Ionosphere variations

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International Workshop on Machine Learning for Space Weather:
Fundamentals, Tools and Future Prospects,
Buenos Aires, 7-11 November 2022

BOSTON COLLEGE ISR INSTITUTE FOR SCIENTIFIC RESEARCH

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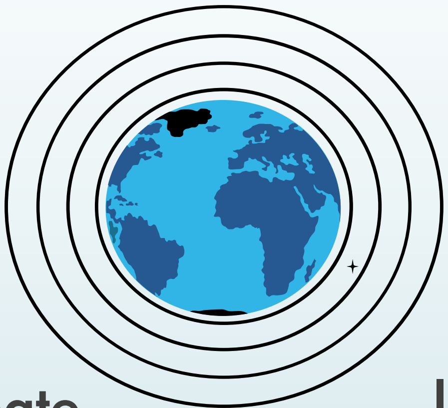
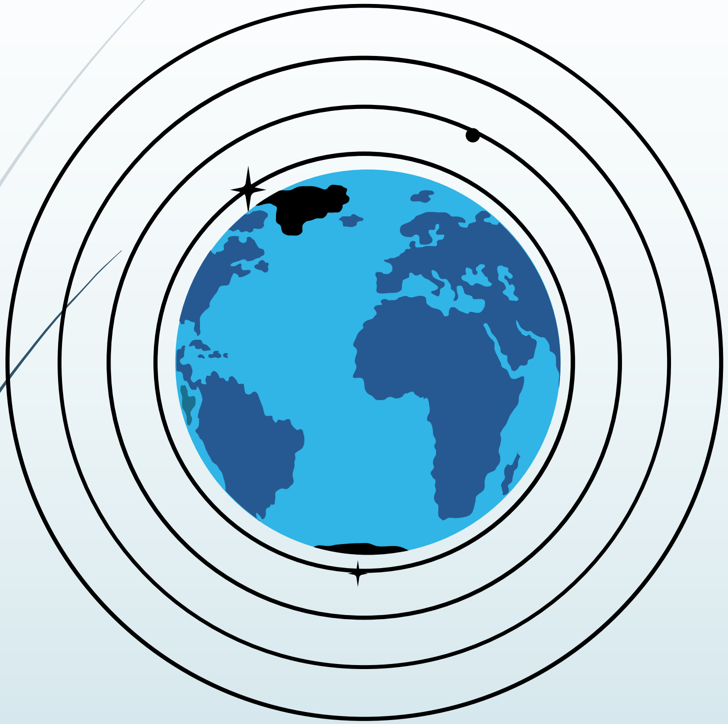
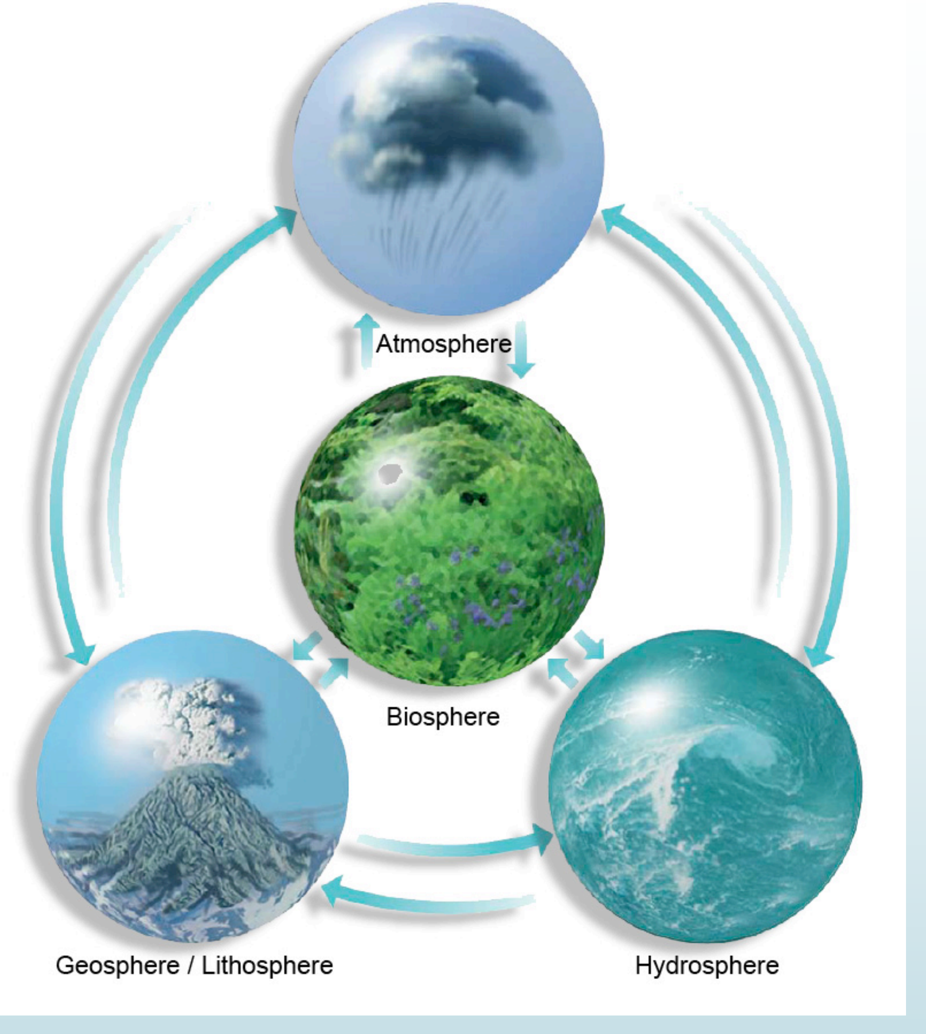




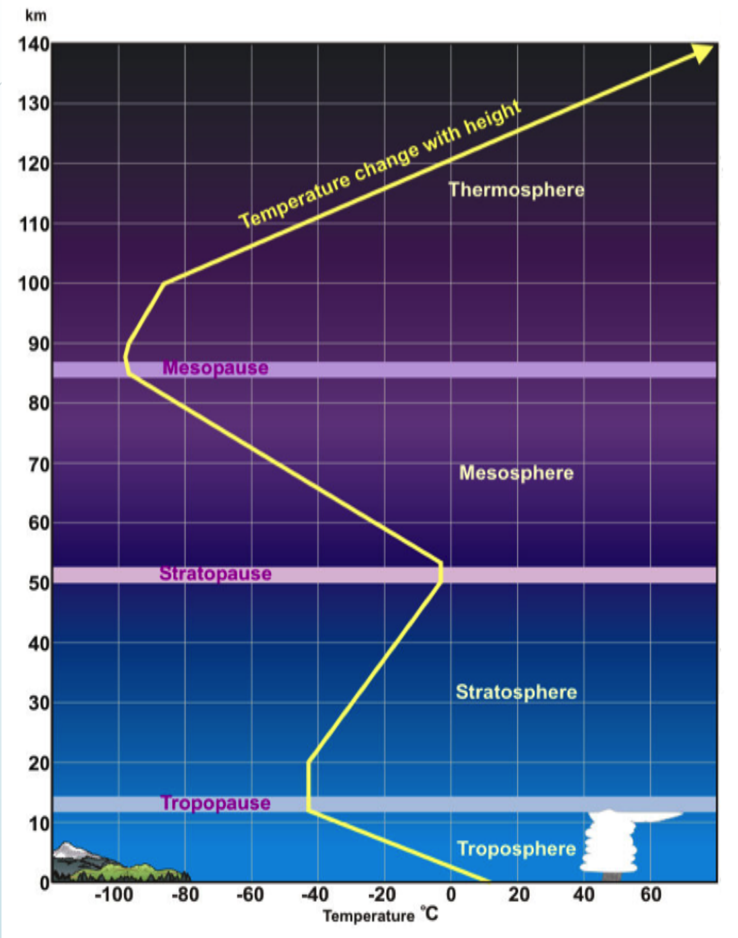
The atmosphere System

The Earth System



A Complex System of *Interacting Systems*

A layered temperature structure



THERMOSPHERE: Temperature increases steadily with altitude because is heated mainly by absorption of EUV and XUV radiation through dissociation of molecular oxygen. Temperature is highly variable with time of day and solar activity.

MESOSPHERE: Temperature decreases with altitude because ozone density decreases faster than the increase of incoming radiation.

STRATOSPHERE: Temperature increases with altitude due to heating from the *ozone* which absorbs the solar ultra-violet radiation that penetrates down to these altitudes.

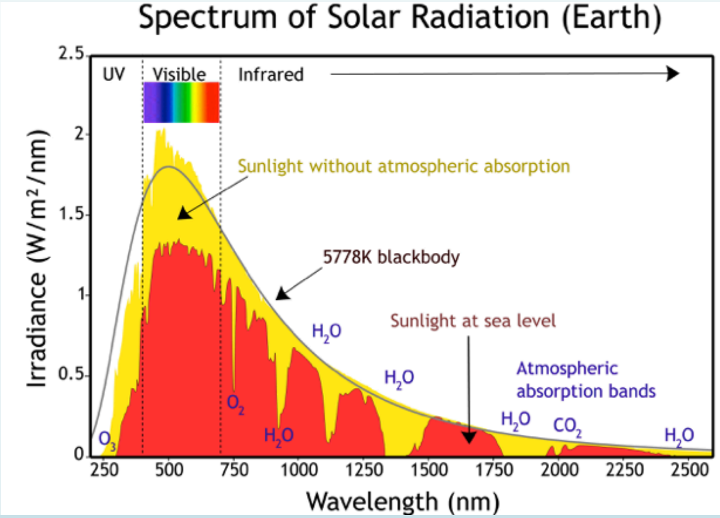
TROPOSHERE: Temperature decreases with altitude. Heated mainly by the ground, absorbs solar radiation and re-emits it in the infra-red.

Photochemical processes in the atmosphere

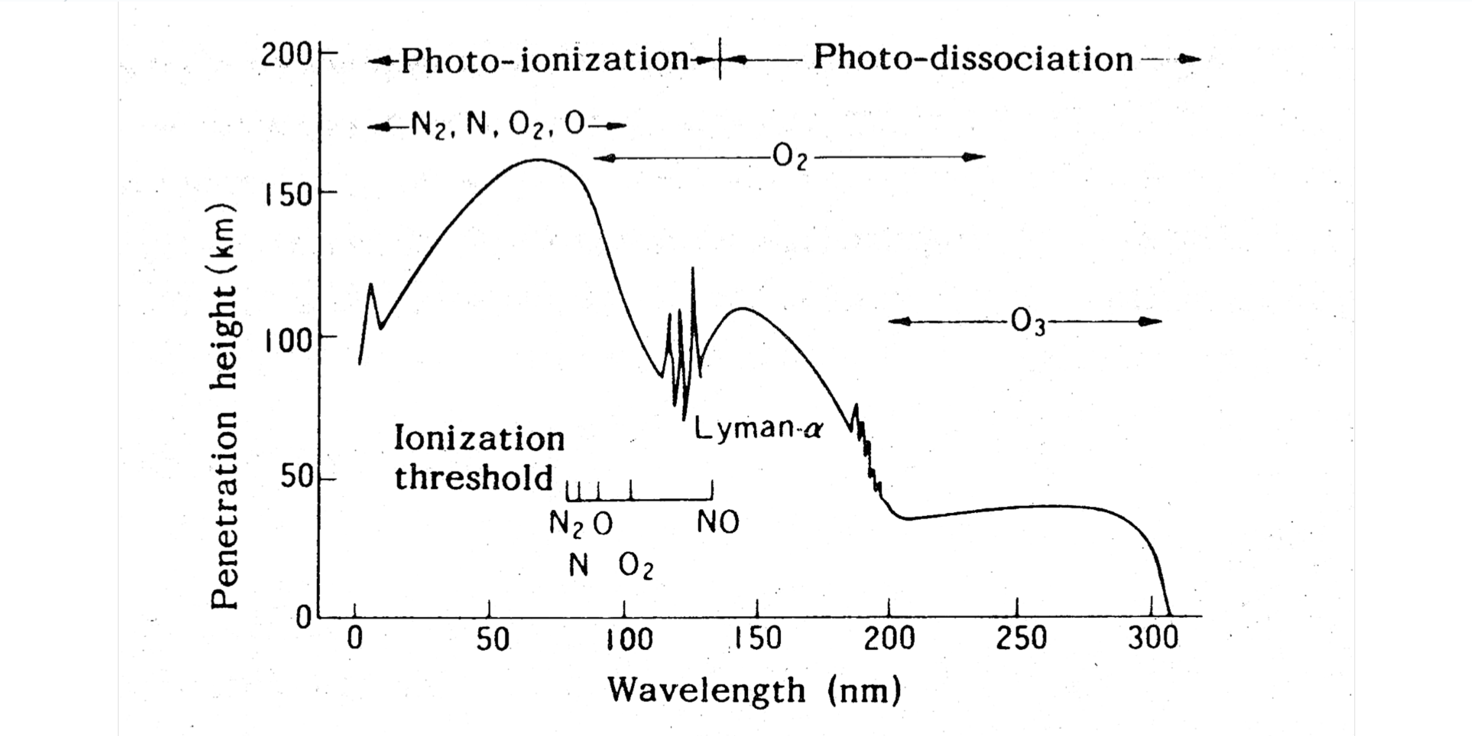
The atmosphere of the Earth is made up of a large number of chemical constituents.

Major constituents are N_2, O_2 and Ar, but many more constituents are produced in the atmosphere by *photochemical processes of solar origin* or at the surface by different natural processes and human activity.

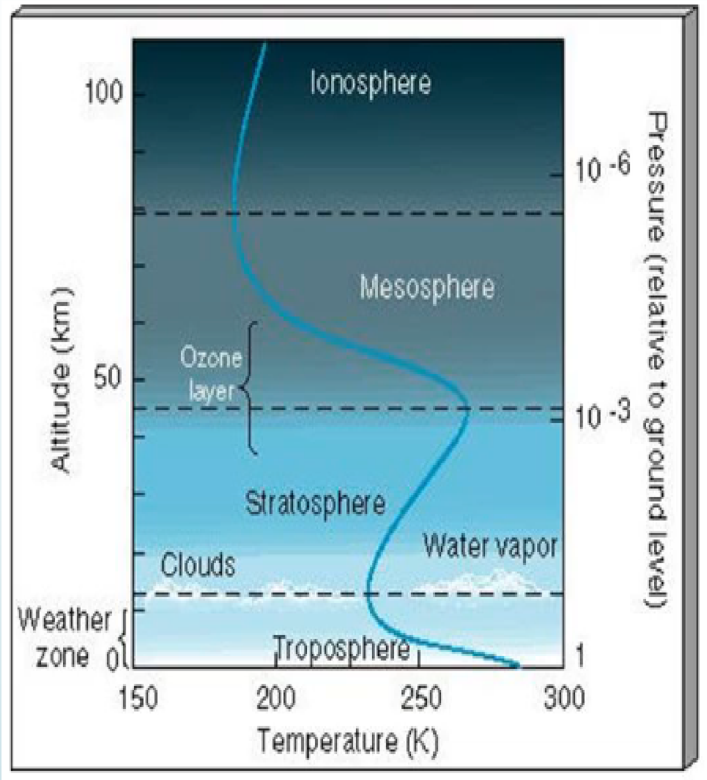
Photochemical processes play a fundamental role in the middle and upper atmosphere including the ionosphere.



Photochemical absorption processes of solar radiation



The effect of photochemical processes



Photoionization processes generates the Ionosphere

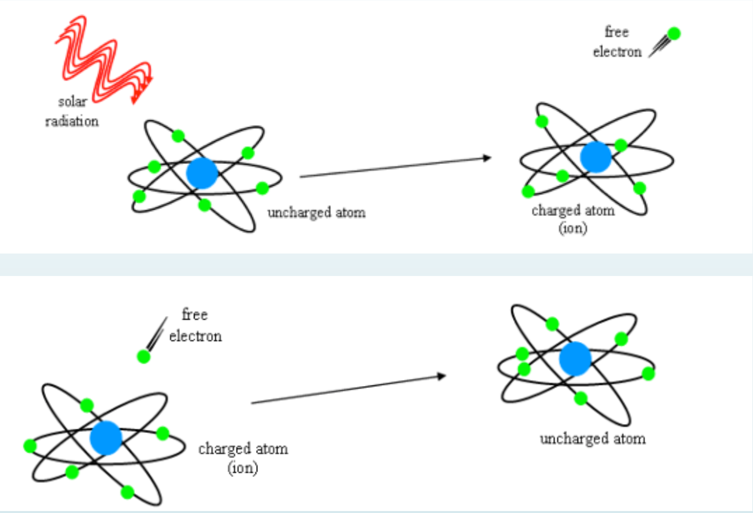
Photodissociation of O2 gererates Ozone layer

Chapman theory of solar radiation ionization in the atmosphere

Named for Sydney Chapman, who first derived mathematically the theory in 1931

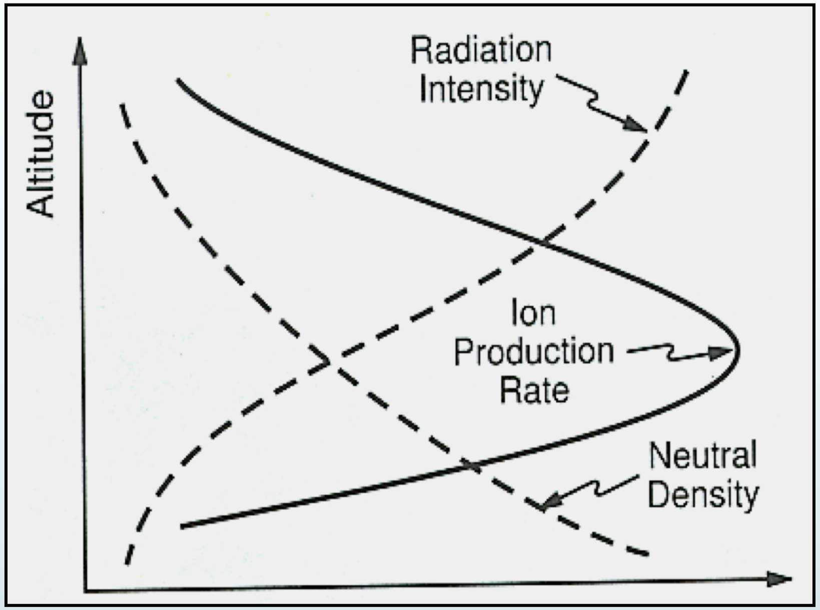
The theory assumes:

- A monochromatic ionizing radiation from the sun,
- A single neutral constituent to be absorbed or ionized distributed exponentially,
- Photochemical equilibrium



A layer of ion-electron production

- Radiation intensity decreases and neutral density increases with decreasing altitude.
- As a consequence ion production reaches a maximum and after that decreases, forming a layer with a clearly defined peak.



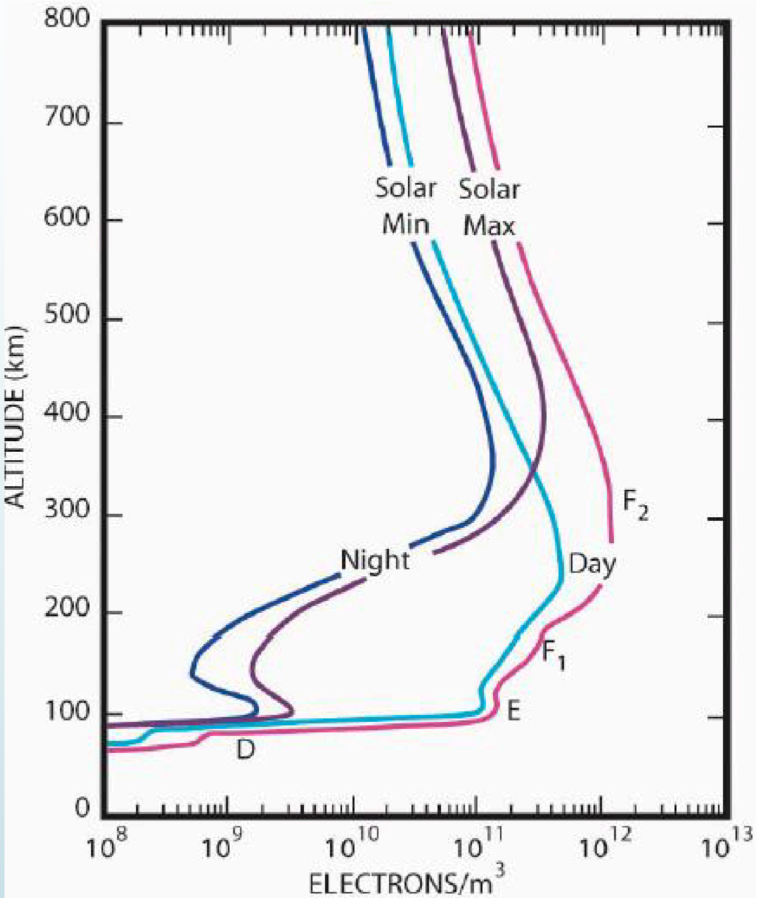
The ionosphere: layered structure

Layered structure varying with time and solar activity due to *different ionization production and loss processes*

Transport processes become important in the F2 region and upper-side, including ambipolar diffusion and wind-induced drifts along B and electromagnetic drifts across B.

E and F1 regions behave as a Chapman layer dominated by photochemical processes.At the E region heights sporadic thin layers can be formed with electron densities above the background values.

D region is characterized by the presence of negative ions due to the attachment of electrons to neutrals



Ionosphere variations

Introduction to the topic

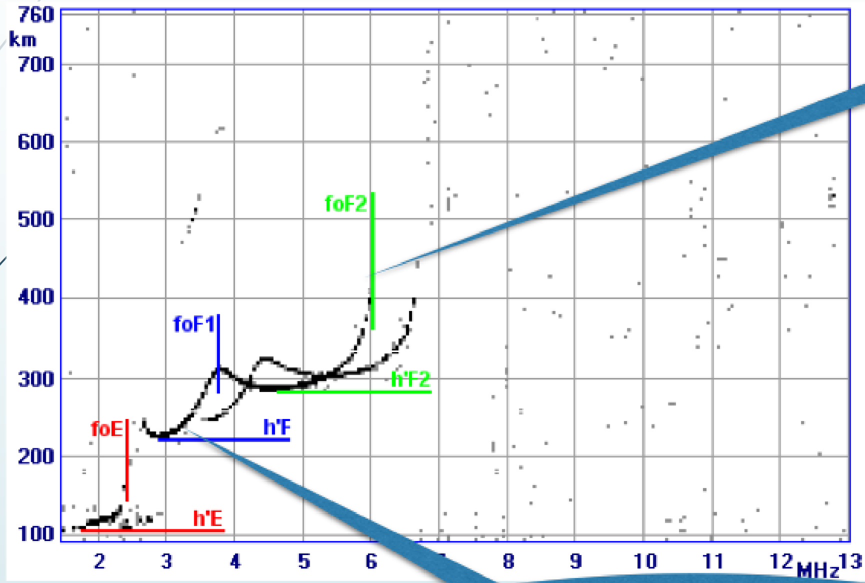
The variations of time and spatial series of ionosphere parametres data are the basic source of information to understand the physical processes that control the behavior of the ionosphere and predict such behavior

We will concentrate on the variations of the F2 layer through two parametres that are related to the peak electron density and the total electron content in the ionosphere.

The starting point will be to mention experimental techniques used to derive these parametres.

We are not going to look at the physical processes that the variations of the time and spatial series reveals and we will concentrate on the characteristics of such variations.

Ionosonde



CRITICAL FREQUENCY
The frequency at which the wave penetrates the layer
foF2, foF1, foE

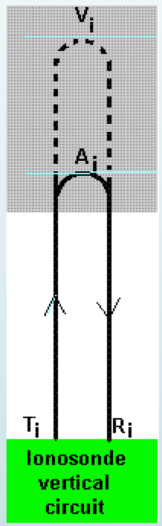
$$N = 0.124 \times 10^{11} (f)^2$$

$$N[m^{-3}], f[MHz]$$

VIRTUAL HEIGHT
The height reached by radio wave if the group velocity is equal to the velocity of light in vacuum.
The presence of the ionosphere slows down the group velocity
h'F2, h'F, h'E

Virtual height →

Real height →



Ionosonde contribution to ionosphere research

- The Earth's ionosphere has been monitored since the 1930s of last century by means of ionosondes, contributing substantially to the understanding of the physical processes that controls its behaviour.
- Today the global network of digital ionosondes continues to be an essential part of the ionosphere monitoring and research.

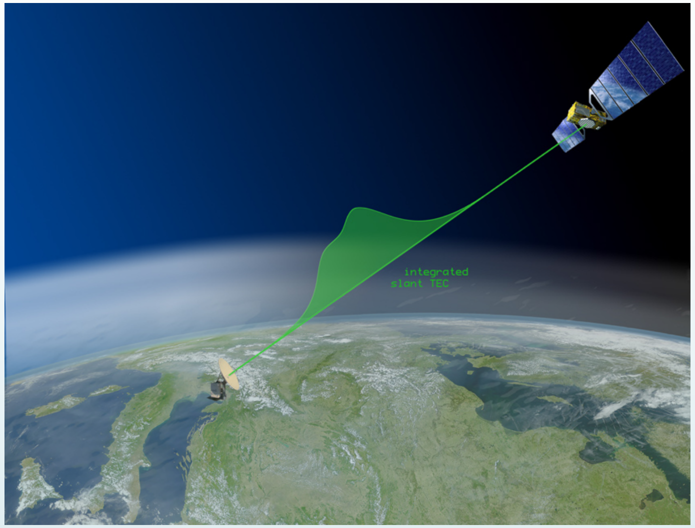
Current and prospective sites with inputs to assimilative models

GIRO, Global Ionosphere Radio Observatory, (Lowell) Network of 124 digisondes

Total electron content

The total electron content (TEC) is the total number of electrons along a path between a transmitter and a receiver

Can be obtained by different means, mainly from GNSS and satellite born altimeters

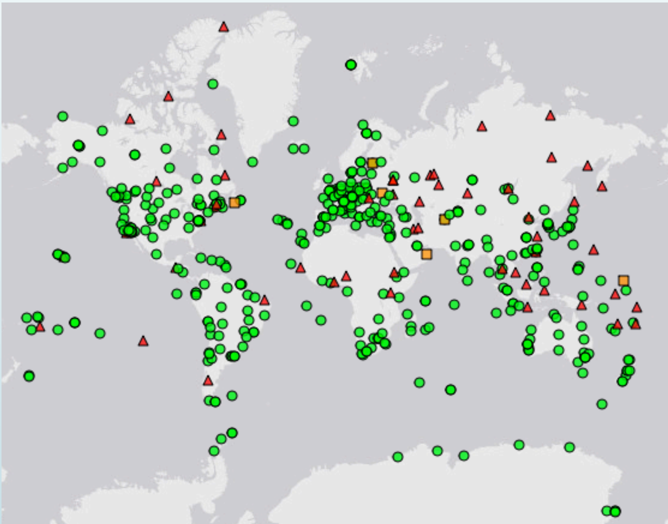


$$N_T = \int_s N(s)$$

$$1 \text{ TEC unit} = 10^{16} m^{-2}$$

GNSS derived TEC contribution to ionosphere research

- ❖ Global navigation satellite systems (GNSSs) derived ionosphere TEC data have become an international standard for monitoring and studying the ionosphere.
- ❖ More than 6000 operating GNSS receivers deliver observations to a series of networks and many of these allows open access to their data.
- ❖ GNSS derived TEC is now an essential source of data for ionosphere research.



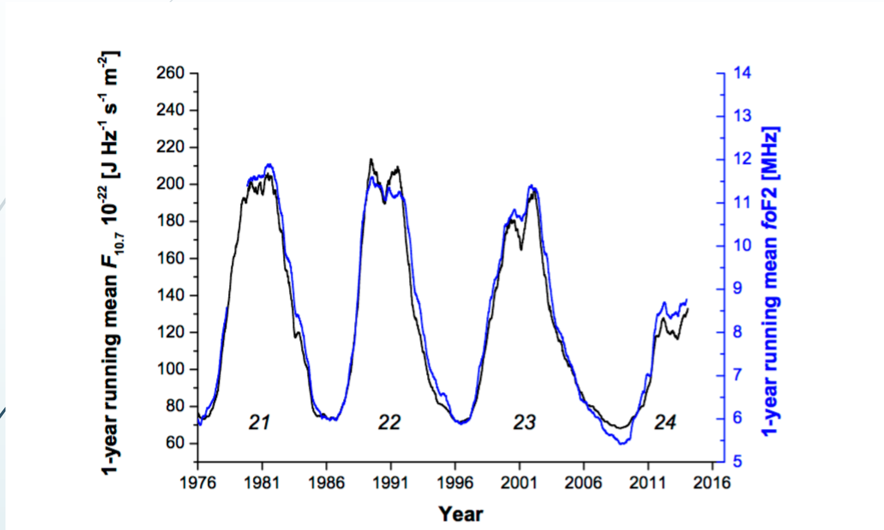
International GNSS Service
Global Network of 513 Stations

Two types of variations

Climate or *Regular*
Variations occurring in cycles.
Can be predicted with reasonable accuracy

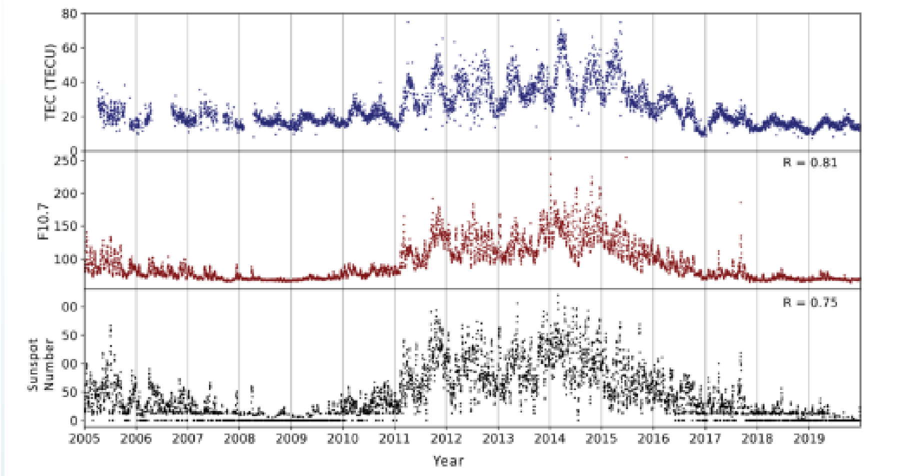
Weather or *Irregular*
Variations mostly due to Solar induced Space Weather but also due by coupling with lower atmosphere

A well defined Solar Activity controlled variations of foF2 and TEC



1 y running mean of F10.7

1 y running mean of foF2 at 12 LT in Rome



From: L. Perna, Ionospheric plasma response to the anomalous minimum of the solar cycle 23/24: modeling and comparison with IRI-2012 PhD Thesis, Università di Bologna, 2017

From: Chintan Jethva, Mala S. Bagiya, H.P. Joshi, On the GPS TEC variability for full solar cycle and its comparison with IRI-2016 model, Astrophysics and Space Science (2022) 367:80 https://doi.org/10.1007/s10509-022-04112-y

Expected cyclic variability from Chapman theory

Following the solar zenith angle, Ne_{max} :

- Should reach the daily highest value when the solar zenith angle is the largest.
- Should be greater in summer than in equinox and smallest in winter.
- Ne_{max} should reach the highest value at the geographical equator.

Ionosphere climate variations and “anomalies”

The “anomalies”

- ❖ Historically, when the behavior of the Ne_{max} deviated significantly in time and in space from the values predicted by Chapman theory, they were called “anomalies”.
- ❖ They behave in cycles.

The " winter anomaly"

Characteristics:

- ❖ It is defined by larger values of Ne_{max} /foF2 in Winter than in Summer.
- ❖ Its maximum development is in the Northern Hemisphere at solar maximum

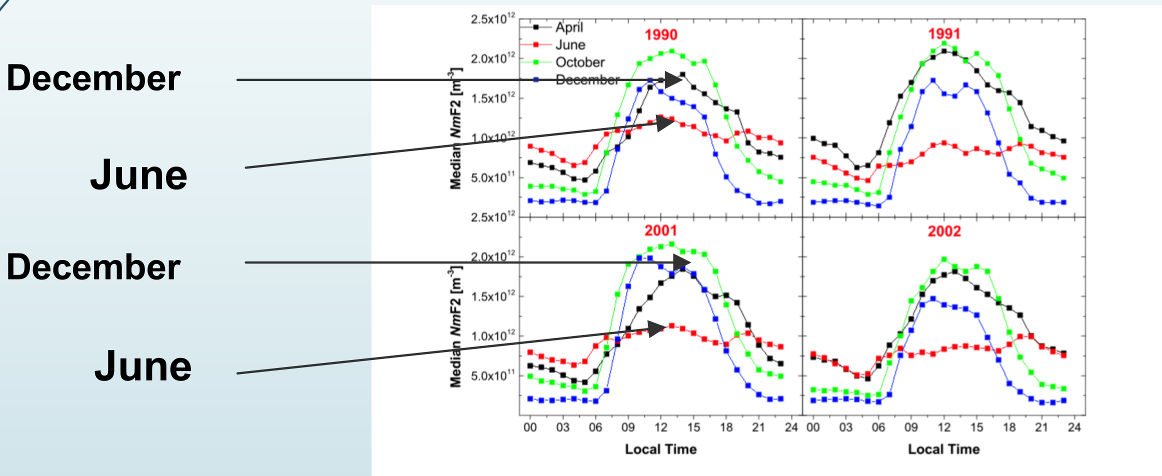


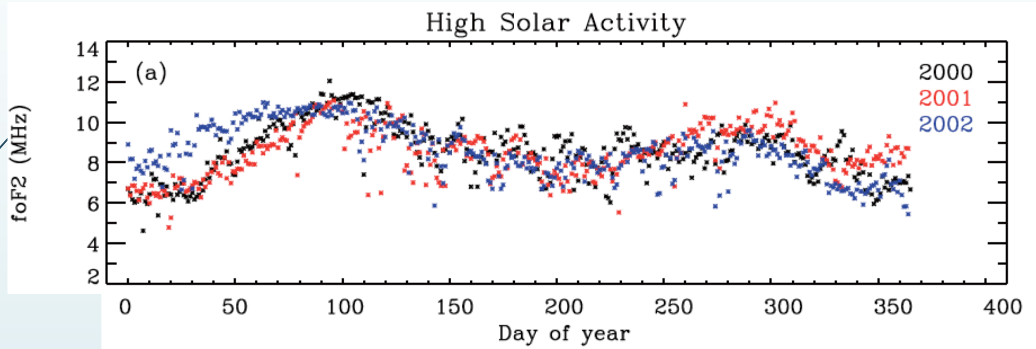
Figure 1.5: Monthly median values of *Nm*F2 as recorded at Rome in April, June, October and December for the years of maximum activity 1990-1991 (max of solar cycle 22) and 2001-2002 (max of solar cycle 23).

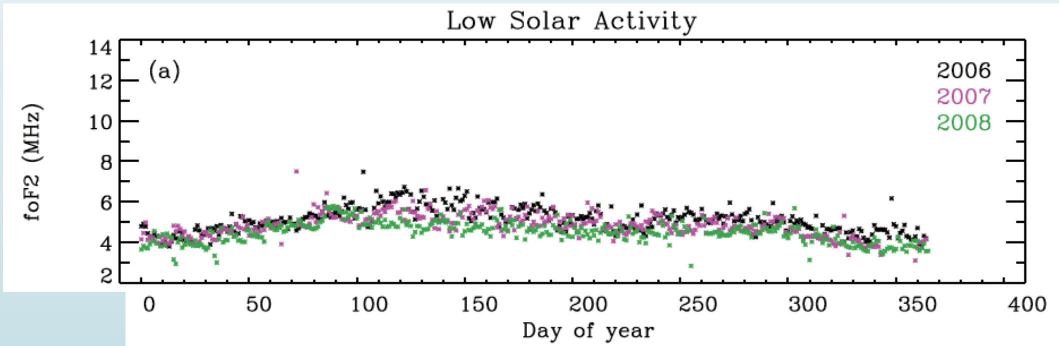
From: L. Perna, Ionospheric plasma response to the anomalous minimum of the solar cycle 23/24: modeling and comparison with IRI-2012, PhD Thesis, Università di Bologna, 2017

The “ semiannual anomaly”

Characteristics:

- ❖ It is defined by larger values of Ne_{max} /foF2 in equinoctial months than in solsticial months.
- ❖ At middle latitudes it develops during HSA.





From: Yoon-Kyung Park, Young-Sil Kwak, Byung-Ho Ahn, Young-Deuk Park, and Il-Hyun Cho, IonosphericF2-Layer Semi-Annual Variation in Middle Latitude by Solar Activity, J. Astron. Space Sci. 27(4), 319-327(2010), DOI: 10.5140/JASS.2010.27.4.319

The "annual anomaly"

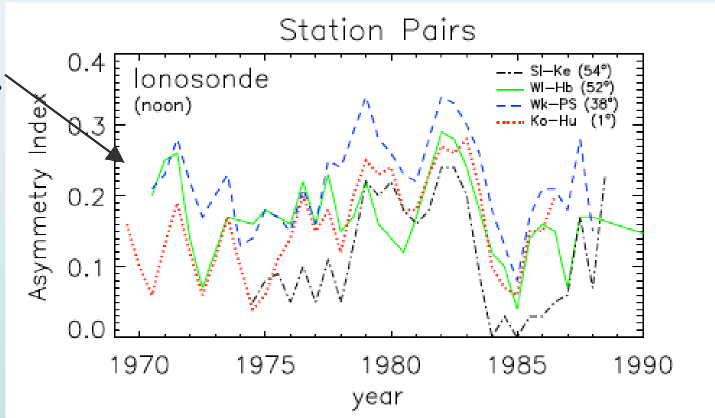
Characteristics:

- ❖ At the Earth as a whole, on average, Ne_{max} is greater in December/January than in June/July.
- ❖ The annual anomaly con be separated from the winter anomaly only by combining data from opposite seasons in the two hemispheres.

Assuming with Rishbeth and Müller-Wodarg (2006) an "annual asymmetry index":

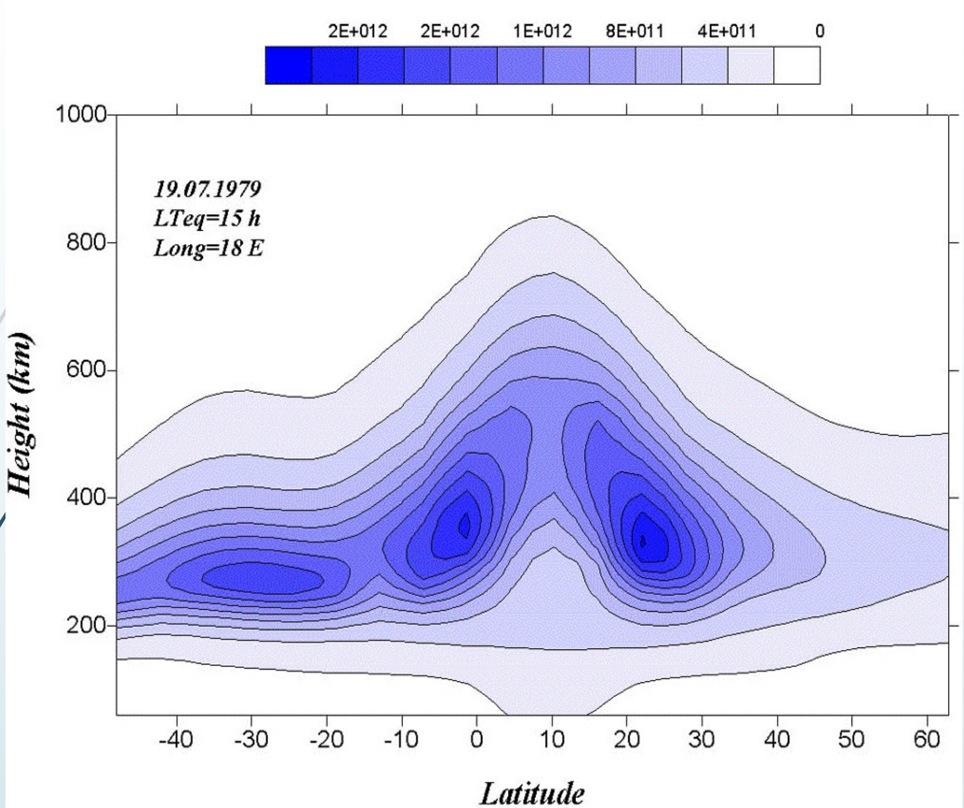
$$AI=(A/M)=\frac{NmF2(N+S)_{Jan}-NmF2(N+S)_{July}}{NmF2(N+S)_{Jan}+Nm\,F2(N+S)_{July}}$$

AI will be positive if January/July ratio exeeds 1.



From :Rishbeth H, Muller-Wodarg ICF (2006) Why is there more ionosphere in January and in July? The annual asymmetry in the F2 layer. Ann Geophys 24:3293–3311. doi:10.5194/angeo-24-3293-2006

The "equatorial anomaly"



Nava B., Radicella S.M., Pulinets S. and Depuev V. "Modelling bottom and topside electron density and TEC with profile data from topside ionograms", Advances in Space Research, V. 27, pp. 31-34, 2001.

From the Chapman theory electron density should maximise over the geographic equator at equinox.

Actually it maximises 15-20 degrees of geomagnetic latitude N and S, with small minimum at the equator

Due to the presence of the geomagnetic field: the 'fountain effect"

Contribution of Machine Learning techniques to the Study of “anomalies” (1)

Principal Component Analysis (PCA) is a machine learning technique to reduce the dimensionality of data but at the same time retaining as much as possible of the variation present in the original data. Applying the PCA technique to the time series of the global vertical (TEC) maps provides an efficient method for analysing the main ionospheric variability on a global scale being able to decompose periodic variations (e.g., annual and semiannual anomalies) while retaining the asymmetry in the temporal and spatial domains (e.g., seasonal hemispheric and equatorial anomalies).

1.-Natali MP, Meza A (2010) Annual and semiannual VTEC effects at low solar activity based on GPS observations at different geomagnetic latitudes. J Geophys Res 115:D18106. doi:10.1029/2010JD014267

2.-Natali MP, Meza A (2011) Annual and semiannual variations of vertical total electron content during high solar activity based on GPS observations. Ann Geophys 29(865–873):2011. doi:10.5194/angeo-29-865-2011

3.-Meza A, Natali MP, Fernández LI (2012) Analysis of the winter and semiannual ionospheric anomalies in 1999–2009 based on GPS global International GNSS Service maps. J Geophys Res 117:A01319. doi:10.1029/2011JA016882

4.-Jingbin Liu, Manuel Hernandez-Pajares, Xinlian Liang, Jiachun An, Zemin Wang, Ruizhi Chen, Wei Sun5, Juha Hyyppä, (2017) Temporal and spatial variations of global ionospheric total electron content under various solar conditions, J Geod 91:485–502 DOI 10.1007/s00190-016-0977-7

Contribution of Machine Learning techniques to the Study of "anomalies" (2)

1.- Natali MP, Meza A (2010): Applied the PCA technique on a time series of global IGS VTEC maps to analyse the main ionospheric anomalies on a global scale.

2.-Natali MP, Meza A (2011): Applied the PCA technique to study Annual and semiannual anomalies of vertical TEC during high solar activity using Global IGS TEC maps.

3.-Meza A, Natali MP, Fernández LI (2012): Applied the PCA technique to study the winter and semiannual ionospheric anomalies in 1999–2009 using Global IGS vertical TEC maps.

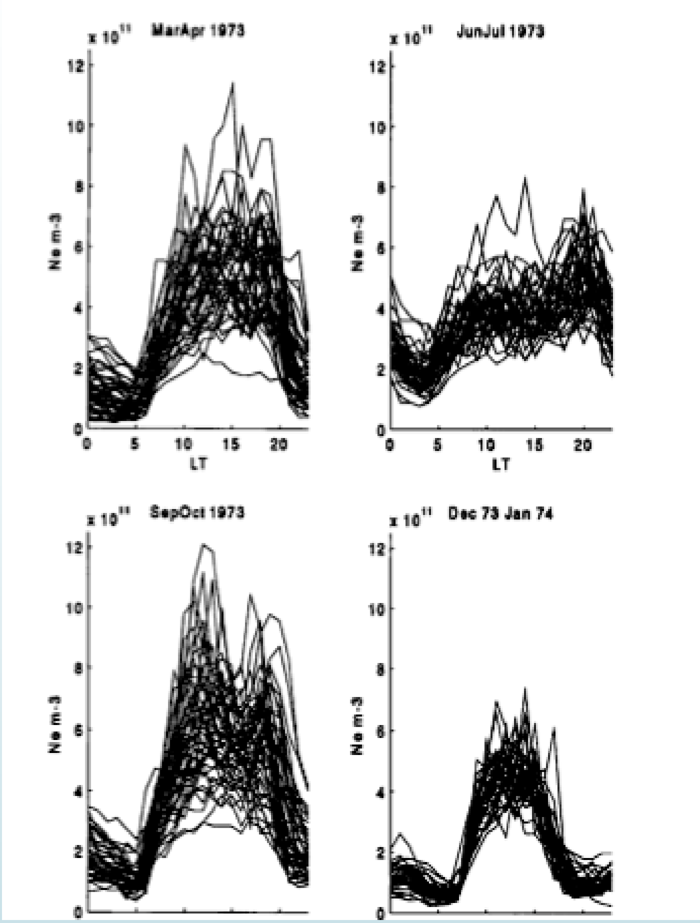
4.-Jingbin Liu, Manuel Hernandez-Pajares, Xinlian Liang, Jiachun An, Zemin Wang, Ruizhi Chen, Wei Sun5, Juha Hyyppä, (2017): Apllied PCA technique to analyse time and spatial variations of the ionosphere under various solar conditions in the period 1999-2013.

Ionosphere weather (irregular)variations

Day-to-day variability of NmF2

Variation of NmF2 at Slough for every day during four 2-month periods in 1973-1974.

From: H. Rishbeth, M. Mendillo, Journal of Atmospheric and Solar-Terrestrial Physics, 63 (2001) 1661–1680



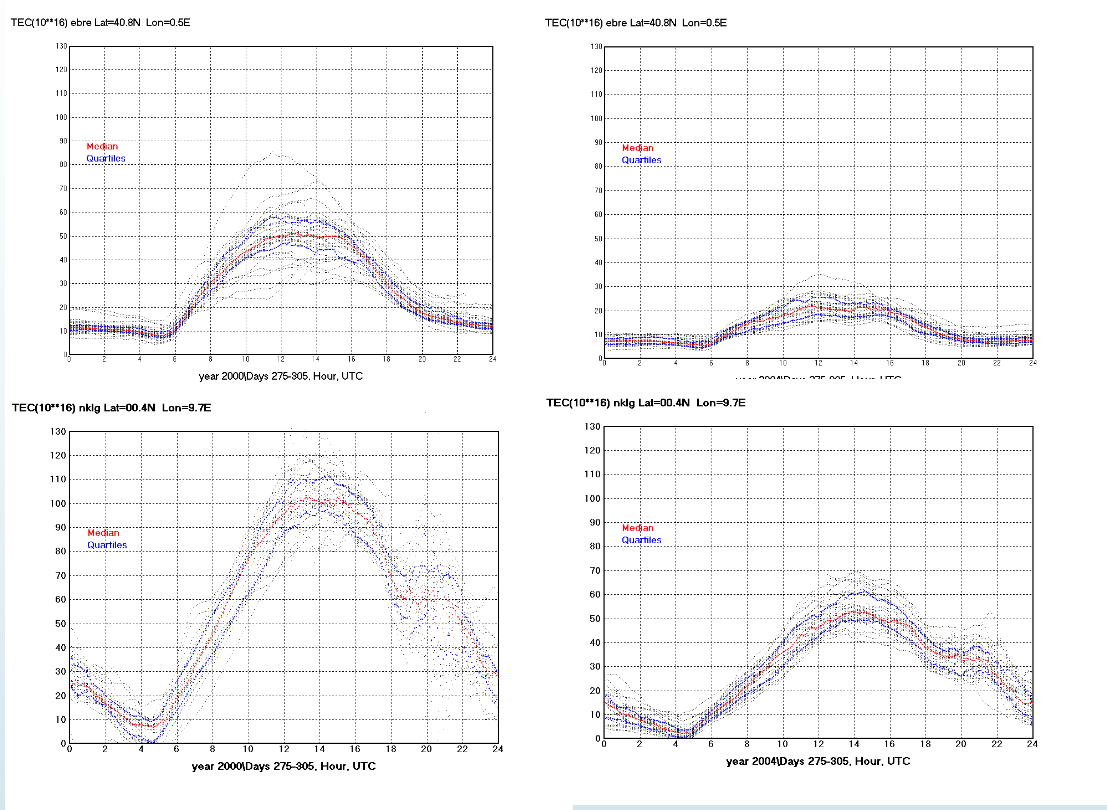
Vertical TEC diurnal and day-to-day variations

Middle Latutude

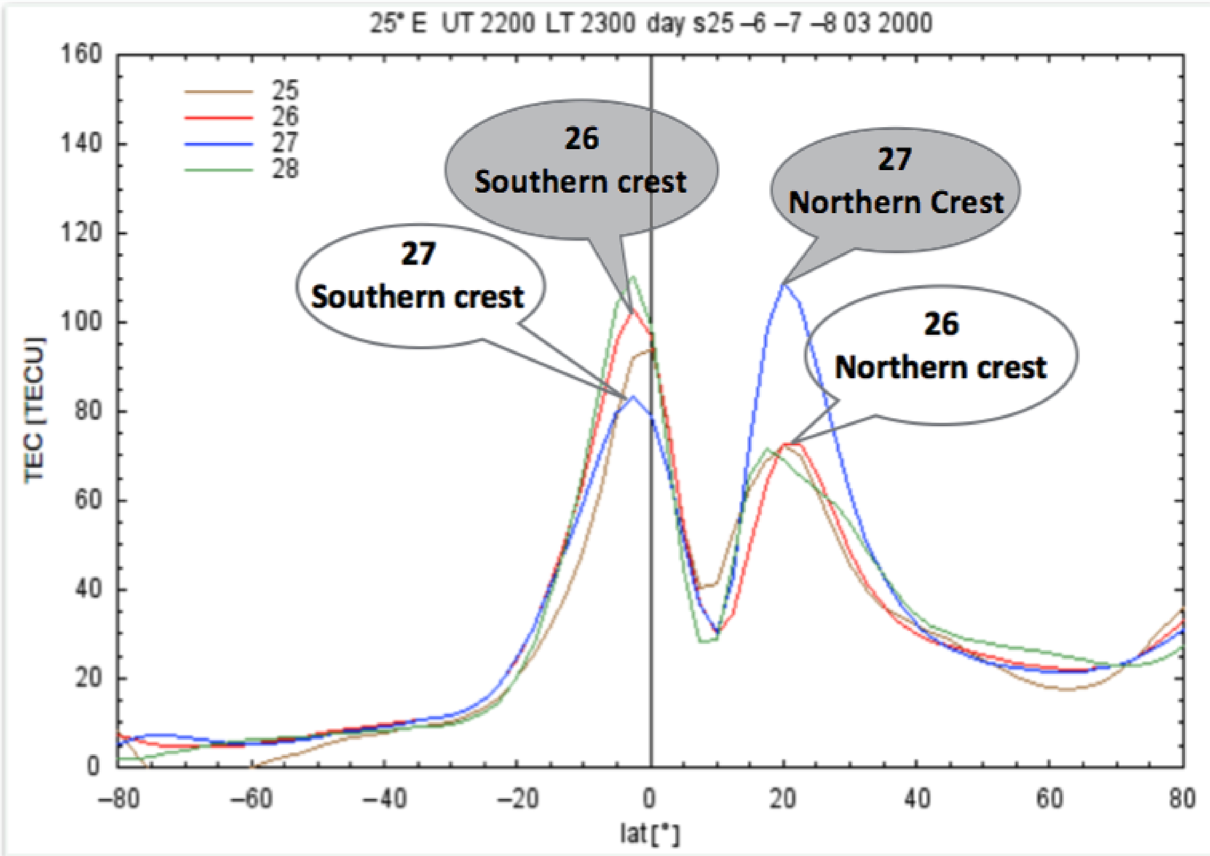
GPS derived vertical TEC at 5 min interval for Libreville (Lat. 0.4° N, Long. 9.7° E, Dip –25°), October 2000 and 2004

Low Latutude

GPS derived vertical TEC at 5 min interval for Roquetes (Lat. 40.8°, Lon. 0.5° E, Mag. Dip 57°), October 2000 and 2004



Vertical TEC Meridional cross section and day-to-day Variations at the crests of the Equatorial “anomaly”



Causes of the day-to-day variations of foF2 and TEC

- **The main cause of the day-to-day variations of foF2 and TEC is being considered as varying effect of Space Weather on the ionosphere. It means essentially the effect of solar and geomagnetic activity.**

- **Now it is recognized that driving from Tropospheric Weather can contribute substantially to the day-to-day variations of ionospheric parametres.**

Tropospheric induced ionospheric variations (1)

From: "Day-to-day ionospheric variability due to lower atmosphere perturbations" by H.-L. Liu, V. A. Yudin, and R. G. Roble;(2013) GEOPHYSICAL RESEARCH LETTERS, VOL. 40 , 665–670.

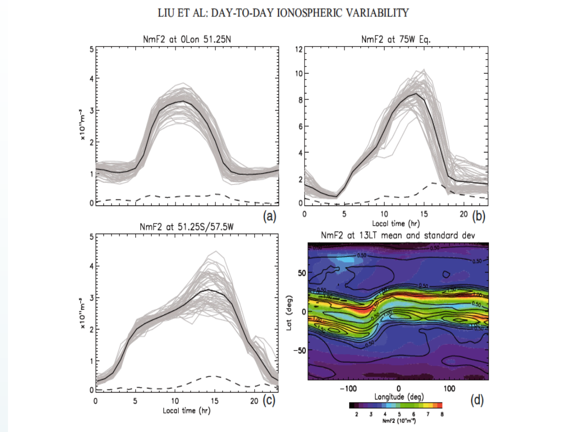


Figure 4. Daily values of NmF2 (gray), their mean values (black solid), and the standard deviation (dashed) for (a) 51.25°N/0 longitude, (b) equator/75°W, and (c) 51.25°S/57.5°W (all geographic). (d) Mean values (shades) and standard deviation (lines) of NmF2 for LT1300. Contour intervals: $2.5\times10^{10}\ m^{-3}$.

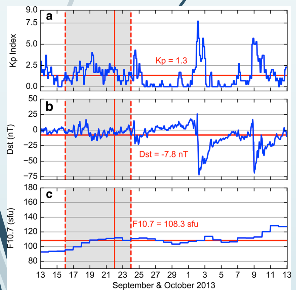
This study demonstrates that the thermosphere-ionosphere-mesosphere electrodynamics general circulation model (TIEGCM) constrained by the atmosphere community climate model (WACCM) simulations is capable of reproducing observed features of day-to-day variations in the F2 region at low latitudes.

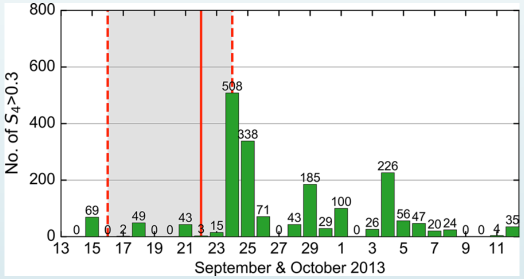
Under constant solar minimum and geomagnetically quiet conditions the meteorological driving may contribute comparably with geomagnetic forcing to the ionospheric day-to-day variability.

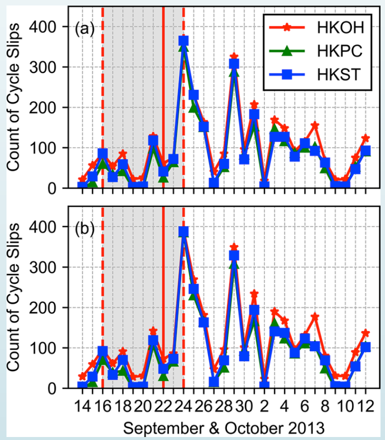
Tropospheric induced ionospheric variations (2)

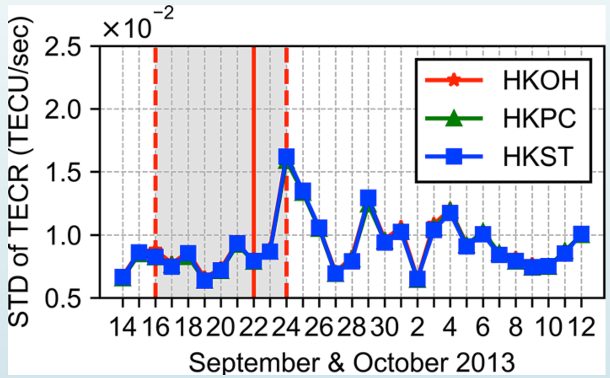
From Yu and Liu (2021) abstract:This study analysed the variation of three ionosphere-related parametres based on the GPS data including ***scintillation index S4, cycle slips, and total electron content (TEC) rate (TECR)**** during the tropical cyclone event (the 2013 TC Usagi) in the Hong Kong region. The results showed that the ionosphere-related parametres had a consistent significant increase on the second day after the Usagi made landfall near Hong Kong.

*** TECR from: Liu Z (2011) A new automated cycle slip detection and repair method for a single dual-frequency GPS receiver. J Geod 85(3):171–183. https ://doi.org/10.1007/s0019 0-010-0426-y**





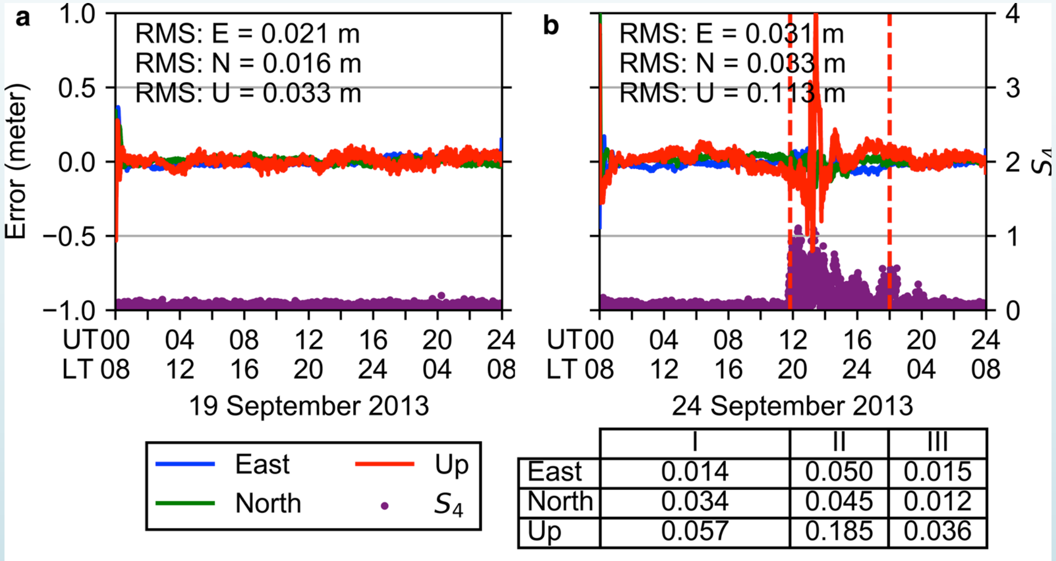




From: Shiwei Yu and Zhizhao Liu, The ionospheric condition and GPS positioning performance during the 2013 tropical cycloneUsagi event in the Hong Kong region, Earth, Planets and Space (2021) 73:66https://doi.org/10.1186/s40623-021-01388-2

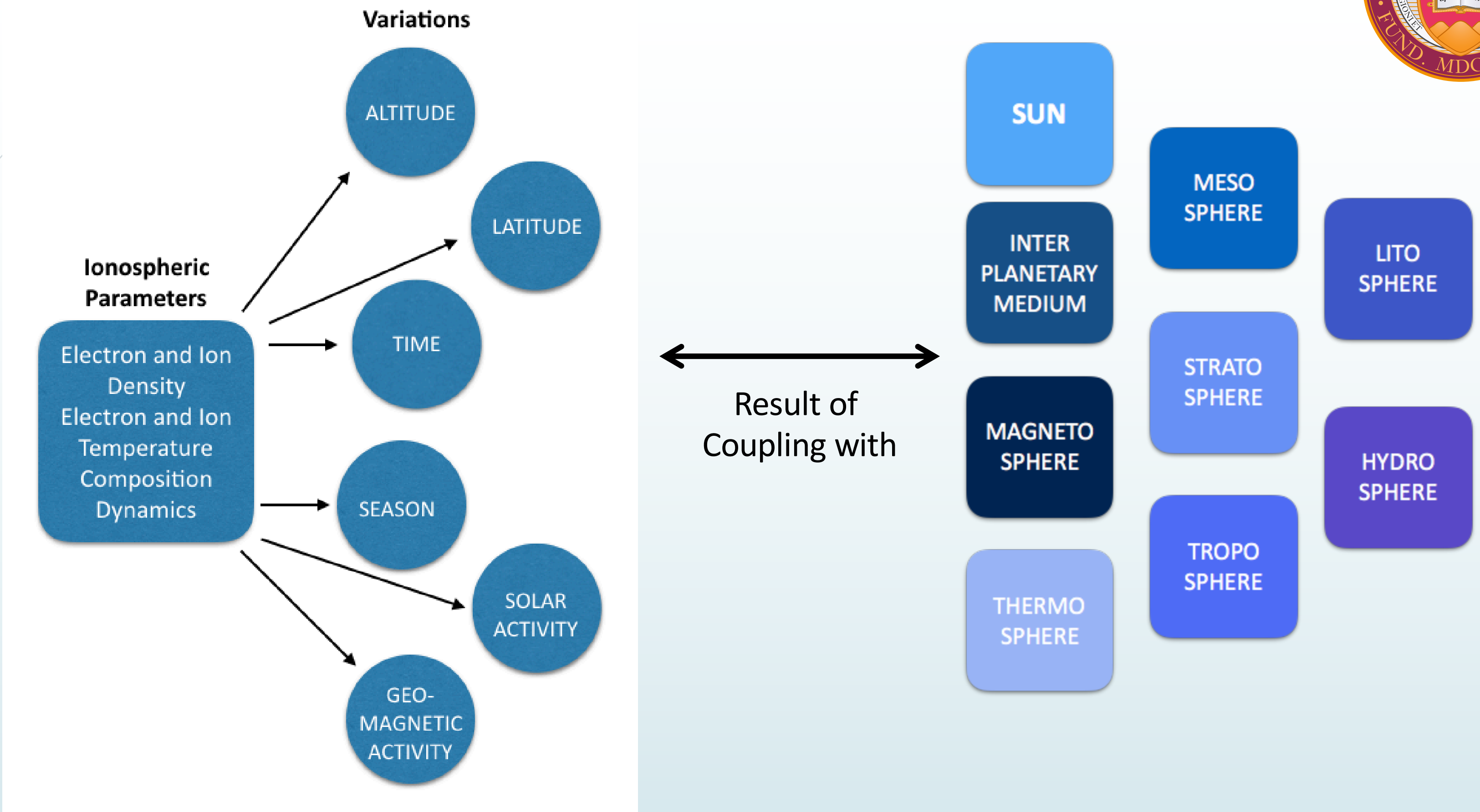
Tropospheric induced ionospheric variations (3)

Consequently, the positioning performance of GPS precise point positioning (PPP) and relative positioning modes was degraded. The degradation was ~ 138%, ~ 181%, and ~ 460% in the east (root mean square (RMS) 0.050 m), north (RMS 0.045 m), and up (RMS 0.185 m), respectively, compared with the RMS of 0.021 m in the east, 0.016 m in the north, and 0.033 m in the up on the normal day.



	I	II	III
East	0.014	0.050	0.015
North	0.034	0.045	0.012
Up	0.057	0.185	0.036

Origin of the Ionosphere variations



Much has to be investigated still to understand all the coupling mechanisms and Machine Learning techniques can contribute substantially to this purpose.

This lecture gives only a pale idea of the complexity of the ionosphere variations but indicates just some aspects of such variations. Much has to be investigated to understand the origin of the ionosphere variations and their predictability.

Thank you for your attention