THE USE OF GNSS FOR SPACE WEATHER STUDIES

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Workshop –GNSS/training programme on GNSS Kathmandu [26 January - 1 February, 2025]

Outlines

Introduction

The use of GNSS for research

Space Weather

Sun, Earth, Magnetosphere, Ionosphere,

Solar electromagnetic emissions and solar particles

Study of ionosphere with GNSS signal (vTEC)

Impact of the solar electromagnetic emissions

Regular and disturbed ionophere

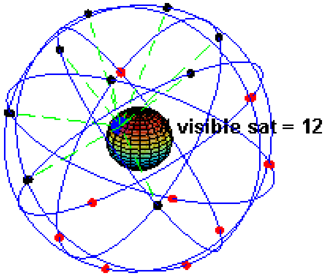
Impact of the solar wind

Coronal Mass Ejections and High Speed solar wind

Scintillations of GNSS Signal and ROTI index at low latitudes

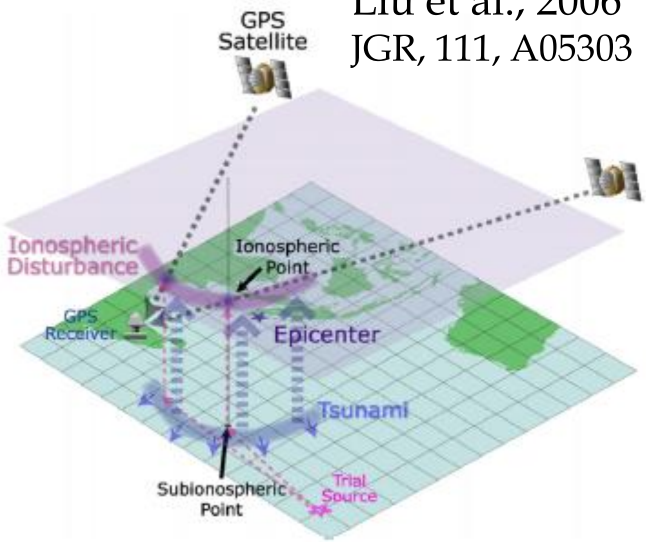
Regular variations and disturbances

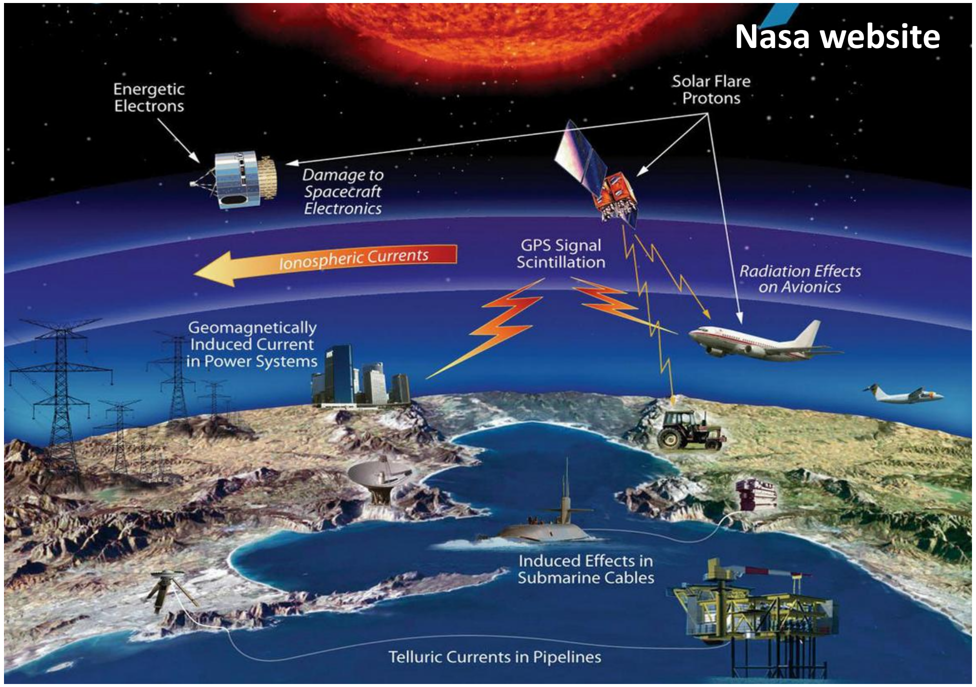
Use of GNSS for research

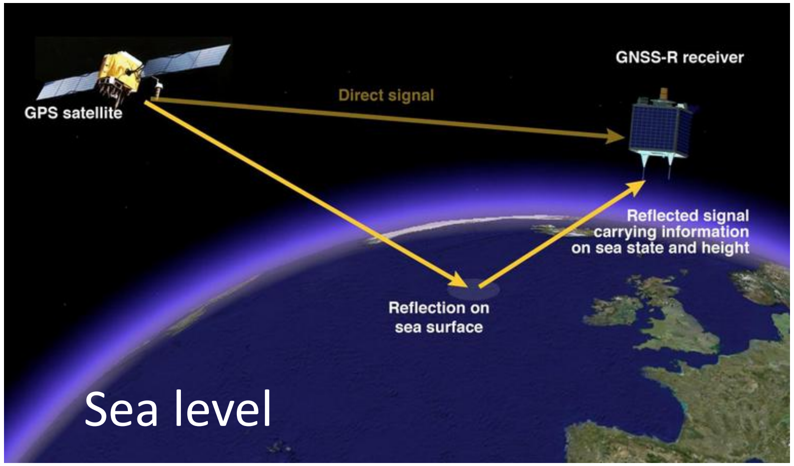


ionosphere is the largest source of perturbations for GNSS signals

Liu et al., 2006
JGR, 111, A05303



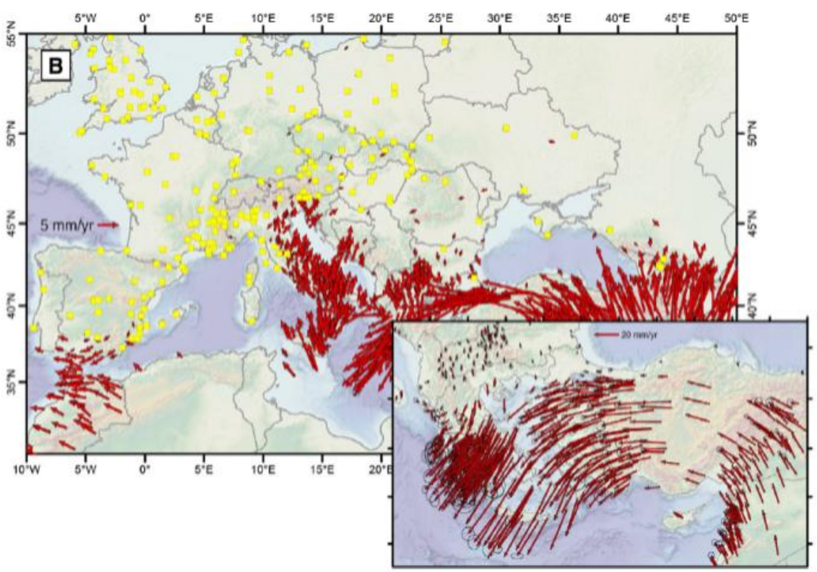




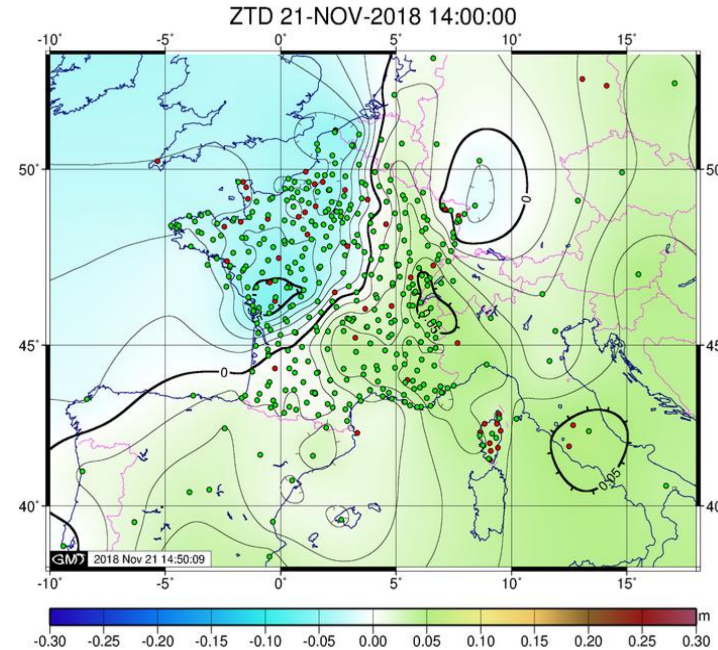
GNSS receivers are cheaper than radar, lidar and other scientific instruments and can be easily installed on the ground.
GNSS receivers are the most common instruments on the globe some tens of thousands.

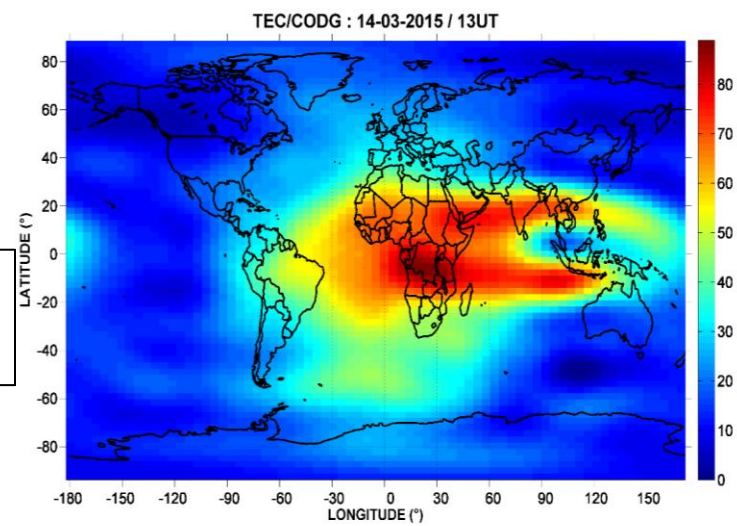
GNSS a universal tool for research and many applications in everyday life

Nocquet (2012) GPS velocity field from the Euro Mediterranean region, relative to Eurasia. Yellow squares indicate velocities
below 1 mm/yr. The inset illustrates the westward movement of Anatolia relative to Eurasia.



ZTD values over France
on 21/11/2018 at 14: 00UT
Zenithal Hydrostatic Delay, ZHD



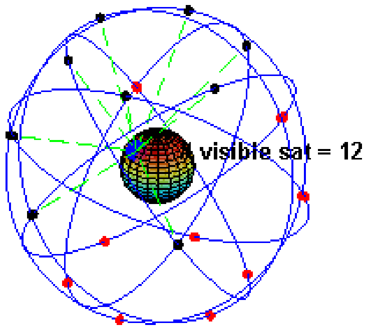


Post-processed ionospheric map of TEC from CODE on 14/03/2015 at 15UT

Figures and references in the paperAmory-Mazaudier, C. R. Fleury, F. Masson, S. Gadimova, E. Anas, Sun and Geosphere, Vol 14/1, pp. 71-79, 2019

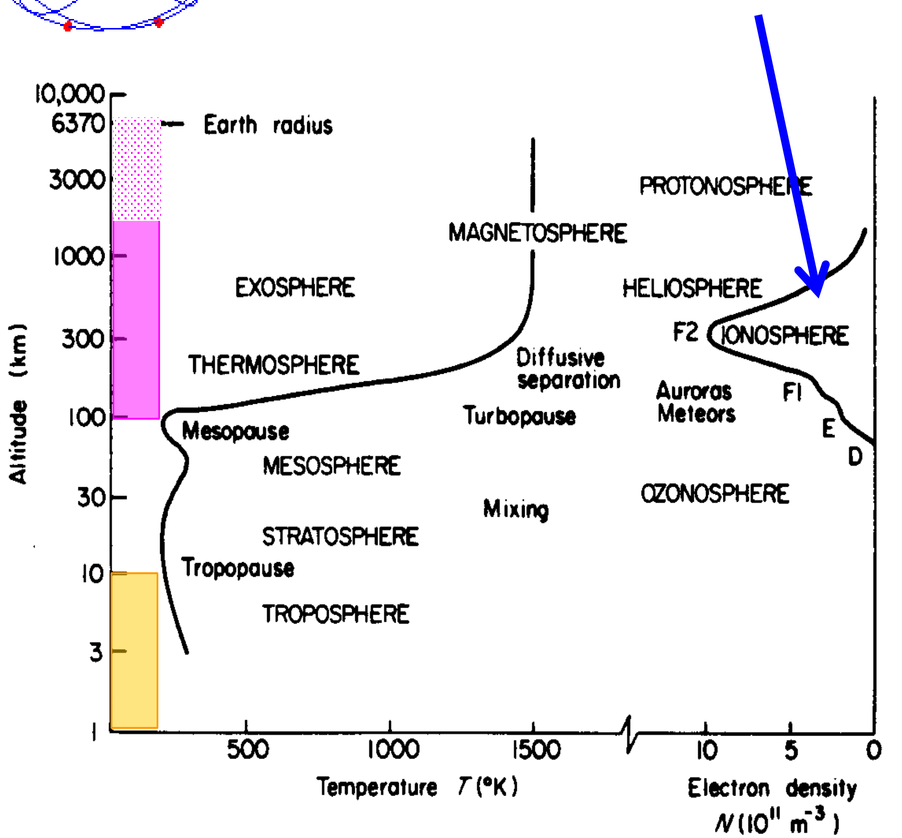
Use of GNSS for SPACE WEATHER

The satellite signal is modified by ionosphere and troposphere



TEC

Total electron content



1 tecu = 10^{16} el/cm^2

LAYERS

> 600 km EXOSPHERE
few collisions, Particles follow balistic orbit

80-600 km THERMOSPHERE
Ionization by the solar X-EUV radiation **IONOSPHERE**

30-80 km MESOSPHERE
Absorption of the radiation UV by the ozone layer

11-30 km STRATOSPHERE
Turbulence

0-11 km TROPOSPHERE
Meteorological phenomena

SUN EARTH CONNECTIONS : THE IONOSPHERE

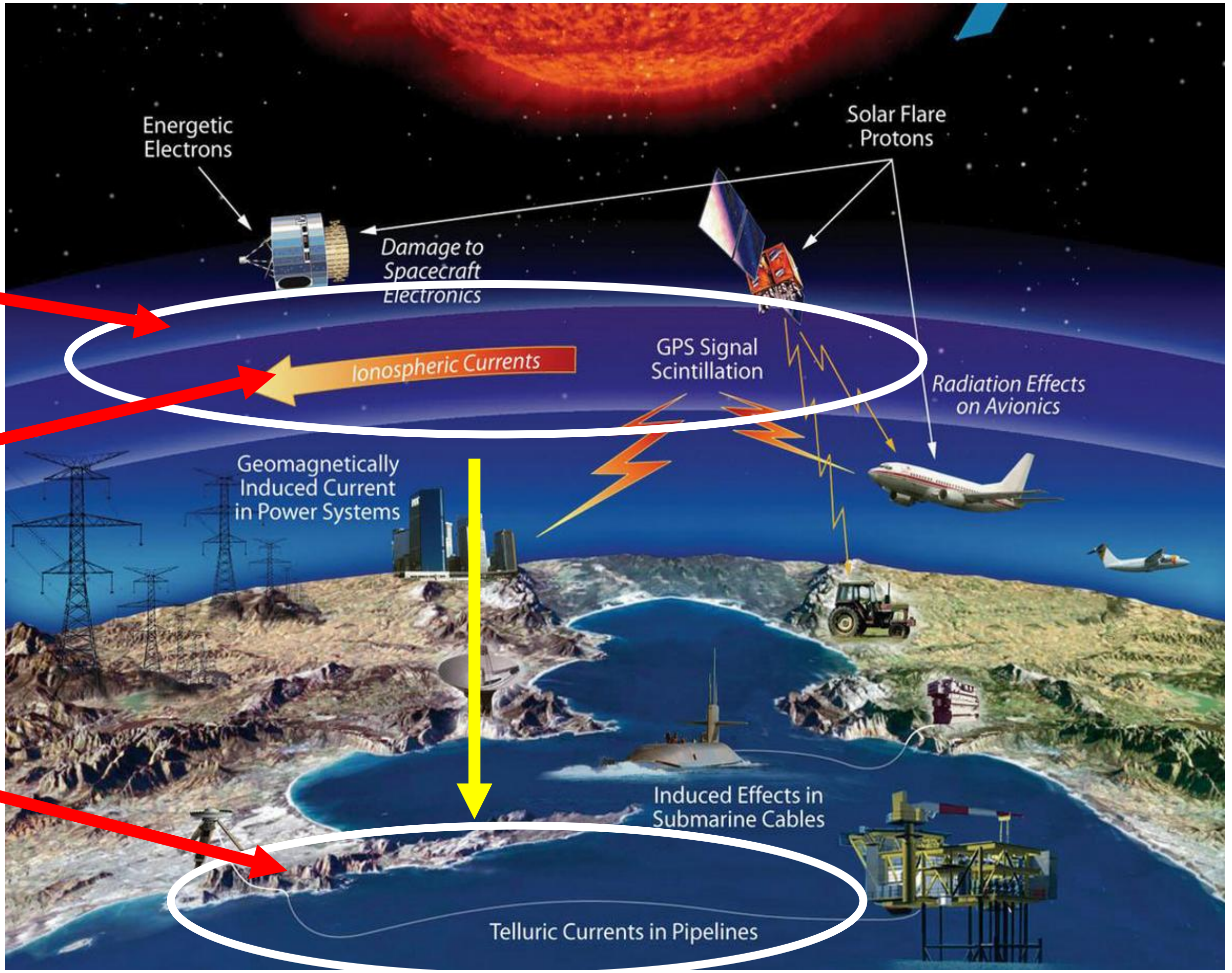
The ionosphere is a ionized layer around the Earth (from ~ 50 km up to 800 km).
Ionospheric electric currents are at the origin of variations of the Earth's magnetic field and Ground Induced Electric Currents (GIC)
The ionosphere is the largest source of perturbations for GNSS

Regular and irregular variations

1) Ionization TEC

2) Ionospheric Electric current

3) Variations of the Earth's magnetic field and GIC



Nasa website

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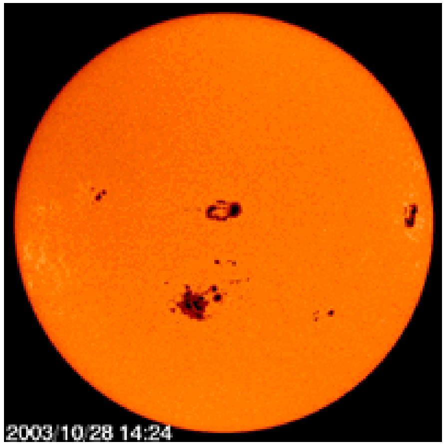
Definition of Space Weather

Space weather is the physical and phenomenological state of natural space environments. The associated discipline aims, through observation, monitoring, analysis and modelling, at understanding and predicting the state of the sun, the interplanetary and planetary environments, and the solar and non-solar driven perturbations that affect them; and also at forecasting and nowcasting the possible impacts on biological and technological systems

Lilensten, J.; Belehaki, A. Developping the scientific basis for monitoring, modeling and predicting space weather. Acta Geoph. 2009, 57, 1.

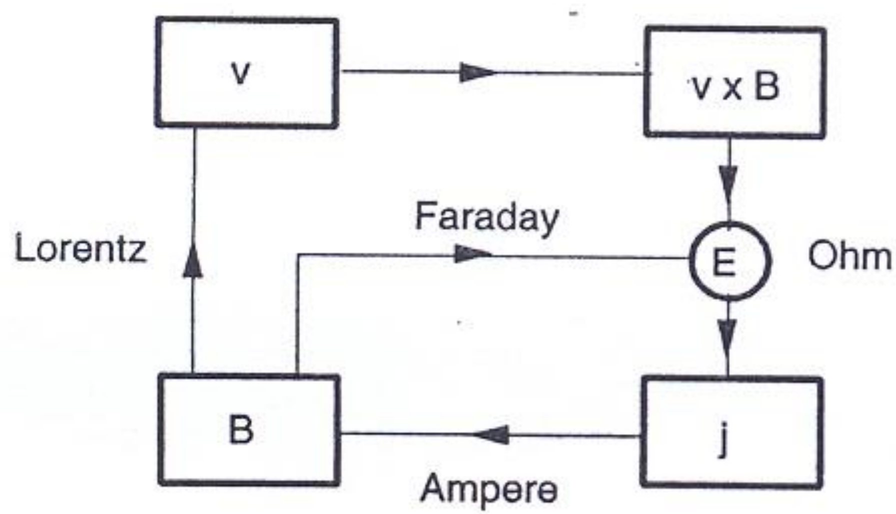
The Sun : a magnetic body in motion

Differential rotation between the poles and equator



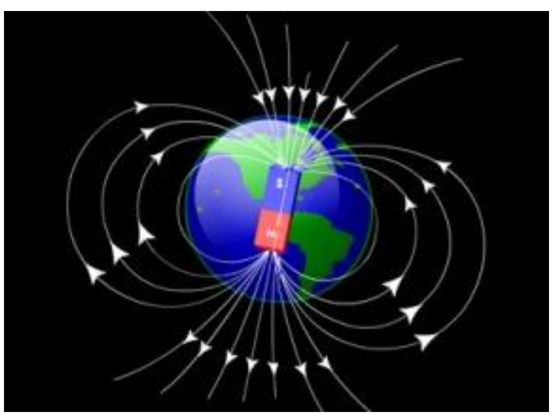
MOTION + MAGNETIC FIELD

DYNAMO Process



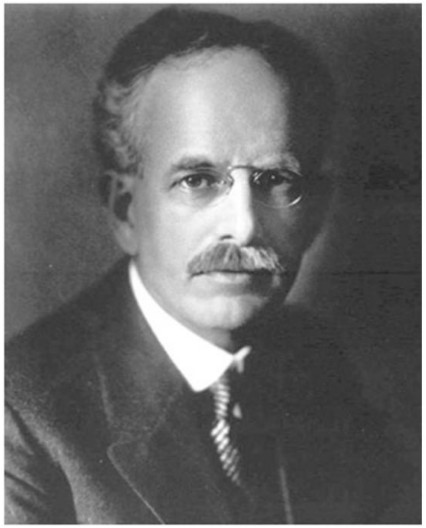
The Earth: a magnetic body in motion

Rotation and revolution around the sun



Schematic representation between plasma motion and magnetic field [after Paterno, 2006]. Comments by Paterno 'A motion v across a magnetic field B induces an electric field vxB, which produces an electric current J=σ (E + v×B) via Ohm's law where s is the electric conductivity and E an electric field. This current produces in turn a magnetic field ∇XB = μJ, where μ is the permeability. The magnetic field creates both electric field E through Faraday's law ∇ E =-δB/δt and Lorentz force J×B which reacts on the motion v.

SOLAR DYNAMO : The Solar Magnetic field



Georges Ellery HALE
[1868-1938] USA

G. E. Hale discovered the magnetic field in sunspots. It is the first detection of a magnetic field beyond Earth

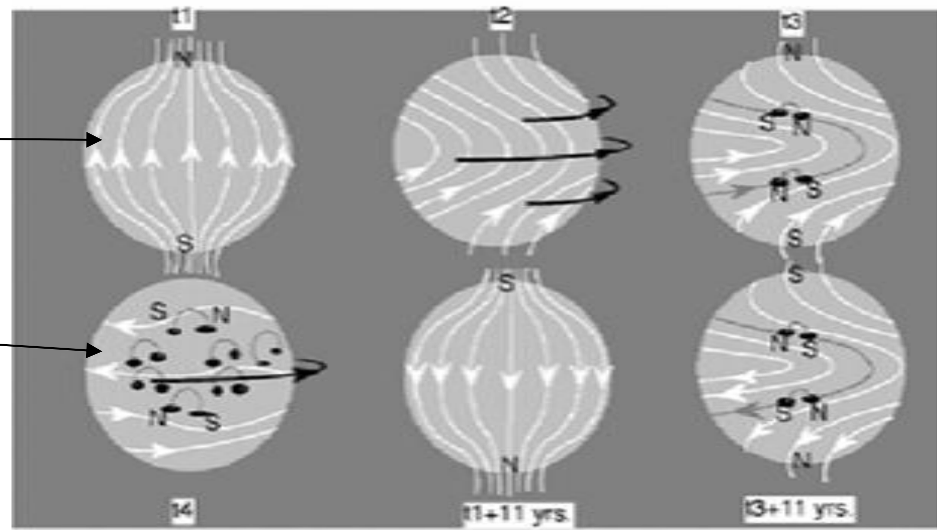
G.E Hale detected the magnetic field by the zeeman effect on the spectral lines of the sun.

The **Zeeman effect** is the **effect** of splitting of a spectral line into several components in the presence of a static magnetic field

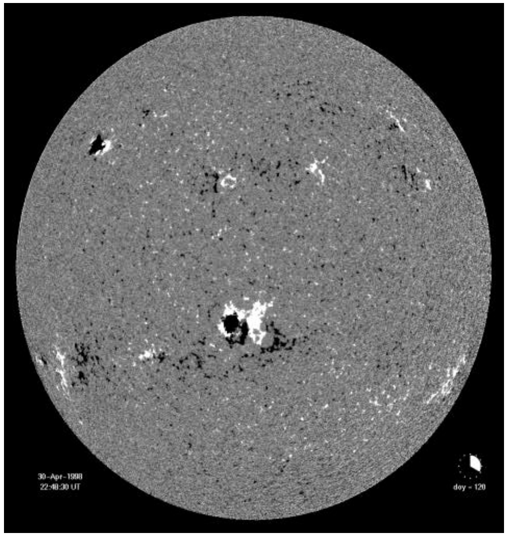
Hale and his colleagues found that sunspots in northern and southern hemispheres reverse polarity every 11 years.

Poloïdal

Toroïdal

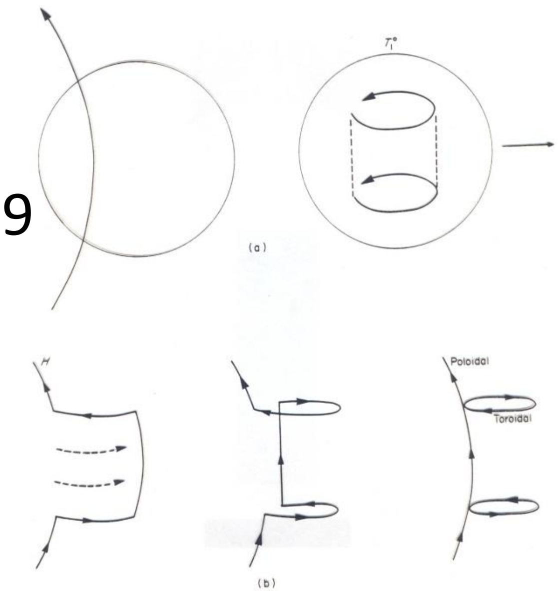


SUN : What is a sunspot ?



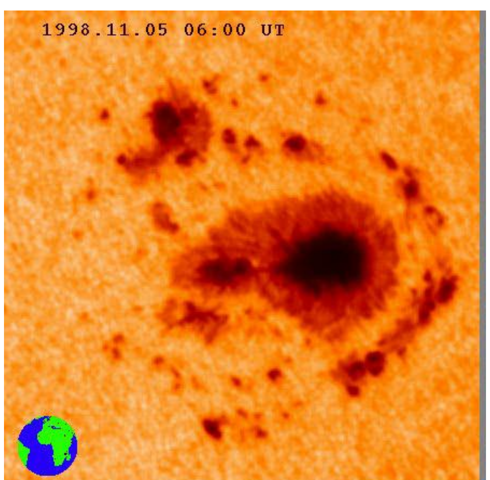
Poloïdal component
~ 10 G
discovered by Hale 1919

Figure from Friedman, 1987



Toroïdal component
Sunspot
~ 3-5 kG

Magnetogram of the Sun
SOHO satellite data



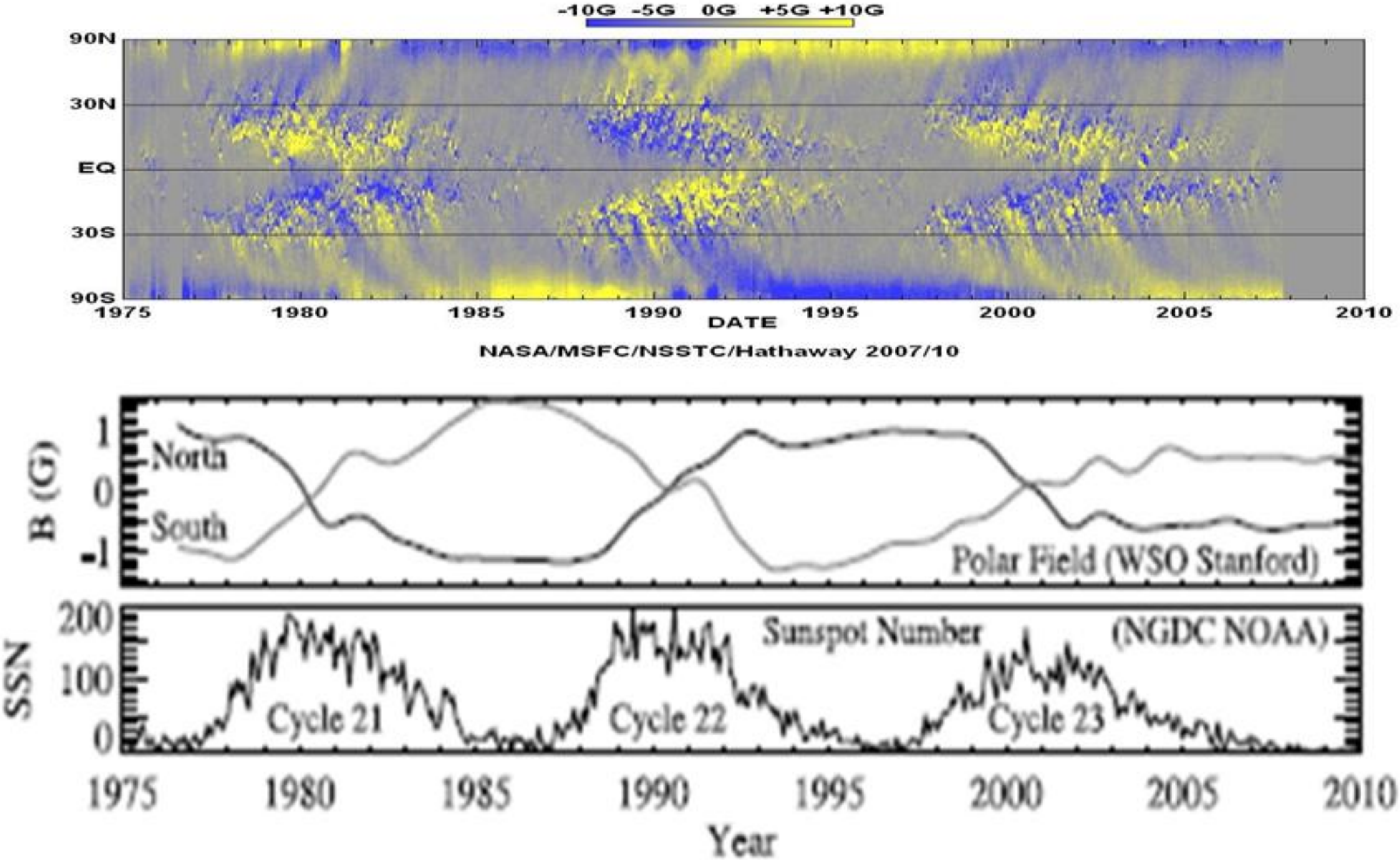
Physical process : Dynamo

*The sun turns on itself.

**Its rotation speed is faster at the equator than at the poles (~ 27 days against ~ 31 days).

***This differential rotation twists the lines of the poloïdal magnetic field and generates magnetic loops called sunspots

Solar Dynamo : THE SOLAR CYCLE

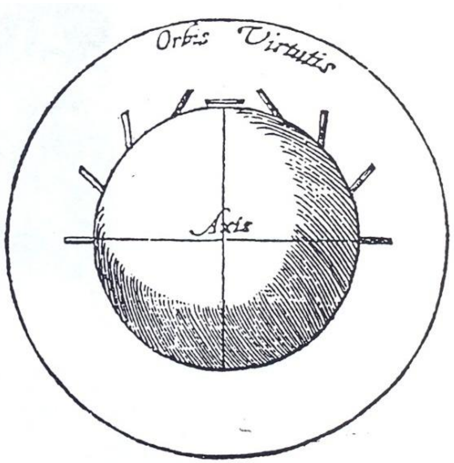


Variability ~ 11 and 22 years

Liu et al., 2011

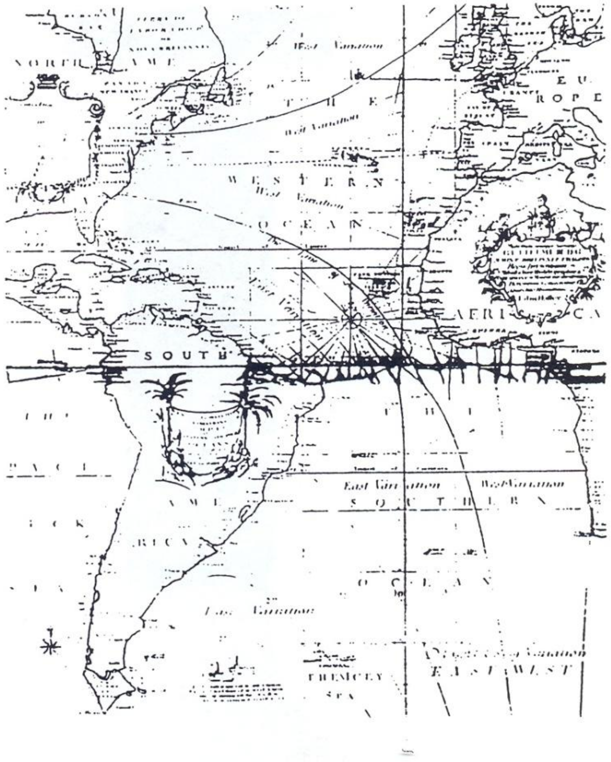
http://solarscience.msf.nasa.gov/dynamo.shtml

EARTH'S MAGNETIC FIELD => EARTH'S DYNAMO
Earth's magnetic field is known since more 2 millenaries



W. Gilbert, 1600
concept of the Earth's dipole magnet inside the Earth

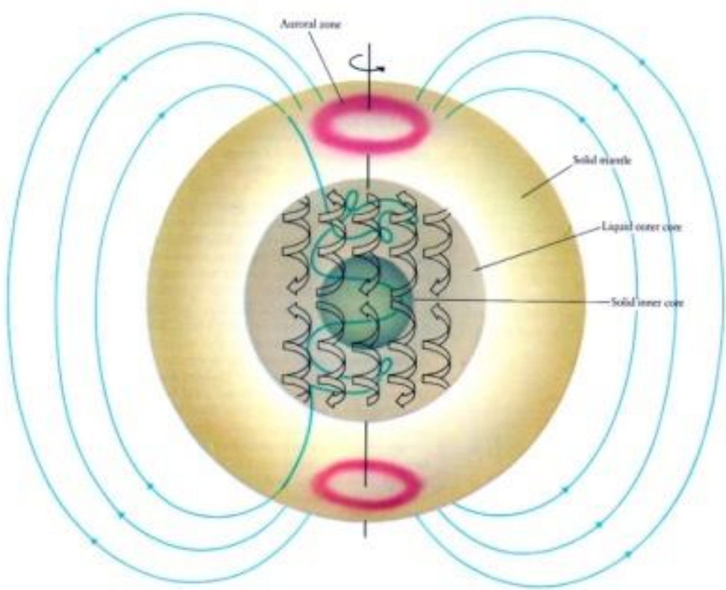
First map of the Earth's magnetic field by Halley 1701



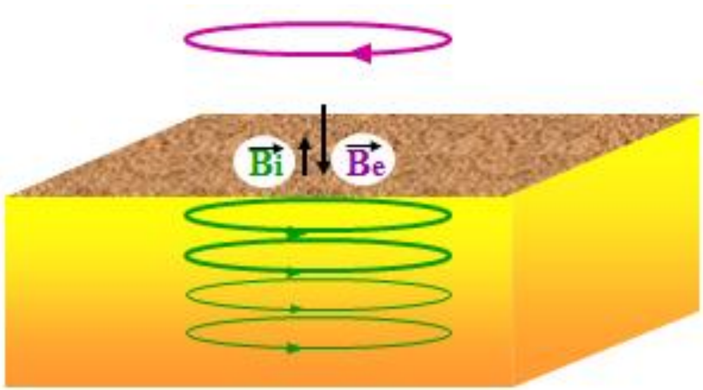
|1544–1603]
England

[1656- 1741]
England

The Earth's dynamo



Model of the terrestrial magnetic field IGRF
http://www.iugg.org/IAGA/iaga_pages/pubs_prods/igrf.htm



B = Bp + Ba + Be + Bi

Bp = main field (secular variations)
(30000-60000nT)

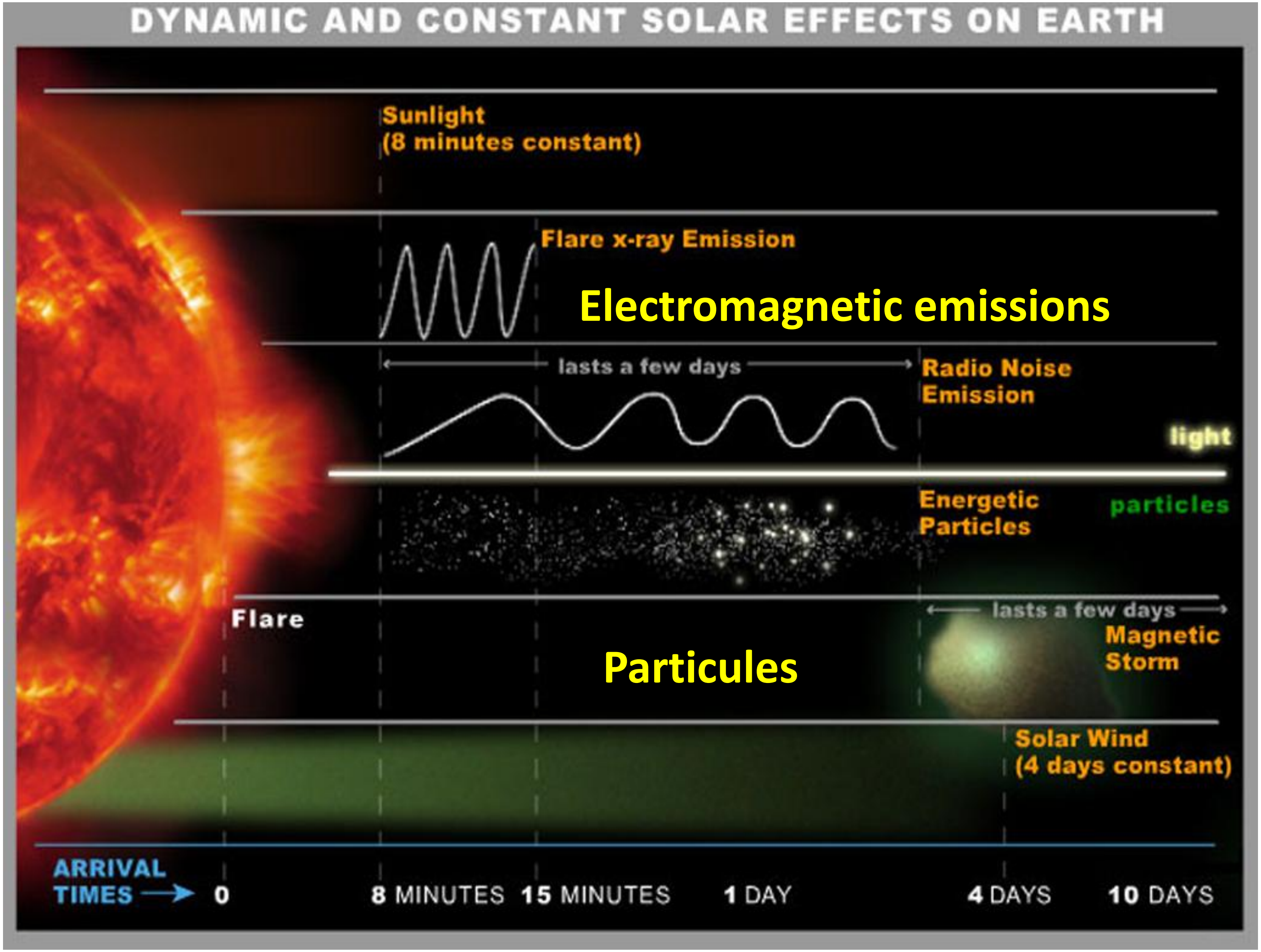
Ba = magnetization of the rocks in the Lithosphere (constant)
(~ 10-1000 nT)

Be = external field related to Ionosphere and magnetosphere
(10nT to 2000nT)

Bi = induced field generated by the external field Be , (Kamide and Brekke, 1975)
(% of Be)

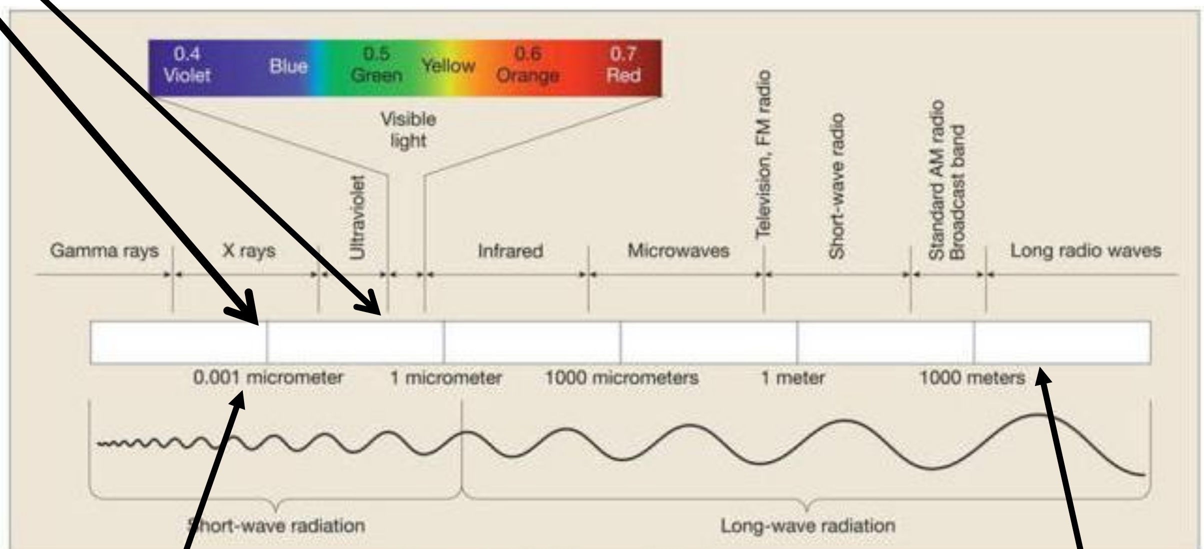
The Earth's magnetic field reflects all the variations of electrical currents of the SUN-EARTH system

SUN EARTH CONNECTIONS



SUN : Electromagnetic emissions
Channel **<u>(REGULAR)</u>** Speed of Light

around sunspots => emissions of EUV, UV, X rays



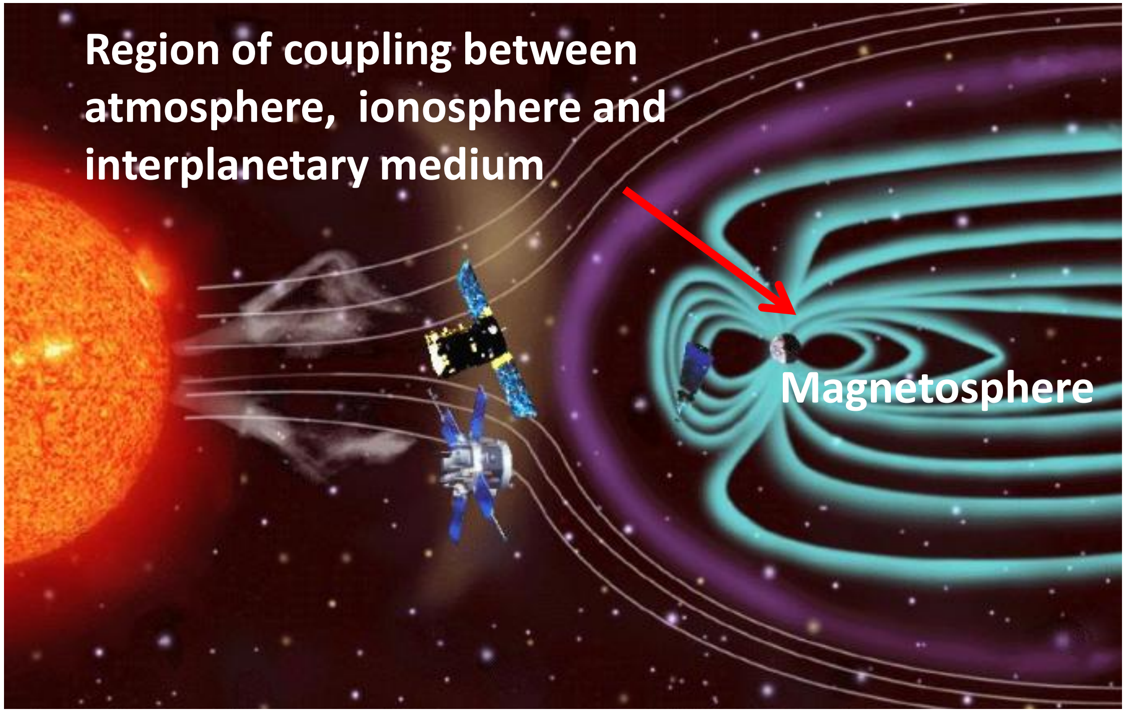
SOLAR FLARE
Extra X rays

SOLAR BURST
Extra Radio waves

DISTURBED EMISSIONS

SUN EARTH CONNECTIONS : PARTICLES Channel : Regular solar wind : V ~ 350-400km/s , Time ~ 2-3 days

The solar wind carries part of the solar magnetic field towards the Earth : Interplanetary Magnetic Field, IMF.

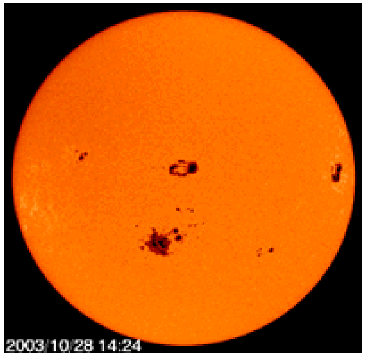


The solar wind is the constant stream of solar coronal material that flows off the sun. Its consists of mostly electrons, protons and alpha particles with energies usually between 1.5 and 10 kEV

The Earth's magnetic field acts as a shield for solar wind particles. However, there are regions of the ionosphere that are directly connected with the interplanetary medium and thus the solar wind flow

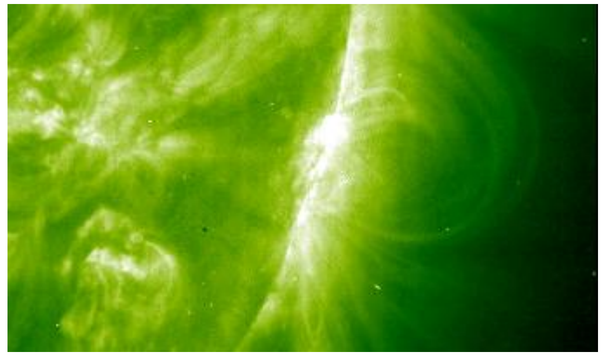
GLOBAL APPROACH OF OF THE SUN-EARTH SYSTEM

Electromagnetic emissions and particles [some large scale phenomena]

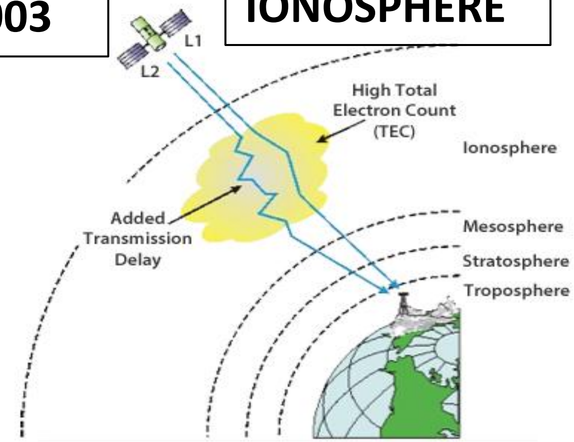


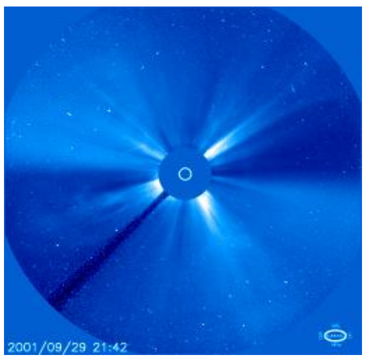
Sunspots

Big solar flare of November 2003



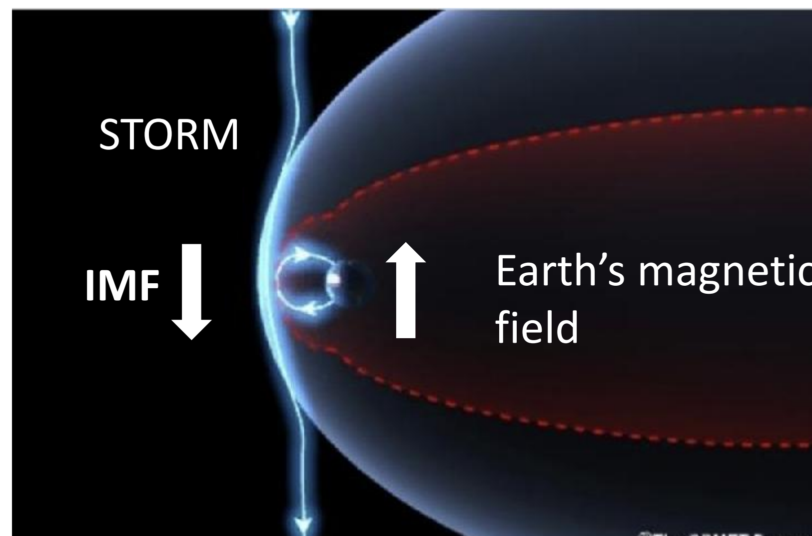
IONOSPHERE

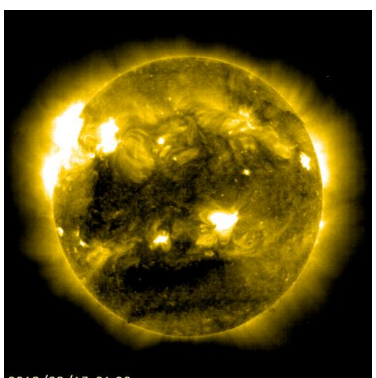




CME: Coronal Mass Ejection
Magnetic cloud
Billions of tons of solar mass

MAGNETOSPHERE





Coronal hole
HSSW –CIR
High speed solar wind

Gopalswamy, N., The Sun and Space Weather, Atmosphere, 13(11), 1781 https://doi.org/10.3390/atmos13111781(2022).

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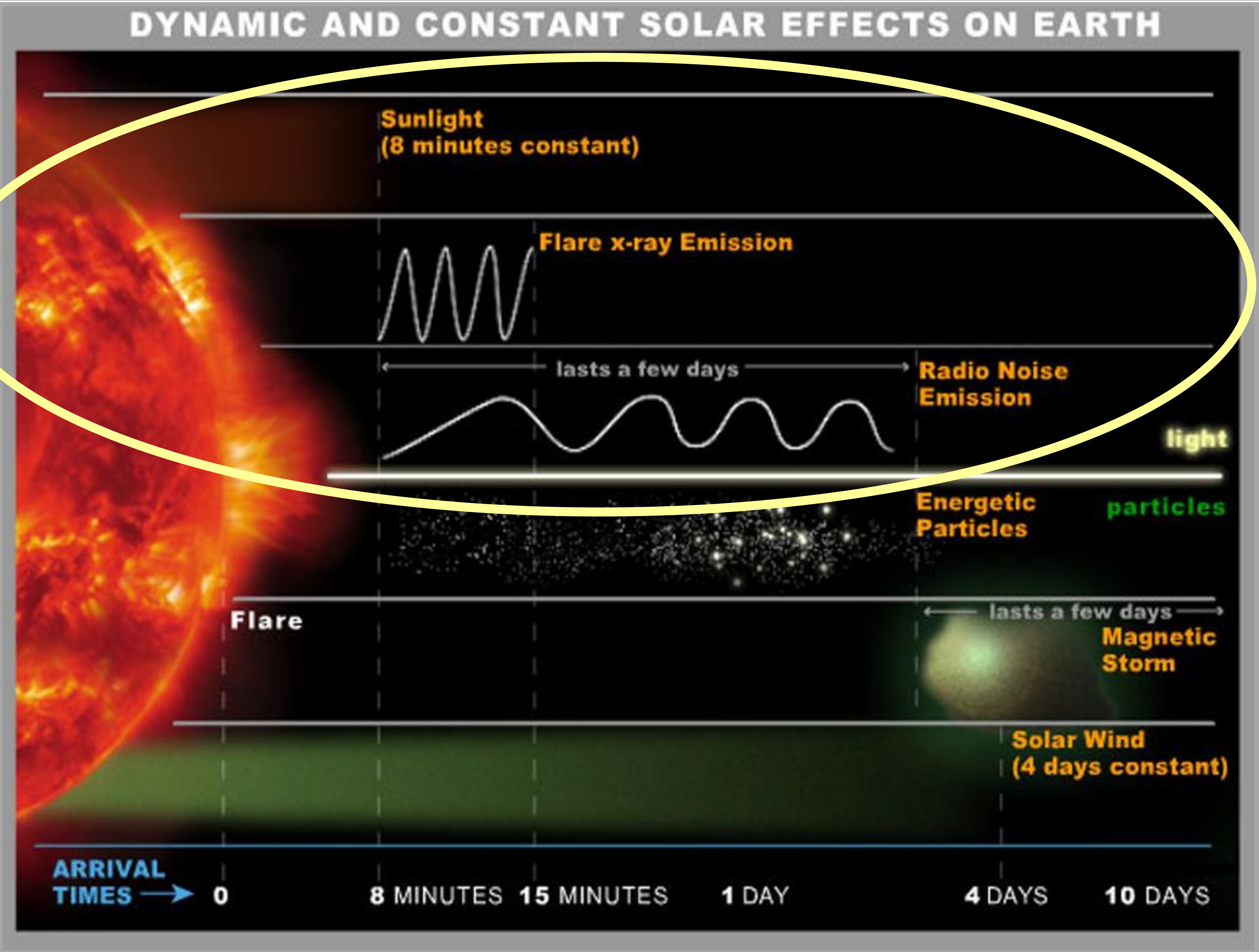
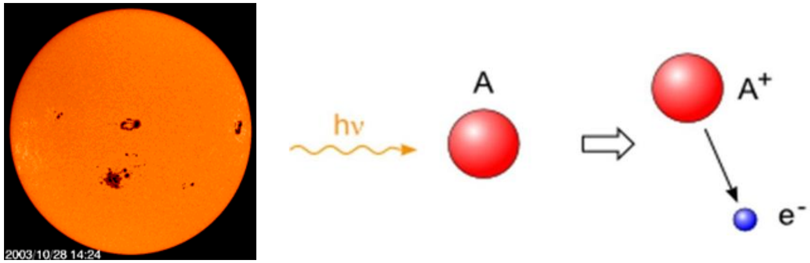
SUN EARTH CONNECTION : EMISSIONS FROM THE SUN



RADIATIONS PARTICLES

from Nasa website



SUN EARTH CONNECTIONS

Ionosphere ⇔ electromagnetic emissions

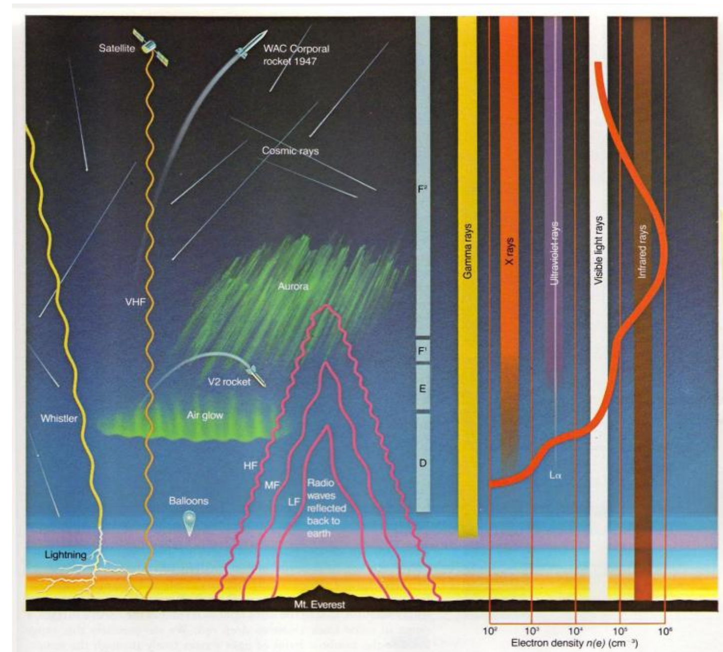
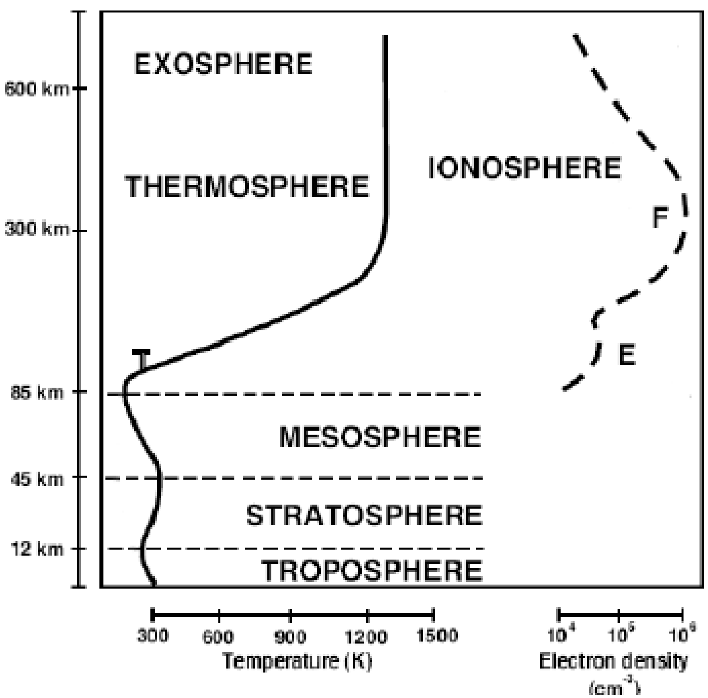


Figure from Friedman, 1987

1st physical process : Photo ionisation

The ionosphere is created by ionization of the atmosphere by UV, EUV and X radiations in the altitude range from 50 km up to ~800 km



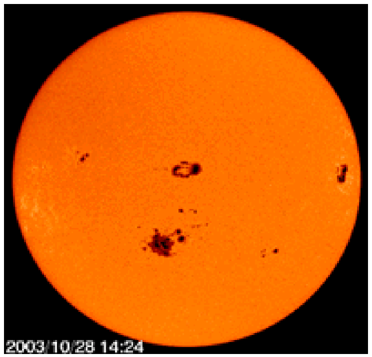
Ionosphere is a ionized part of the **atmosphere**

1 atom among 1 000 000

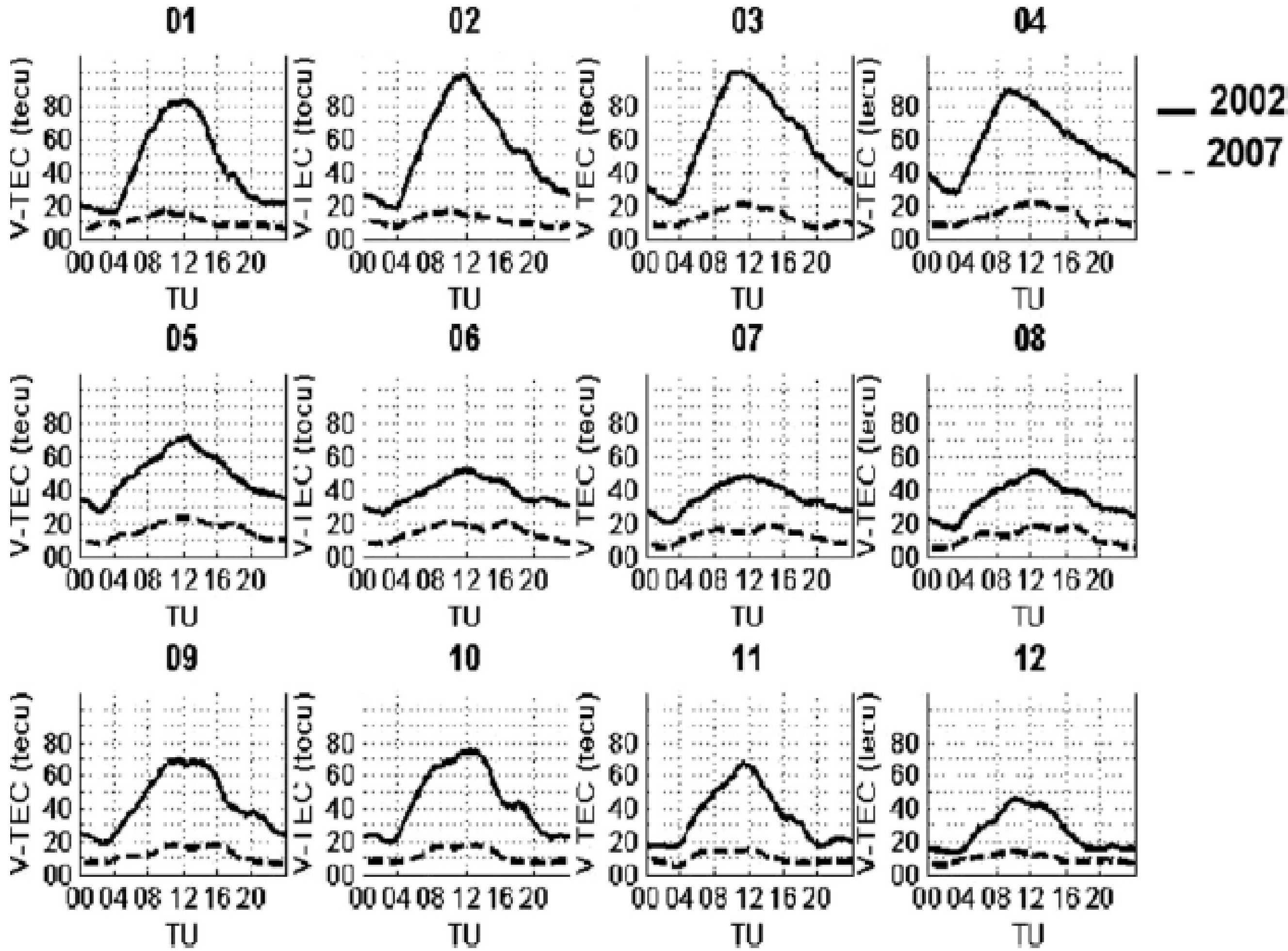
BOOKS : Risbheth and Gariott, 1969

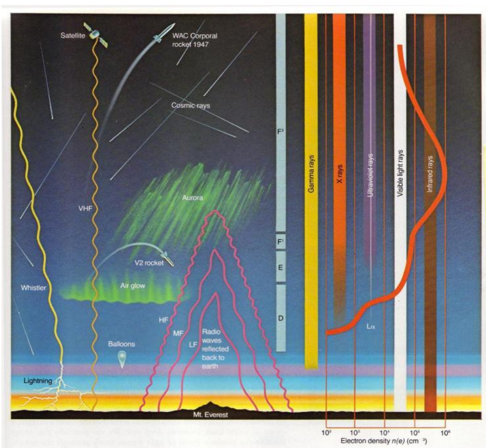
Friedman, 1987, Kelley ,2009

Diurnal variations of VTEC for 2 years 2002 and 2007
2002 : maximum of sunspot cycle 23, 2007 : minimum of sunspot cycle 23



ALEXANDRIE / EGYPT 29.9110E 31.1971N

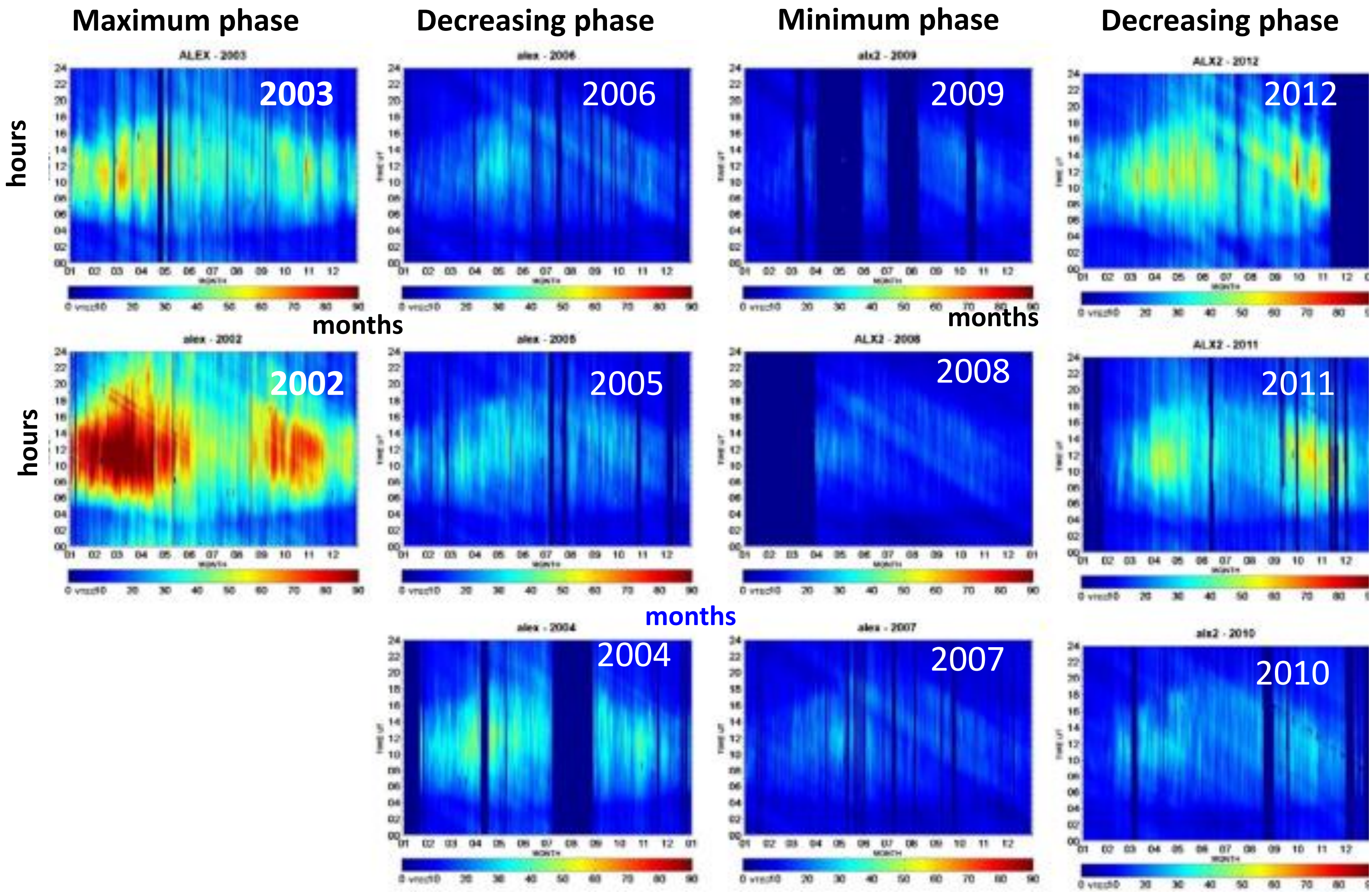




Regular Solar Radiations
UV, EUV, X rays

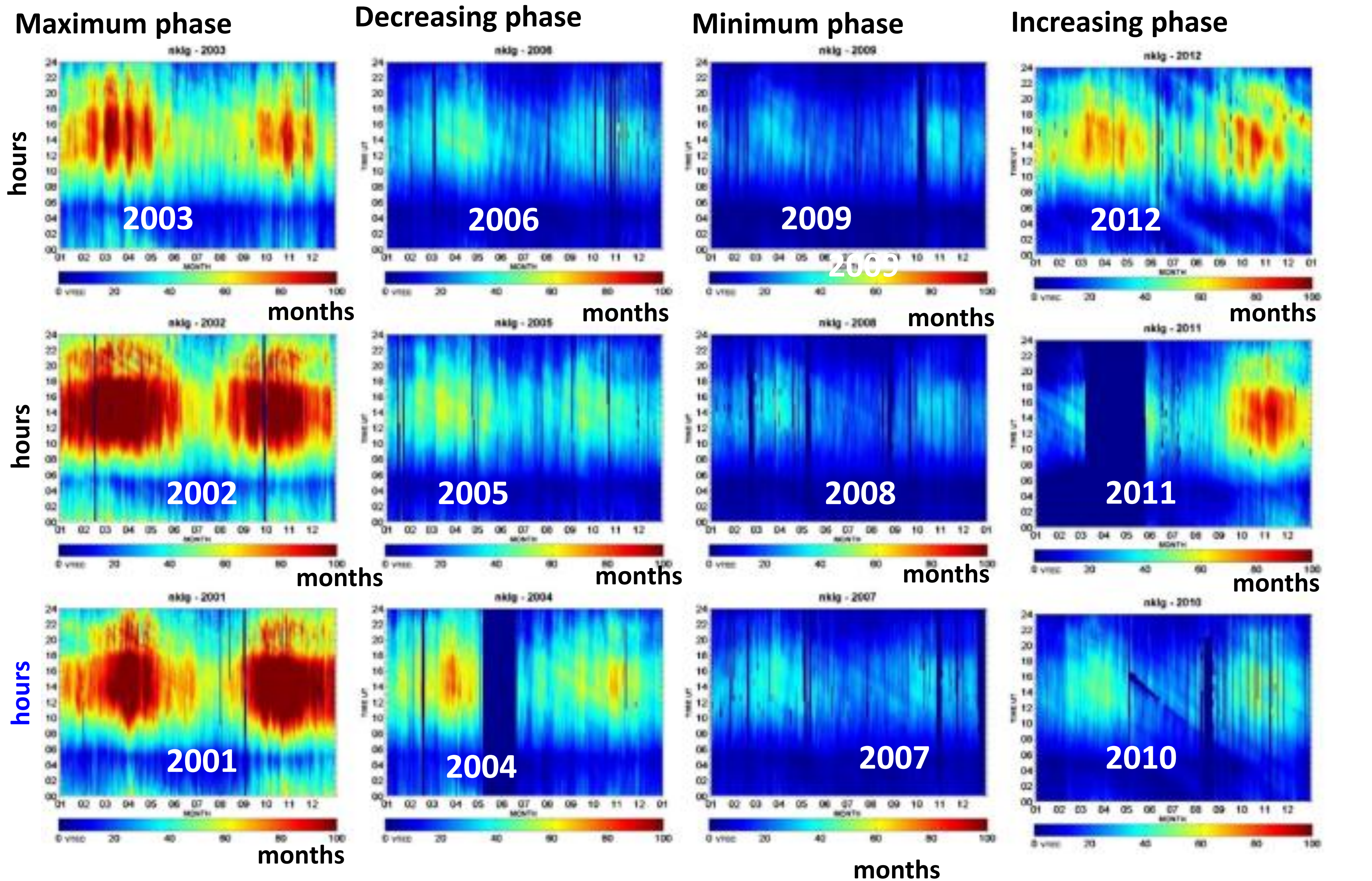
Shimeis, A., C. Amory-Mazaudier, R.Fleury ,A.M. Mahrous,A. F.Hassan, 2014, Transient Variations of Vertical Total Electron Content over Some African Stations from 2002 to 2012, Advances in Space Research 54, 2159-2171

Two dimensional (2D) diurnal variation of hourly vTEC at ALEX from 2002 to 2012
Geopgraphic coordinates 29.9110E 31.1971N



Shimeis, A., et al. Advances in Space Research 54, 2159-2171

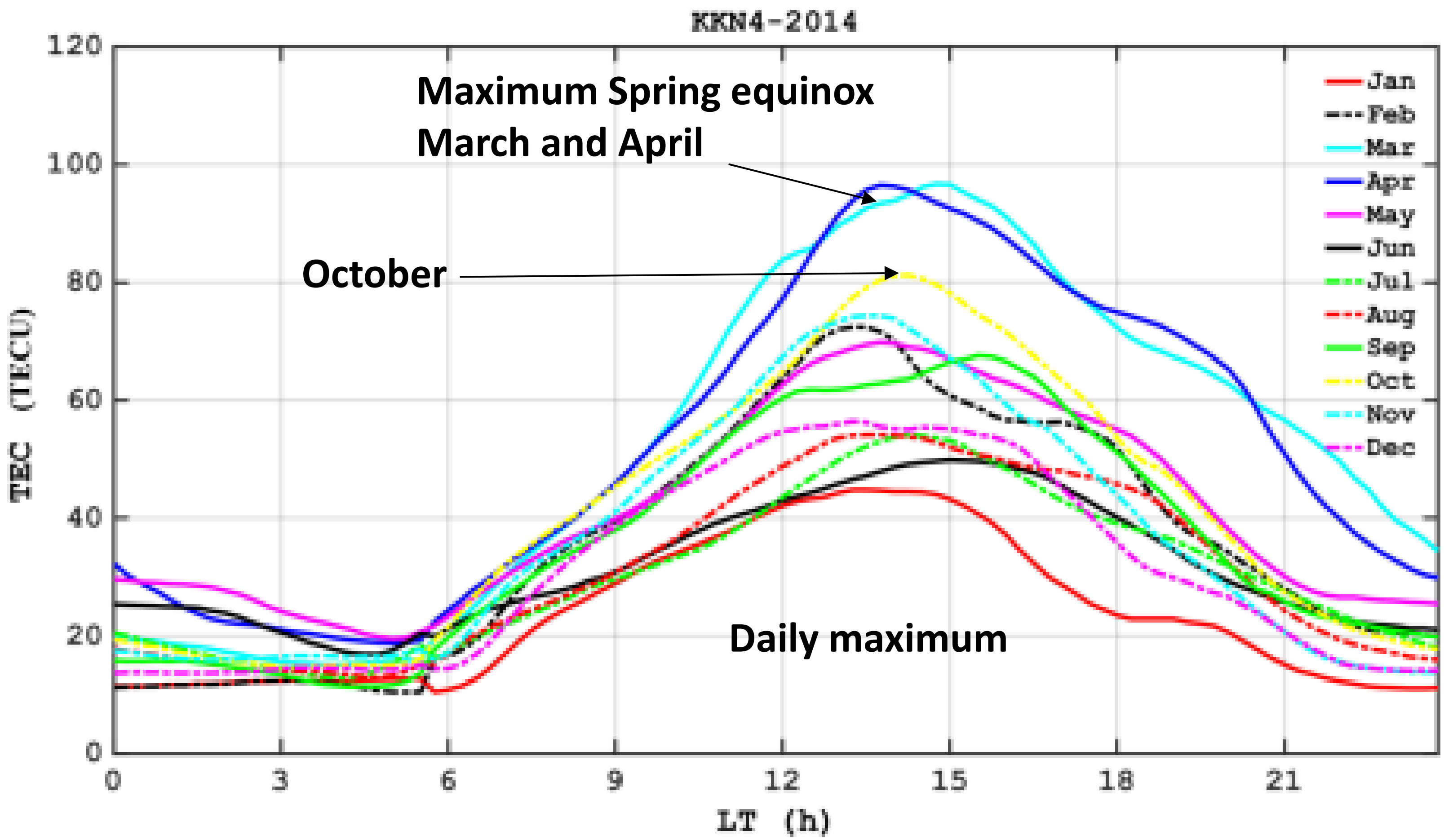
Two dimensional (2D) diurnal variation of hourly vTEC at LIBREVILLE / Gabon - NKLG from 2002 to 2012 Geopgraphic coordinates 9.6721E 0.3539N



Shimeis, A., et al. Advances in Space Research 54, 2159-2171

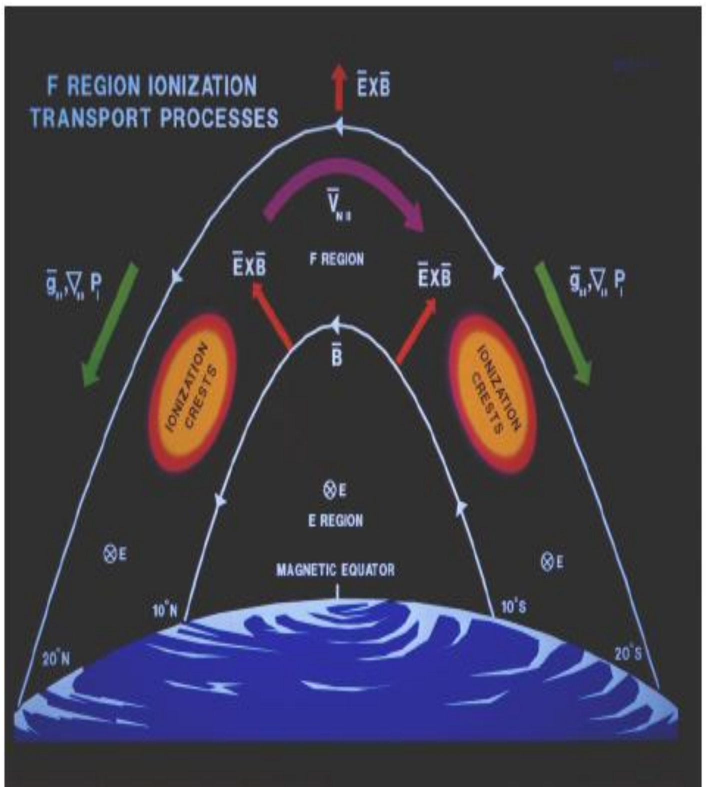
MONTHLY Variations / NEPAL

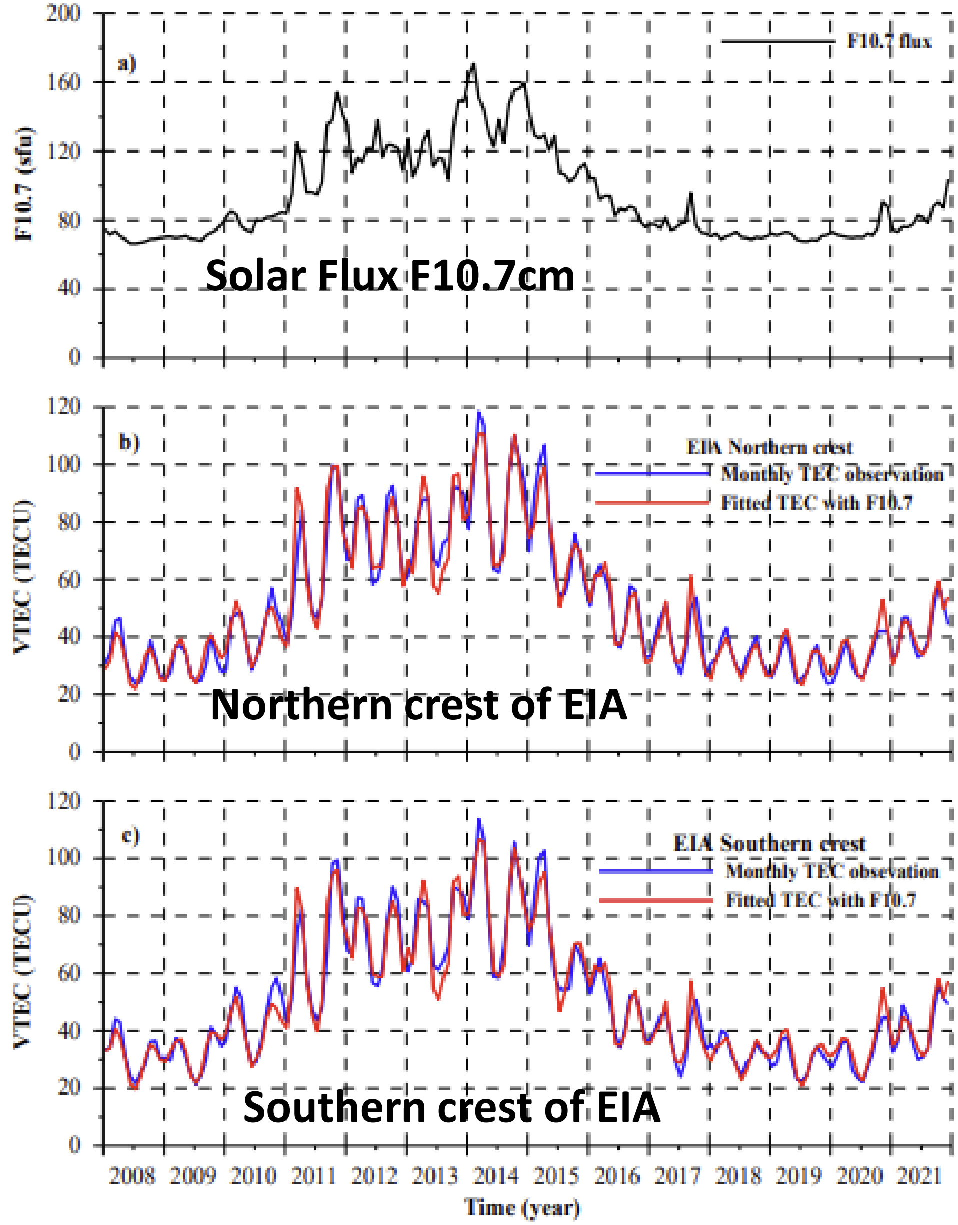
Monthly variation in vertical TEC in LT for 2014 at KKN4 station.



Pandit, D. B. Ghimire, C. Amory-Mazaudier, R. Fleury, N. P. Chapagain, B. Adhikari, Climatology of ionosphere over Nepal based on GPS TEC data from 2008 to 2018, Ann. Geophys., 39, 743–758, 2021 https://doi.org/10.5194/angeo-39-743-2021

Equatorial Ionization Anomaly
Equatorial Fountain



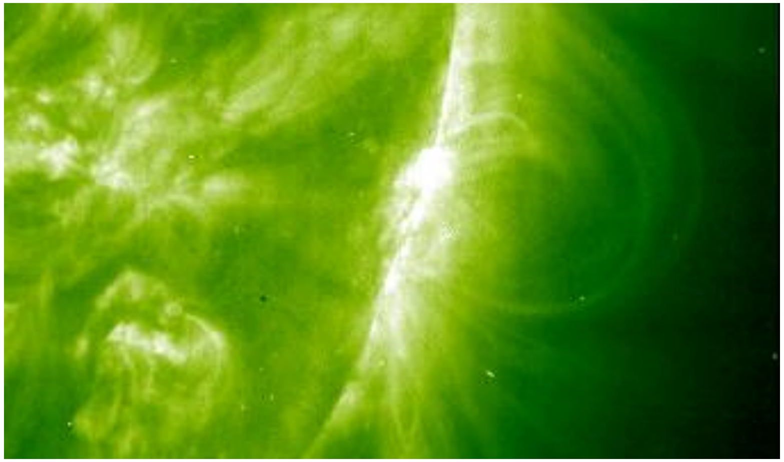


Dung Nguyen Thanh, et al., Ionospheric quasi-biennial oscillation of the TEC amplitude of the equatorial ionization anomaly crests from continuous GPS data in the Southeast Asian region , Vietnam Journal of Earth Sciences, 1-18, https://doi.org/10.15625/2615-9783/17490

SOLAR FLARE : Disturbed solar electromagnetic émissions

The extra X-rays UV an EUV emitted by the solar Flare directly ionize the atmosphere and thus increase the electron density and the TEC.

Big solar flare of November 2003



SOHO data

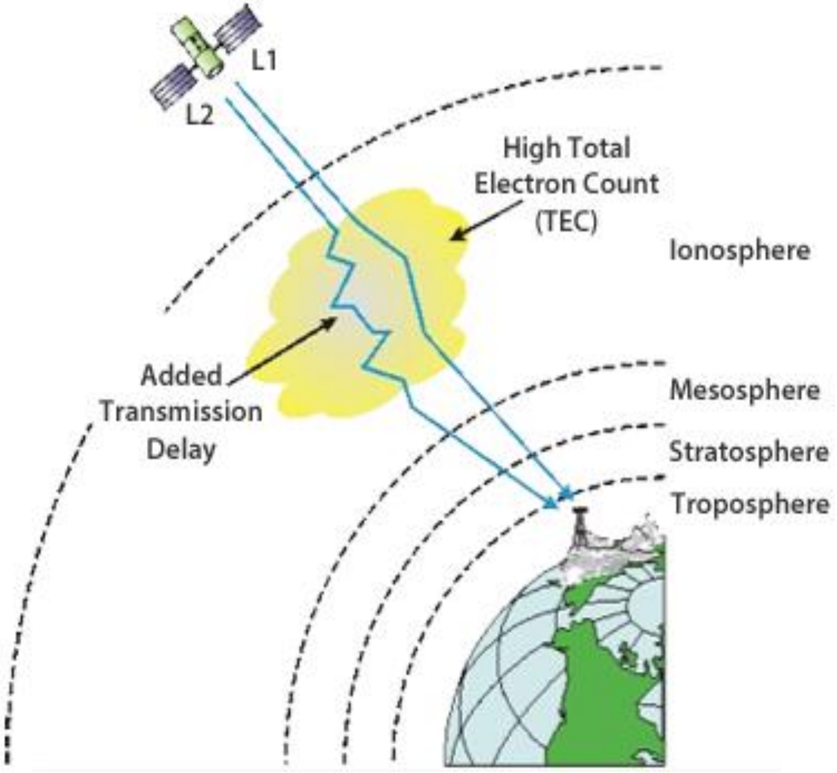
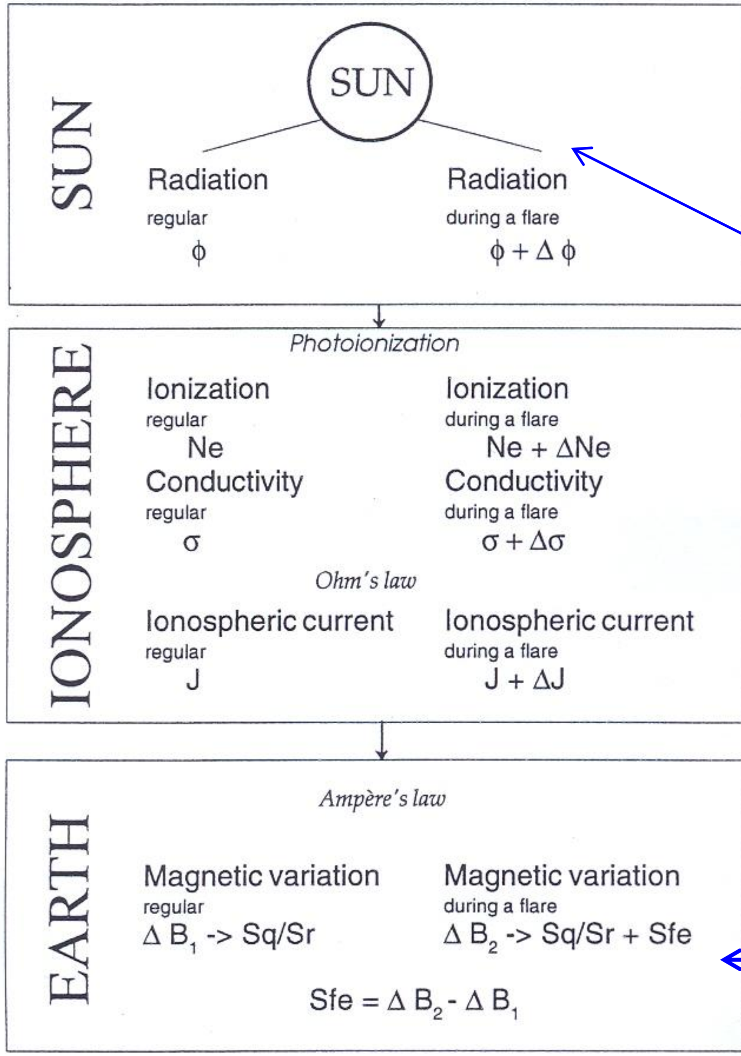
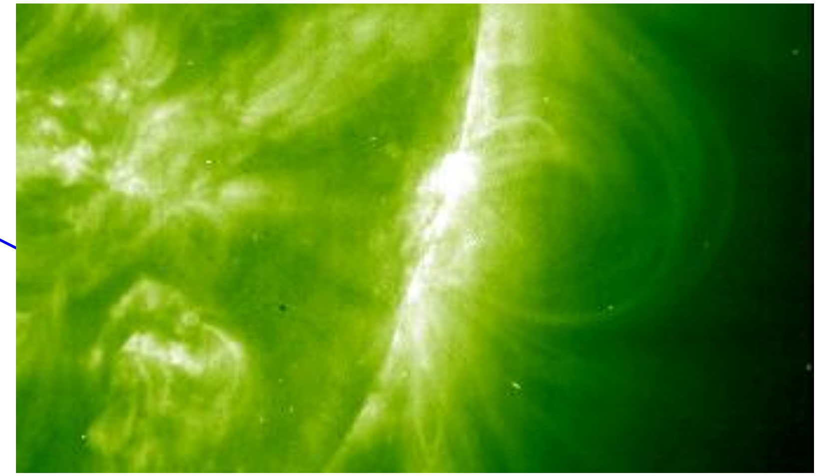


Figure from http://reflexions.ulg.ac.be

SUN EARTH CONNECTIONS : DISTURBED MAGNETIC VARIATIONS





Magnetic variation : crochet

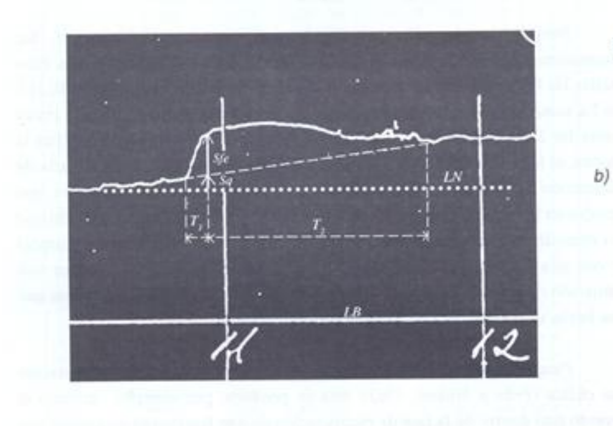
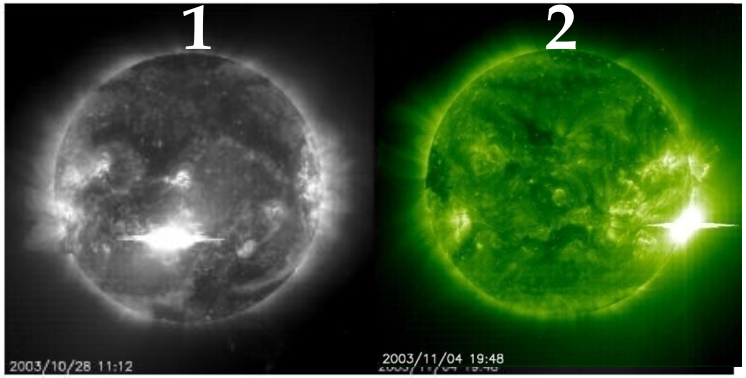


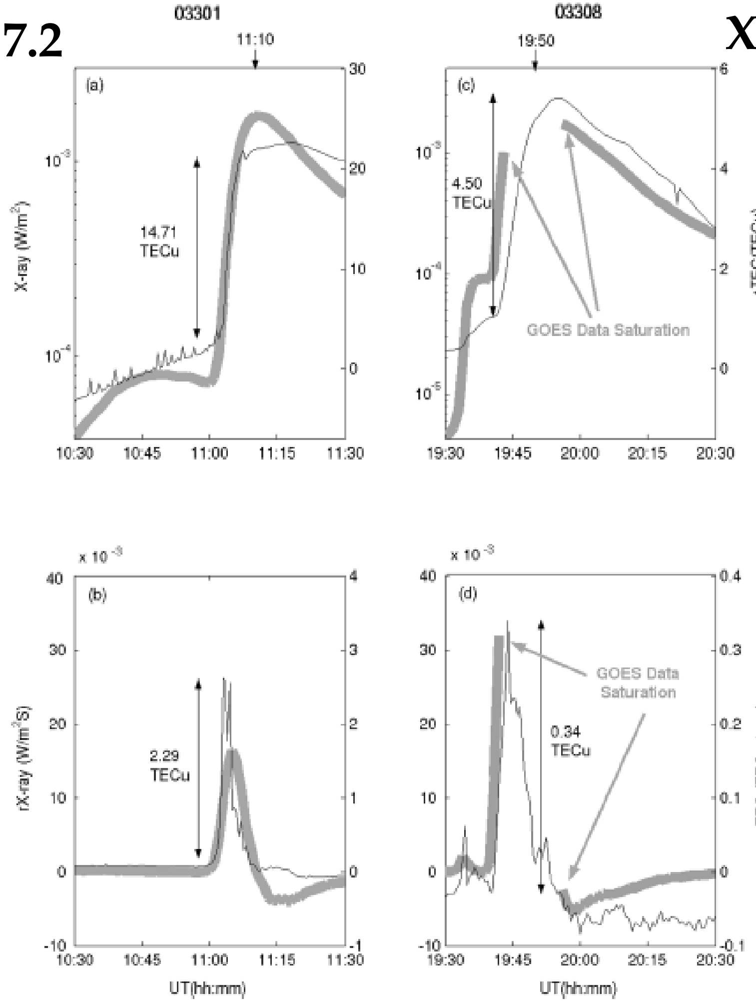
Fig. III.1 Registro magnético de un sfe en Ebro (dibujo superior) y detalle del mismo sfe para la componente H (dibujo inferior).

Curto, J-J. et al., "Study of Solar Flare Effects at Ebre : 2. Unidimensional physical integrated model, J. of Geophys. Research, A, 12 23289-23296,1994.



2003/10/28 : 11h12 **2003/11/04 : 19h48**

X17.2 **X28**



2003/10/28 : 11h12 2003/11/04 : 19h48
SOHO Extreme ultraviolet Imaging Telescope (EIT) of the fourth largest (1) and the largest solar flare (2)

SOLAR FLARES AFFECT TEC

$$rTEC = \frac{\partial TEC}{\partial t}$$

Liu et al, 2006, Solar flare signatures of the ionospheric GPS total electron content, JGR, vol 111, A05308

Outlines

Introduction

The use of GNSS for research

Space Weather

Sun, Earth, Magnetosphere, Ionosphere,
Solar electromagnetic emissions and solar particles

Study of ionosphere with GNSS signal (vTEC)

Impact of the solar electromagnetic emissions

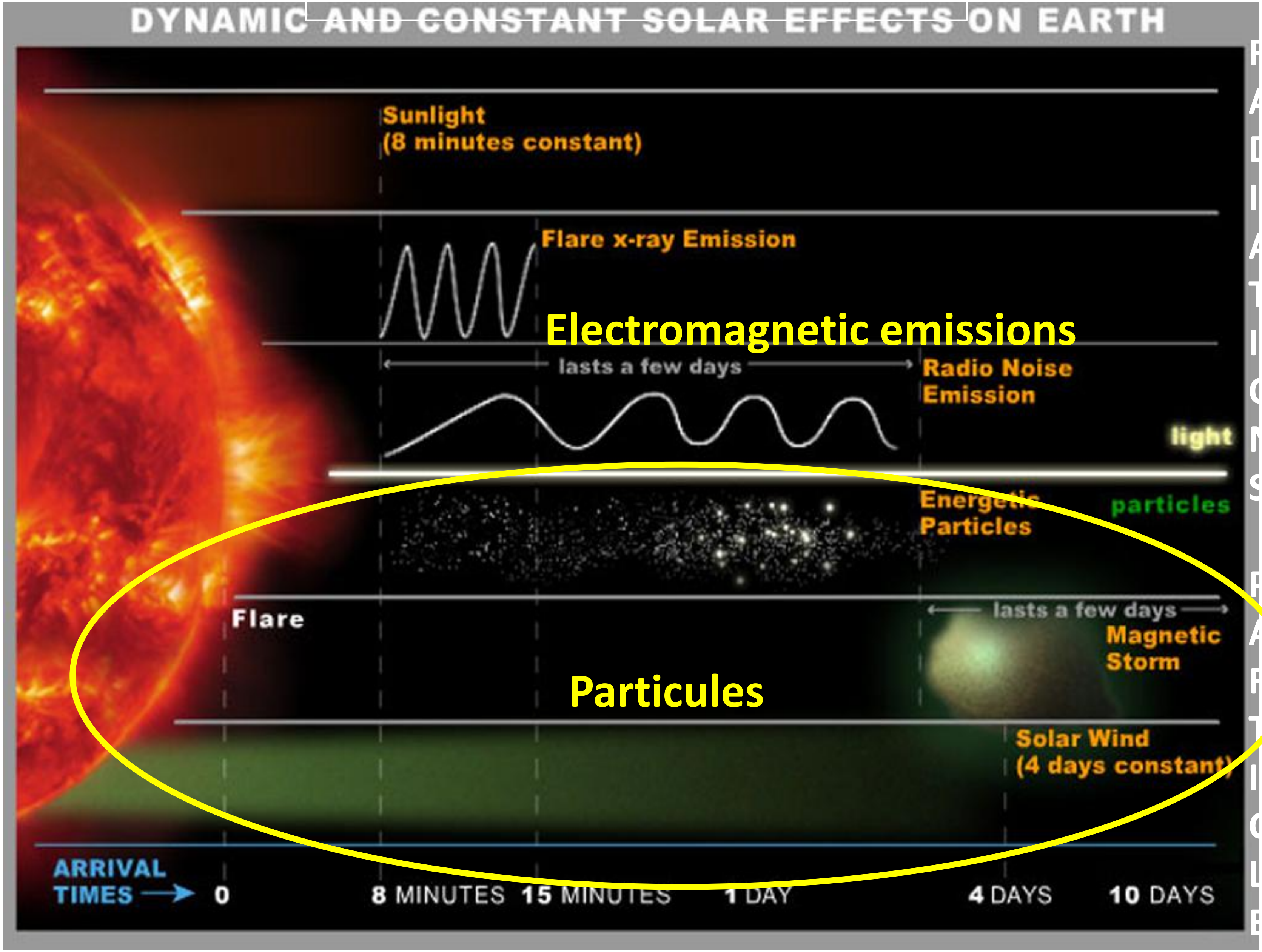
Regular and disturbed ionophere

Impact of the solar wind

Coronal Mass Ejections and High Speed solar wind

Scintillations of GNSS Signal and ROTI index at low latitudes

Regular variations and disturbances


DYNAMIC AND CONSTANT SOLAR EFFECTS ON EARTH
Sunlight
(8 minutes constant)
Flare x-ray Emission
Electromagnetic emissions
lasts a few days
Radio Noise
Emission
light
Energetic
Particles
particles
Flare
lasts a few days
Magnetic
Storm
Particules
Solar Wind
(4 days constant)
ARRIVAL
TIMES
0
8 MINUTES
15 MINUTES
1 DAY
4 DAYS
10 DAYS

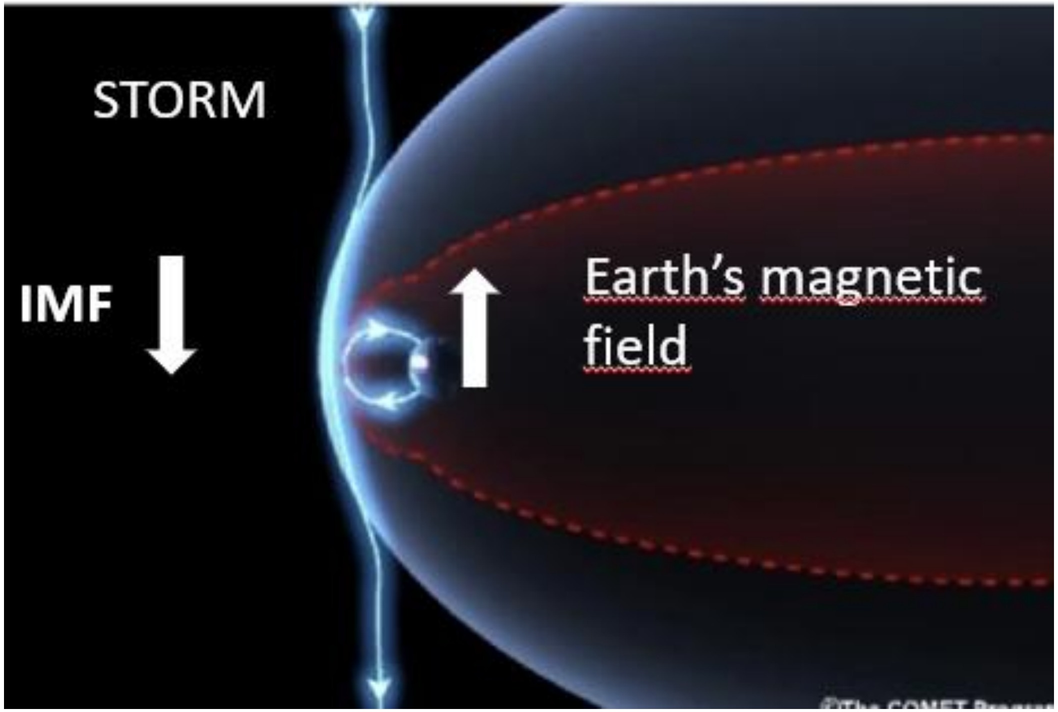
SOLAR WIND - MAGNETOSPHERE DYNAMO

Physical processes : Reconnection and Dynamo

If the Interplanetary Magnetic Field , IMF field is opposite to the terrestrial magnetic field, i.e directed toward the South, there is reconnection (Dungey,1961) between the IMF and the Earth's magnetic field and **there is a geomagnetic storm**

Key parameters for Space Weather :B_z IMF
Vs : solar wind speed
E_y=- V_x.B_z

Alexander Von HUMBOLD
[1769-1859] Germany



Solar wind – Magnetosphere Dynamo : E=VsxB movement is converted into electrical energy

CORONAL MASS EJECTION

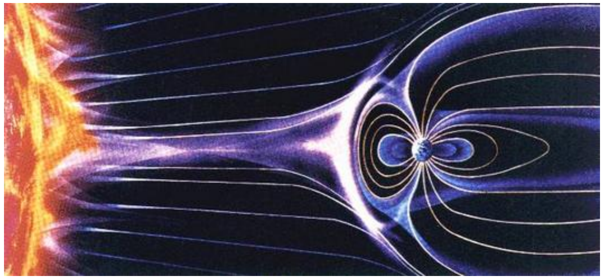
CME : billions tons of matter ejected from the sun

Near the sun

SOHO satellite data

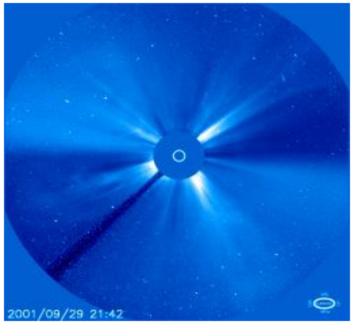
From the Sun to the Earth

Movie from the NASA



CME produce magnetic storms

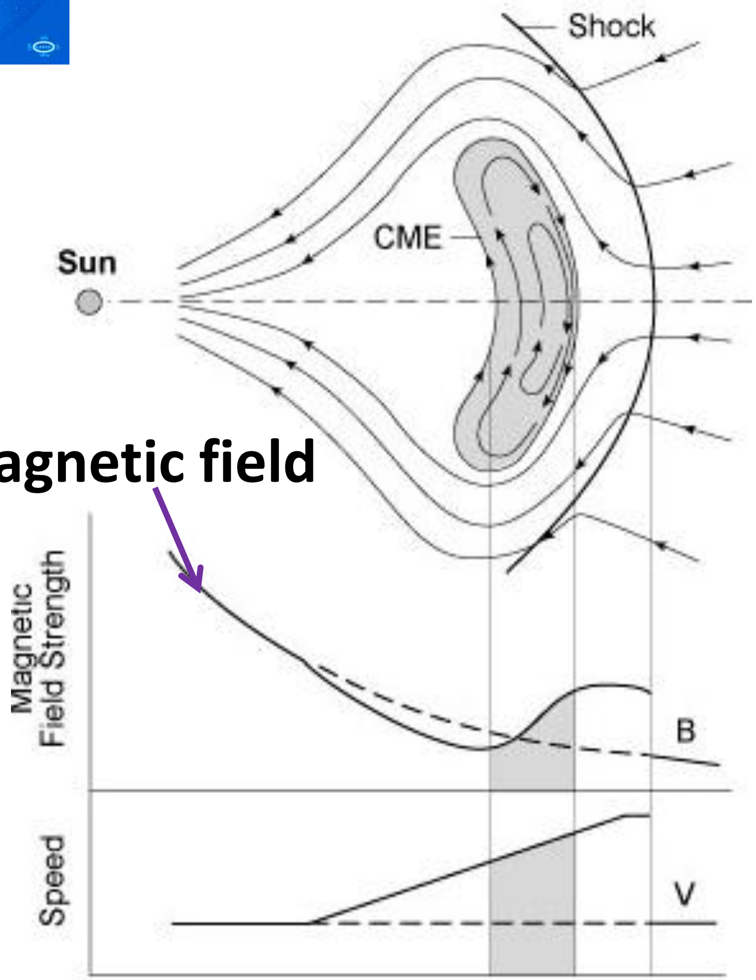
if the IMF inside the CME is southward



Interplanetary CME Shocks

http://ase.tufts.edu/cosmos/pictures/sept09/

Strong magnetic field

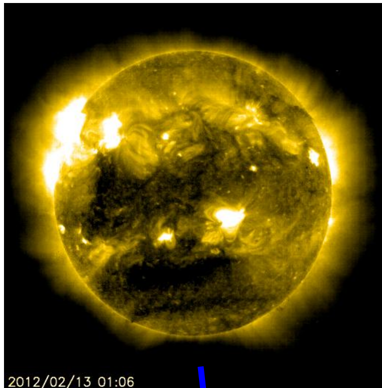


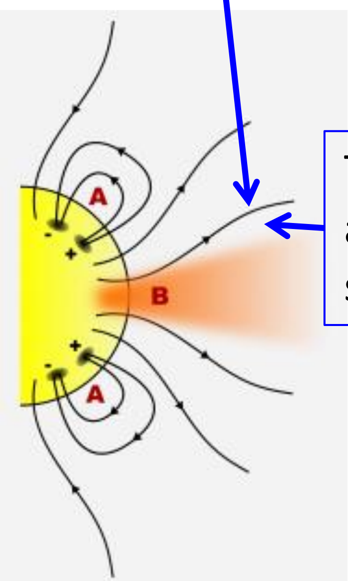
A fast coronal mass ejection CME pushes an interplanetary shock wave

Increases of solar wind speed V and magnetic field strenght B by the interplanetary shock wave in front f the CME

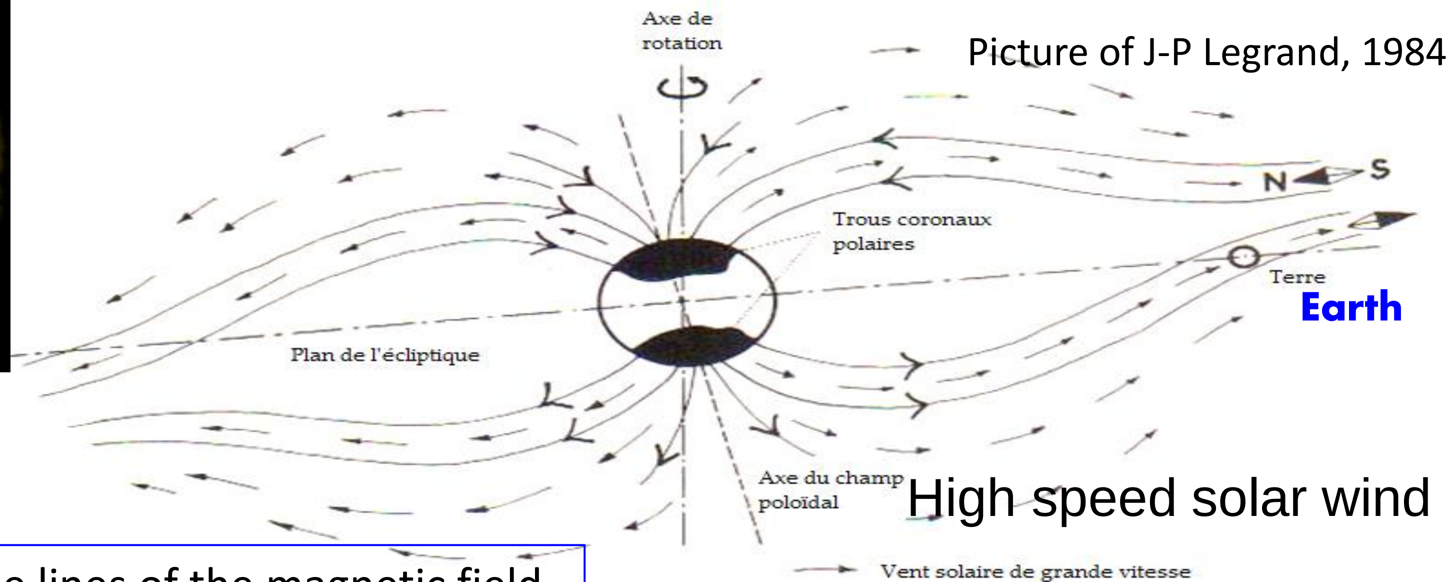
Maximum occurrence of CME during the maximum of the solar sunspot cycle

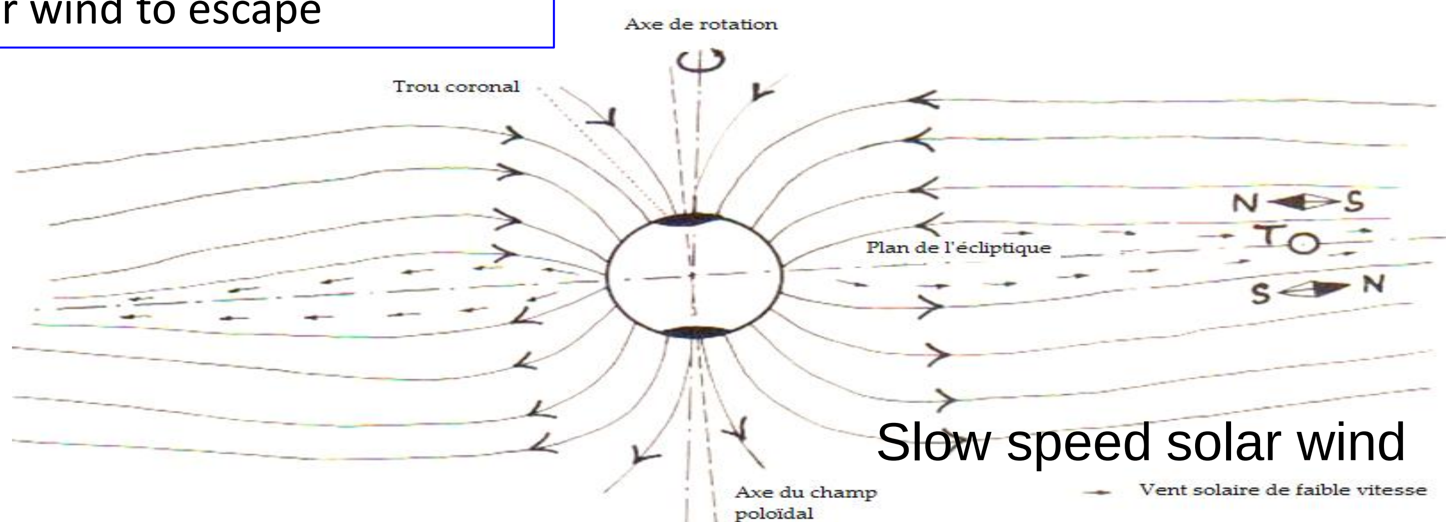
CORONAL HOLE – reccurrent geomagnetic activity





The lines of the magnetic field are open .This allows for the solar wind to escape





Maximum occurrence during the declining and minimum phases of solar sunspot cycle

Coupling between high and low latitudes

- 1 Transmission of an electric field PPEF

- 2.a Thermal expansion of the atmosphere
  - Changes in pressure, temperature, motions and composition of the Atmosphere

- 2.b Transmission of a disturbance electric field dynamo DDEF, by the disturbed atmospheric motions in the dynamo layer

COUPLING between AURORAL and EQUATORIAL regions
ELECTRIC FIELD ALONE
Prompt penetration of the magnetospheric convection electric field [PPEF]

Nishida, A. (1968), Geomagnetic DP2 fluctuations and associated phenomena, *J. Geophys. Res.*, 73, 1795–1803, doi: 10.1029/JA073i005p01795

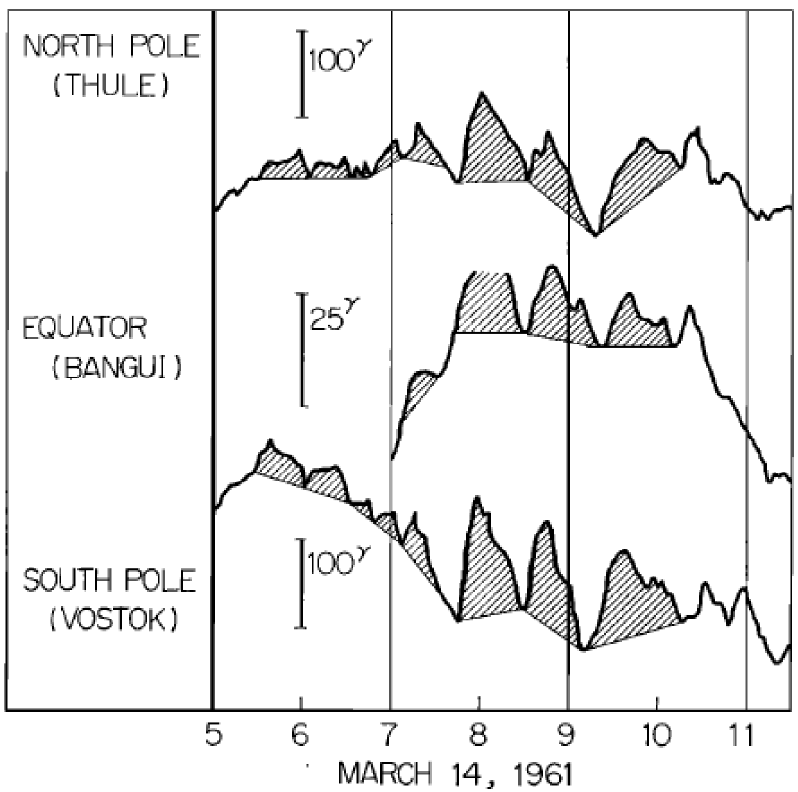
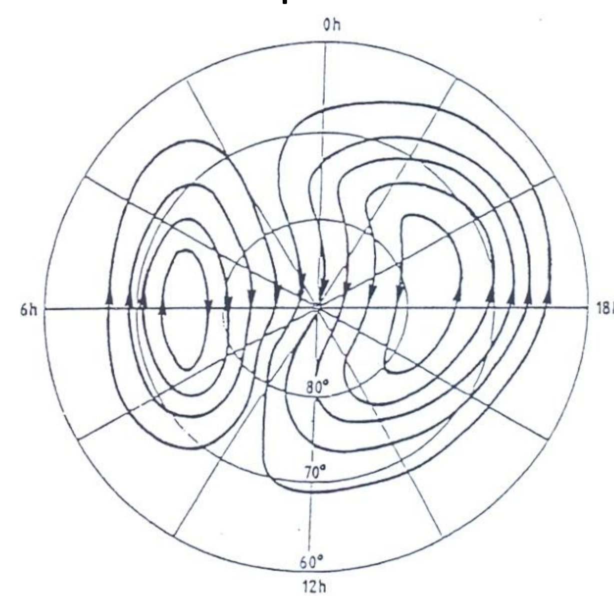


Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

The electric field of magnetospheric convection is transmitted to the whole ionosphere
=> simultaneity of the disturbances from auroral to equatorial latitudes

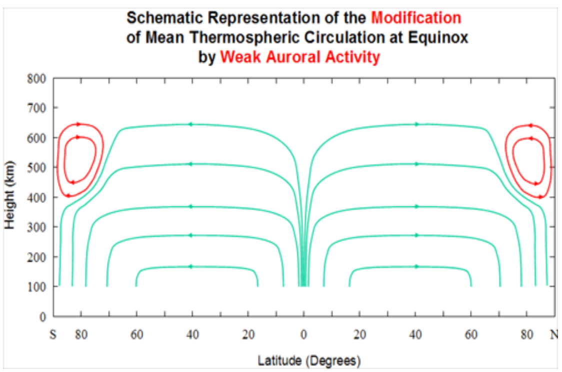


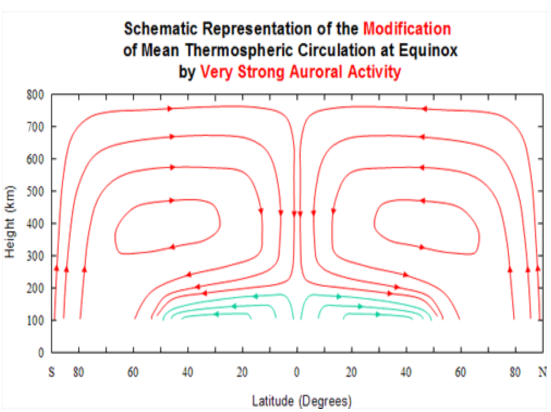
Magnetic signature : DP2

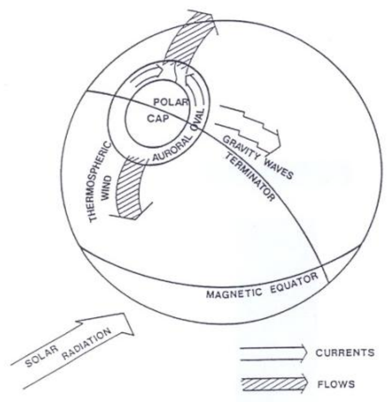
IONOSPHERIC DISTURBED DYNAMO [DDEF]

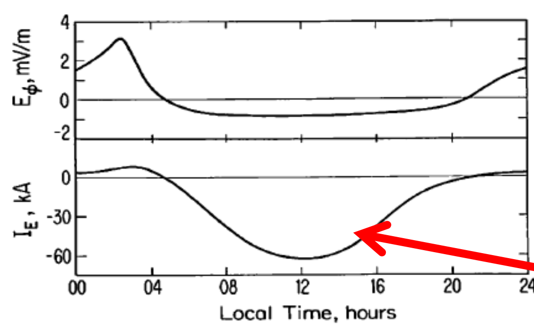
Magnetic disturbance from the Pole to the Equator : D_{dyn}

The Ionospheric Disturbance Dynamo (Blanc and Richmond , JGR 1980) : model
Le Huy and Amory-Mazaudier JGR 2005 : magnetic disturbance Ddyn
This physical process related to the circulation of thermospheric winds disturbed by the storm takes several hours to reach the equator









Blanc and Richmond, 1980.

JOULE HEATING in auroral zone [AE]

ΔVn : disturbance of wind, circulation from pole to Equator Gravity waves, HADLEY convection cell etc…

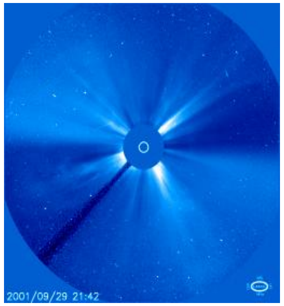
*ΔE_{dyn} : disturbance of Electric field due to storm winds

*ΔJ : Disturbance of ionospheric electric current

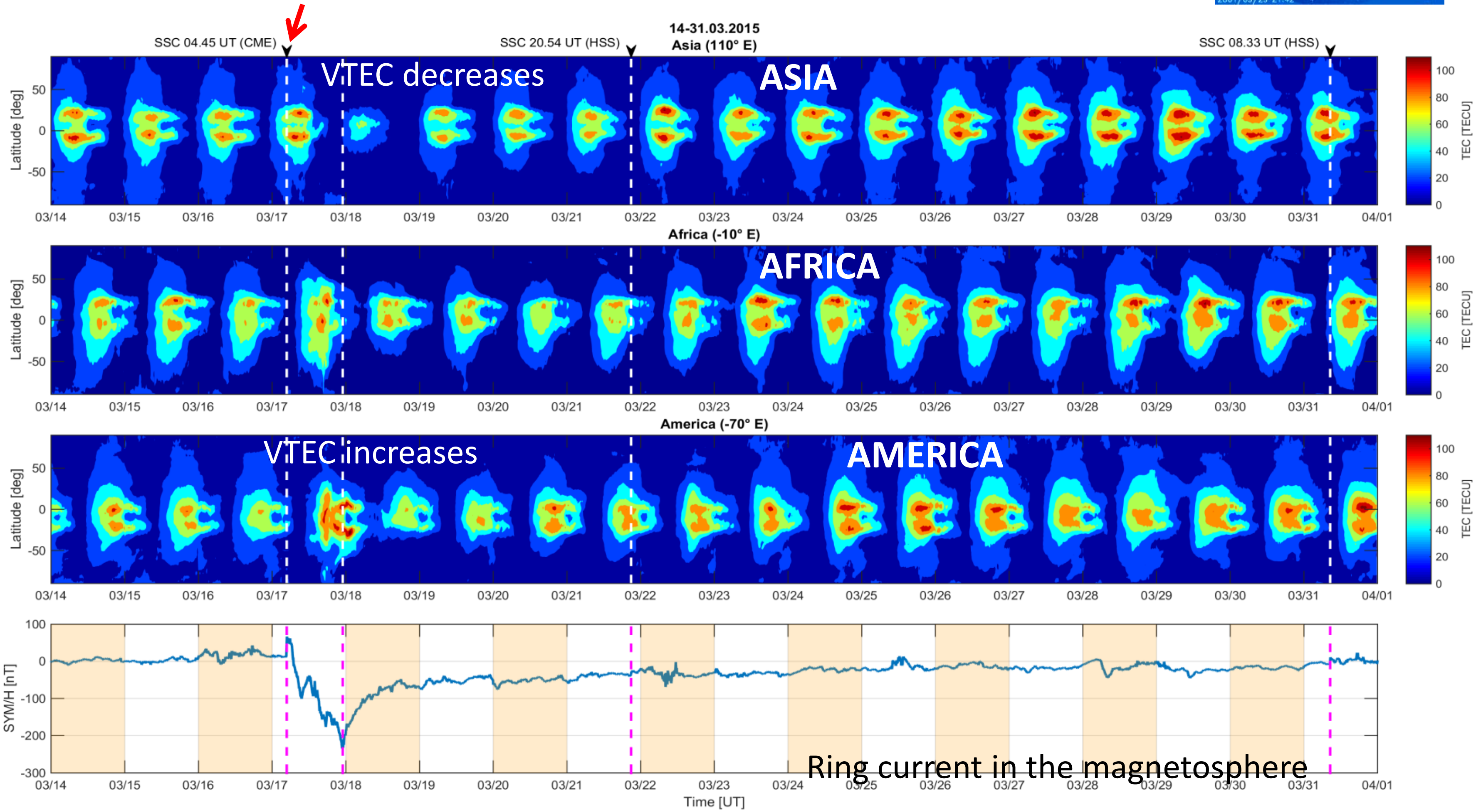
*ΔB : Disturbance of the Earth's magnetic field D_{dyn} due to a reversed electrojet

MAGNETIC STORM of St PATRICK's DAY : MAPS of VTEC

Variations near the magnetic Equator due to a CME (~200 GPS stations)

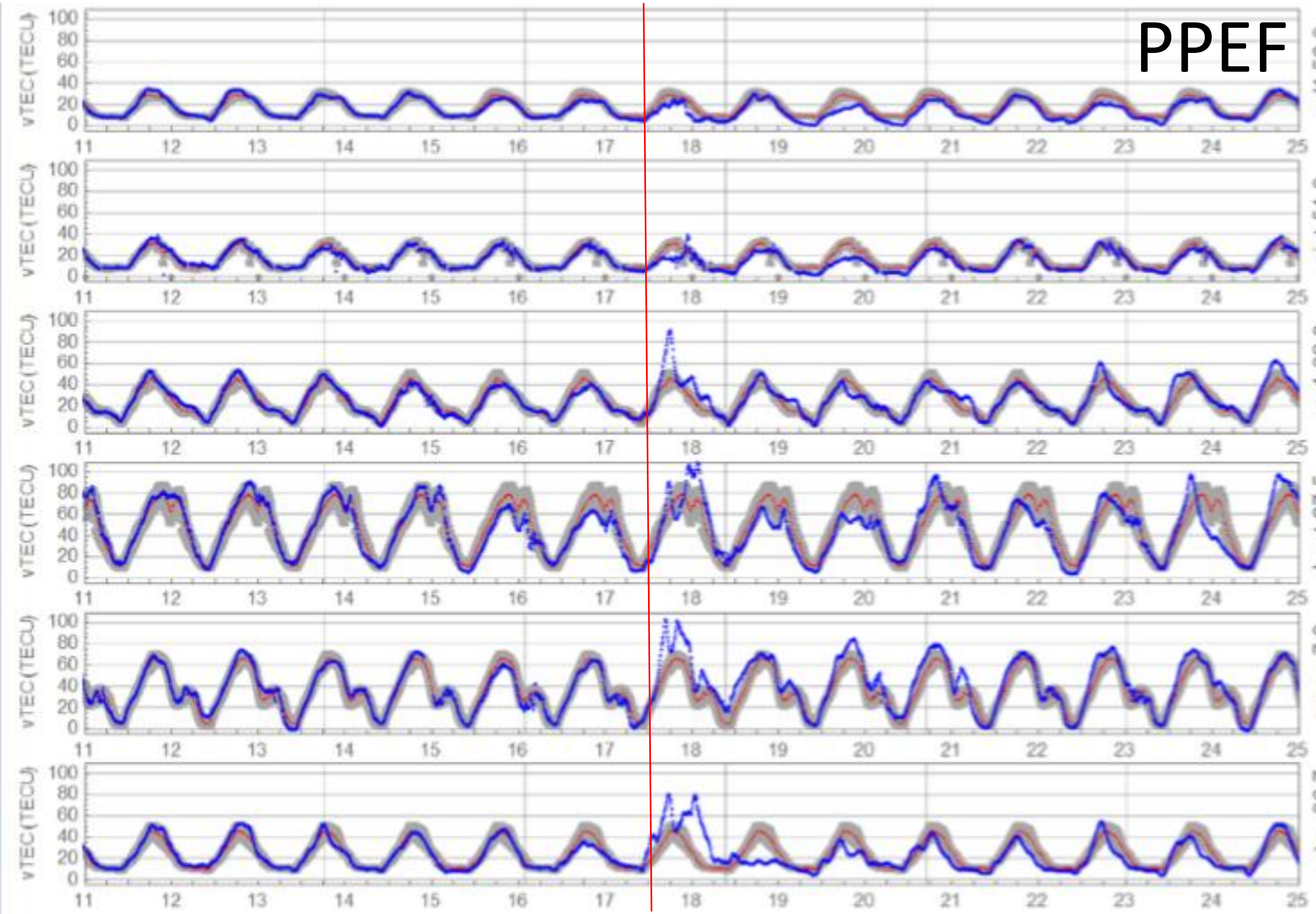


Impact of a CME (solar event, SSC on March 17 ~ 04.45UT)



Nava,, et al., "Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

VTEC in the AMERICAN SECTOR DURING MARCH 2015



"Middle and low latitude ionosphere response to 2015 St. Patrick's Day geomagnetic storm", Nava, B., J. Rodríguez-Zuluaga, K. Alazo-Cuartas, A. Kashcheyev, Y. Migoya-Orué, S.M. Radicella, C. Amory-Mazaudier, R. Fleury, 2016, J. Geophys. Res. Space Physics,121, 3421–3438, doi:10.1002/ 2015JA022299.

LATITUDINAL CHAIN OF GPS IN EAST AFRICA

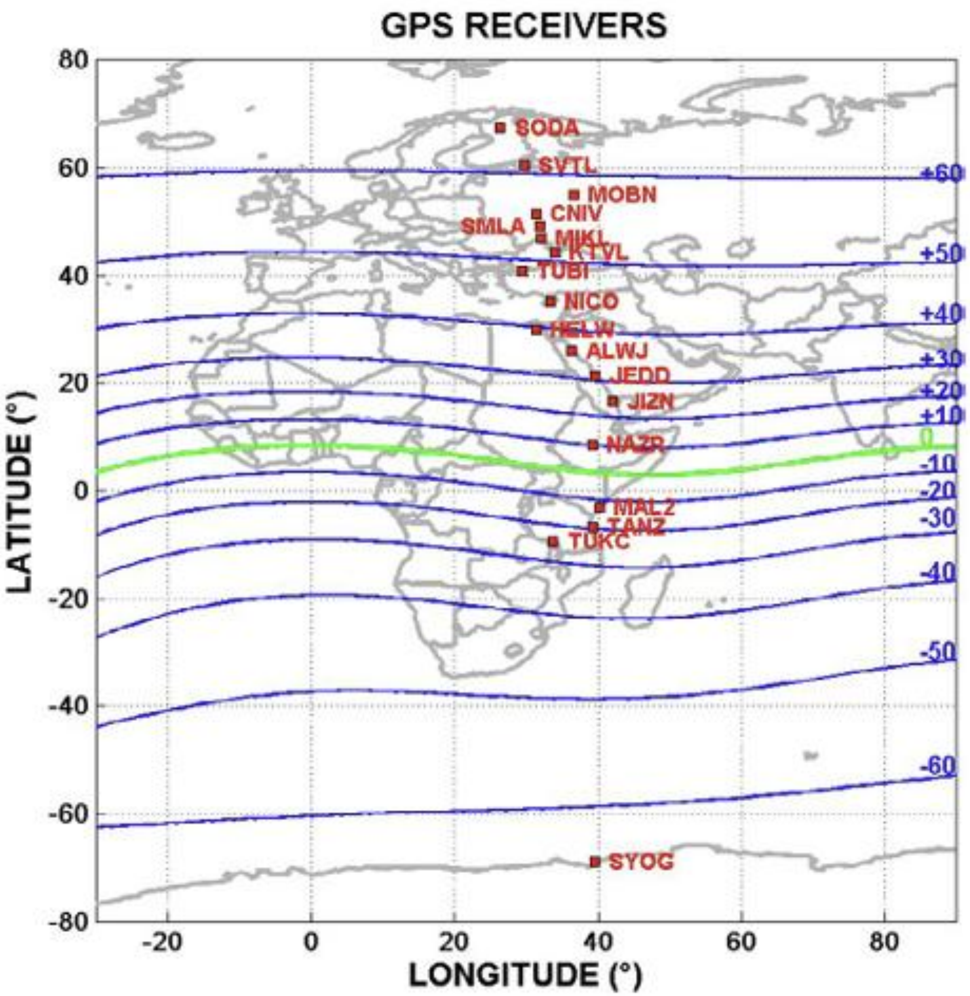


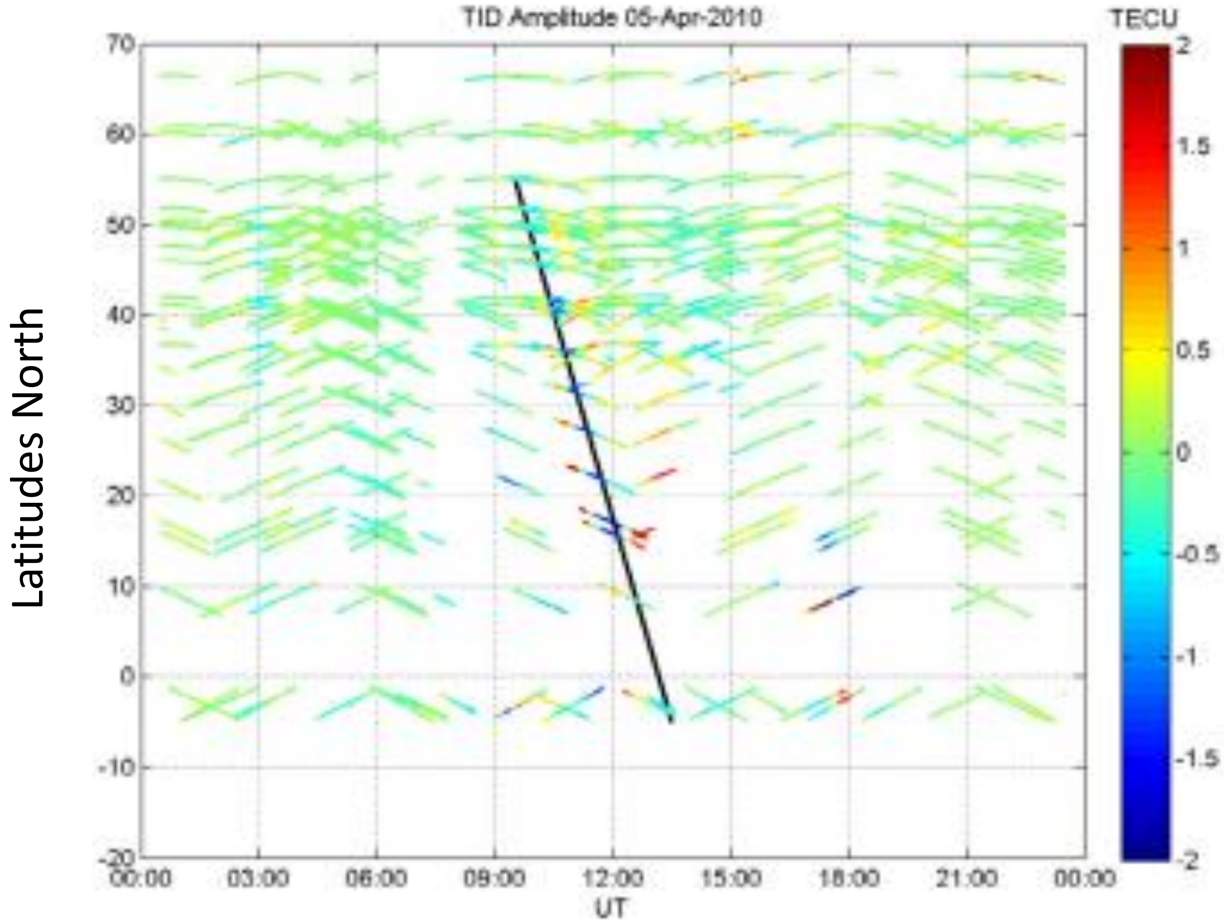
Table 1
Latitude and longitude station chain.

	Longitude (°)	Latitude (°)	D (°)	I (°)
SODA	26.39	67.42	10.528	77.281
SVTL	29.781	60.533	9.586	73.767
MOBN	36.57	55.115	9.569	70.775
CNIV	31.31	51.52	7.146	67.975
POLV	34.54	49.6	7.247	66.696
SMLA	31.87	49.2	6.651	66.223
MIKL	31.97	46.97	6.14	64.384
EVPA	33.16	45.22	5.934	62.92
KTVL	33.97	44.39	5.863	62.214
TUBI	29.451	40.787	4.699	58.251
ANKR	32.76	39.89	4.917	57.567
NICO	33.37	35.17	4.33	51.978
ALX2	29.9109	31.197	3.726	45.899
RAMO	34.7631	30.5978	3.907	45.703
HELW	31.33	29.85	3.708	44.006
ALWJ	36.37	26	3.516	38.4
JEDD	39.63	21.36	2.996	30.304
NAMA	42.04	19.21	2.581	26.401
JIZN	42.1	16.69	2.336	20.974
ASMA	38.91	15.33	2.551	17.1
NAZR	39.29	8.57	1.809	0.857
MAL2	40.194	−2.996	−0.828	−26.89
TANZ	39.2	−6.76	−2.13	−35.25
TUKC	33.75	−9.33	−2.271	−42.22
SYOG	39.584	−69.007	−49.649	−63.57

http://www.geomag.nrcan.gc.ca/calc/mfcal-eng.php.

Shimeis A. , C.Borries, C. Amory-Mazaudier, R.Fleury,A.M. Mahrous,A. F.Hassan, TEC Variations along an East Euro-African Chain during 5th April 2010 Geomagnetic Storm, in Advances in Space Research,Volume 55, Issue 9, pp 2239-2247, 2015.

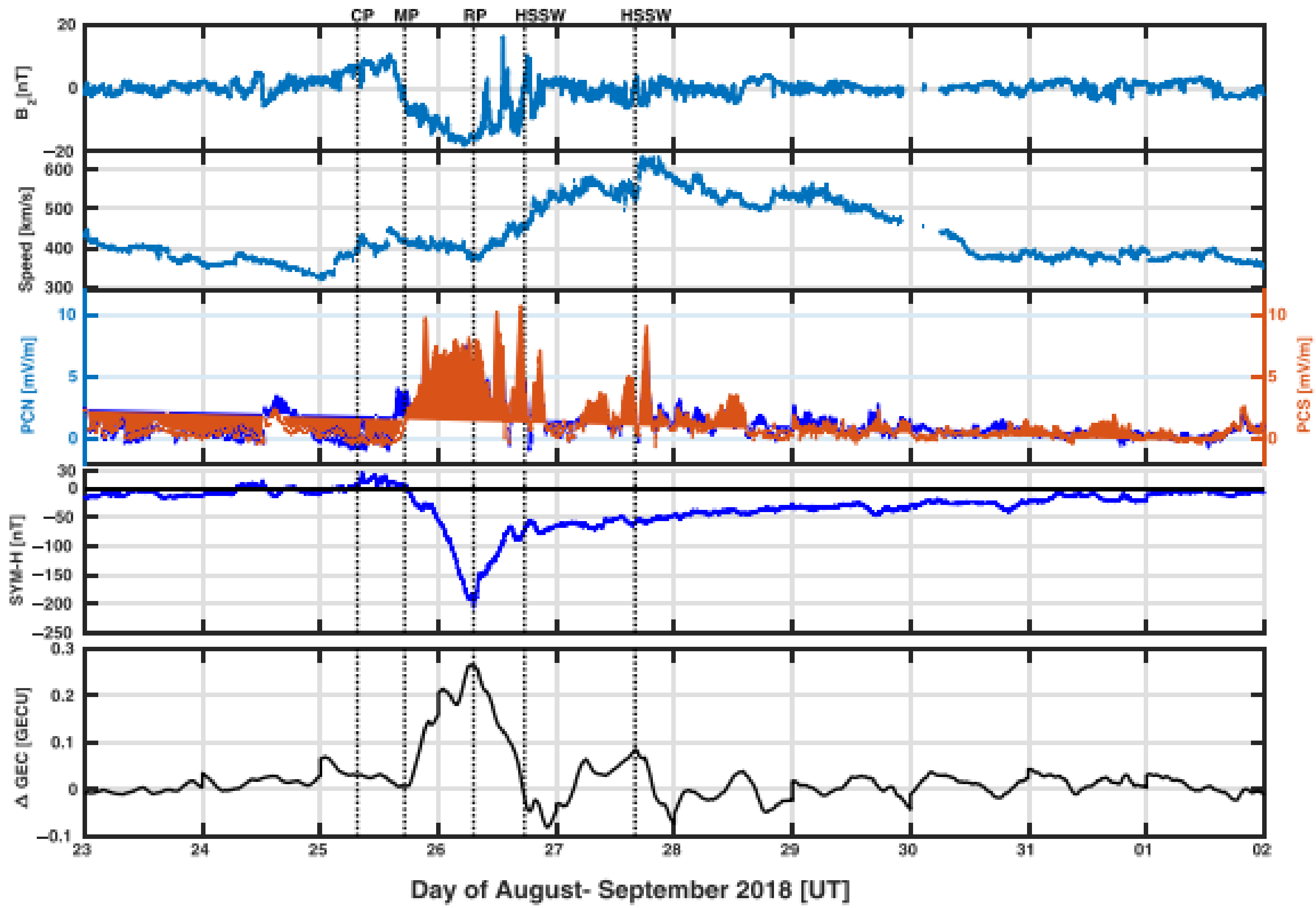
Latitudinal variation of vTEC of Euro-African Chain of GPS stations during the geomagnetic storm . The solid black line represents the traveling ionospheric disturbance



The slope of the black line gives the speed of the TID : 500m/s

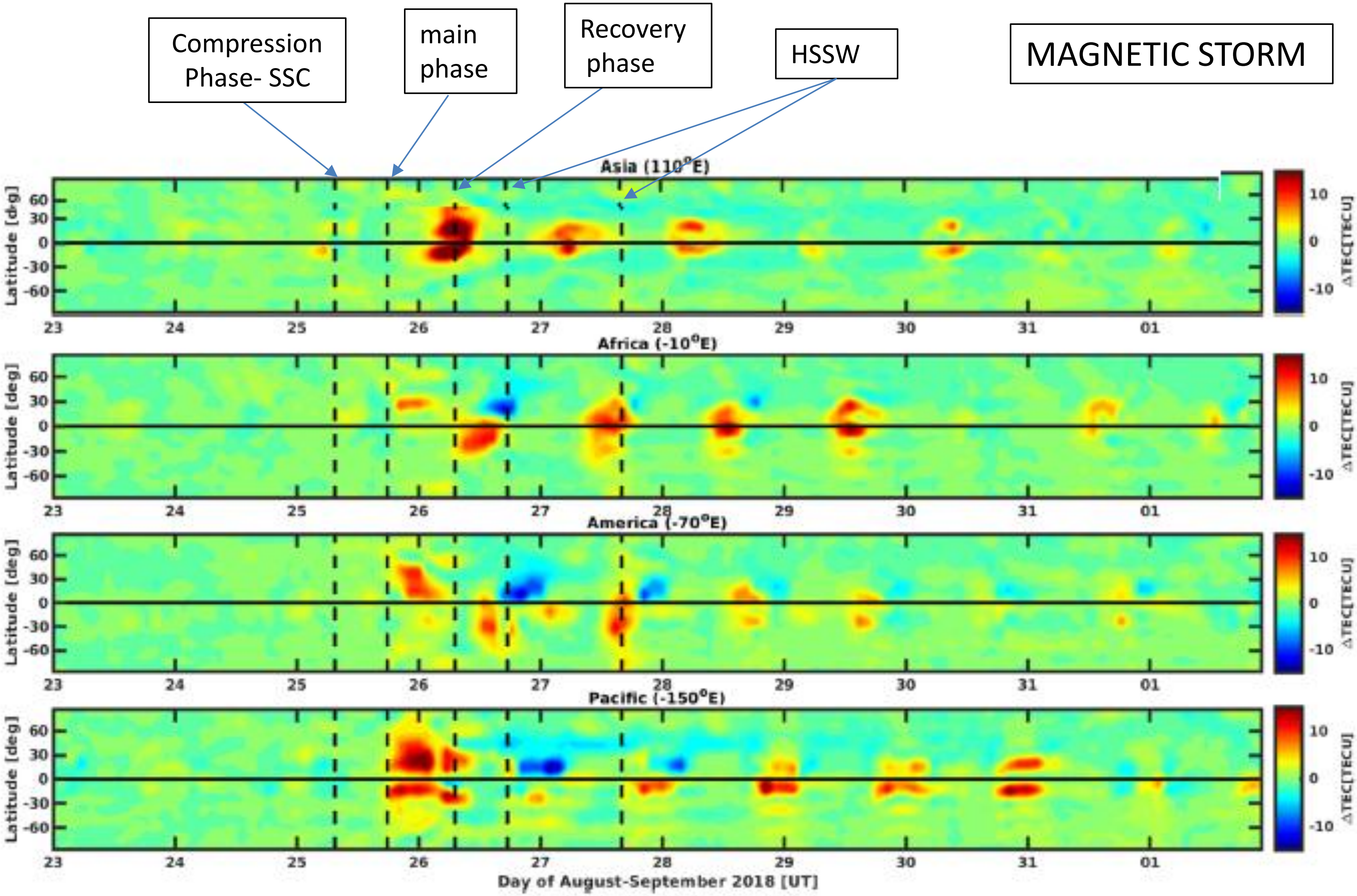
Shimeis A. et al., Advances in Space Research,Volume 55, Issue 9, pp 2239-2247, 2015.

Global parameters, from 23 August to 1 September: (from top to bottom) the Bz component of IMF in nanotesla, the solar wind speed in km/s, the SYM-H index in nanotesla, polar cap indices in mV/m, and GEC in GECU **[PAKISTAN]**



Younas, W. C., C. Amory-Mazaudier, M. Khan, R. Fleury, Ionospheric and Magnetic signatures of a Space Weather event on 25-29 August 2018 : CME and HSSSWs, , Journal of Geophysical Research: Space Physics, 125, e2020JA027981.
https://doi.org/10.1029/2020JA027981

MAGNETIC STORM



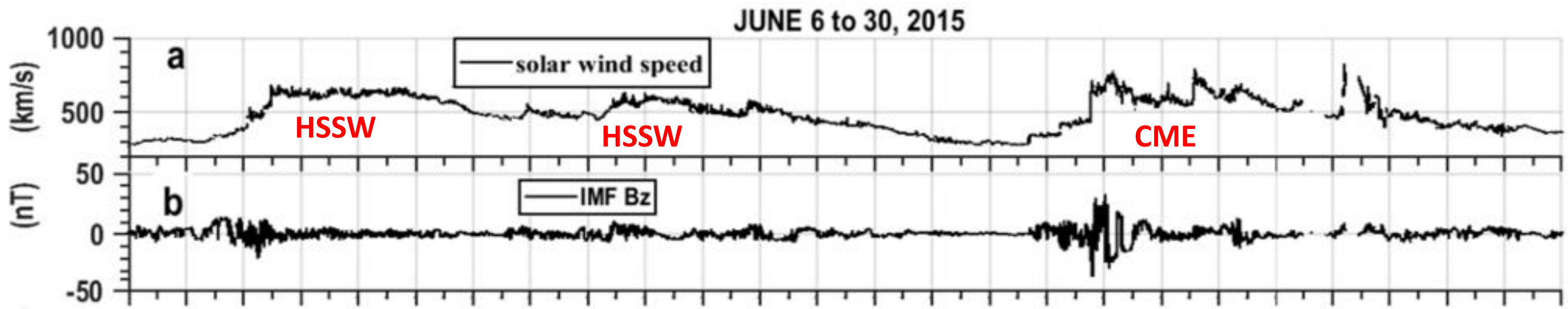
VTEC is influenced by PPEF, DDEF and Thermal expansion of atmosphere

Younas,W et al., Journal of Geophysical Research, Space Physics, 125, e2020JA027981. https://doi.org/10.1029/2020JA027981

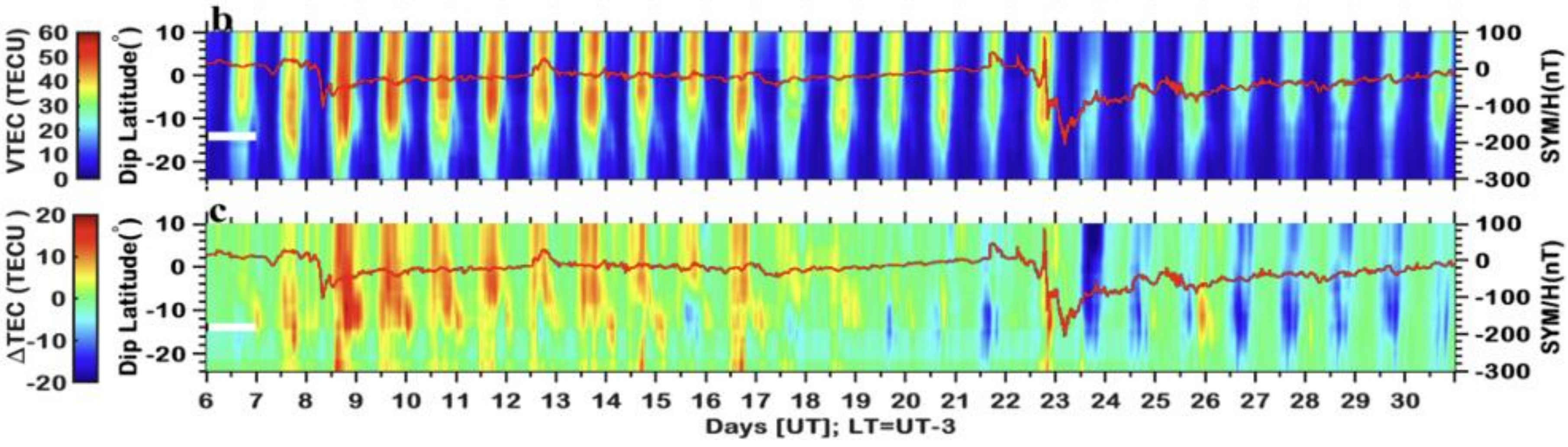
BRAZIL

JUNE 2015

Solar wind speed and Bz component of the IMF



vTEC and ΔvTEC



Oladayo O. Afolabi, C. M. N. Candido, F. Becker-Guedes and C. Amory-Mazaudier, Study and Modelling of the Impact of June 2015 Geomagnetic Storms on the Brazilian Ionosphere, Atmosphere 2024, 15, 597. https:// doi.org/10.3390/atmos15050597

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AT EQUATOR : scintillations a regular phenomenon

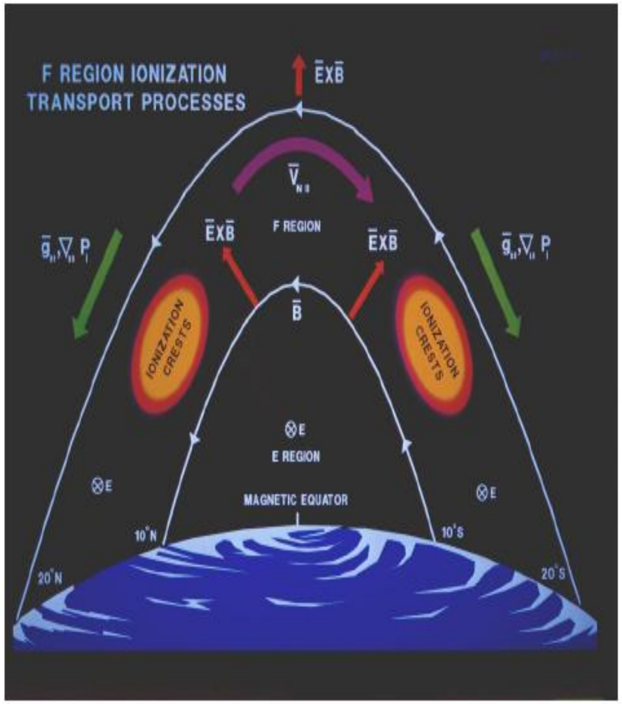
Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere **: Plasma Instabilities**

S_4 and ROTI indices derived from GNSS data

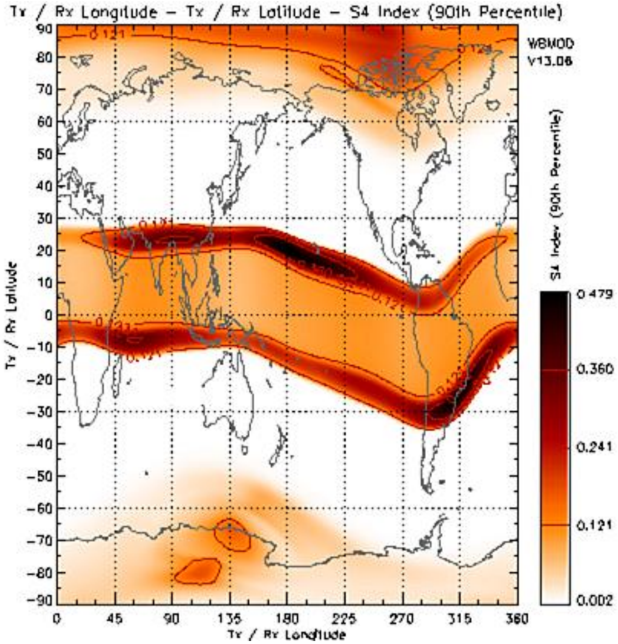
$$S_4 = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

I : intensity of the signal

$$\mathrm{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

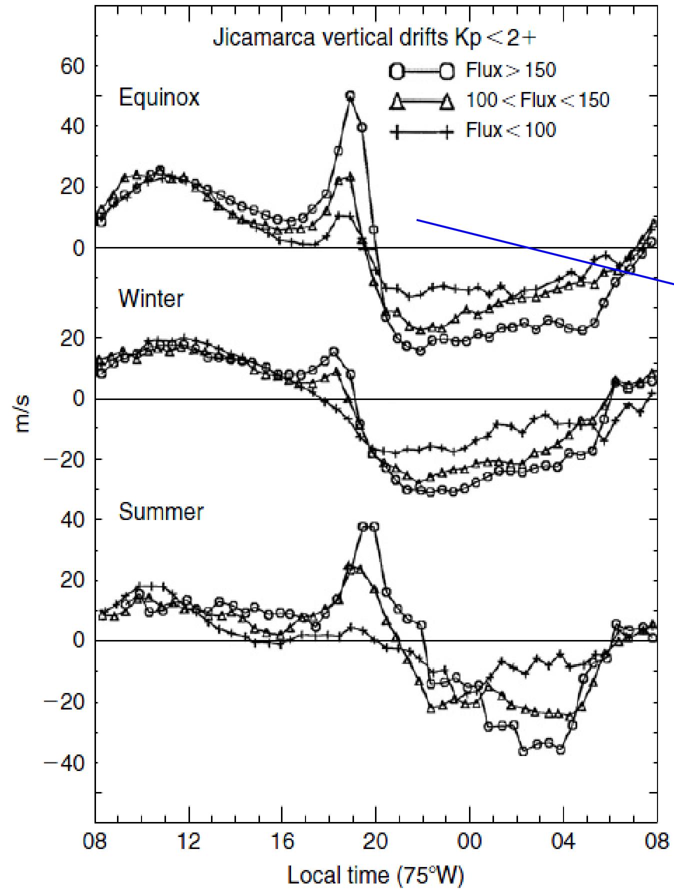


Equatorial Fountain

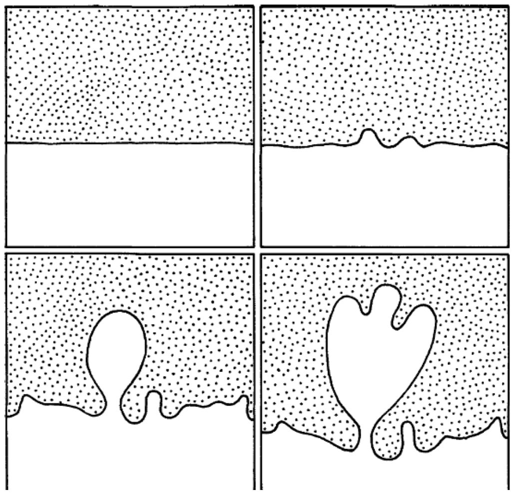


Scintillation index at GPS L1 (1575.42 MHz)
assuming constant local time 23.00 at all longitudes
(from http://www.sws.bom.gov.au)

PRE : Pre Reversal Enhancement



Equatorial Plasma Bubbles

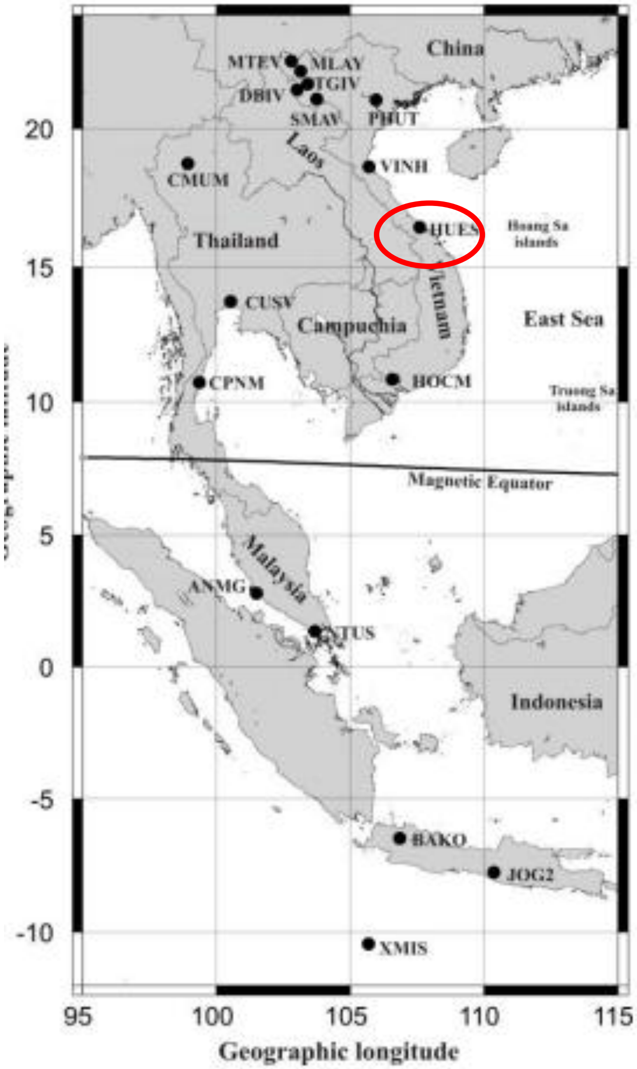


Sequential diagram, from photos, of the development of a Rayleigh Taylor instability. The heaviest fluid [... ..], over a lighter and more transparent fluid Kelley, M.C., (1989), the Earth Ionosphere, ed. Academic Press, San Diego.

Average vertical plasma velocities at Jicamarca during the equinox (March-April, September-October), summer (May-August), winter (November-February) for 3 solar flux values Fejer, et al., Average vertical and zonal F region drifts over Jicamarca, Journal of Geophys. Res, Vol. 96, N° A8, page 13901-13906, 1991

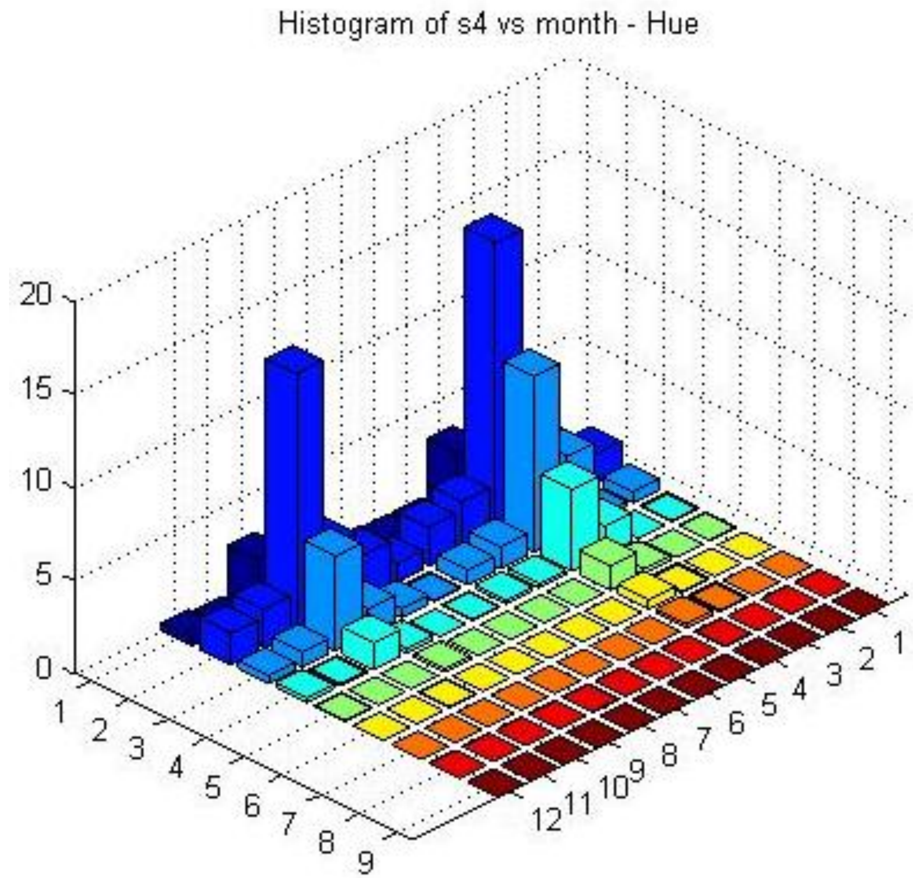
Archana Bhattacharyya, [Equatorial Plasma Bubbles: A Review](https://doi.org/10.3390/atmos13101637) *Atmosphere* 2022, *13*(10),1637, https://doi.org/10.3390/atmos13101637

Scintillation index S4 observed at Hue (Vietnam) from 2006 to 2008 -> fluctuations of the GPS power signal



Distribution of GPS receivers in Vietnam
And adjacent region

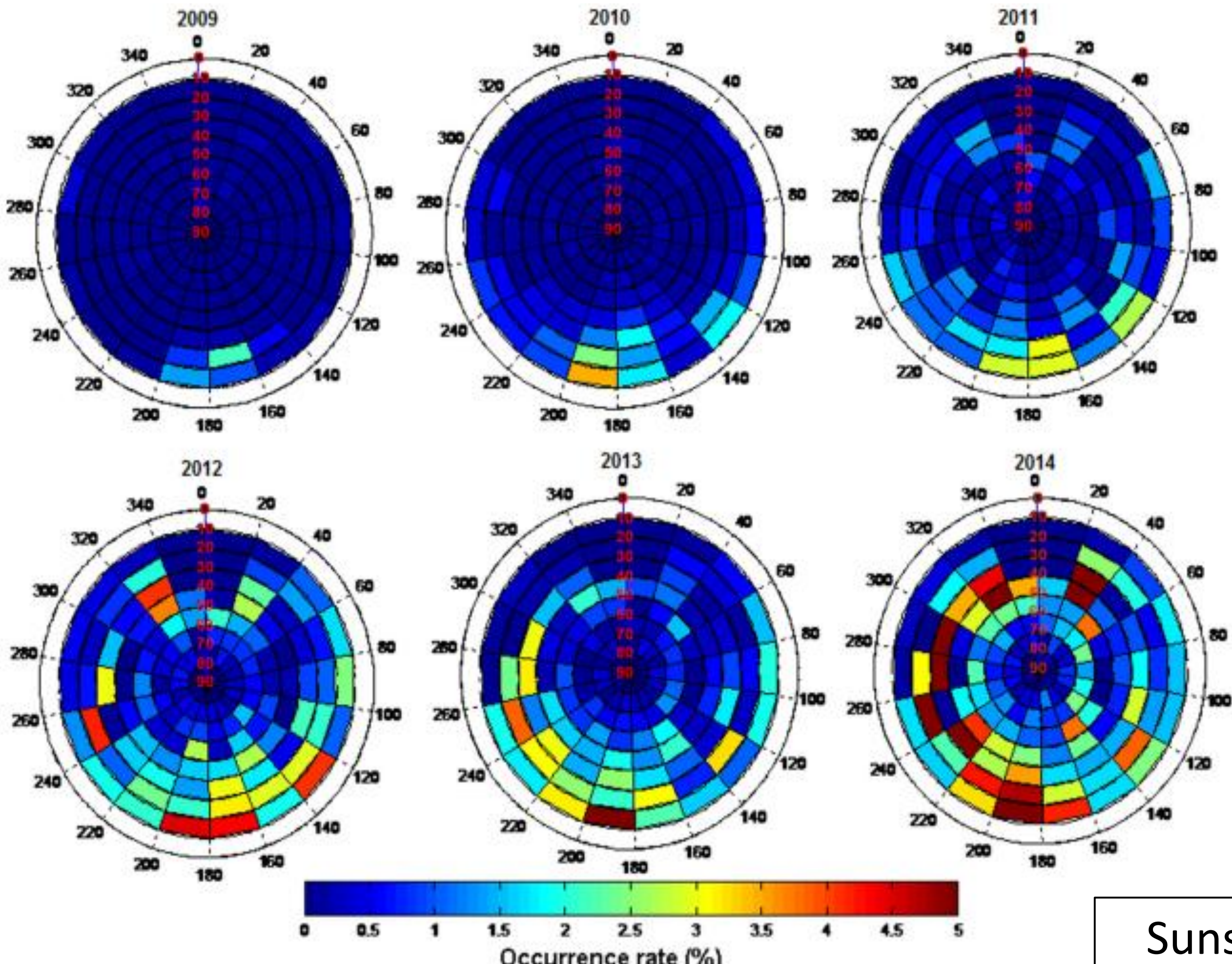
$$I = \frac{A^2}{2} \qquad s4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}$$

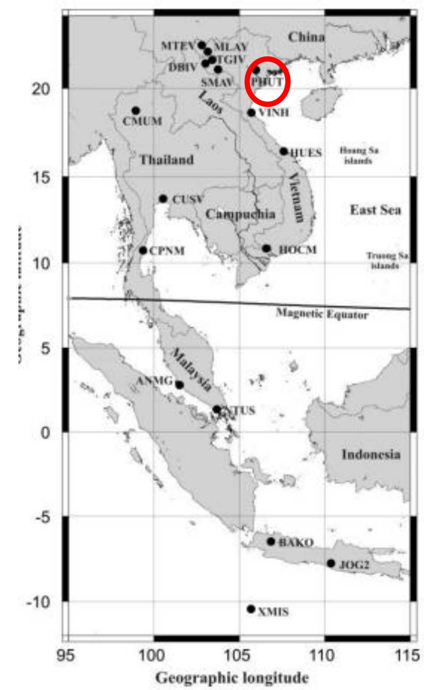


Seasonal variations: equinox maximum

The directional distribution of scintillations observed from PHUT station during 2009–2014.

VIETNAM





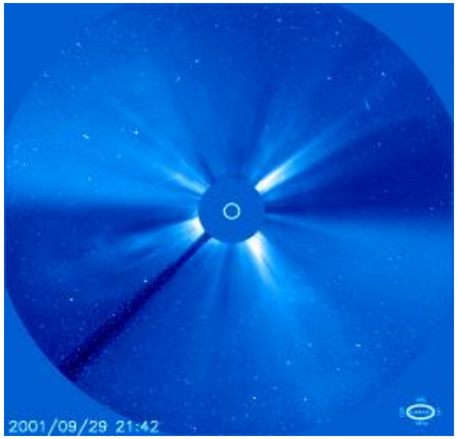
Sunspot cycle Maximum
2012,2013,2014

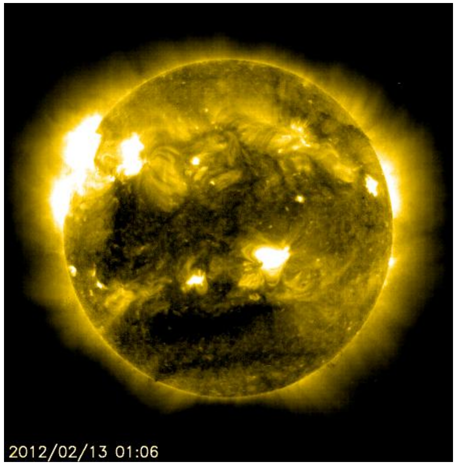
Tran Thi L., M. Le Huy et al.,Climatology of ionospheric scintillation over the Vietnam low-latitude region for the period 2006-2014, Advances in Space Res. http://dx.doi.org/10.1016/j.asr.2017.05.005.

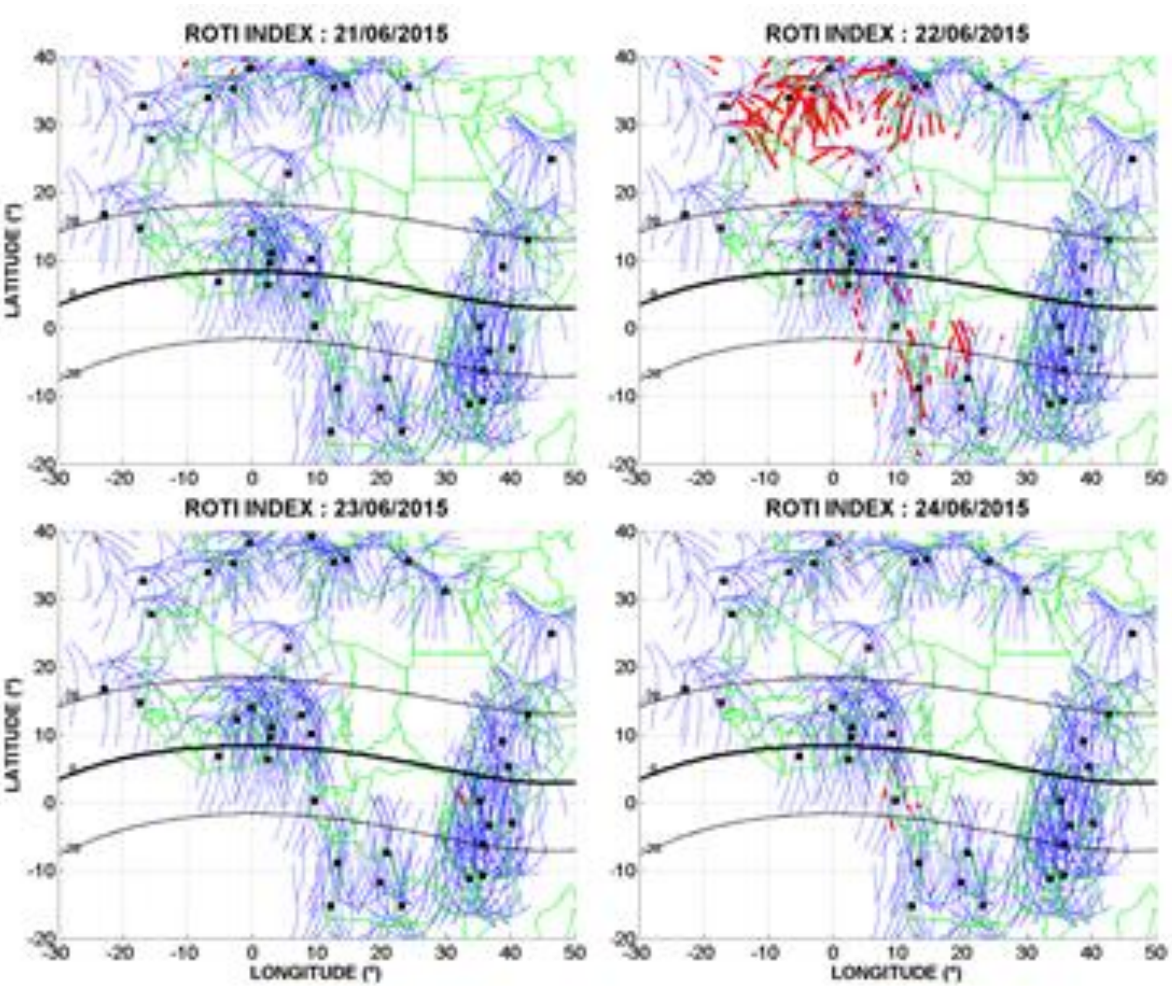
SUN EARTH CONNECTIONS

some solar perturbations inhibit or increase the irregularities and as consequence the scintillations

Effect of CME (and Magnetic cloud)
or Coronal Hole (High Speed Solar Wind HSSW)
2 cases of CME + HSSW (March and June 2015)







Storm June 22, 2015 solstice

$$rot = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

Dst < -200 nT

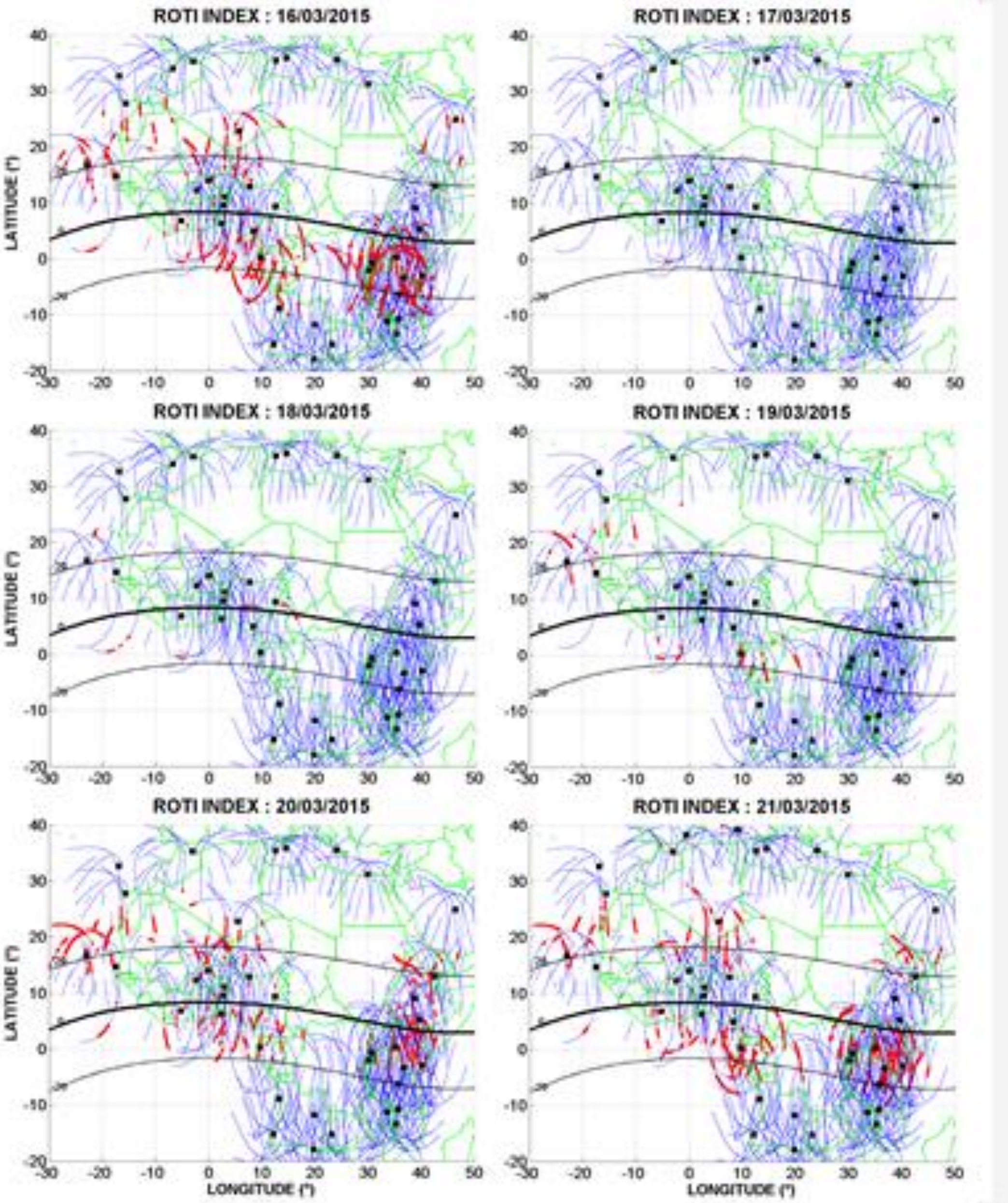
Storm started at 18.33 UT

Increase of scintillations at the beginning of the storm

<u>Short duration</u>

It is the effect of the penetration of the magnetospheric electric field (PPEF), just at the time of the Pre reversal enhancement of the Eastward ionospheric electric field

Kashcheyev et al., ' "Multi-variable comprehensive analysis of two great geomagnetic storms of 2015", Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/ 2017JA024900



Storm March 17, 2015
equinox

$$\mathrm{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

Dst < -200 nT
Storm started at 04.45 UT

Inhibition of scintillations over the whole Earth during several days due to the disturbance dynamo (DDEF) effect
<u>long duration</u>

Kashcheyev et al., ‘ “Multi-variable comprehensive analysis of two great geomagnetic storms of 2015", Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/ 2017JA024900

Disturbed magnetic field

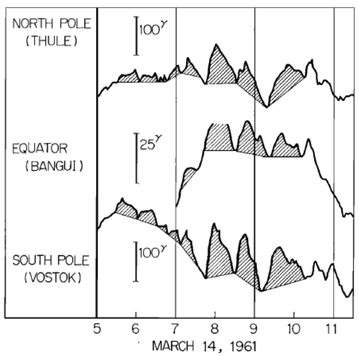


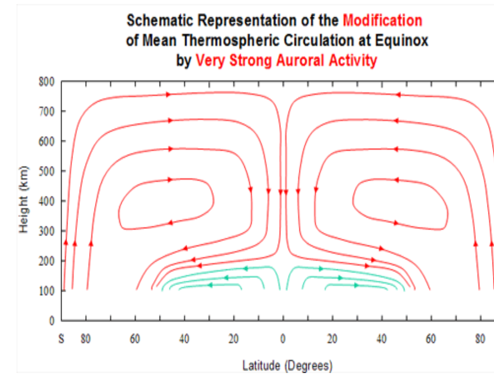
Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

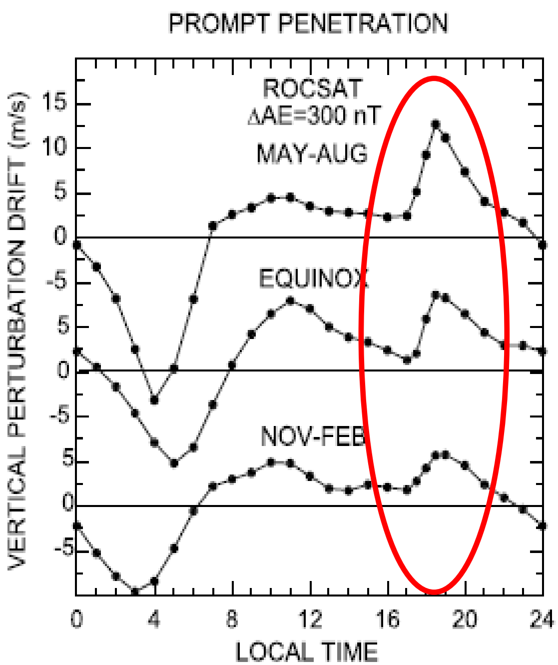
Model of Fejer et al.,(2008)

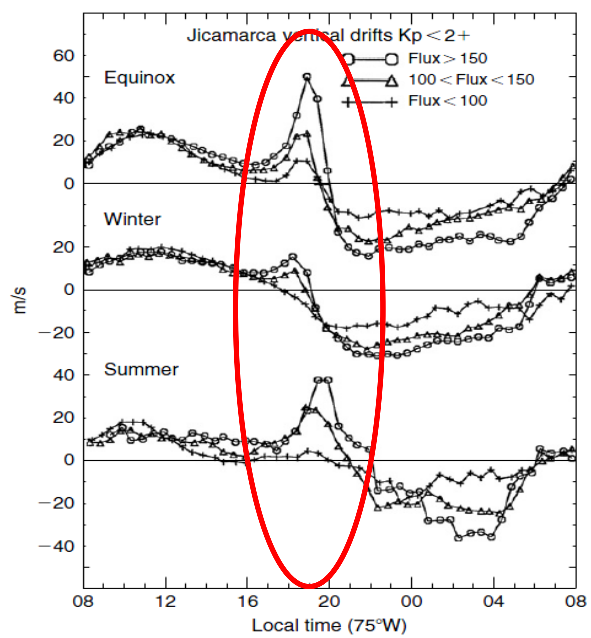
Geophysical Research Letters, 35, L20106.
https://doi.org/10.1029/2008GL035584

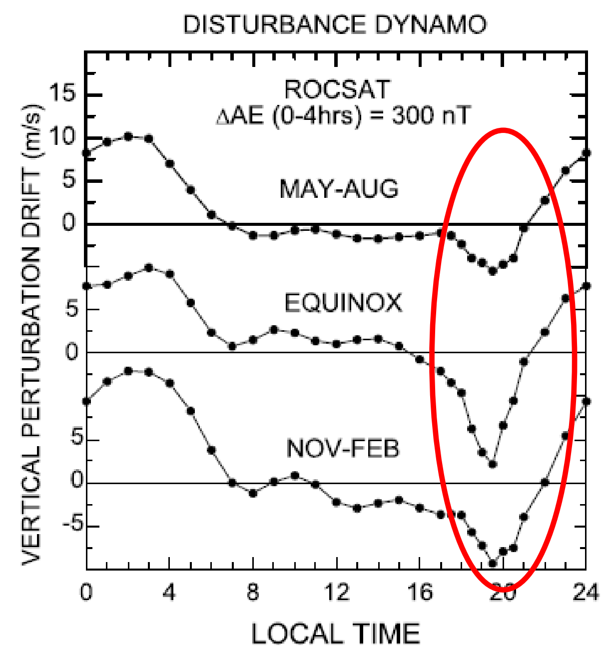
PPEF is an eastward Ey, increases the PRE
DDEF is a westward Ey, decreases the PRE
Eastward electric field => moves up
Westward electric field => moves down

Disturbed thermospheric wind









PPEF : Increase of PRE

Quiet day

DDEF: Inhibition of PRE

CONCLUSION-2

The use of the GNSS technique has allowed the development of studies on the ionosphere in countries where the ionosphere was not studied for lack of scientific tools.

These studies carried out within the framework of the IHY 2007-2009) and ISWI (2010-2012) projects integrating a systemic approach of the Sun-Earth system have enabled the emergence of pioneers in the discipline of Space Weather in many countries.

These students had new data that led them to publish in the best journals, to have a position in their country and to be recognized internationally.

The strength of the GNSS technique is that it works continuously and it can capture all the variations of ionospheric ionization due to different physical phenomena and therefore study their impacts on ionosphere (geomagnetic storm, solar flare, eclipse, earthquake, stratospheric warming, quasi biennal oscillation, hurricane, etc…)