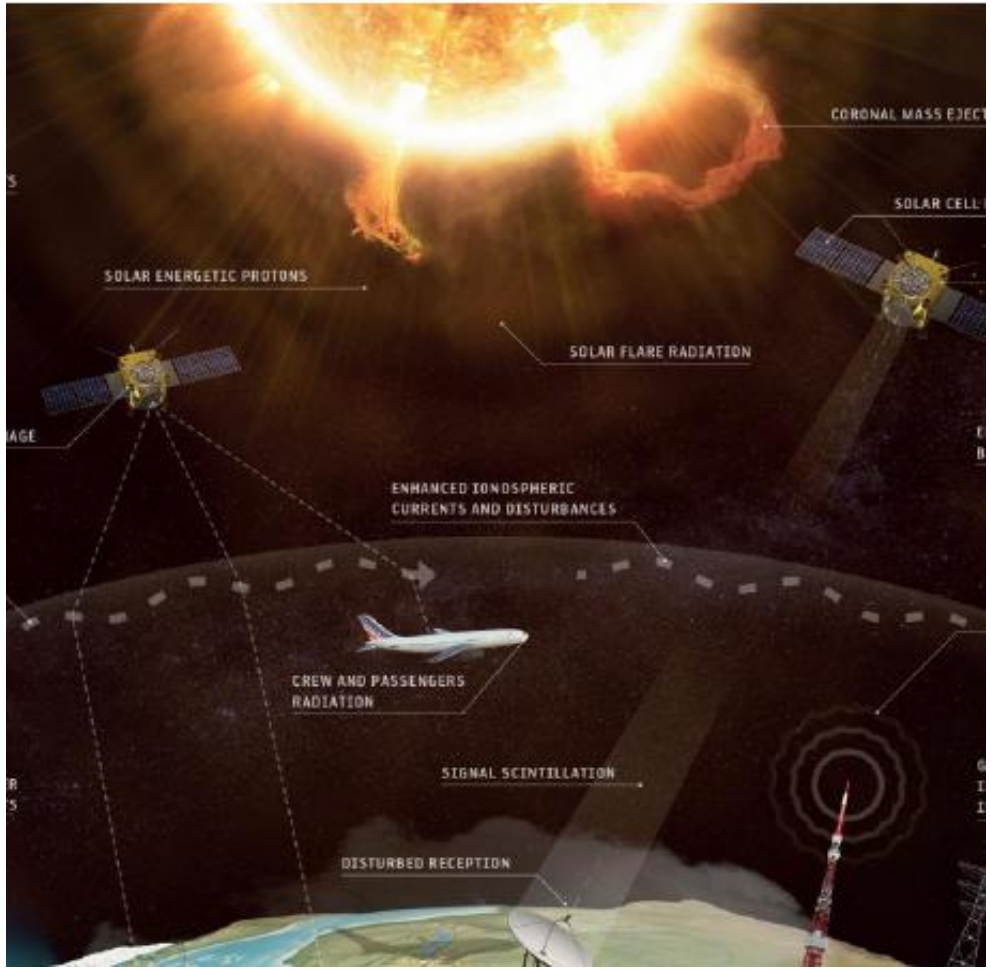
DISPEC TRAINING SCHOOL

Ionospheric disturbances and irregularities



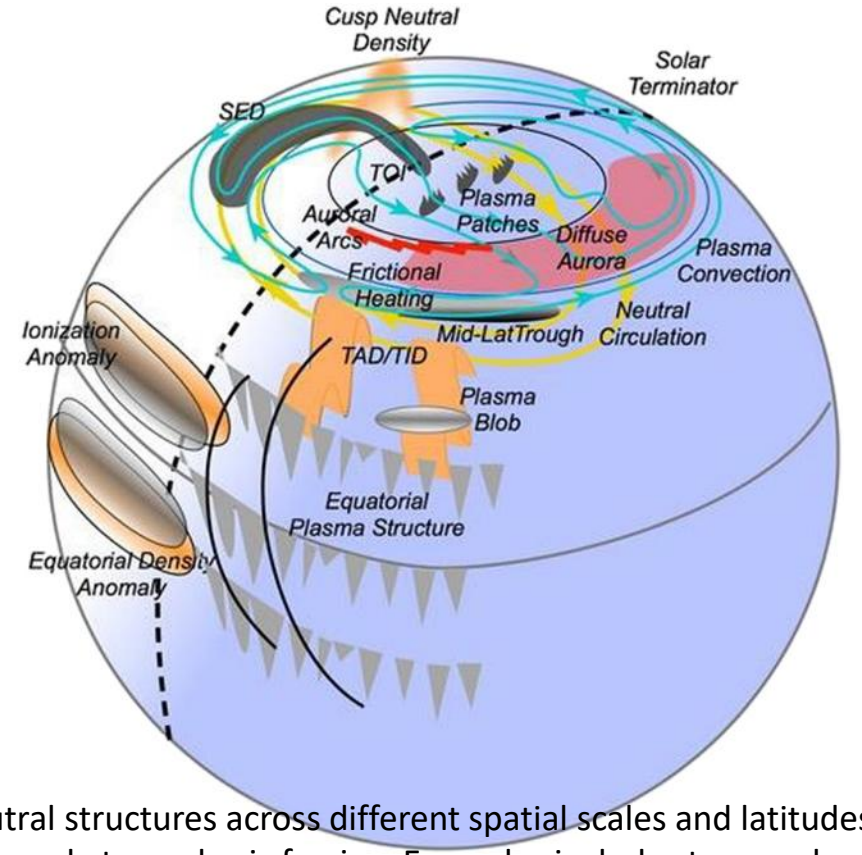
Anna Belehaki (1) and Manuel Hernandez-Pajares (2)
(1) Ionospheric Group, IAASARS, National Observatory of Athens, Greece
(2) UPC-IonSAT Research Group, IGS Associate Analysis Center, Spain

After the introductory questions, this lecture explains

01	**Drivers**	How solar, magnetospheric, and atmospheric forcing changes the ionosphere
02	**Responses**	How winds, electric fields, chemistry, and plasma transport interact
03	**Phenomena**	How weather evolves into TIDs, Spread-F, and plasma bubbles
04	**Impacts**	Why these changes matter for GNSS, HF radio, satellites, and forecasting

The ionosphere and thermosphere form one coupled system

Schematic representation of the coupled ionosphere–thermosphere (I–T) system



Plasma and neutral structures across different spatial scales and latitudes and their coupling to magnetospheric and atmospheric forcing. Examples include storm-enhanced density (SED), the midlatitude trough, plasma patches, the Equatorial Ionization Anomaly (EIA), and smaller-scale plasma irregularities. (After Heelis and Maute, 2020)

The I-T system

- Ions, electrons, and neutral particles share the same region
- Collisions exchange momentum and energy
- Electric and magnetic fields redistribute plasma
- Disturbances can propagate across regions and scales

Two pathways shape the ionosphere

Forcing from above

Solar EUV and X-rays

Solar wind and magnetic reconnection

Electric fields, currents, and particle precipitation

Geomagnetic storms

Forcing from below

Gravity waves

Atmospheric tides

Planetary waves

Weather, convection, mountains, and large-scale circulation

The observed ionosphere is the result of both pathways — acting at the same time.

PART 1

Forcing from above

Solar radiation creates the ionosphere; solar-wind energy reorganizes it.

Different wavelengths ionize different altitude regions

F region	150–500+ km	**EUV**	Highest TEC; GNSS signals traverse it
E region	90–150 km	**Soft X-rays + UV**	Conductivity, dynamo, electrojet
D region	60–90 km	**Hard + soft X-rays**	HF absorption and radio blackouts

Ionization depends on solar zenith angle, local time, season, and solar activity.

Solar forcing repeats across three characteristic timescales

Minutes

Solar flares

Sudden ionization

~27 days

Solar rotation

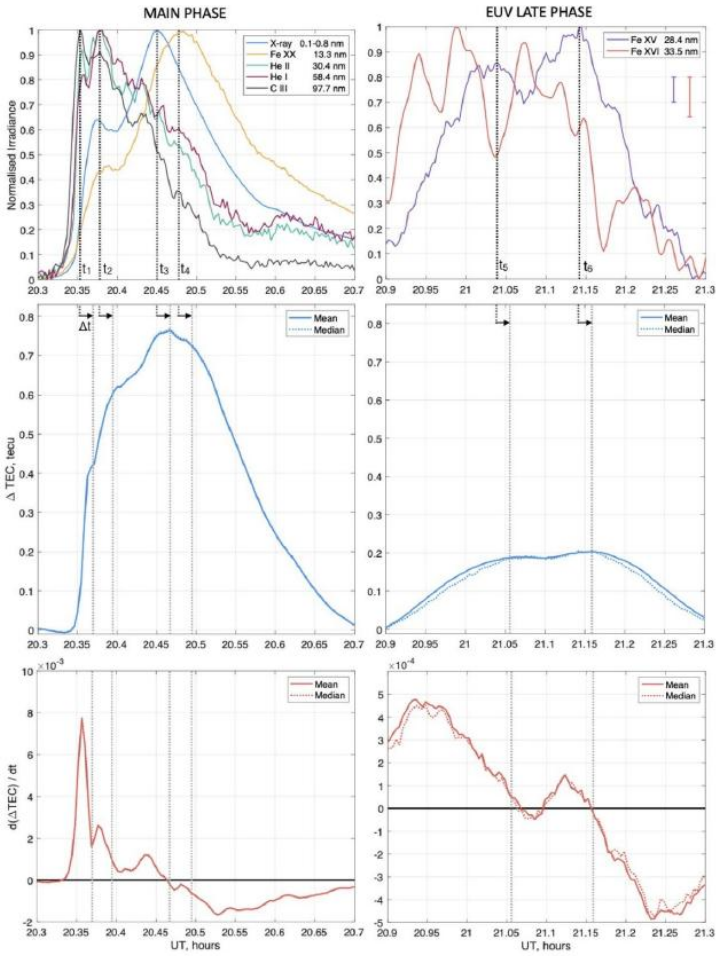
Recurrent active regions and HSS/CIRs

~11 years

Solar cycle

Large change in background electron content

A solar flare changes the dayside ionosphere within minutes

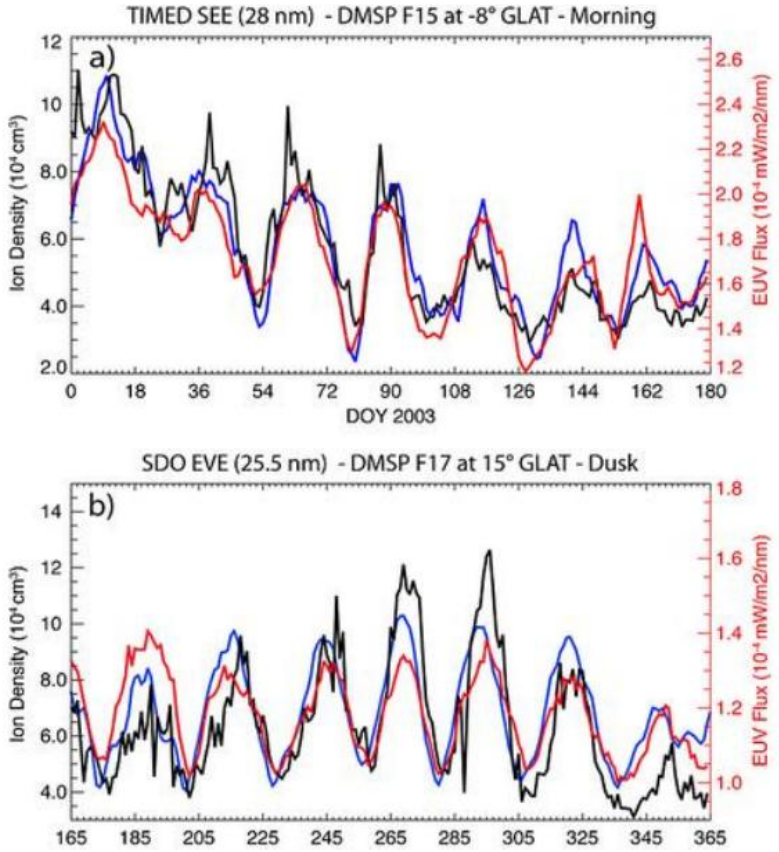


Cause → response → impact

- X-ray and EUV output rises suddenly
- Photoionization increases by altitude
- Conductivity and TEC change
- D-region absorption causes HF fadeouts
- TEC gradients and radio bursts degrade GNSS

Electromagnetic radiation reaches Earth in about 8 minutes.

Solar rotation produces recurrent ionospheric variability



Two pathways

1 Radiation

Active regions rotate into view, changing EUV and X-ray ionization. Electron density may peak 1–2 days later because the coupled atmosphere responds more slowly.

2 Solar wind

Coronal holes generate high-speed streams and CIRs, producing recurrent geomagnetic activity and plasma redistribution.

The 11-year cycle shifts the background state of the ionosphere

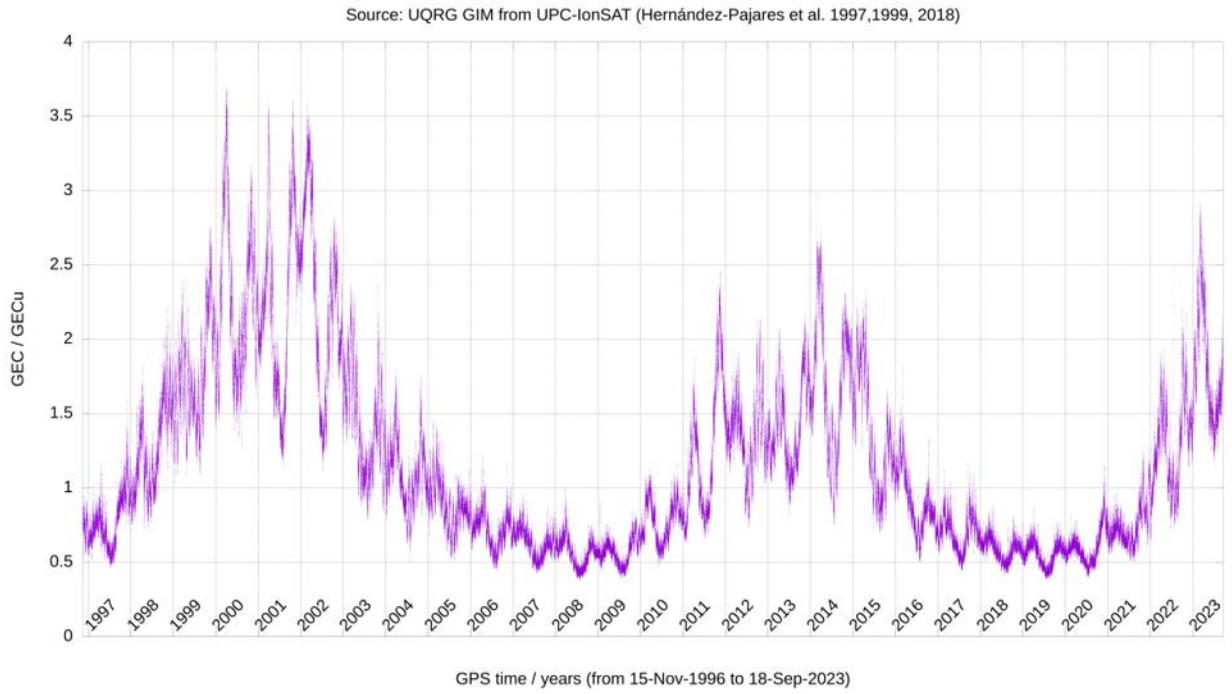


Figure 4b: Global Electron Content computed from UQRG UPC-IonSAT Global Ionospheric Maps of VTEC performed since end of 1996, showing up the solar cycle and other characteristics electron content periods (extracted from Aroca-Farrerons et al. 2024).

At solar maximum

- Higher EUV/X-ray output
- More ionization and TEC
- Expanded thermosphere
- More disturbances and scintillation

At solar minimum

- Lower electron density
- Weaker HF support at high frequencies
- Reduced thermospheric density

Magnetic reconnection opens the energy-transfer pathway

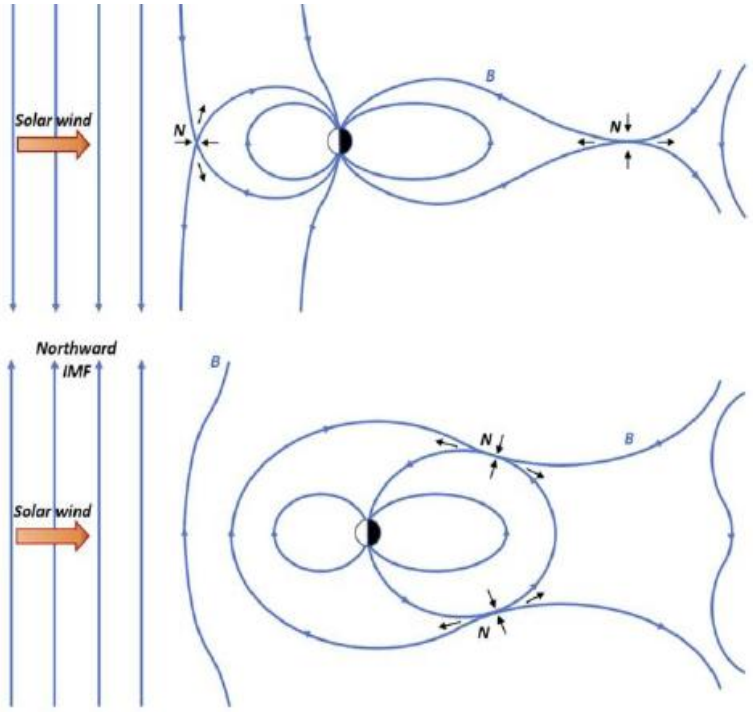


Figure 5. Early 2D representations of reconnection between the magnetic fields (blue traces) of the solar wind and the Earth's magnetosphere, as first described by Dungey (1961, 1963). Top: A pure southward IMF condition, showing magnetic reconnection occurring at null points (N) in the subsolar region and within the magnetotail, with associated magnetic field motion and plasma inflow and outflow (represented by black arrows). Bottom: An instance of pure northward IMF, showing magnetic reconnection at high latitudes just downstream of the Earth. Adapted from Russell (2000)

Solar wind → magnetosphere → high-latitude ionosphere

- Reconnection transfers solar-wind energy
- Electric fields map into the ionosphere
- Field-aligned currents close through the conducting plasma
- Auroral precipitation adds ionization
- Convection and heating spread the response

Joule heating reorganizes the thermosphere and ionosphere

$$QJ = J \cdot E$$

Current flowing through a partially conducting medium converts electromagnetic energy into heat.

Heat	Gas expands; neutral temperature and satellite drag rise
Composition	Upwelling reduces O/N_2 and accelerates plasma loss
Circulation	Pressure gradients drive equatorward winds and wind reversals
Waves	Thermal pulses launch TADs that appear as TIDs

Neutral winds create electric fields through the dynamo

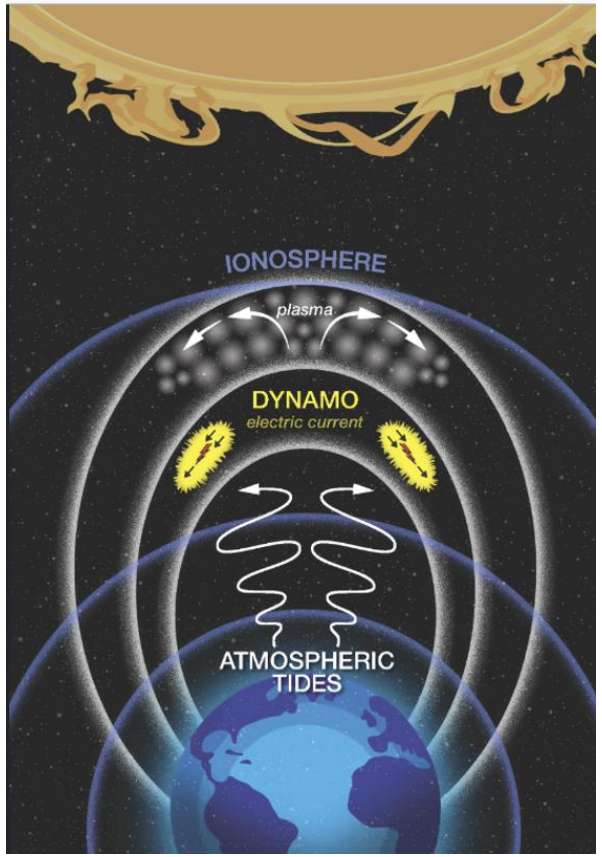


Figure 7. Schematic illustration of the ionospheric wind dynamo. Atmospheric tides generated in the lower atmosphere propagate upward into the E-region, where neutral winds move ions across the geomagnetic field, producing electric currents and polarization electric fields. These electric fields map along magnetic field lines into the F region, driving plasma transport and contributing to the formation of the Equatorial Ionization Anomaly.
Credit: NASA Conceptual Animation Lab (ICON mission).

Tidal winds

↓

Charge separation

↓

Polarization E field

↓

E × B drift

↓

Plasma redistribution

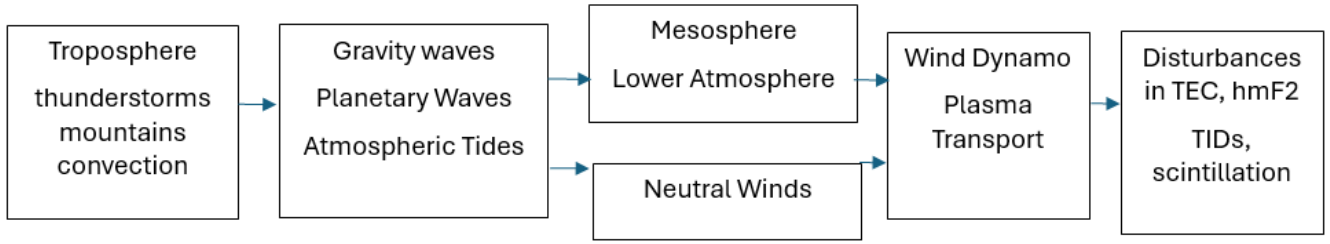
At low latitudes this produces the plasma fountain and Equatorial Ionization Anomaly.

PART 2

Forcing from below

The ionosphere is also the uppermost part of Earth’s atmosphere.

Lower-atmosphere disturbances grow as they propagate upward



How do lower-atmospheric waves affect the ionosphere?

Although gravity waves, tides and planetary waves differ in spatial and temporal scales, they influence the ionosphere through the same sequence of processes:

- They propagate upward as atmospheric density decreases.
- Their amplitudes increase with altitude.
- They modify thermospheric neutral winds and temperatures.
- The altered winds change the ionospheric dynamo electric fields.
- Plasma transport is modified through **E × B** drifts and diffusion along magnetic field lines.
- Electron density, TEC and ionospheric currents consequently change.

The relative importance of each mechanism depends on latitude, local time, season and solar activity.

Why amplitudes grow

Atmospheric density decreases exponentially with altitude. To conserve energy, upward-propagating waves increase in amplitude and may become unstable or break.

Result

Momentum and energy are deposited into thermospheric winds, temperature, electrodynamics, and plasma density.

Three wave families connect weather to the ionosphere

Gravity waves

Scale
Tens–hundreds km

Period
Minutes–hours

Sources
Mountains, convection, storms

Buoyancy acts as a restoring force

Atmospheric tides

Scale
Planetary scale

Period
8, 12, 24 hours

Sources
Periodic solar heating

Restoring driver
Thermal forcing

Planetary waves

Scale
Thousands km

Period
2–30 days

Sources
Rotation, land–sea contrast, topography

Restoring driver
Coriolis variation

These different wave types modify thermospheric winds and therefore ionospheric dynamics

Atmospheric waves affect plasma through a common sequence

1

Propagate

Amplitude grows as density falls

2

Modify winds

Momentum and heat enter the background flow

3

Alter fields

The wind dynamo changes electric fields

4

Move plasma

E × B drift and field-aligned diffusion respond

5

Change density

TEC, hmF2, currents, and irregularities vary

PART 3

Ionospheric weather

Short-term changes over minutes to days can be driven from above or below.

Weather is the departure from the expected background

Climatology

Predictable average behavior

- Local time and day–night cycle
- Season
- Solar cycle
- Latitude and longitude

Weather

Short-term disturbances

- Solar flares, CMEs, HSS/CIRs
- Geomagnetic storms
- Atmospheric waves and SSWs
- TIDs and plasma irregularities

The distinction between climatology and weather matters: to recognize an anomaly, we first need to know what would normally be expected at that location and time.

Geomagnetic storms can increase or decrease electron density

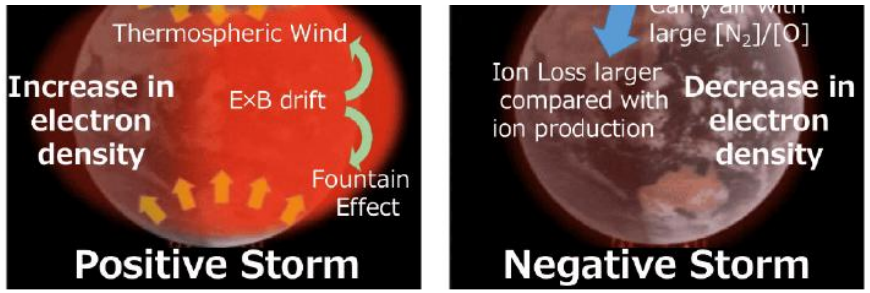


Figure 10. Positive (left) and negative (right) ionospheric storms (Courtesy: NICT Space Environment Laboratory).

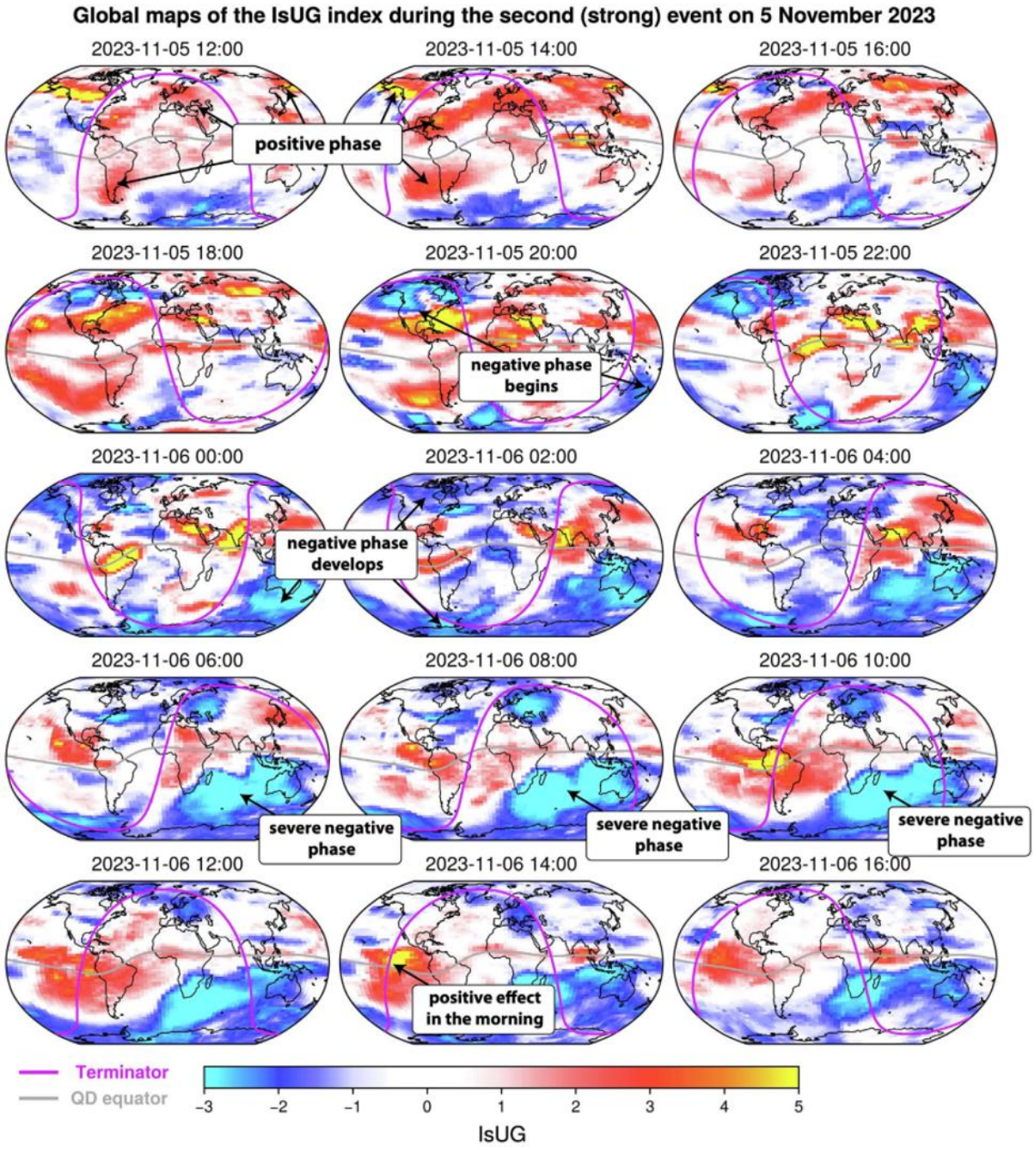
Positive phase

Upward transport and wind-driven plasma redistribution increase F-region density, often early in a storm.

Negative phase

Molecular-rich upwelling lowers O/N_2, accelerates recombination, and reduces density—often during recovery.

The outcome depends on latitude, local time, season, storm intensity, and the pre-storm state.



Spatial and temporal evolution from positive to negative storm effects

Figure 10b. Global maps of Ionospheric Storm Indices (IsUG, obtained from the UQRG VTEC GIMs) during the strong geomagnetic storm event on Nov 5, 2023, showing every two hours the occurrence in space and time of positive and negative phases

(extracted from Smirnov et al. 2026 where more details can be found).

Variability creates the environment; plasma instability creates irregularity

Variability- large scale

Large-scale changes in electron density, TEC, or layer height.

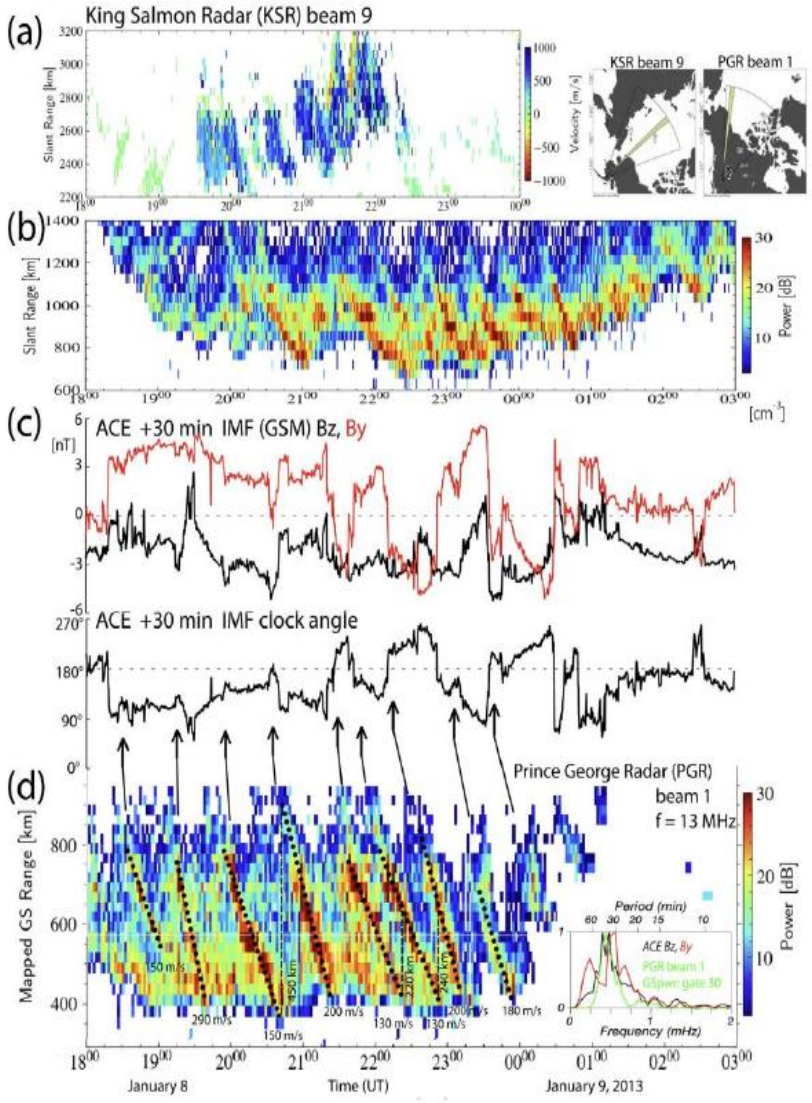
favorable gradients + plasma instability

Irregularity – small scale

Localized plasma structures spanning hundreds of kilometres down to metres.

Examples: TIDs • Spread-F • equatorial plasma bubbles

TIDs are traveling wave signatures in electron density



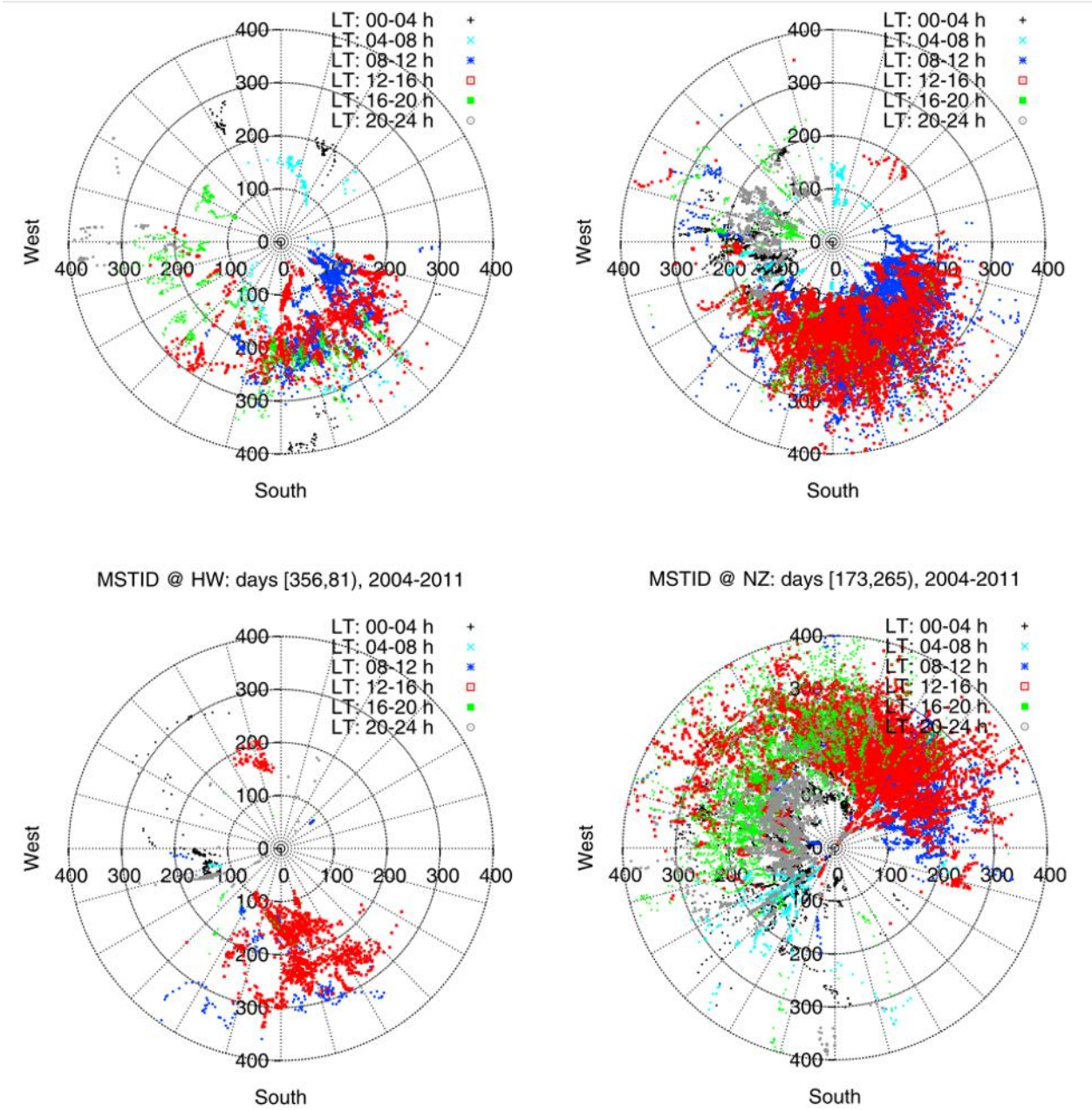
Large-scale TIDs

1,000–3,000 km • 400–1,000 m/s • 30 min to hours
Usually linked to geomagnetic storms and auroral heating.

Medium-scale TIDs

50–500 km • 50–300 m/s • 10–40 min
Often seen in quiet conditions, following a seasonal climatology, and linked to lower-atmosphere gravity waves.

Observed with GNSS TEC, ionosondes, radars, airglow, HF Doppler, and radio occultation.



MSTID propagation has systematic geographical/local-time characteristics

Figure 12b. Polar plots representing MSTID velocities (in m/s) and azimuths for local winter, for four local GNSS networks at: Alaska (AS, top left), California (CA, top right), Hawaii (HW, bottom left), and New Zealand (NZ, bottom right) NZ during the indicated available periods, and local times (color palette: black for LT 00–04 h, light blue for LT 04–08 h, dark blue for LT 08–12 h, red for LT 12–16 h, green for LT 16–20 h and gray for LT 20–24 h)

Extracted from Hernández-Pajares et al. 2012b.

Spread-F reveals a reflecting layer filled with irregularities

Spread-F is one of the most important manifestations of ionospheric irregularities because it affects radio-wave propagation. Small-scale plasma structures scatter and diffract trans-ionospheric signals, producing amplitude and phase scintillations on GNSS signals, degradation of positioning accuracy, interruptions of satellite communication links, and reduced performance of HF radio systems.

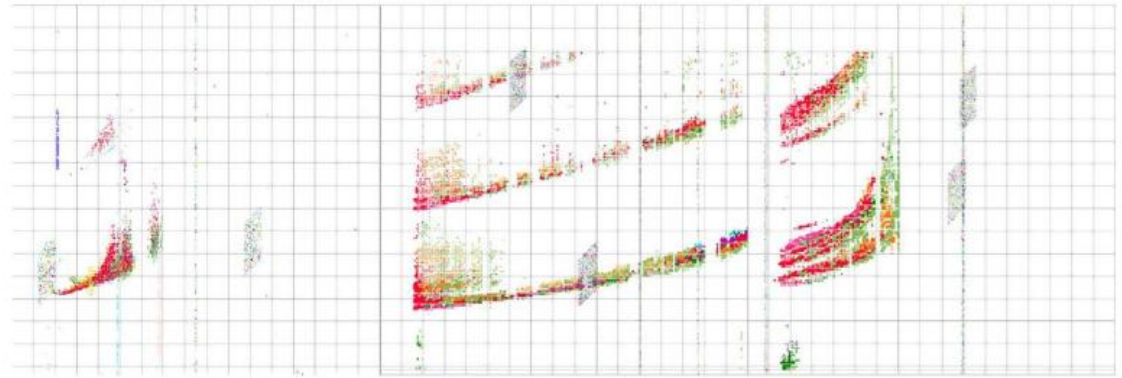


Figure 13: (a) is FSF with salt-and-pepper noise (density = 0.2), (b) is RSF with Poisson noise (λ=4), and (c) is MSF with Gaussian noise (σ^2=0.15); each was augmented by adding one or two column- and parallelogram-shaped noises (After Gao et al., 2026).

Range Spread-F

Broadening in virtual height from reflections at multiple locations.

Frequency Spread-F

Broadening near the critical frequency due to strong irregularities and Doppler effects.

Consequence: scattering and diffraction produce GNSS scintillation and degraded radio performance.

Equatorial plasma bubbles grow after sunset

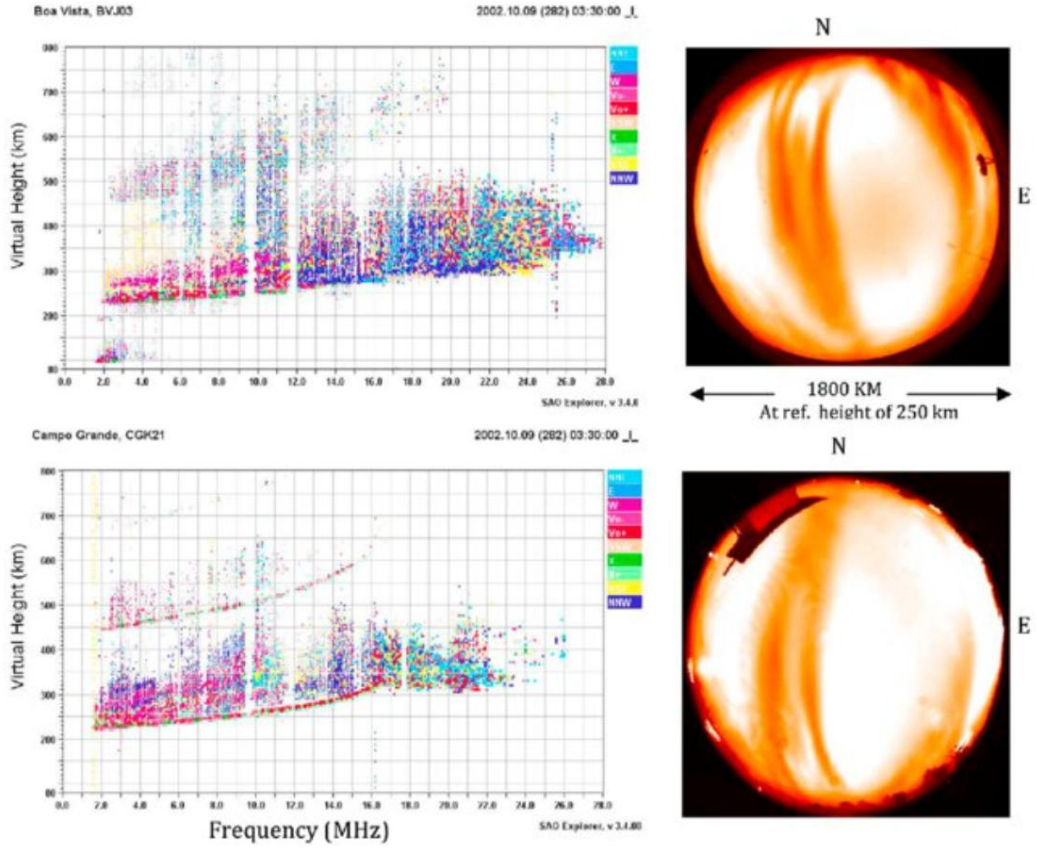


Figure 14. Illustrative ionograms over (top left) Boa Vista and (bottom left) Campo Grande. (right) The simultaneous all-sky images on the night of 9 October 2002 [from Abdu et al., 2009]. The North-South elongated streaks are the footprints, in the airglow emission region, of the magnetic field aligned plasma bubbles/depletions. The North is to the top and the East to the right. The horizontal extension of the all sky imager field of view projected at 250 km height is also shown (as 1800 km).

1. E-region conductivity falls
2. PRE lifts the F layer
3. Rayleigh–Taylor instability grows
4. Bubbles rise and fragment
5. **Signals scintillate**

Gravity waves may seed the initial perturbation; storm-time electric fields can modify occurrence.

Ionospheric structure directly affects modern technology

GNSS

TEC delays, gradients, loss of lock, scintillation

HF radio

Absorption, changing reflection heights, fadeouts

Satellites

Thermospheric expansion increases drag and orbit error, and risk of early satellite fall on ground.

Radar & links

TIDs and irregularities disturb propagation and convergence

PART 4

Climatology, trends, and models

Separate the predictable background from weather and long-term change.

Ionospheric climatology follows three predictable cycles

Day–night

Production dominates in sunlight; recombination removes plasma after sunset

Season

F2 density can be higher in winter because thermospheric composition favors production

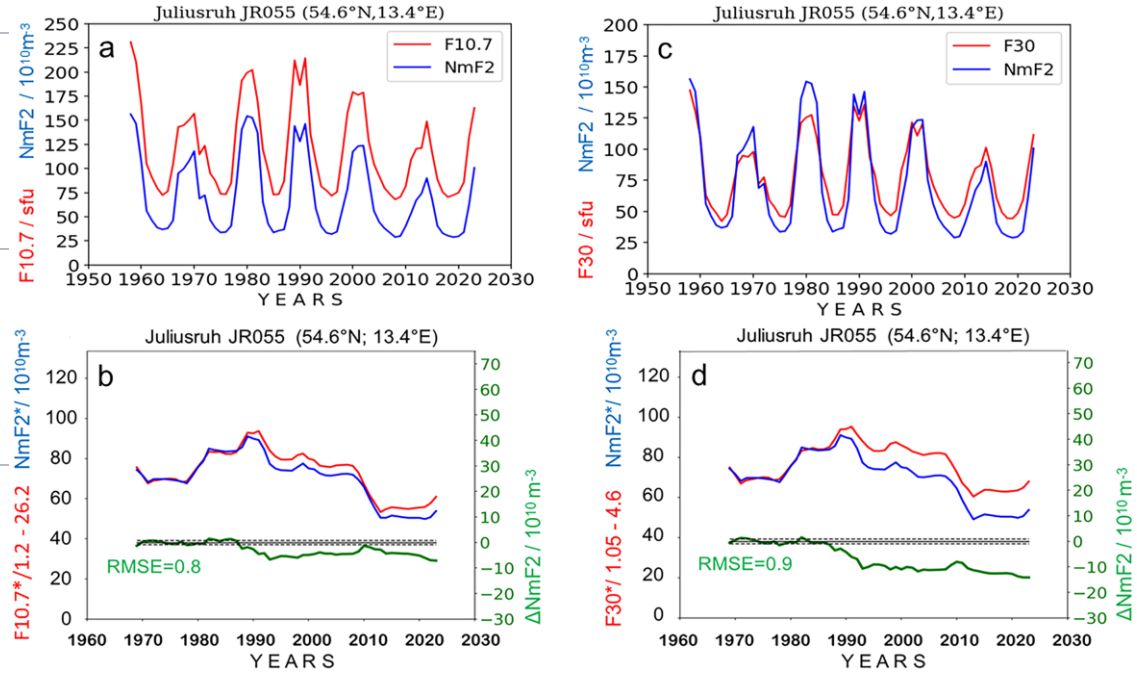
Solar cycle

EUV/X-ray variability shifts TEC and peak density over ~11 years

Climatology provides the baseline needed to recognize ionospheric weather.

Long-term change shifts the baseline over decades

CO_2-driven upper-atmosphere cooling	Thermospheric contraction and a lower F2 peak height
Secular magnetic-field change	Regional shifts in plasma transport and accumulation
Solar and geomagnetic baselines	Multi-decadal changes beyond the 11-year cycle
Changing atmospheric-wave forcing	Regional trends transmitted upward from below



Long-term trends in NmF2 compared linear models (Jakowski and Hoque, 2025)

Reference models answer different operational questions

IRI

Empirical climatology

Main output
Ne, temperature, ions, TEC

Strength / limitation
Global and validated; limited during disturbances

NeQuick

Semi-empirical

Main output
Electron-density profiles and TEC

Strength / limitation
Efficient; used for Galileo corrections

GIM

GNSS data-driven

Main output
Global vertical TEC maps

Strength / limitation
Captures weather; limited vertical detail and weaker far from receivers

No single observing system or model captures every place, altitude, and disturbance.

A compact map from driver to impact

DRIVER	PHYSICAL RESPONSE	PHENOMENON	MAIN IMPACT
Solar flares	Photoionization	SID	HF blackout
Geomagnetic storms	Fields + heating	LSTIDs, storms	GNSS, satellite drag
Gravity waves	Wind perturbations	MSTIDs	GNSS
Atmospheric tides	Wind dynamo	Daily TEC variability	Navigation
Planetary waves	Tide modulation	SSW response	TEC
Plasma instability	Density irregularities	Spread-F, EPBs	Scintillation

SYNTHESIS

Can you connect the chain DRIVER – RESPONSE – PHENOMENON - IMPACT?

1. Why can a quiet Sun still produce a variable ionosphere?
2. What determines whether a storm produces a positive or negative phase?
3. How does a neutral wind ultimately move plasma?
4. Which observation would you use for TIDs, Spread-F, or global TEC?