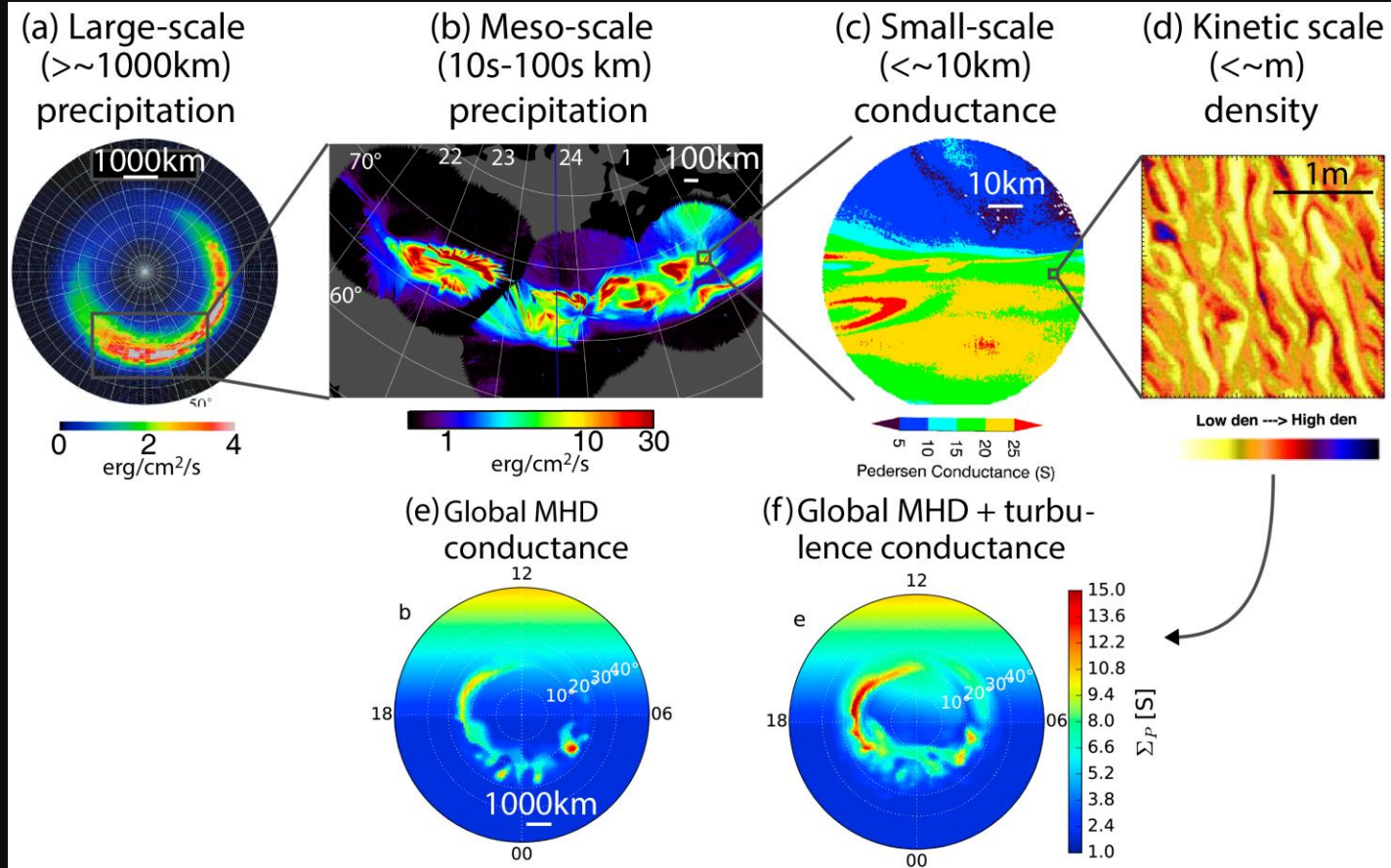
McCattrey and Jayachandran, 2019

Multi-scale ionosphere

- Temporal variations from “milliseconds” to solar cycle
- Spatial variations from cm to a few thousand km
- Scale-dependent effects on systems
- Power law behaviour?
- Energy transfer across scales



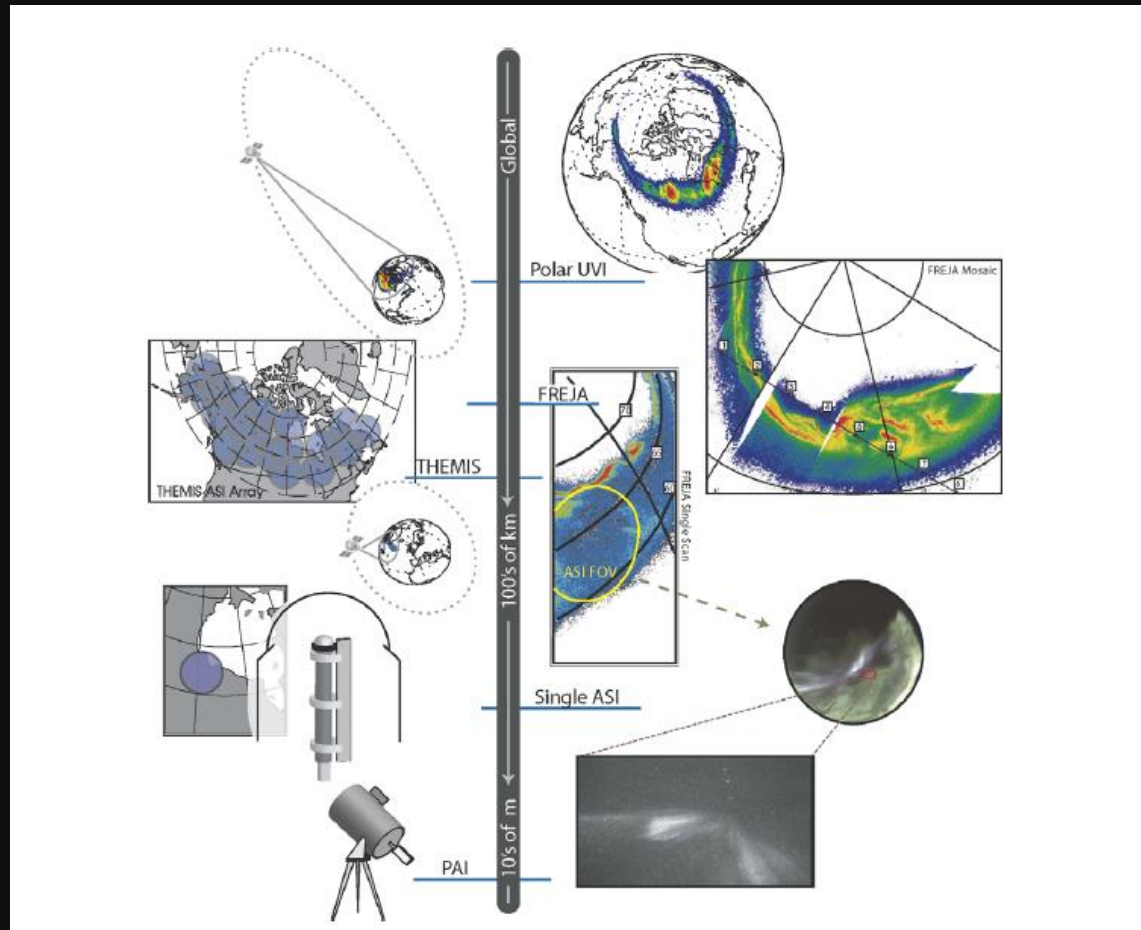
Multi-scale Ionosphere - Modeling and observations (hybrid approach)



Nishimura et al., 2018

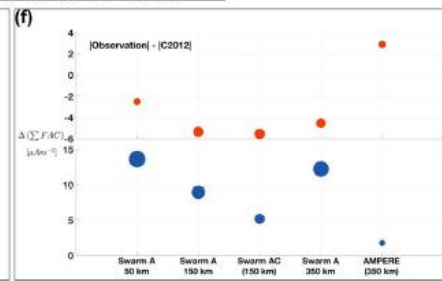
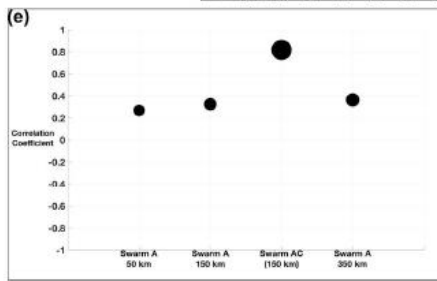
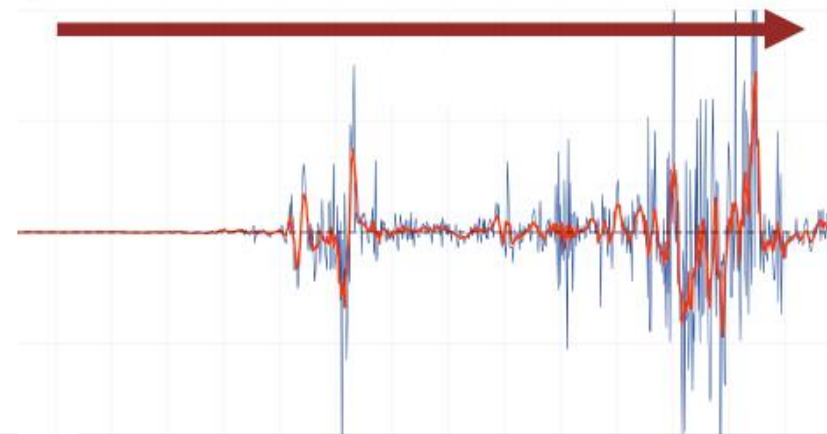
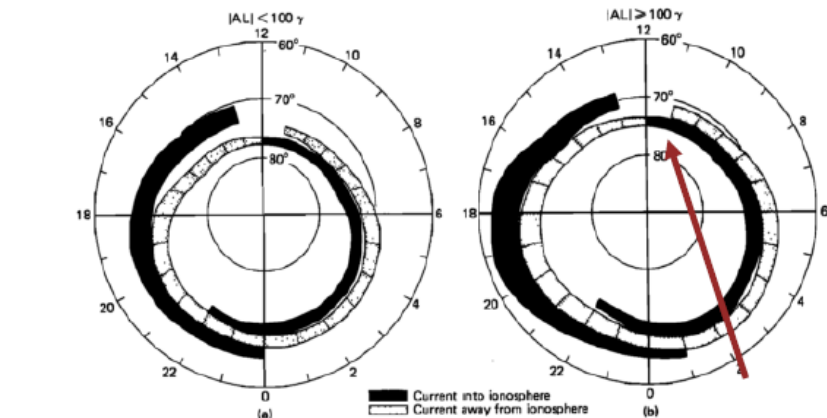
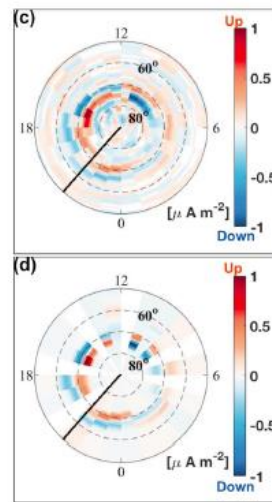
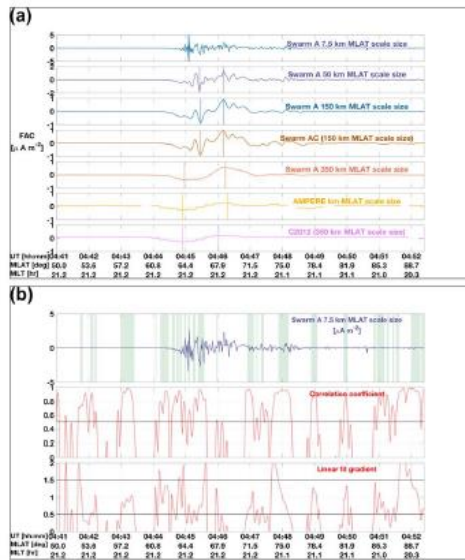
Multi-scale – Observations

Satellite and ground-based optical measurements



From Donovan et al., 2007

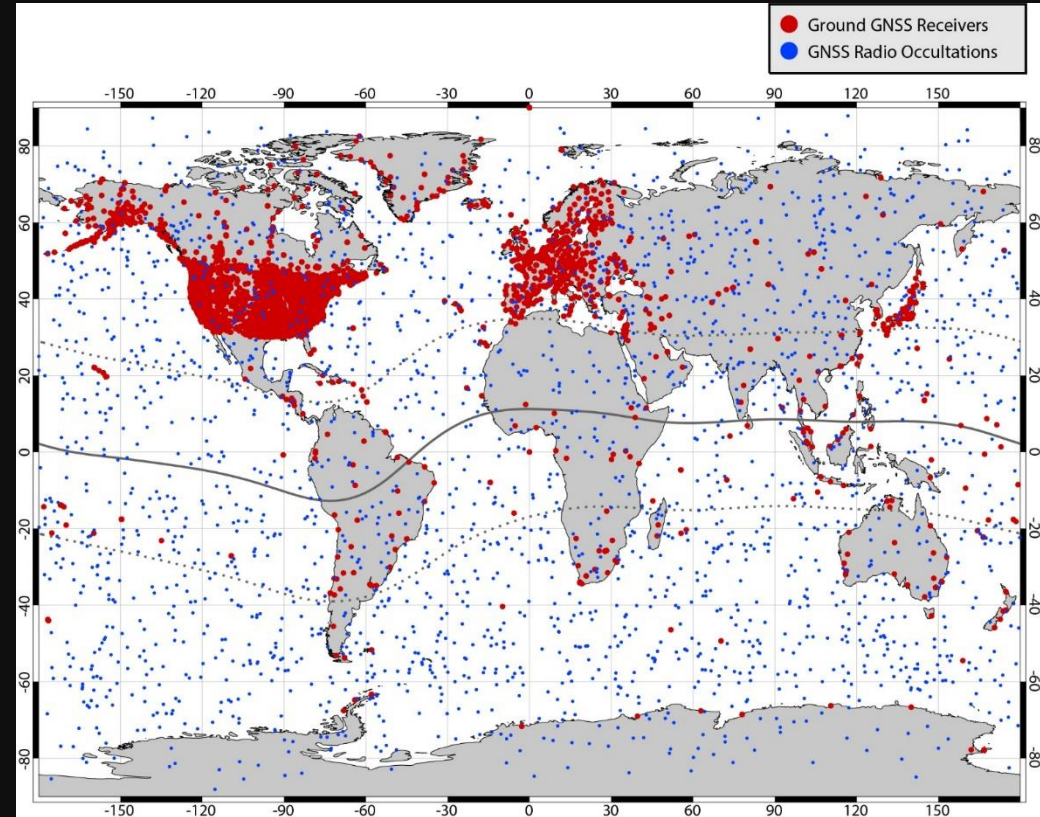
Magnetometer-based approach



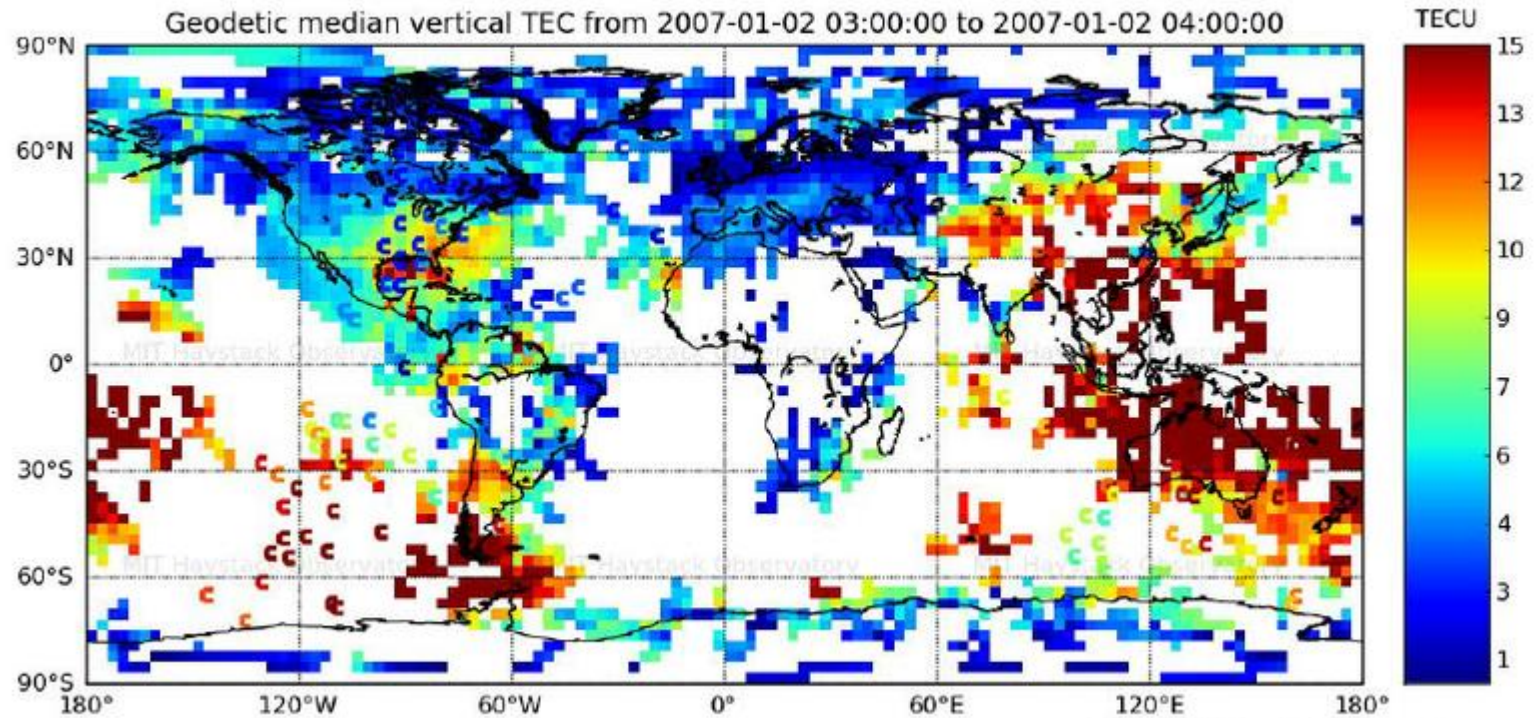
From McGranaghan et al., 2017

Global Navigation Satellite System (GNSS)

- A fast expanding global network of GNSS receivers
- Many satellites with RO and GNSS receivers
- Commercial aircraft with GNSS devices
- More than 2 billion GNSS-enabled devices by 2024

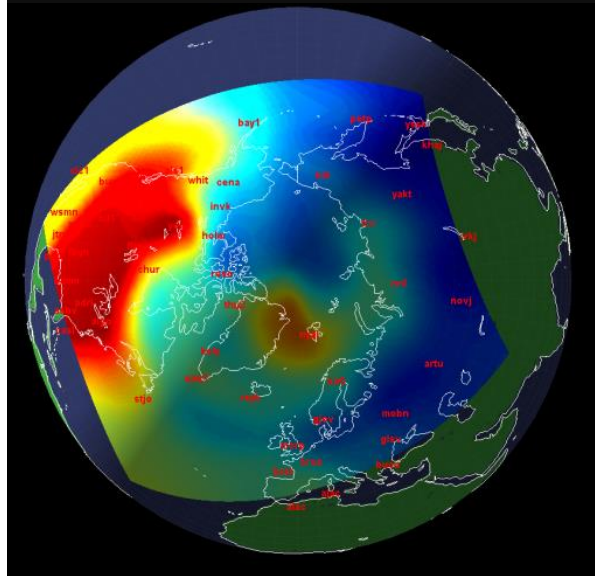
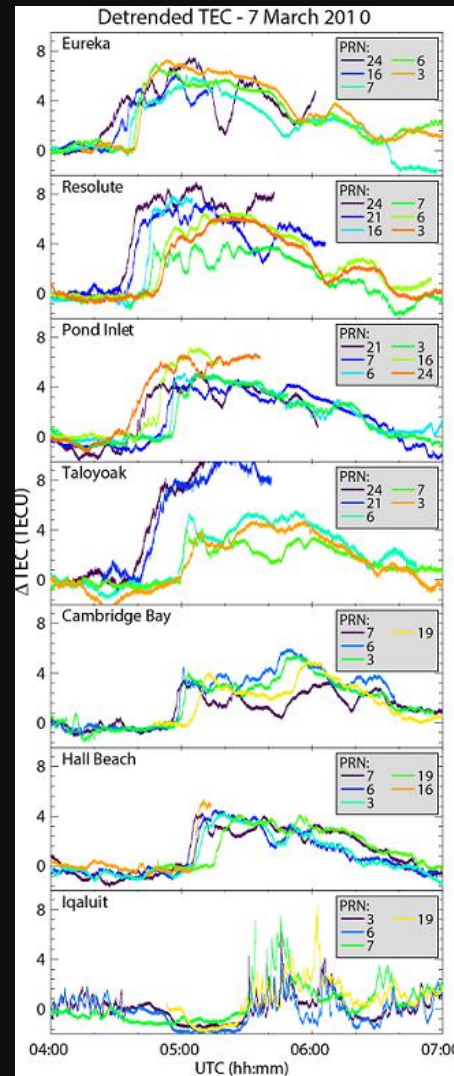
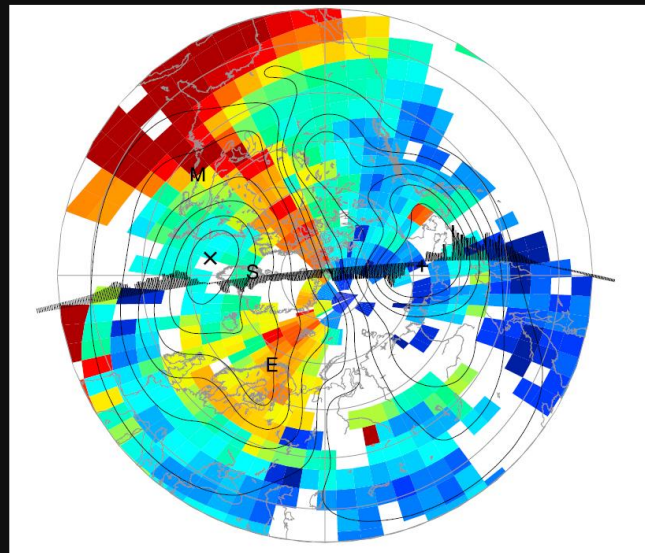
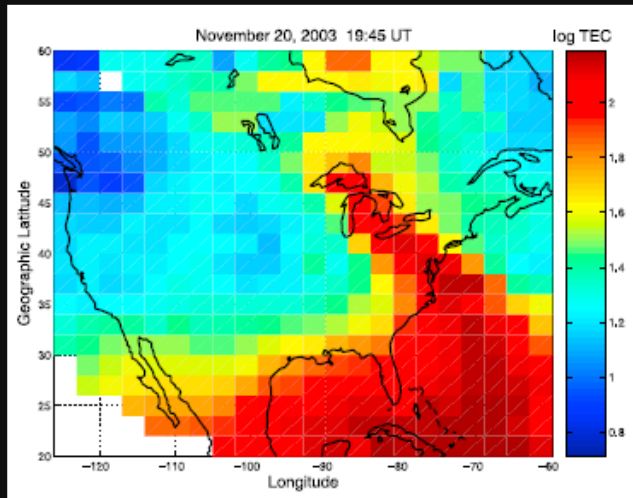


An example



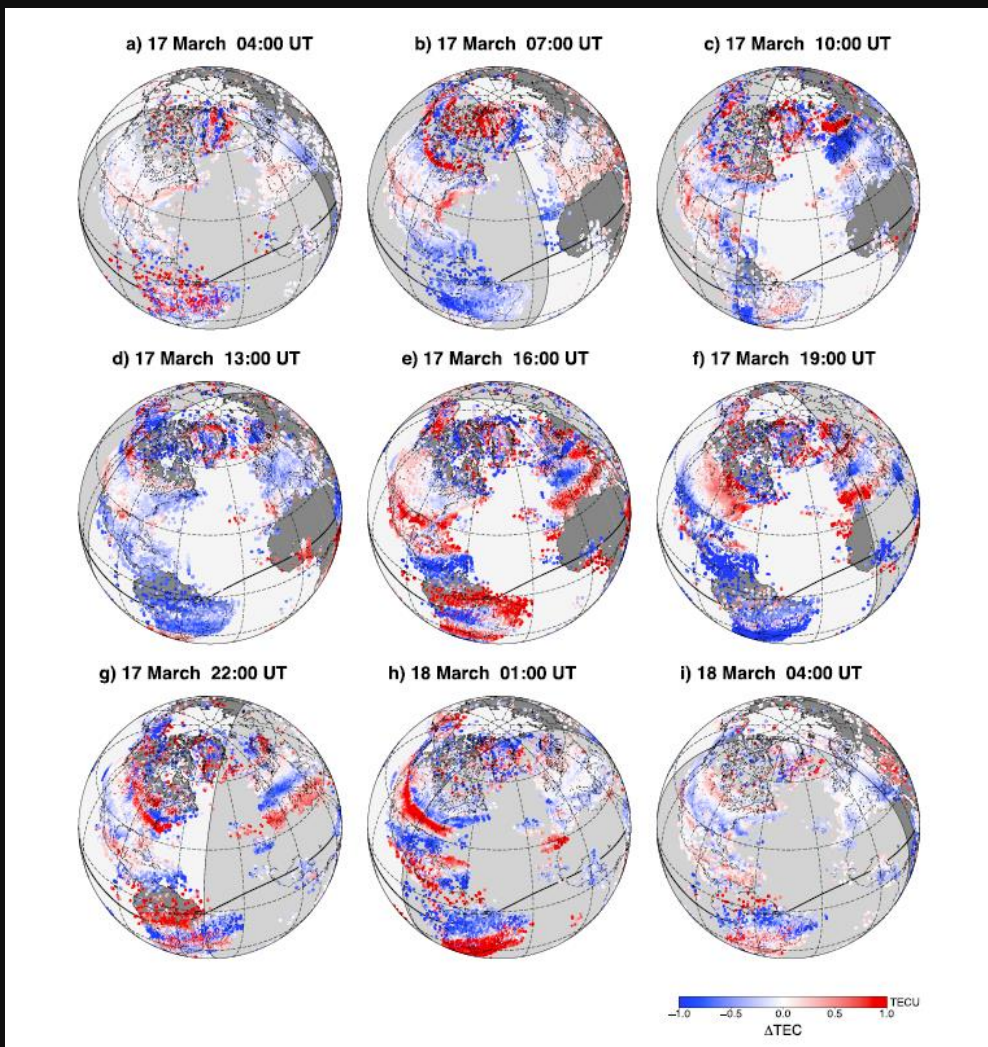
© 2008 MIT Haystack Observatory

Tongue of ionisation and patches

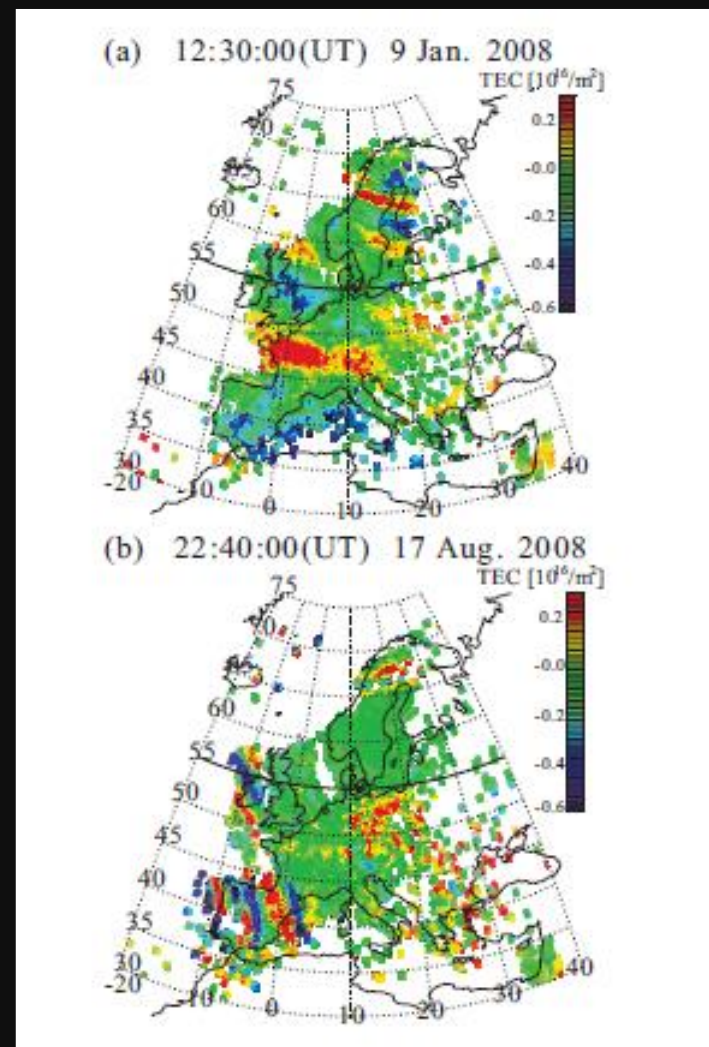


Foster et al., 2003

Jayachandran et al., 2019

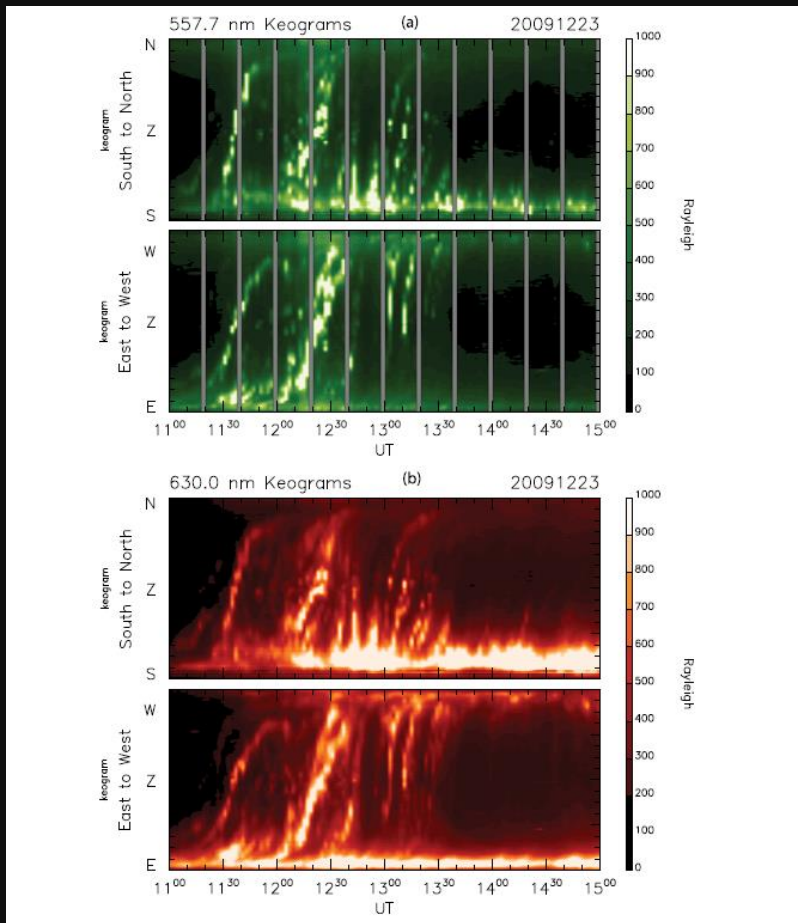
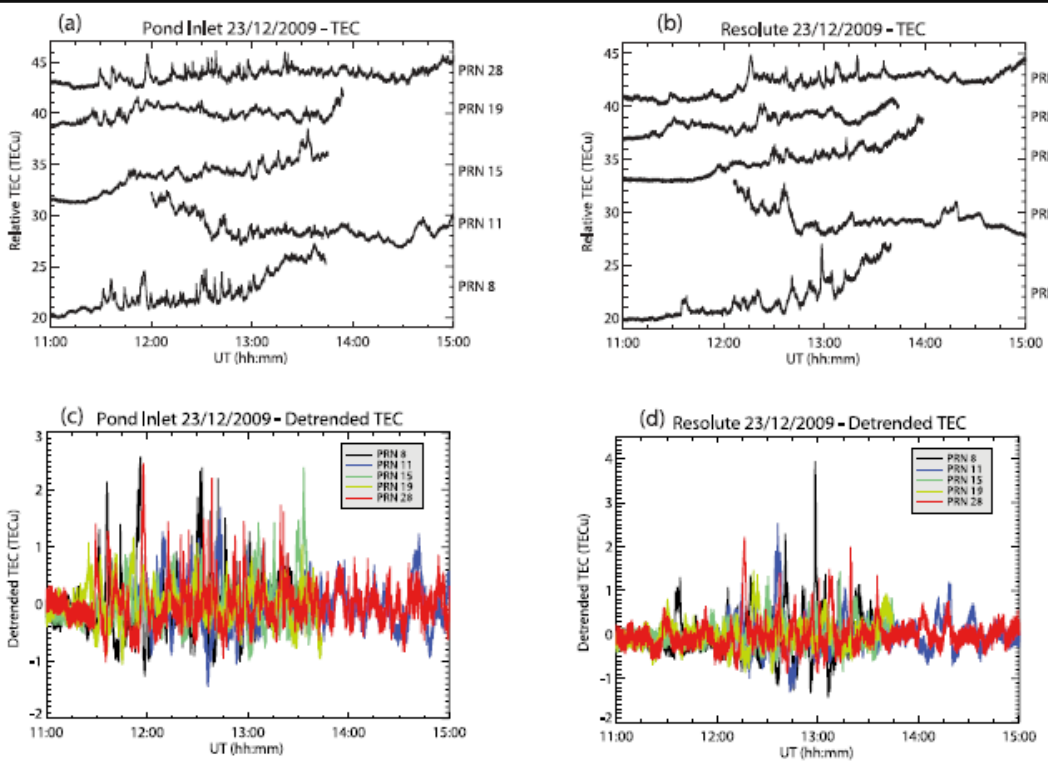


Zakharenkova et al., JGR, 2016



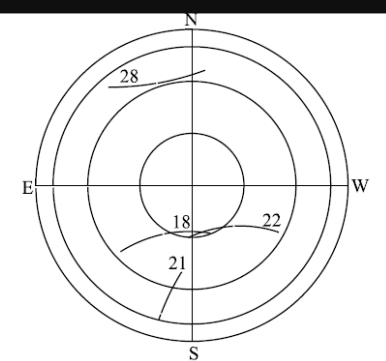
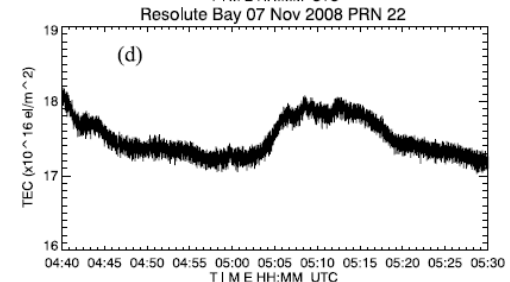
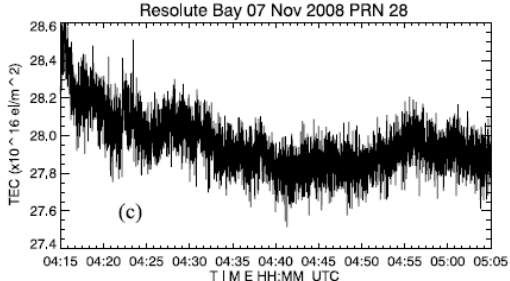
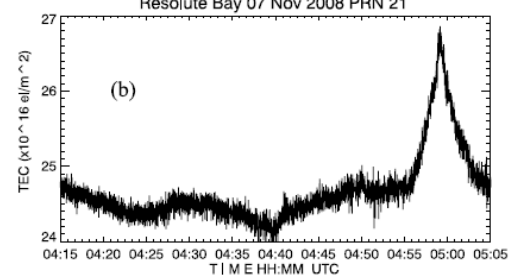
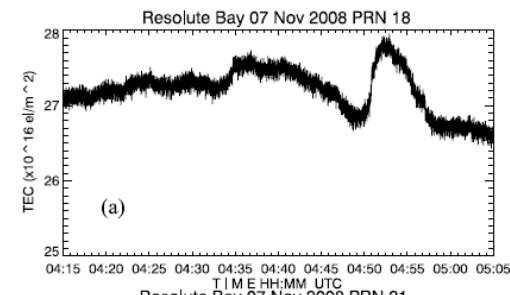
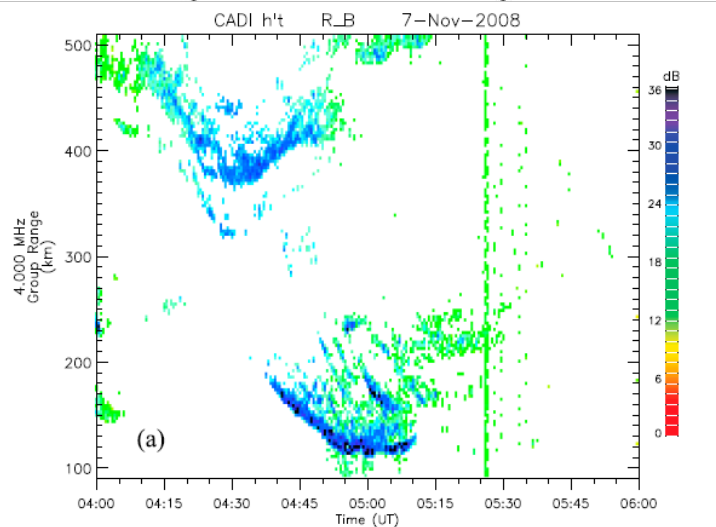
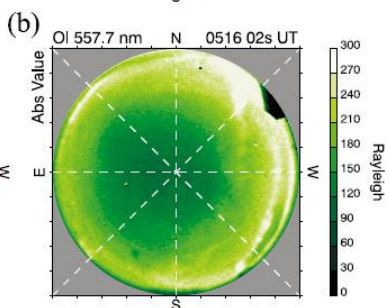
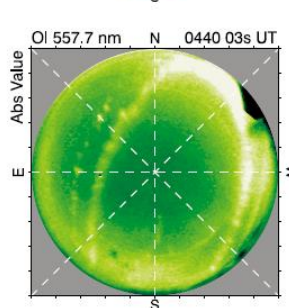
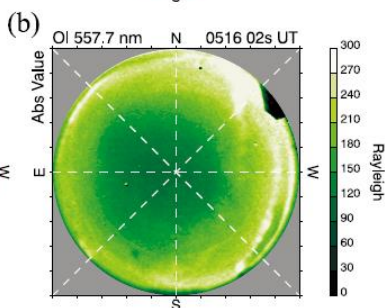
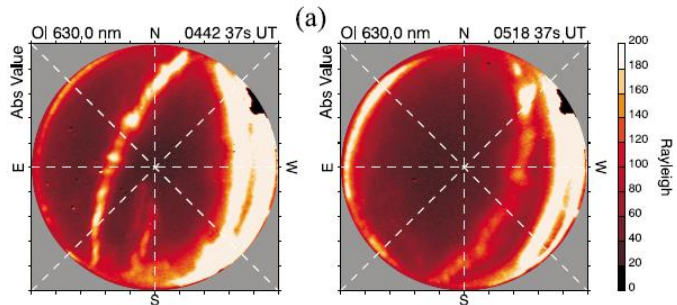
Otsuka et al., Ann. Geophys., 2013

Poleward moving auroral forms

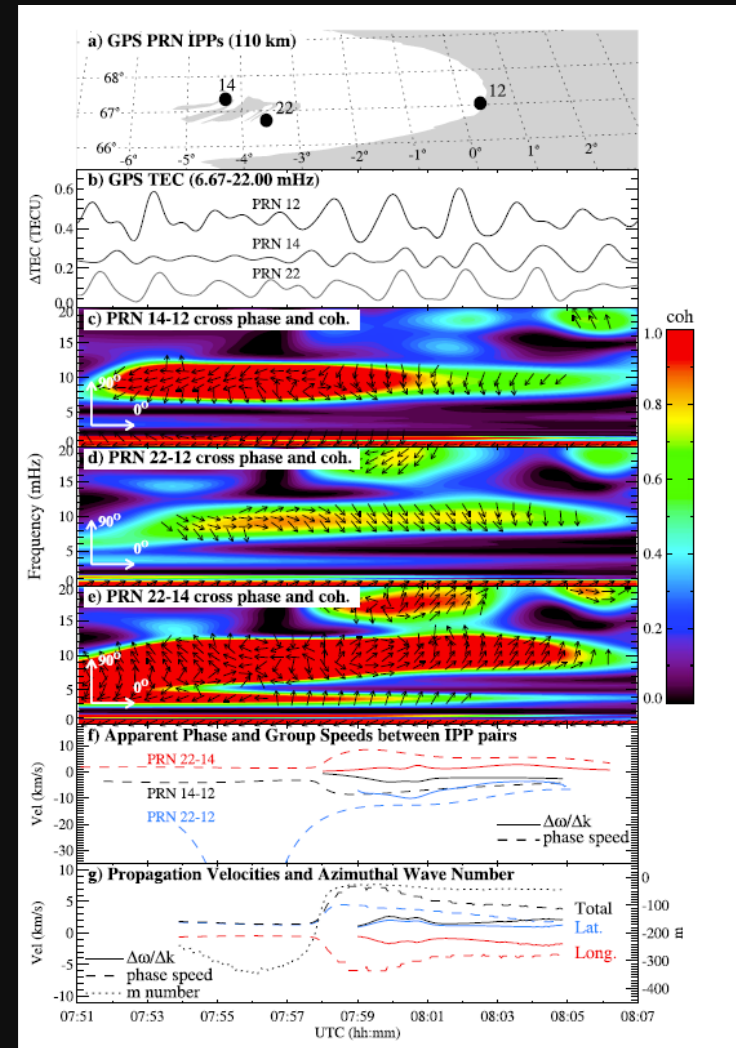
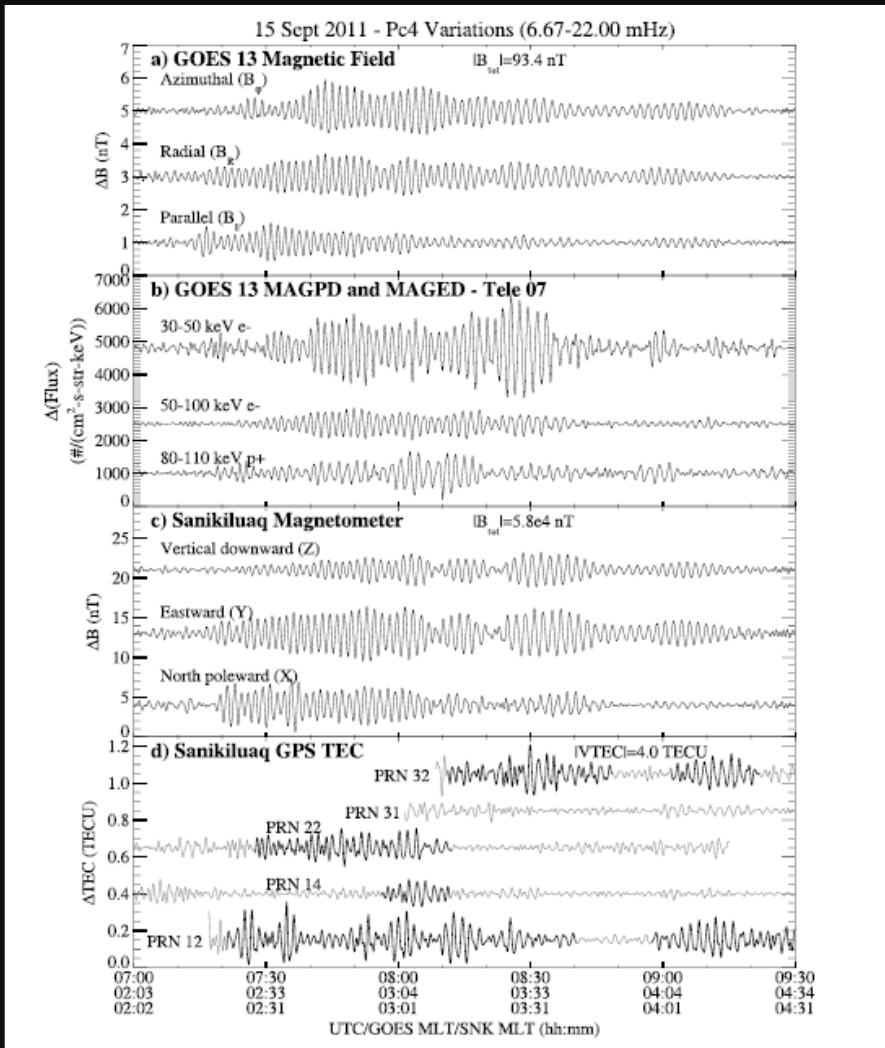


Jayachandran et al., 2012

Polar cap arcs

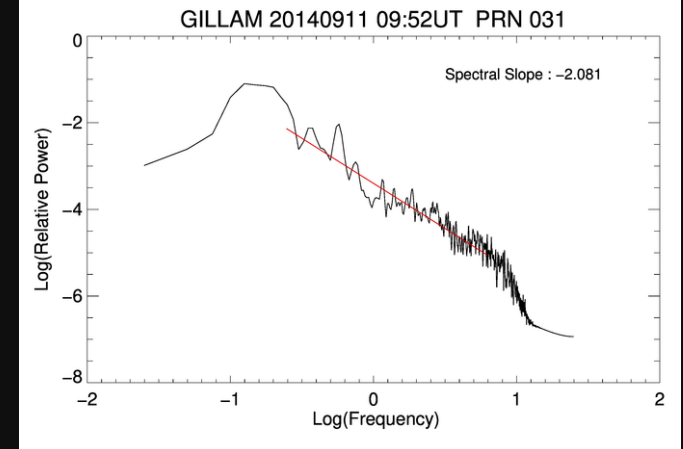
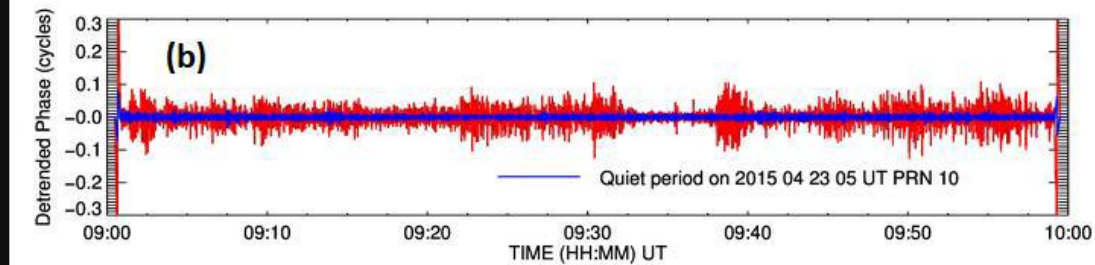
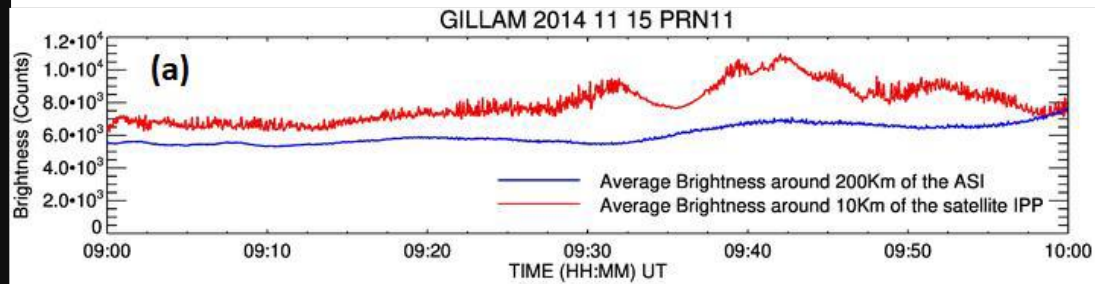
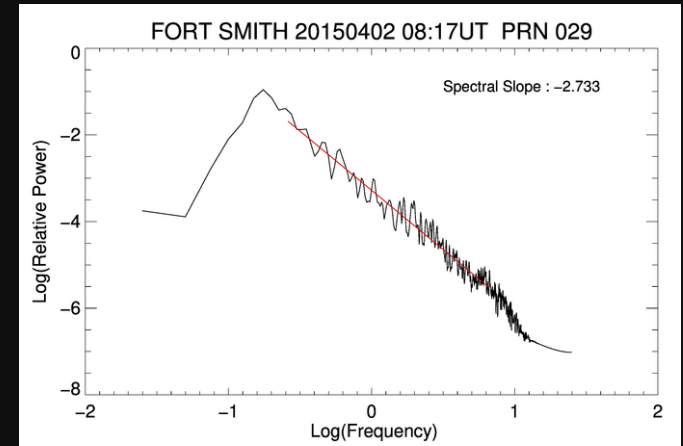
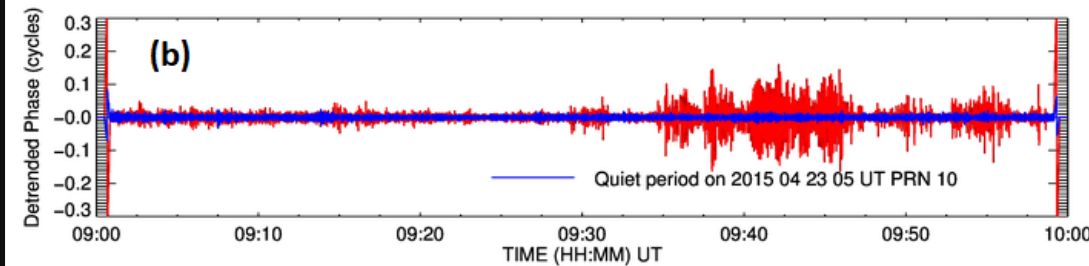
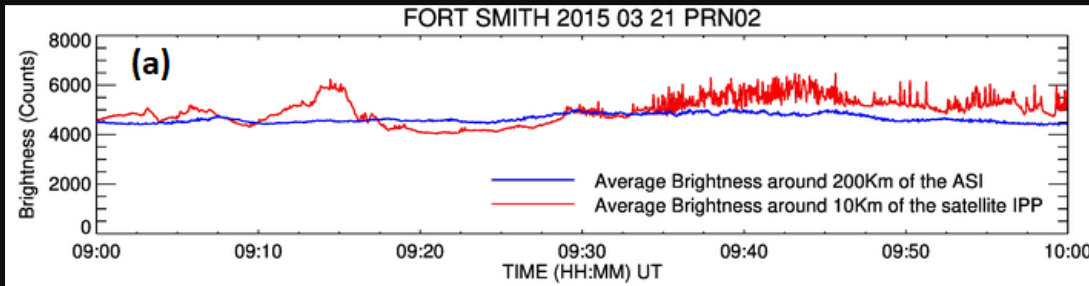


Pulsations



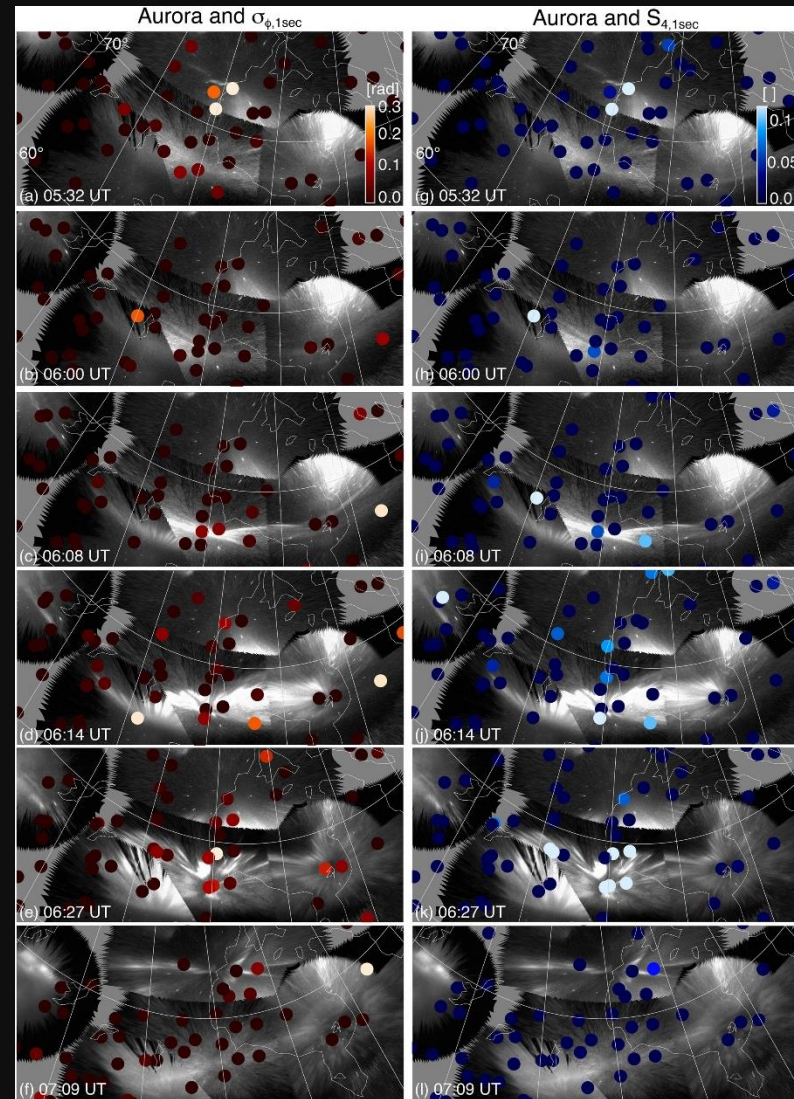
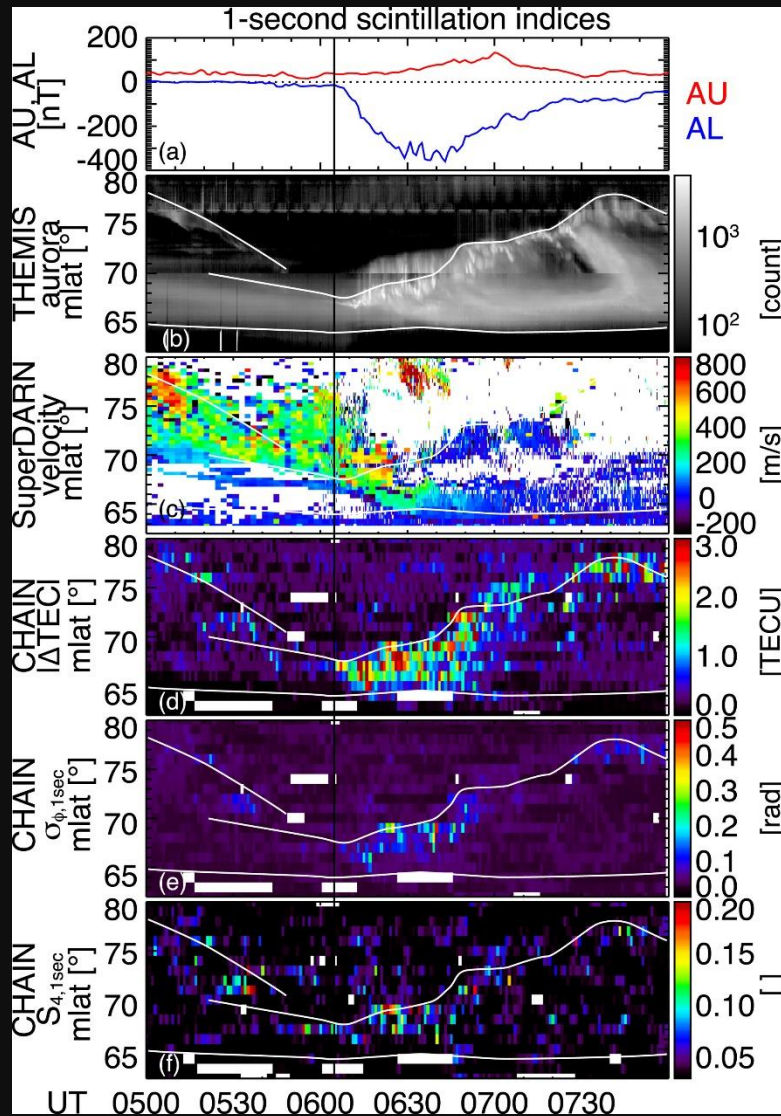
Watson et al., JGR, 2016

Patchy pulsating aurora



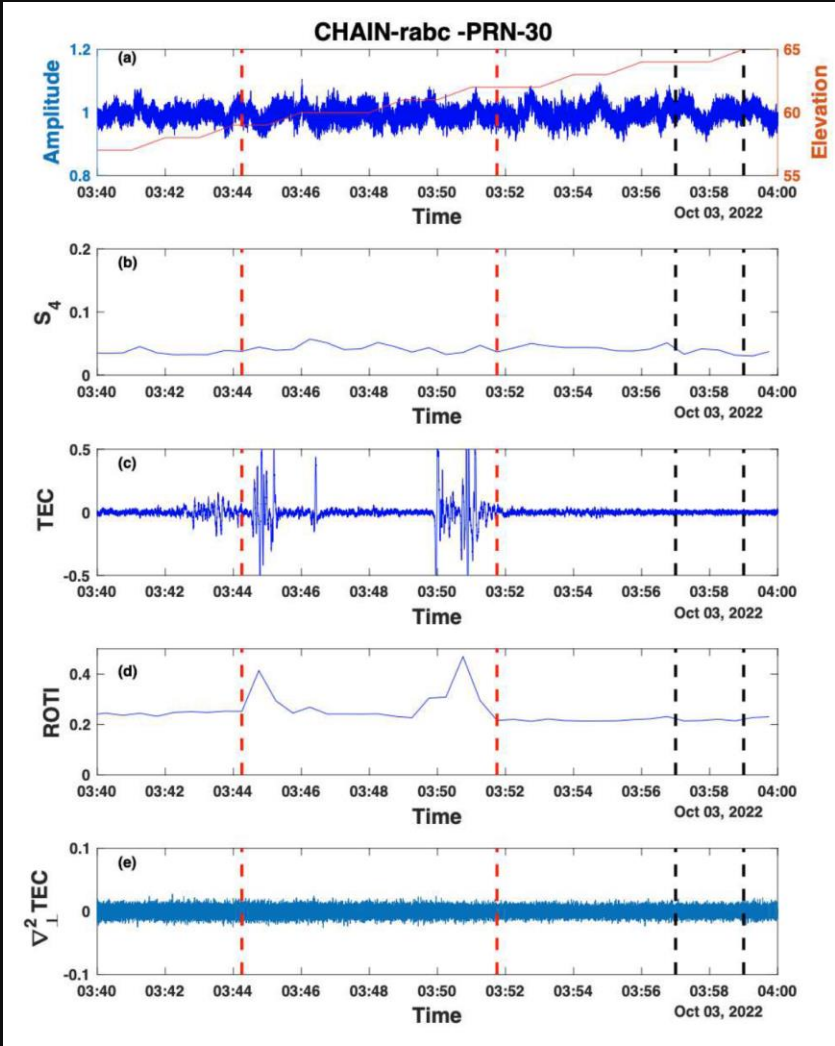
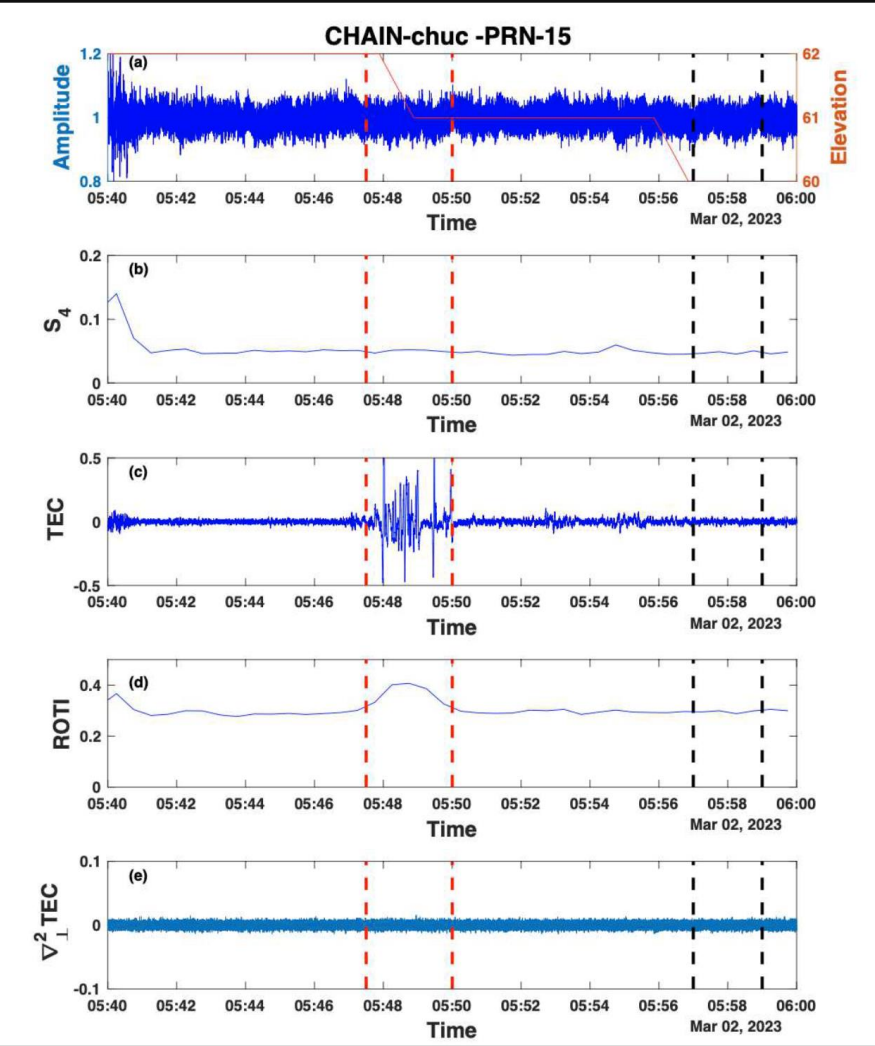
Mushini et al., 2024

Auroral substorms



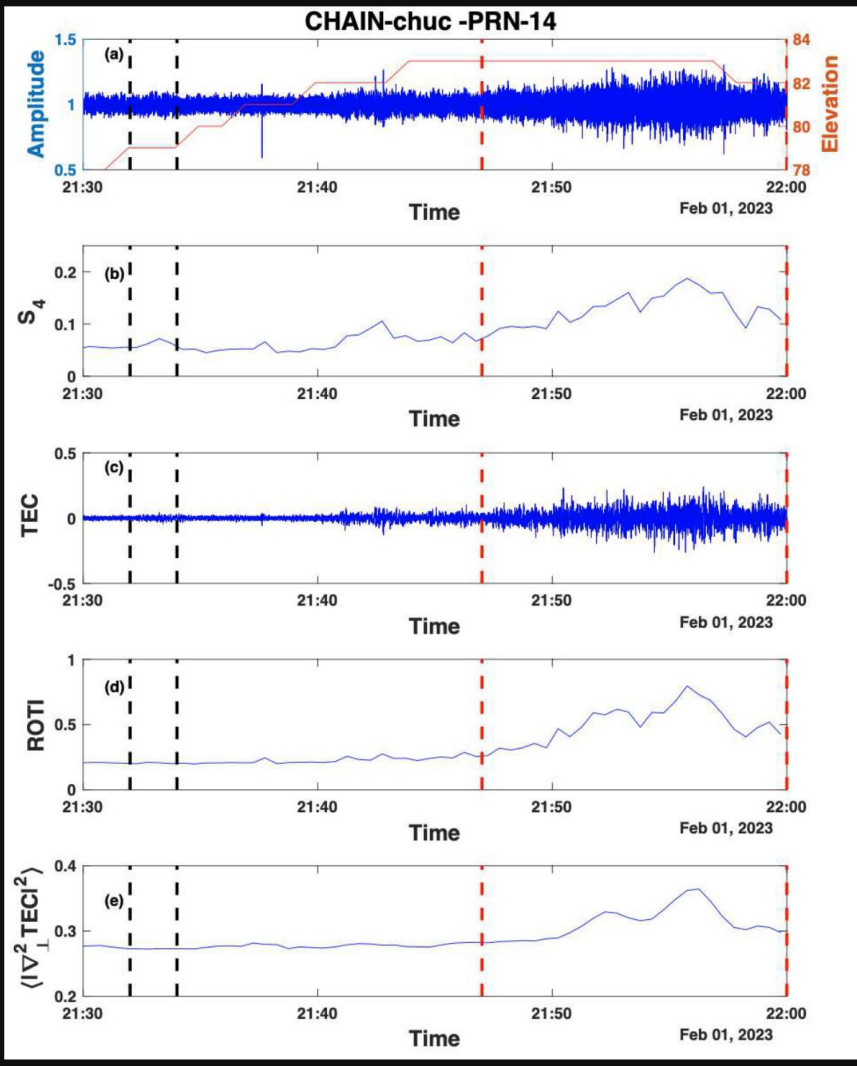
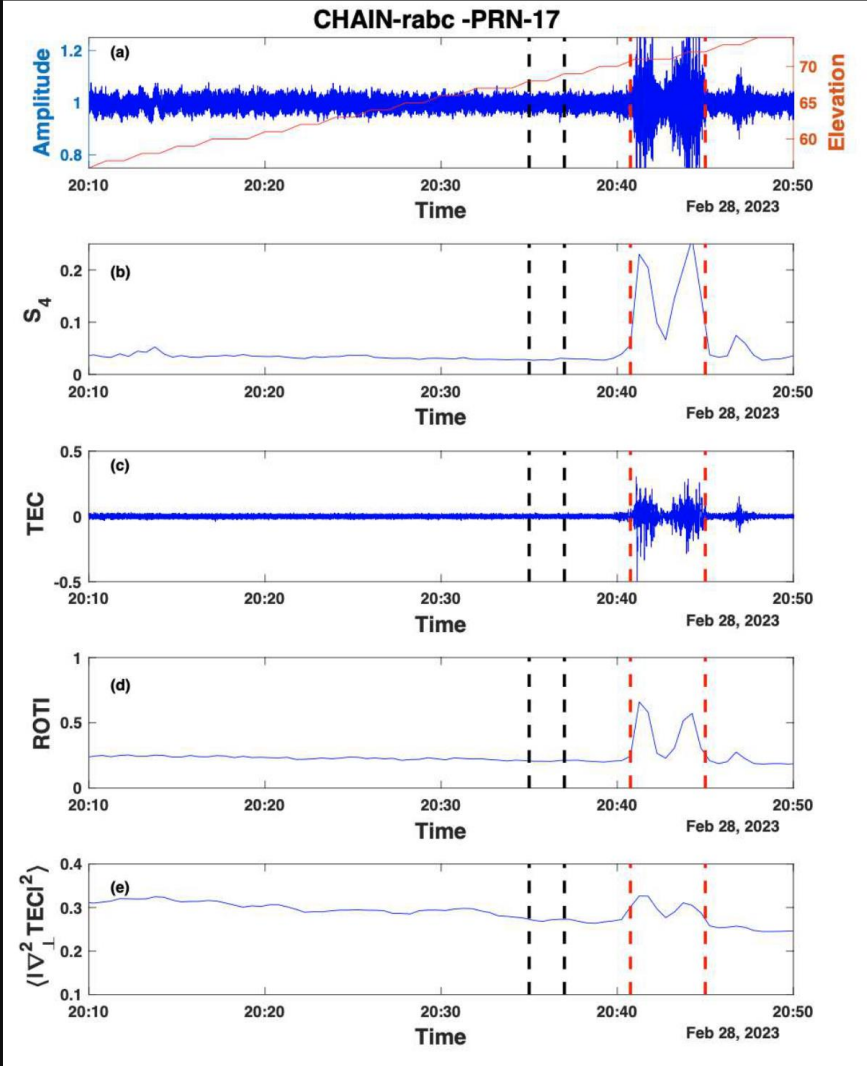
Nishimura et al., 2023

ROTI & Scintillation



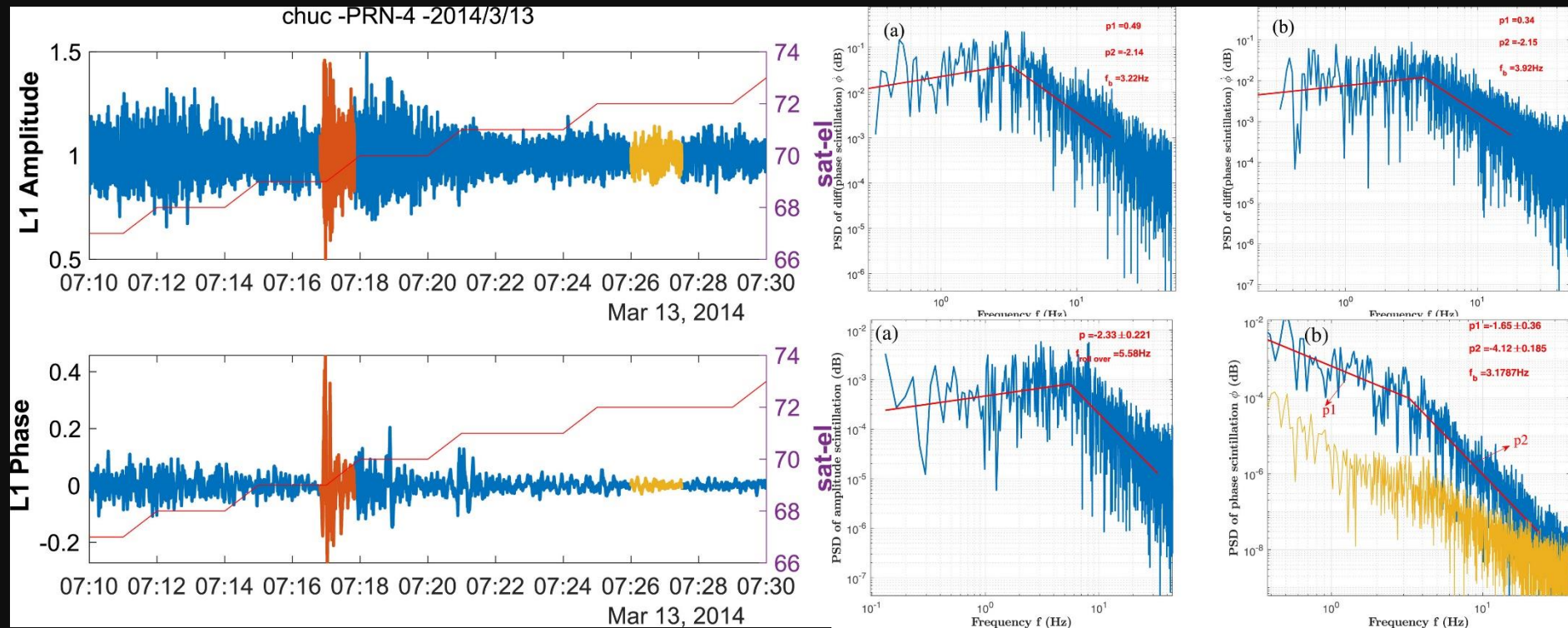
Meziane et al; 2024

ROTI & Scintillation



Meziane et al; 2024

Fresnel scale - Scintillation



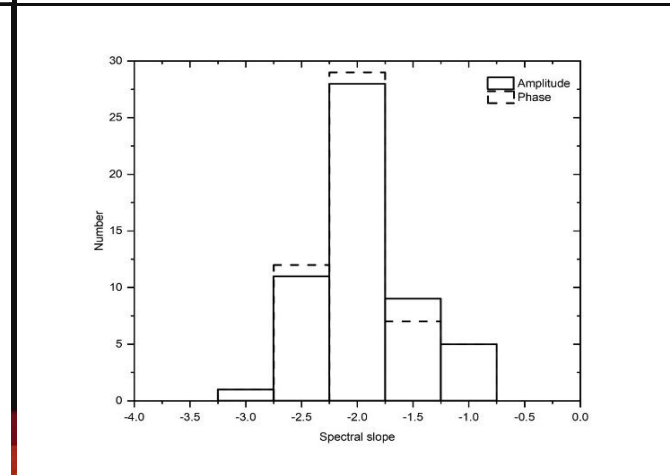
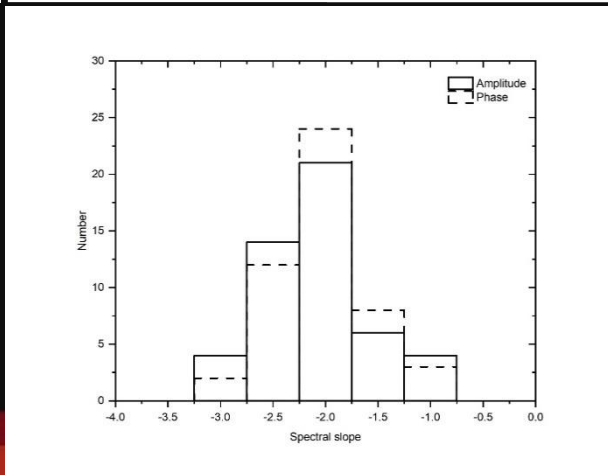
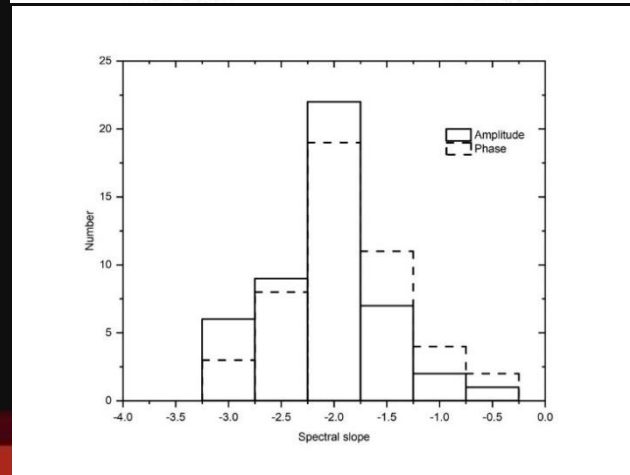
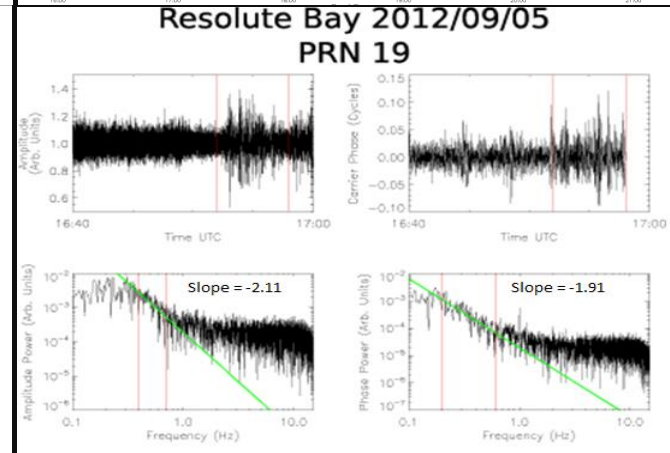
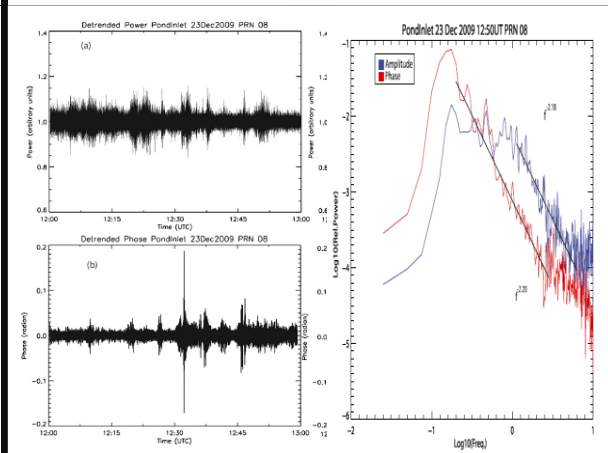
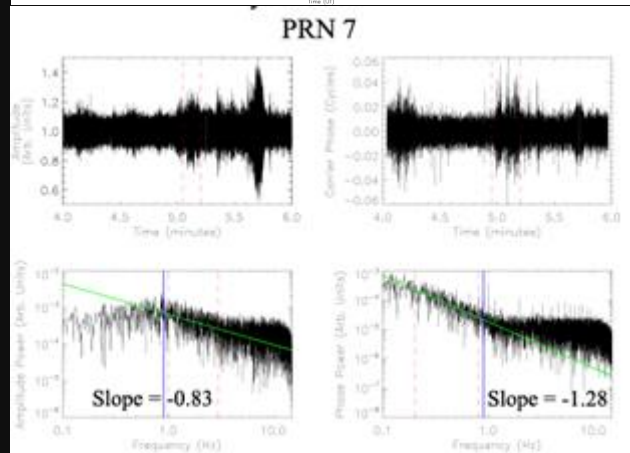
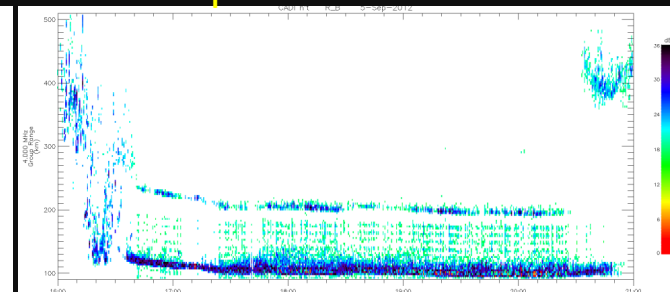
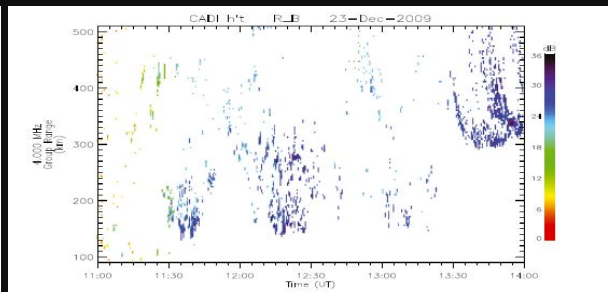
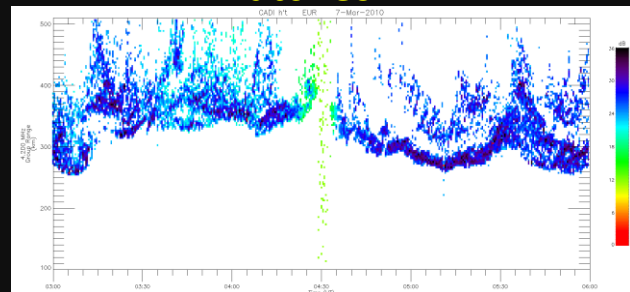
Hamza et al., 2023

Different types of irregularities

Patches

Arcs

Sporadic E



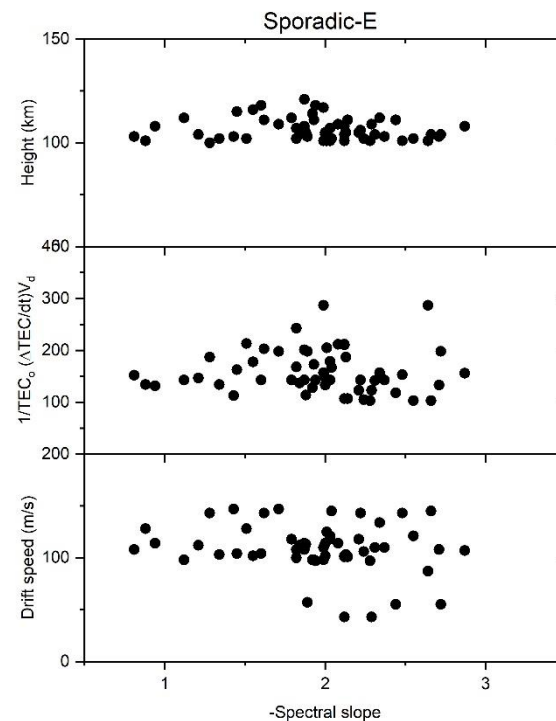
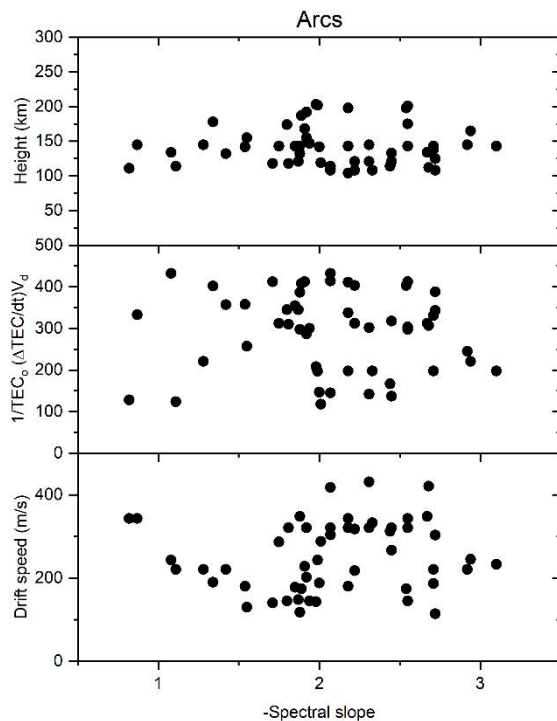
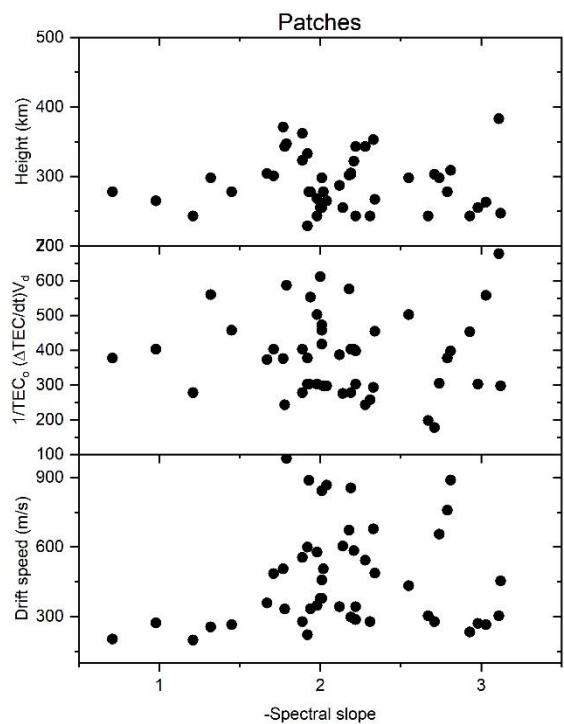
Spectral properties

- GNSS signal spectra of scintillations associated with polar cap arcs, patches, Sporadic E layers, and auroral forms show similar spectral characteristics
- Distribution of spectral index shows more or less similar distribution for polar cap arcs, patches, and sporadic E layers with an average spectral slope of -2
- What does this tell us about the irregularity mechanism?

Does the spectral slope depend on any ionospheric/irregularity parameter?

- V_d (magnitude of $\mathbf{E} \times \mathbf{B}$ drift) – A measure of the electric field
- Height of the ionosphere - a proxy for collision frequencies
- $\frac{1}{TEC_o} \frac{\Delta TEC}{\Delta t} V_d$ – A measure of gradient scale length

No obvious dependence!



Is slope just a dimensionality parameter?

Extending to meter scales

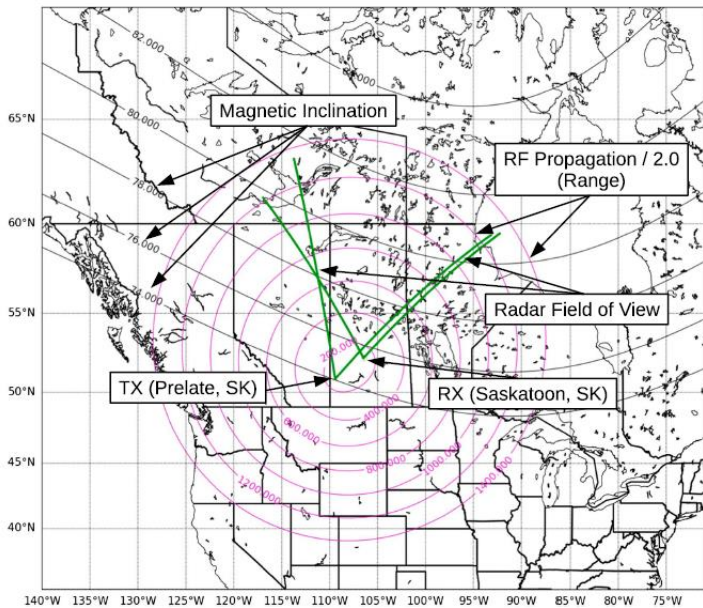
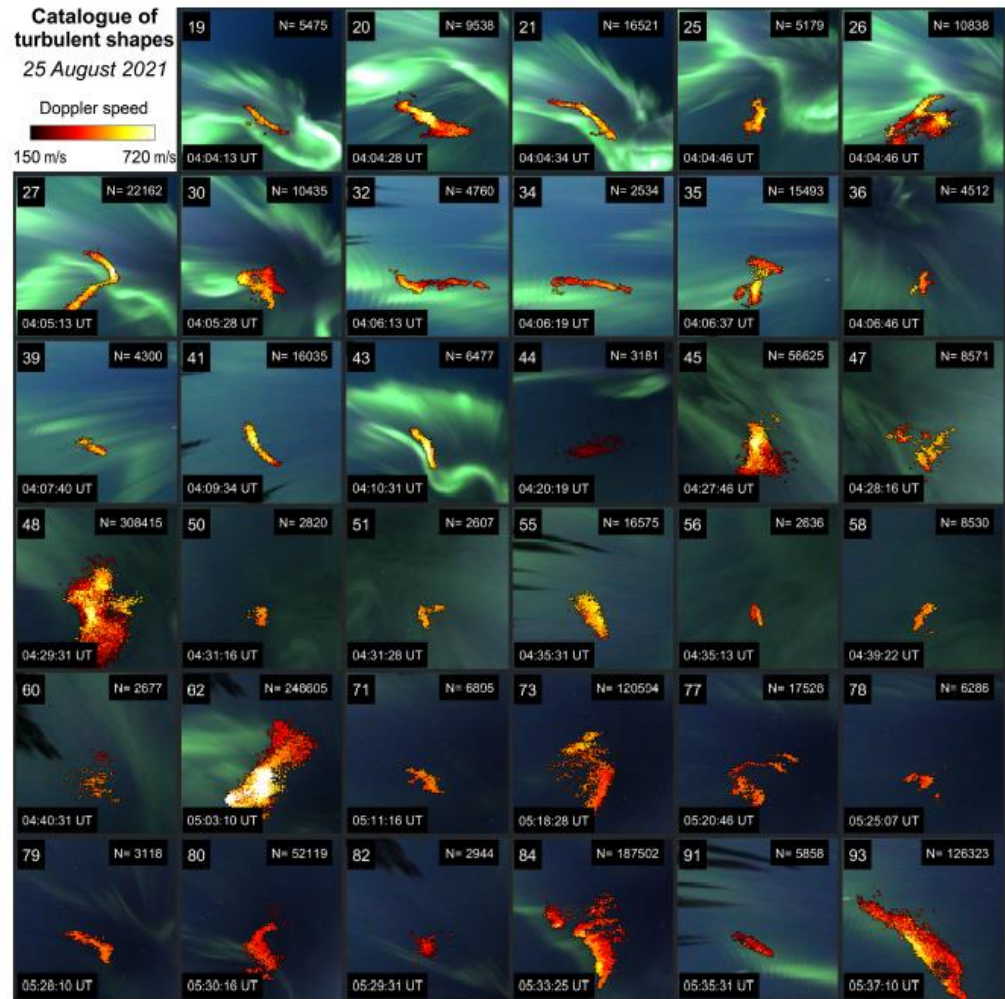


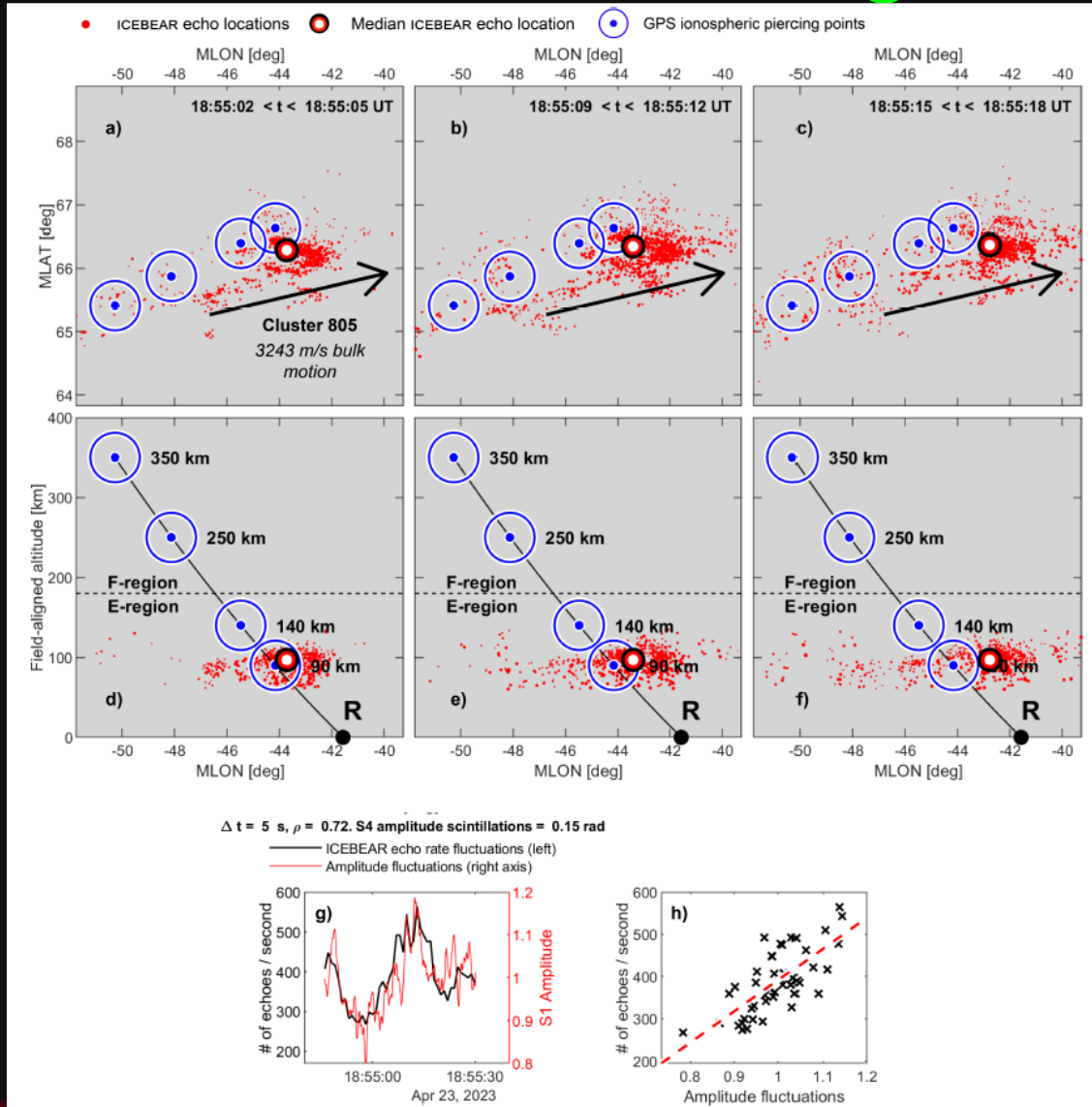
Figure 1. The locations and fields of view of the transmitter and receiver sites for the ICEBEAR radar. A zoomed-in version of this figure, with ionospheric scatter and the aspect angle at an altitude of 100 km, is shown later in Figure 7. ICEBEAR = Ionospheric Continuous-wave E-region Bi-static Experimental Auroral Radar.

Huyghebaert et al., 2018



Ivarsen et al., 2024

Extending to meter scales



Ivarsen et al., 2024

Irregularity Scales

