ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

MAKING THE TERRESTRIAL IONOSPHERE
IN 45 minutes's WORK

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Inspired by the lesson from Prof. Mendillo (BU) @ International School of Space Science (ISSI), L'Aquila (Italy), Prof. Sandro Radicella

The beginning

- In 1864 James Clerk Maxwell published a theory of electromagnetic waves

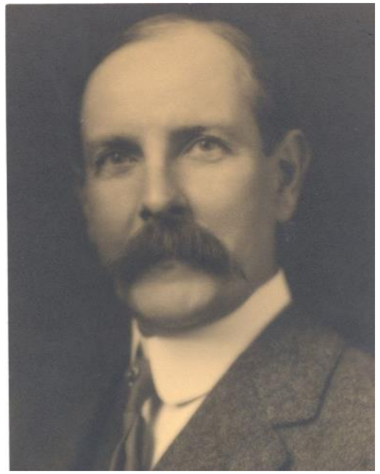
- In 1899 Guglielmo Marconi invented the first radio telegraph system sending signals across the English Channel.

- At Signal Hill (Canada) on December 12, 1901,
Guglielmo Marconi and his assistant, George Kemp,
confirmed **the reception of the first transatlantic radio signals**.
With a telephone receiver and a wire antenna
kept aloft by a kite, they heard Morse code
for the letter "S" transmitted from Poldhu, Cornwall (UK).

- Guglielmo Marconi was awarded the Nobel Prize in Physics in 1909

The ionosphere

Marconi demonstrated that radio transmission was not bounded by the horizon, thus prompting **Arthur Kennelly** and **Oliver Heaviside** to suggest, shortly thereafter, the existence of a layer of ionized air in the upper atmosphere (the Kennelly-Heaviside layer, now called the ionosphere)

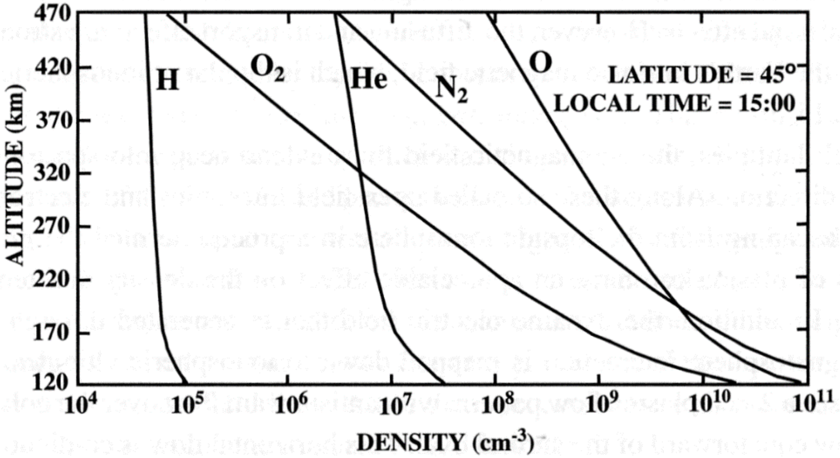


Scientists did not experimentally prove the existence of this atmospheric layer until 1924, thanks to research into the movement of radio signals in the ionosphere by British scientist **Edward V. Appleton**.

Edward V. Appleton he received the Nobel Prize in Physics in 1947

The Photo-Ionization Process

- Start with Neutral Atmosphere



- Ionization Potentials of Atoms and Molecules

Species	Energy (ev)
O	13.62
O_2	12.06
N_2	15.58

$\lambda_{\text{ionization}}$
910 Å
1028 Å
796 Å

- Photon energy, E = $h\nu = hc/\lambda$

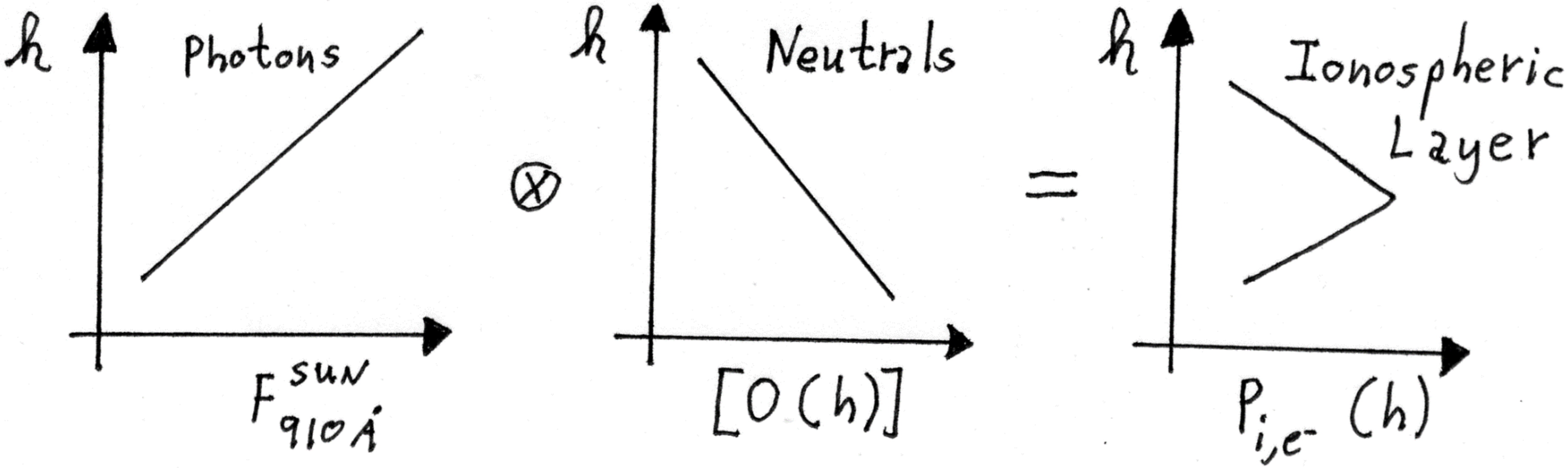
or $\lambda(\text{Å}) \approx \dfrac{12345}{E(ev)}$

Thus, Photon (910 Å) + O → O^{+} + e^{-}

Knowing

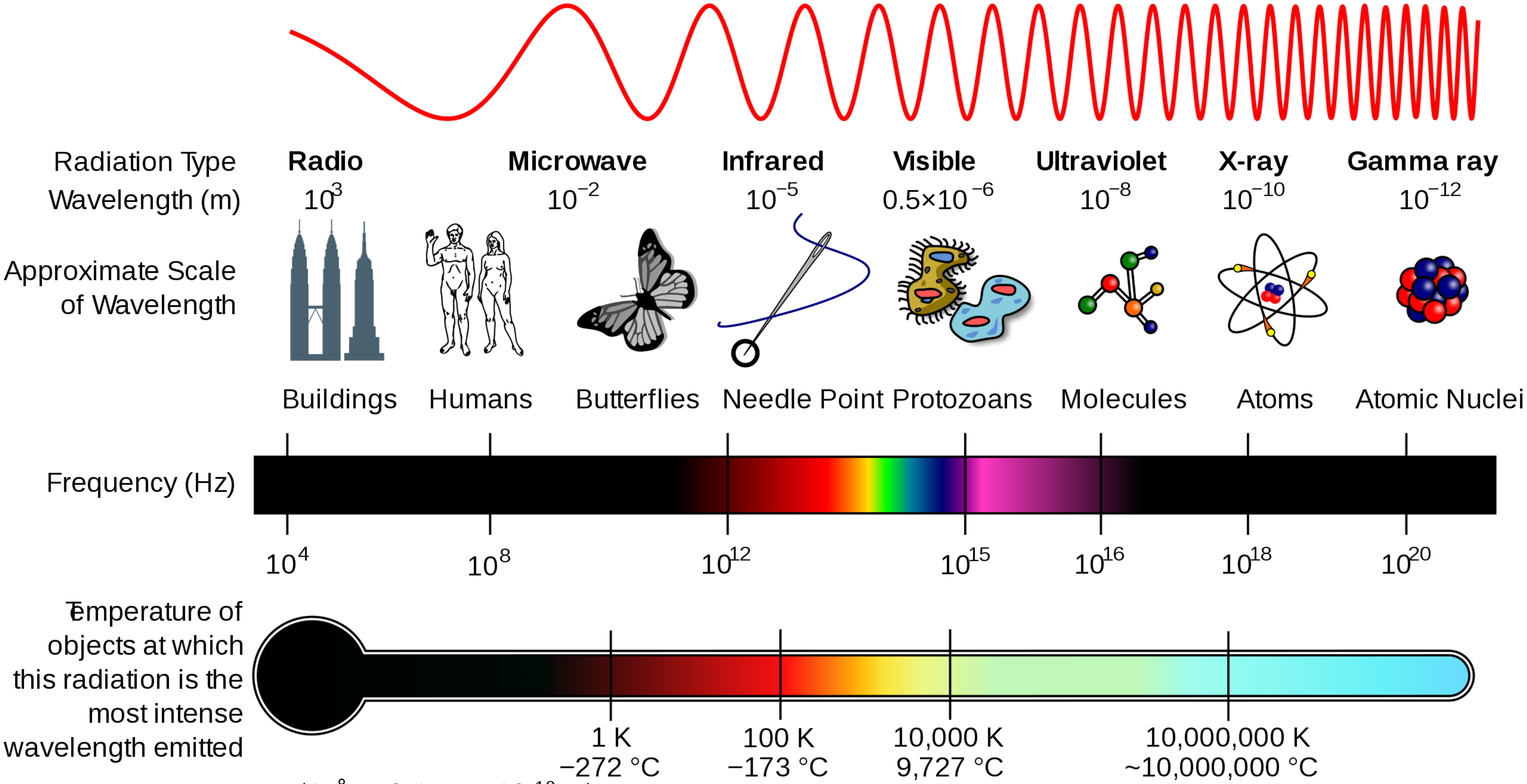
$$\underbrace{F_{910}^{SUN}(h)\ \&\ \left[O(h)\right] \rightarrow \left[O^{+}(h)\right] + \left[e^{-}(h)\right]}_{\substack{\text{Production Function (P)}\\ \text{for monochromatic ionizing radiation}\\ \text{(called "Chapman Theory")}}}$$

How should P(h) look?



For a complete model of Photo-Ionization, the flux of solar photons at all relevant λs is needed:

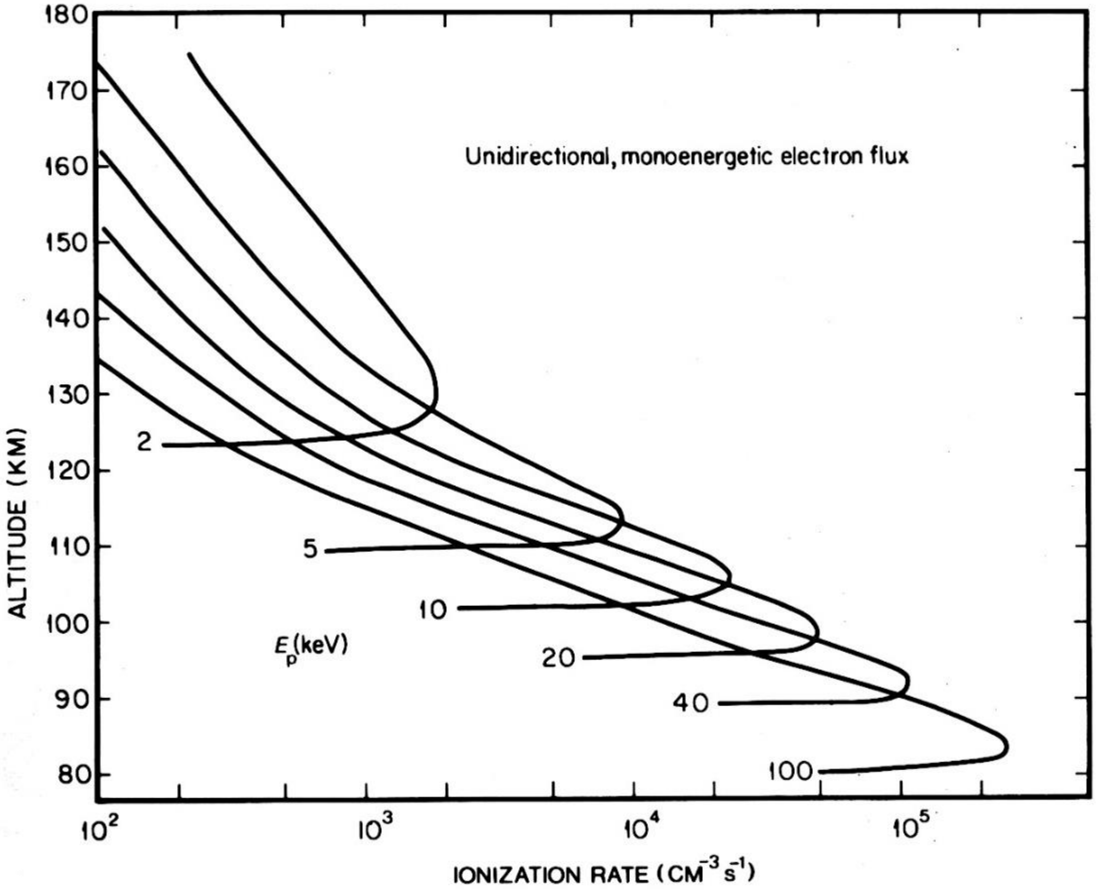
$$P_{\text{Total}}(h) = \sum_{\lambda=0}^{\lambda_{\text{ion}}} F_{\lambda}^{\text{sun}}(h)\cdot\sigma_{ion}(\lambda)\cdot[N(h)]$$



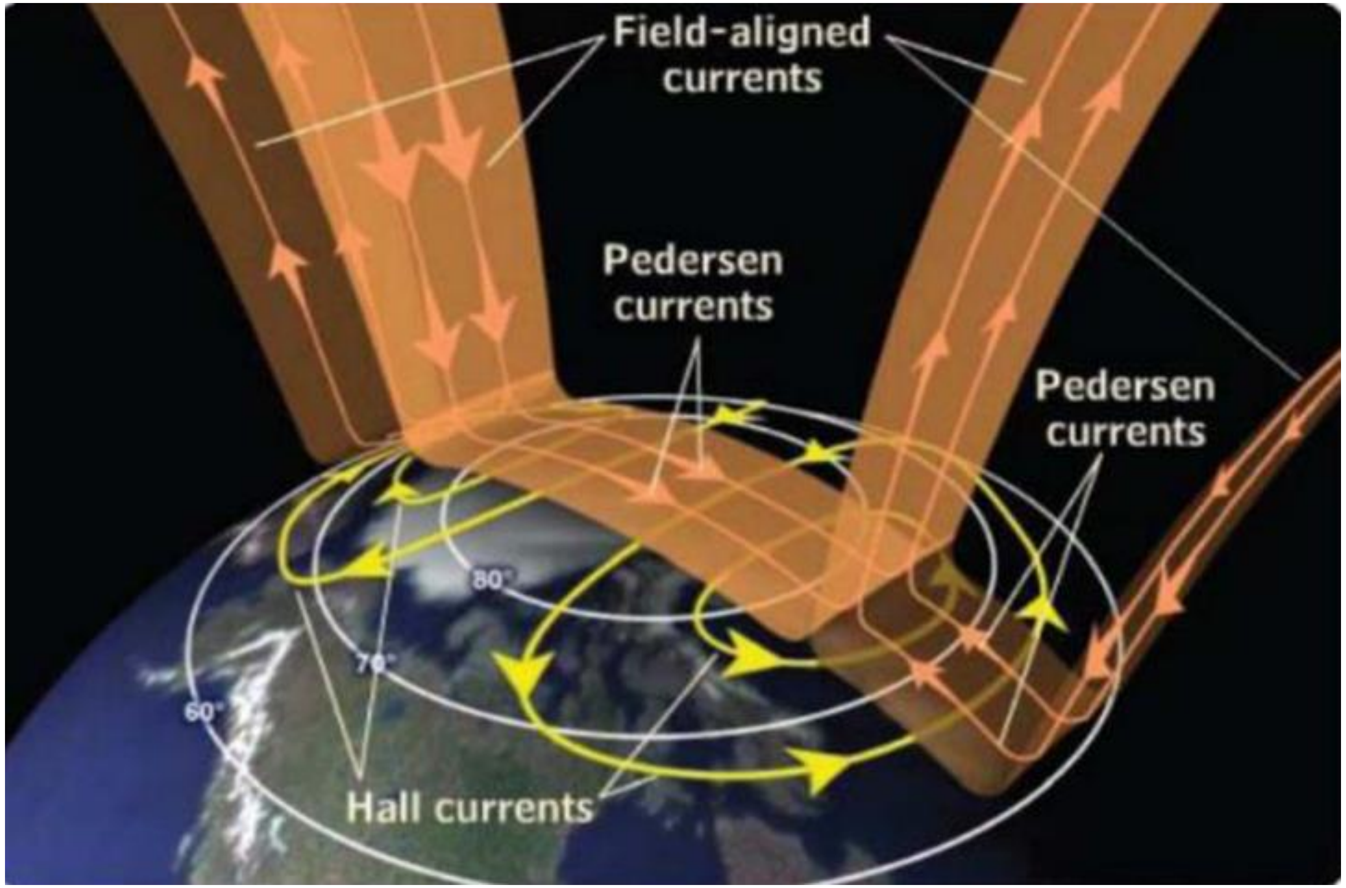
(1 Å = 0.1 nm=10^{-10} m)

Production of Ionospheric Plasma by Energetic Particles

Precipitating Electrons



--- taken from Rees (1989)



COMET program, UCAR

Precipitation particle ionization is important at high latitudes!!

Ionospheric Transformations

- What does "production only" imply?

  e.g., use $P(O^+)$

$$P_{max} = 4000\ e^-/cm^3/sec \times 3\ \text{hours}\ (\approx 10^4\ sec)$$

$$\text{gives}\ N_{max} \approx 4\times10^7\ e^-/\,cm^3$$ ***Never Measured!!!***

Message: Something happens to these ions and electrons!!!

Answer: Chemistry → Plasma recombination

Answer: Chemistry → Neutral-Plasma Processes

CASE # 1: Atomic ions + electrons

$$O^+ + e^- \xrightarrow{\alpha} O$$

[very rare due to precise energetics needed for electron capture]

CASE # 2: Molecular ions + electrons

$$O_2^+ + e^- \xrightarrow{\alpha} O + O$$

[fast due to excess energetics used for dissociation]

CASE #3: Transform Atomic ions to Molecular ions

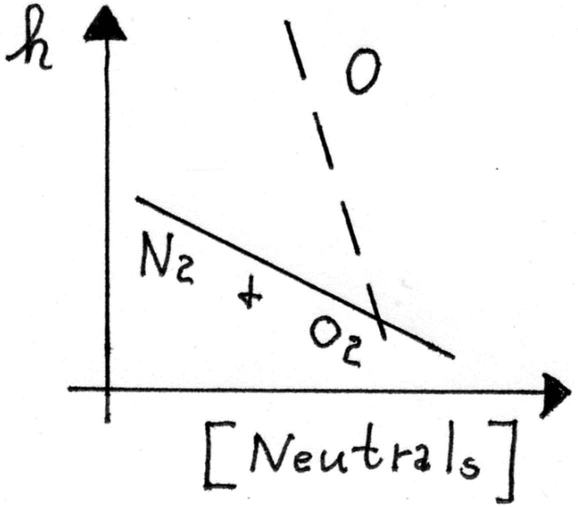
$$O^+ + \begin{bmatrix} N_2 \\ O_2 \end{bmatrix} \xrightarrow{k} \underbrace{\begin{bmatrix} NO^+ \\ O_2^+ \end{bmatrix}}_{\substack{\text{followed by} \\ \text{CASE \#2 (quick)}}} + \begin{bmatrix} N \\ O \end{bmatrix} \quad \text{(slow)}$$

The 2-stage recombination process governed by slower step, e.g.,

$$\boxed{\frac{dN_e}{dt} = -k[N_2]N_e = -\beta N_e}$$

Messages from Simple Photochemical Theory

- Plasmas should be ionized form of dominant neutral



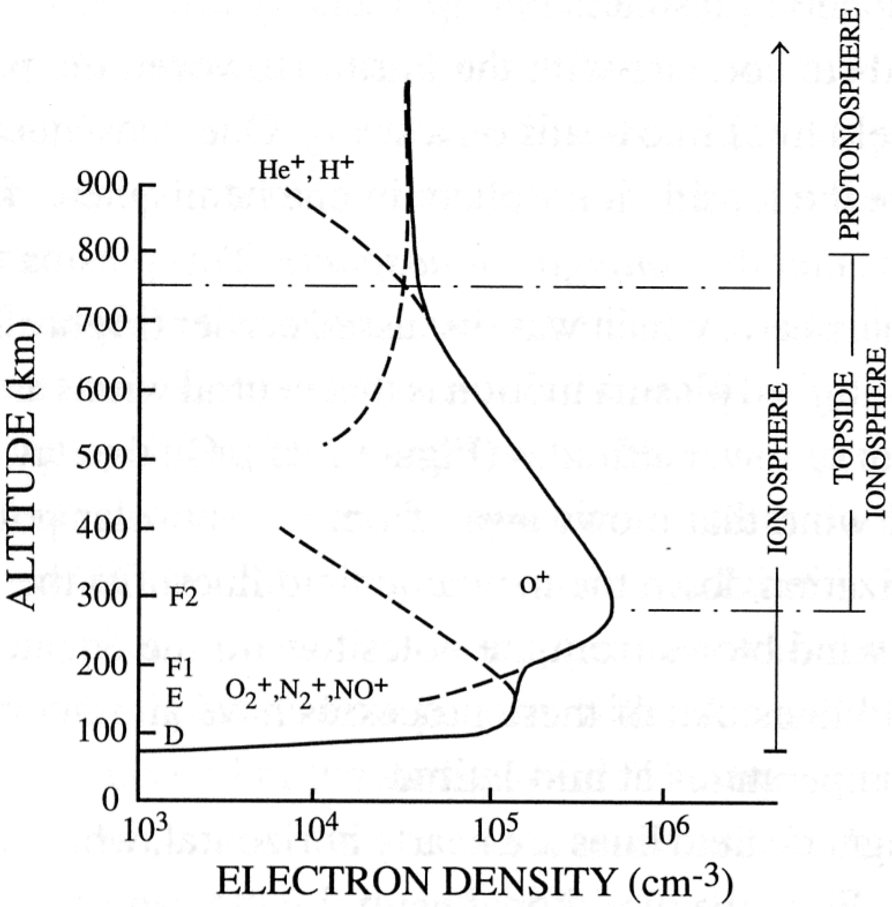
→ CASE #1 : $O^+ + e^-$

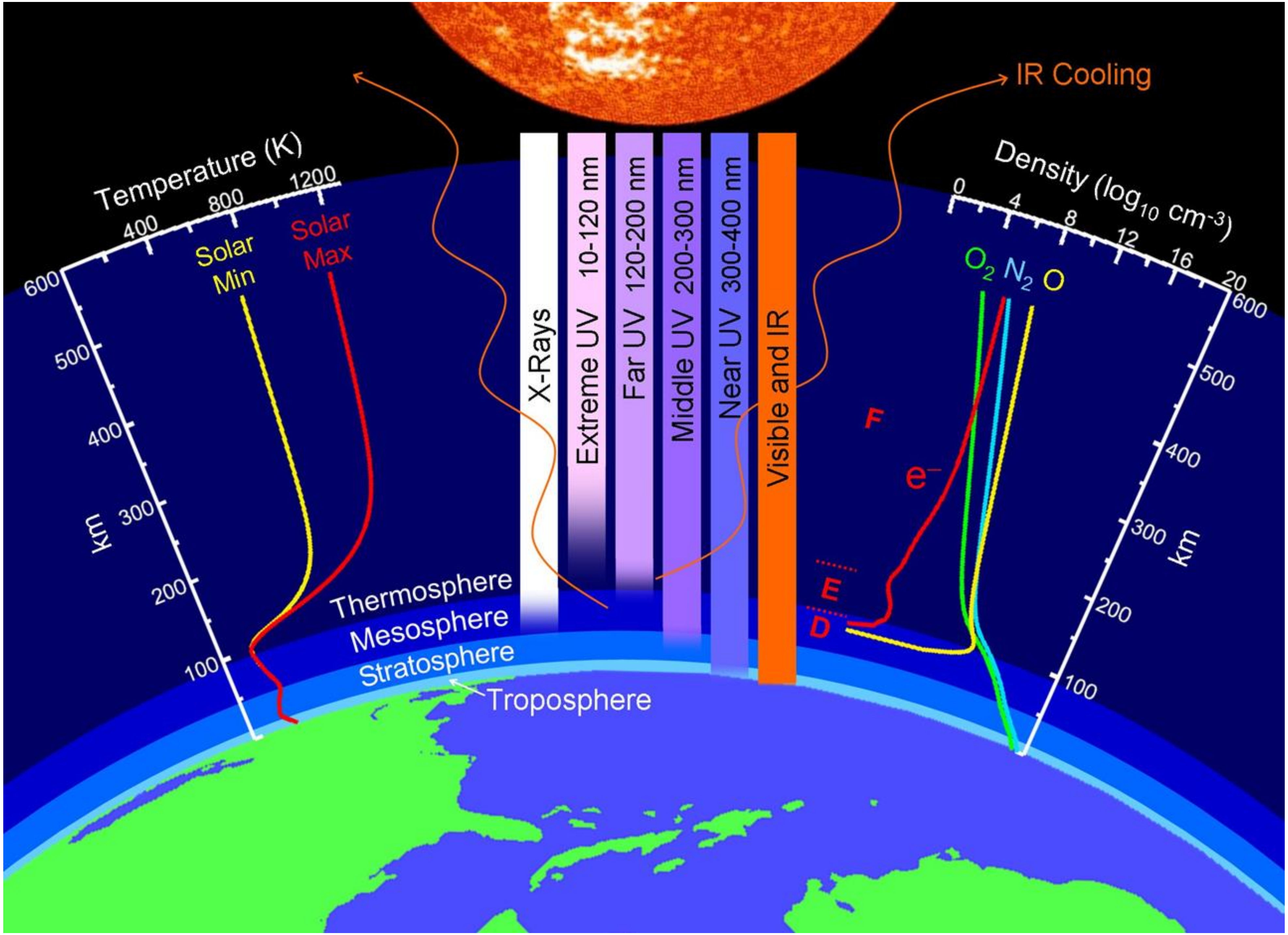
→ CASE #2 : $O_2^+ + e^-$
$N_2^+ + e^-$

- The actual case:

— some chemical transformations to form NO^+ and H^+

- Two main layers: F-layer and E-layer
  (EUV) (X-rays)



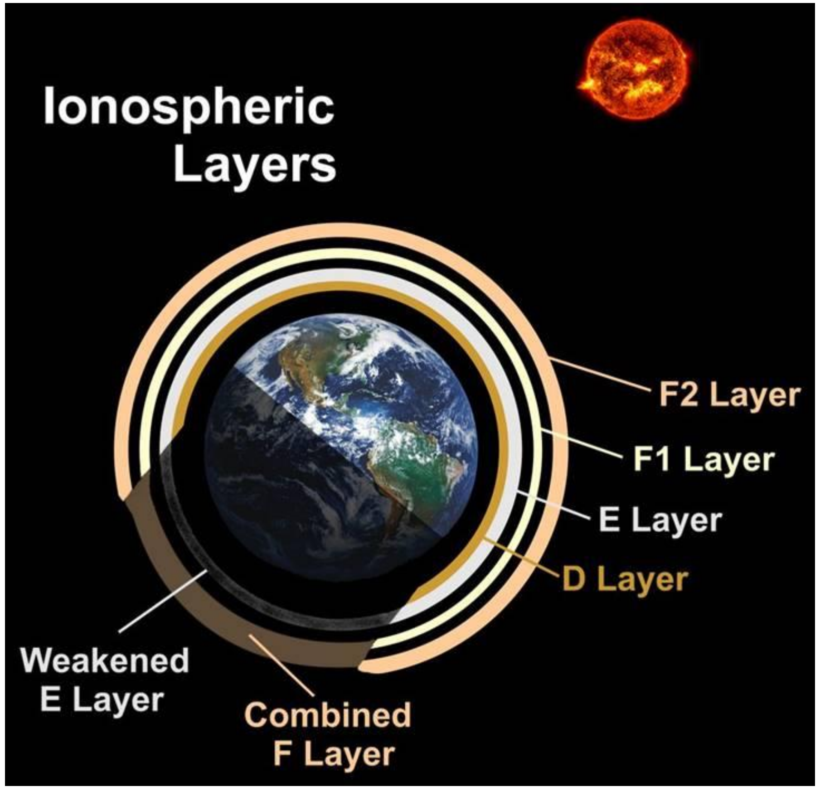

IR Cooling
Temperature (K)
400
800
1200
Solar Min
Solar Max
600
500
400
300
200
100
km
X-Rays
Extreme UV 10-120 nm
Far UV 120-200 nm
Middle UV 200-300 nm
Near UV 300-400 nm
Visible and IR
Density ($\log_{10}$ cm^{-3})
0
4
8
12
16
20
O_2
N_2
O
F
e^-
E
D
600
500
400
300
200
100
km
Thermosphere
Mesosphere
Stratosphere
Troposphere

Some D-layer Characteristics

- **About 60 to 90 km altitude**
- **Tends to absorb the lower radio frequencies** (<3 MHz)
- **Production is mainly due to solar Lyman alpha (121.567 nm) ionization of nitric oxide (NO) and to X-rays ionization of molecular N2 and O2.**
- Molecular ions react with water vapour to produce water vapour cluster ions.
- Electrons rapidly recombine with water vapour ions cluster causing a loss of ionization
- **D-layer rapidly disappears few minutes after dusk due to rapid recombination**

$$\alpha = 1.16 * 10^{-15}\frac{N\nu}{f^2} \sim \frac{12}{f^2}$$

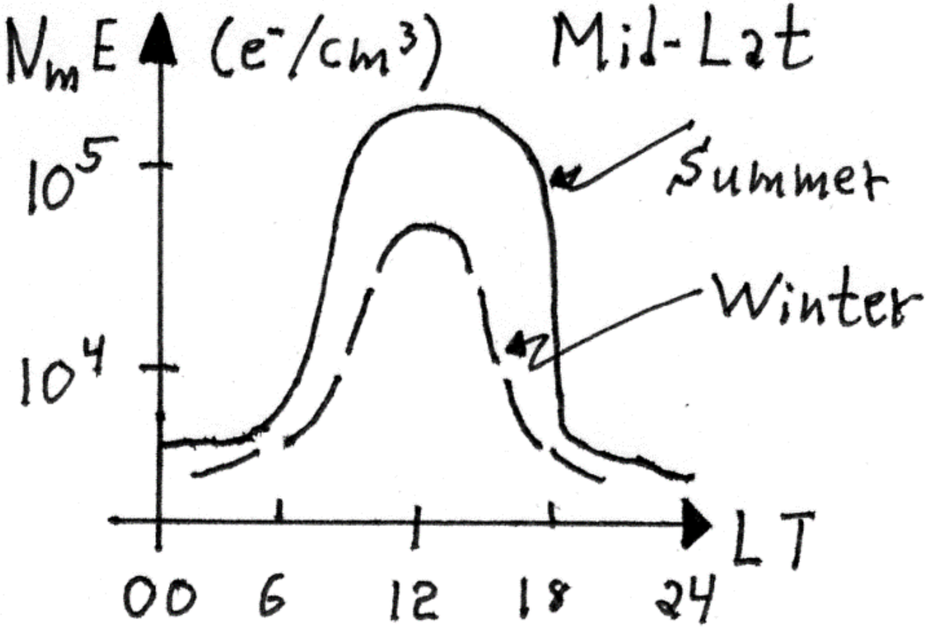
$$\alpha = \text{loss}\left(\frac{\text{dB}}{\text{km}}\right) \qquad \nu = collision\,rate\;(sec^{-1})$$

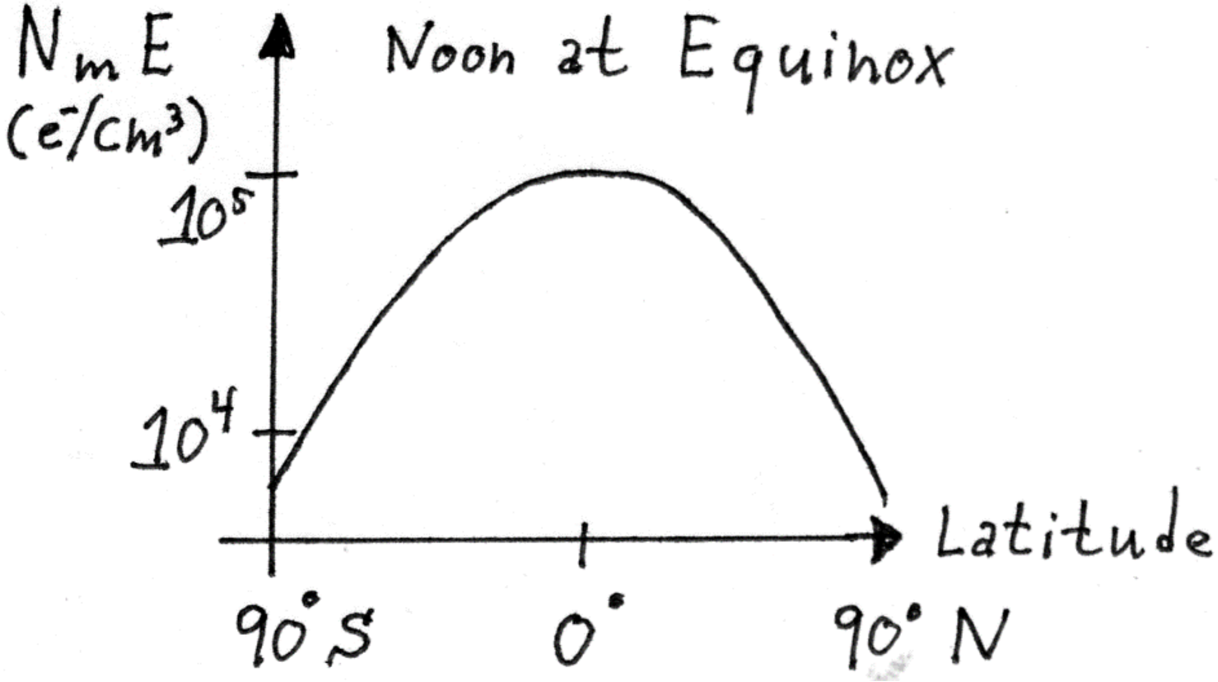


Some E-layer Characteristics

In regions of a **dense neutral atmosphere (h ≤ 150 km)** all ions are molecular (rapid chemistry) and the **ions + electrons stay where produced** (too many collisions to move away)

Example of diurnal behavior

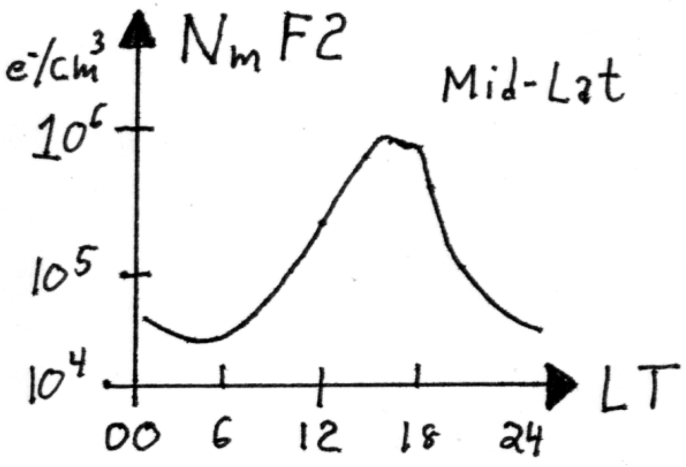


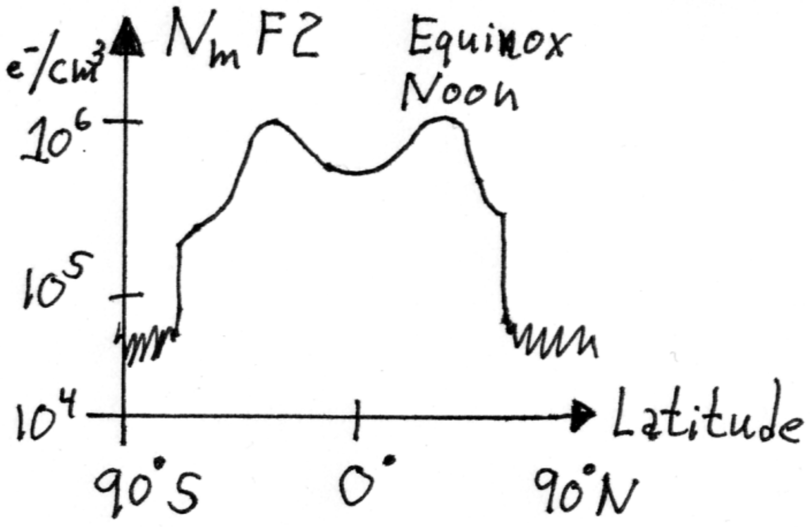


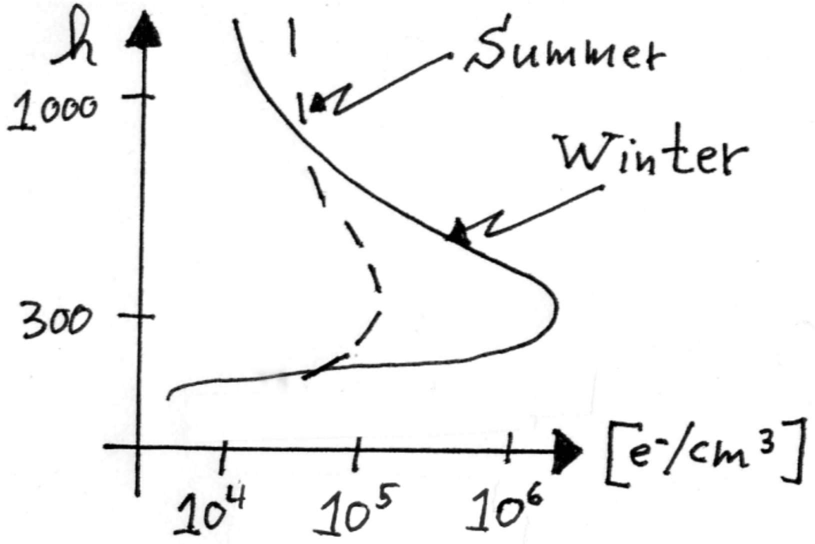
The E-layer is controlled by the Sun's flux and its position (dec + $\chi_\odot$)

Photochemistry-Plus-Dynamics

Some F-layer Characteristics

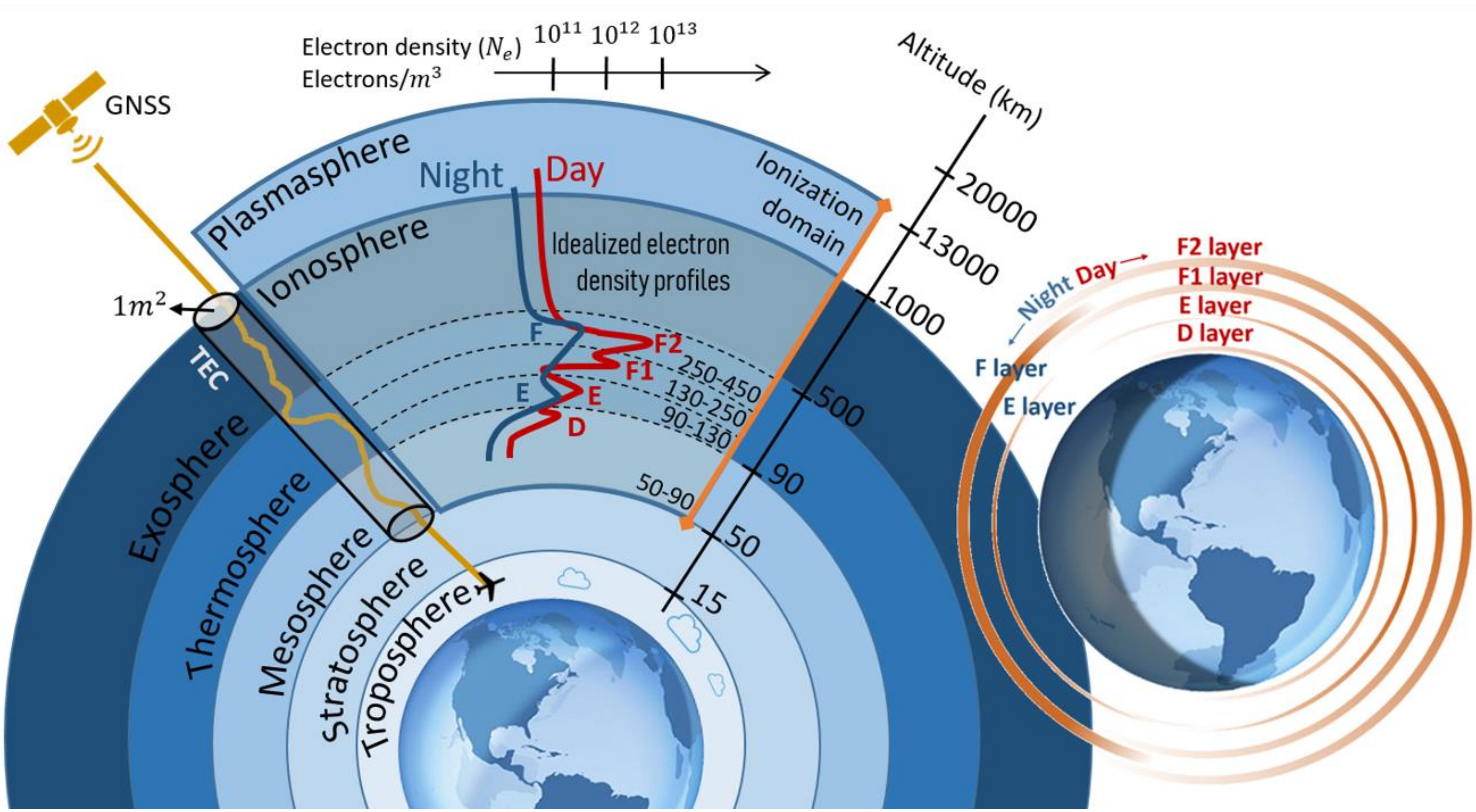






The F-layer is produced by sunlight BUT its behavior does not follow $\chi_{\odot} \Rightarrow$ "Anomalies"

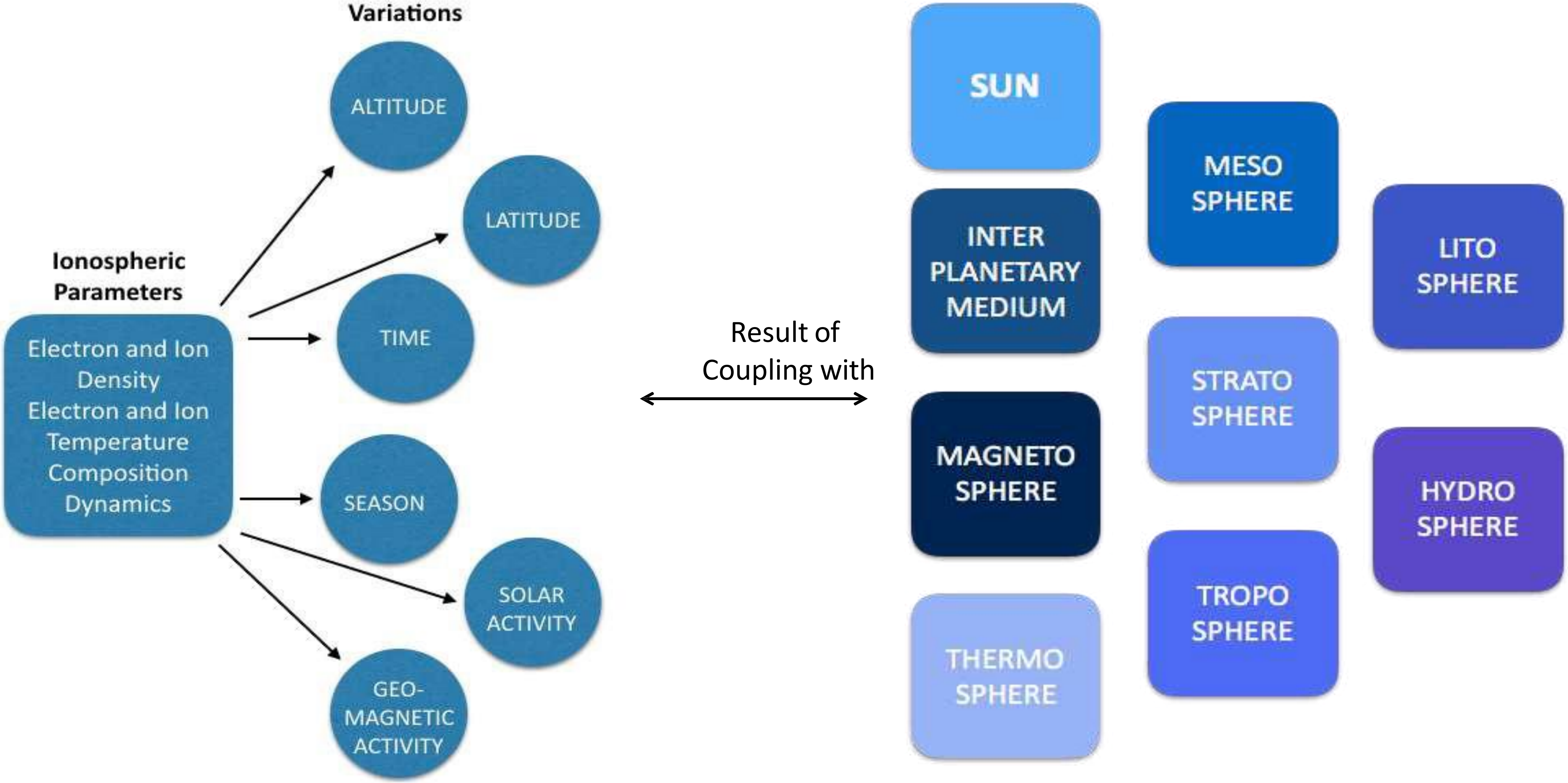
- **Winter anomaly**
- **Annual anomaly**
- **Semi-annual anomaly**



To characterize the condition of the ionosphere the scientists use mainly two key parameters:

- The **F2-layer peak electron density NmF2** (10^{12} electrons/m^3)
- The **Total Electron Content (TEC)** defined as is the total number of electrons present along a path between a radio transmitter and receiver (1 TEC Unit TECU = 10^{16} electrons/m^2)

Ionospheric variability



Variations

Ionospheric Parameters

Electron and Ion Density
Electron and Ion Temperature
Composition
Dynamics

ALTITUDE
LATITUDE
TIME
SEASON
SOLAR ACTIVITY
GEO-MAGNETIC ACTIVITY

Result of Coupling with

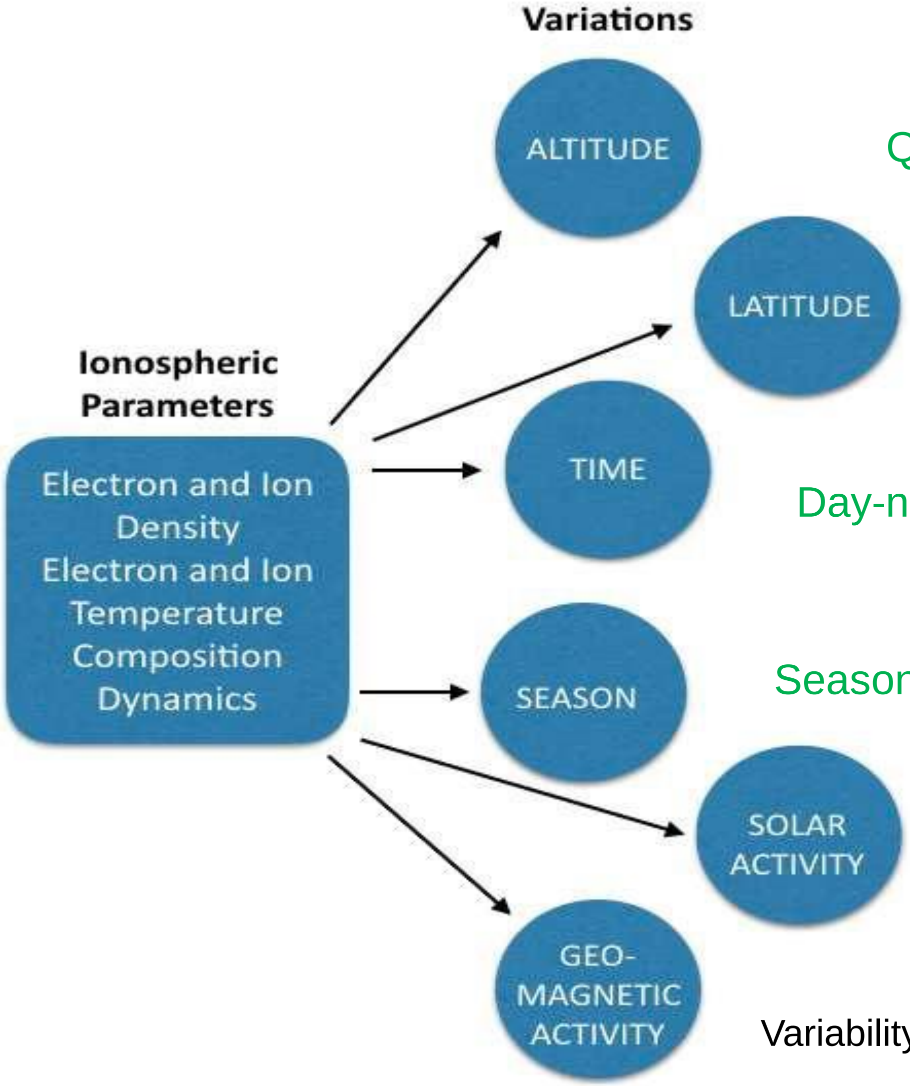
SUN
INTER PLANETARY MEDIUM
MAGNETO SPHERE
THERMO SPHERE
MESO SPHERE
STRATO SPHERE
TROPO SPHERE
LITO SPHERE
HYDRO SPHERE

Ionospheric variability

Regular (mostly predictable) variability

Irregular (mostly unpredictable) variability

Sometimes it is not easy to catalogue the variability as only regular or irregular



Quiet and disturbed variability vs height

Quiet and disturbed variability vs latitude

Day-night and storm time variability

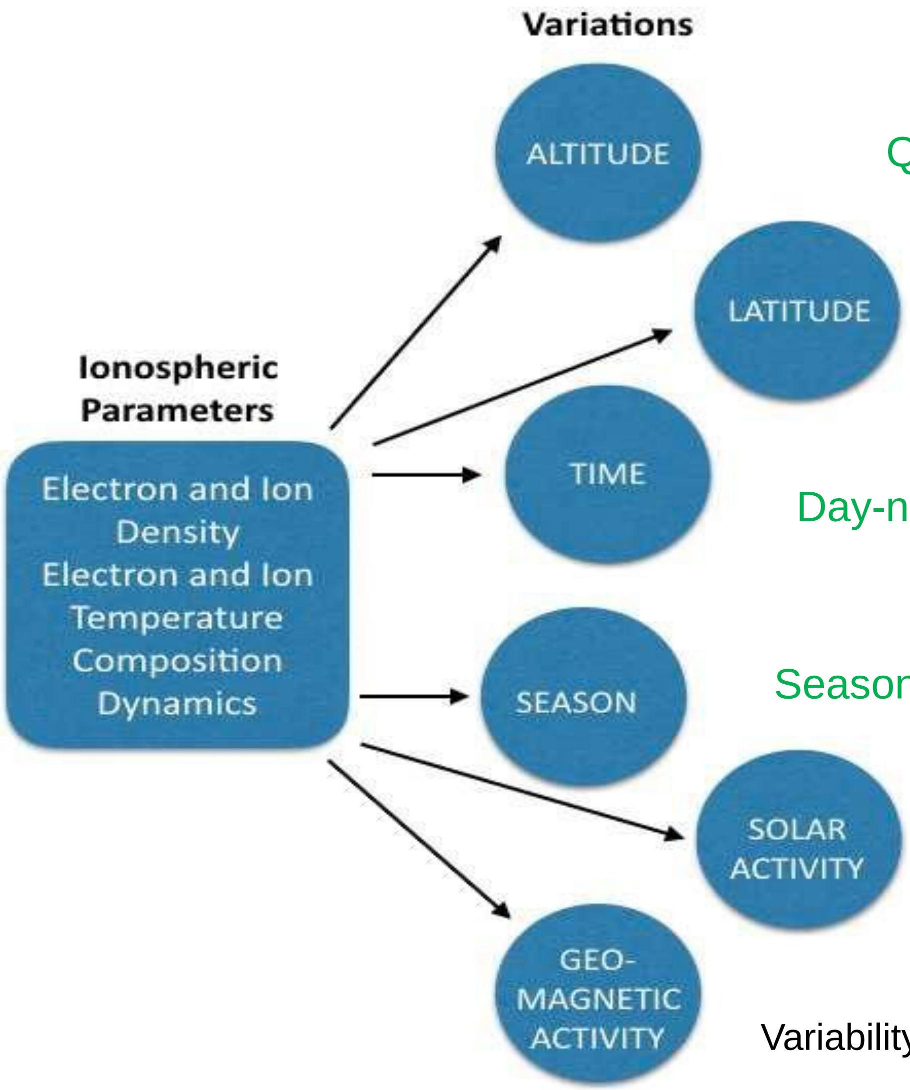
Seasonal variability

11-years solar activity and space weather variability

Variability induced by existence of geomagnetic field and by space weather

Ionospheric variability

Regular (mostly predictable) variability



Quiet

Quiet

Day-night

Seasonal

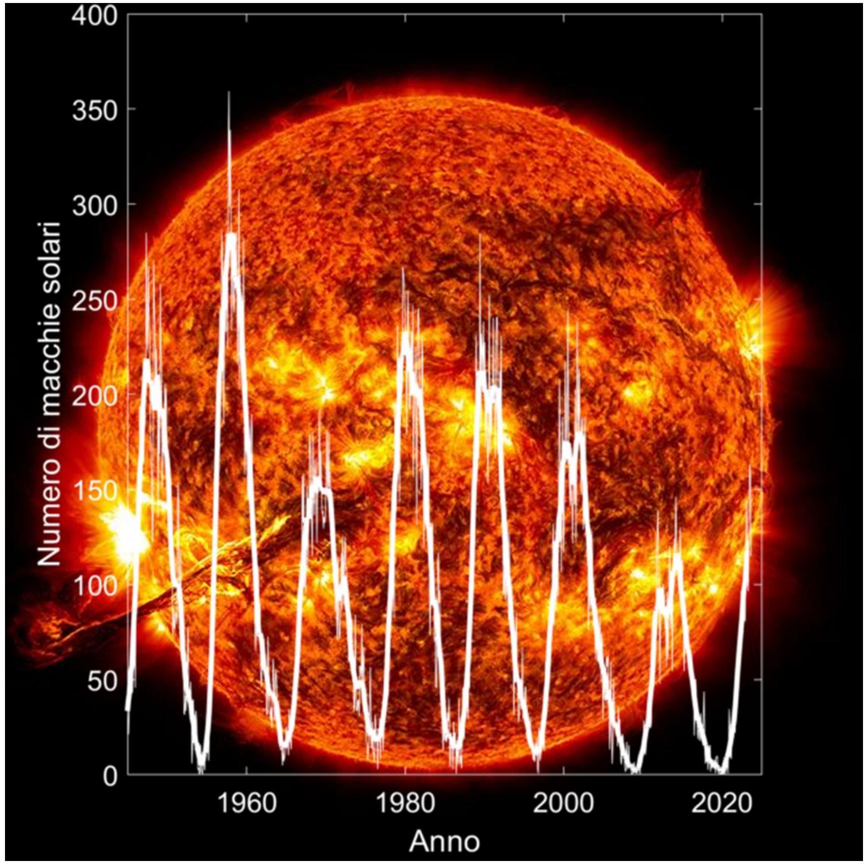
11-years solar activity

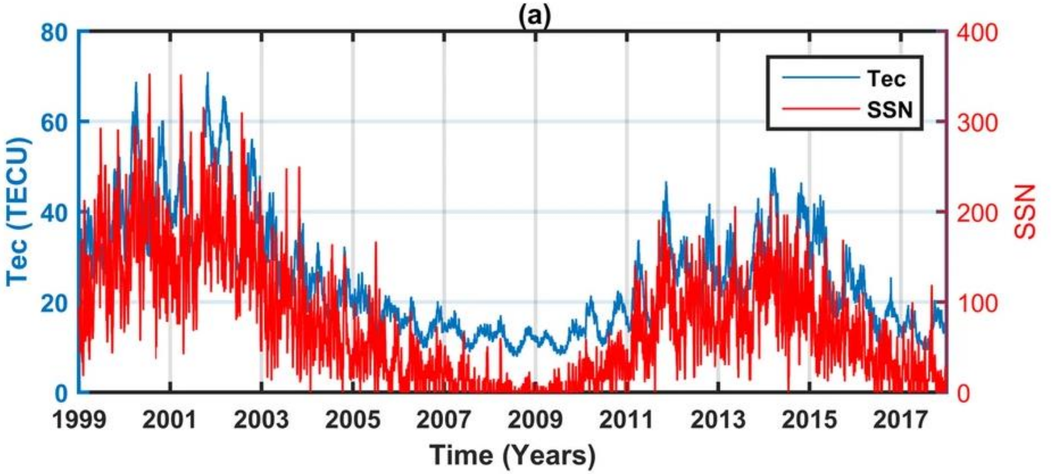
Variability induced by existence of geomagnetic field

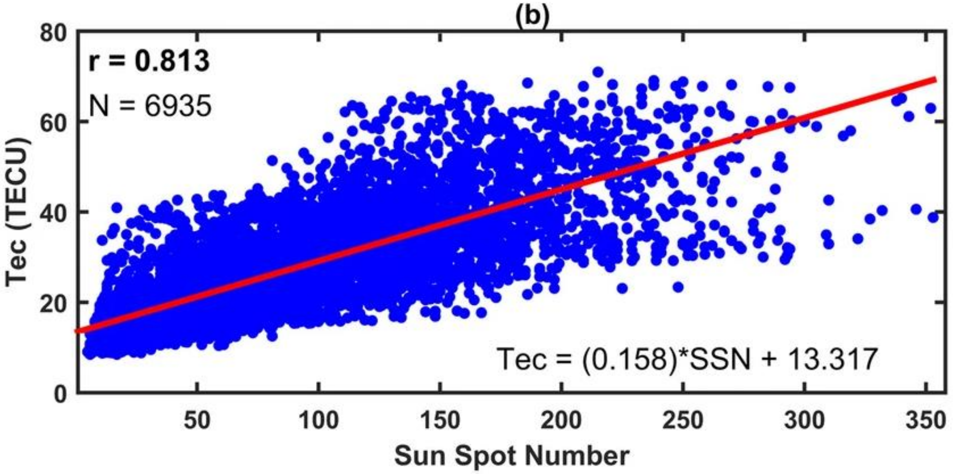
11-years solar activity variability

The Sun exhibits a ~ 11-years variability identified by the number of sunspots (SSN)

TEC variation along ~ 2 solar cycle shows A very nice agreement with the solar activity







Moses et al., 2022

Seasonal variability: **winter anomaly**

Greater F2-layer peak density (NmF2) values in the winter hemisphere than in the summer hemisphere during the solstices. Berkner et al. (1936)

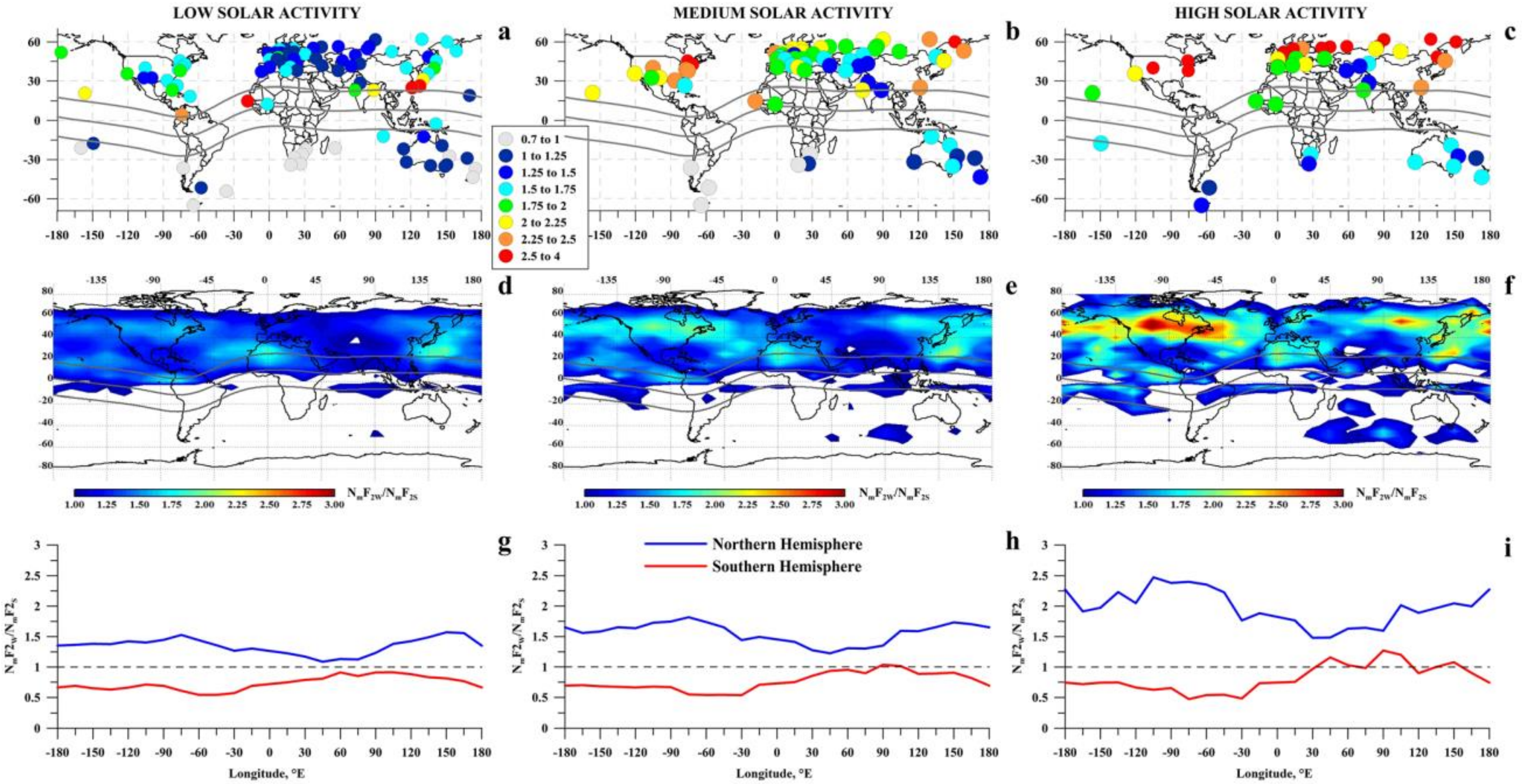


Fig. 3. Maps for the N_mF_2 winter anomaly intensity distribution from Pavlov and Pavlova (2012) (a)–(c) and from the RO measurements (d)–(f), as well as the longitudinal variation of the N_mF_2 winter anomaly intensity averaged at 40–60° geographic latitudinal bands based on the RO data (g)–(i). Panels (a, d, g) correspond to low solar activity; (b), (e), (h) correspond to moderate solar activity; and (c), (f), (i) display high solar activity. White color on panels (d)–(f) shows the regions, for which the winter/summer ratio is less than 1. Bold gray curves (a)–(f) are the geomagnetic equator and ±15° geomagnetic latitudes.

$$I = \frac{N_mF2_w}{N_mF2_s}$$

RO measurements

Seasonal variability: **semi-annual anomaly**

F2-layer peak density (NmF2) is greater at equinox than at solstice

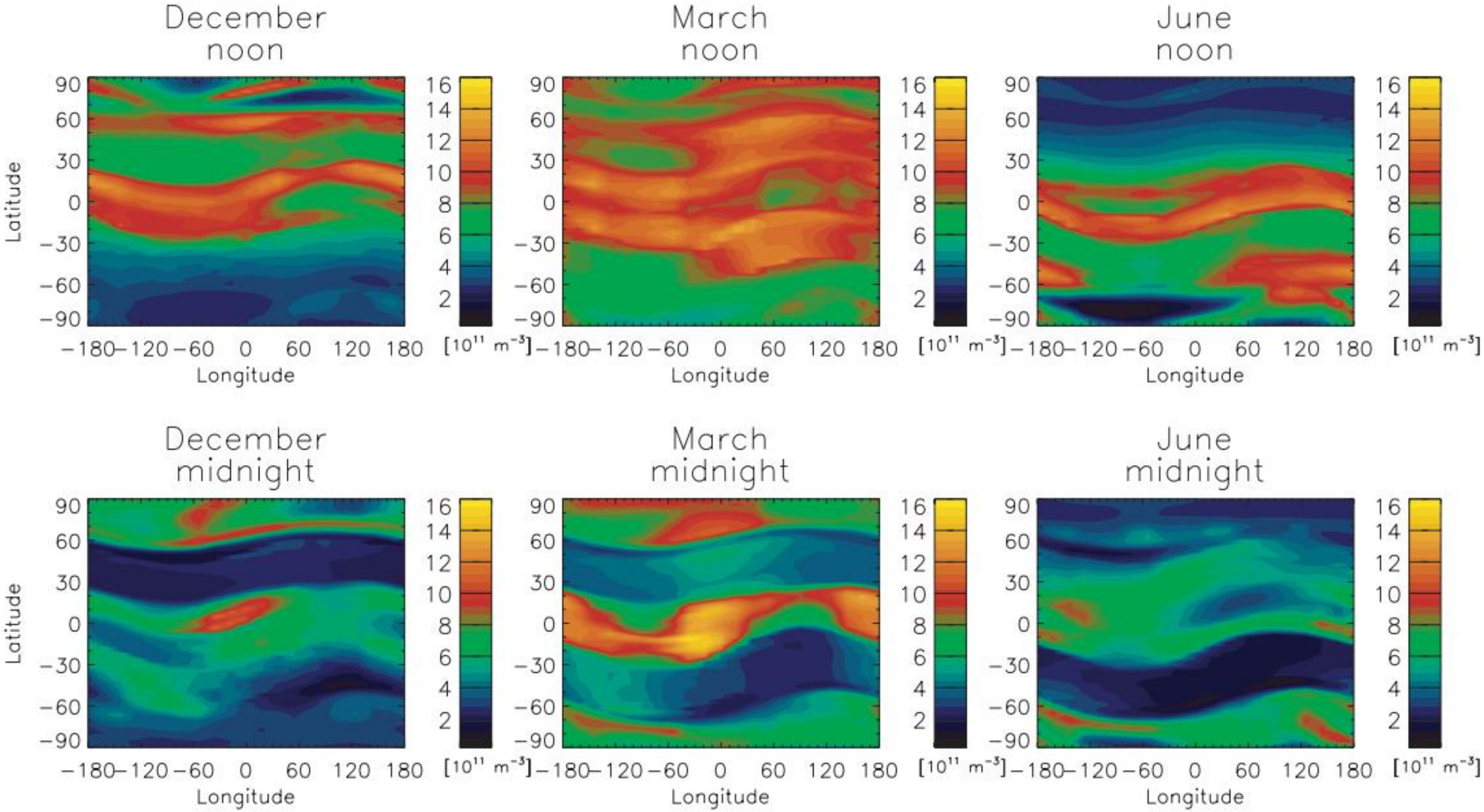
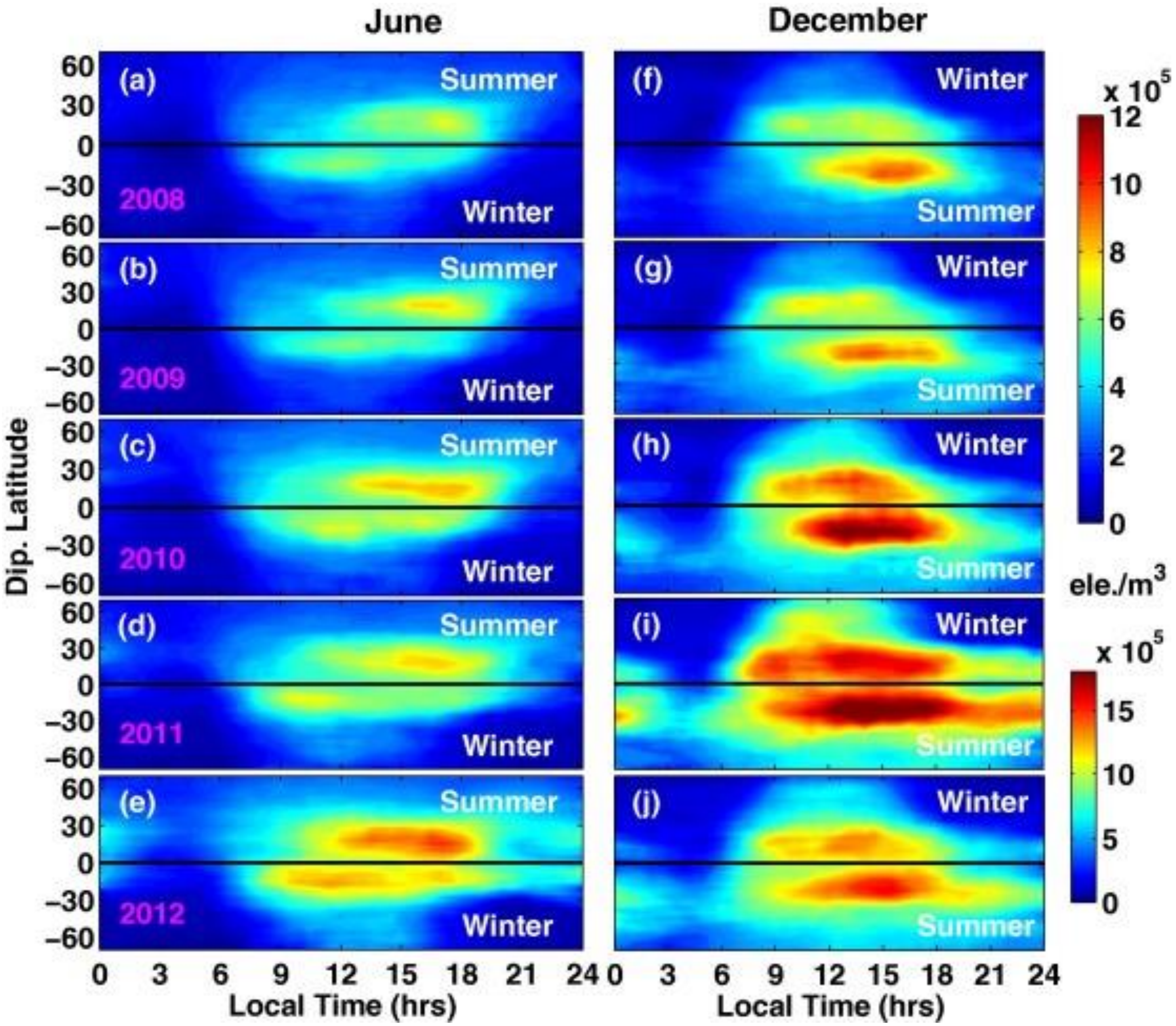


Fig. 5. Noon and midnight maps of *N*mF2 in December, March, June, $F_{10.7} = 100$

Seasonal variability: Annual anomaly

Greater F2-layer peak density (NmF2) at global level during December solstice than June solstice

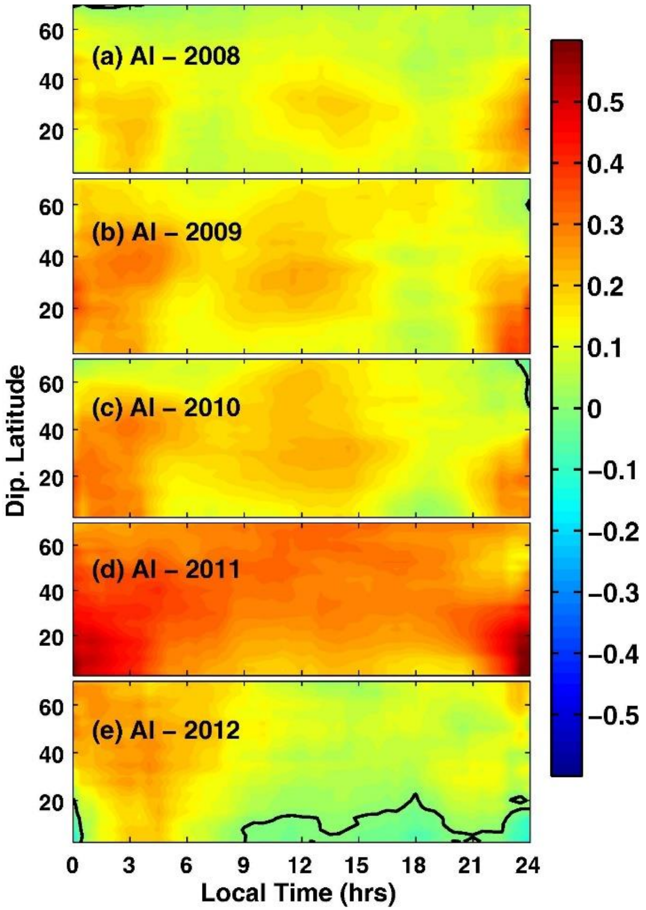


Sai Gowtam and Tulasi Ram, 2017

$$\mathrm{AI} = \frac{NmF2_{NS}(DEC) - NmF2_{NS}(Jun)}{NmF2_{NS}(DEC) + NmF2_{NS}(Jun)}$$

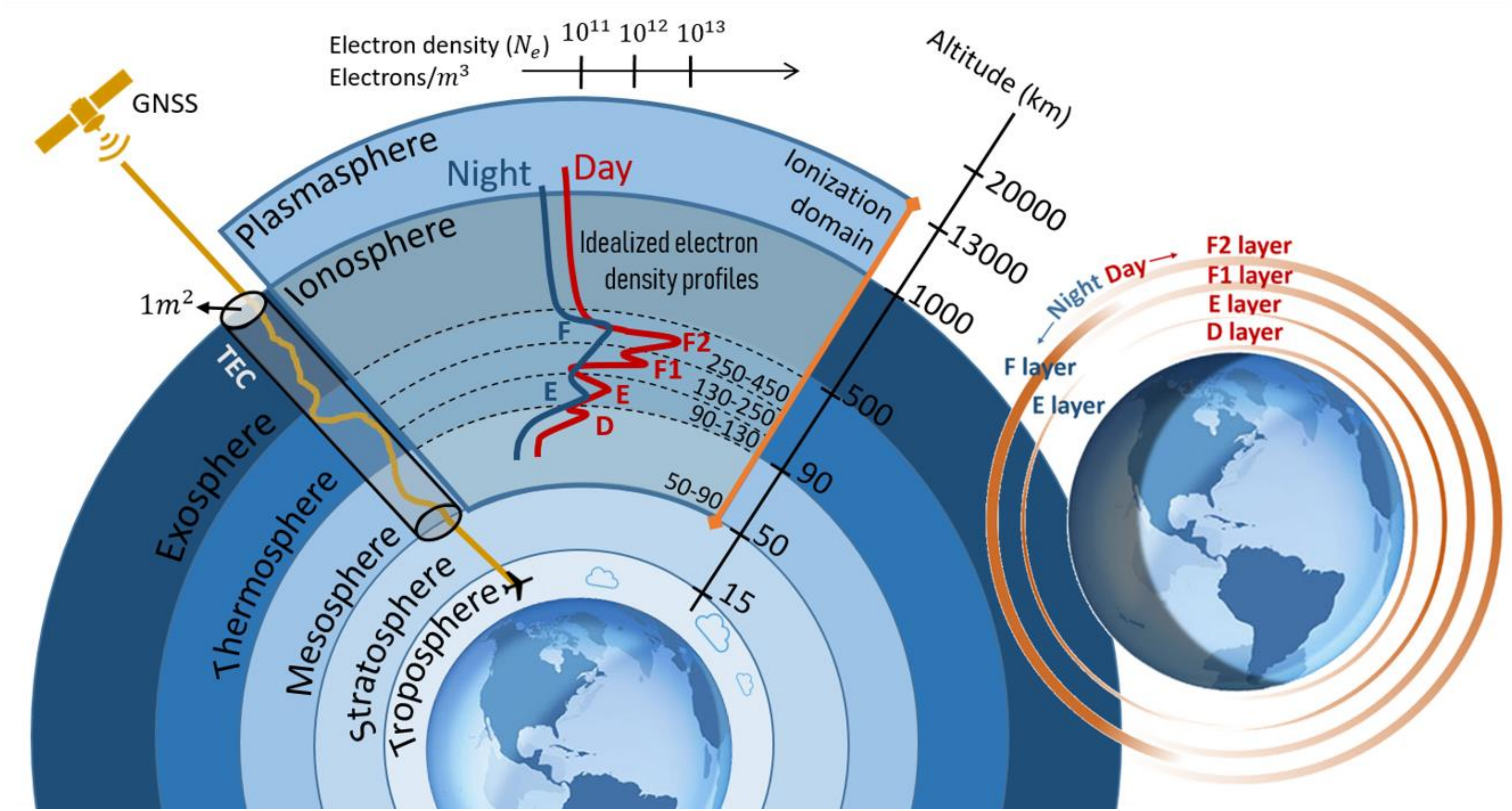
where

$$NmF2_{NS}(\theta,\lambda) = \frac{1}{2} \cdot [NmF2(\theta_N,\lambda) + NmF2(\theta_S,\lambda)]$$



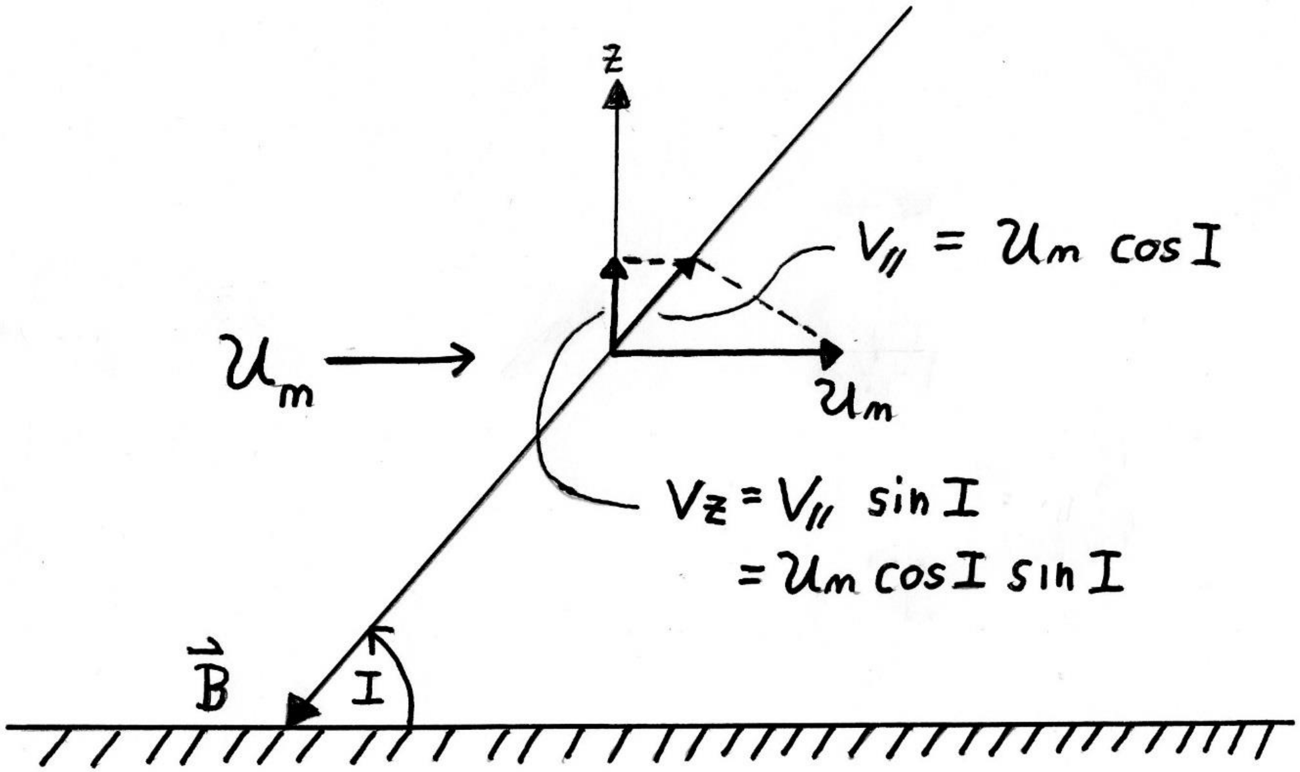
Daily variability

Electron density also varies between night and day mainly due to lack of photoionization process and changes in upper atmosphere dynamics



What else causes Vertical Motions? Roles of Magnetic Field

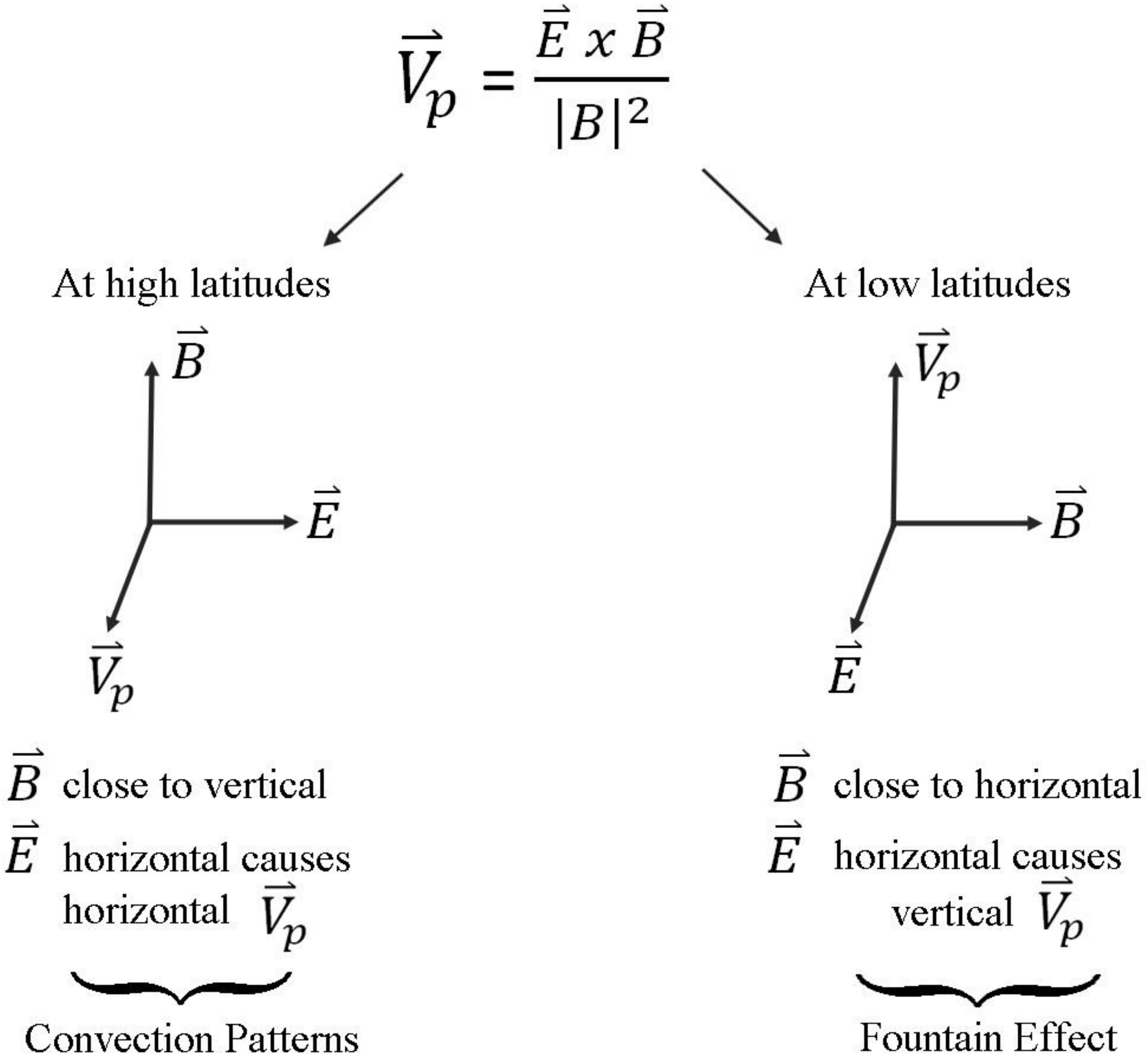
- Neutral Winds (U_m) are horizontal
- Plasma constrained to move || $\vec{B}$



- Middle Latitudes – maximum effect
- Equatorial Latitudes (I = 0º) – small effect
- High Latitudes (I = 90º) – small effect

Unless U_m generates polarization $\vec{E}$-field

Electrodynamics: Motions caused by induced or penetrating $\vec{E}$ -fields



$$\vec{V}_p = \frac{\vec{E}\ x\ \vec{B}}{|B|^2}$$

At high latitudes

$\vec{B}$ close to vertical

$\vec{E}$ horizontal causes horizontal $\vec{V}_p$

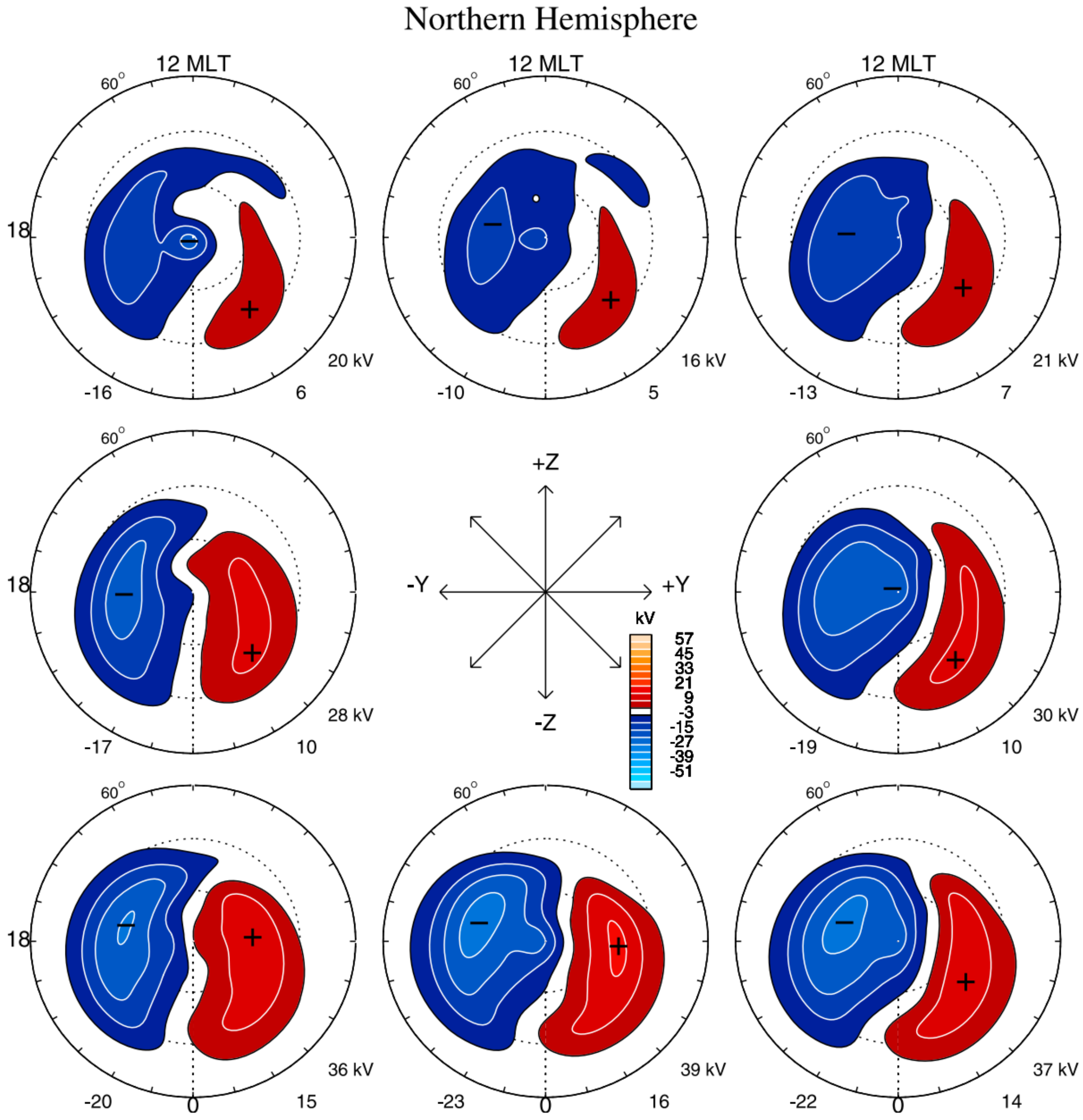
Convection Patterns

At low latitudes

$\vec{B}$ close to horizontal

$\vec{E}$ horizontal causes vertical $\vec{V}_p$

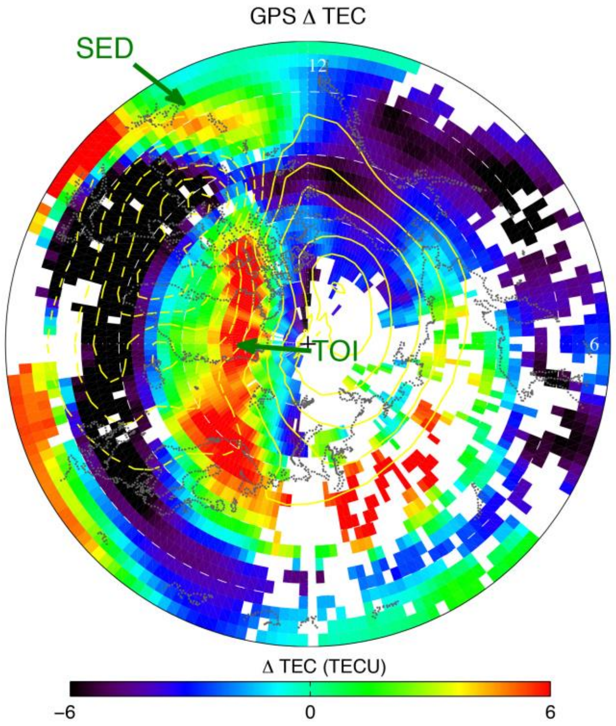
Fountain Effect

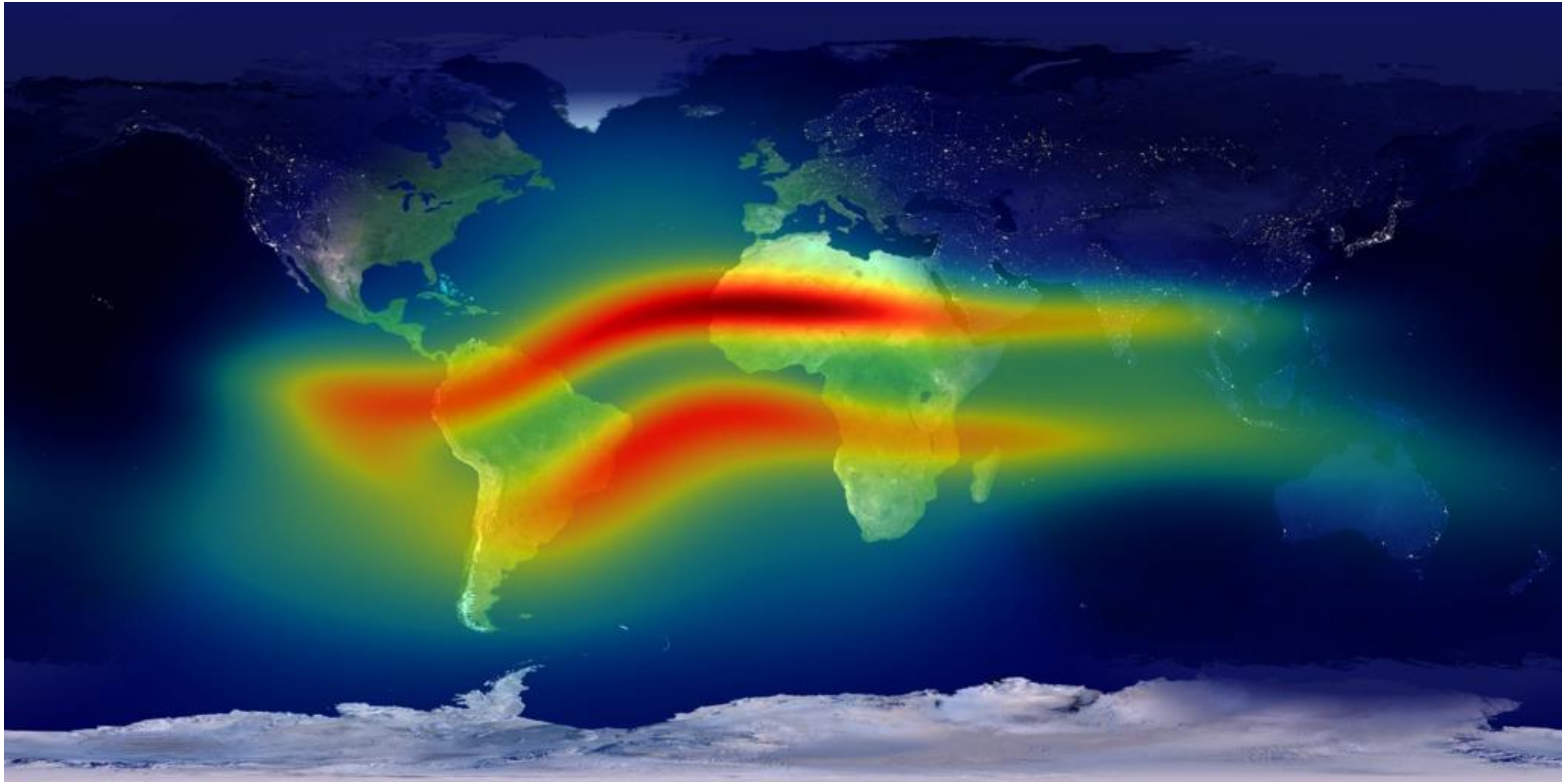


Pettigrew, E. D. et al., 2010

- **Bz** < 0 (under shielding) the electric potential enhances;

- **By** drives the shape of the convection cell impacting on the formation of the ionospheric irregularities (Polar cap patches, TOI)

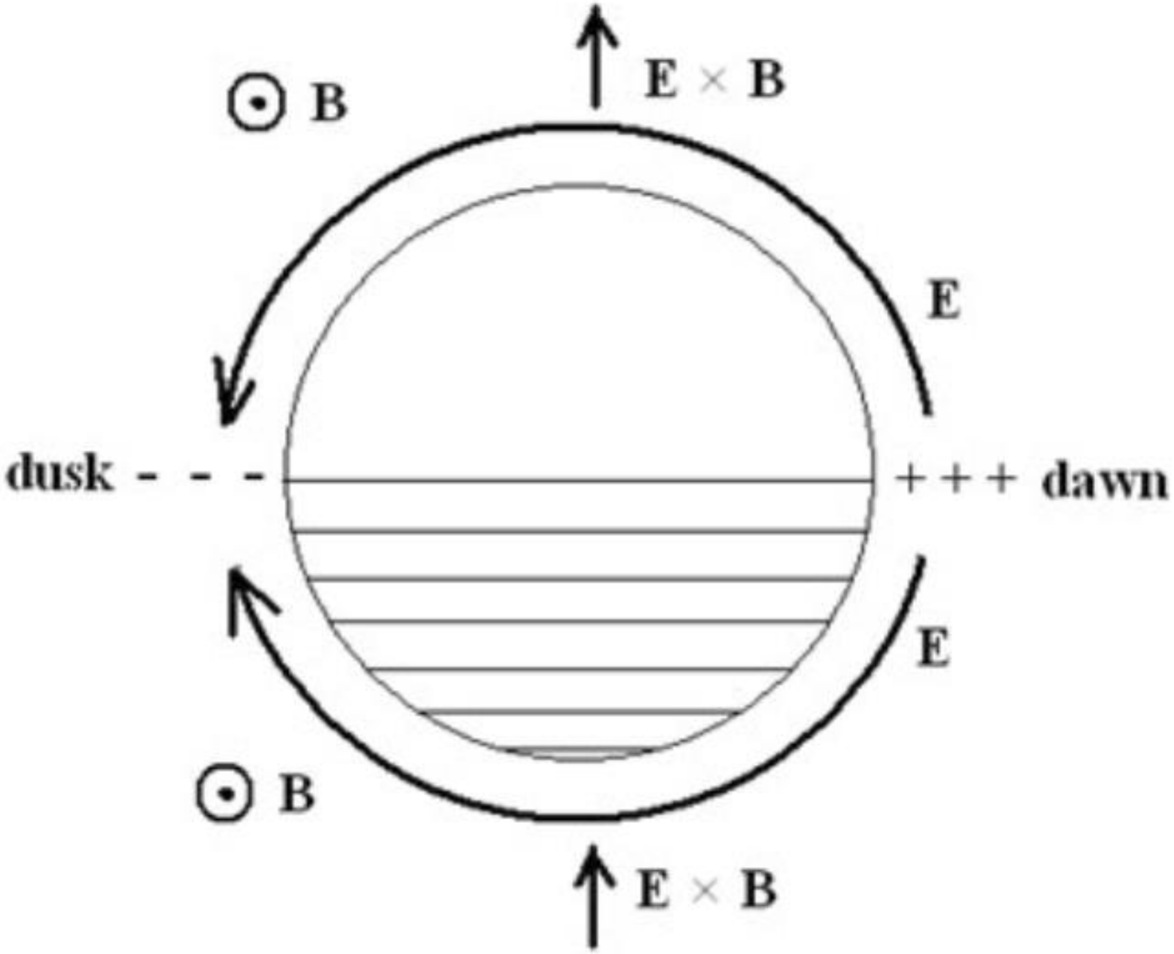


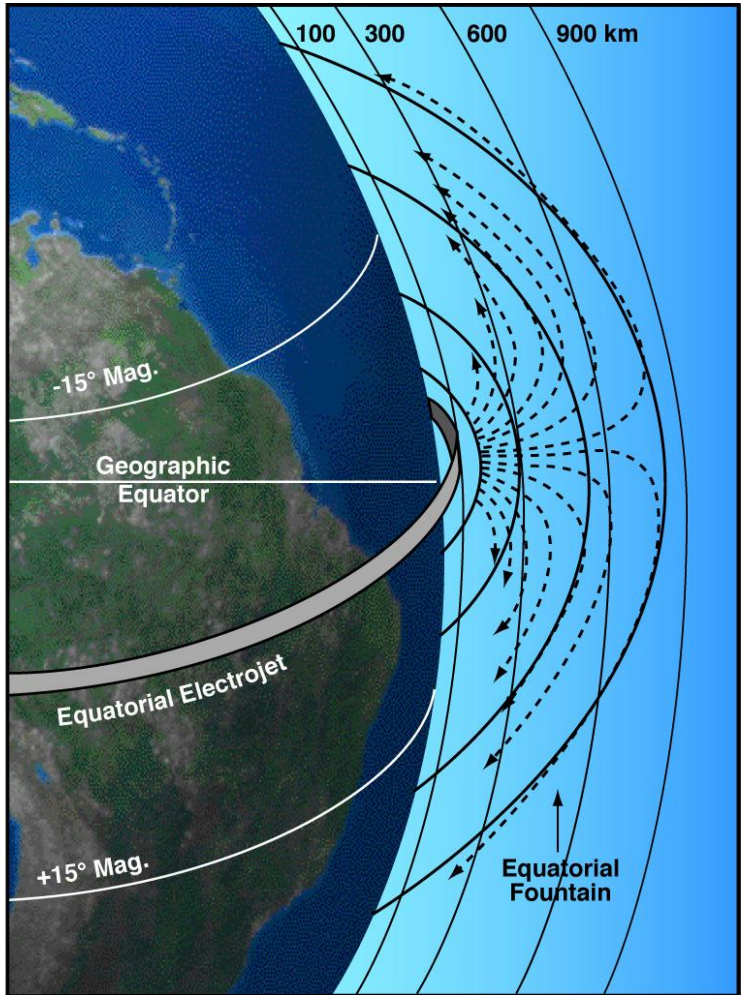


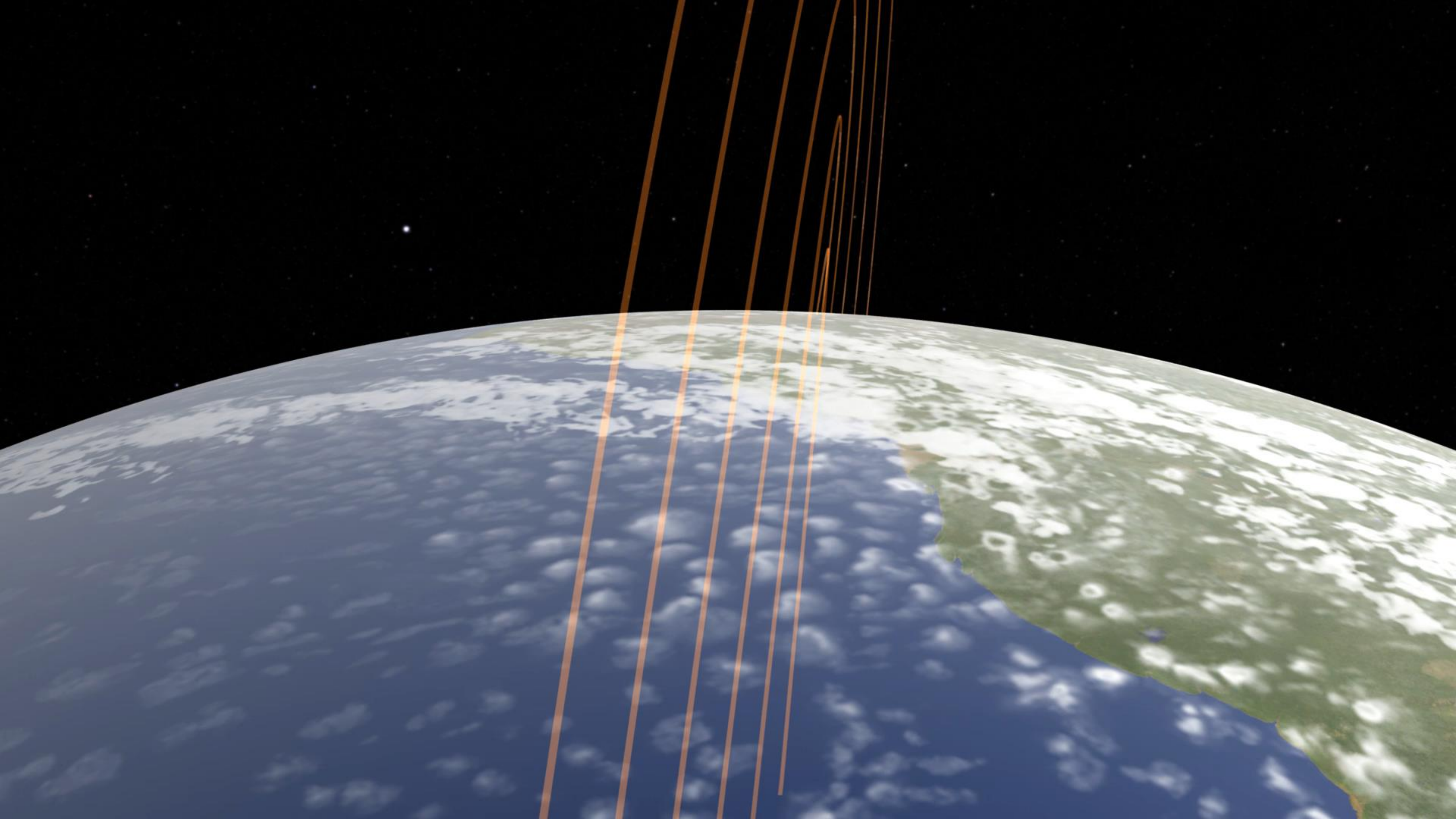
From Chapman theory is expected that the electron density maximizes over the geographic equator at equinox. Actually, the maximum is reached 10°-20° off equator in both hemisphere with a minumum at the magnetic equator. The reason is the combine effect of the electric and geomagnetic field: **the fountain effect**

At equatorial latitudes the electric field is dawn to dusk (i.e. eastward in dayside and westward in nightside) while magnetic field is meridional (S to N)

$\vec{E} x \vec{B}$ **results in an uplift of the ionospheric plasma in the dayside**.

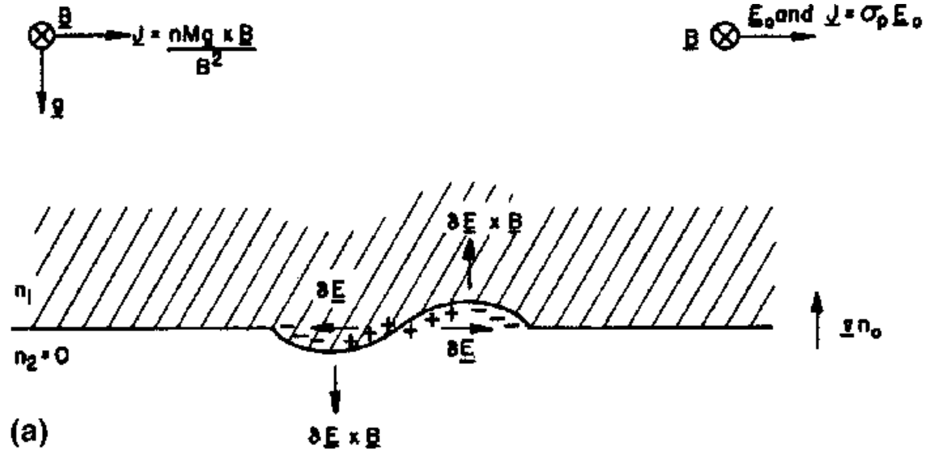


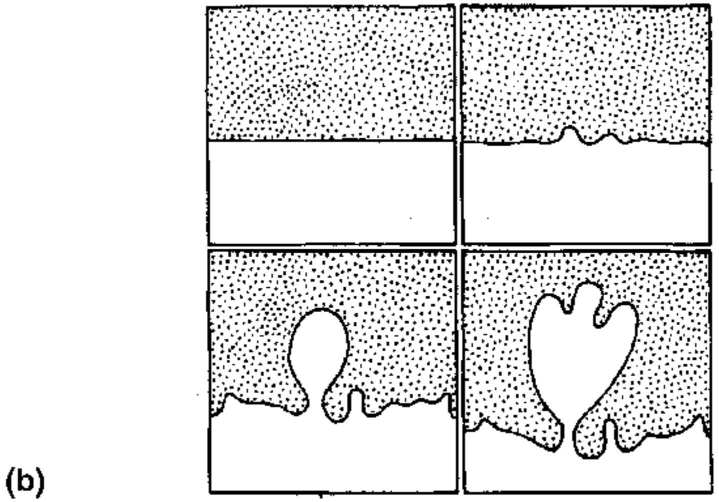


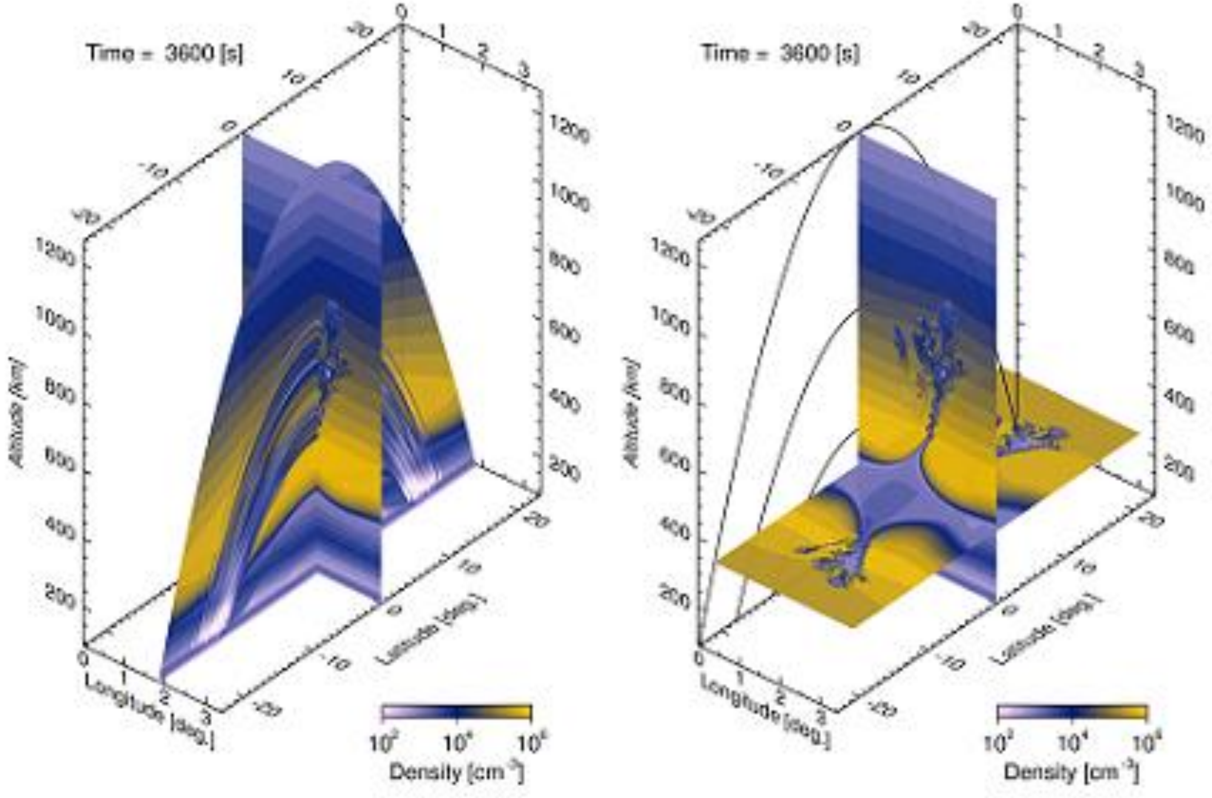


In analogy with the fluid Rayleigh-Taylor instability, bottomside plasma is unstable to perturbations (density gradients against gravity).

Plasma irregularities start at large scale (100 km) and cascade at small scale (<1 m)

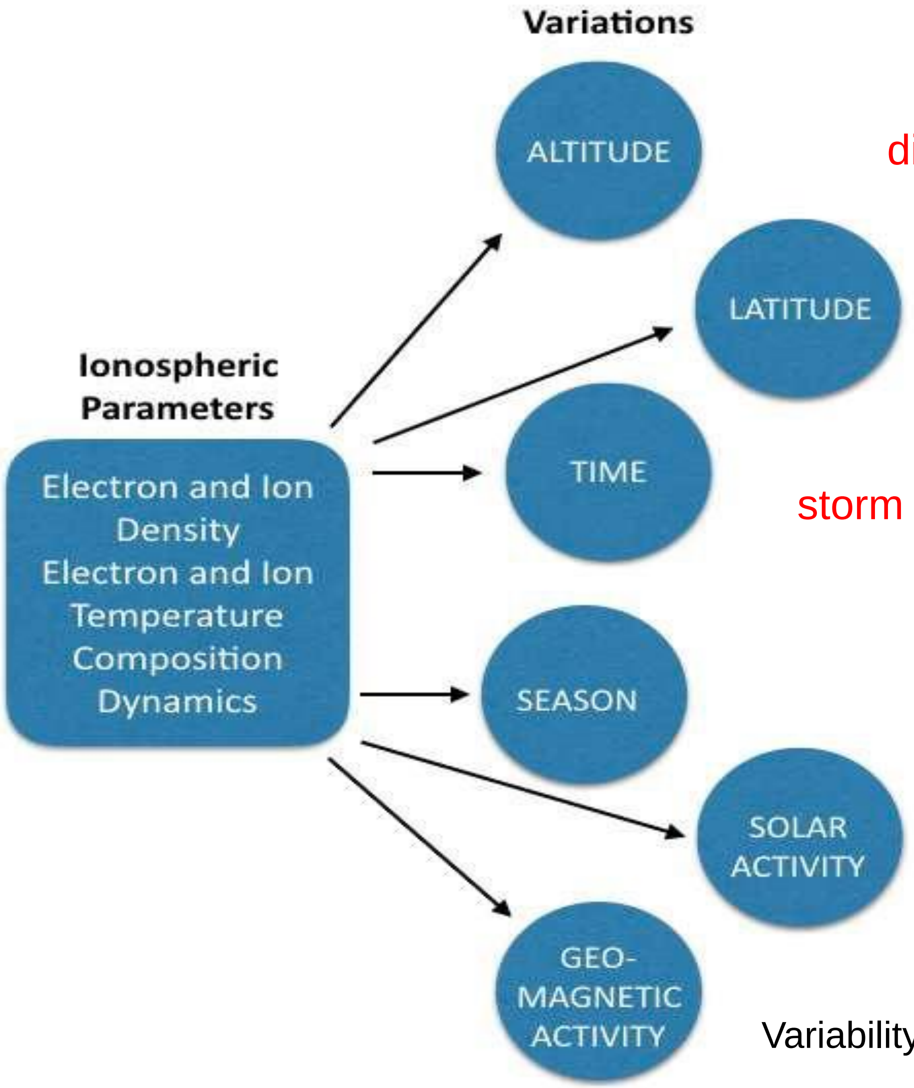






Ionospheric variability

Irregular (mostly unpredictable) variability



disturbed variability vs height

disturbed variability vs latitude

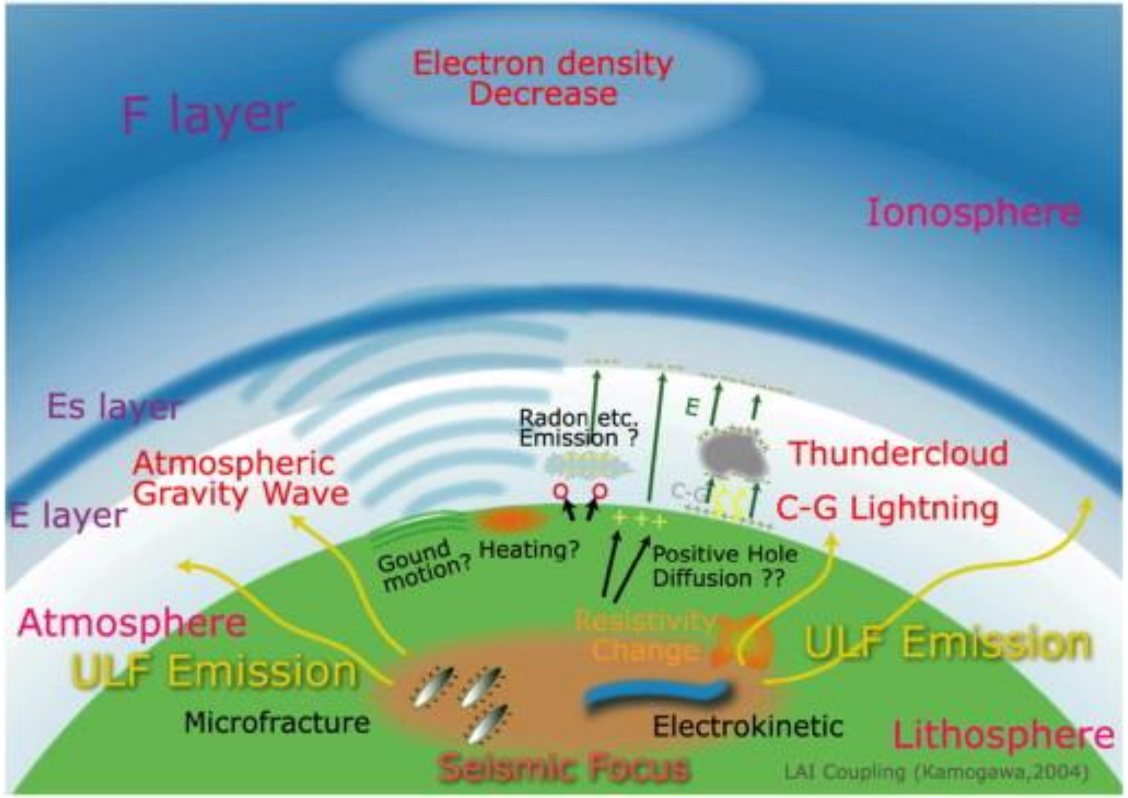
storm time variability

space weather variability

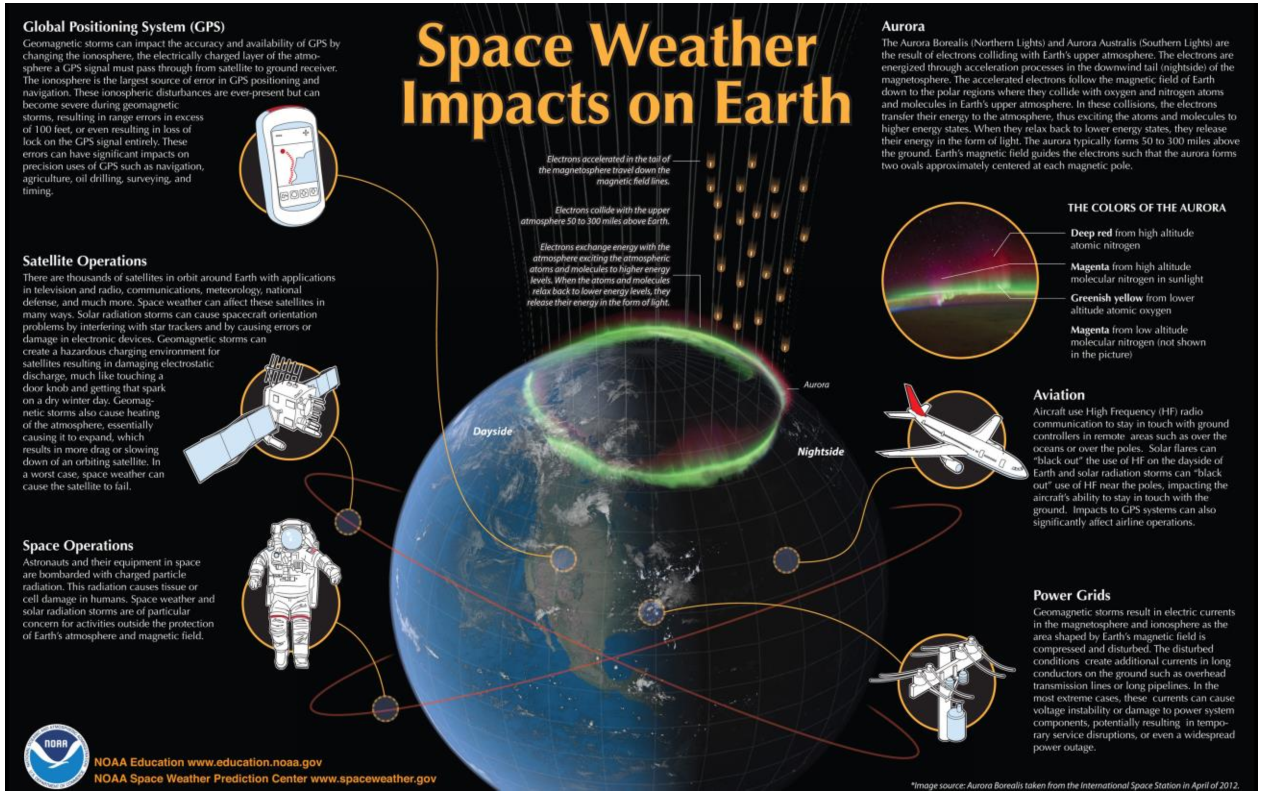
Variability induced by space weather

Ionospheric irregular variability = presence of irregularities: regions of uneven electron density distribution

- Neutral atmosphere variability
- Earthquake, volcanic and tsunami events
- Eclipses
- Anthropogenic sources
- **Space weather events**



From Jin et al., 2015 (adapted from Kamogawa, 2004)



Global Positioning System (GPS)

Geomagnetic storms can impact the accuracy and availability of GPS by changing the ionosphere, the electrically charged layer of the atmosphere a GPS signal must pass through from satellite to ground receiver. The ionosphere is the largest source of error in GPS positioning and navigation. These ionospheric disturbances are ever-present but can become severe during geomagnetic storms, resulting in range errors in excess of 100 feet, or even resulting in loss of lock on the GPS signal entirely. These errors can have significant impacts on precision uses of GPS such as navigation, agriculture, oil drilling, surveying, and timing.

Satellite Operations

There are thousands of satellites in orbit around Earth with applications in television and radio, communications, meteorology, national defense, and much more. Space weather can affect these satellites in many ways. Solar radiation storms can cause spacecraft orientation problems by interfering with star trackers and by causing errors or damage in electronic devices. Geomagnetic storms can create a hazardous charging environment for satellites resulting in damaging electrostatic discharge, much like touching a door knob and getting that spark on a dry winter day. Geomagnetic storms also cause heating of the atmosphere, essentially causing it to expand, which results in more drag or slowing down of an orbiting satellite. In a worst case, space weather can cause the satellite to fail.

Space Operations

Astronauts and their equipment in space are bombarded with charged particle radiation. This radiation causes tissue or cell damage in humans. Space weather and solar radiation storms are of particular concern for activities outside the protection of Earth's atmosphere and magnetic field.

Electrons accelerated in the tail of the magnetosphere travel down the magnetic field lines.

Electrons collide with the upper atmosphere 50 to 300 miles above Earth.

Electrons exchange energy with the atmosphere exciting the atmospheric atoms and molecules to higher energy levels. When the atoms and molecules relax back to lower energy levels, they release their energy in the form of light.

Aurora

The Aurora Borealis (Northern Lights) and Aurora Australis (Southern Lights) are the result of electrons colliding with Earth's upper atmosphere. The electrons are energized through acceleration processes in the downwind tail (nightside) of the magnetosphere. The accelerated electrons follow the magnetic field of Earth down to the polar regions where they collide with oxygen and nitrogen atoms and molecules in Earth's upper atmosphere. In these collisions, the electrons transfer their energy to the atmosphere, thus exciting the atoms and molecules to higher energy states. When they relax back to lower energy states, they release their energy in the form of light. The aurora typically forms 50 to 300 miles above the ground. Earth's magnetic field guides the electrons such that the aurora forms two ovals approximately centered at each magnetic pole.

THE COLORS OF THE AURORA

Deep red from high altitude atomic nitrogen

Magenta from high altitude molecular nitrogen in sunlight

Greenish yellow from lower altitude atomic oxygen

Magenta from low altitude molecular nitrogen (not shown in the picture)

Aviation

Aircraft use High Frequency (HF) radio communication to stay in touch with ground controllers in remote areas such as over the oceans or over the poles. Solar flares can "black out" the use of HF on the dayside of Earth and solar radiation storms can "black out" use of HF near the poles, impacting the aircraft's ability to stay in touch with the ground. Impacts to GPS systems can also significantly affect airline operations.

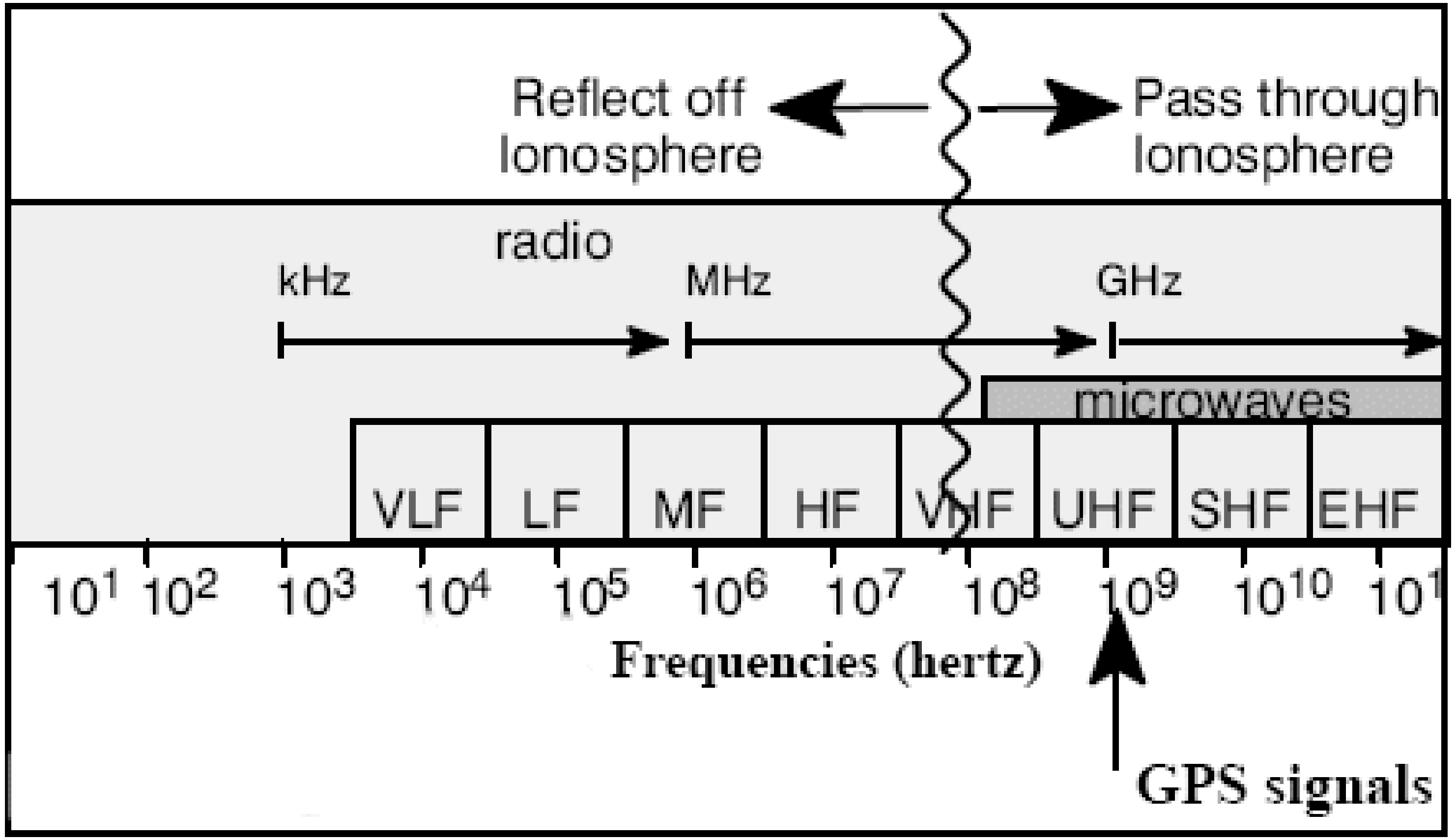
Power Grids

Geomagnetic storms result in electric currents in the magnetosphere and ionosphere as the area shaped by Earth's magnetic field is compressed and disturbed. The disturbed conditions create additional currents in long conductors on the ground such as overhead transmission lines or long pipelines. In the most extreme cases, these currents can cause voltage instability or damage to power system components, potentially resulting in temporary service disruptions, or even a widespread power outage.

NOAA Education www.education.noaa.gov
NOAA Space Weather Prediction Center www.spaceweather.gov

**Image source: Aurora Borealis taken from the International Space Station in April of 2012.*

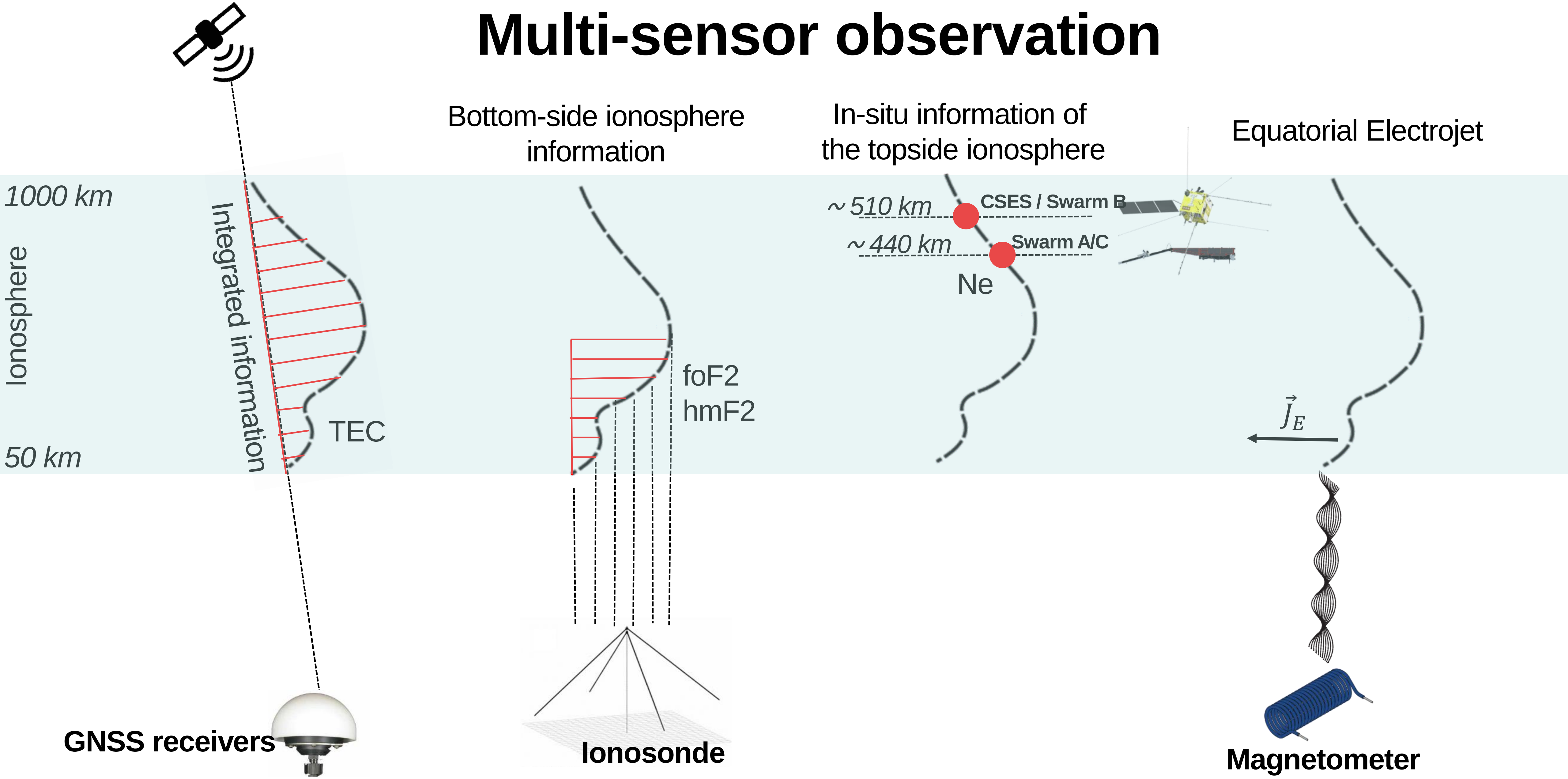
The ionospheric electron density and the height can be derived from radio probing (ground and space-based) exploiting the ionosphere property of influencing the radio wave propagation (by working frequencies spanning from kHz to GHz range).



VHF, HF radars and receivers provide several information on plasma structuring and variability but the devices are sparse and offer poor coverage (in time and space)

L-band (eg. GNSS) is a very powerful diagnostic tool but often does not provide a complete picture in time and space

Multi-sensor observation



Bottom-side ionosphere information

In-situ information of the topside ionosphere

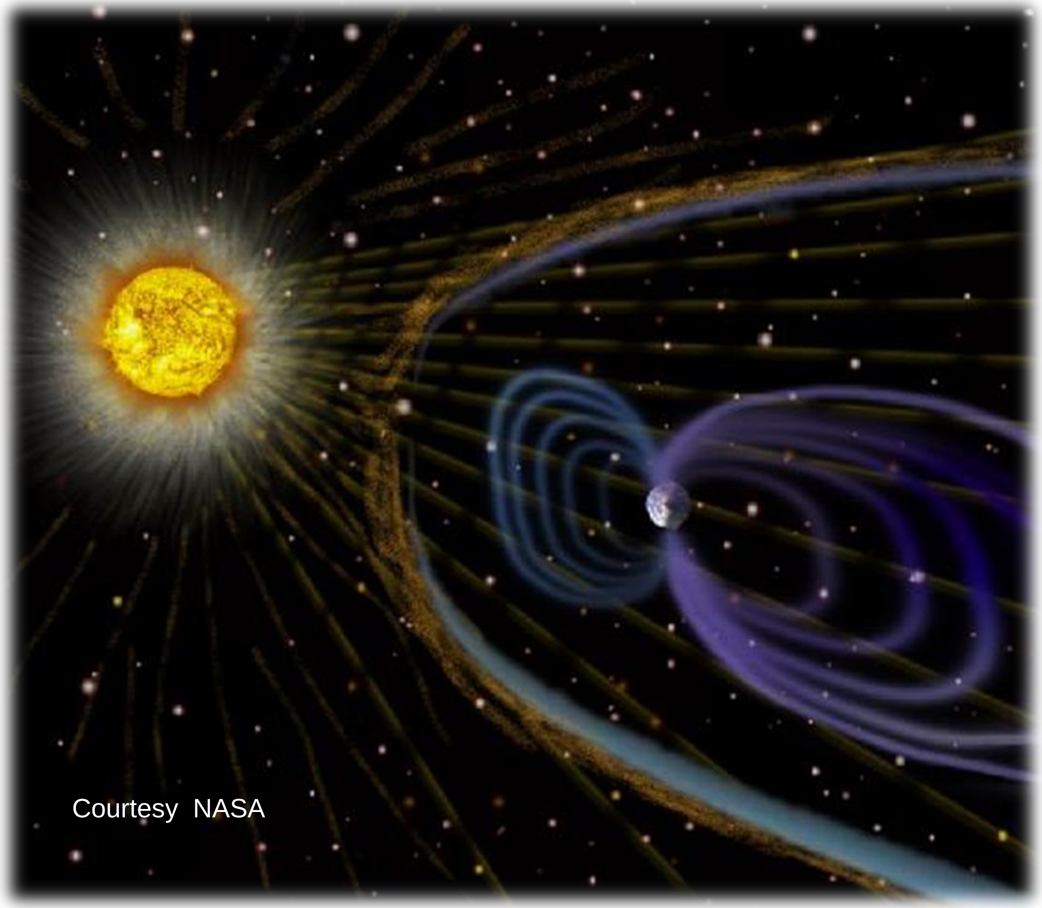
Equatorial Electrojet

GNSS receivers

Ionosonde

Magnetometer

The study of the ionospheric irregularities from the GNSS perspective

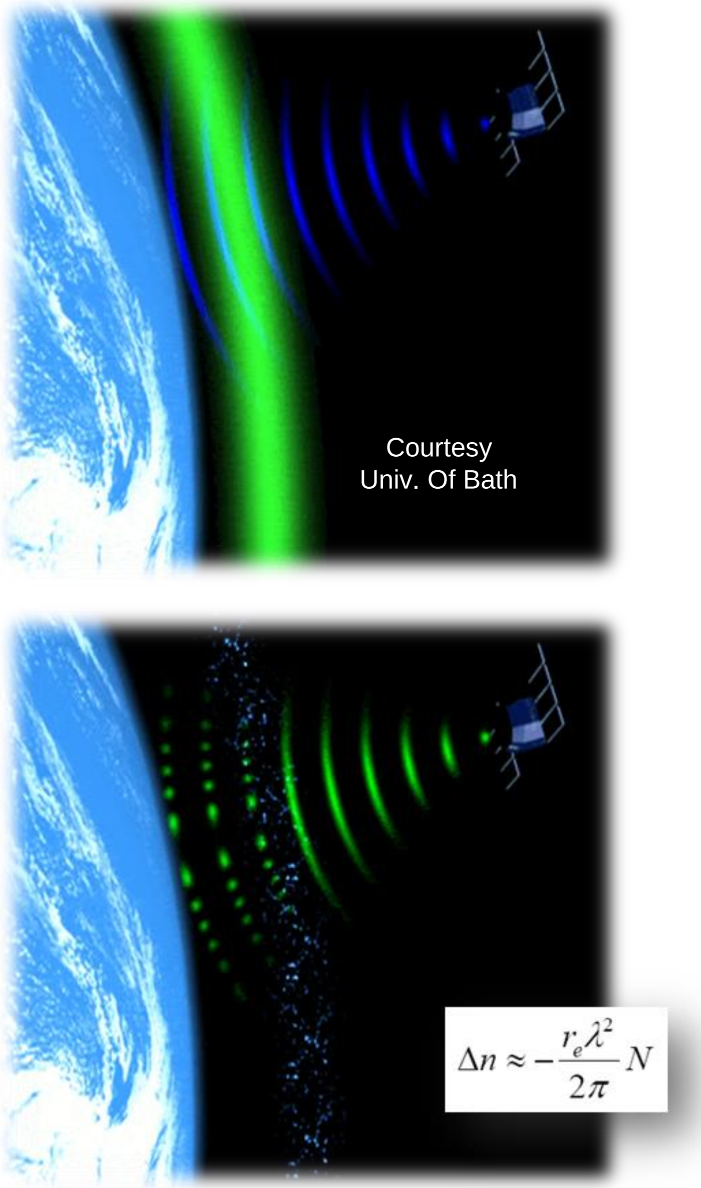


Courtesy NASA

Solar Wind-Magnetosphere coupling causes turbulences of the ionosphere

Gradients of the electron density

Large range of spatial and temporal scales



Courtesy Univ. Of Bath

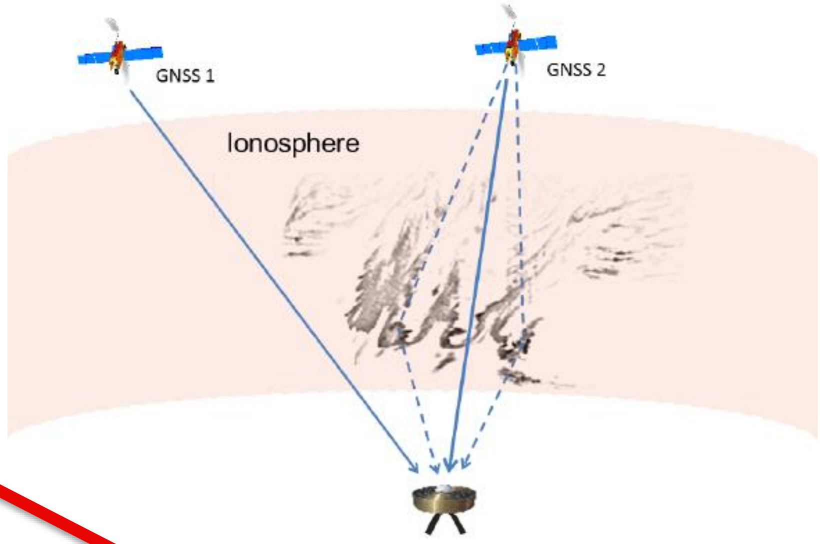
$$\Delta n \approx -\frac{r_e \lambda^2}{2\pi} N$$

Scintillation: phase and amplitude sudden fluctuations of the trans-ionospheric e.m. wave

The study of the ionospheric irregularities from the GNSS perspective

Ionospheric scintillations: sudden and rapid fluctuations of phase and amplitude of the GNSS signals triggered by ionospheric plasma irregularities due to the diffraction of the signal.

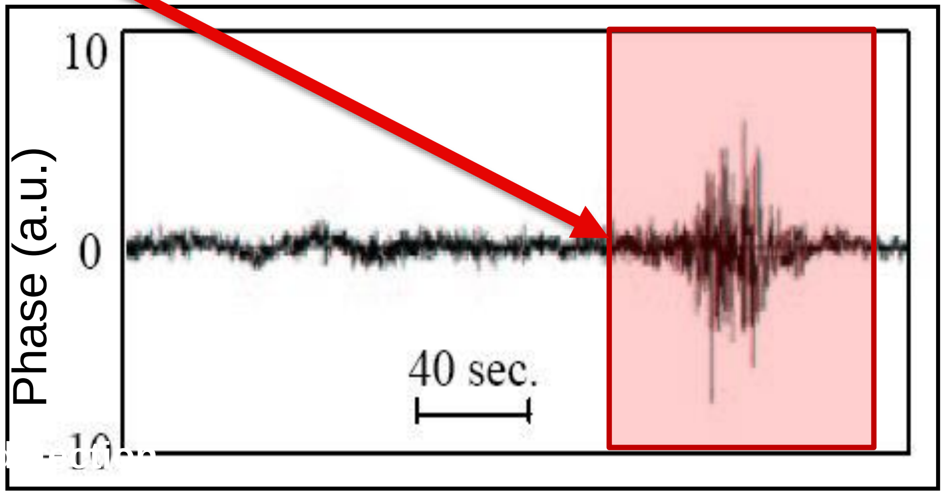
If the signal meets the "irregularities of the ionosphere" the signal may "Scintillate"



How to monitor

$$\sigma_\phi = \sqrt{\langle \phi_{\mathrm{detr}}^2 \rangle - < \phi_{\mathrm{detr}} >^2}$$

$$\boxed{S_4 = \sqrt{\frac{\langle \mathrm{SI}^2 \rangle - < \mathrm{SI} >^2}{< \mathrm{SI} >^2}}}$$



What about the irregularities scale-size triggering scintillations on GNSS signals?

Amplitude scintillation:

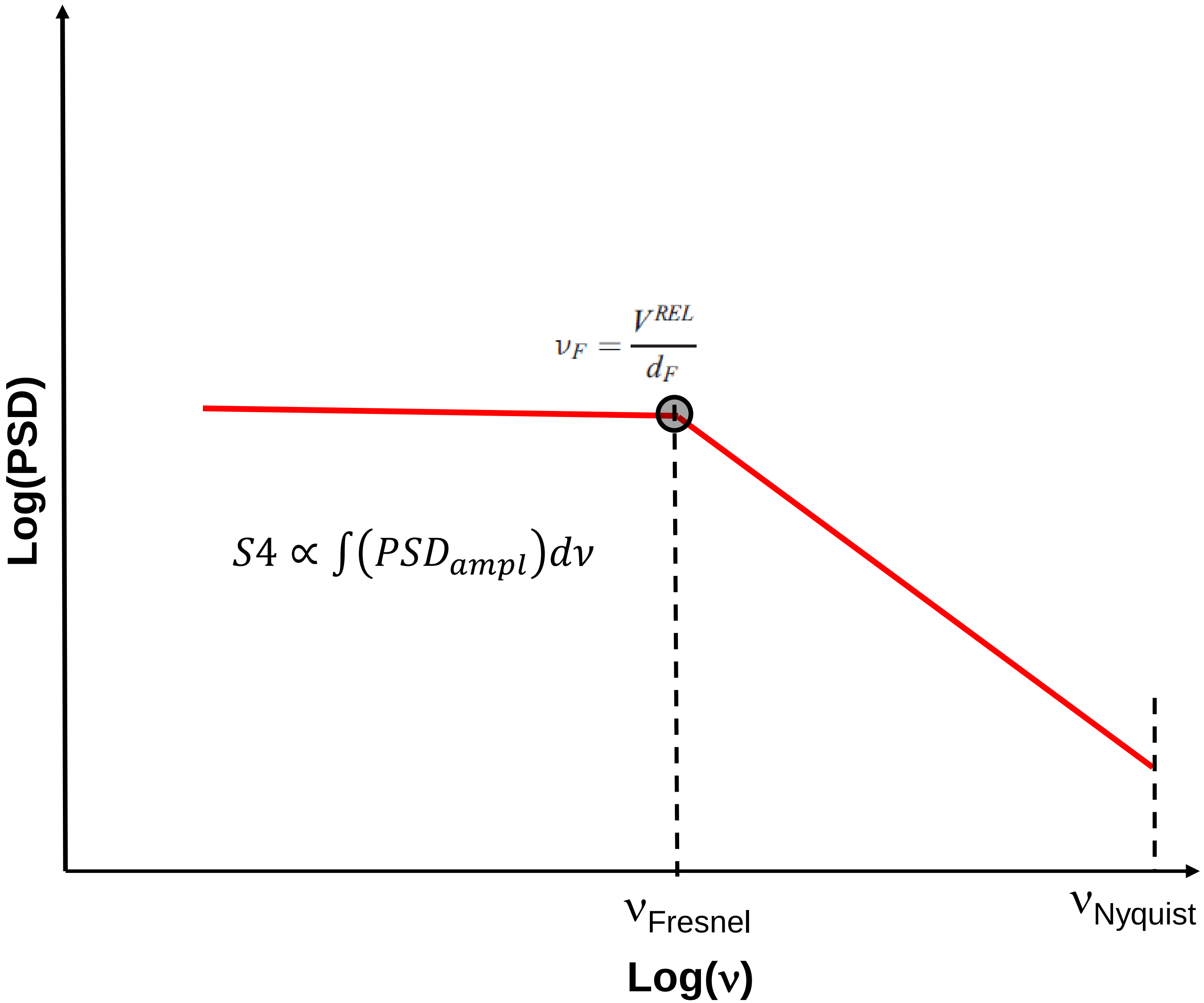
Diffraction triggered by **small-scale irregularities**

What does “small” means?

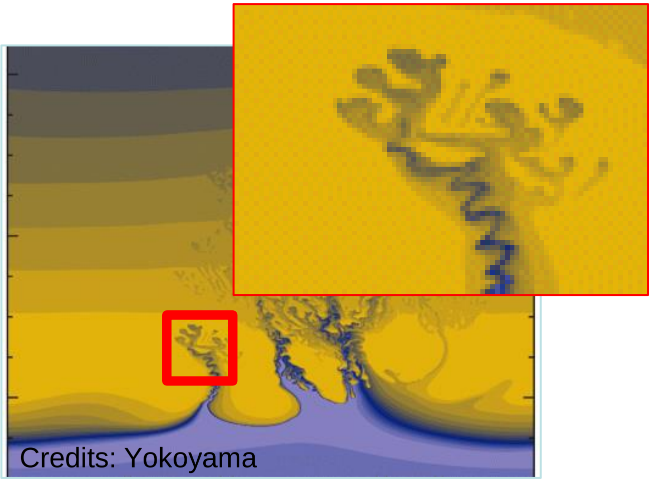
ν_F: Fresnel’s Frequency
V^{REL}: relative velocity ray-path-ionosphere
$d_F = \text{sqrt}(2*\lambda*h_{IPP})$

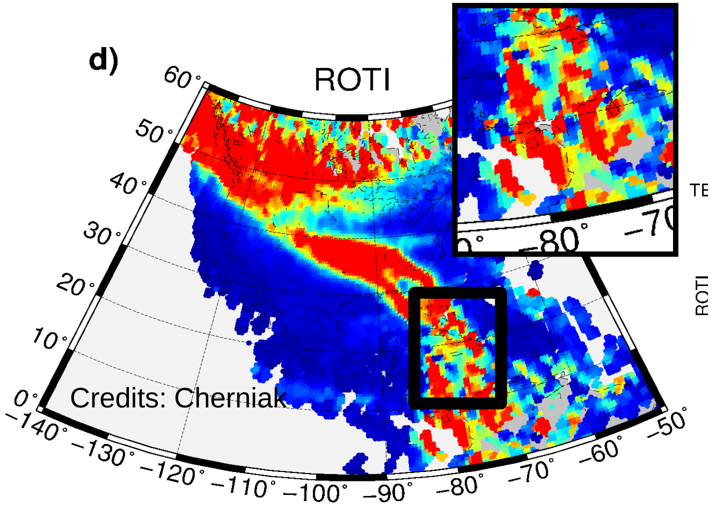
$\lambda \sim 19$ cm for L1, assuming $h_{IPP} = 350$ km
d_F is about 250 m

Small for GNSS signals: scale-sizes up to hundreds of meters

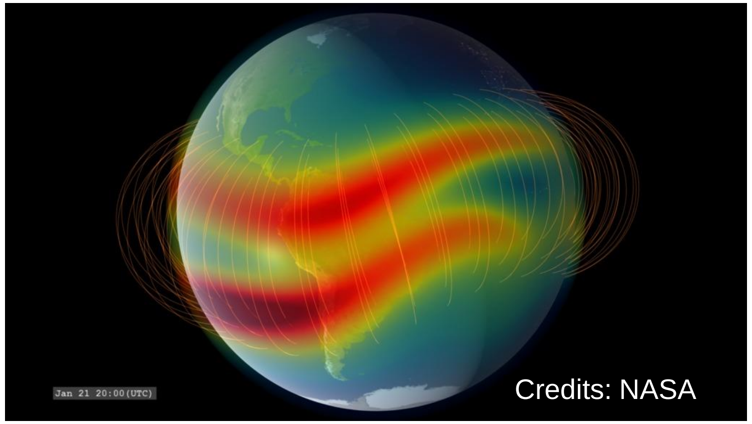


The study of the ionospheric irregularities

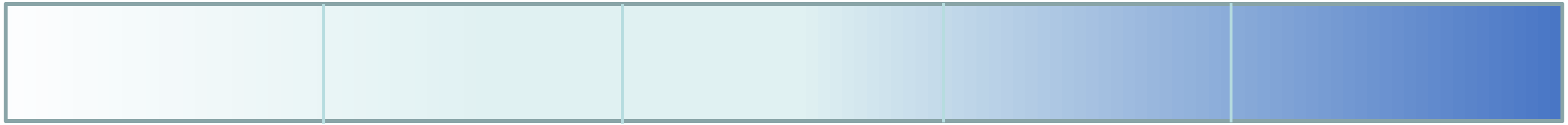

Credits: Yokoyama



Credits: Cherniak



Credits: NASA



100 m

1 km

10 km

100 km

1000 km

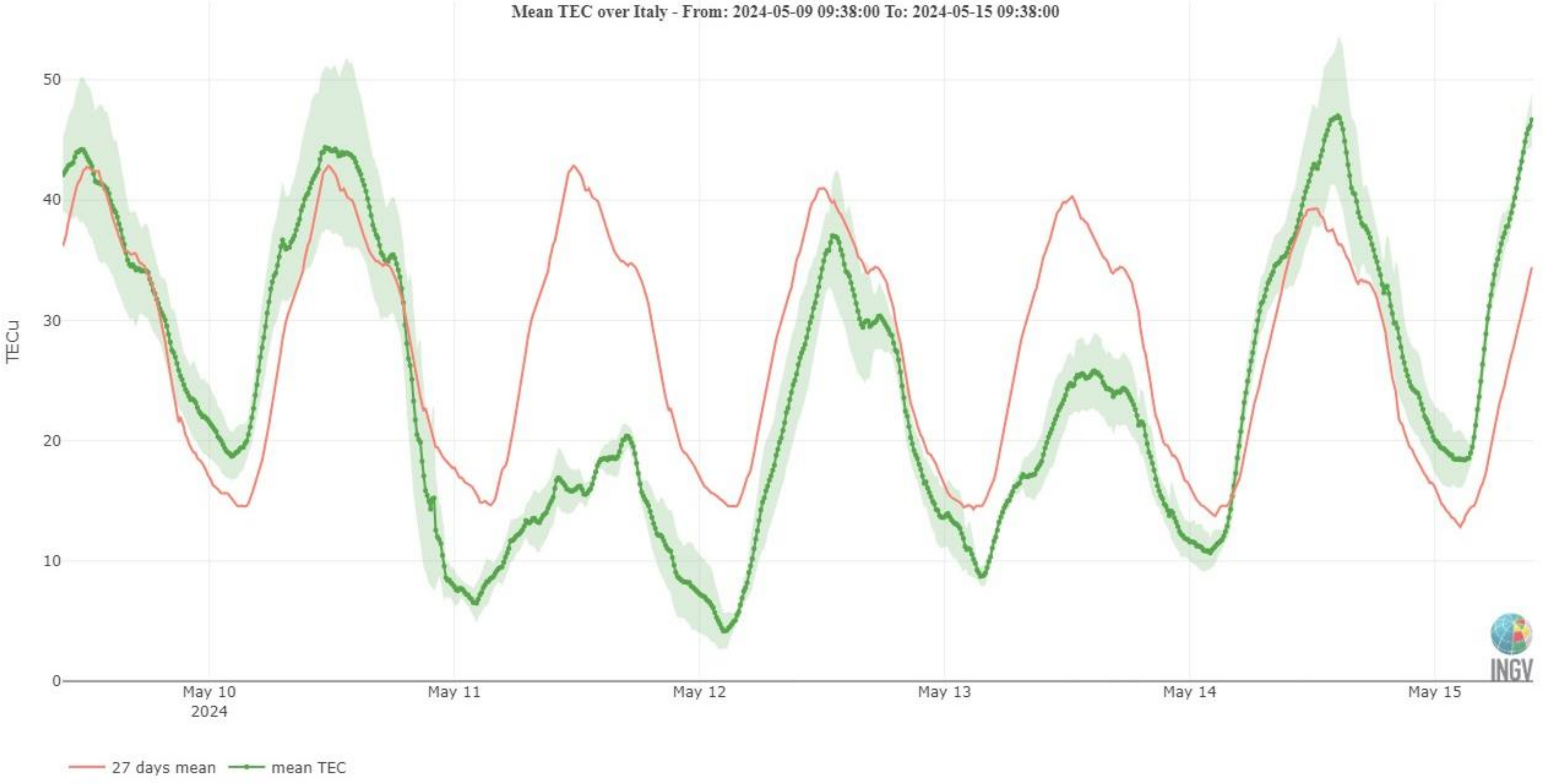
*Small scale
(Fresnel's scale)

*Medium scale

*Large scale

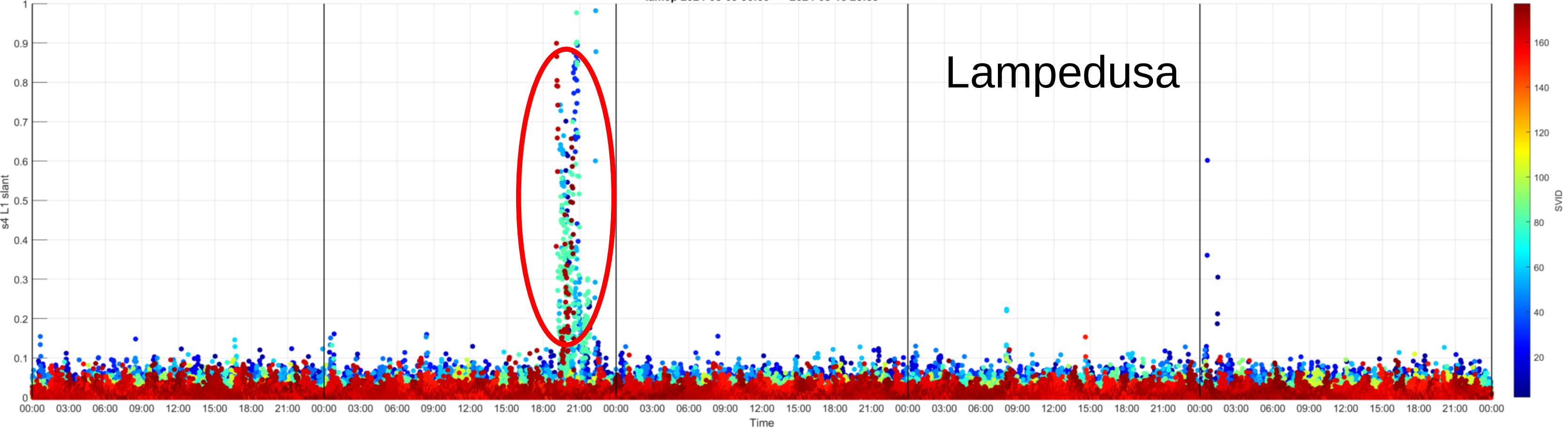
*from a GNSS perspective

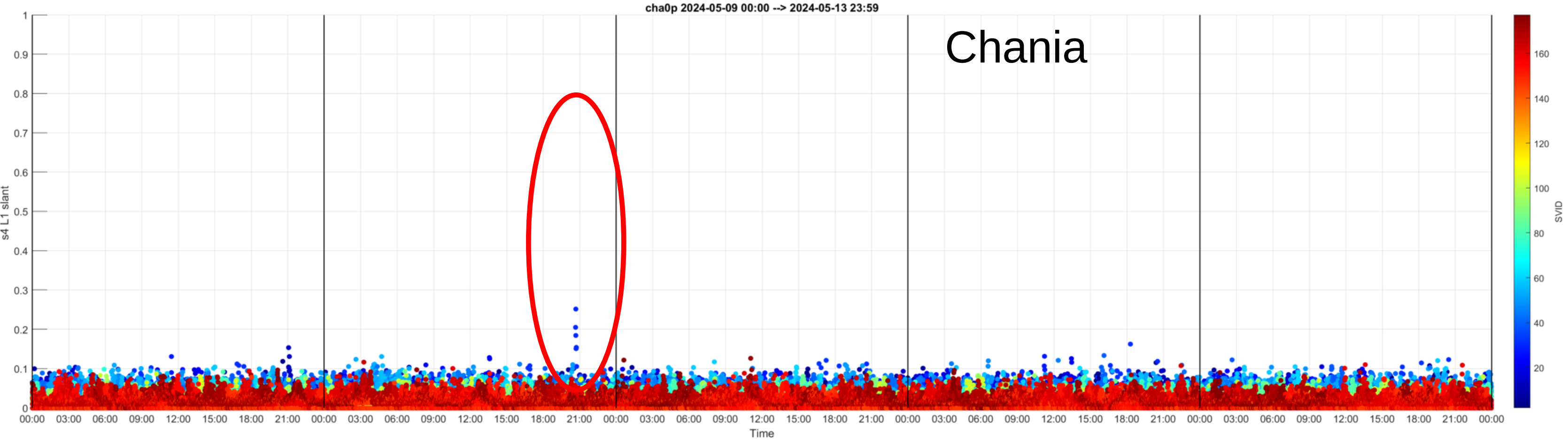
The *Mother's day* storm effect on the TEC over Italy

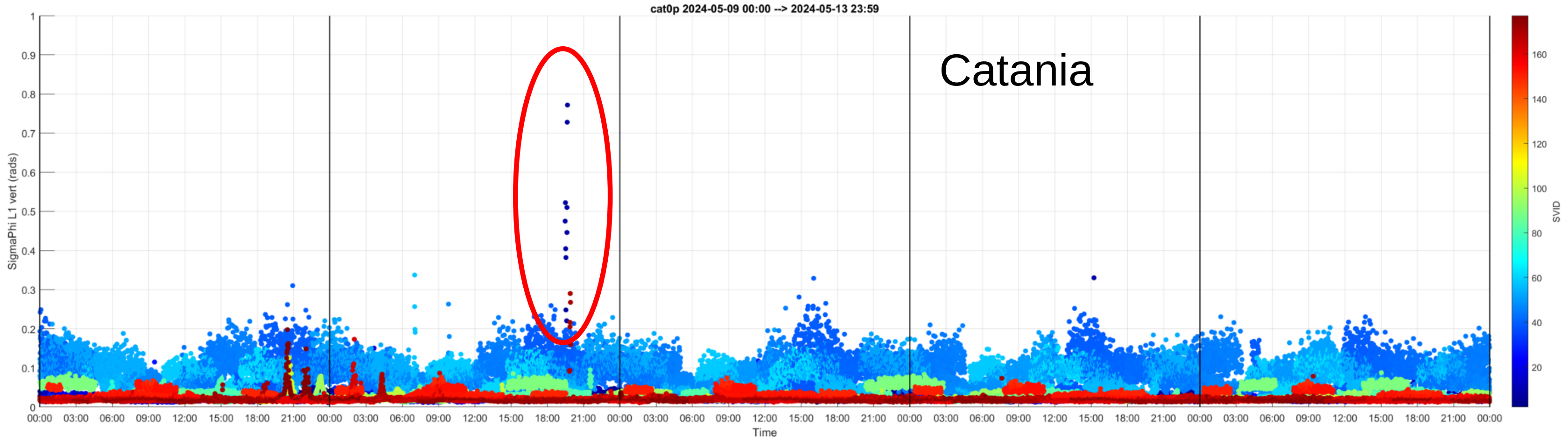


www.eswua.ingv.it

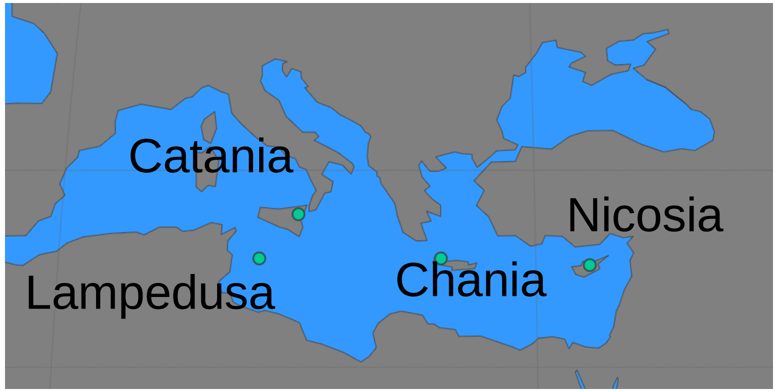
The *Mother's day storm:* scintillations recorded in the Mediterranean area







A strong plasma bubble event on 10 May has been recorded up to Catania (lat: 37.7°N)!



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Thank you for your attention during this very brief introduction to the ionospheric fundamentals

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