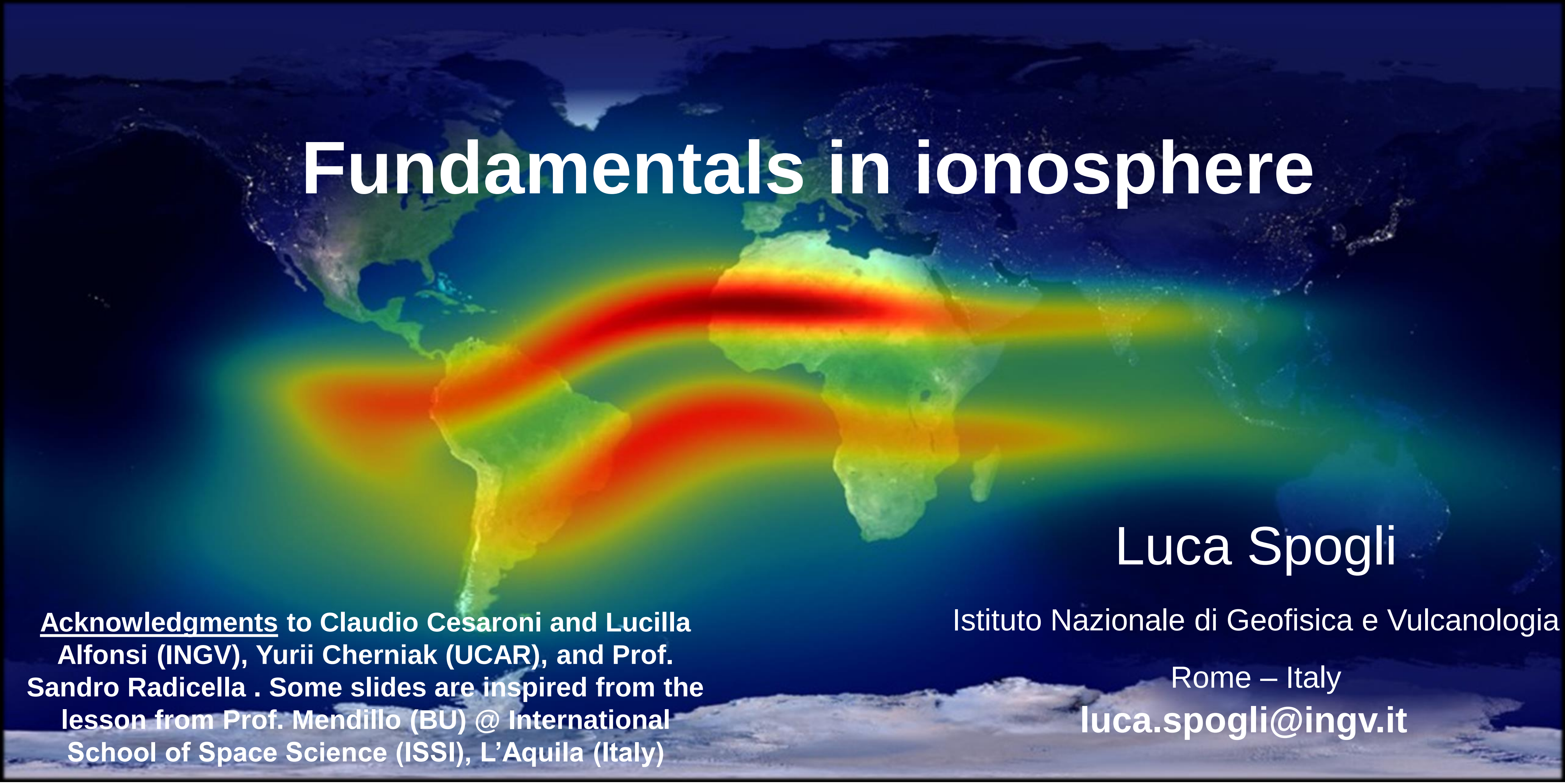

Fundamentals in ionosphere

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<u>Acknowledgments</u> to Claudio Cesaroni and Lucilla Alfonsi (INGV), Yurii Cherniak (UCAR), and Prof. Sandro Radicella . Some slides are inspired from the lesson from Prof. Mendillo (BU) @ International School of Space Science (ISSI), L'Aquila (Italy)

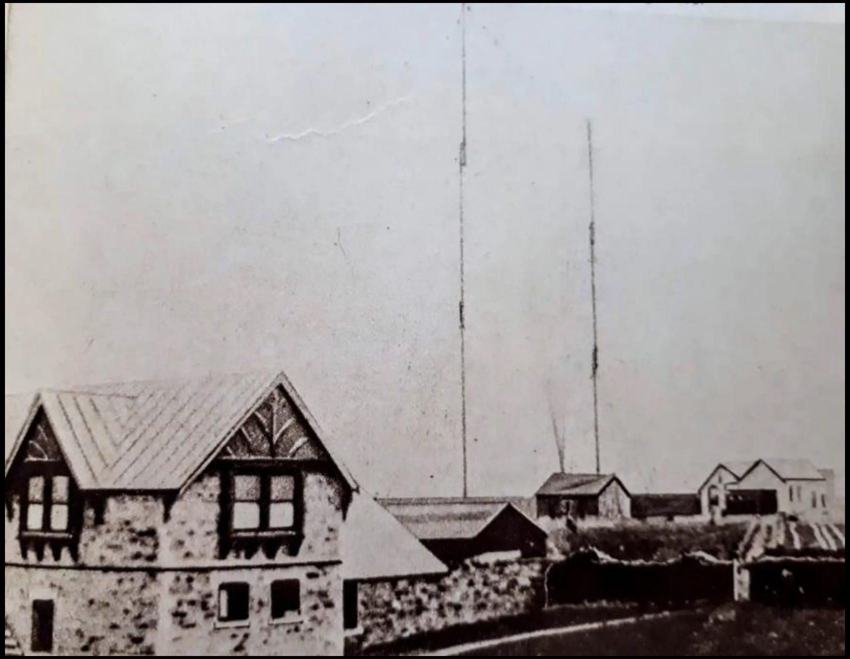
ISTITUTO NAZIONALE
DI GEOFISICA E VULCANOLOGIA

2nd PITHIA-NRF Training School supported by T-FORS project
February 5 - 9, 2024, Leuven

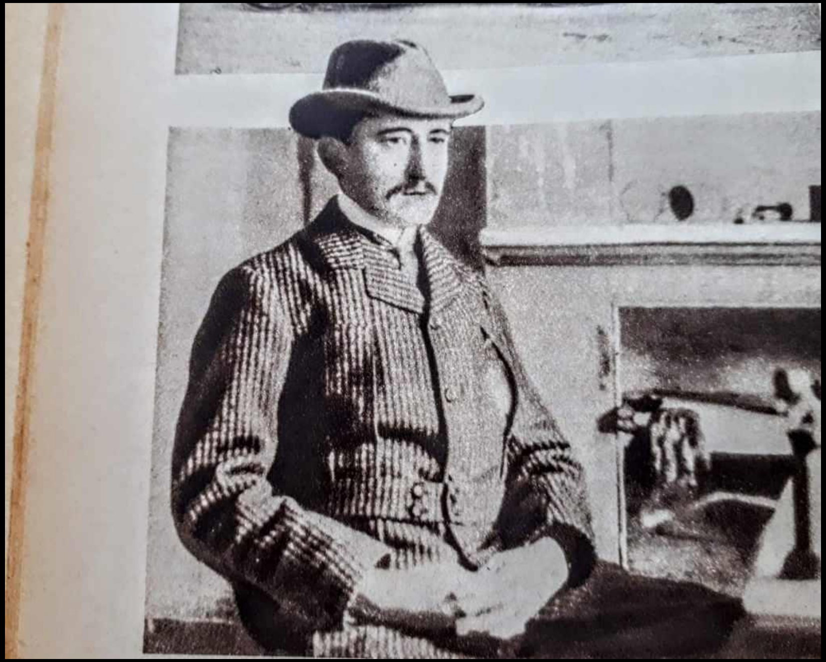
How everything began…

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

Guglielmo Marconi
(1874-1937)



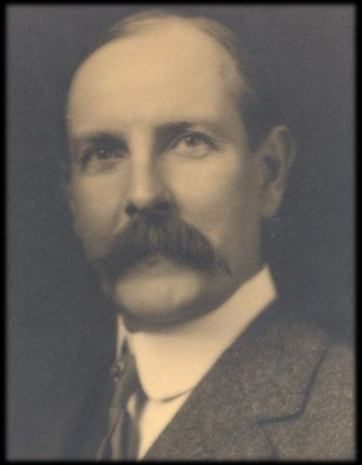
Marconi's primitive transmission station at Poldhu Cornwall. Note the fragile antenna.



Marconi seated with his experimental receiving equipment at Signal Hill.

The ionosphere was born!

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 ***ionosphere***)



Arthur Kennelly (1861-1939)

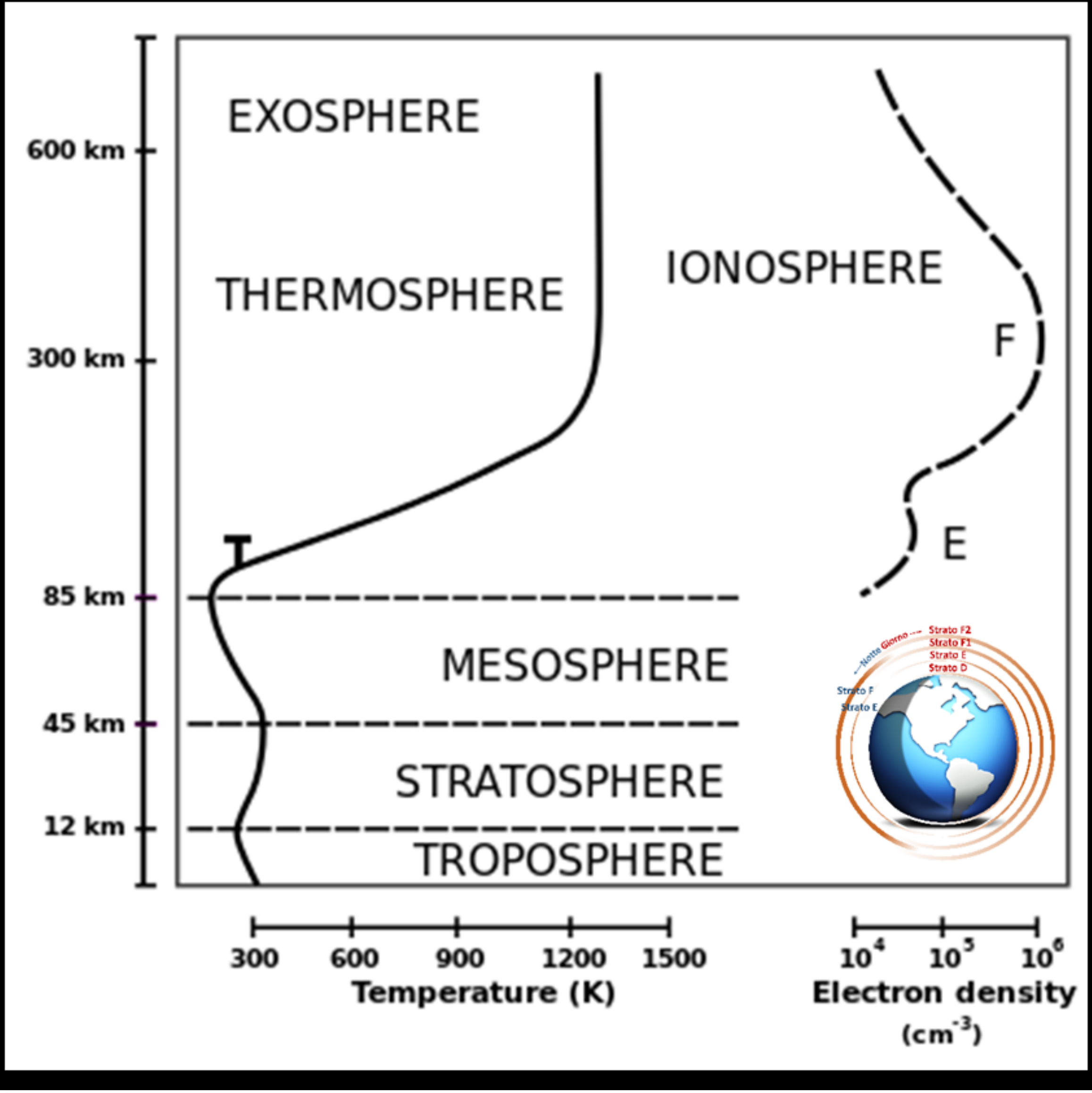
Oliver Heaviside (1850-1925)

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 (1892-1965)

Ionosphere is

A plasma in which ions and electrons exhibit such a density to influence the radio wave propagation (from kHz to GHz range).



- Globally neutral
- The density of ion and electrons is very low wrt the neutral density.
- Cold plasma (collision energy can be neglected in most of the cases)
- It has its own plasma frequency (critical frequency), is the frequency of oscillation that occurs in a plasma disturbed from local electrical neutrality as it relaxes back toward equilibrium. **The frequency of this oscillation depends on the density of free electrons in the plasma that varies in space and time.**
- Relative maxima and minima of electron density identify the ionospheric regions and layers.

Recipe for Earth’s ionosphere

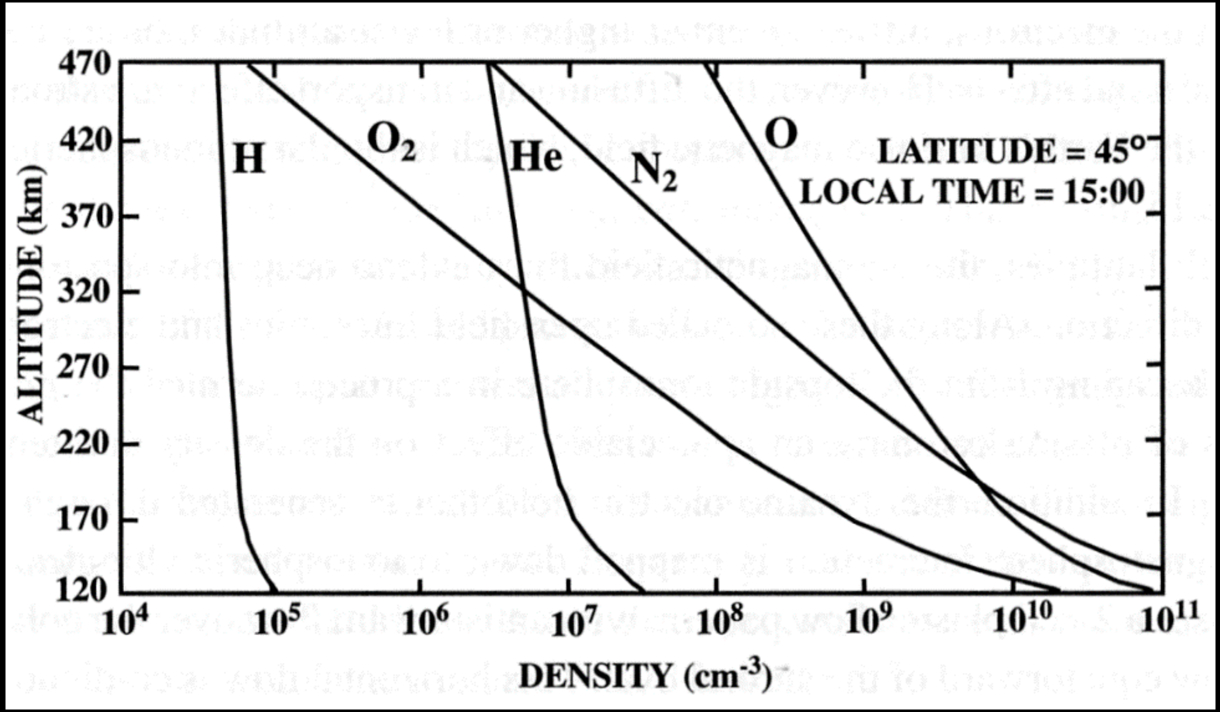
Doses for 1 planet

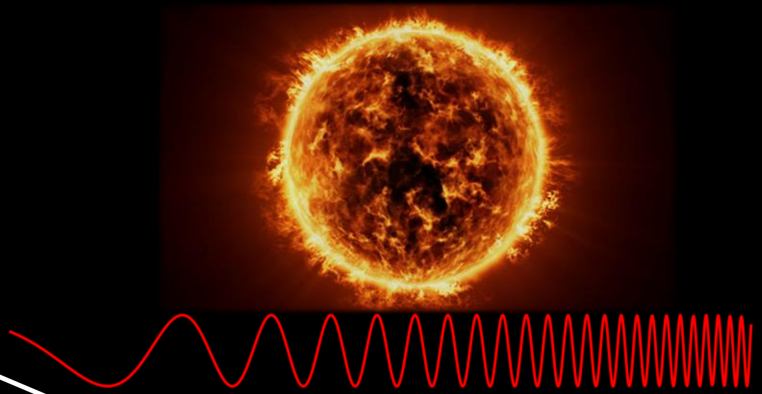
1. Sprinkle a generous amount of Photoionisation

Photoionisation

$$X + h\nu \rightarrow X^{+} + e^{-}$$

Composition of the Neutral Atmosphere





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

Species	**E (eV)**	**λ(Å)**
H	13.60	910
O	13.62	910
O_2	12.06	1030
N_2	15.58	790
He	24.59	500

$$\lambda(\text{Å}) \approx \frac{12345}{E\ (eV)})$$

The Oxygen case

$$O + \gamma(910\ \text{Å}) \rightarrow O^{+} + e^{-}$$

Production Function P for
monochromatic ionizing radiation
“Chapman Theory”

$$P(h) = [O](h) \otimes F_{910}^{Sun}(h) \rightarrow [O^{+}](h) + [e^{-}](h)$$

So, what shape we do expect for $P(h)$?

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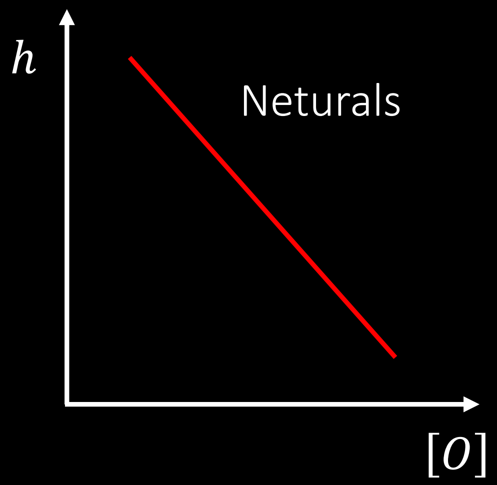

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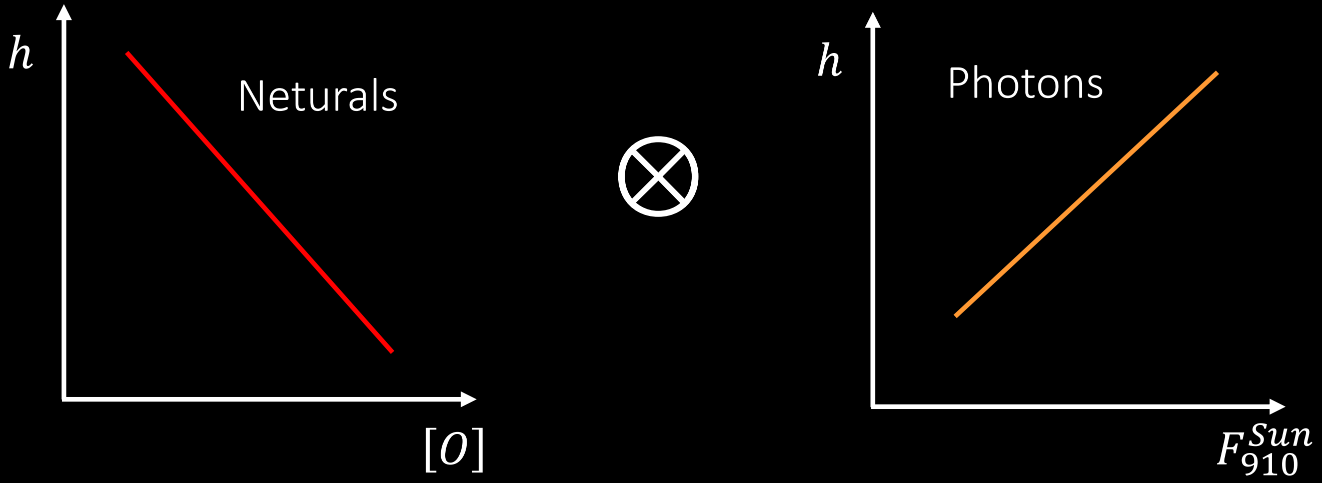

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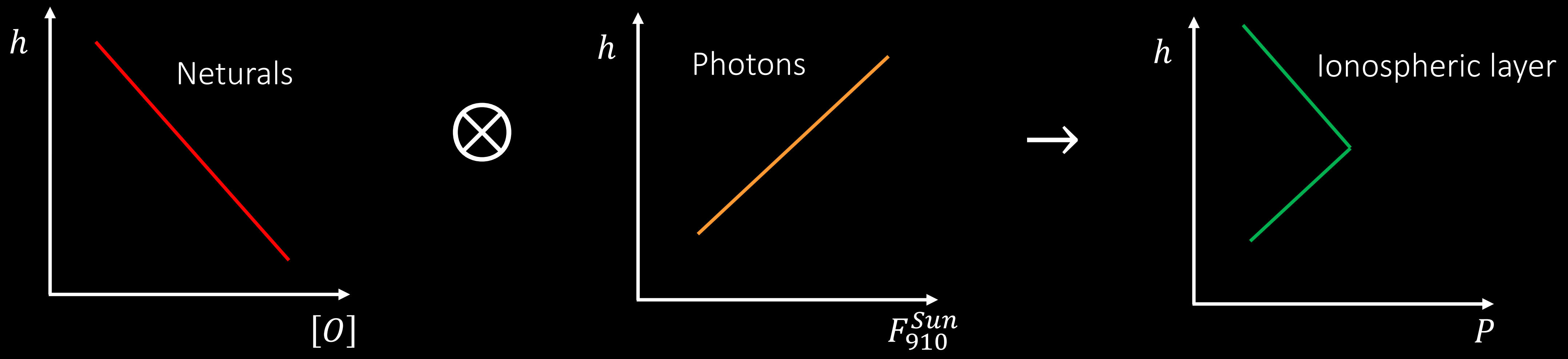
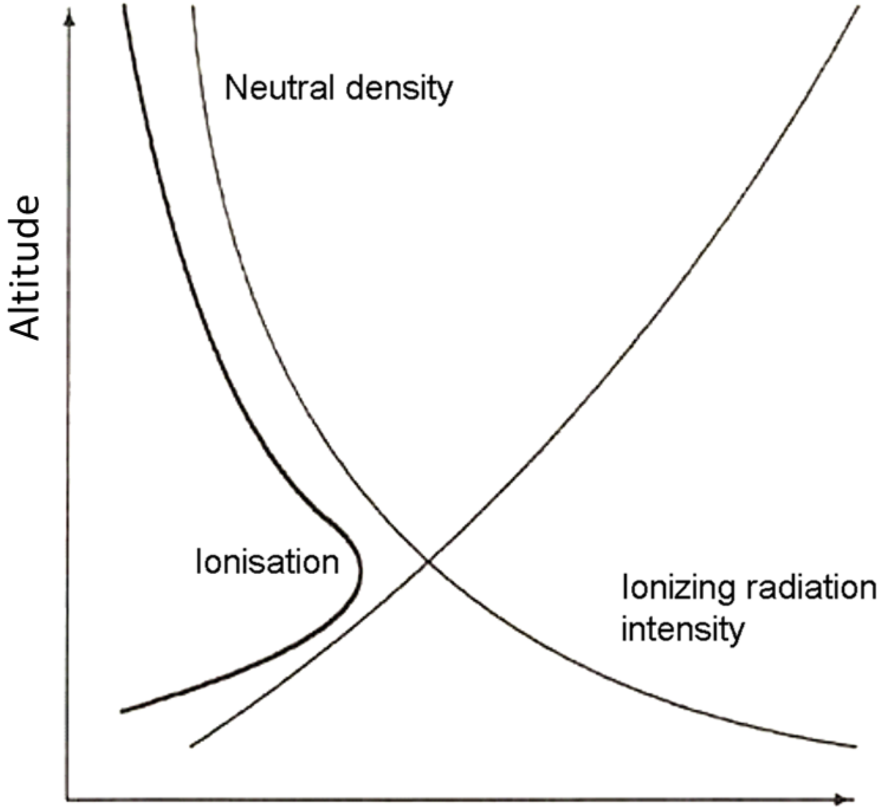


Chapman theory (1931)



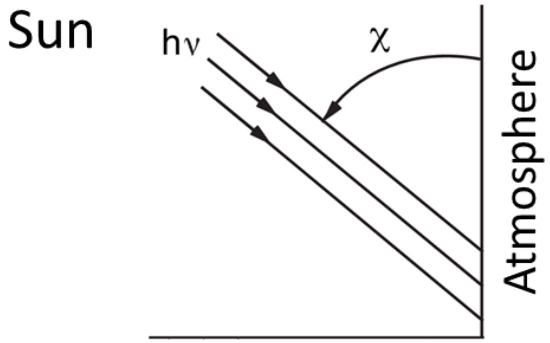
$$n_e = \sqrt{\frac{S_0}{\alpha}\exp\left(\frac{1}{2}-\frac{z}{2H}-\frac{\sec\chi}{2}\exp\left[-\frac{z}{H}\right]\right)}$$

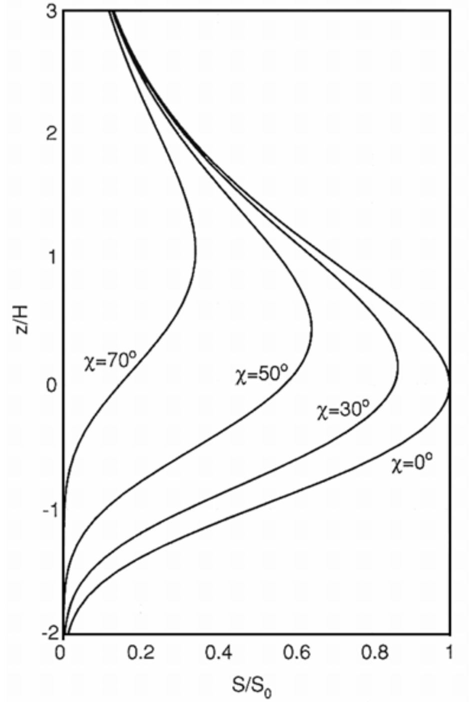
S – rate of ionization
a – recombination rate
χ – solar zenith angle

$$z = \left(\frac{h - h_{max}}{H}\right)$$

$$H = kT/mg$$

Mathematically formulated by Sydney Chapman





Rate of photo-ionization (per volume) = electron production rate (relative)

The Oxygen case

Ionisation cross-section

$$P(h) = P_{i,e^-}(h) = F^{Sun}_{\lambda_{ion}}(h) \cdot [O](h) \cdot \sigma_{ion}$$

Photons

$\lambda > \lambda_{ion}$ No photoionisation

$\lambda < \lambda_{ion}$ Photoionisation + Extra Energy

The Oxygen case

Ionisation cross-section

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$O + \gamma(\lambda < \lambda_{ion}) \rightarrow O^+ + e^{-*}$ Energetic Photo-electron with kinetic energy $E_{e^{-*}}$

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If $E_{e^{-*}} > E_O^{ion} \longrightarrow O + e^{-*} \rightarrow O^+ + e^-$ Secondary ionisation

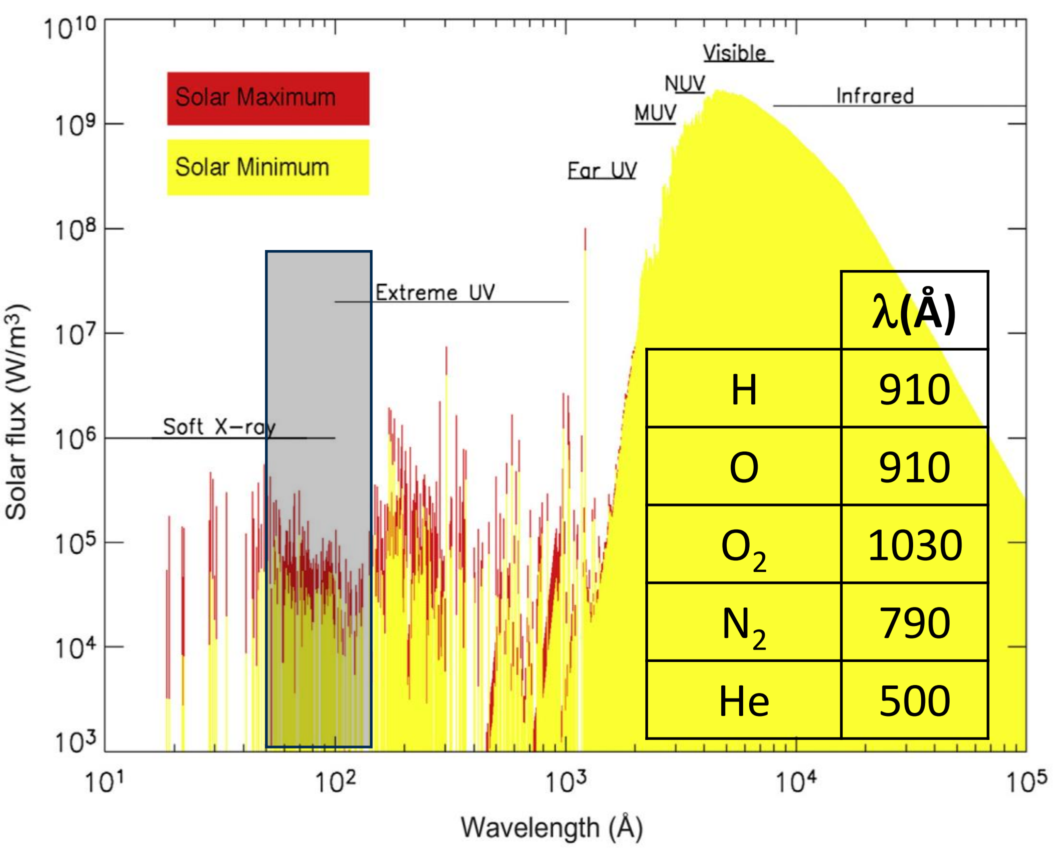
Ionization Potential

A very energetic photon can lead to several ion-electron pairs

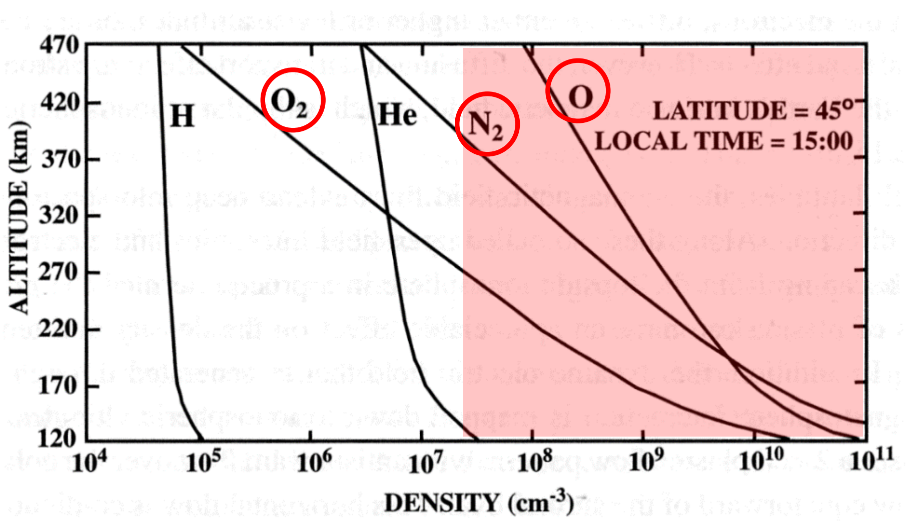
Complete photo-ionisation

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

$$P_{total}(h) = \sum_0^{\lambda_{ion}} F_\lambda^{Sun}(h) \cdot [N](h) \cdot \sigma_{ion}$$



	λ(Å)
H	910
O	910
O_2	1030
N_2	790
He	500



$\gamma + O \rightarrow O^+ + e^-$

$\gamma + N_2 \rightarrow N_2^+ + e^-$

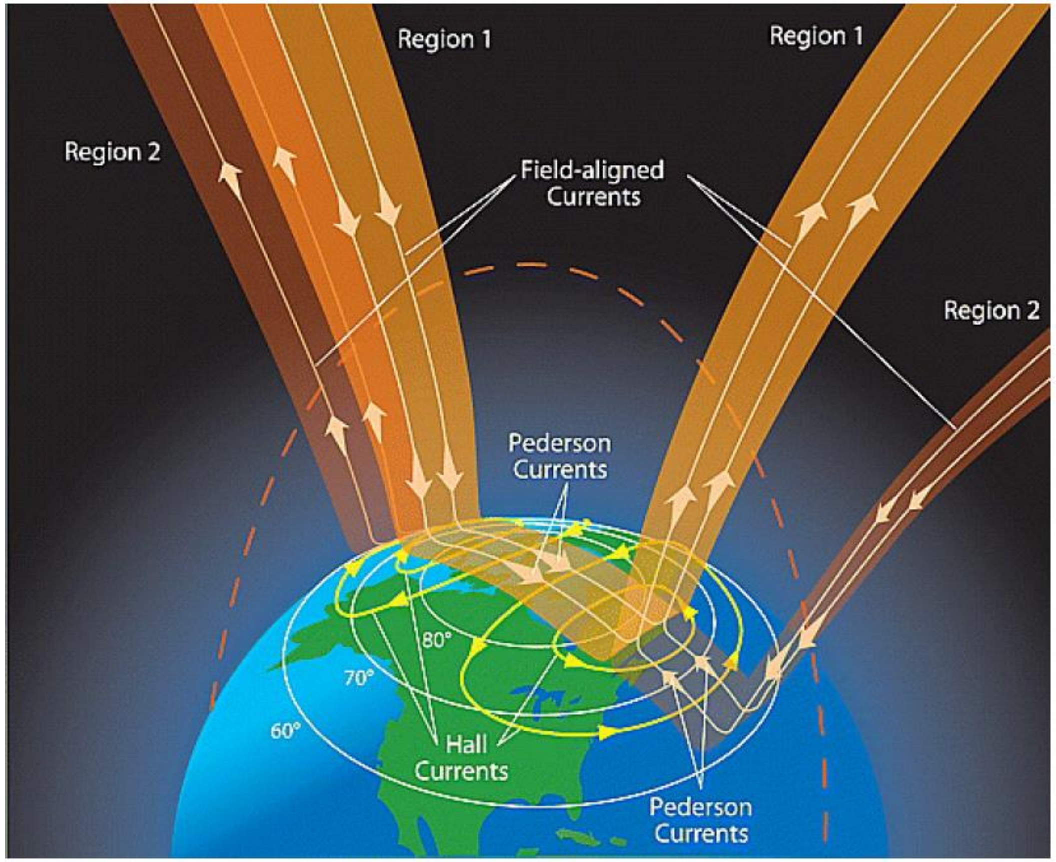
$\gamma + O_2 \rightarrow O_2^+ + e^-$

Recipe for Earth’s ionosphere

Doses for 1 planet

1. Sprinkle a generous amount of Photoionisation
2. Add an almost uniform dusting of Particle Precipitation around the (magnetic) poles

Production of Ionospheric Plasma by Energetic Particles



COMET program, UCAR

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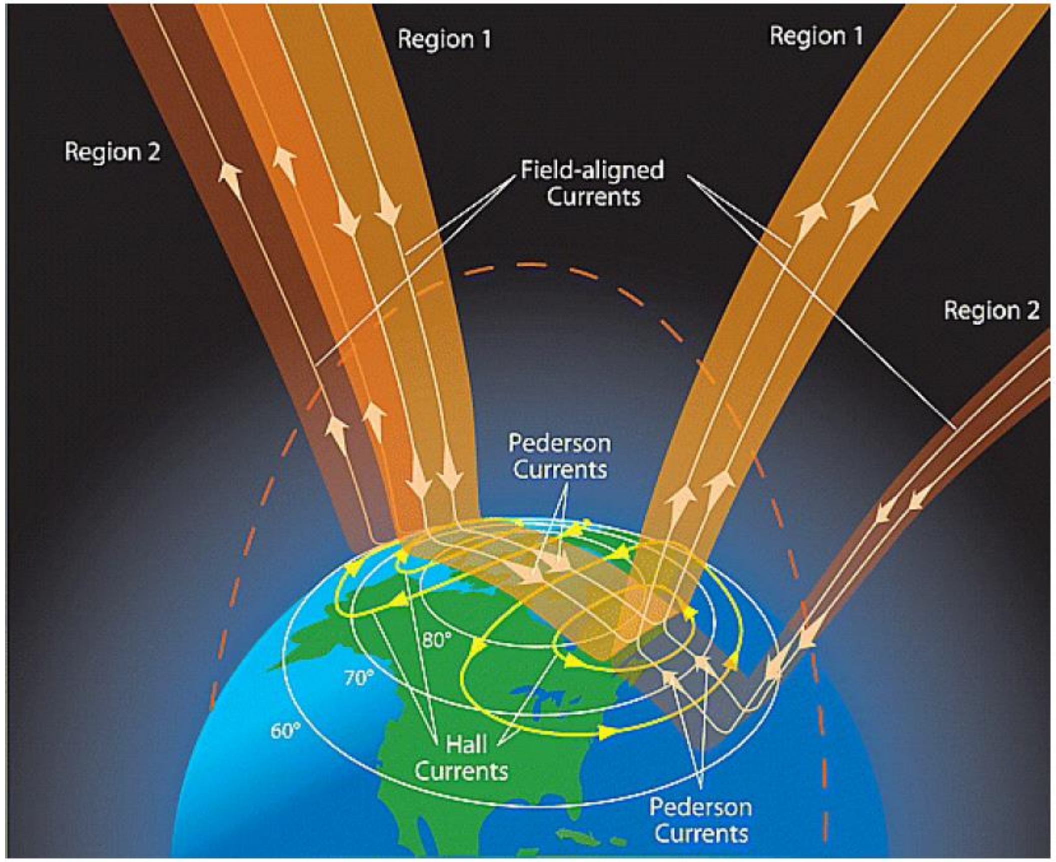
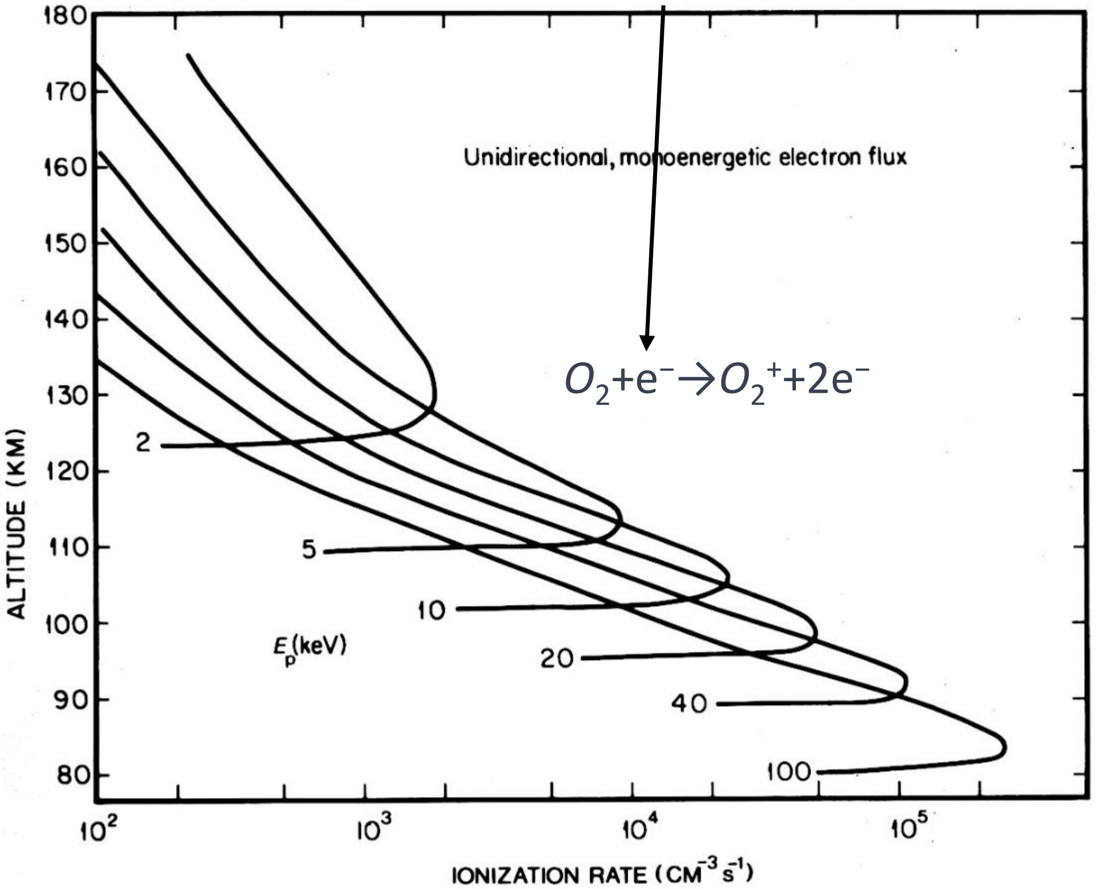


COMET program, UCAR

Precipitating Electrons



$O_2 + e^- \rightarrow O_2^+ + 2e^-$

--- taken from Rees (1989)

Recipe for Earth’s ionosphere

Doses for 1 planet

1. Sprinkle a generous amount of Photoionisation
2. Add an almost uniform dusting of Particle Precipitation around the (magnetic) poles
3. Add a wise dose of chemistry

Why a wise dose of chemistry?

Because we put too much ionisation!

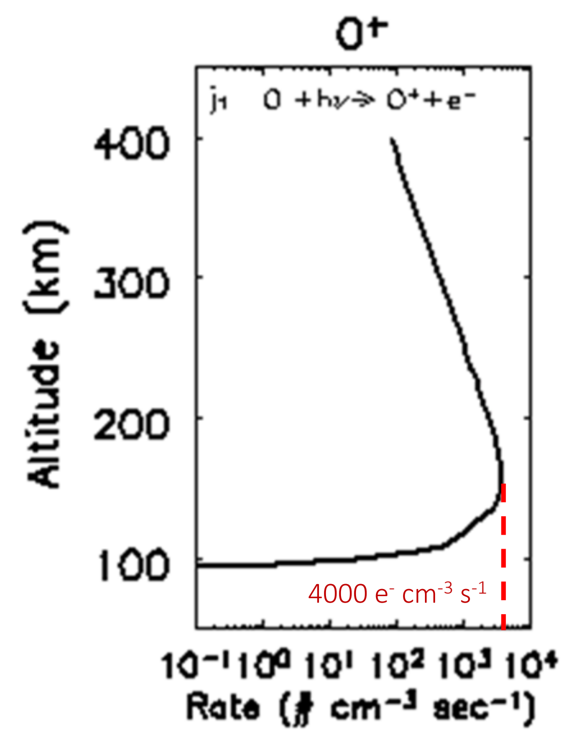
- What does “production only” imply?
  e.g., use P(O^+) value from graphs (photons or particles)

$$P_{max} = 4000e^{-1}\ cm^{-3}\ s^{-1} \times 3\ hours (\approx 10^4\ s)$$

$$\Downarrow$$

$$N_{max} \approx 4 \times 10^7 e^{-1}\ cm^{-3}$$

Never measured!



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

Answer: Chemistry → Plasma recombination

Answer: Chemistry → Neutral-Plasma Processes

Recombination

CASE # 1: Atomic ions + electrons

$$O^{+} + e^{-} \rightarrow \mathrm{O}$$

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

CASE # 2: Molecular ions + electrons

$$O_2^{+} + e^{-} \rightarrow \mathrm{O} + \mathrm{O}$$

[fast due to excess energetics used for dissociation]

CASE #3: Transform Atomic ions to Molecular ions

[slow]

$$O^{+} + \begin{bmatrix} N_2 \\ O_2 \end{bmatrix} \rightarrow \begin{bmatrix} NO^{+} \\ O_2^{+} \end{bmatrix} + \begin{bmatrix} N \\ O \end{bmatrix}$$

$$\hookrightarrow O_2^{+} + e^{-} \rightarrow \mathrm{O} + \mathrm{O}$$

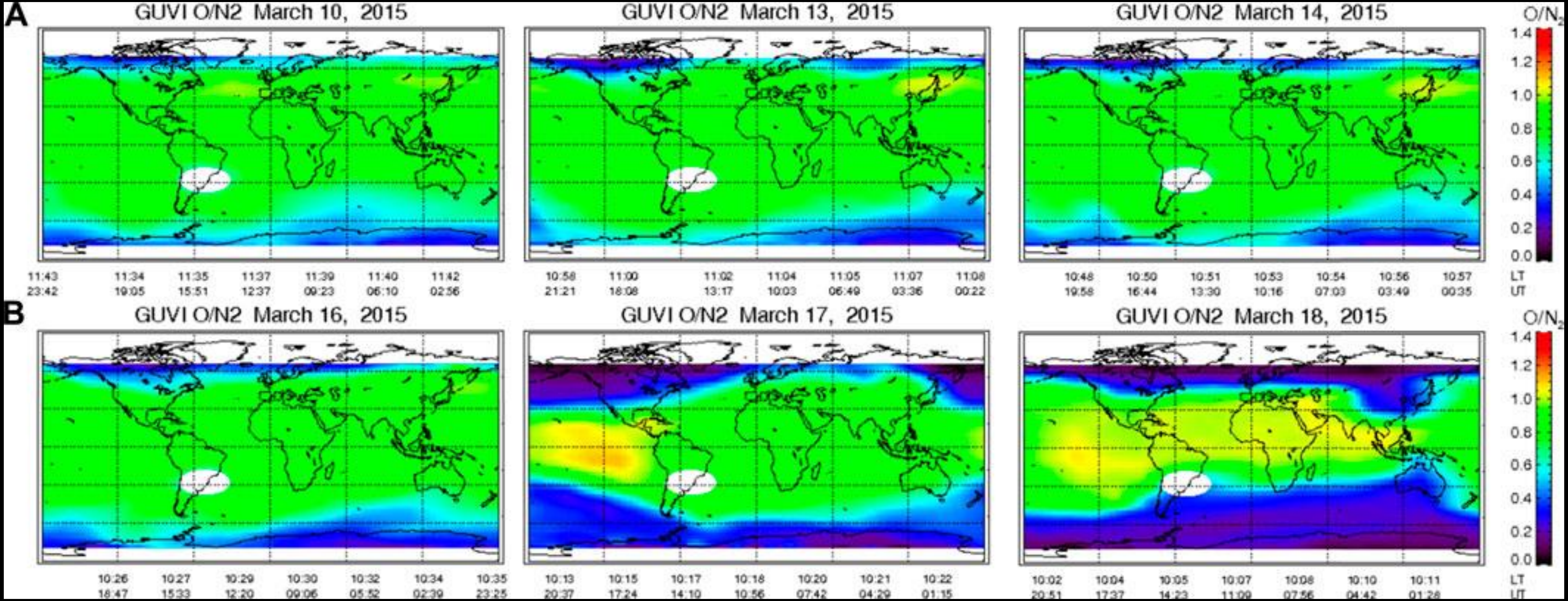
The 2-stage recombination process governed by slower step, e.g.,

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

The role of recombination

The ratio of O to N_2 provides essential knowledge of the ionospheric state.

Berényi et al., 2023

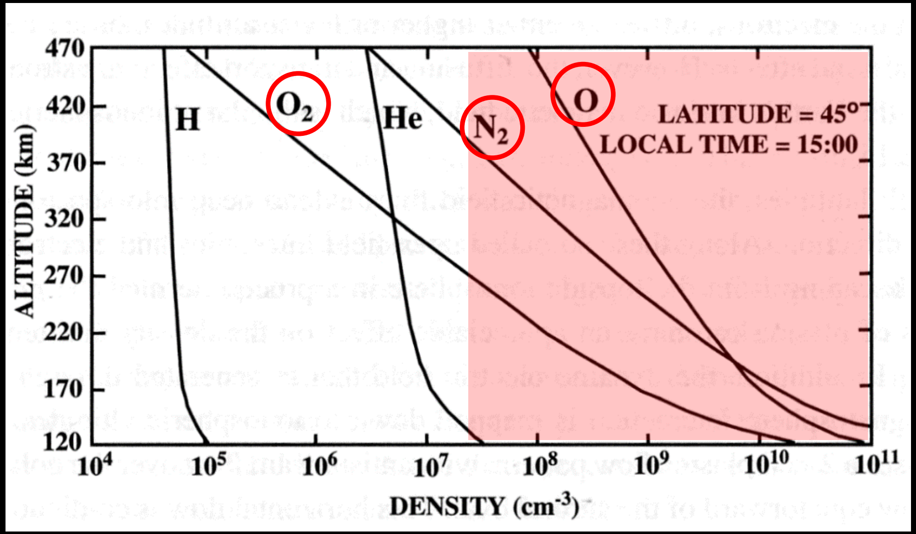


The density of O affects the production rate of O^+ in the F-region ionosphere (primarily via charge exchange with N_2^+, with a contribution from direct ionization of O; e.g. Torr and Torr, 1985).

The lifetime of O^+ at F-region altitudes is governed by dissociative recombination with N_2 (e.g., Schunk, 1983).

The role of recombination

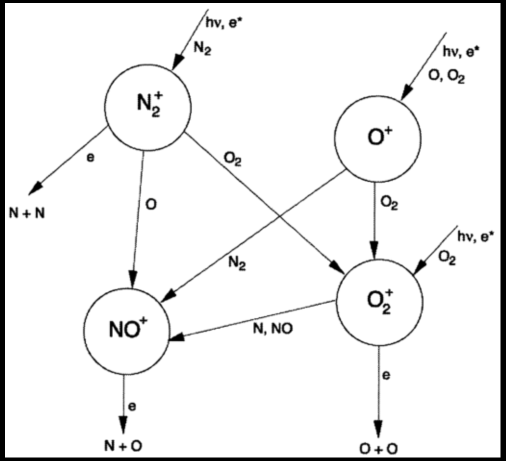
Plasmas should be ionized form of dominant neutral O, O_2, N_2



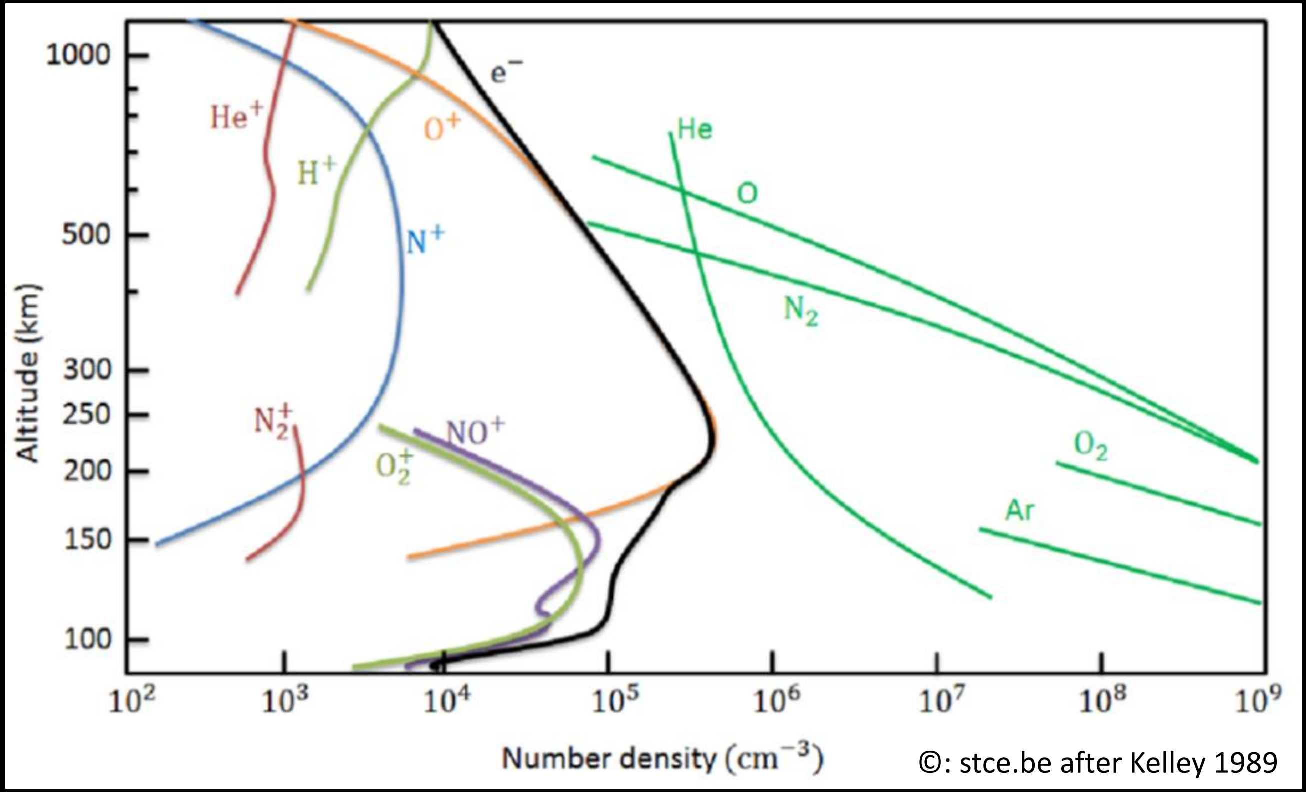
$$O^+ + e^- \rightarrow O$$

$$N_2^+ + e^- \rightarrow N + N$$

$$O_2^+ + e^- \rightarrow O + O$$



The actual case



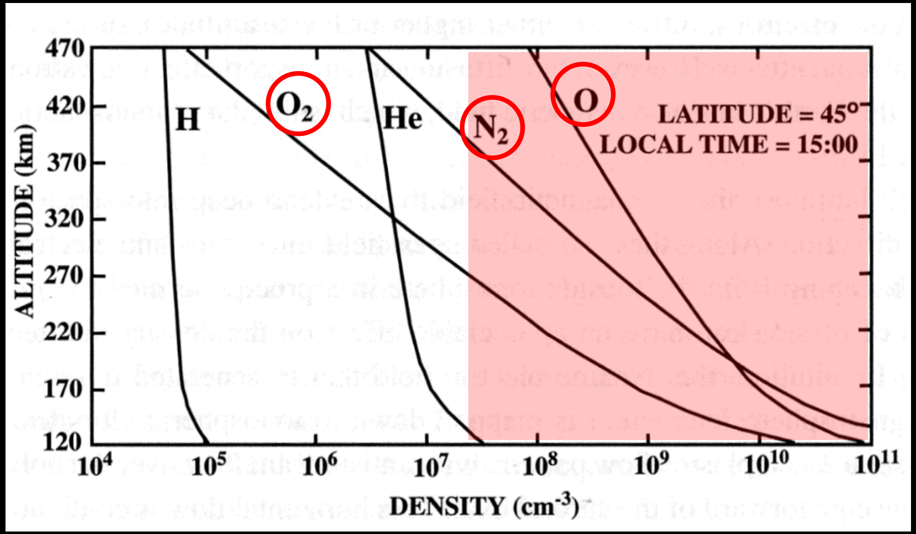
©: stce.be after Kelley 1989

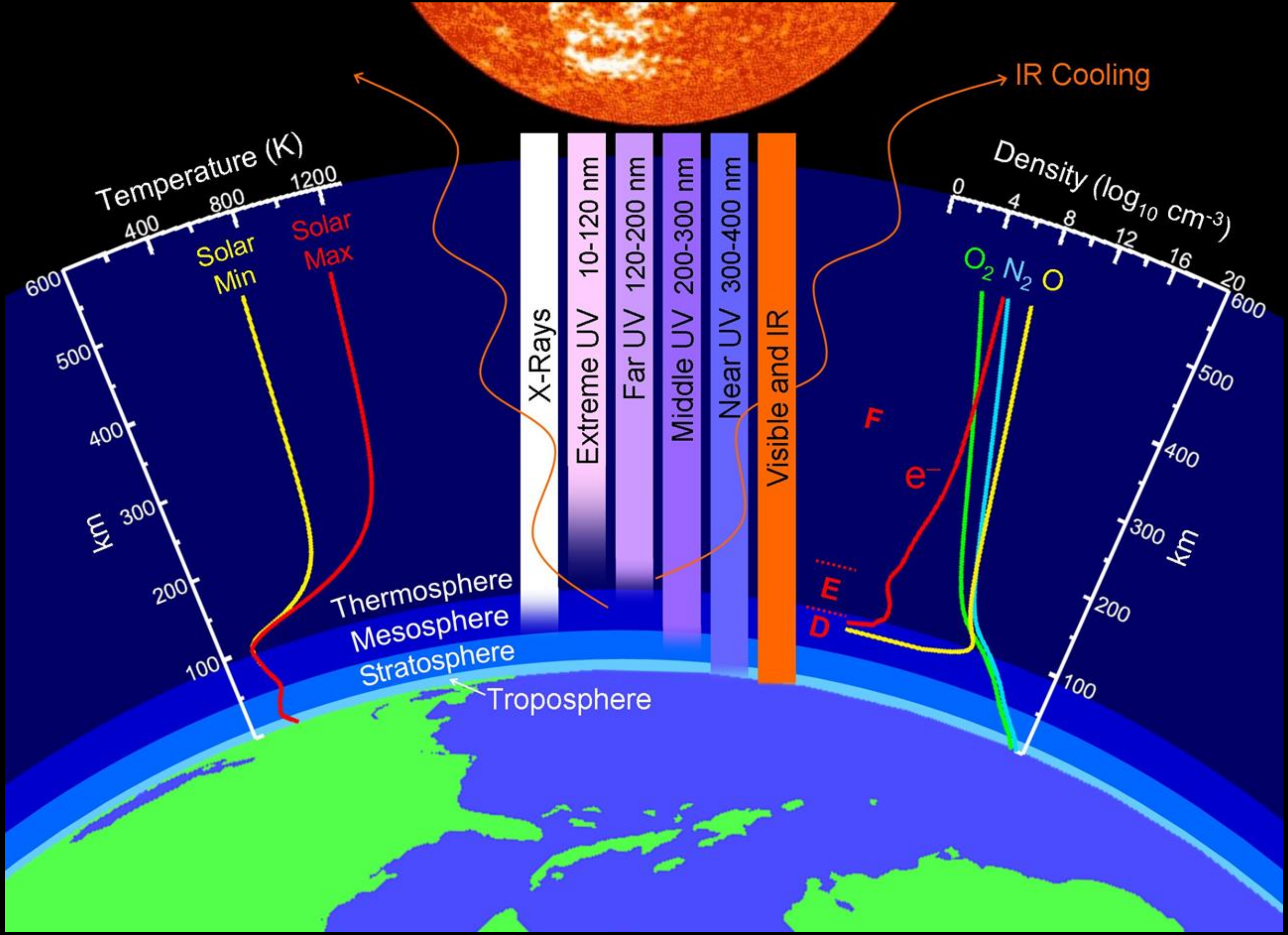
- The electron density distribution (black profile) coincides mainly with evolution of density of ionized oxygen (O^+ ; orange line). Near F peak, O^+ is dominant.
- At lower altitudes (below 150 km), the major ions are: O_2^+ and NO^+.
- At higher altitudes (transition height at ~800 km at solar max and ~500 km at solar min), H^+ solar becomes dominant – marking transition from ionosphere to protonosphere/plasmasphere

The role of recombination

Plasmas should be ionized form of dominant neutral
O, O_2, N_2

The actual case
some chemical transformations to form NO+ and H+





$$O^+ + e^- \rightarrow \mathrm{O}$$

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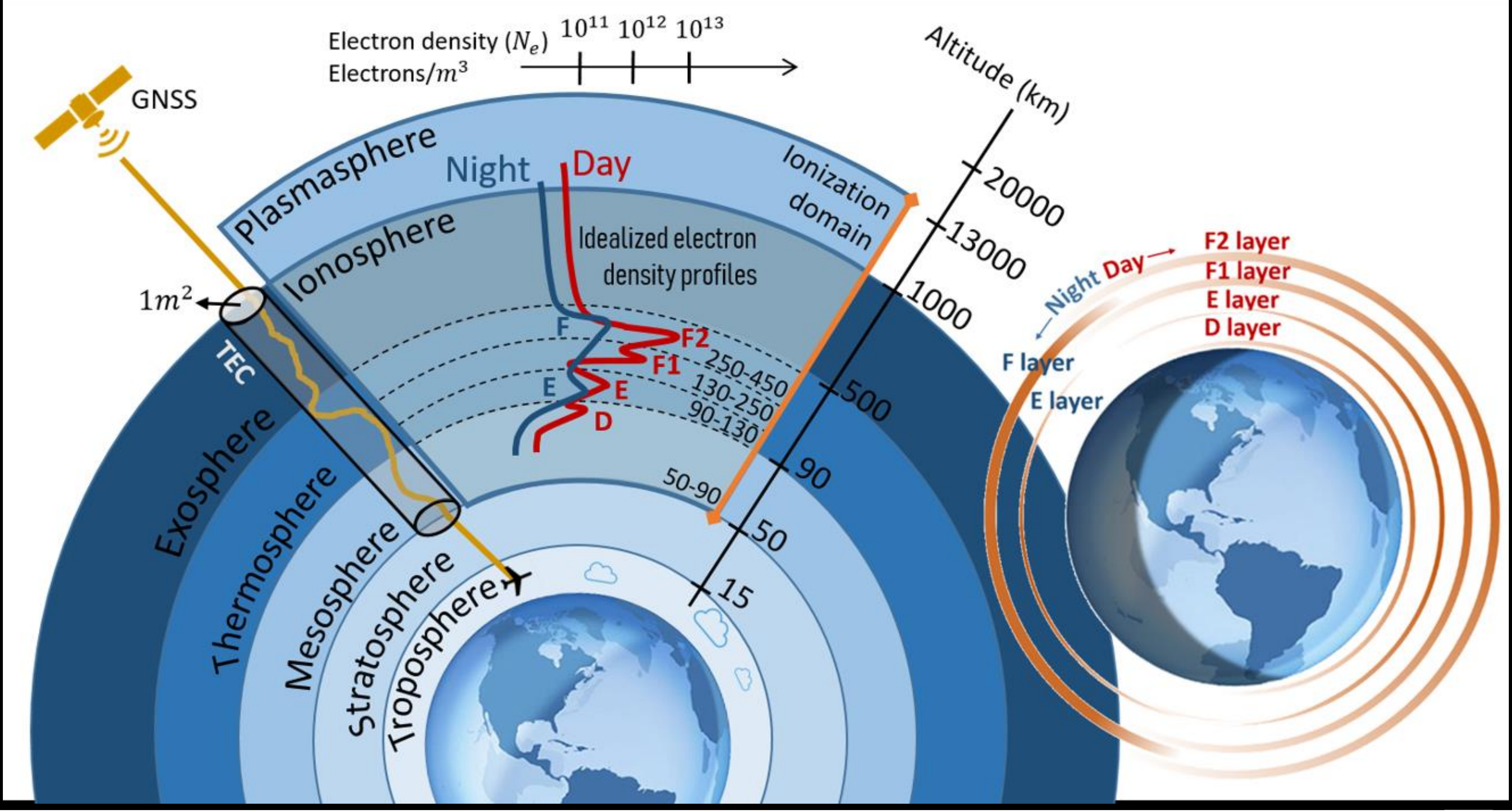
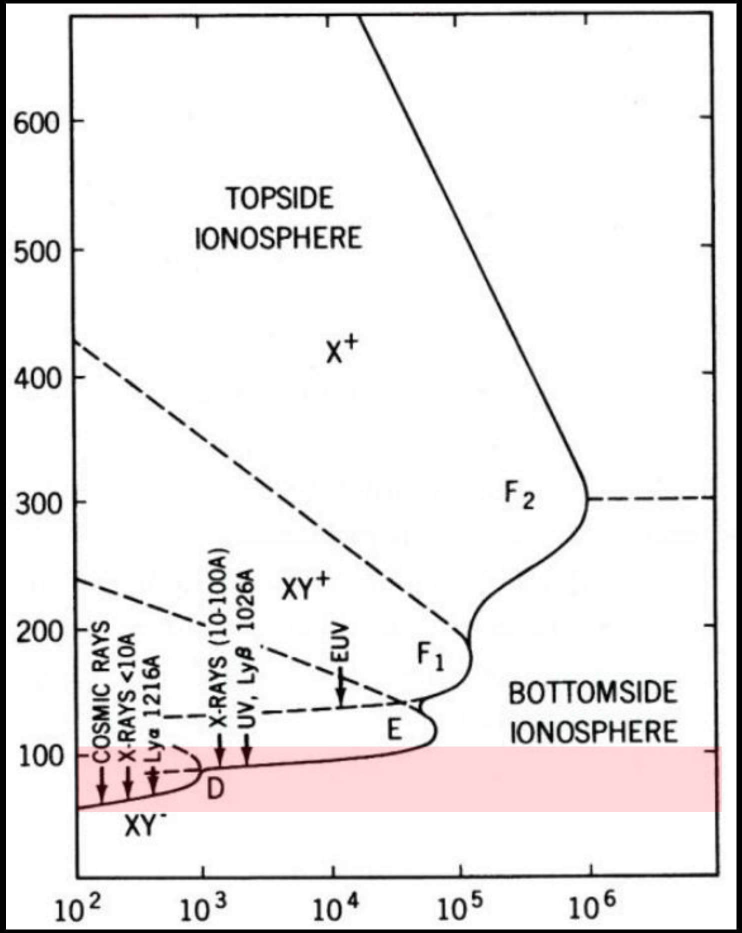
The ionospheric layers



Ionospheric layers

- **D layer** (~60 to~90km)
  Production: daytime ionization of NO due to solar Lyman alpha (121.567 nm)
  Loss: recombination with complex ions
  Tends to absorb the lower radio frequencies (<3 MHz)
  Disappear right after sunset



From Bauer and Lammer, 2004

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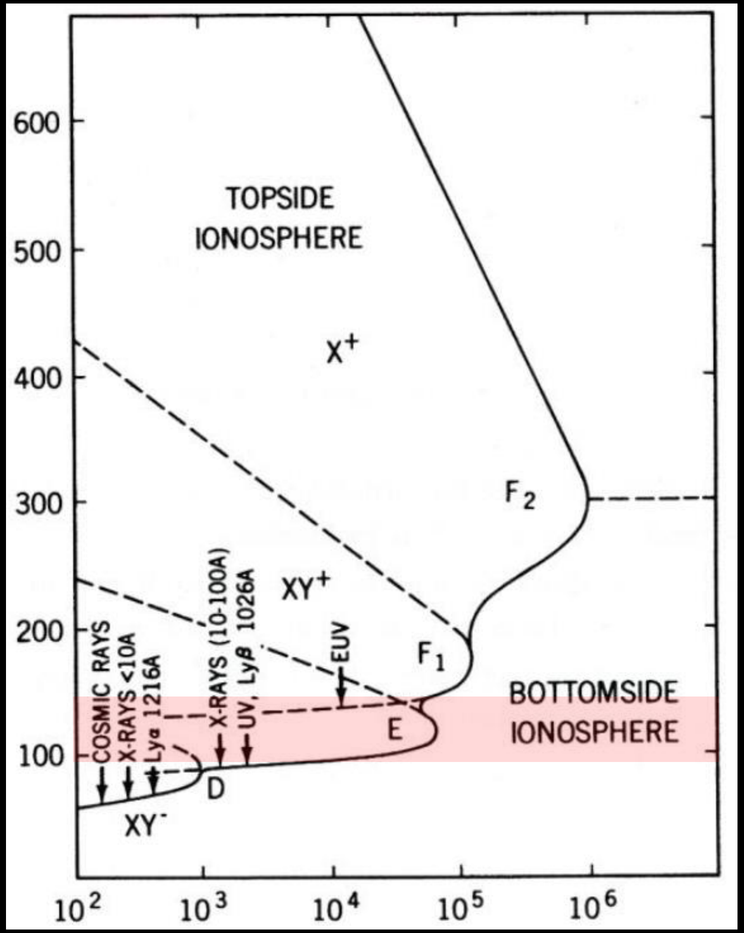
- **E layer** (~90 to~140km)
  Production: daytime ionization of O2 (soft X-ray and UV, energetic particles at high latitudes)
  Loss: recombination with molecular ions D-E-F > photochemistry dominates
  Controlled by the Sun’s flux and its position (dec + $\chi_\odot$)
  Tends to behave like a Chapman layer



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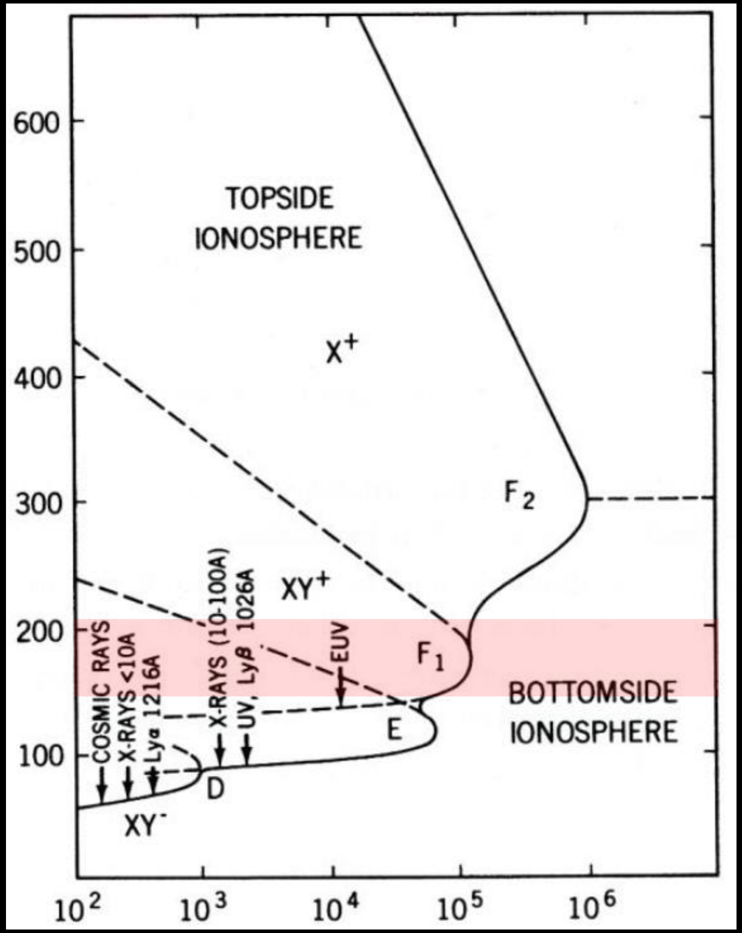
- **F1 layer** (~140 to 200 km)
  Production: daytime ionization of O
  Loss: recombination of NO+ and electrons Tends to behave like a Chapman layer



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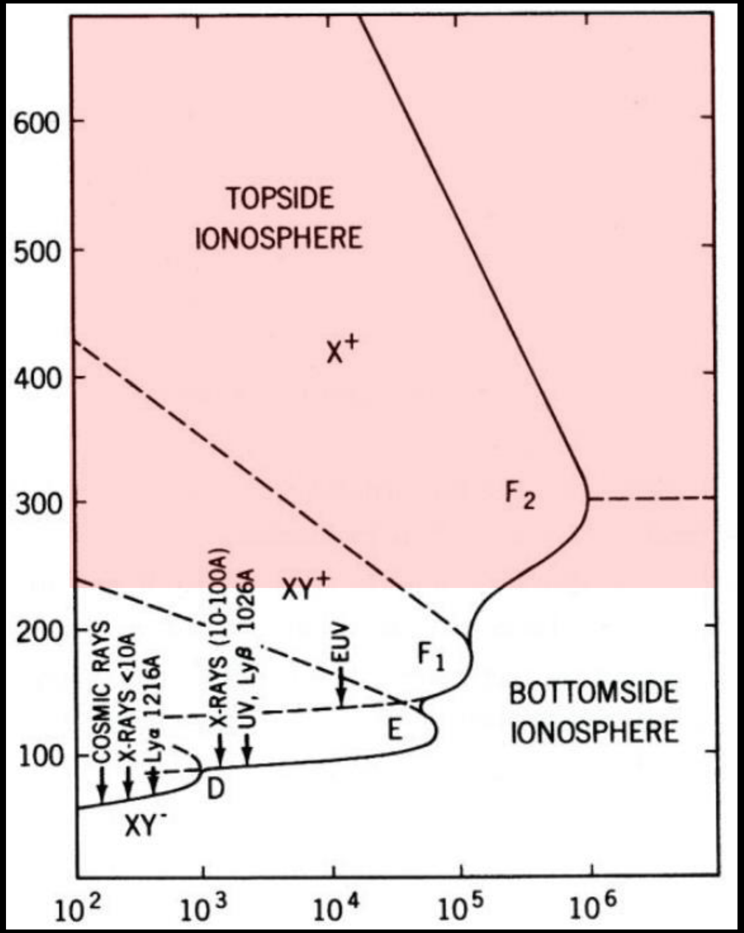
- **F1 layer** (~140 to 200 km)
  Production: daytime ionization of O
  Loss: recombination of NO+ and electrons Tends to behave like a Chapman layer

- **F2 layer** (~200 to 1000+ km, main peak ~ 300km)
  Production: daytime ionization of O
  Loss: O+ reaction with N2, recombination of NO+ and electrons
  Diffusion and transport processes important in the F2



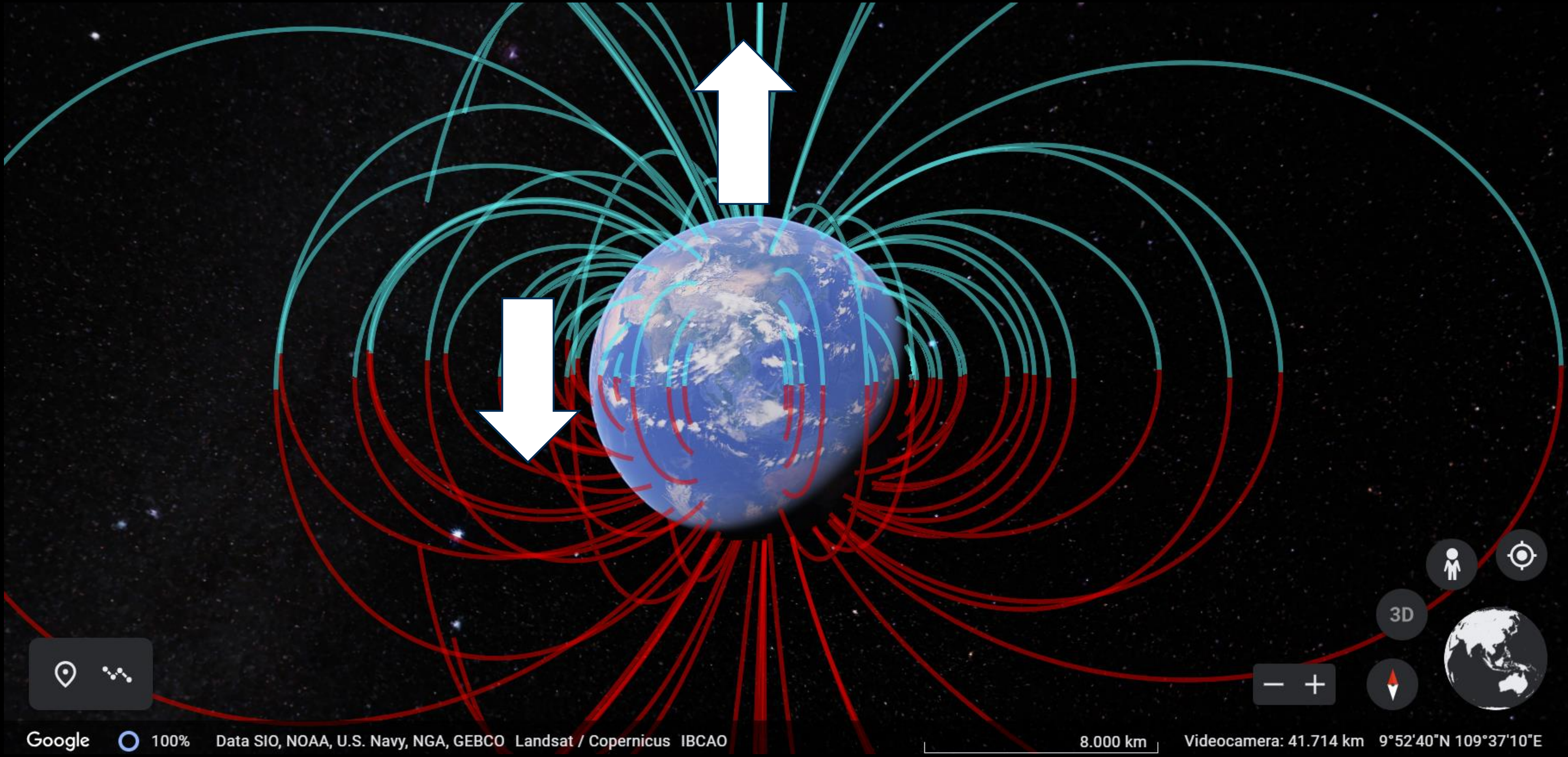
From Bauer and Lammer, 2004

Recipe for Earth’s ionosphere

Doses for 1 planet

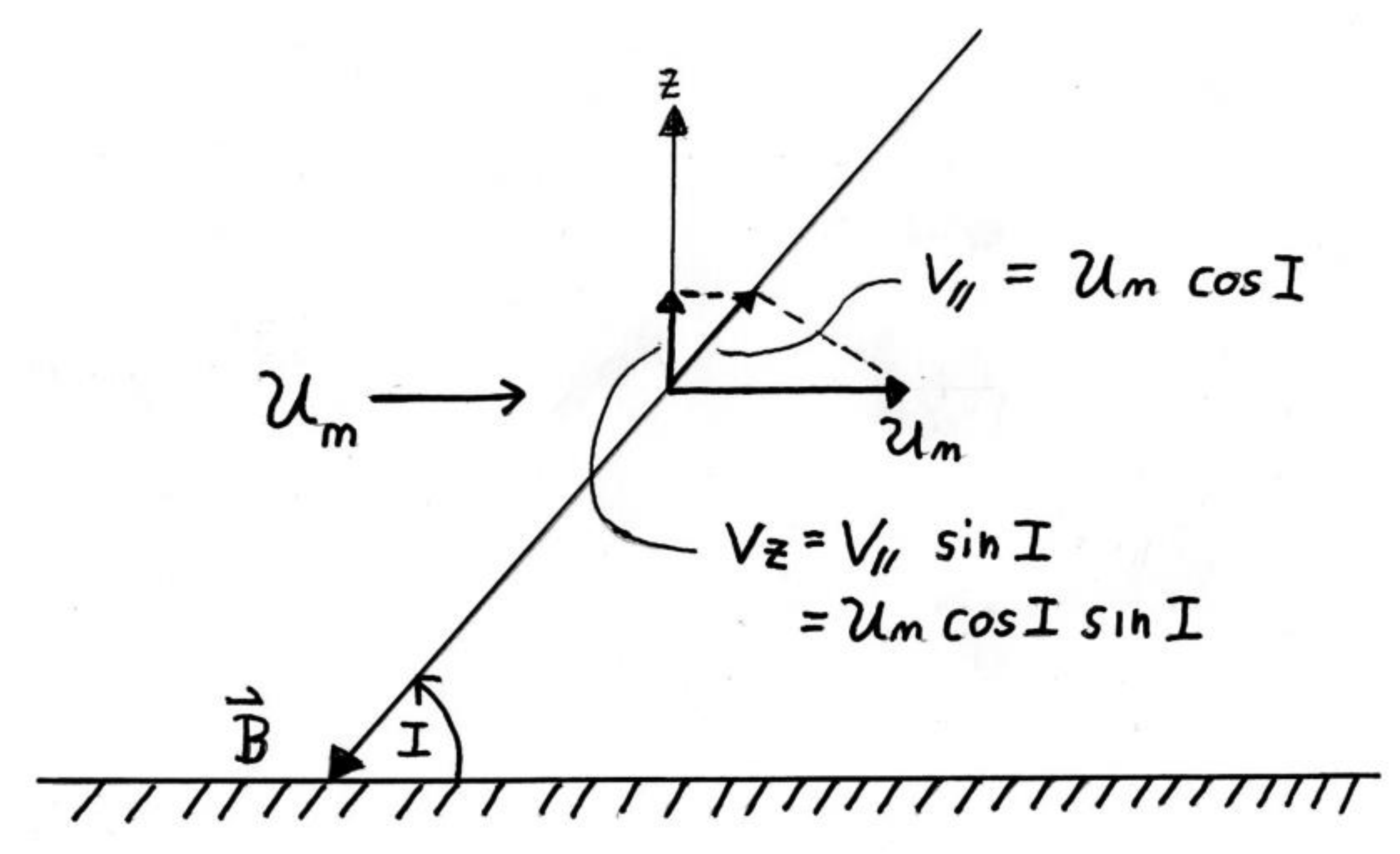
1. Sprinkle a generous amount of Photoionisation
2. Add an almost uniform dusting of Particle Precipitation around the (magnetic poles)
3. Add a wise dose of chemistry
4. Season it all with a strong internal magnetic field.

The role of the magnetic field



The role of the magnetic field: vertical motions

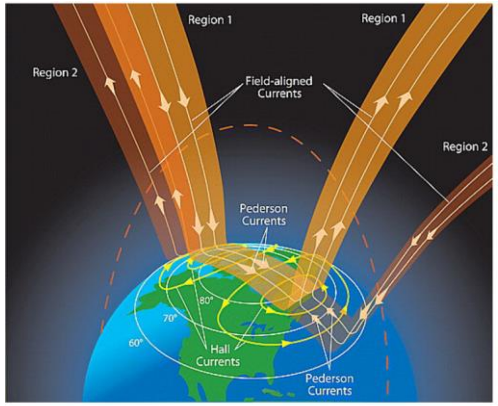
Neutral winds (Um) are mostly horizonthal
Plasma constrained to along **B**



Mid-latitudes – maximum effect
Equatorial latitudes (I=0°) – small effect
High latitudes (I=90°) – small effect

(neglecting the polarization fileds that the neutral winds may create)

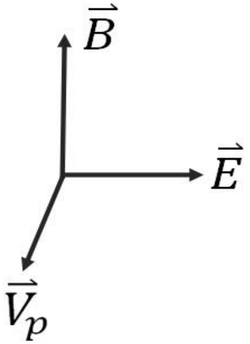
Role of magnetic field



COMET program, UCAR

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

At high latitudes



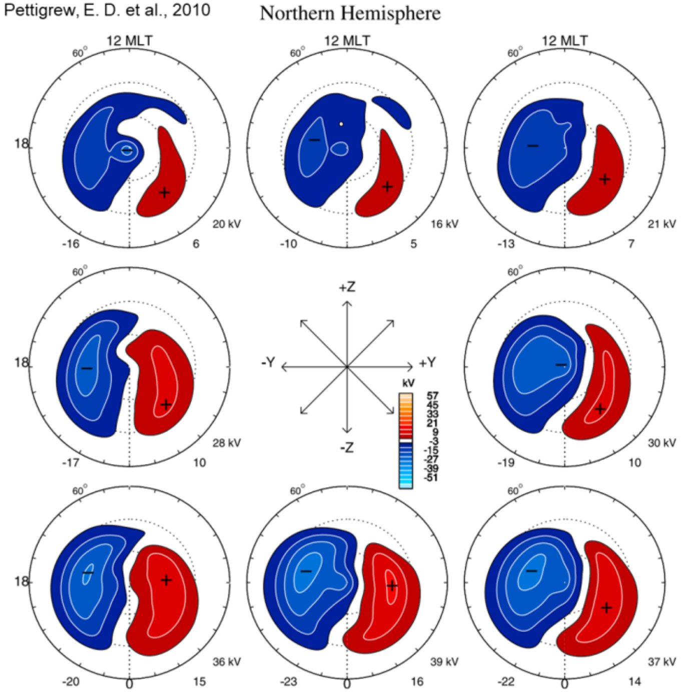
$\vec{B}$ close to vertical

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

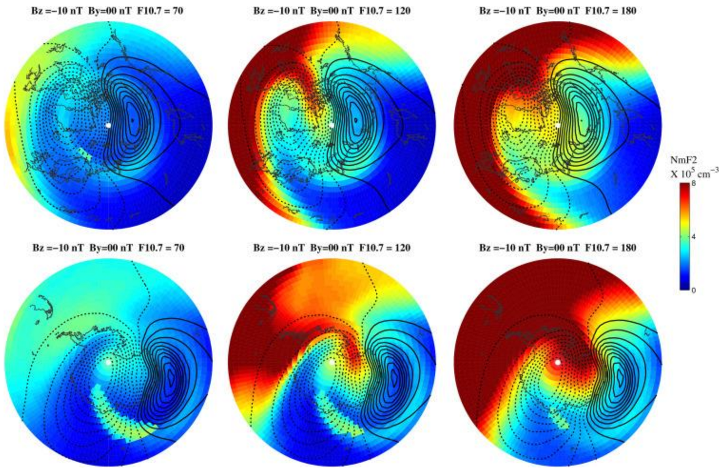
Convection Patterns

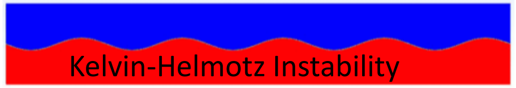
Convection cells

Pettigrew, E. D. et al., 2010



Tongue of Ionisation



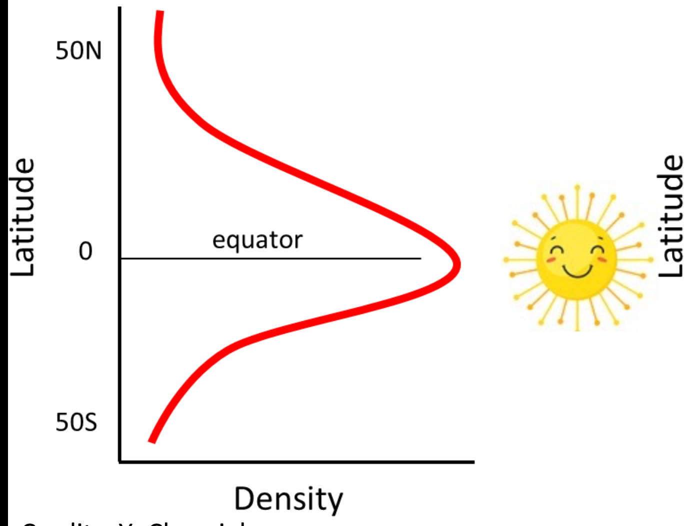


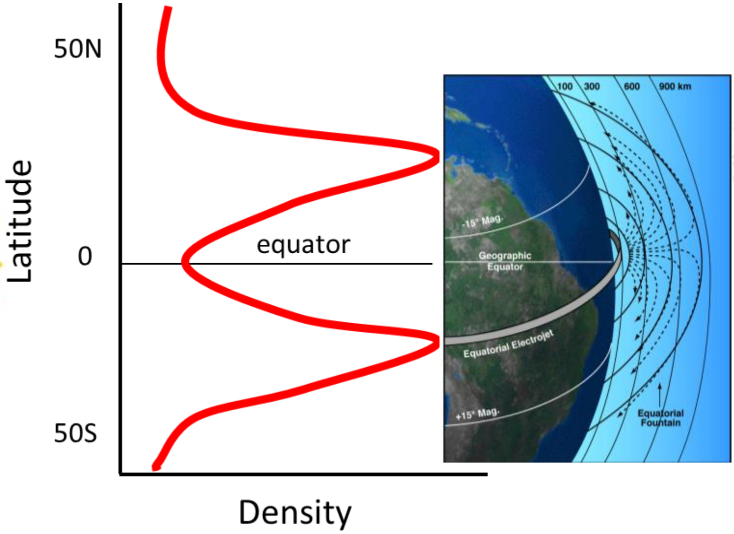
Role of magnetic field

Daytime ionosphere

Equatorial Ionization Anomaly (EIA) or Appleton Anomaly

Minimum (trough) at equator and two far-away crests =
Equatorial Ionization Anomaly

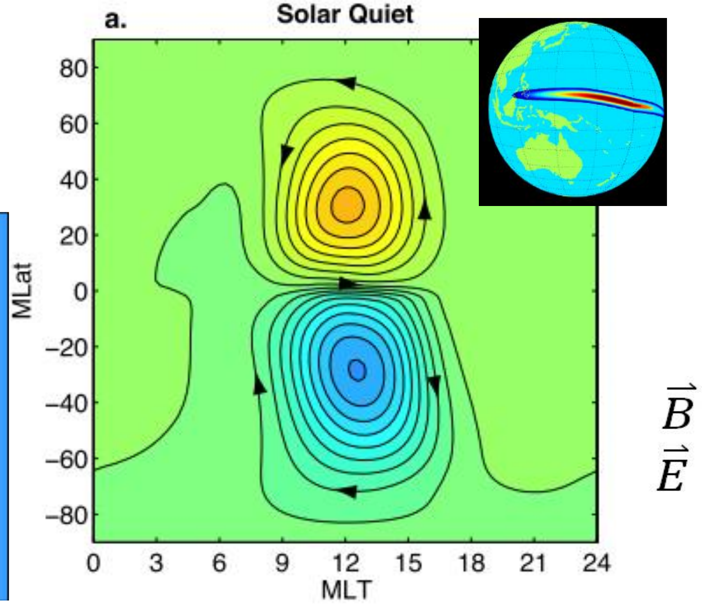




Credits: Y. Cherniak

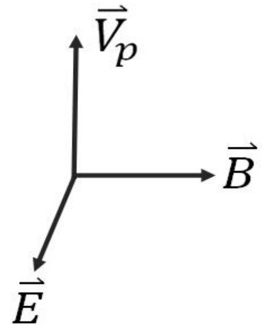
$$\vec{V}_p = \frac{\vec{E} \; x \; \vec{B}}{|B|^2}$$ *Plasma velocity*

Equivalent Ionospheric Currents (TIE-GCM)



Yamazaki, Y., & Maute, A. (2017). Space Science Reviews

At low latitudes



$\vec{B}$ close to horizonta

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

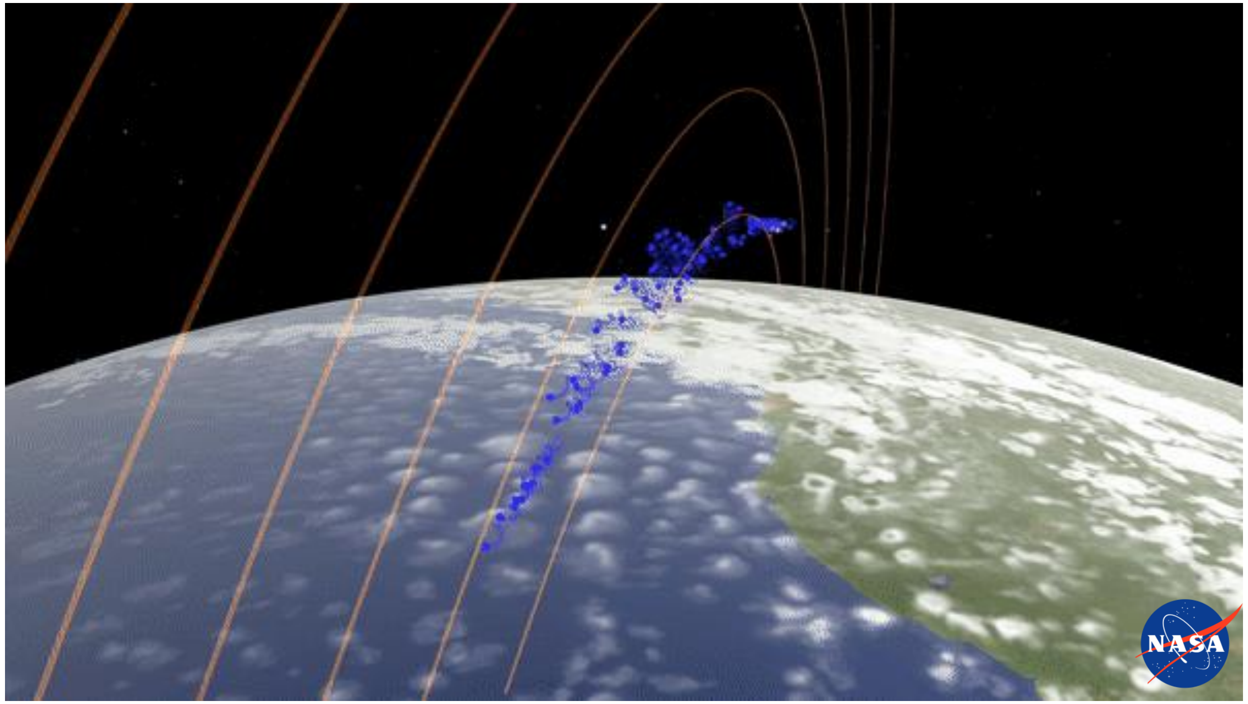
$$\underbrace{\hphantom{xxxxxxxxxx}}_{\text{Fountain Effect}}$$

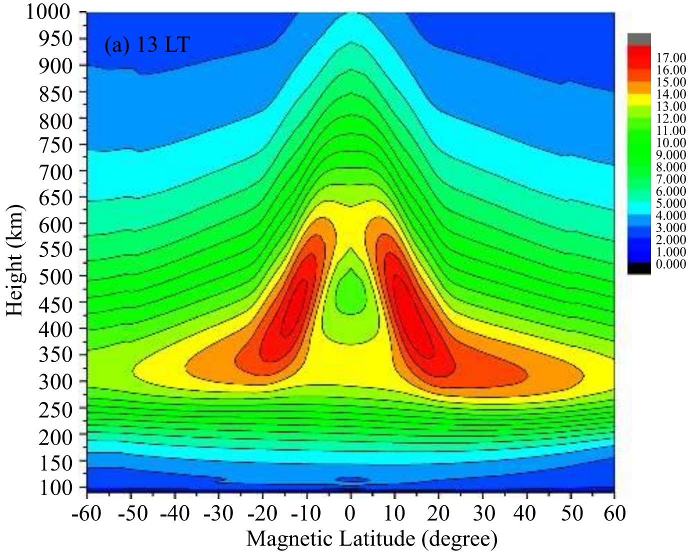
Role of magnetic field

Daytime ionosphere

Upward E x B drift + Plasma diffusion along B-field lines

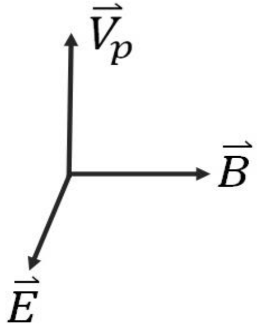
$$\vec{V}_p = \frac{\vec{E}\ x\ \vec{B}}{|B|^2}$$ *Plasma velocity*





Model simulation of ionospheric density distribution with altitude [Balan et al, 2018]

At low latitudes



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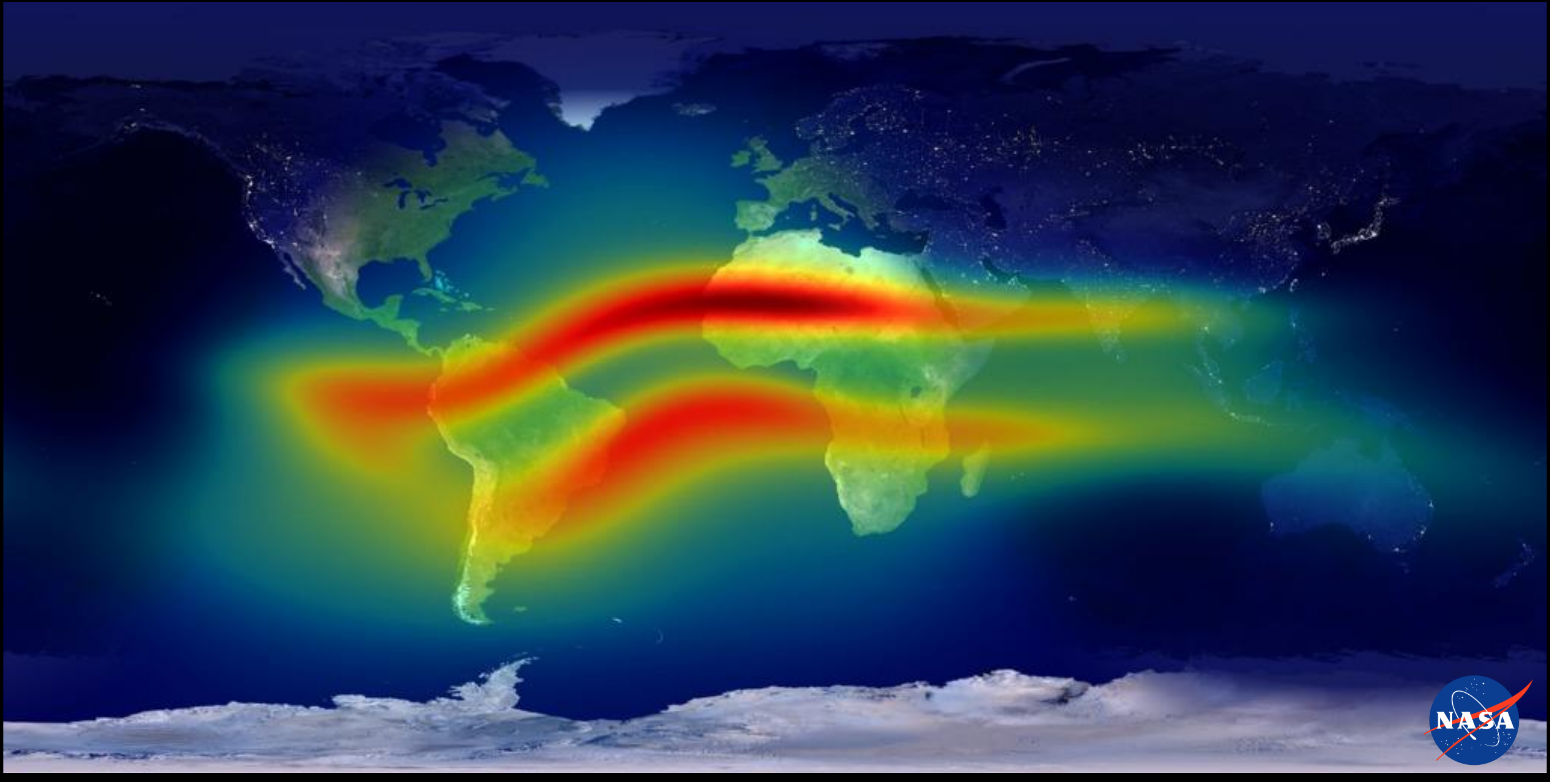


Role of magnetic field

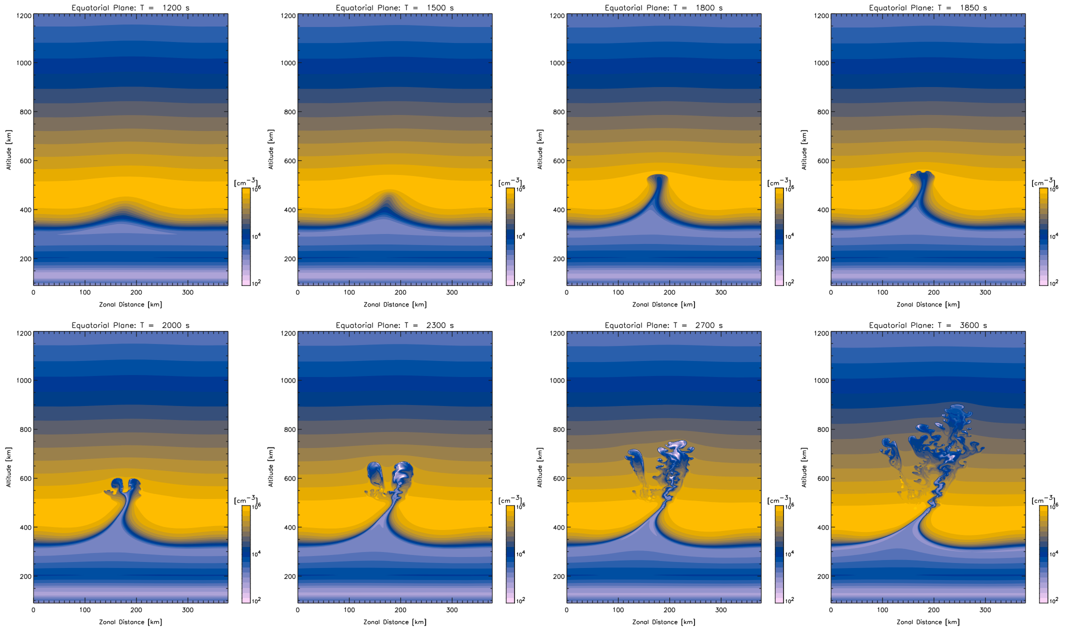
Night-time Ionosphere: Equatorial Plasma Bubbles

Sunset, the Sun is disappearing over the horizon, the Equatorial Ionization Anomaly gradually weakens? “Normal” quiet ionosphere at the equator? NO!

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

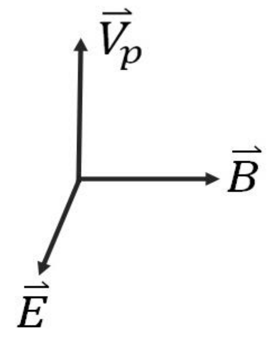
Changes in the electrodynamics (Pre-Reversal Enhancement) -- > uplift of F-layer -- > bottomside density gradient -- > “bubbles” develop -- > R-T instability

Equatorial Plasma Bubbles (EPBs) can develop from the bottomside ionosphere and stretch into the topside ionosphere (above 500 km). Such plasma depletions have east-west dimension of ~1°-2°, can extend over 10°-15° in north-south direction.



Yokoyama (2017) DOI 10.1186/s40645-017-0153-6

At low latitudes



$\vec{B}$ close to horizontal

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

Fountain Effect

Role of magnetic field

Night-time Ionosphere: Equatorial Plasma Bubbles

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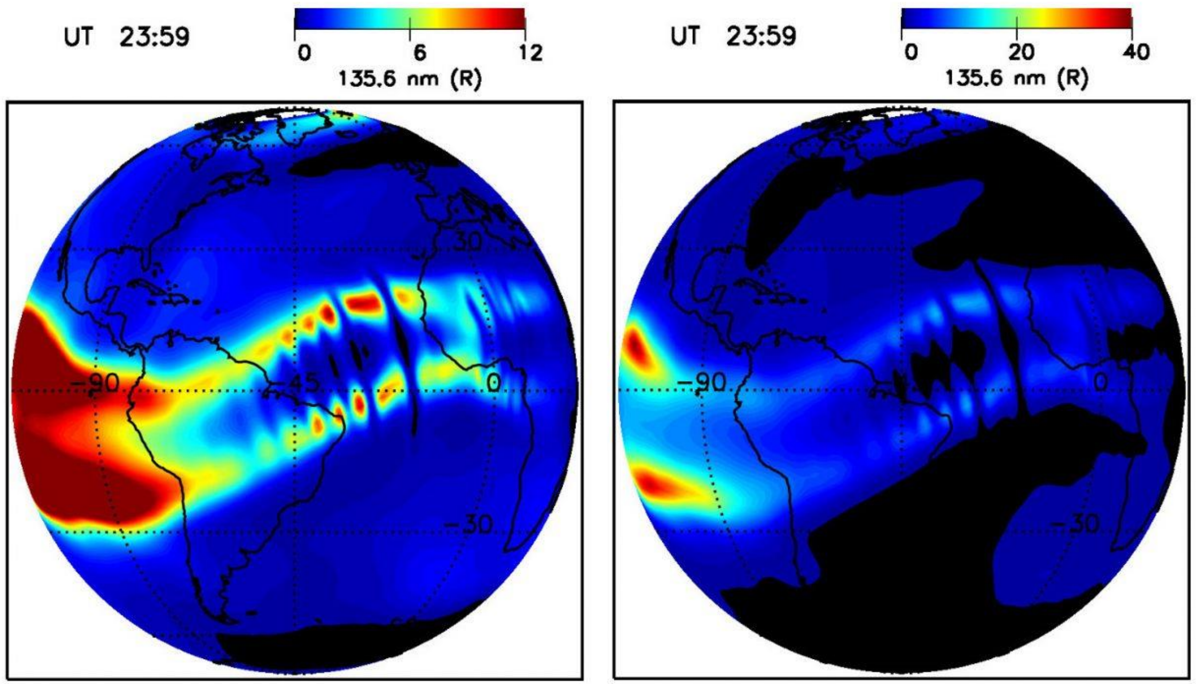

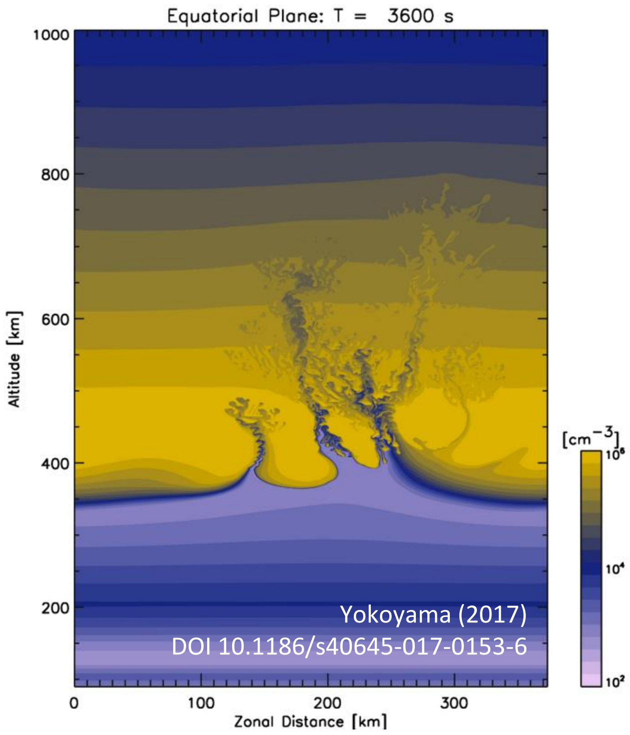

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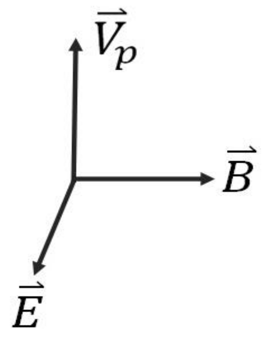
At low latitudes



$$\underbrace{\begin{array}{l}\vec{B}\ \text{close to horizontal}\\ \vec{E}\ \text{horizontal causes}\\ \qquad\text{vertical}\ \vec{V}_p\end{array}}_{\text{Fountain Effect}}$$

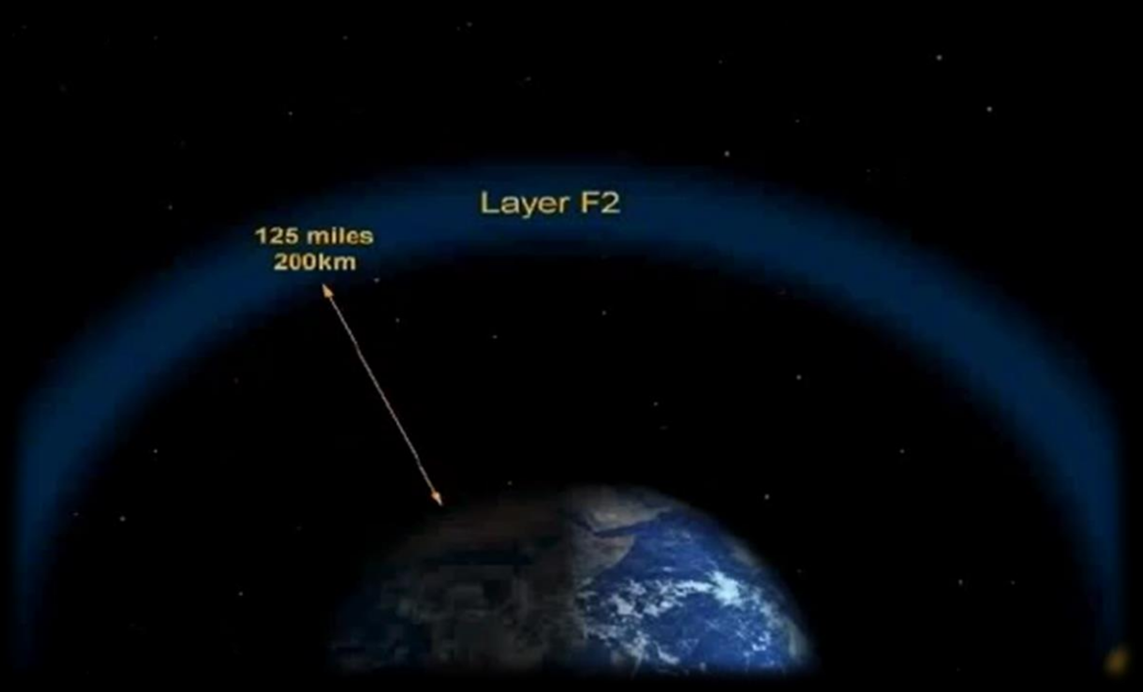
Recipe for Earth’s ionosphere

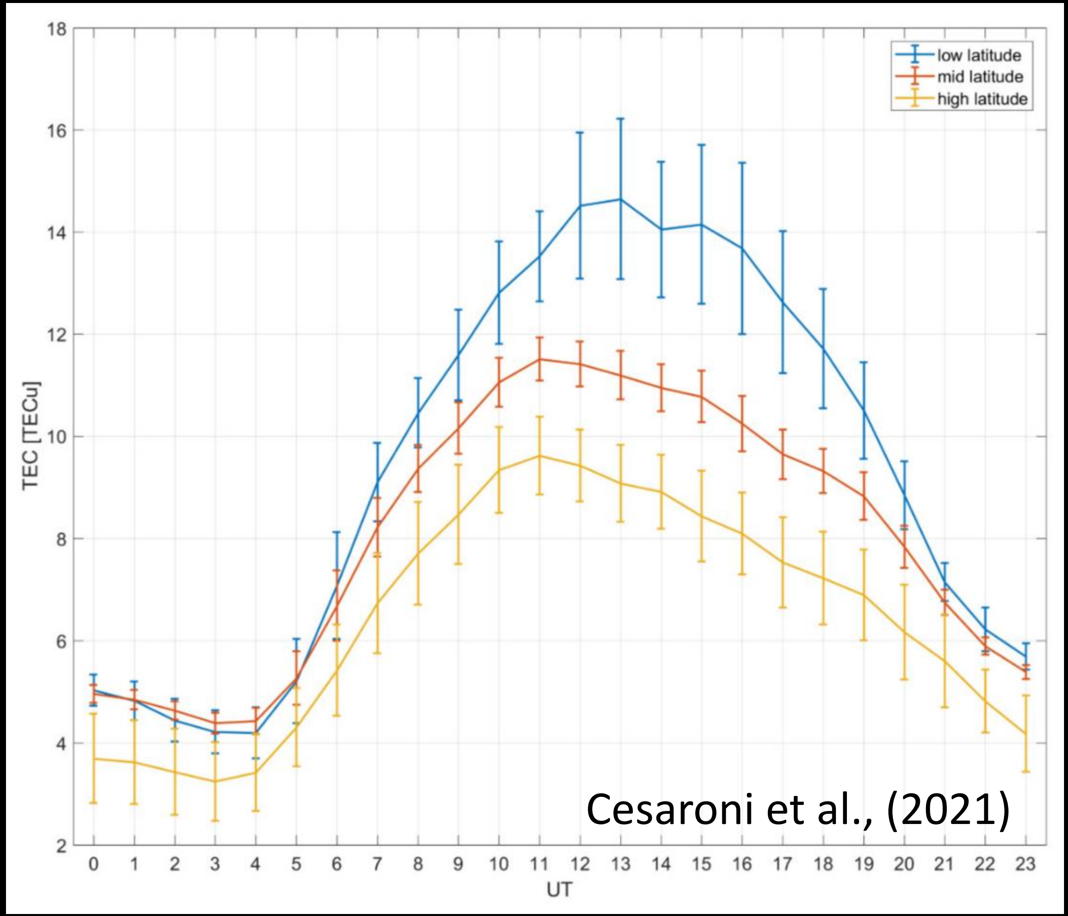
Doses for 1 planet

1. Sprinkle a generous amount of Photoionisation
2. Add an almost uniform dusting of Particle Precipitation around the (magnetic poles)
3. Add a wise dose of chemistry
4. Season it all with a strong internal magnetic field.
5. Stir everything to achieve regular variations.

Ionosphere daily variation

Midlatitude ionosphere tends to behave like in the Chapman theory where ionospheric density varies regularly with the solar zenith angle χ. More radiation leads to higher density – thus, with a latitude decrease towards the equator, the ionospheric density is increased during daytime at midlatitudes.





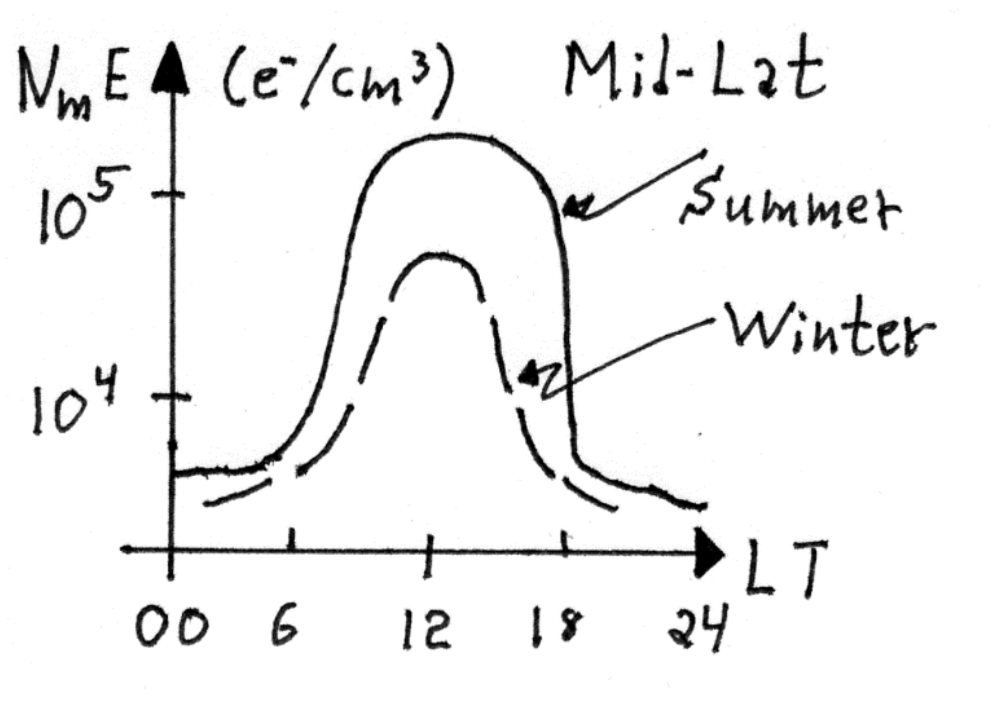
Cesaroni et al., (2021)

Mean daily variation of the TEC for Italian low (blue), mid (orange) and high (yellow) latitudes for the period 1 May 2017 to 30 April 2020.

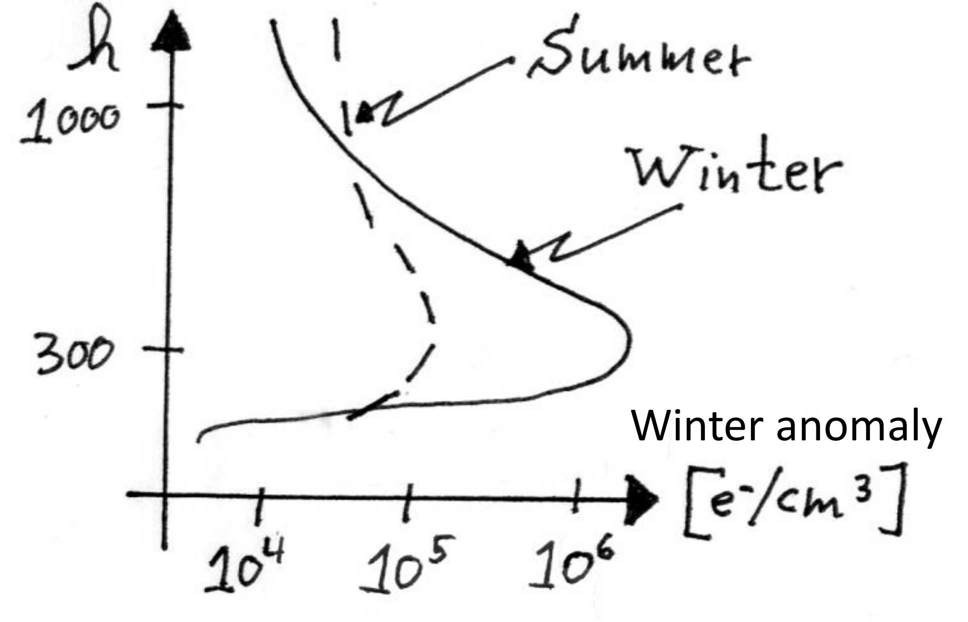
Ionosphere seasonal variation

As with normal weather, atmosphere/ionosphere at midlatitudes (e.g. in Europe) during winter season gets much less solar radiation compared to that level at summertime

E-layer



Ionospheric Anomalies (F-layer)



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

- Winter anomaly
- Annual anomaly
- Semi-annual anomaly

Ionosphere seasonal variation

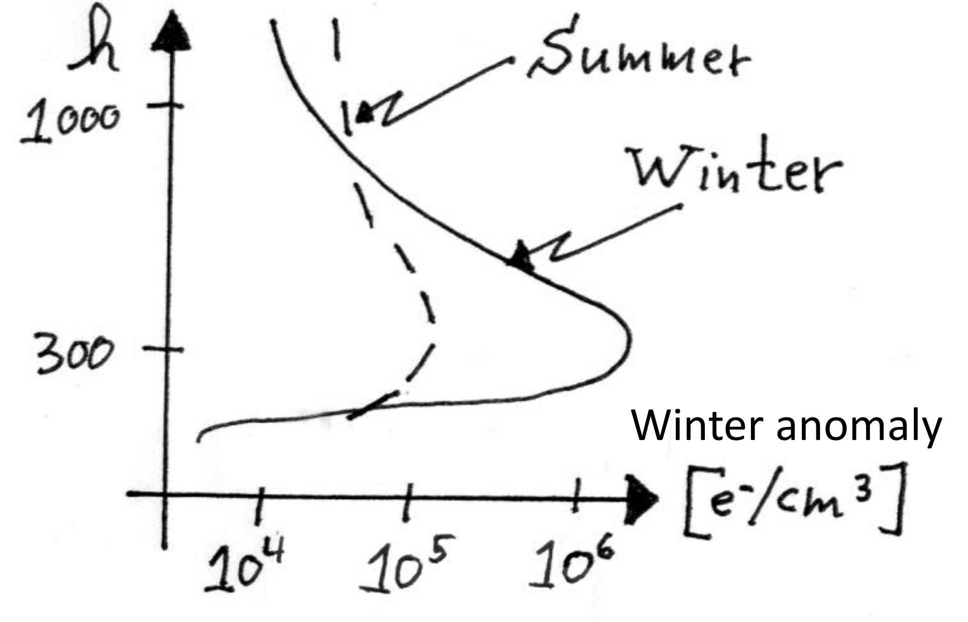
As with normal weather, atmosphere/ionosphere at midlatitudes (e.g. in Europe) during winter season gets much less solar radiation compared to that level at summertime

Winter Anomaly:
Greater F2-layer peak density (NmF2) values in the winter hemisphere than in the summer hemisphere during the solstices.

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

Semi-annual anomaly:
F2-layer peak density (NmF2) is greater at equinox than at solstice

Ionospheric Anomalies (F-layer)



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

- Winter anomaly
- Annual anomaly
- Semi-annual anomaly

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)

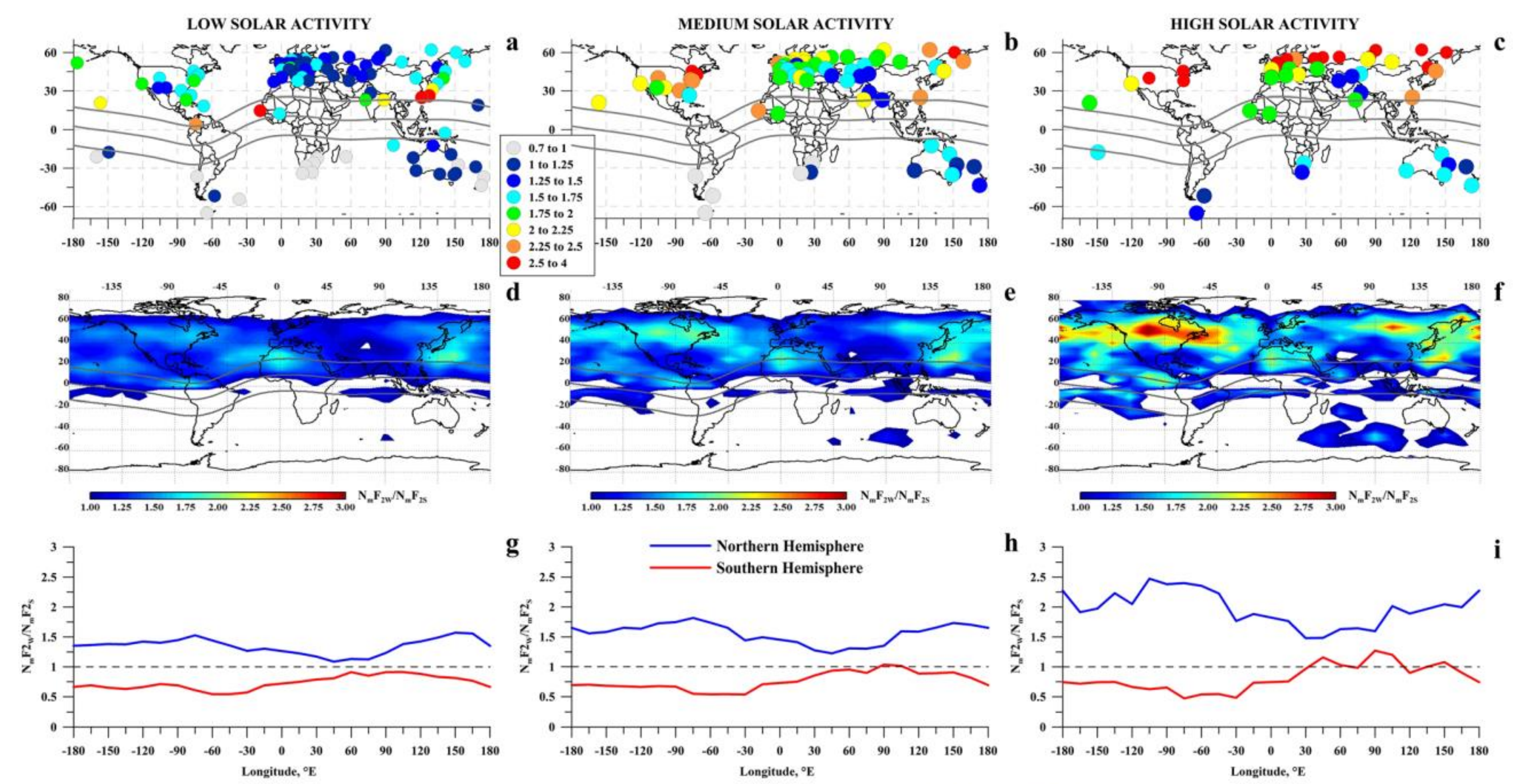


Fig. 3. Maps for the N_mF_2 winter anomaly intensity distribution from Pavlov and Pavlova (2012) (a)–(c) and from the RO measurements (d)–(f), as well as the longitudinal variation of the N_mF_2 winter anomaly intensity averaged at 40–60° geographic latitudinal bands based on the RO data (g)–(i). Panels (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.

Yasyukevich et al., 2018

Ionosonde measurements

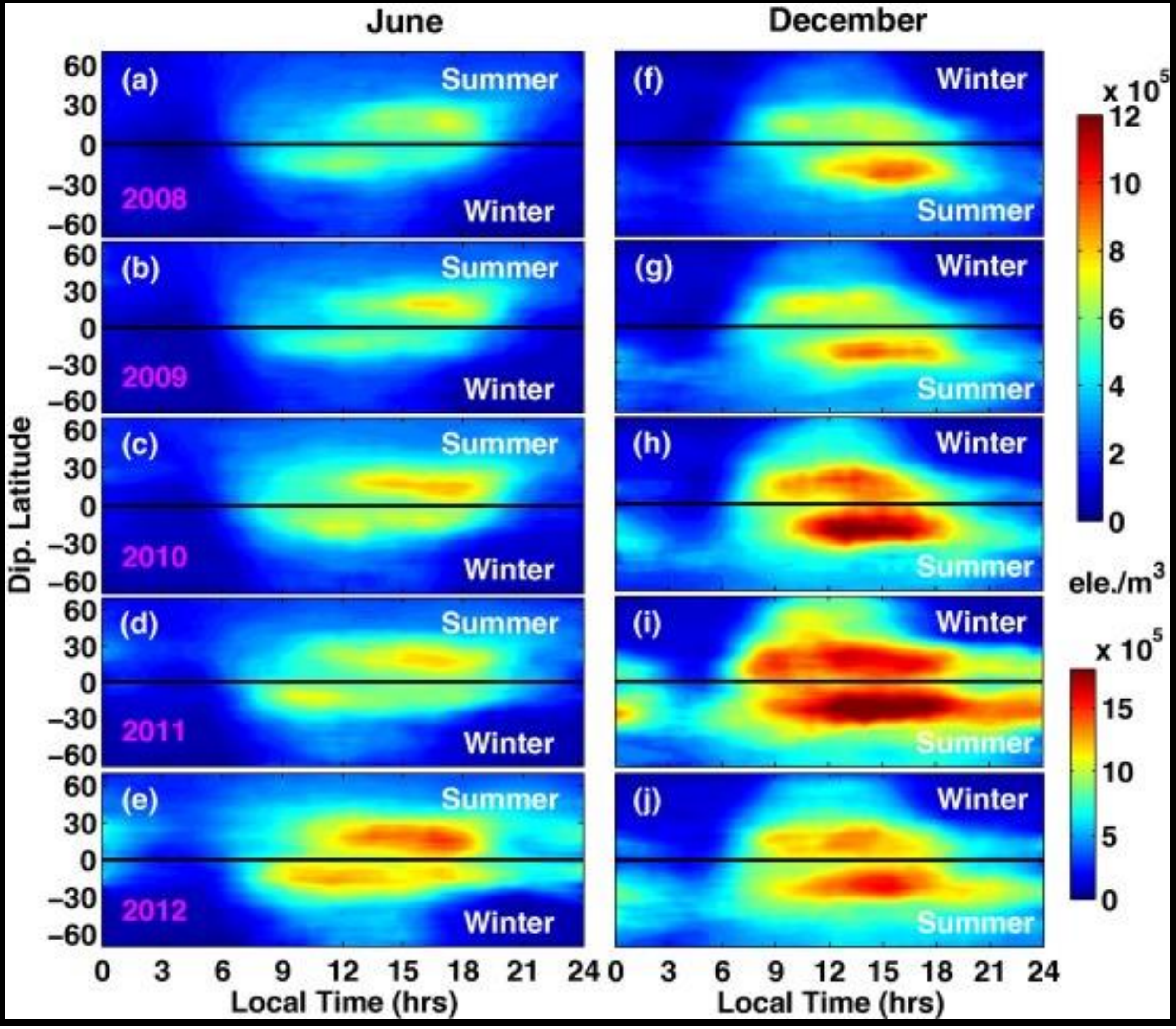
$$I = \frac{N_mF2_w}{N_mF2_s}$$

Radio Occultation measurements

The explanation of the winter anomaly given by Rishbeth (1998, 2000) is based on seasonal neutral composition changes (density ratio of atomic oxygen to molecular nitrogen O/N_2 is greater in winter than in summer).

Seasonal variability: Annual anomaly

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



Important factors that are responsible for ionospheric annual anomaly are:

- solstice difference of Sun-Earth distance
- offset between geomagnetic and geographic center
- tilt of geomagnetic dipole axis
- only a minor contribution from atmospheric tides of lower atmospheric origin.

Sai Gowtam and Tulasi Ram, 2017

Seasonal variability: semi-annual anomaly

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

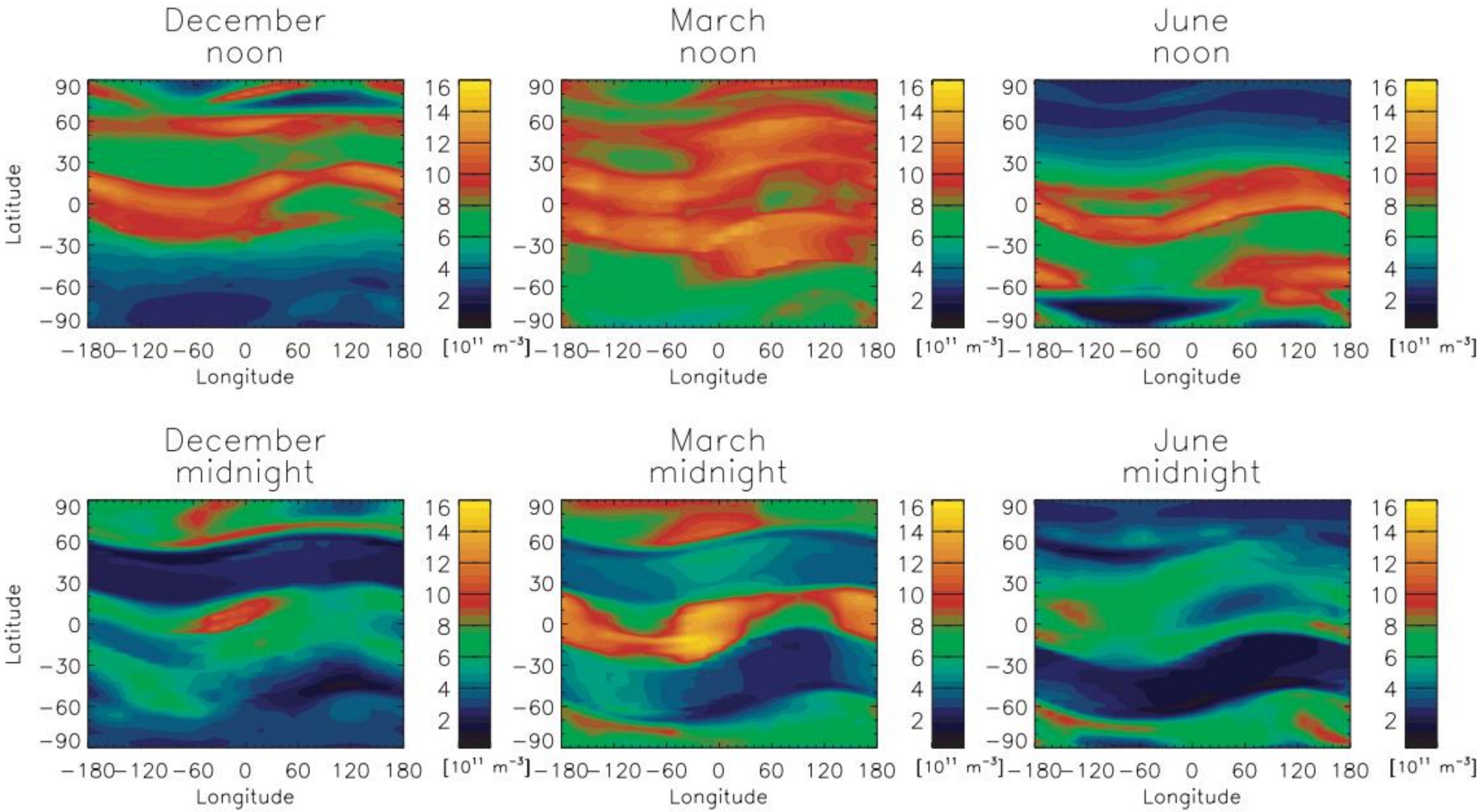


Fig. 5. Noon and midnight maps of *N*mF2 in December, March, June, $F_{10.7} = 100$

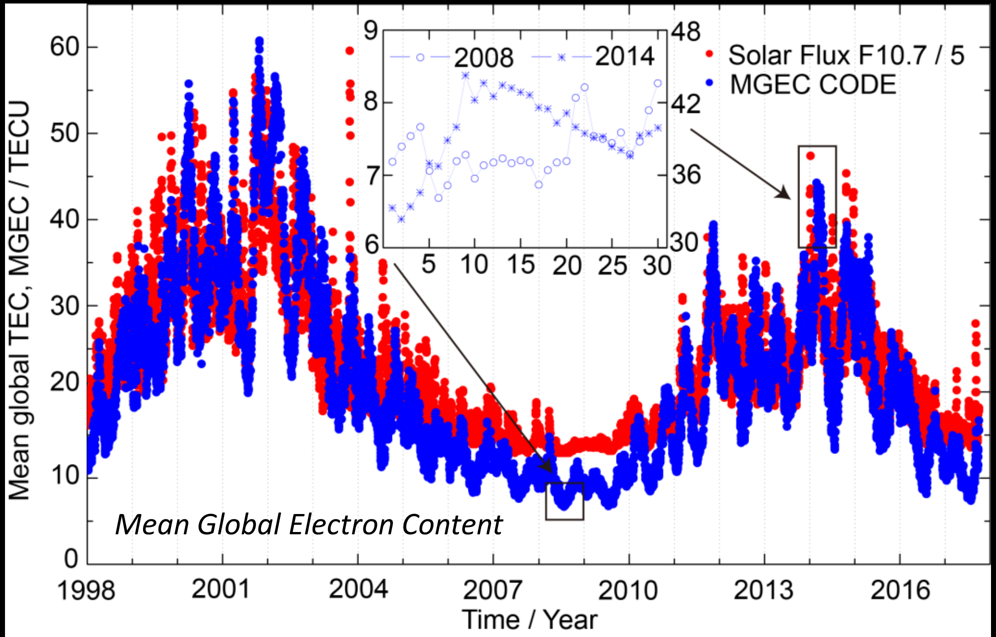
Yonezawa [1971] proposed the role the variation of the upper atmosphere temperature.

Torr and Torr [1973] suggested that this is due to semiannual variation in neutral densities associated with geomagnetic and auroral activity.

Mayr and Mahajan [1971] showed that the semiannual effect appears as a persistent feature of the ionosphere which is not related to fluctuations in the 10.7 cm noise or the EUV radiation.

This gives support to theories that attribute the semiannual effect to variations in the lower atmosphere.

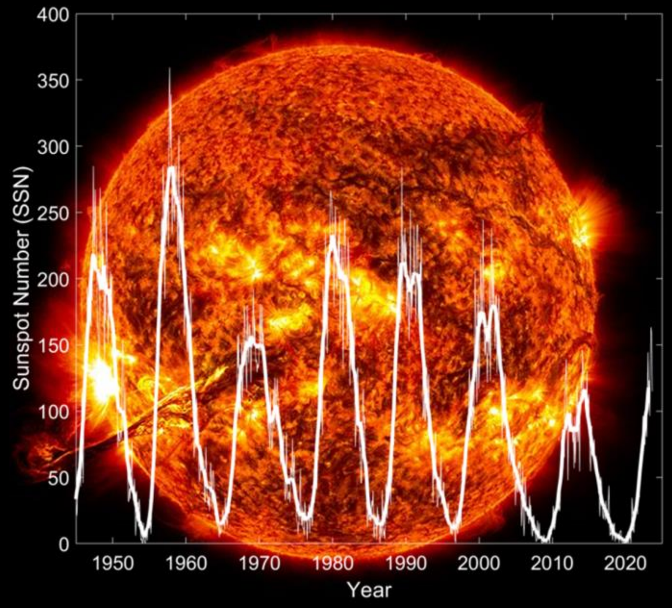
Ionosphere solar cycle (flux) variation

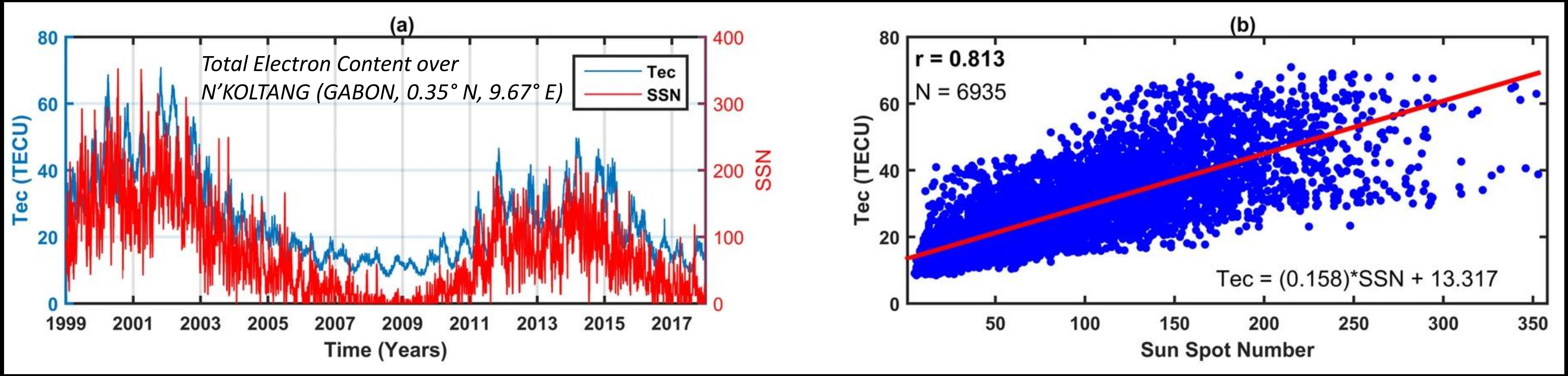


Zhang et al., 2018

The Sun exhibits a ~ 11-years variability identified by the number of sunspots (SSN)/solar flux @ 10.7 cm (F10.7)

Nice agreement with the solar activity





Moses et al., 2022

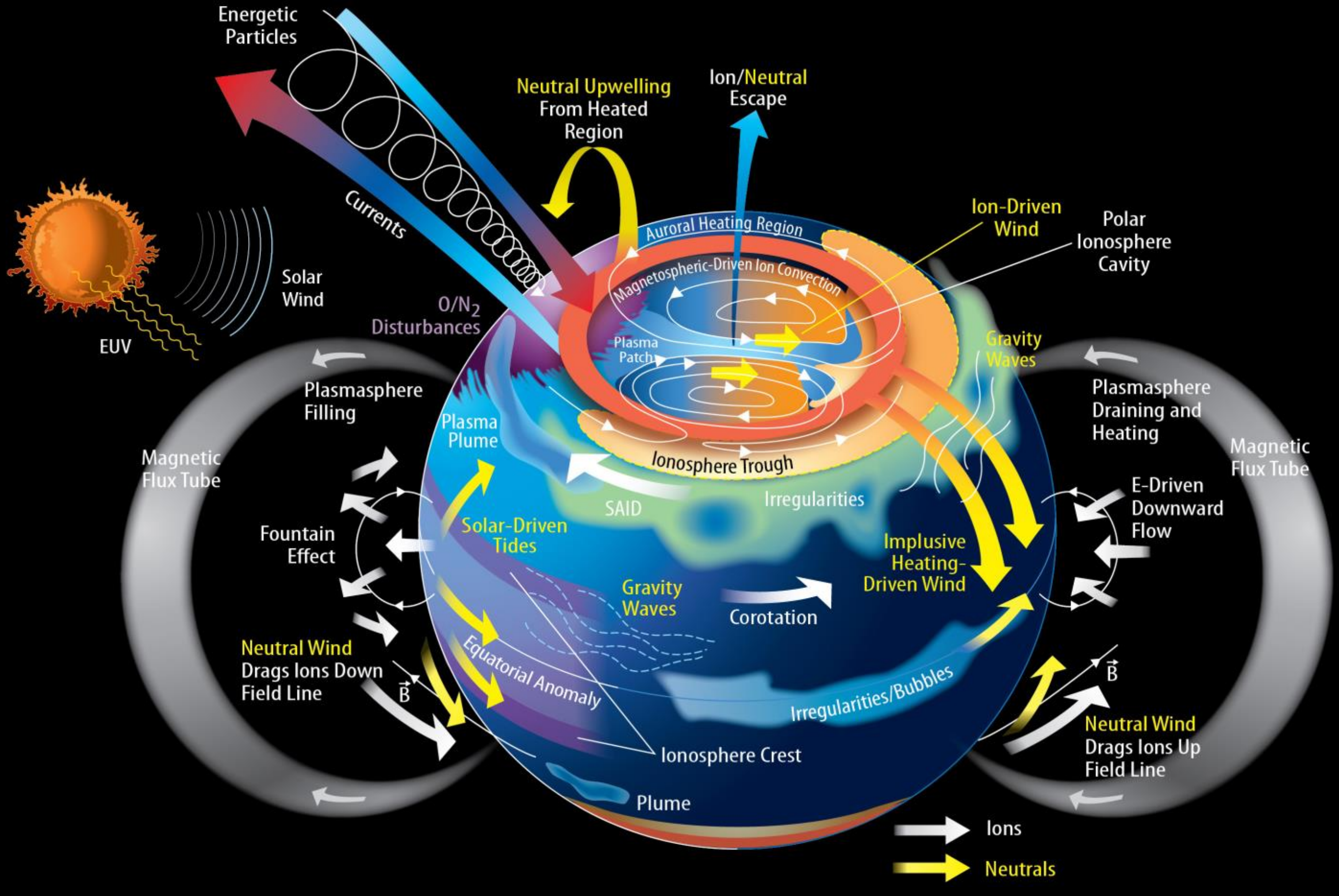
Recipe for Earth’s ionosphere

Doses for 1 planet

1. Sprinkle a generous amount of Photoionisation
2. Add an almost uniform dusting of Particle Precipitation around the (magnetic poles)
3. Add a wise dose of chemistry
4. Season it all with a strong internal magnetic field.
5. Stir everything to achieve regular variations
6. Shake with irregular variations

Ionosphere’s interactions

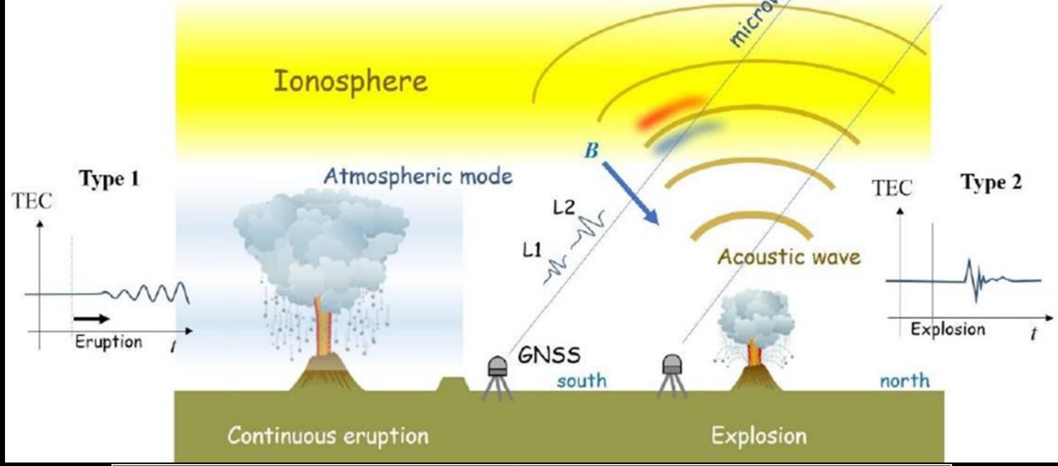
Solar Wind – Magnetosphere – Ionosphere Coupling

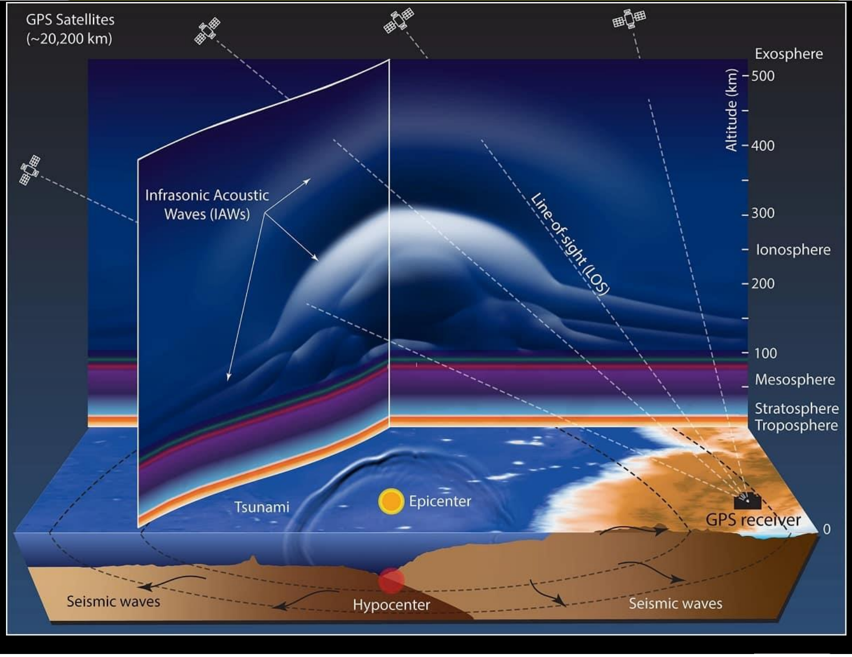


©: J. Grebowsky, NASA

Lithosphere – Atmosphere – Ionosphere Coupling

From Mokhamad Nur Cahyadi et al., 2021





Ionosphere irregular variation (solar storm)

Flares

UV and X-rays

↓

Directly affects ionosphere

↓

8.3 min

Coronal Mass Ejections

CME

↓

Affects ionosphere through SW-M-I Coupling

↓

1 – 3 days

High Speed Streams

Fast protons and α particles

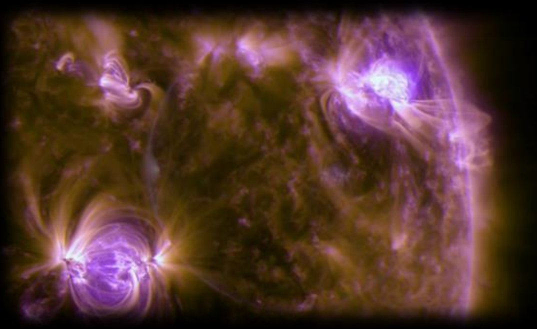
↓

Affects ionosphere through SW-M-I Coupling

↓

15 min – few hours

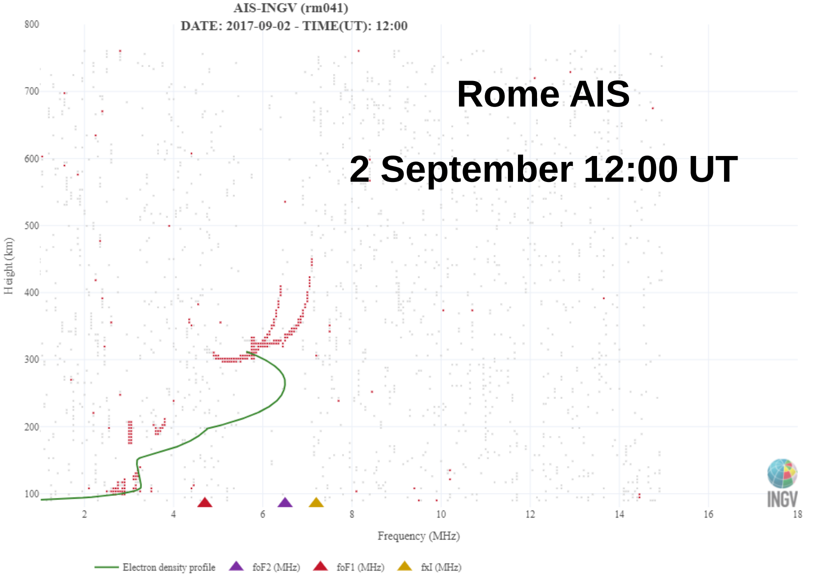
Flares

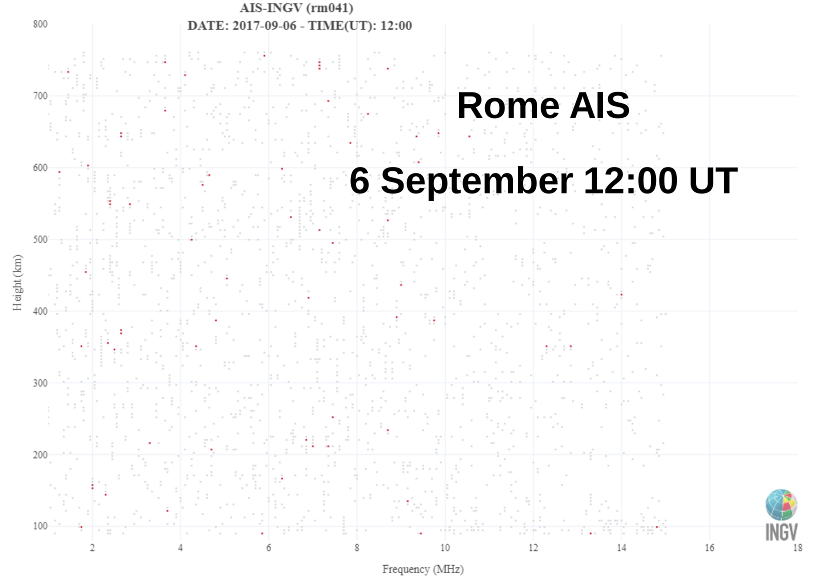


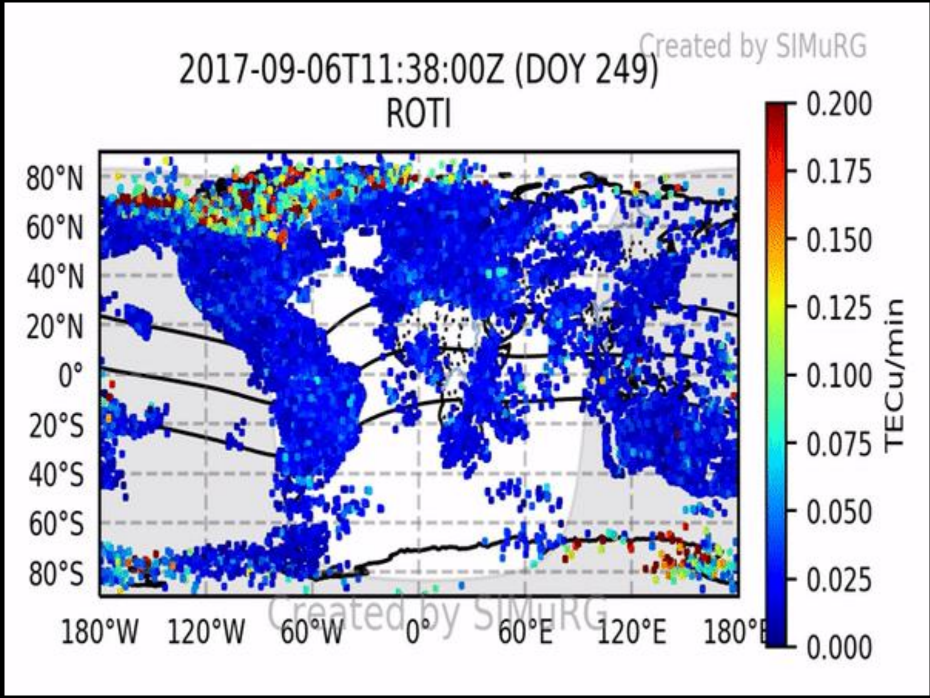
UV and X-rays

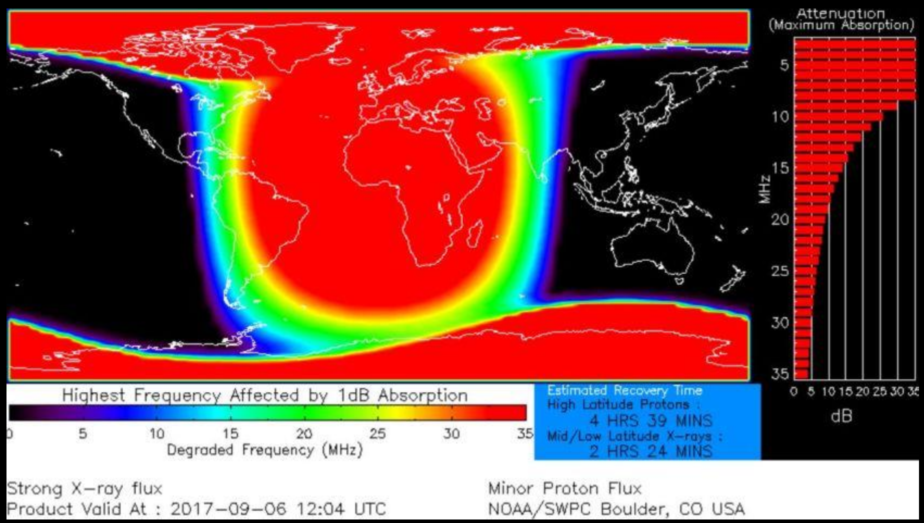
Directly affects ionosphere

8.3 min



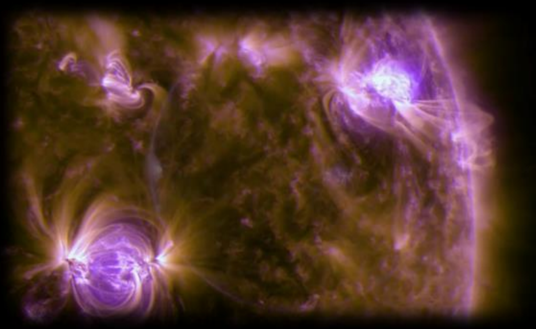






X9.3 Flare – 6 September 2017

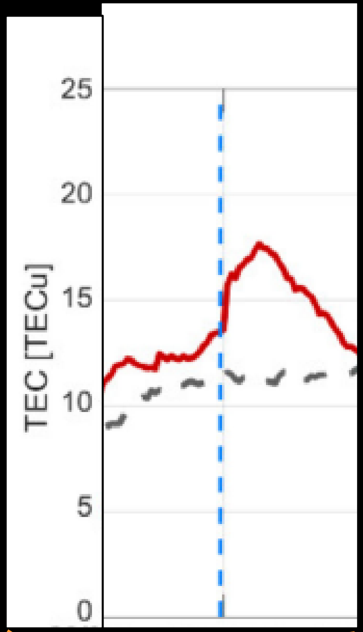
Flares

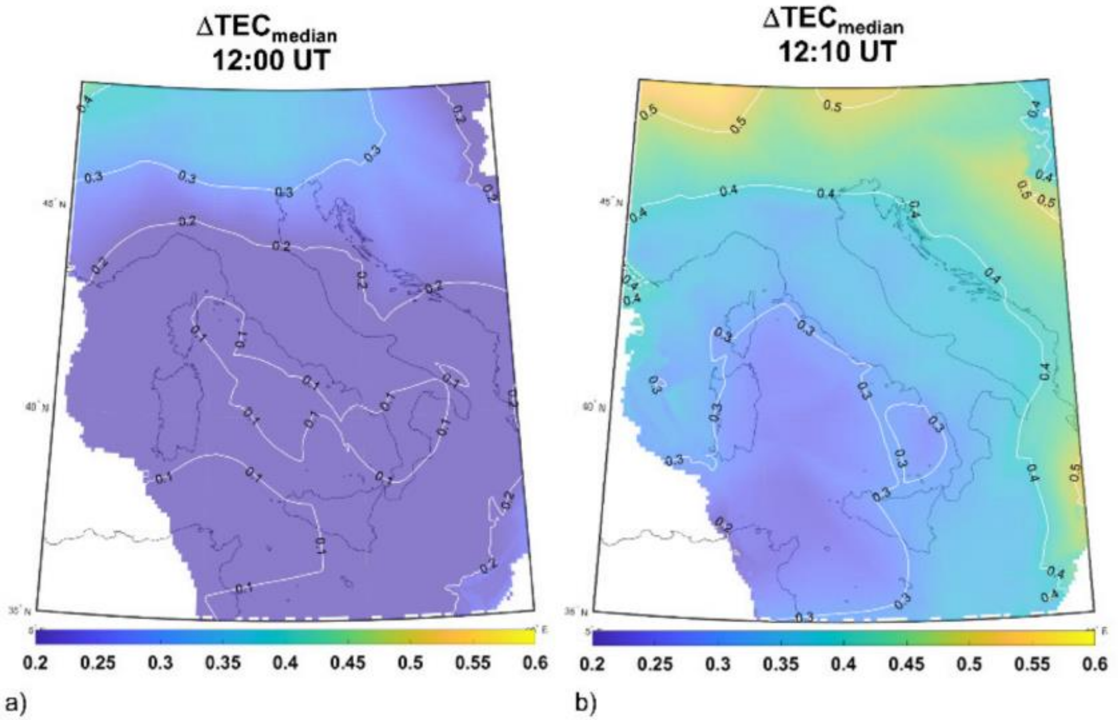


UV and X-rays

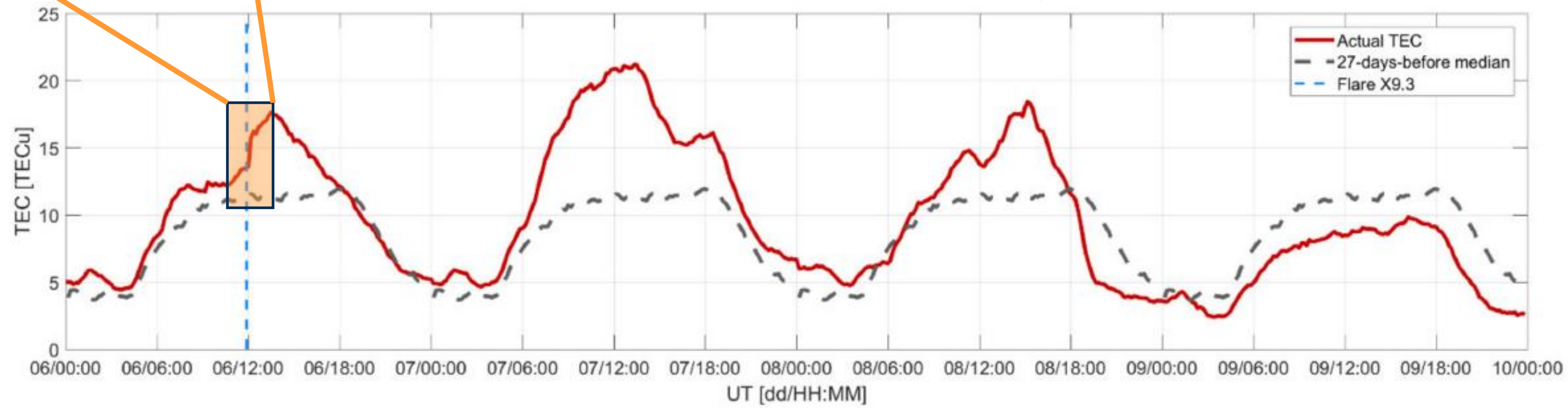
Directly affects ionosphere

8.3 min





Cesaroni et al., **2021**, https://doi.org/10.3390/rs13163290

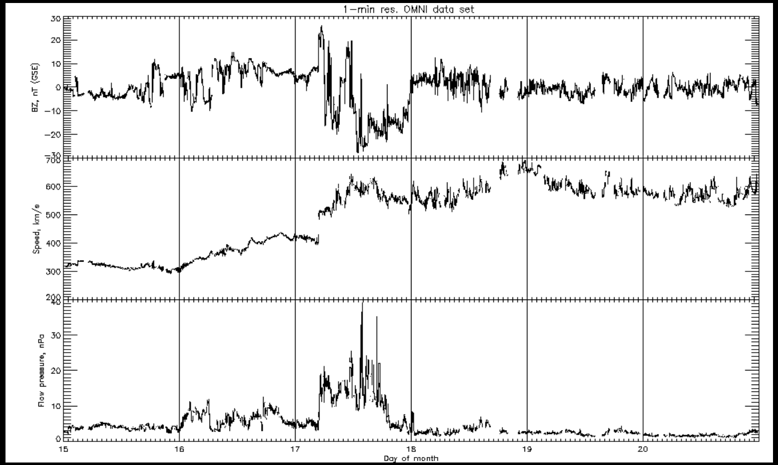


eSWua electronic SPACE WEATHER upper atmosphere

Real-time TEC maps on eswua.ingv.it

IONORING real-timetotalelectroncontentoveritaly

Ionosphere irregular variation (solar storm)



Interplanetary magnetic field Bz component, solar wind flow speed and dynamic pressure (from NASA OMNI)

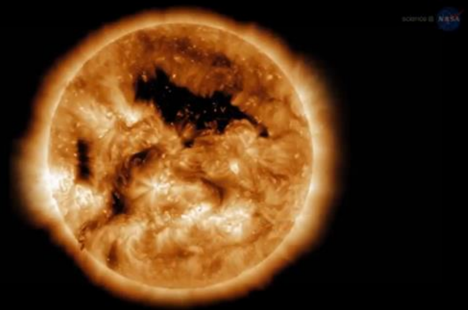
Coronal Mass Ejections

CME

Affects ionosphere through SW-M-I Coupling

1 – 3 days

High Speed Streams



Fast protons and α particles

Affects ionosphere through SW-M-I Coupling

15 min – few hours

Solar Wind – Magnetosphere – Ionosphere Interaction

When CME/fast solar wind stream hits the Earth, the SW–M–I coupled conditions may lead to several effects affecting high, mid and low latitudes.

Enhanced particle precipitation at auroral latitudes

Modification of the ionospheric current system at high latitudes

Modification of the ionospheric current system at low latitudes

Modification of the neutral composition

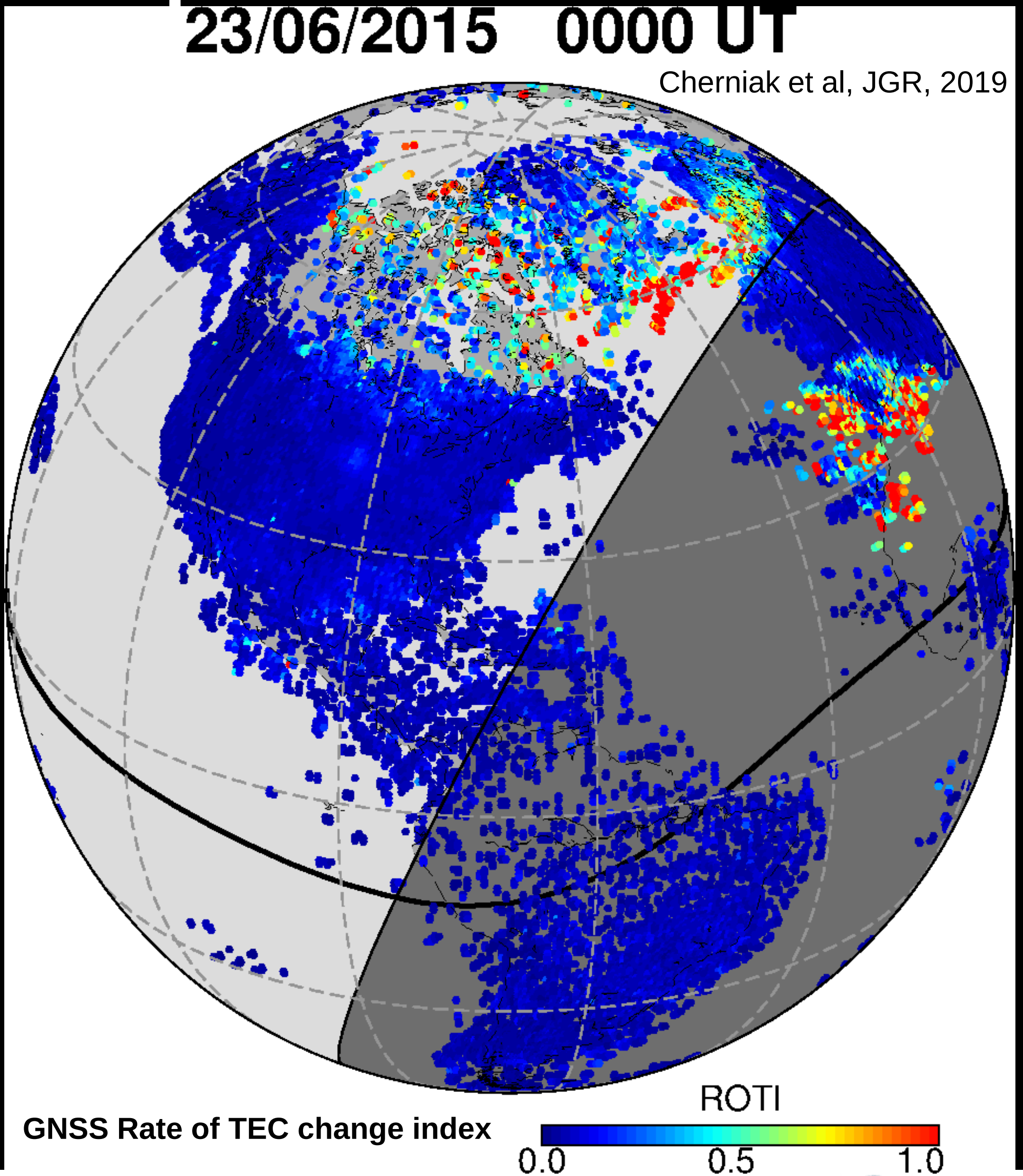
Ionospheric heating

Displacement of the boundaries of auroral oval

Traveling Ionospheric Disturbances

Changes in the polar cap circulation

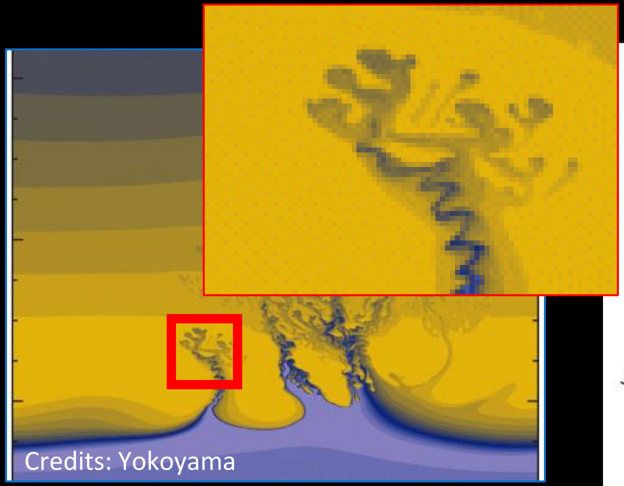
[and more…]



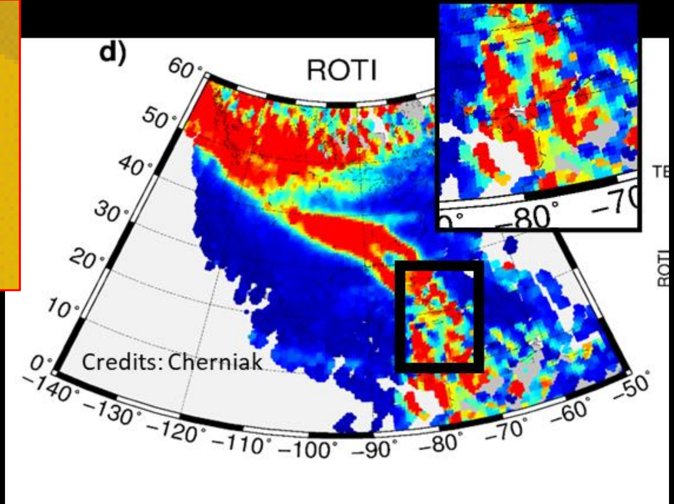
Cherniak et al, JGR, 2019

GNSS Rate of TEC change index

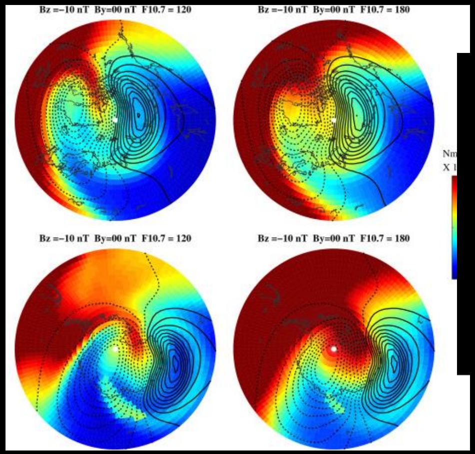
Geomagnetic storms and ionospheric irregularities

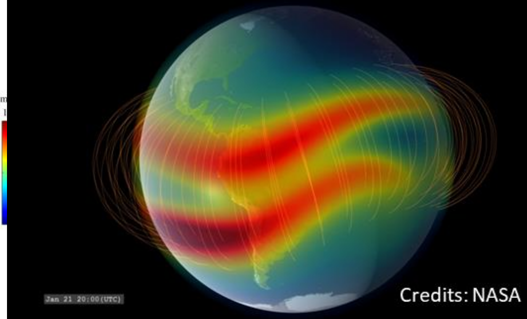


Credits: Yokoyama



Credits: Cherniak





Credits: NASA

100 m

1 km

10 km

100 km

1000 km

Small scale (Fresnel's scale)

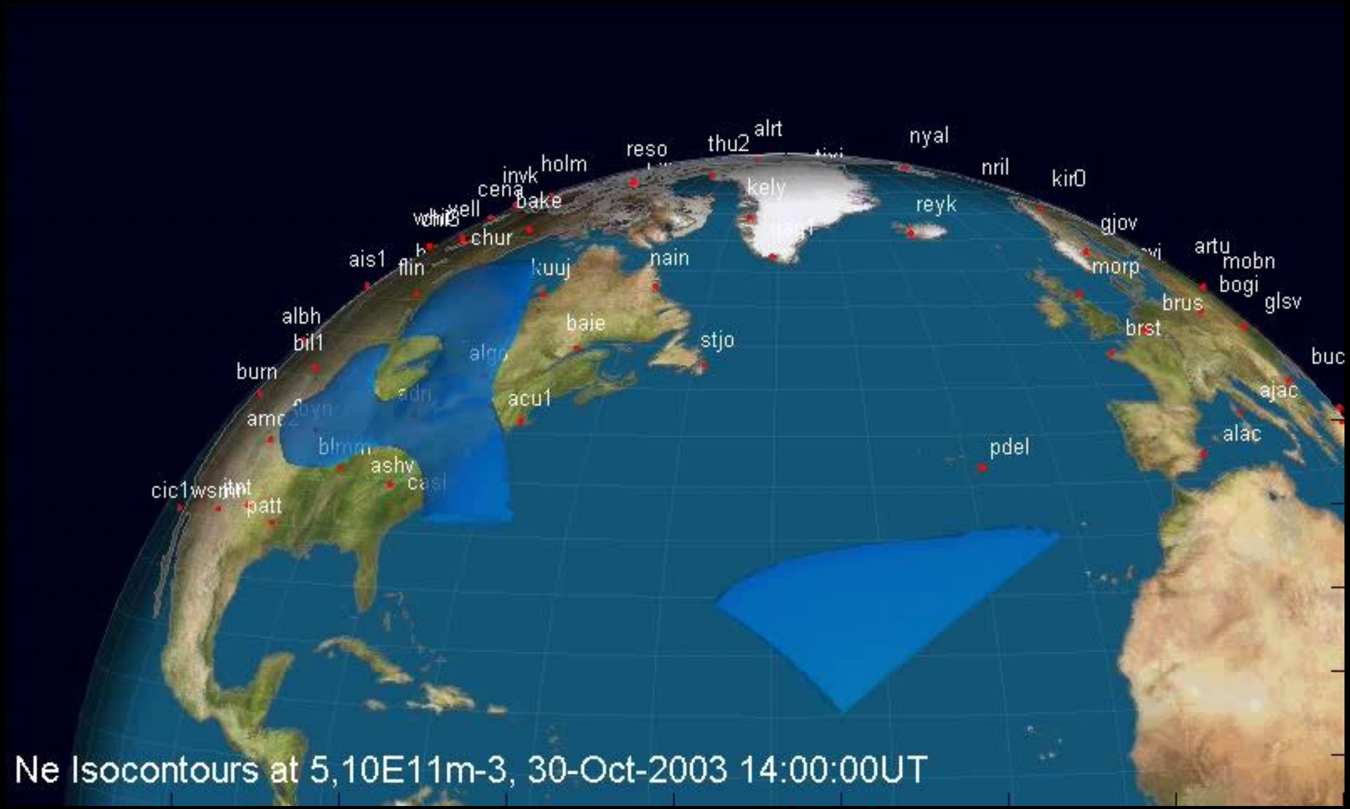
Medium scale

Large scale

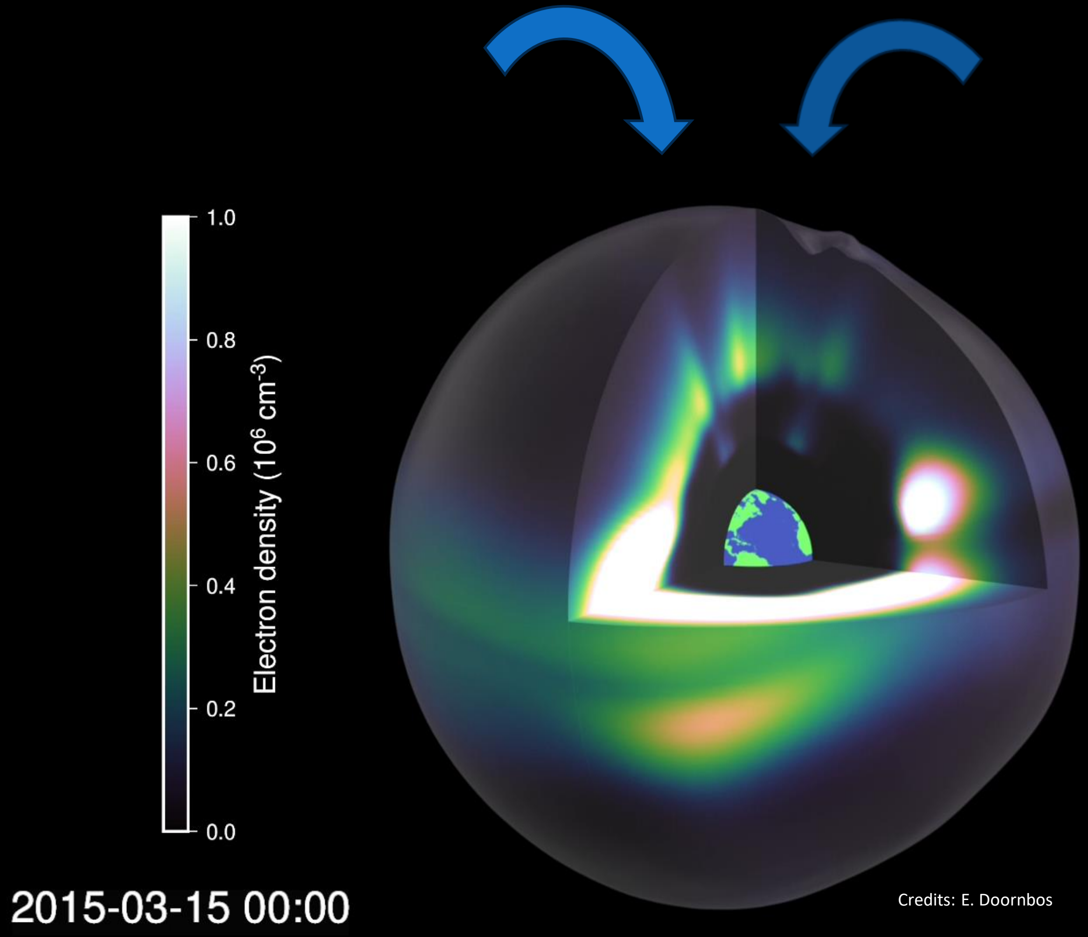
Ionospheric irregularities are plasma density variation w.r.t. background ionosphere

Ionospheric irregularities formation, occurrence, dynamics and response to solar forcing are of interest for understanding the underlying phenomena and for applications (e.g. GNSS positioning, HF communication etc.)

High-latitude response: increased ionisation due to particle precipitation



Credits: University of Bath



Credits: E. Doornbos

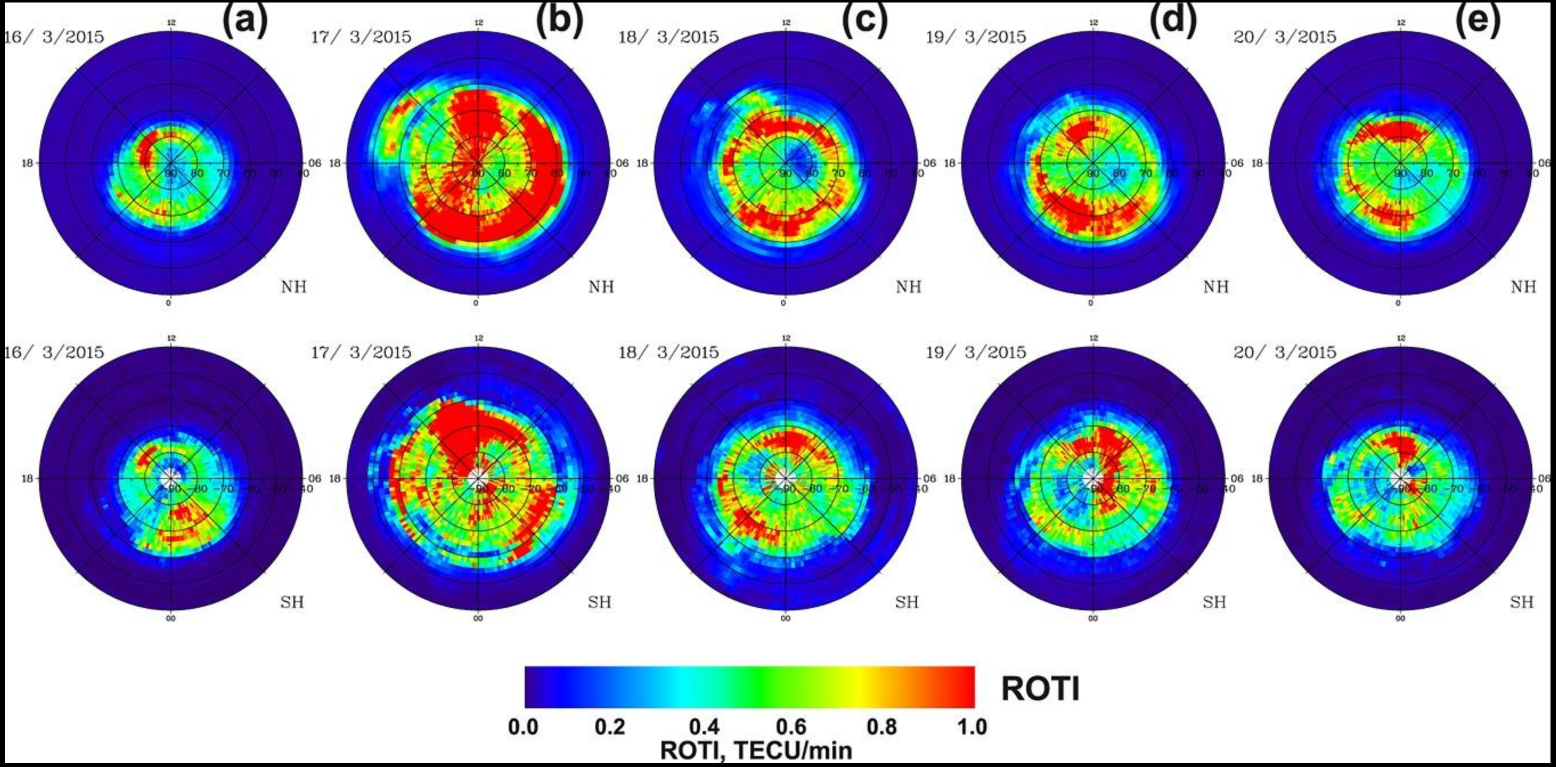
Electron density during the 2003 Halloween storm
(GPS Tomography with MIDAS)

Electron density during the 2015 St.Patrick's Day storm
(Modeled with WACCM-X)

Response of the high-latitude ionosphere

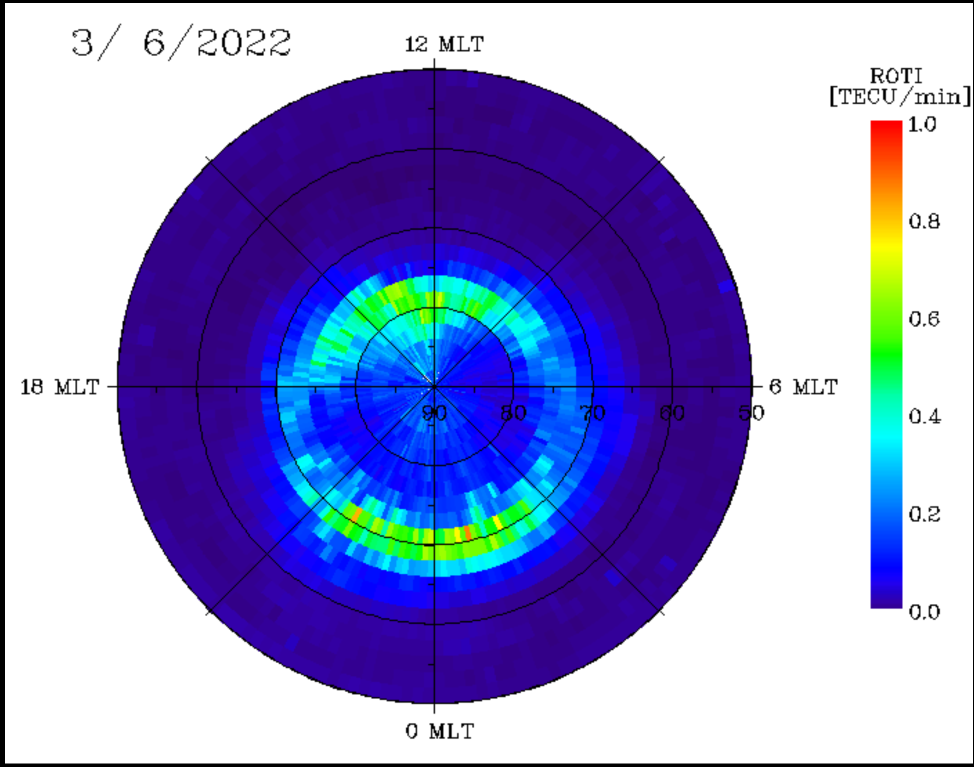
Signatures of:

- Convection cells
- Auroral oval displacement
- Tongue of ionisation



2015 St. Patrick’s Day Storm

Cherniak et al., 2015

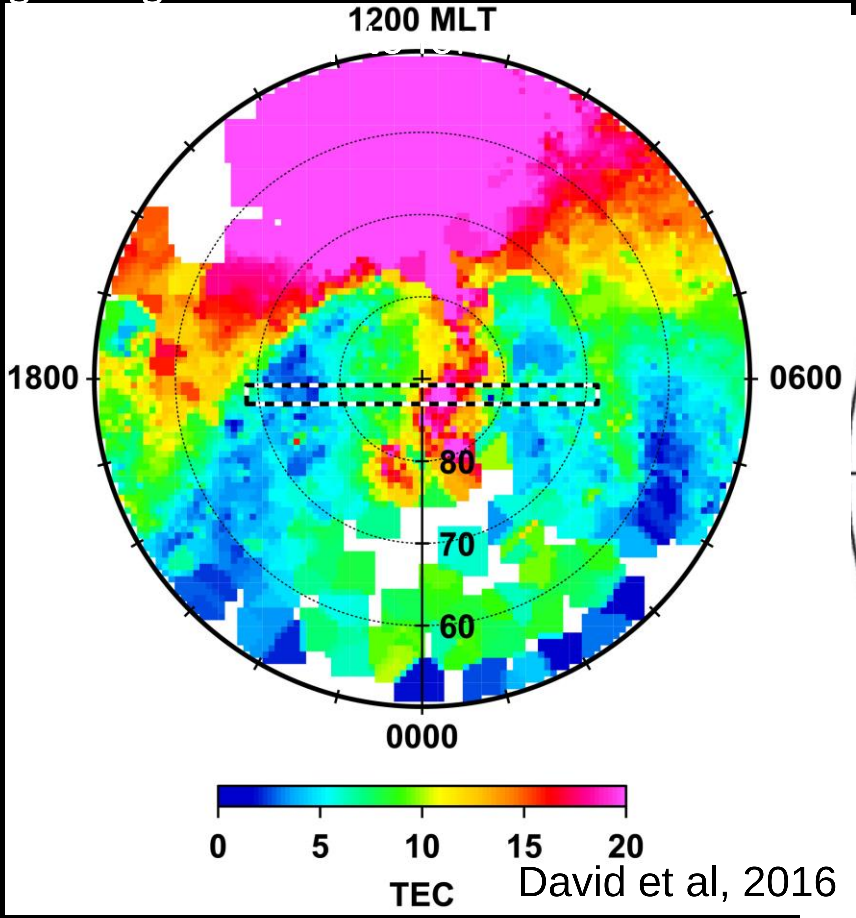


June 2022 storm

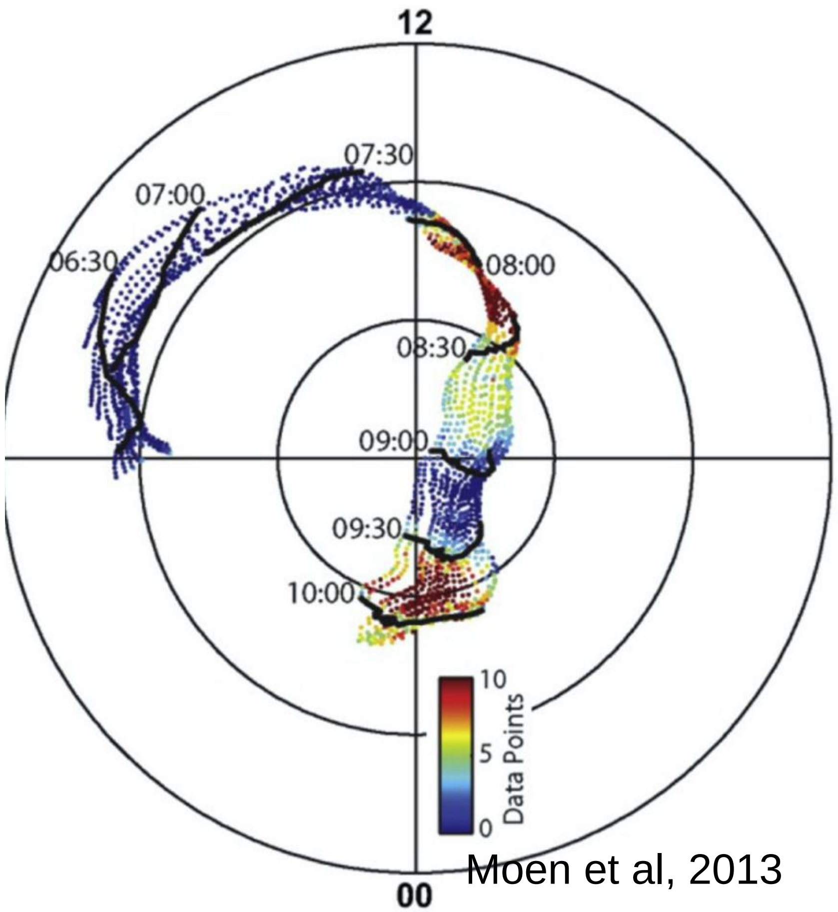
Cherniak et al, 2017

Creation of large-scale structures (which embed medium and small-scale irregularities)

Storm enhanced density(SED), tongue of ionization (TOI) and plasma patches. *F* region plasma from middle and low latitudes is transported due to large-scale enhancement of the ionospheric convection electric field during disturbed geomagnetic conditions. Horizontal drifts transporting plasma from the throat region

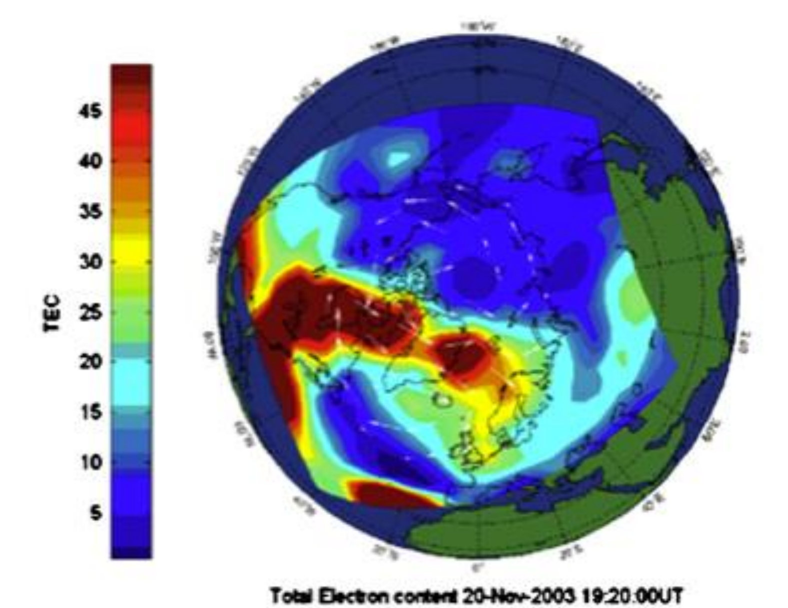


David et al, 2016

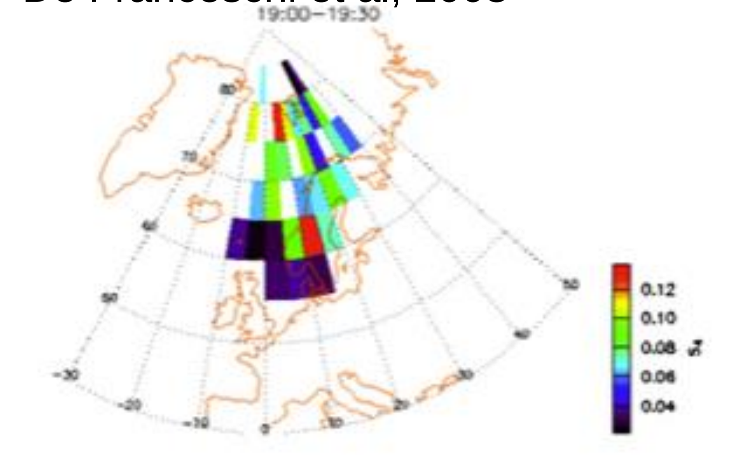


Moen et al, 2013

TOI and plasma patches transporting across polar cap



De Franceschi et al, 2008

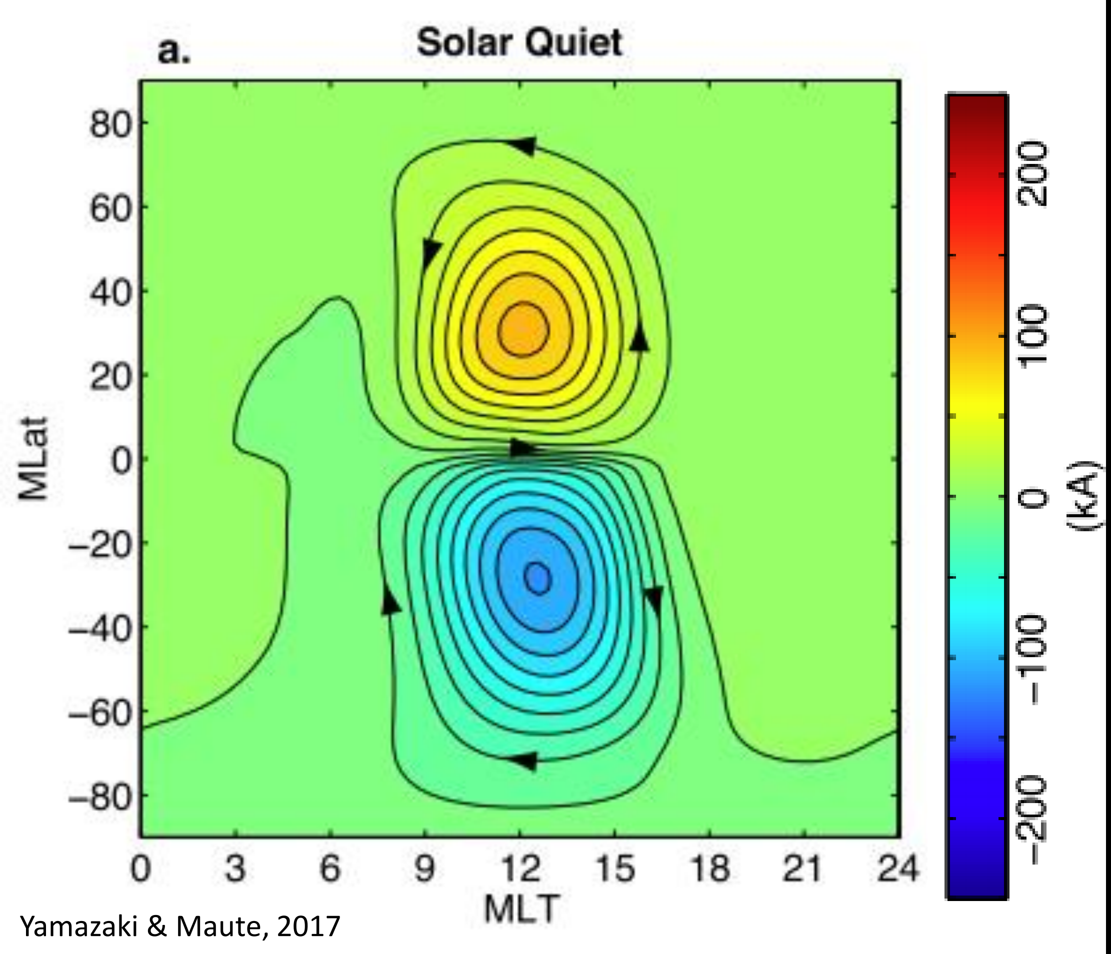


GD and K-H instabilities can grow up to produce small-scale irregularities (hundred of meters)

What’s the role of the external drivers in modulating EIA, EPB and scintillation occurrence?

In case of a geoffective Space Weather event, the low latitude electrodynamics is altered

Equatorial zonal electric field **E**, eastward in dayside and westward in nightside, is modified and the mechanisms ruling out the formation of EIA and EPB is altered.



Yamazaki & Maute, 2017

Equivalent ionospheric current systems simulated by the NCAR TIE-GCM under active geomagnetic conditions (Kp=5−)

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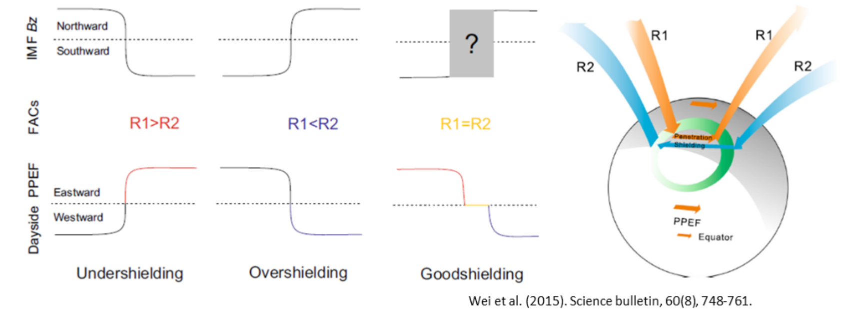
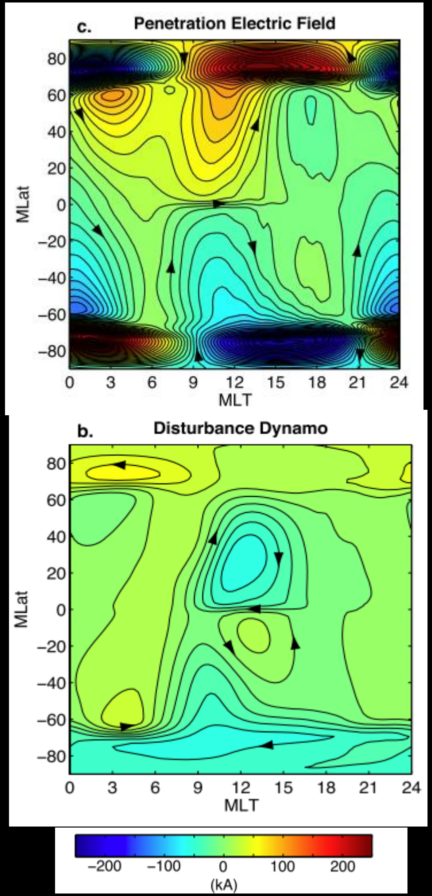
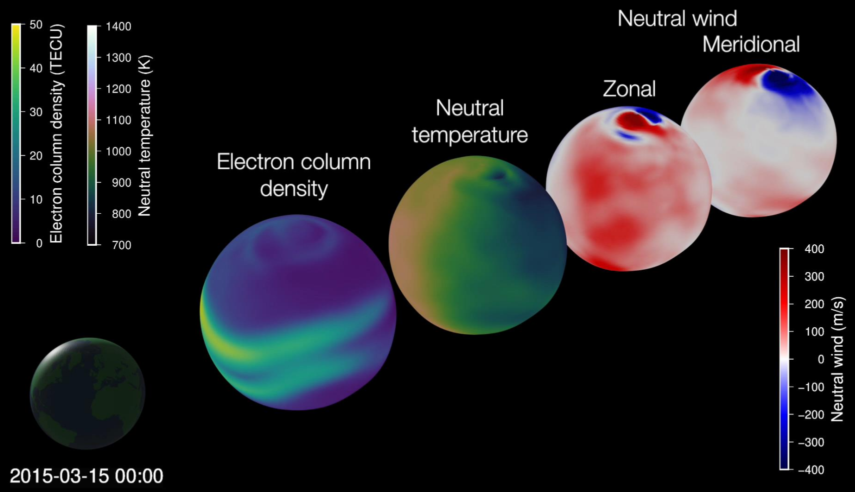


Wei et al. (2015). Science bulletin, 60(8), 748-761.

Prompt Penetration Electric Fields (PPEF)

Penetration of Electric Field from Interplanetary Electric Field. Prompt effect, perturbations in the zonal electric field for shorter durations of about 30 min to 2 h

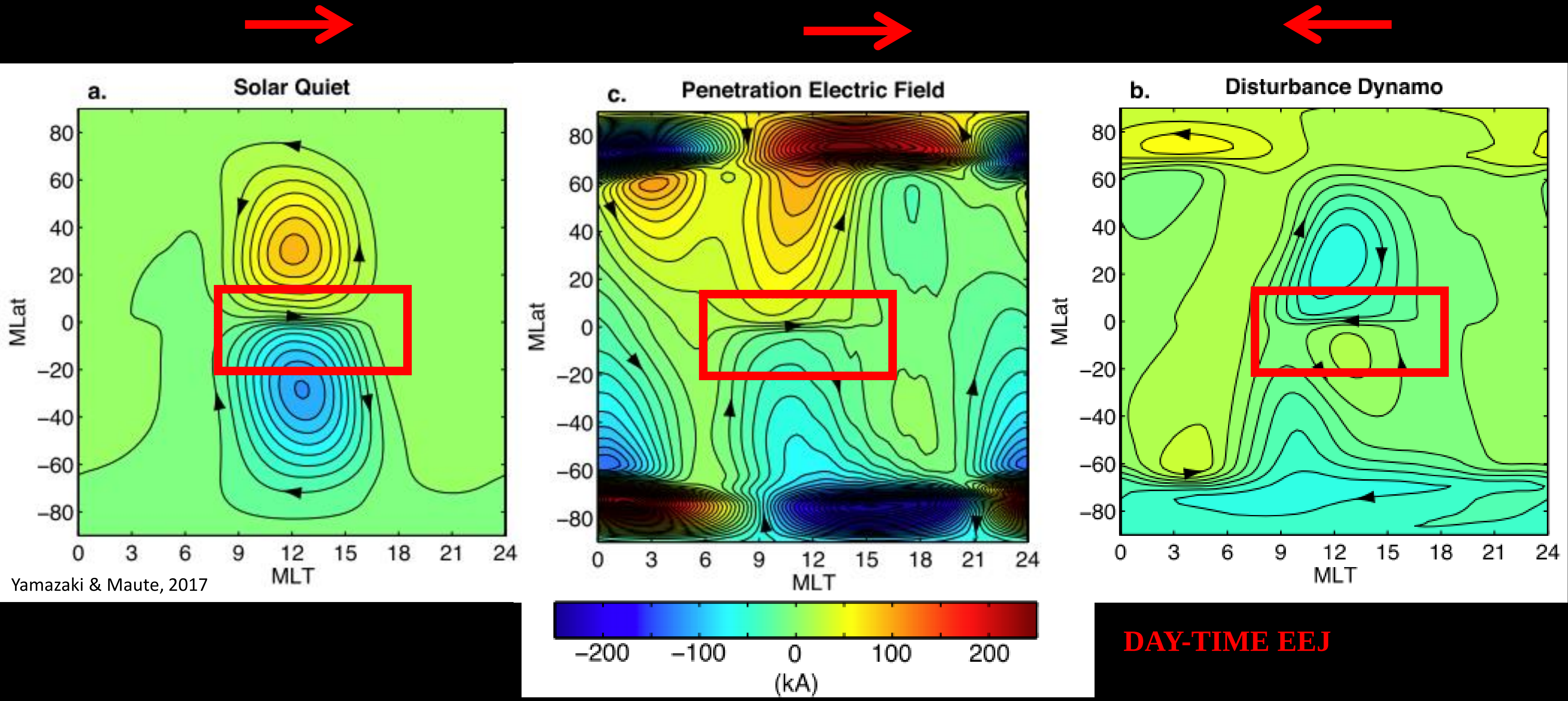




Disturbance Dynamo Electric Fields (DDEF)

Cross-equatorial winds due to thermospheric changes induced by heating at high latitude (often with LSTID). Delayed effect, non-uniform time delays at different latitudes and lasts for few hours to more than a day

Interplay between PPEF and DDEF

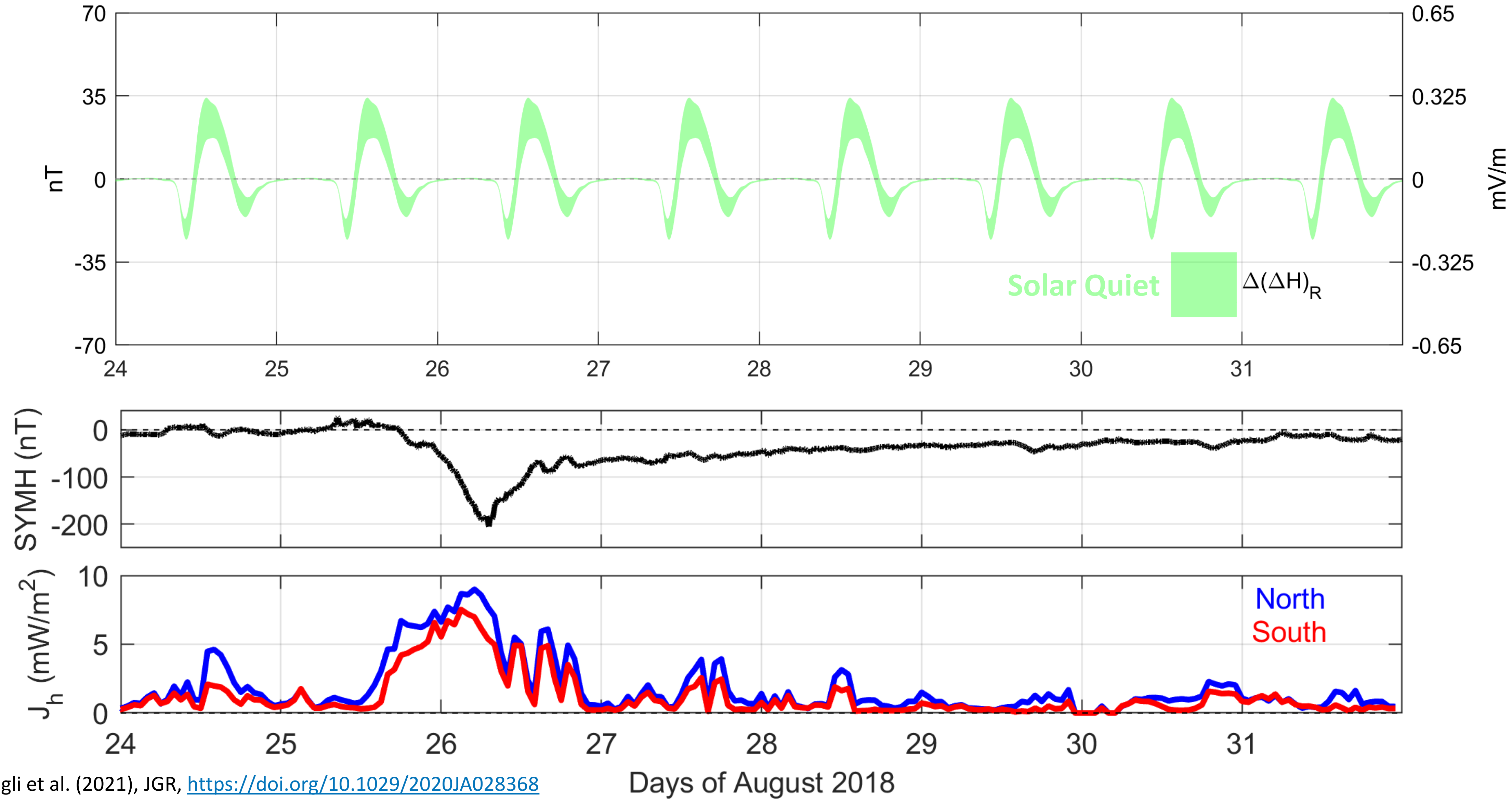


Yamazaki & Maute, 2017

DAY-TIME EEJ

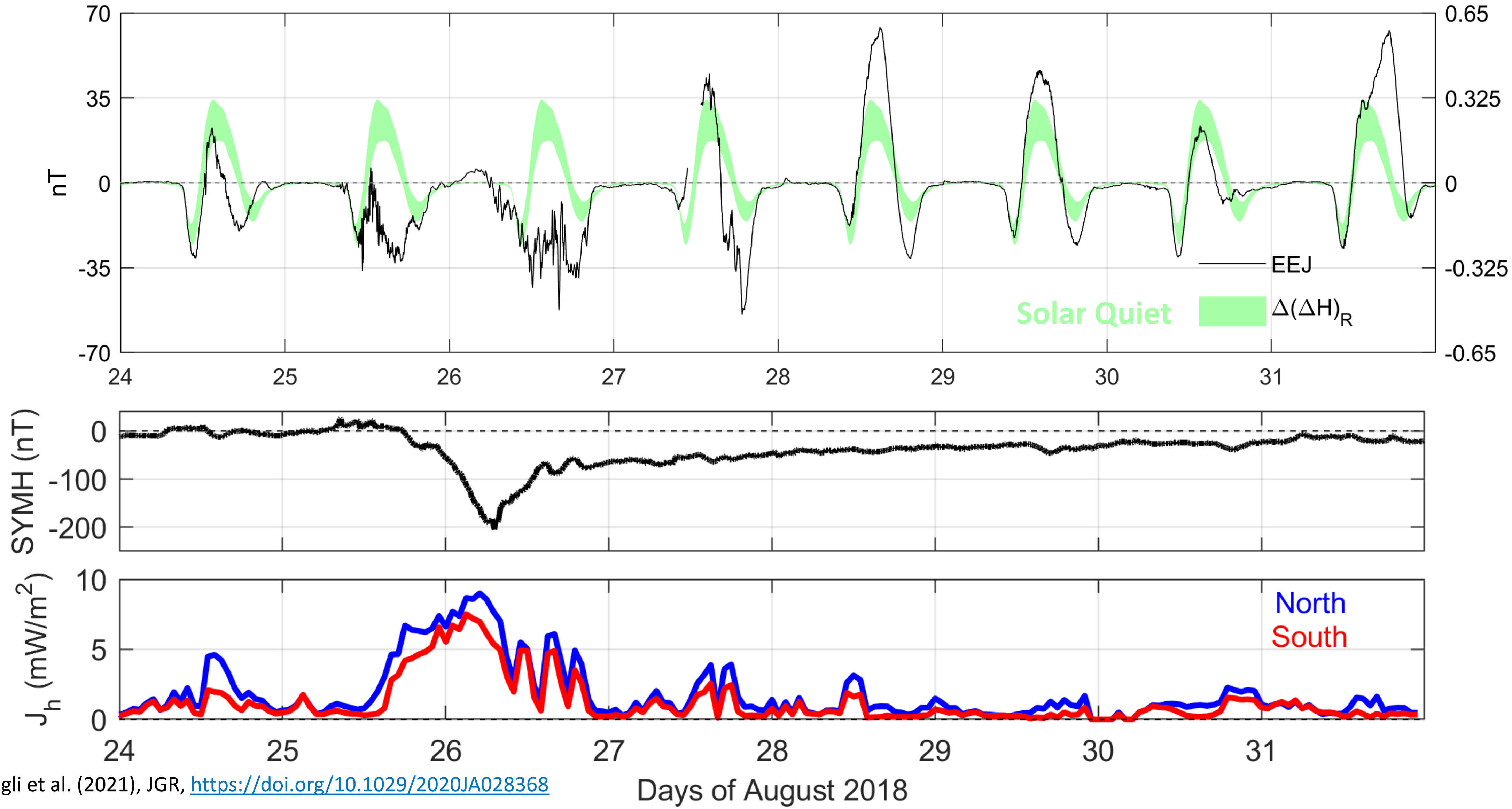
Equivalent ionospheric current systems simulated by the NCAR TIE-GCM under active geomagnetic conditions (Kp=5−)

Interplay between PPEF and DDEF: a case event



Spogli et al. (2021), JGR, https://doi.org/10.1029/2020JA028368

Interplay between PPEF and DDEF: a case event



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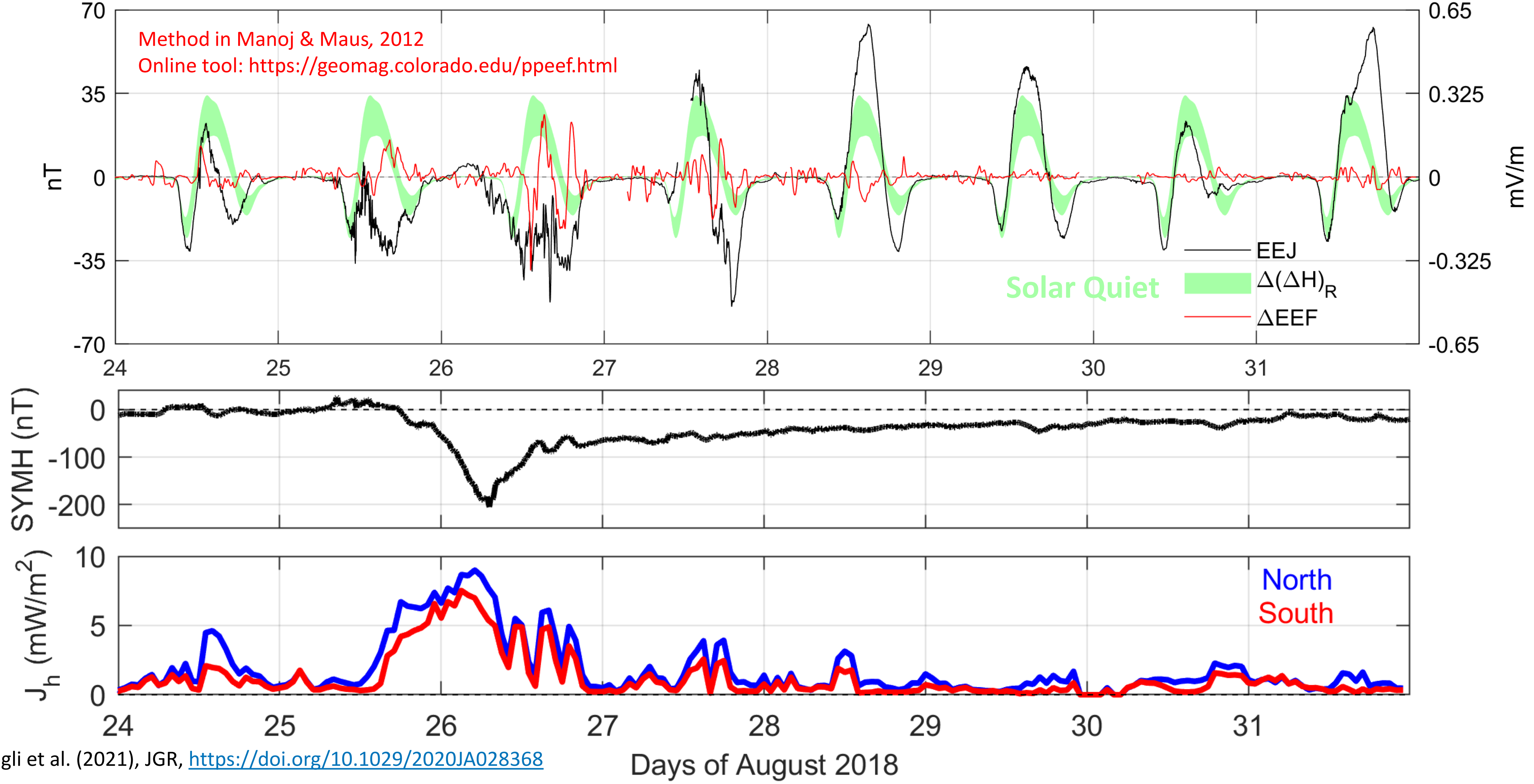
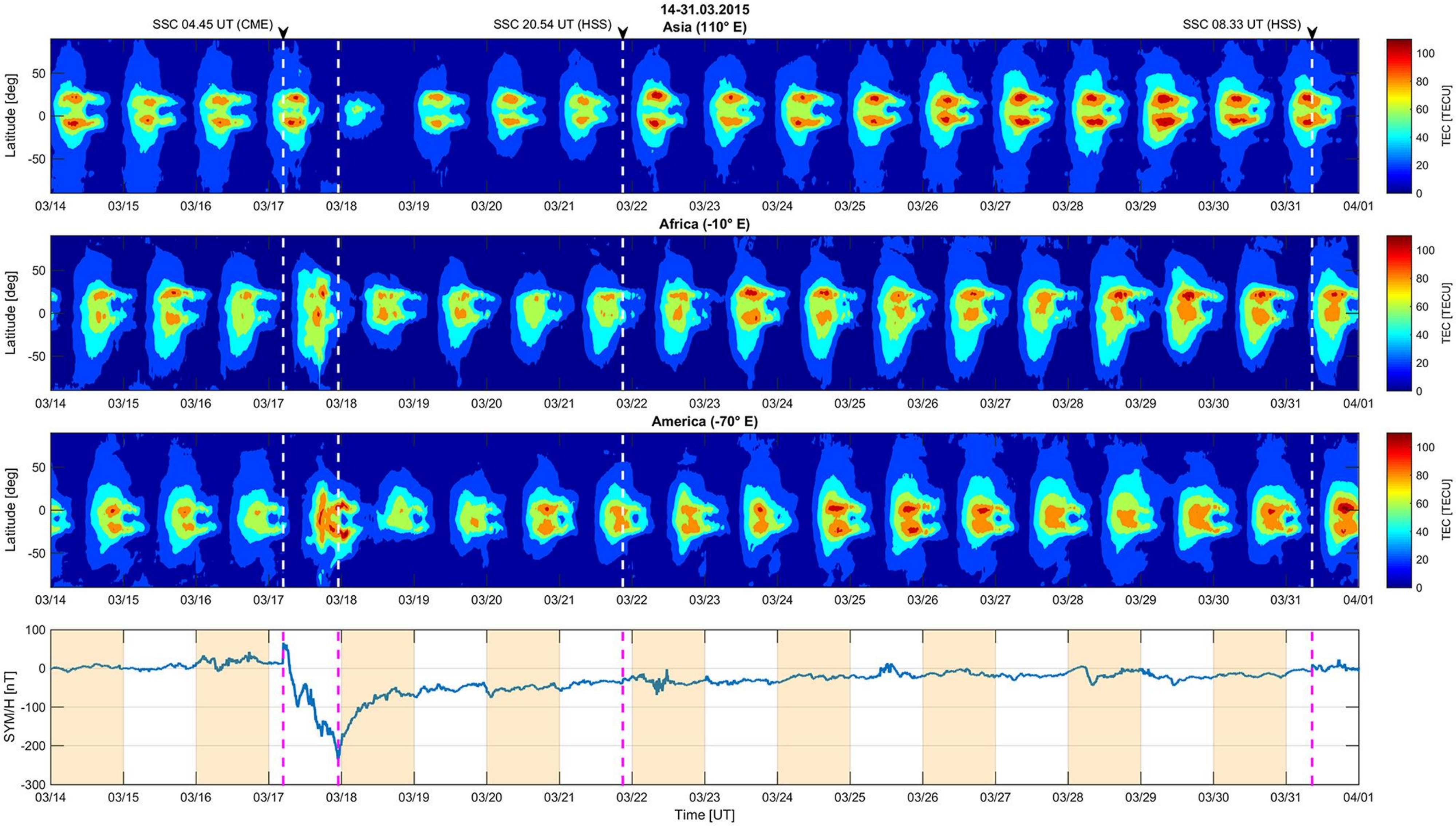
Interplay between PPEF and DDEF: a case event



Method in Manoj & Maus, 2012
Online tool: https://geomag.colorado.edu/ppeef.html

Spogli et al. (2021), JGR, https://doi.org/10.1029/2020JA028368

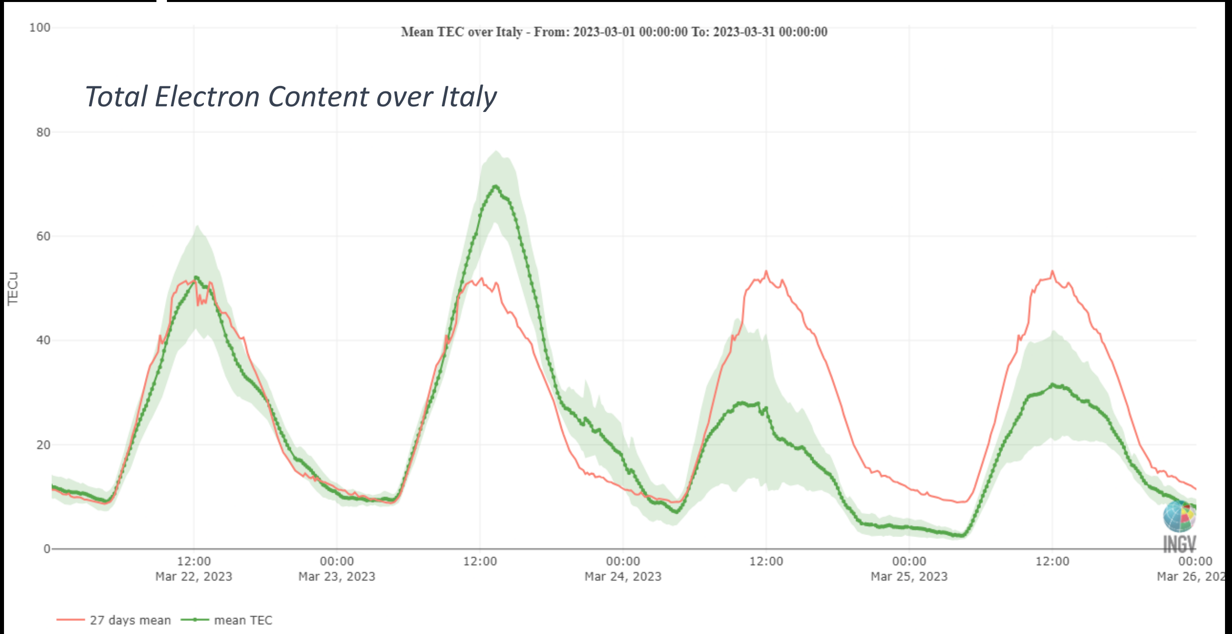
Displacement of the EIA crests

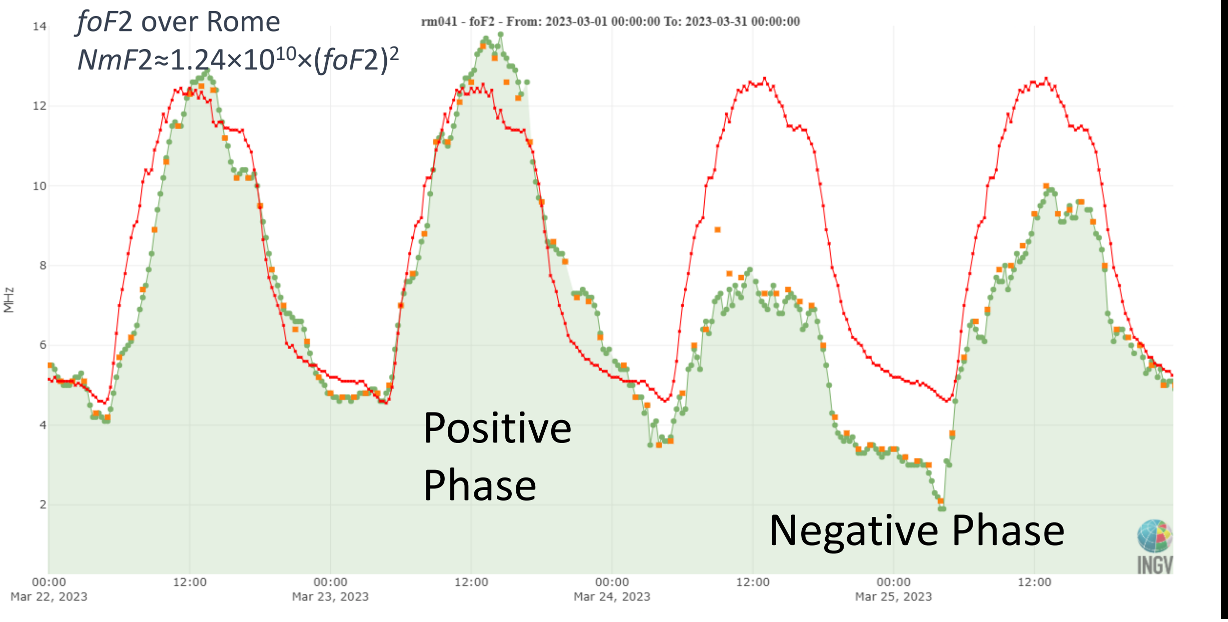


Nava et al., 2016

Storm development strongly depends on the local time sector

Response to storm at mid-latitudes



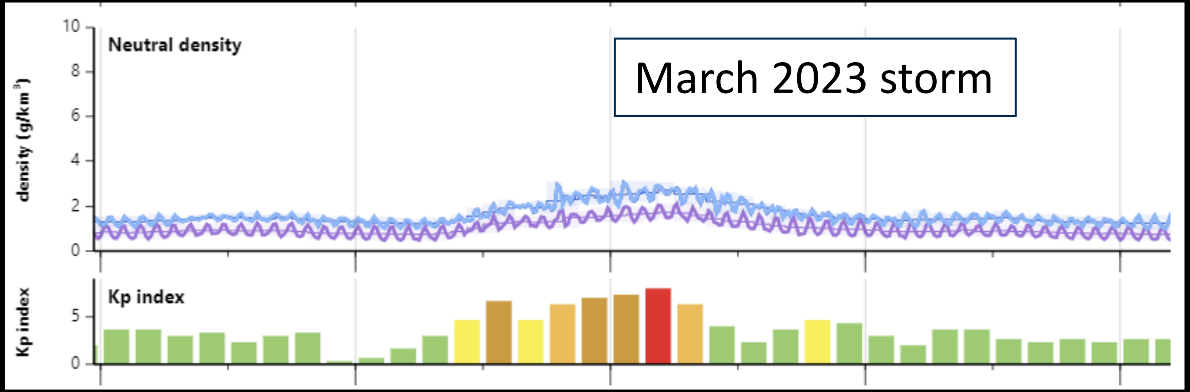


$NmF2 \approx 1.24 \times 10^{10} \times (foF2)^2$

Positive Phase

Negative Phase

Swarm-SWITCH timeline viewer



March 2023 storm

The positive phase lasts longer and becomes more prominent with decreasing latitude, followed by a prolonged negative phase that is stronger with increasing latitude

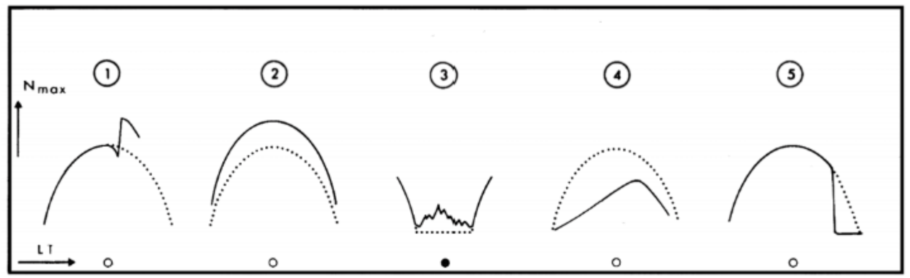
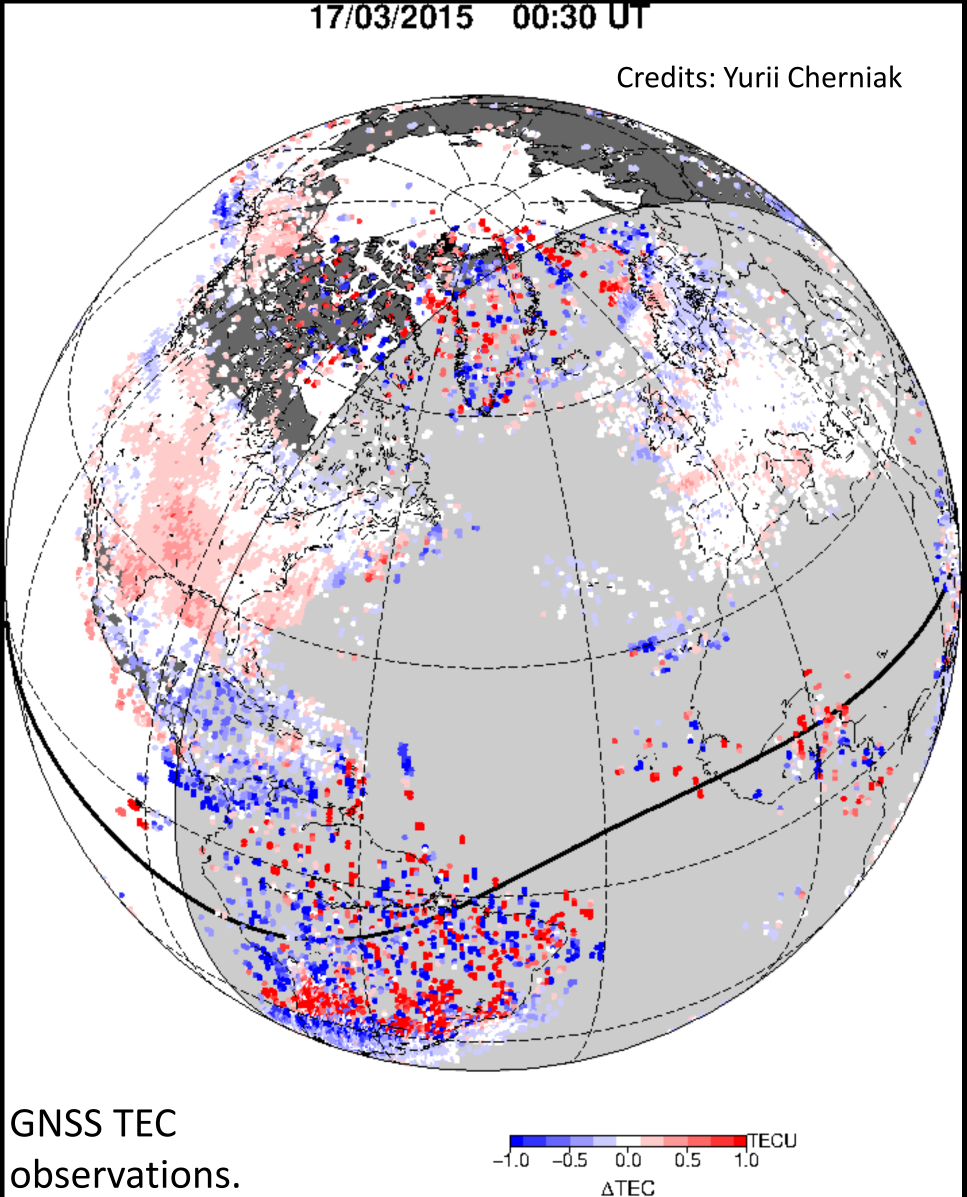


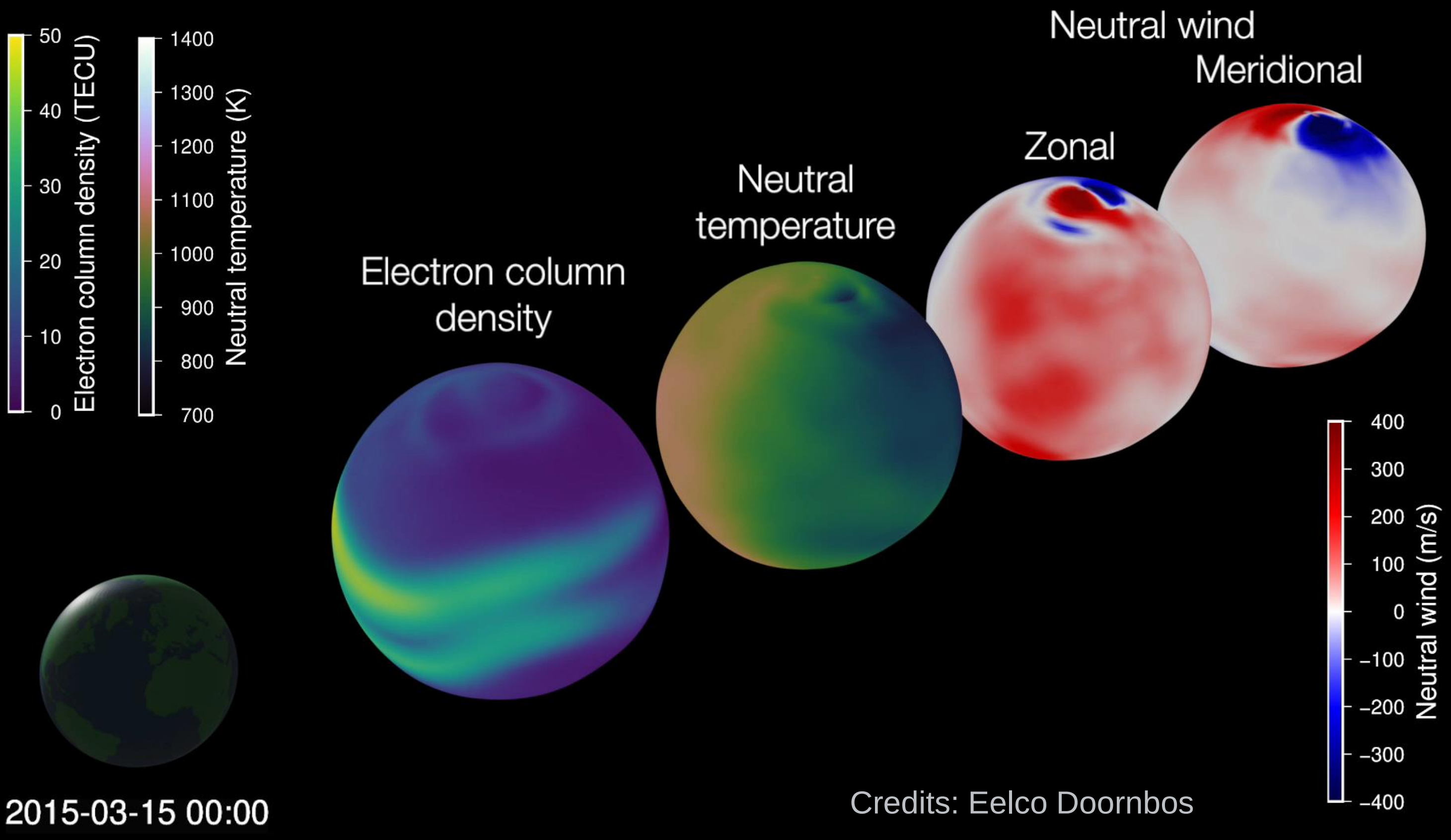
Figure 1. Types of ionospheric disturbances found during geomagnetic storms [from *Prölss*, 1995]. While intended to describe only winter storm effects in N_{max} at subauroral latitudes, this classification scheme is appropriate for the general characterization of TEC storm patterns in any season. The interpretation offered here is to identify the (1) magnetospheric convection-driven "dusk effect" in the positive phase, (2) wind-driven positive phase, (3) auroral precipitation-induced enhancement of the trough's poleward wall, (4) negative phase due to postsunrise convection effects plus longer-lived composition-induced depletions, and (5) termination of the dusk effect in item 1 via the convection-induced appearance of the trough.

Mendillo, 2006

Large-scale Travelling Ionospheric Disturbances



GNSS TEC observations.



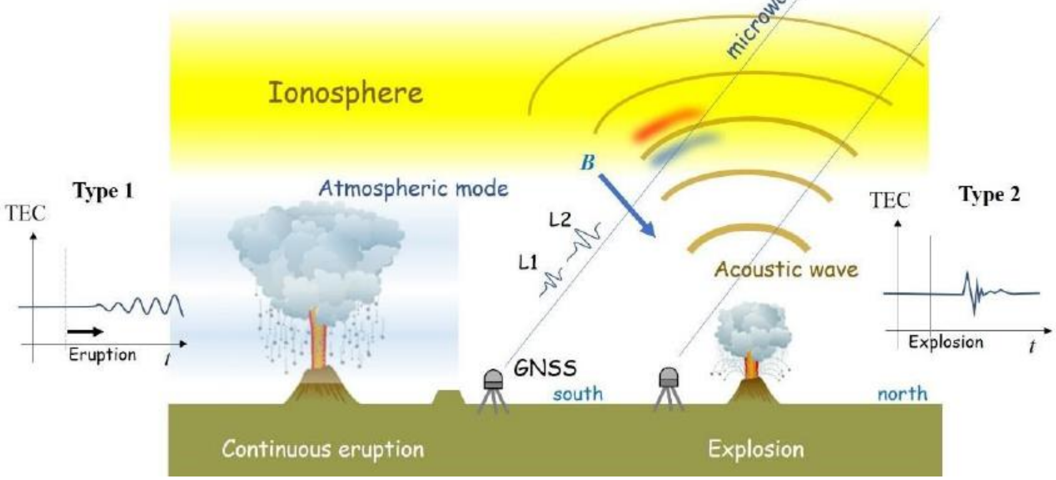
Whole Atmosphere Community Climate **Model** with thermosphere and ionosphere extension (WACCM-X)

(Medium-Scale) Travelling Ionospheric Disturbances

TID are the principal ionospheric threat at mid-latitude

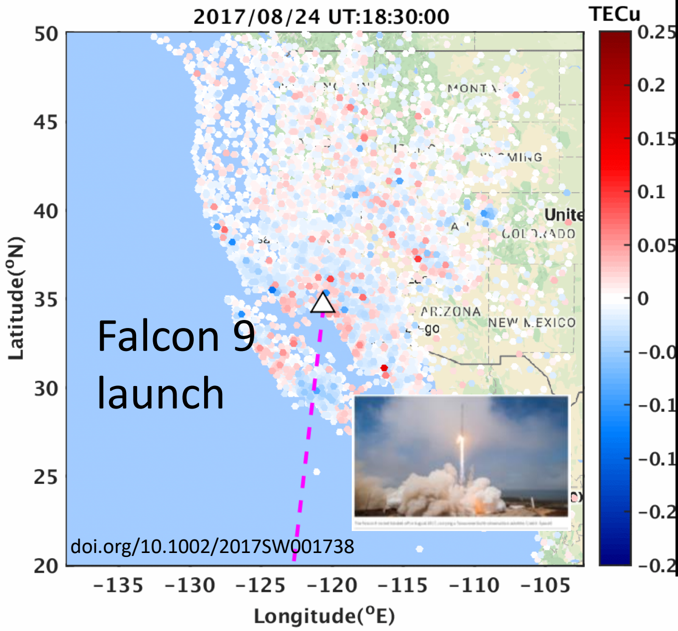
TID Type	T, min	Λ, km	ΔNe/Ne	Vp, m/s	Underlying phenomena
Large scale (LS)	>60	600-1200+	60-80%	400-10,000	Aurora brightening during geostorms
Medium scale (MS)	20-60	50-600	5-30%	100-300	Lower atmospheric and surface forcing, including tropospheric weather events (typhoon, tornado)

From Mokhamad Nur Cahyadi et al., 2021

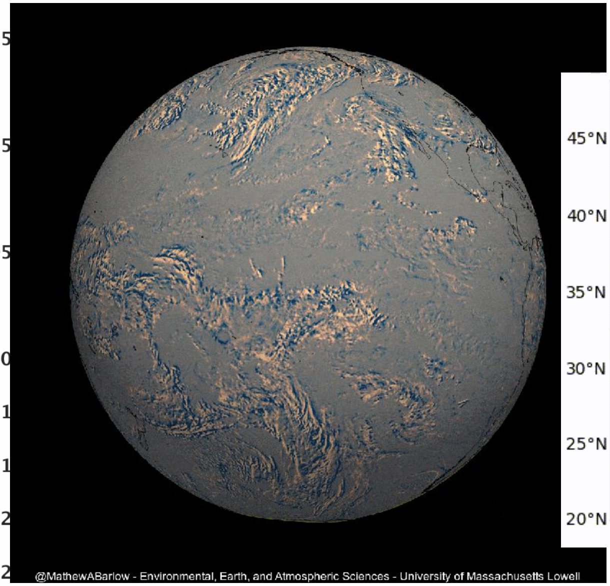


Travelling Ionospheric Disturbances are "silent accuracy killers" and are generated by a plethora of phenomena:

- Space Weather events
- Rocket launches
- Earthquakes
- Nuclear explosions
- Volcanic explosions
- Hurricanes and Tornadoes
- Thunderstorms



doi.org/10.1002/2017SW001738



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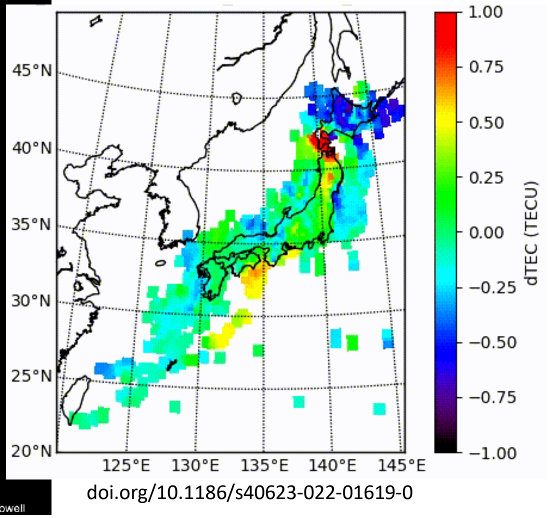
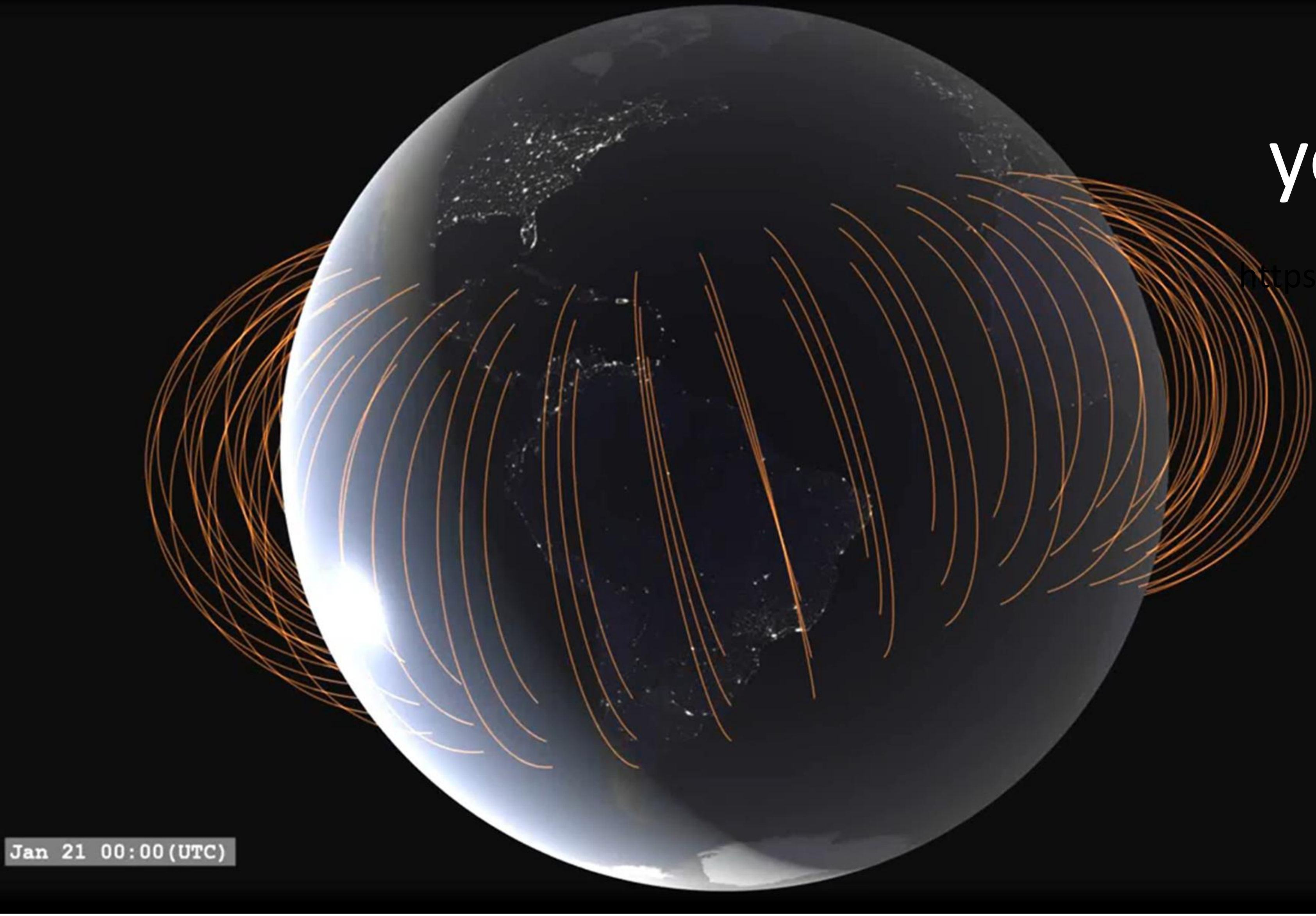


doi.org/10.1186/s40623-022-01619-0

Hunga Tonga–Hunga Ha'apai eruption

Takehome messages

1. The ionosphere is the upper atmosphere region containing large concentrations of electrons and ions due to ionization of the neutral atmospherics gases by solar ultraviolet and X-rays.
2. Ionospheric layered structure is formed due to deferent balance of ionization, production, loss, and transportation processes
3. The presence of the Earth’s magnetic field plays an important role in the ionospheric morphology and dynamics
4. The ionospheric plasma density distribution varied with altitude, local time, latitudinal/longitudinal dependences, seasons and solar activity level
5. Ionospheric plasma impacts on sub and transionospheric radio signals propagation
6. Ionosphere presents regular and irregular behaviours
7. Ionospheric weather involves a plethora of complex phenomena driven by geospace forcing (SW-M-I/T coupling) and forcing from below (LAIC)



Thanks for your attention

https://pithia-nrf.eu

luca.spogli@ingv.it