Signatures of Space Weather events in low latitudes ionosphere quiet and disturbed magnetic periods

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African Capacity building workshop on space weather effects on GNSS, Trieste 3 -14 October 2022

Outline

- Introduction
- Characteristics of the low latitudes

Equatorial Fountain,Pre Reversal Enhancement, Equatorial electrojet

- Plasma irregularities

ROTI-S4

- Variations of ionospheric parameters due to solar electromagnetic emissions

Total electron content TEC, Earth's magnetic field varaitions

- Electrodynamic coupling between high and low latitudes

TEC, ROTI, Earth's magnetic field varaitions

- Conclusion

IMPACT on Technologies

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)

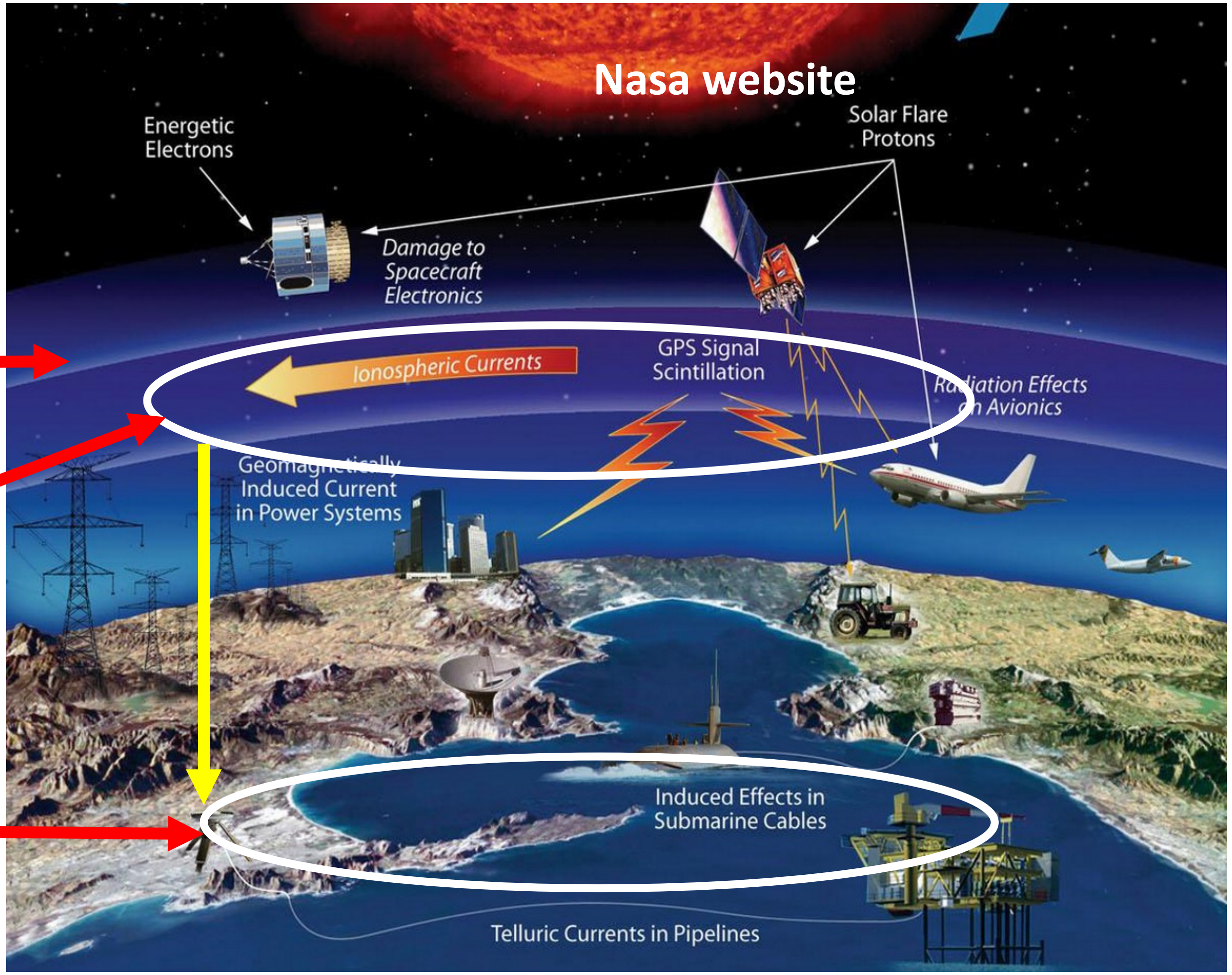
Regular and irregular variations

1 Ionization

Propagation of electromagnetic waves

2) Ionospheric electric current

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



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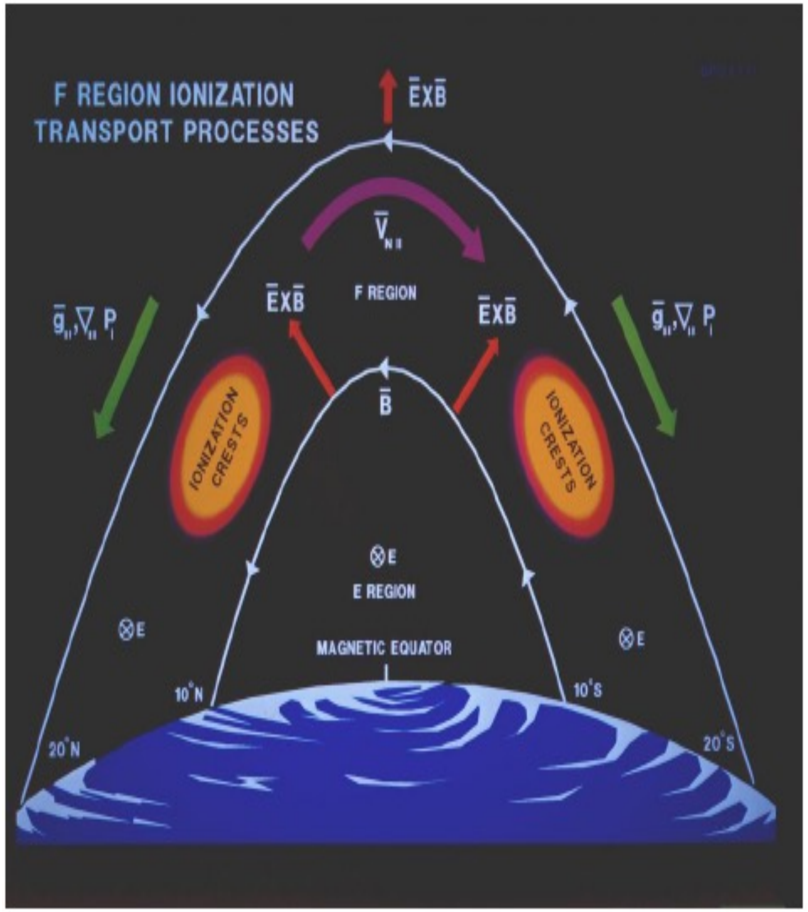
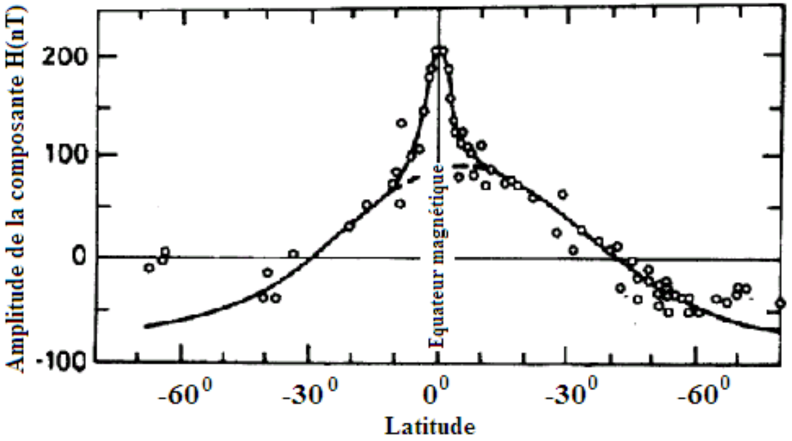
PHYSICS of Low latitudes



Equatorial Fountain

Eastward electric field => moves up
Westward electric field => moves down

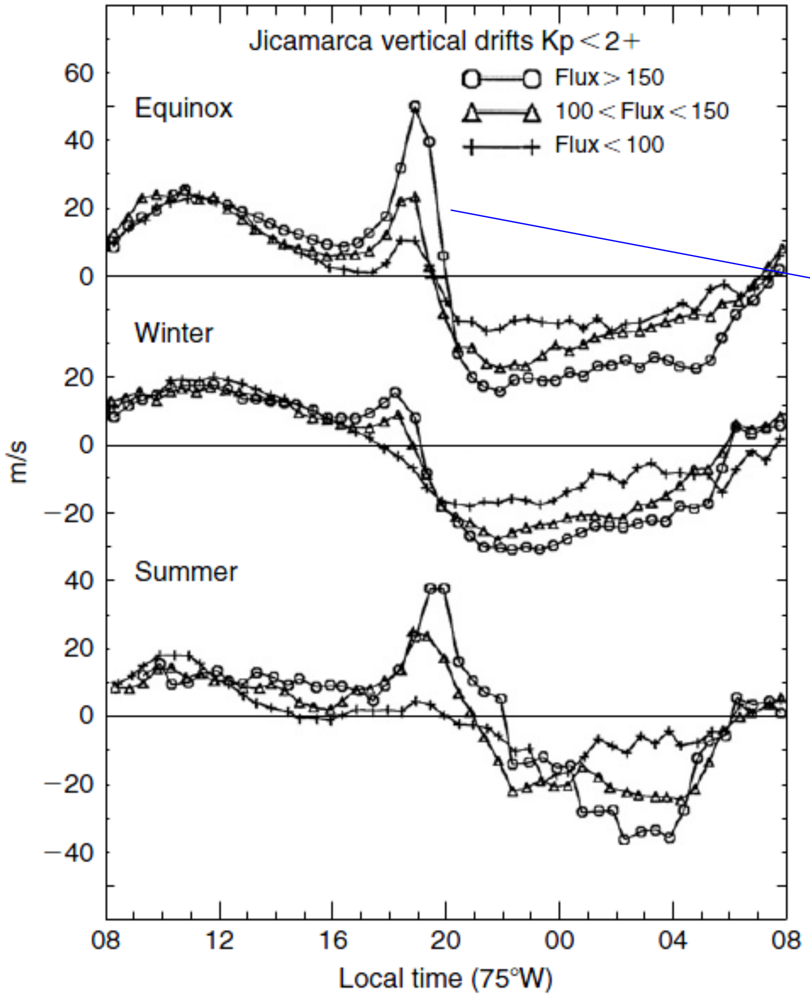
At equator the Earth's magnetic field is horizontal
During the daytime the east–west electric field and the north–south geomagnetic field produce the lift of plasma in E ionospheric region by **vertical E X B drift**. At higher altitudes in F region, the plasma diffuses downward along the geomagnetic field lines into both hemispheres under the influence of gravity and pressure gradients, this produces the EIA which is characterized by an electron density trough at the magnetic equator, and two crests of enhanced electron density at about ±15° magnetic latitude

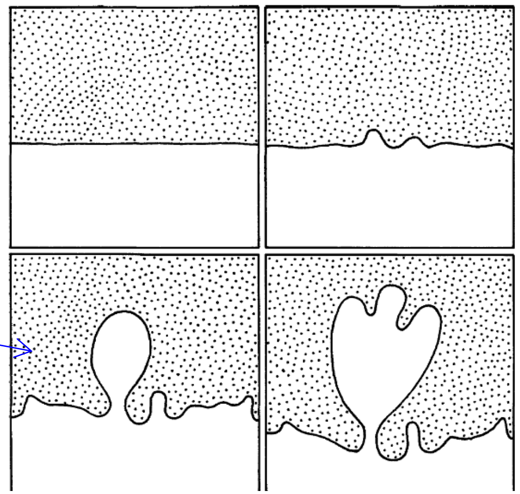


The Equatorial Electrojet (Jacobs, 1990)

PRE : Pre Reversal Enhancement

Equatorial Plasma Bubbles





Magnetic quiet time

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.

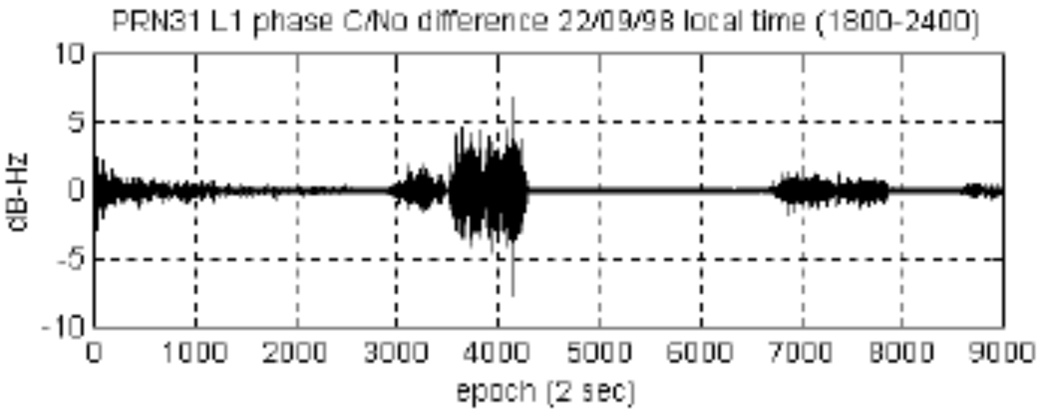
Average vertical plasma velocities at Jicamarca during the equinox (March-April, September-October), winter (May-August), summer (November-February) for 3 solar flux values
Fejer, et al., Average vertical and zonal F region drifts over Jicamarca, Journal of Geophys. Res, Vol. 96, N° A8, page 13901-13906,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

Ionospheric propagation

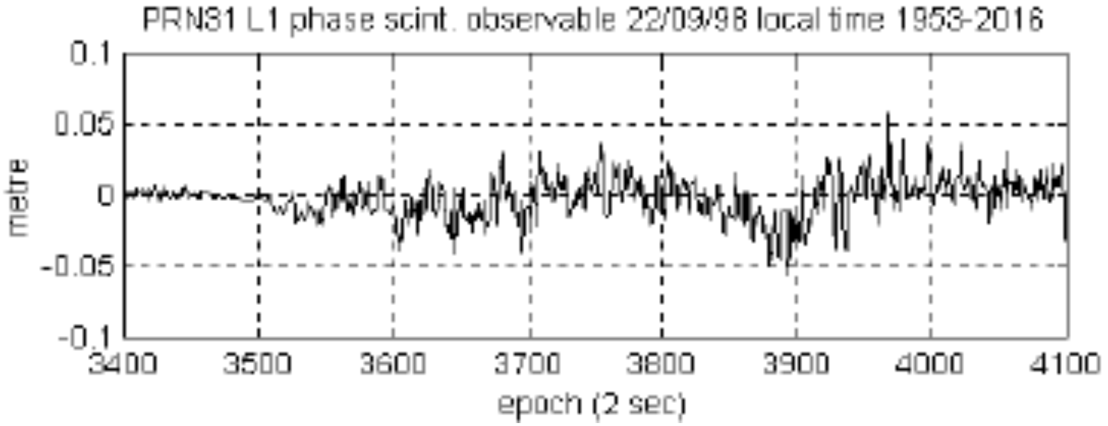
Scintillations

Fluctuations of the signal dues to the inhomogeneity of the medium as plasma bubbles

Scintillations of amplitude



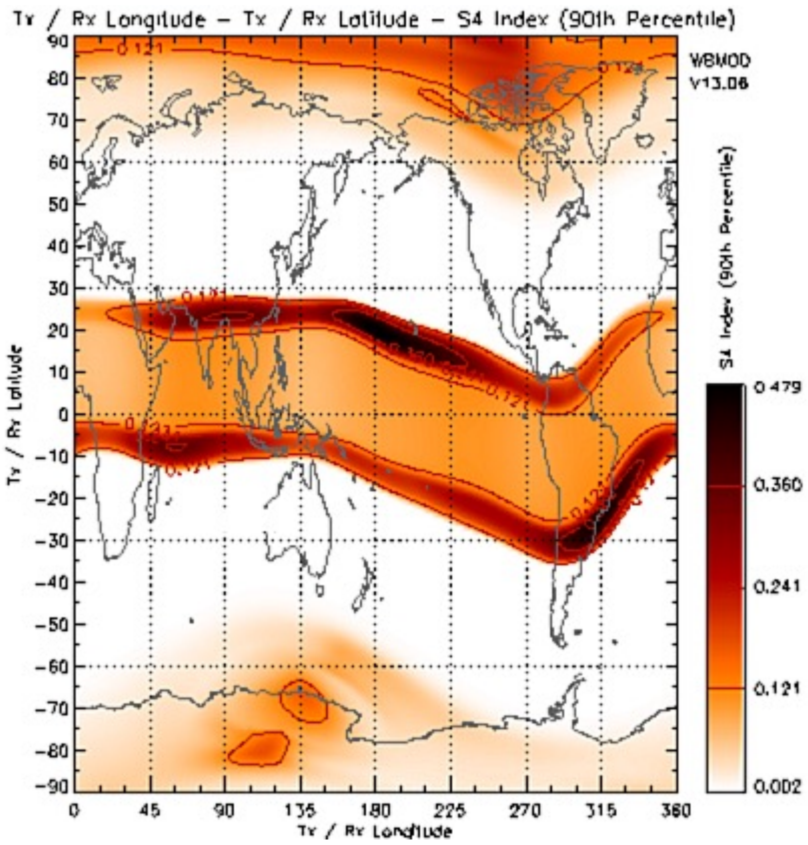
Scintillations of phase



scales : ± 3 rad.

Scintillations a regular phenomenon

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



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

Indice of scintillation $$s4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}$$

"Ionospheric scintillation is primarily an equatorial and high-latitude ionospheric phenomenon, although it can (and does) occur at lower intensity at all latitudes.
Ionospheric scintillation generally peaks in the sub-equatorial anomaly regions, located on average ~15° either side of the geomagnetic equator."

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PLASMA IRREGULARITIES

S4 -> fluctuations of the GPS power signal

$$I = \frac{A^2}{2}$$

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

ROTI Index

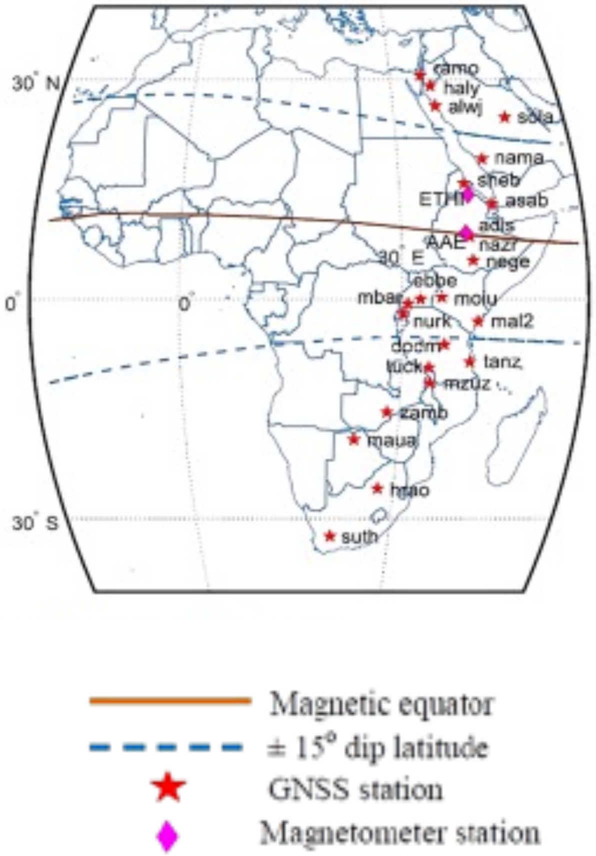
$$\mathbf{rot} = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

$$\mathbf{roti} = \sqrt{\langle \mathbf{rot}^2 \rangle - \langle \mathbf{rot} \rangle^2}$$

Training on daily global positioning system GPS data , Coordinates a monthly magazine on positioning, navigation and beyond, http://www.mycoordinates.org, **Volume XIII, Issue 03, March 2017** *(Amory-Mazaudier, Rolland Fleury, Sharafat Gadimova, Abderrahmane Touzani)*
Software of Rolland Fleury on www.girgea.org

Quiet-time ionospheric irregularities over the African Equatorial Ionization Anomaly (EIA) Region on April 9th 2013,

Amaechi et al., Radio Science, 55, e2020RS007077. https://doi.org/ 10.1029/2020RS007077



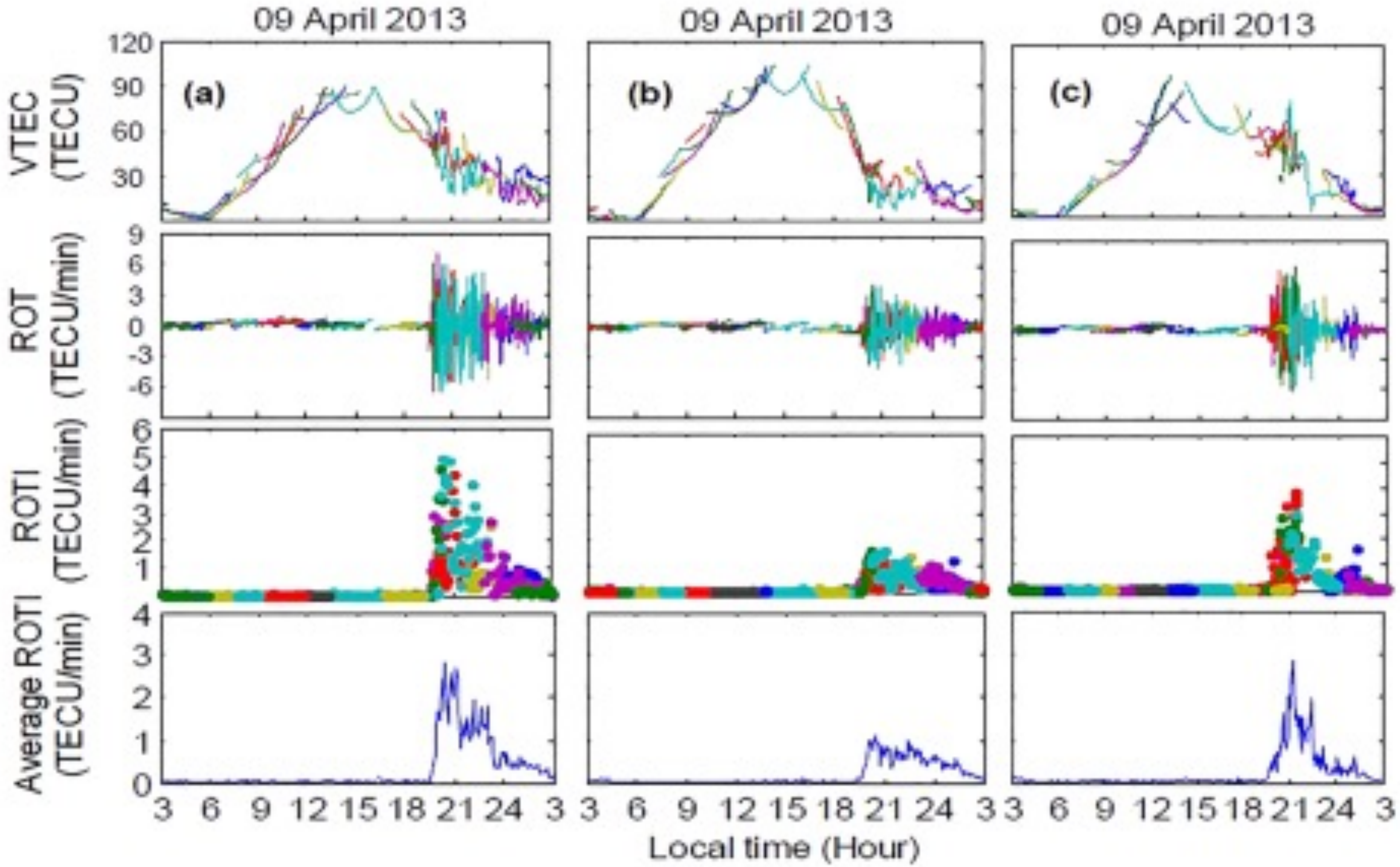


Figure 2. Typical example of ionospheric irregularities on 9th April 2013 over the (a) northern crest, (b) trough, and (c) southern crest. (first row) VTEC, (second row) ROT, (third row) ROTI, and (fourth row) average ROTI ($ROTI_{AVE}$).

Quiet-time ionospheric irregularities over the African Equatorial Ionization Anomaly (EIA) region : Monthly variation

Amaechi et al., Radio Science, 55, e2020RS007077. https://doi.org/ 10.1029/2020RS007077

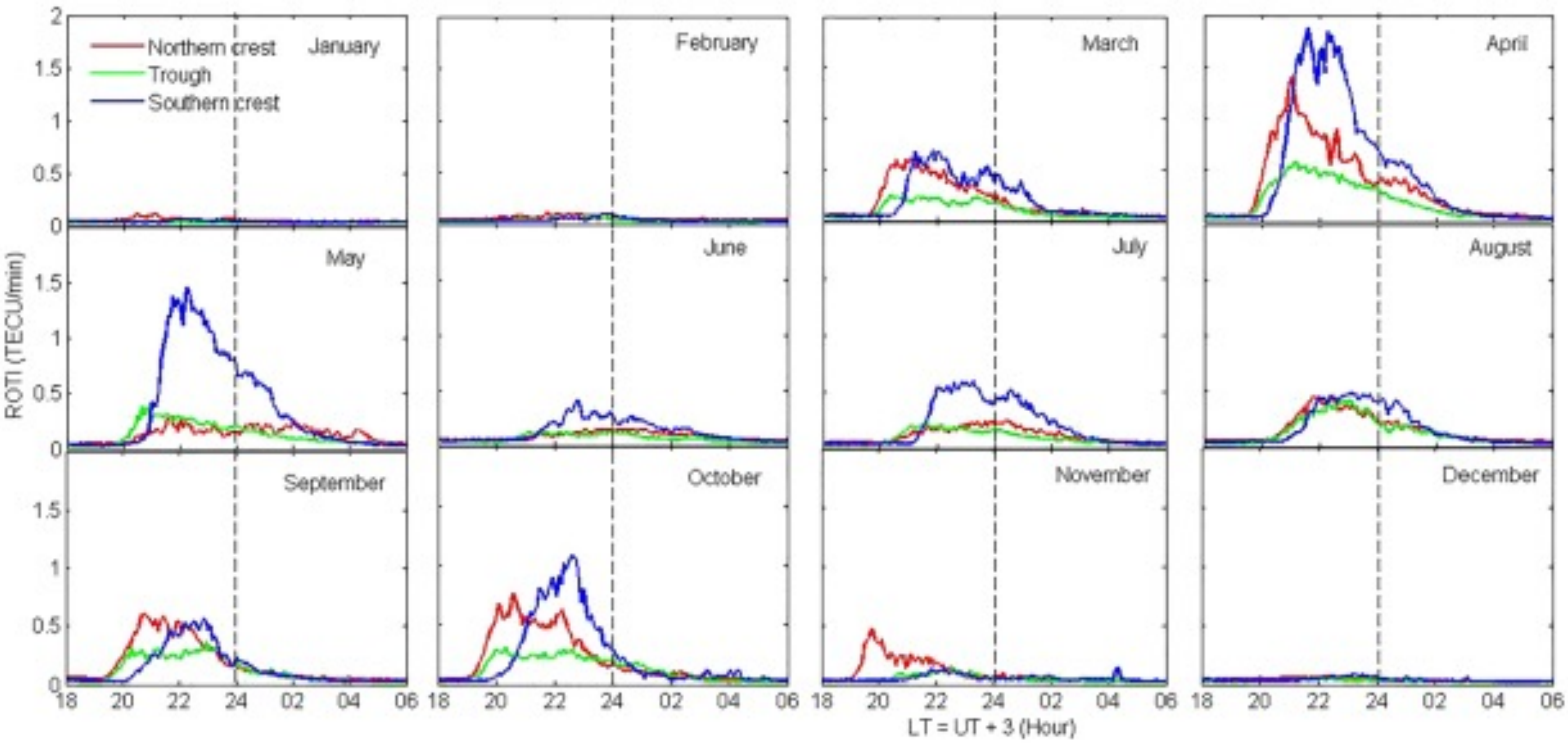
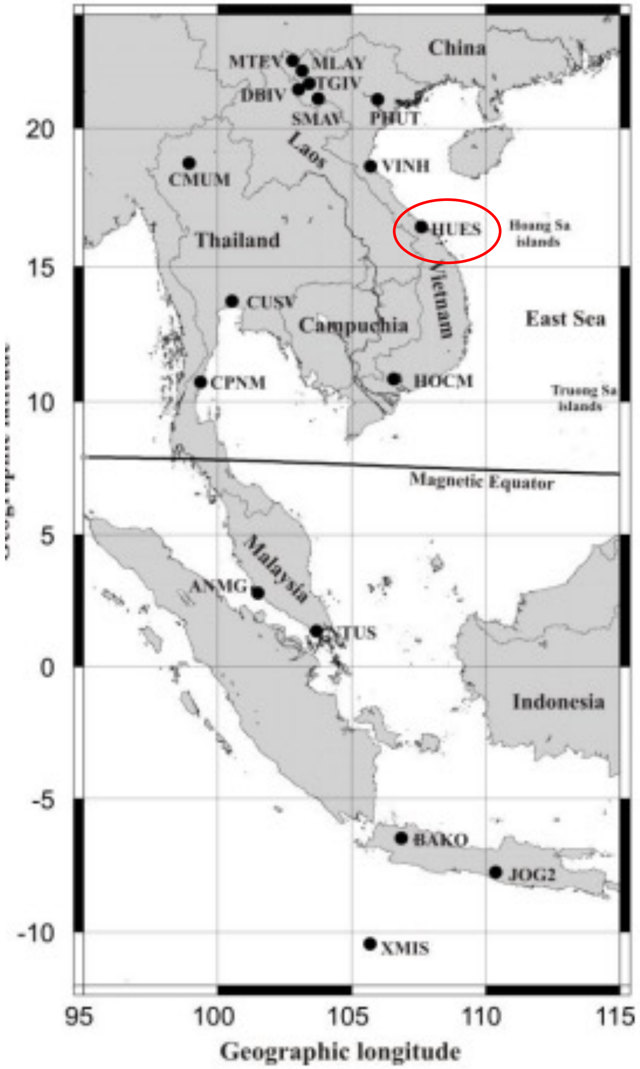


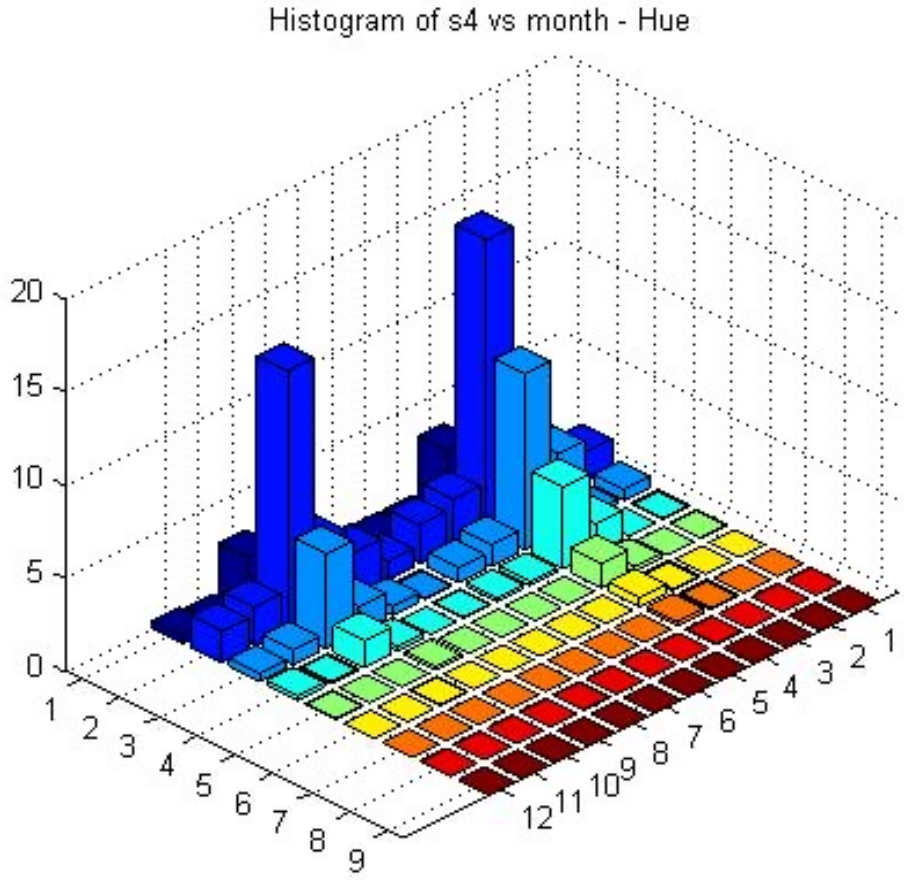
Figure 5. Monthly mean variations of quiet time irregularities over the northern crest (red line), trough (green line), and southern crest (blue line) in 2013.

Scintillation index S4 observed at Hue during the period 2006-2008 / S4 -> fluctuations of the GPS power signal



Distribution of GPS receivers in Vietnam
And adjacent region

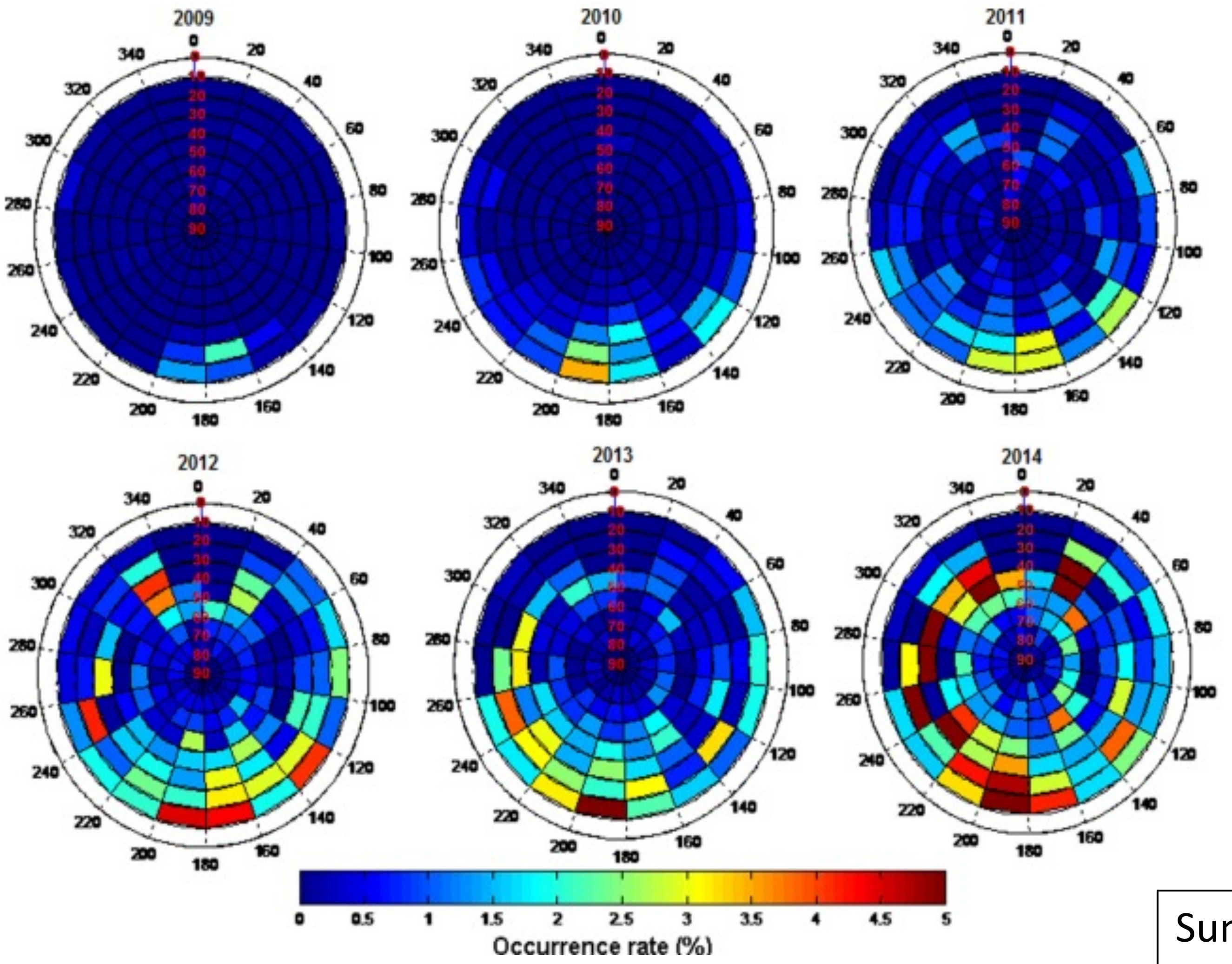
$$I = \frac{A^2}{2} \qquad s4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}$$

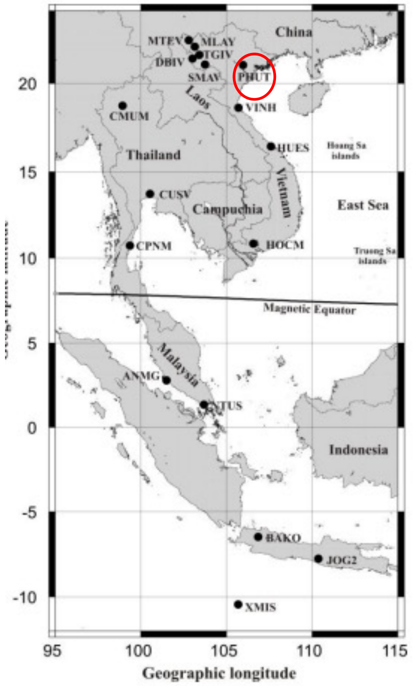


VIETNAM

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

VIETNAM

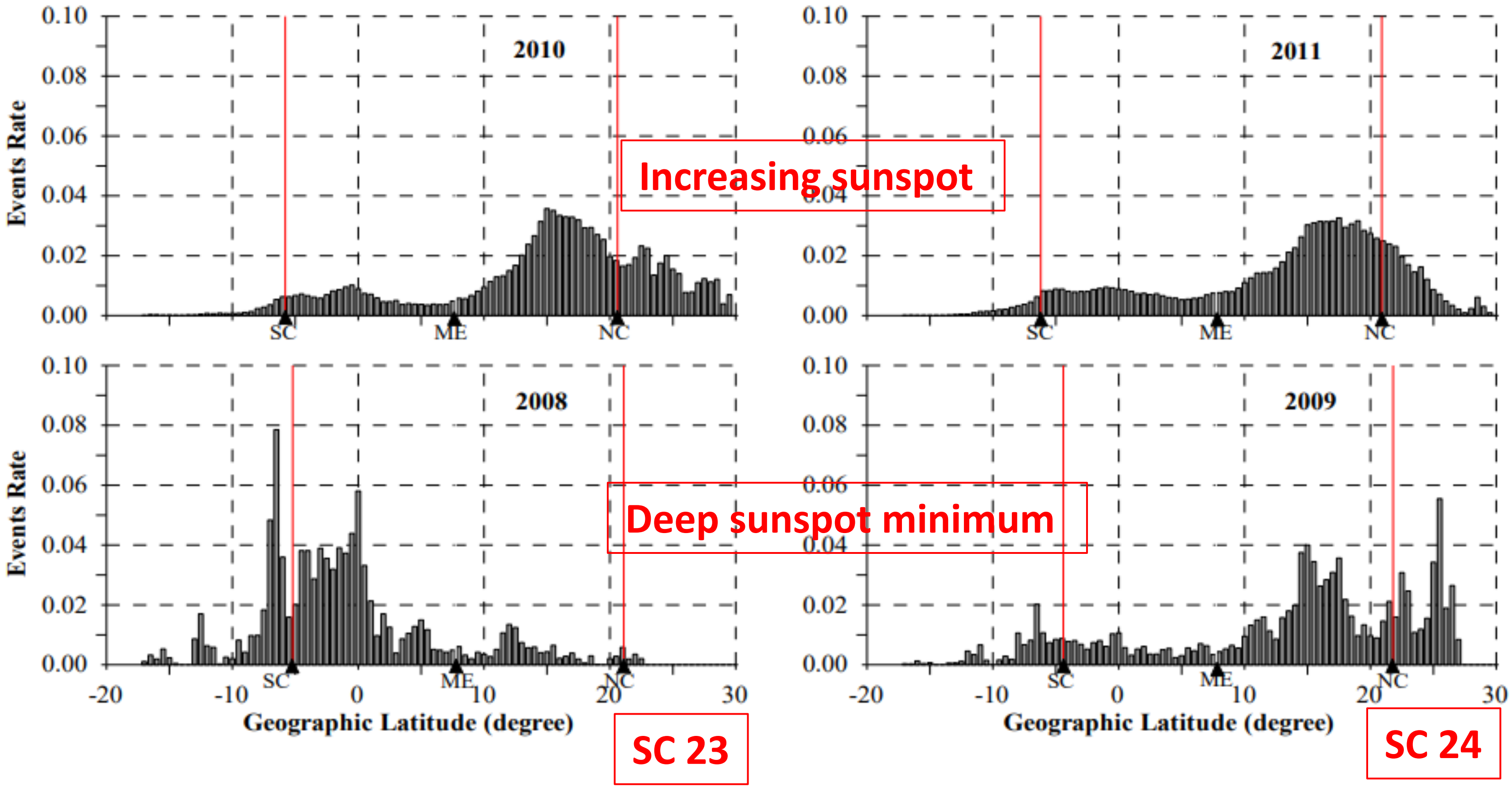




Sunspot cycle Maximum
2012,2013,2014

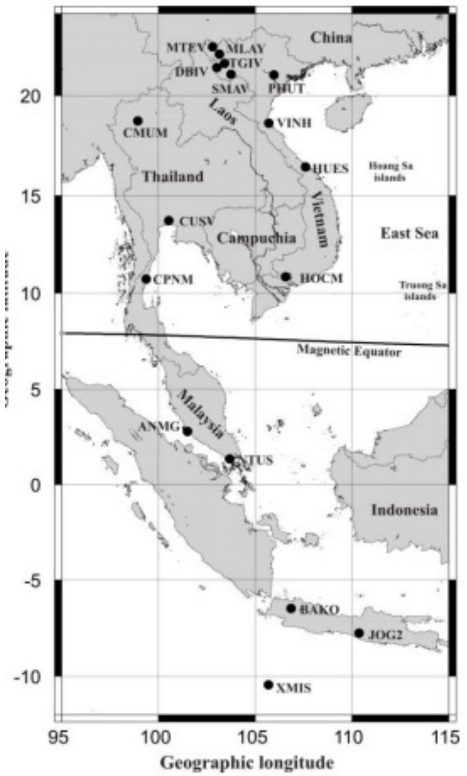
Tran Thi L., M. Le Huy et al.,Climatology of ionospheric scintillation over the Vietnam low-latitude region for the period 2006-2014, Advances in Space Res. http://dx.doi.org/10.1016/j.asr.2017.05.005.

Statistics of ionospheric irregularities (ROTI≥0.5) along geographic latitude during the period 2008-2018. ME: magnetic equatorial; SC: southern crest; NC: northern crest **ASIAN SECTOR**



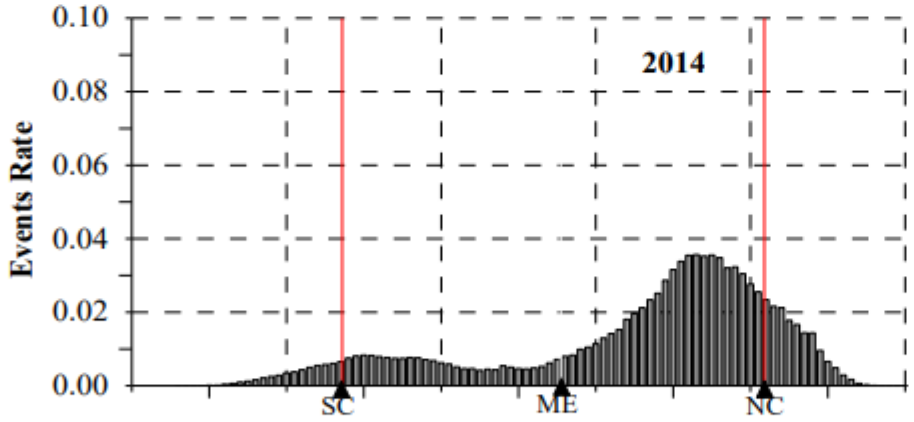
Dung Nguyen Thanh, Minh Le Huy, Christine Amory-Mazaudier, Rolland Fleury, Susumu Saito, Thang Nguyen Chien, Hong Pham Thi Thu, Thanh Le Truong, Mai Nguyen Thi, Characterization of ionospheric irregularities over Vietnam and adjacent region for the 2008-2018 period, Vietnam Journal of Earth Sciences, 1-20, https://doi.org/10.15625/2615-9783/16502

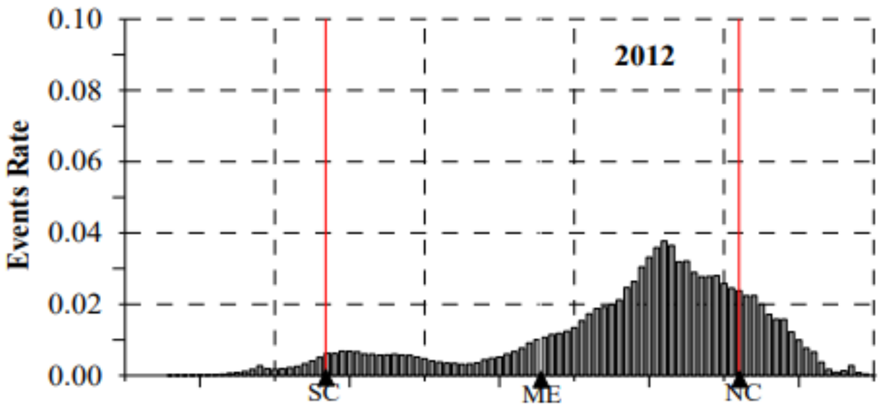
Statistics of ionospheric irregularities (ROTI≥0.5) along geographic latitude during the period 2008-2018.

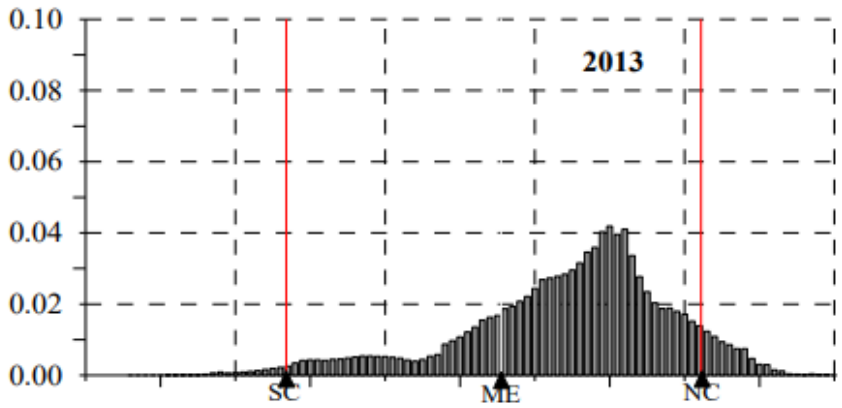


ASIAN SECTOR

Phase maximum of sunspot cycle 24





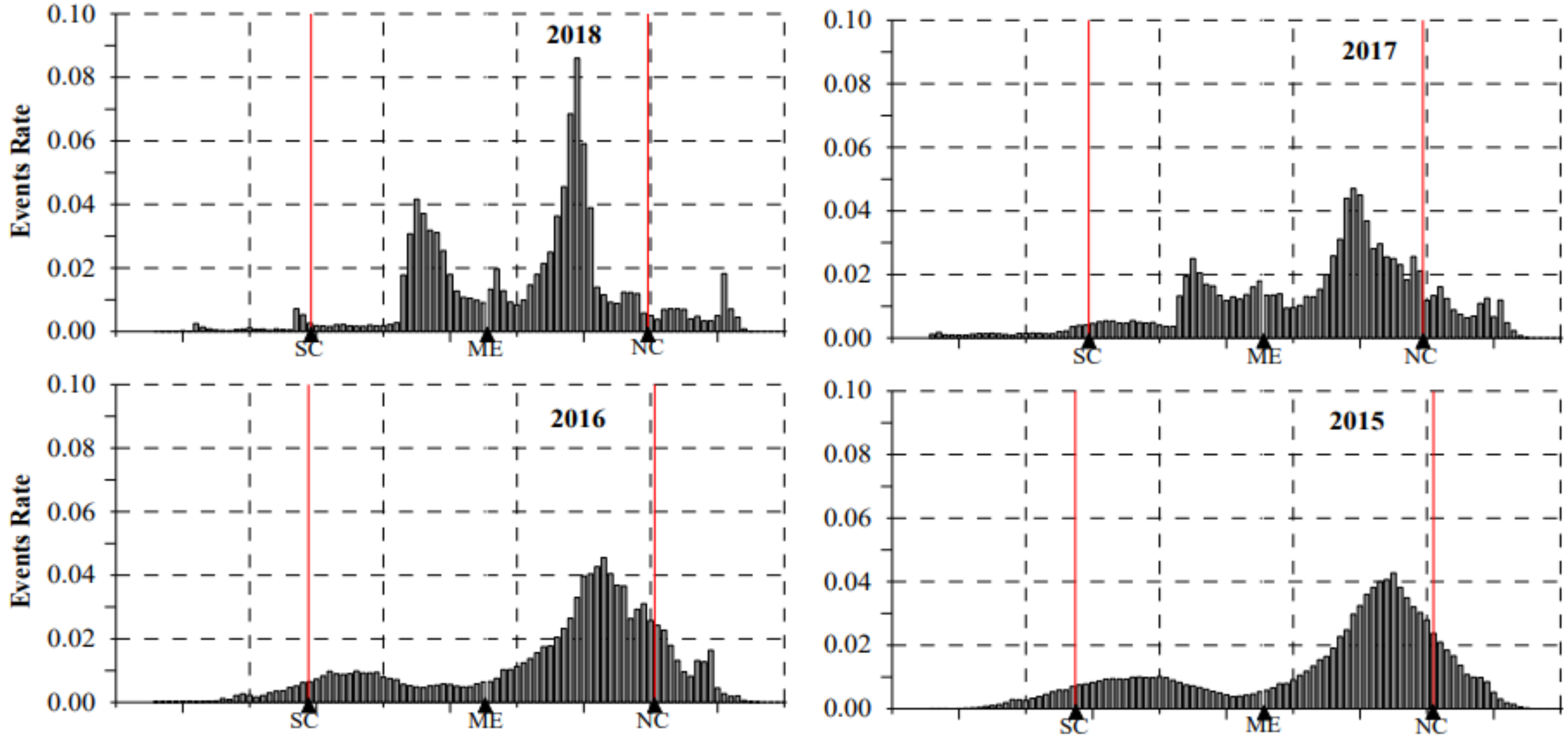


Dung Nguyen Thanh et al., https://doi.org/10.15625/2615-9783/16502

Statistics of ionospheric irregularities (ROTI≥0.5) along geographic latitude during the period 2008-2018. ME: magnetic equatorial; SC: southern crest; NC: northern crest

ASIAN SECTOR

Decreasing phase of sunspot cycle 24



Dung Nguyen Thanh et al., https://doi.org/10.15625/2615-9783/16502

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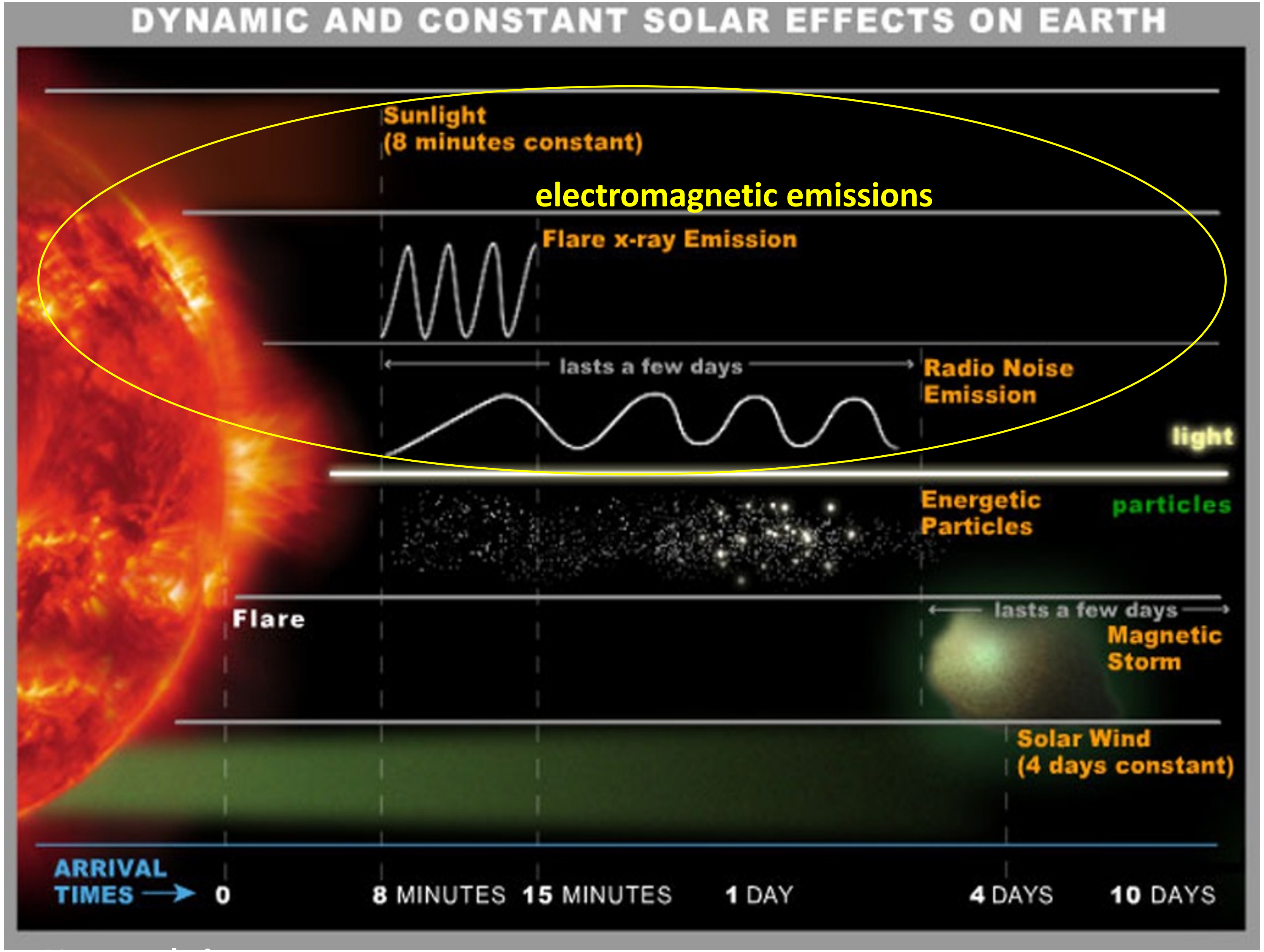
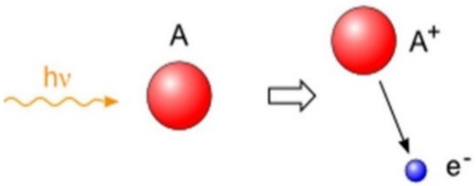
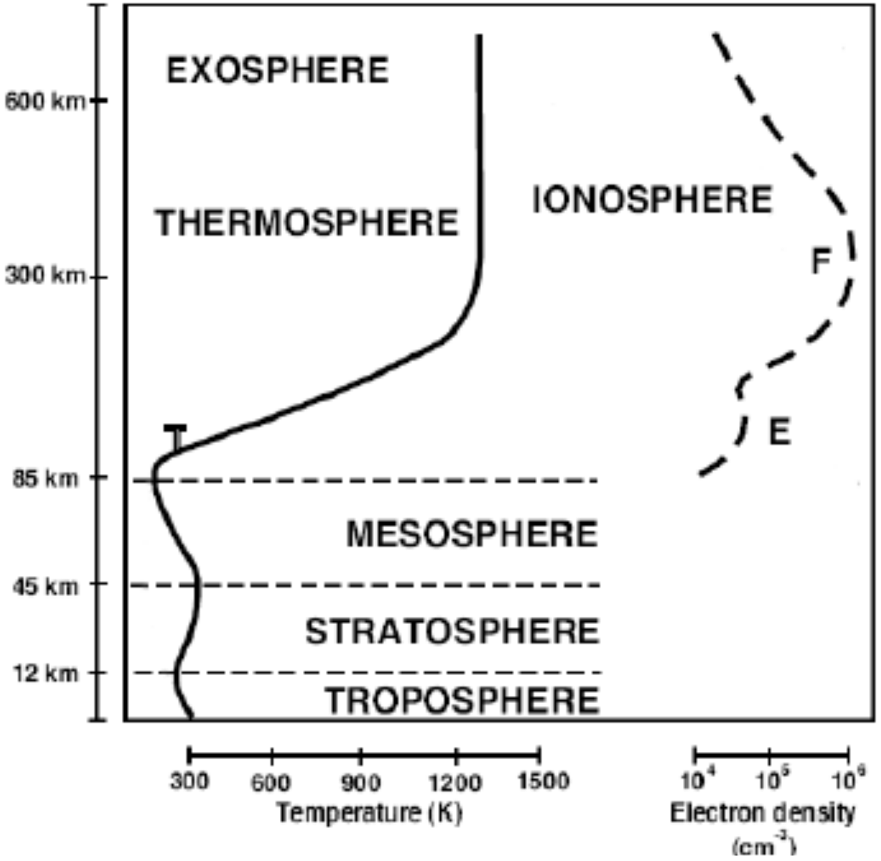
SOLAR DYNAMO/ TOROÏDAL COMPONENT : REGULAR RADIATIONS





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**

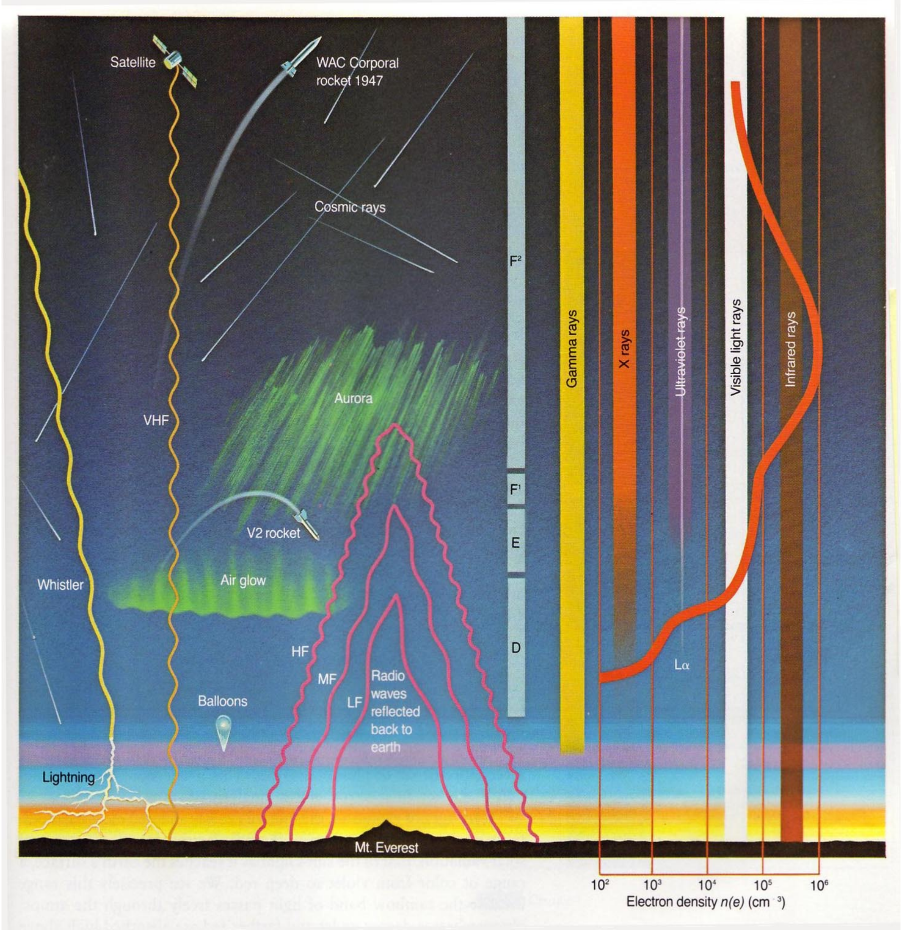
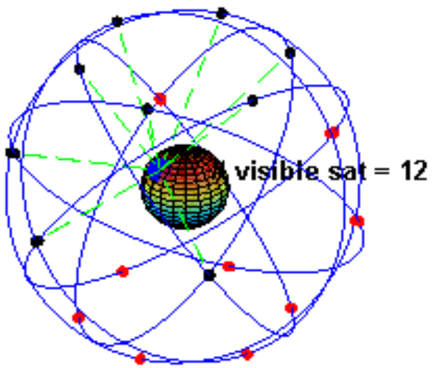
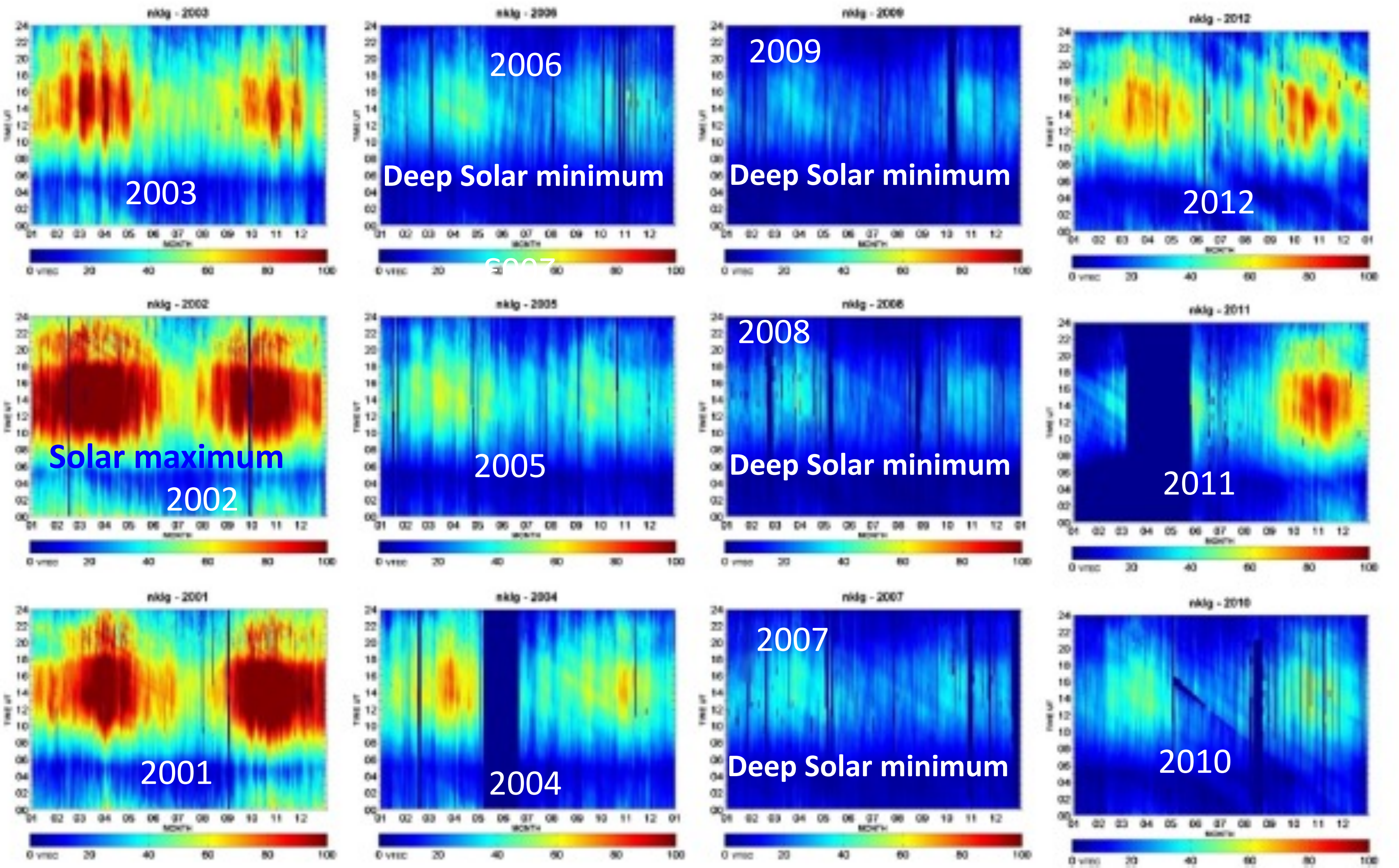


Figure from Friedman, 1987

Sunspot seasonal and diurnal variation of VTEC at Libreville/Gabon

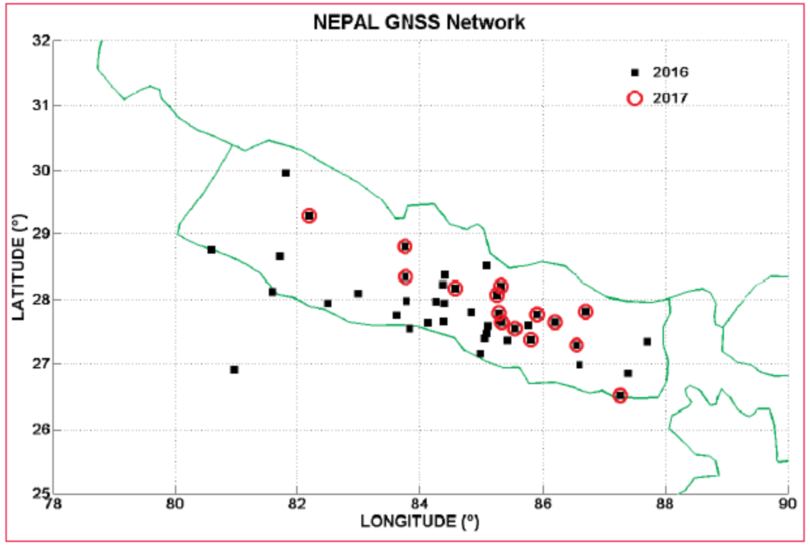


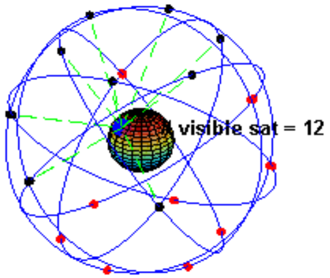
0.3539°N,
9.6721°E
Southern crest of EIA

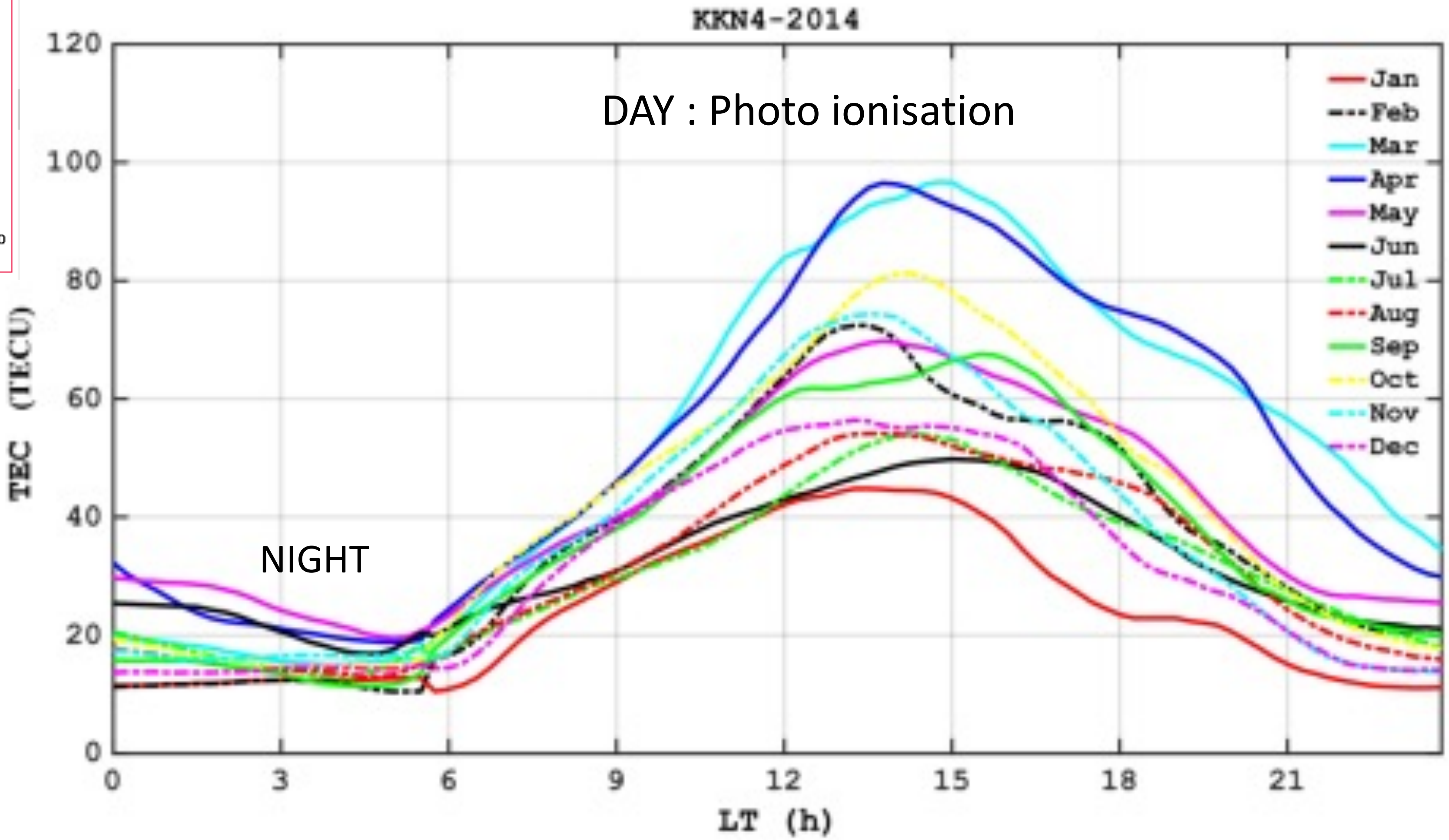


Two dimensional (2D) diurnal variation of hourly vTEC at NKLG from 2002 to 2012. Shimeis et al., Advances in Space Research 54 (2014) 2159–2171.

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



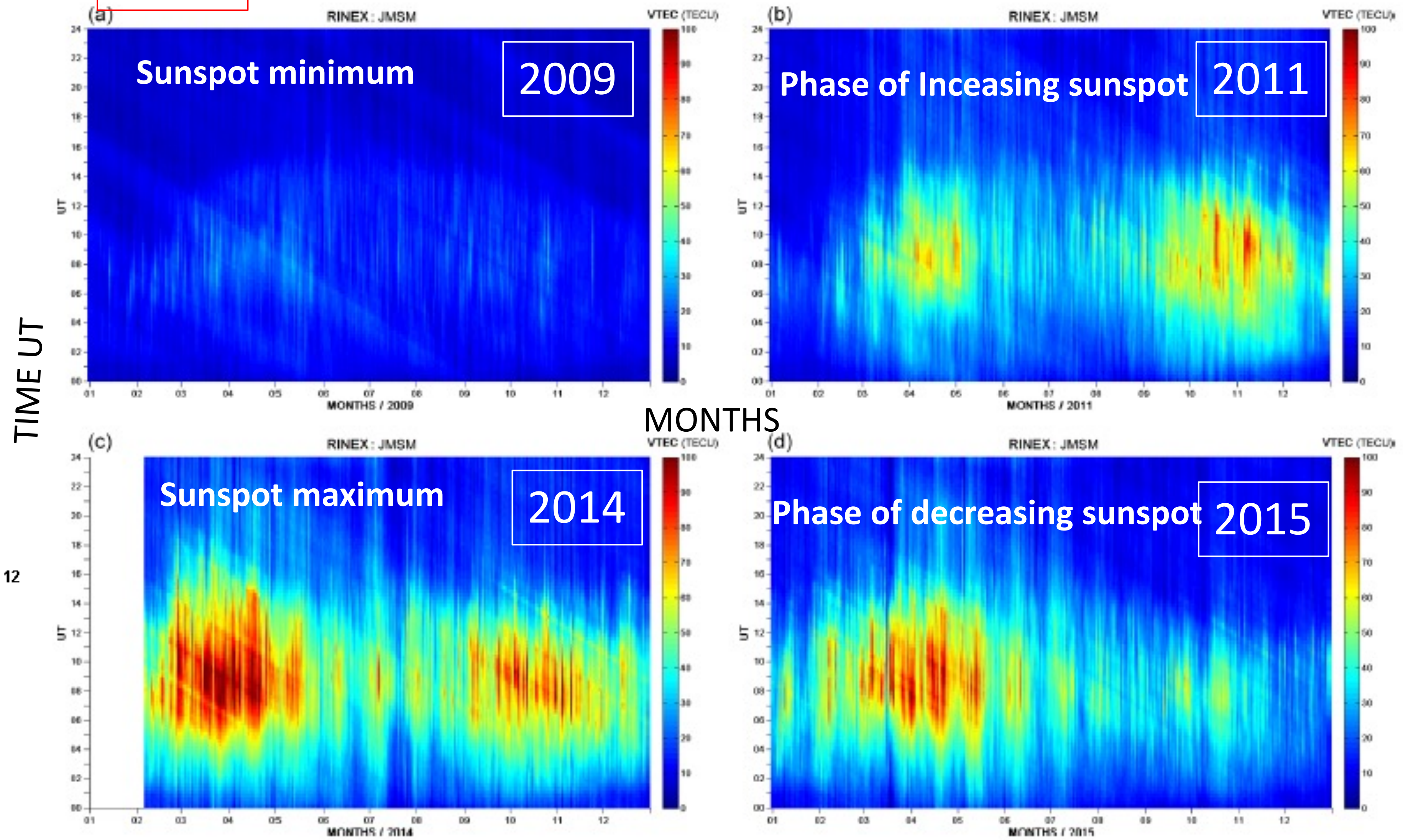


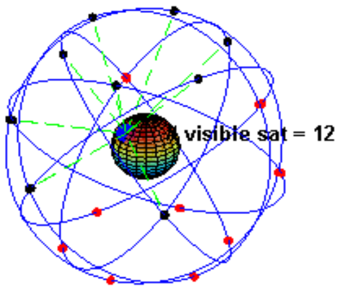


Pandit, D. B. Ghimire, C. Amory-Mazaudier, R. Fleury, N. P. Chapagain, B. Adhikari, Climatology of ionosphere over Nepal based on GPS TEC data from 2008 to 2018, Ann. Geophys., 39, 743–758, 2021 https://doi.org/10.5194/angeo-39-743-2021

YEAR

Station GPS JOMSON (JMSM)

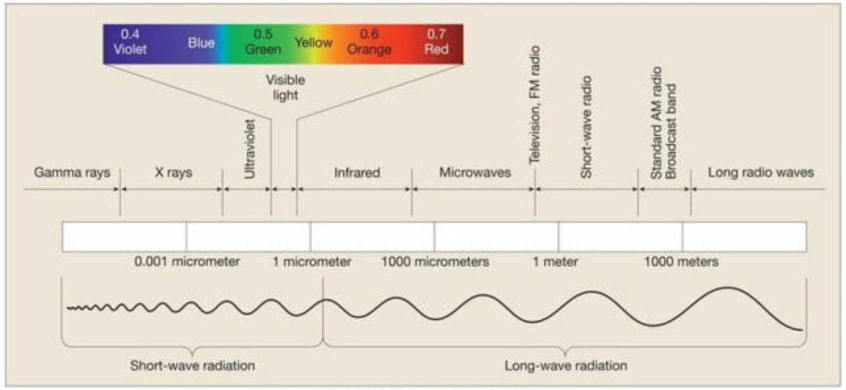




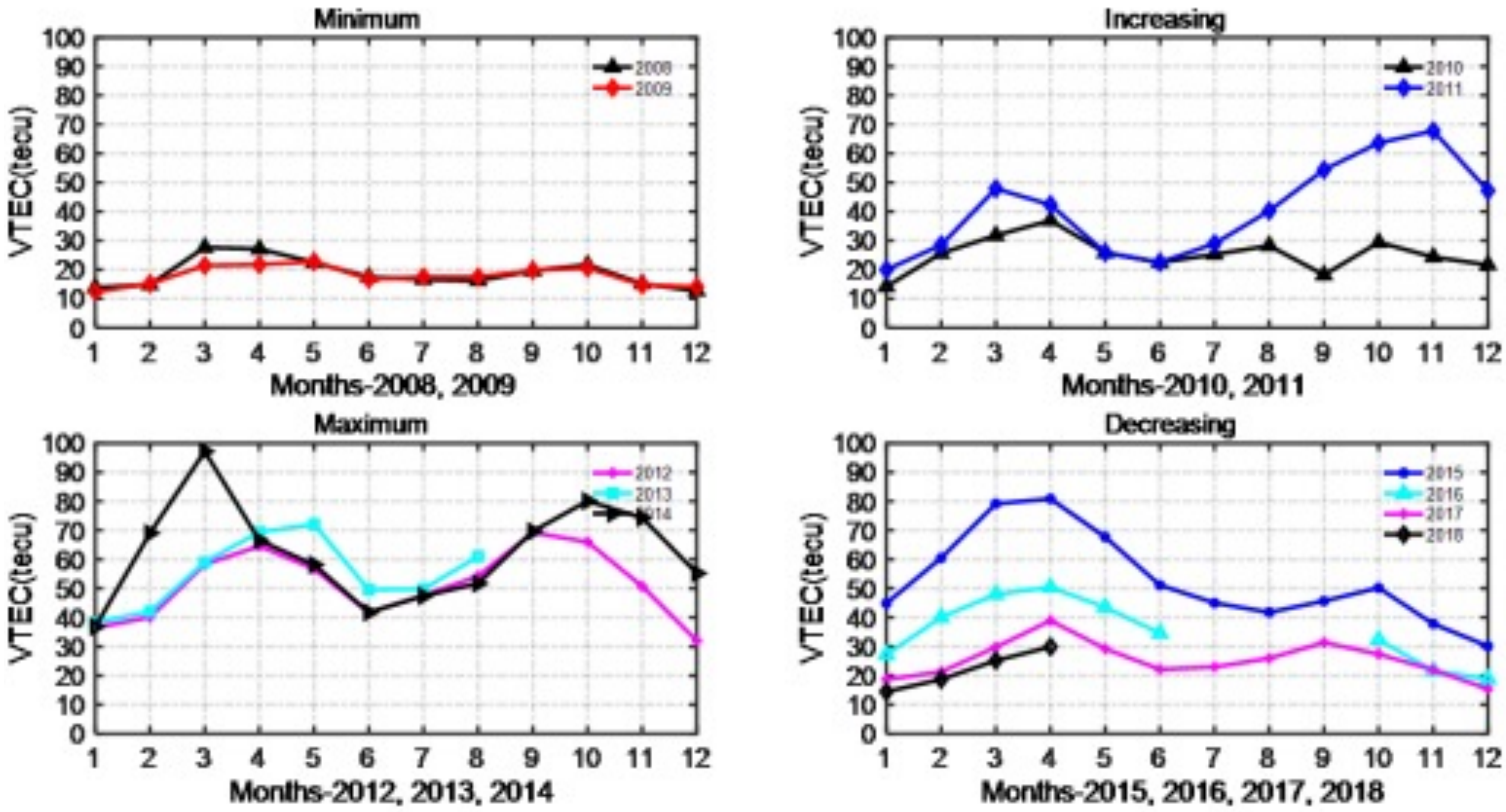
(a–d) A two-dimensional (2D) variation in vertical TEC according to UT at the JMSM station for one of the years of the minimum (2009), ascending (2011), maximum (2014) and descending (2015) phases of solar cycle 24.

Solar electromagnetic emissions/ Sunspot cycle

PHYSICS



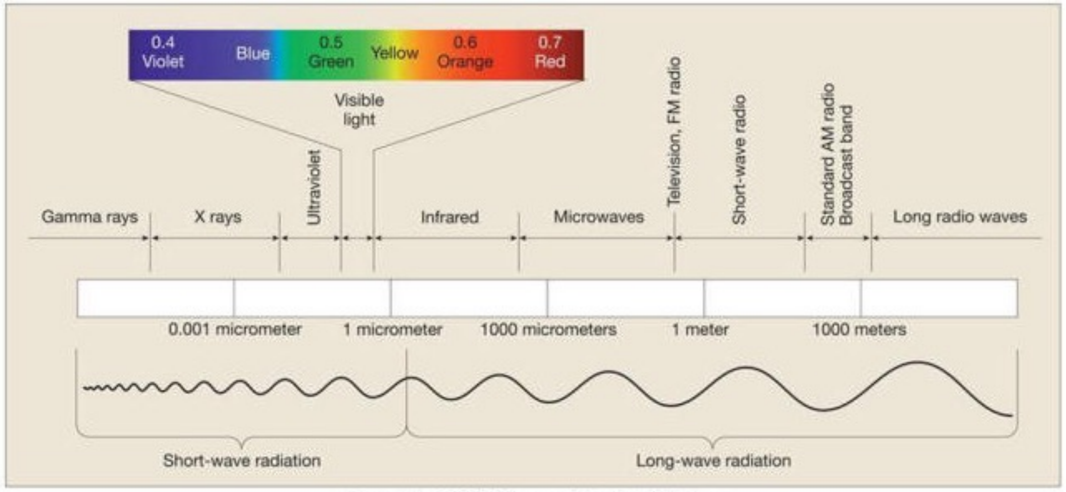
PHASES OF SUNSPOT CYCLE



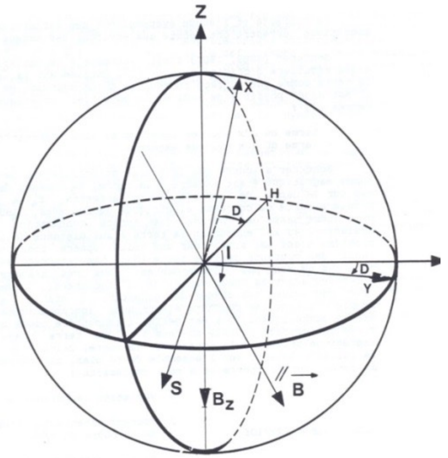
VTEC variability in GRHI station during minimum, increasing, maximum and decreasing phases of solar cycle 24

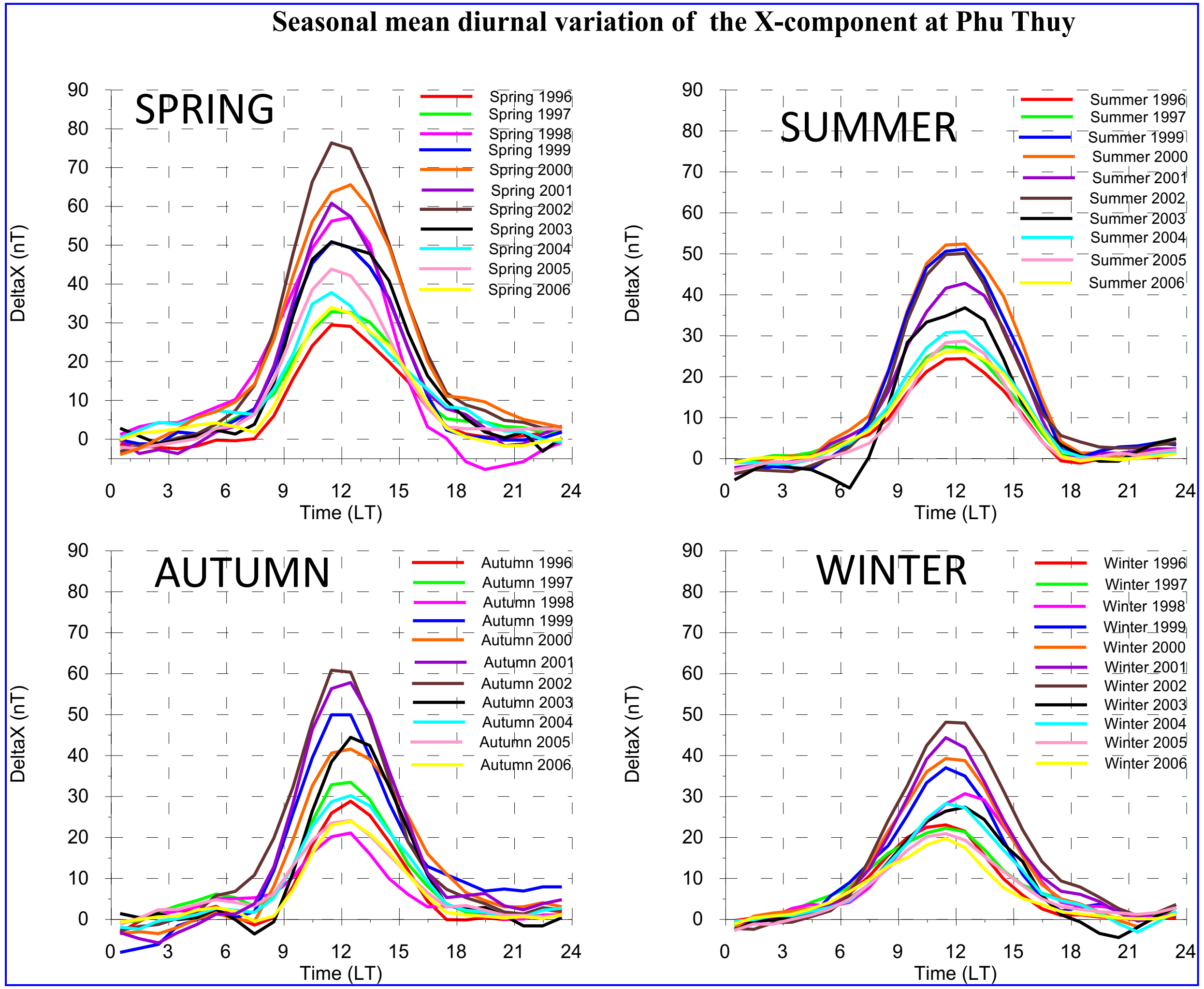
Ionospheric Dynamo

Toroïdal component of the solar magnetic field [Sunspots] => Solar Radiations EUV, UV => Ionosphere=> ionospheric electric current => Regular variation of the Earth's on magnetic quiet days (Kp or Km < 2+)



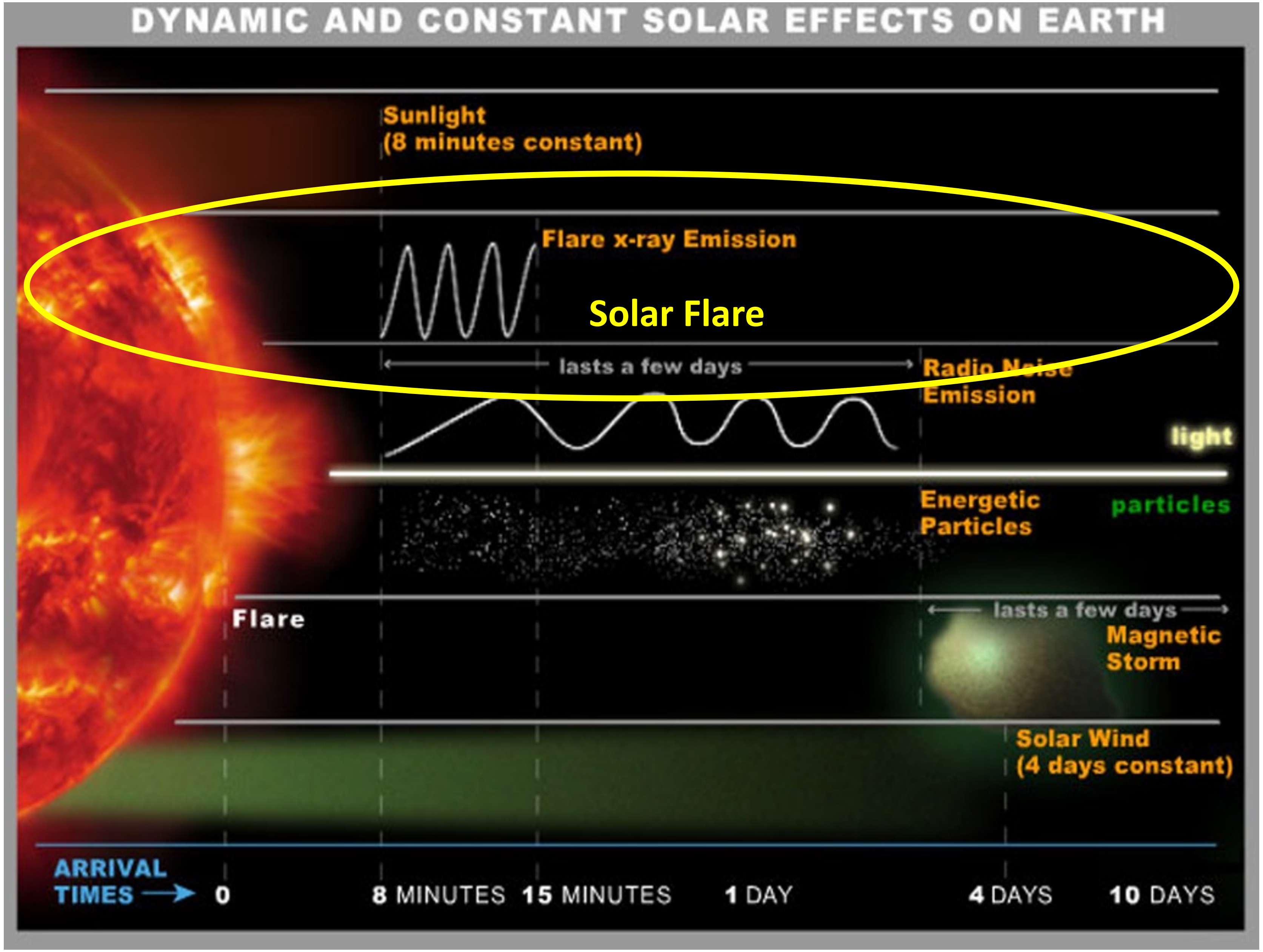
Images du satellite SOHO NASA - ESA





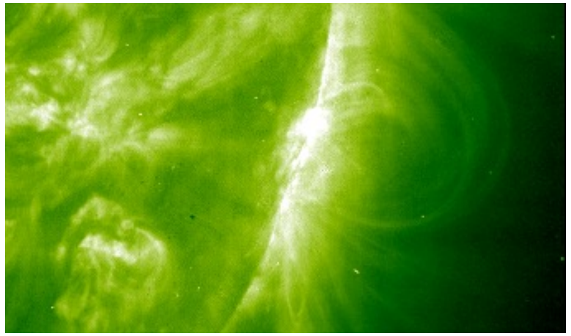
X component of the Earth's magnetic Field at Phu Thuy/ Vietnam

Pham Thi Thu, H., C. Amory-Mazaudier, M. Le Huy (2011), Sq field at Phu Thuy – Vietnam during solar cycle 23, Ann. Geophys., 29, 1-17


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

Geo-electric field variations due to the solar flare on 04 April, 1993

Solar Flare
extra electromagnetic emissions



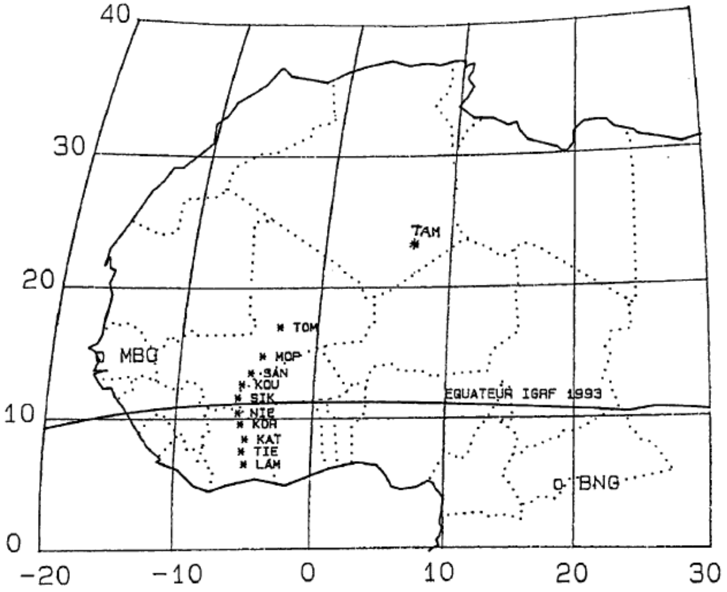
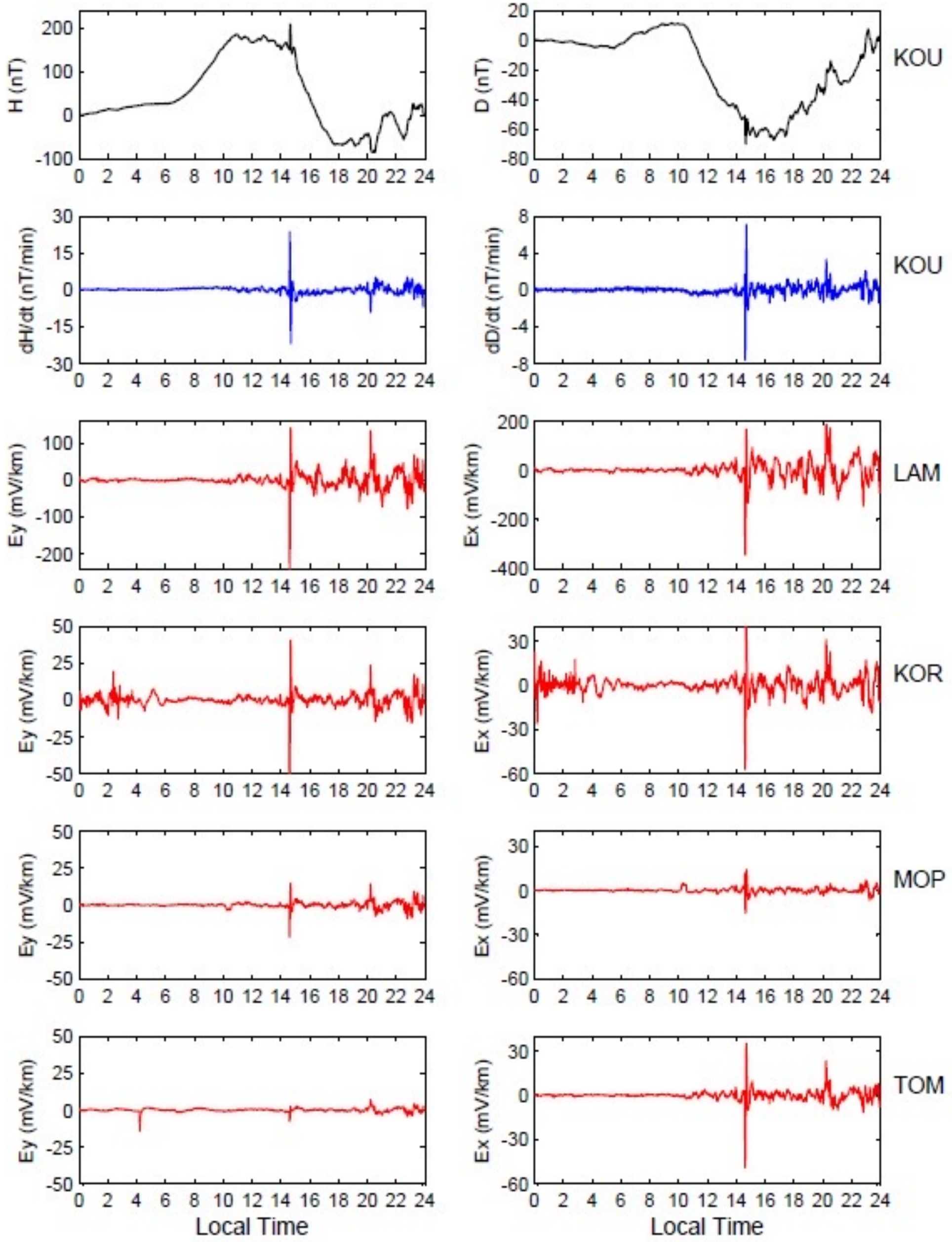


Fig. 1. Experimentation sites of the African sector during the IEEY project.

Magneto telluric station
Côte d'Ivoire



V. Doumbia, K. Boka, O. D. F. Grodji, C. Amory-Mazaudier, and M. Menvielle, 2017, Induction Effects of Geomagnetic Disturbances in the Geo-electric Field Variations at Low-latitude, Ann. Geophys., 35, 1-13

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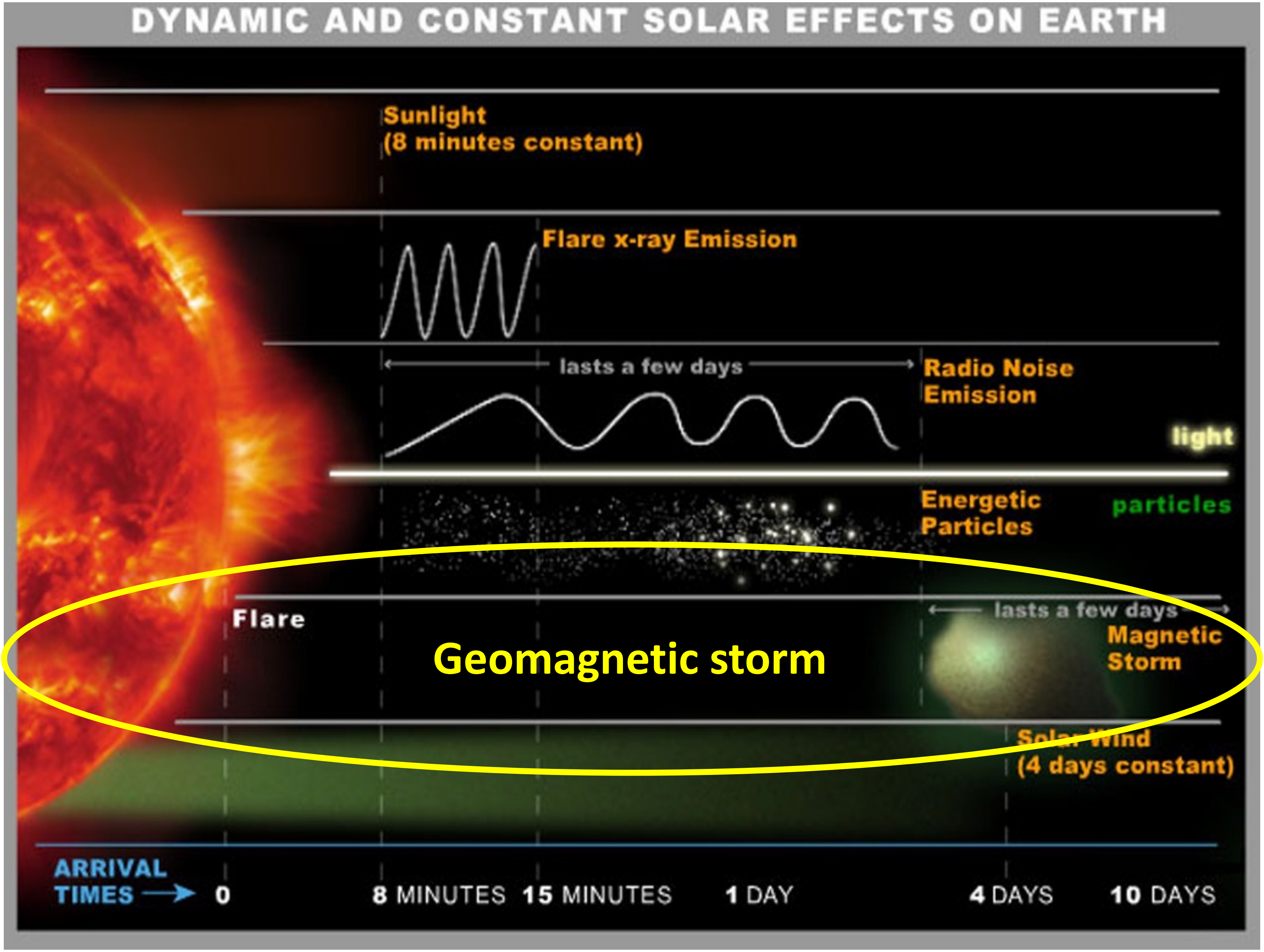

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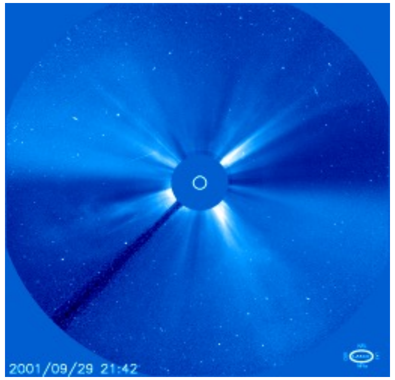
light
Energetic
Particles
particles
Flare
Geomagnetic storm
lasts a few days
Magnetic
Storm
Solar Wind
(4 days constant)
ARRIVAL
TIMES
0
8 MINUTES
15 MINUTES
1 DAY
4 DAYS
10 DAYS

CME: Coronal Mass Ejection
Magnetic cloud

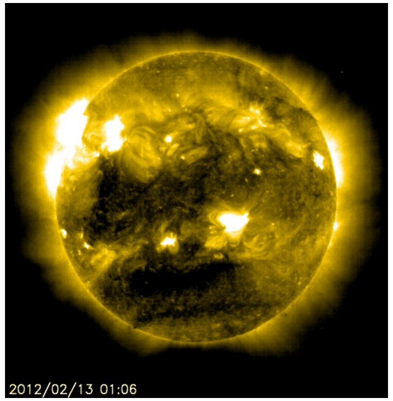


SUN-EARTH CONNECTIONS

Solar wind

from the Sun to the Earth

Coronal hole
HSSW -CIR



Coupling between high and low latitudes

1. Transmission of an electric field PPEF

*Magnetic disturbance **DP_2** (large scale disturbed ionospheric electric current)*

2.a Thermal expansion of the atmosphere

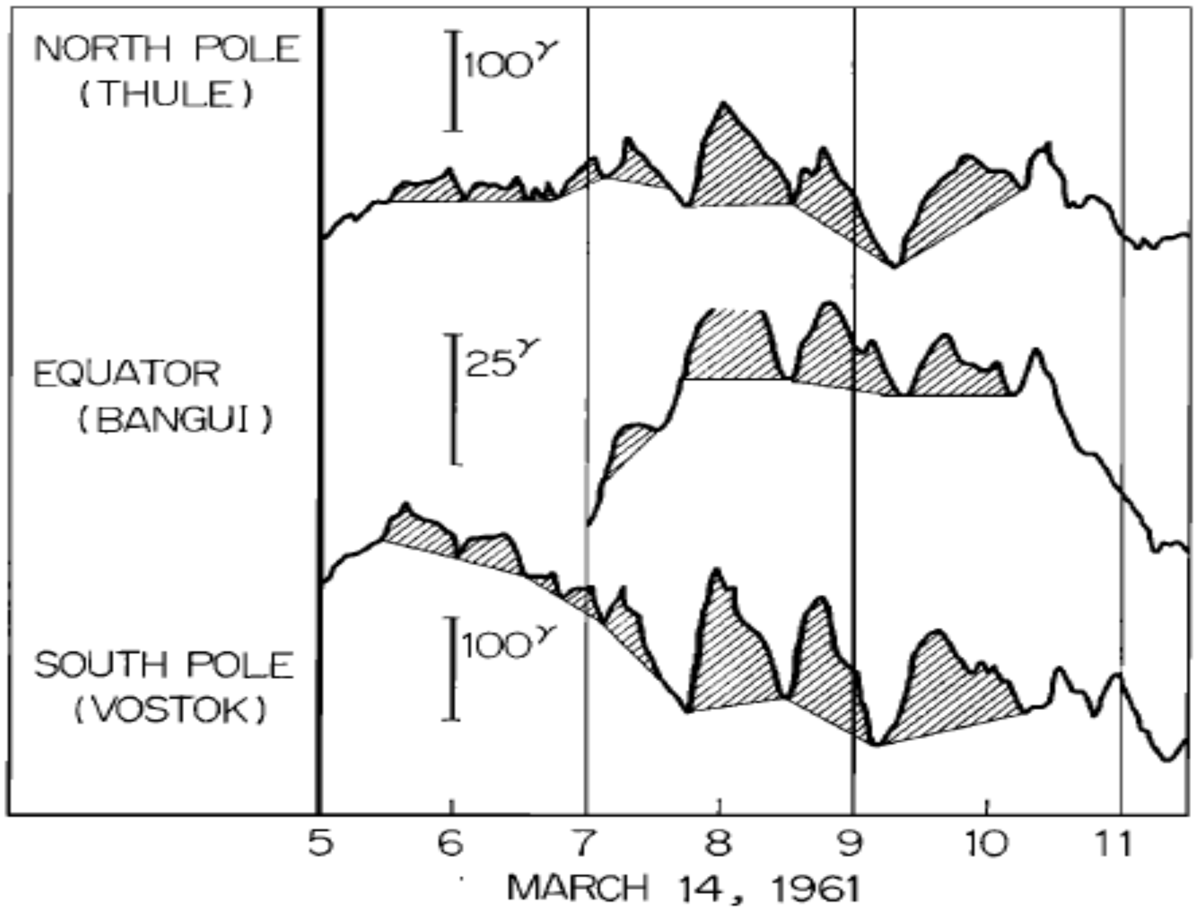
Changes in pressure, temperature , motions , composition

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

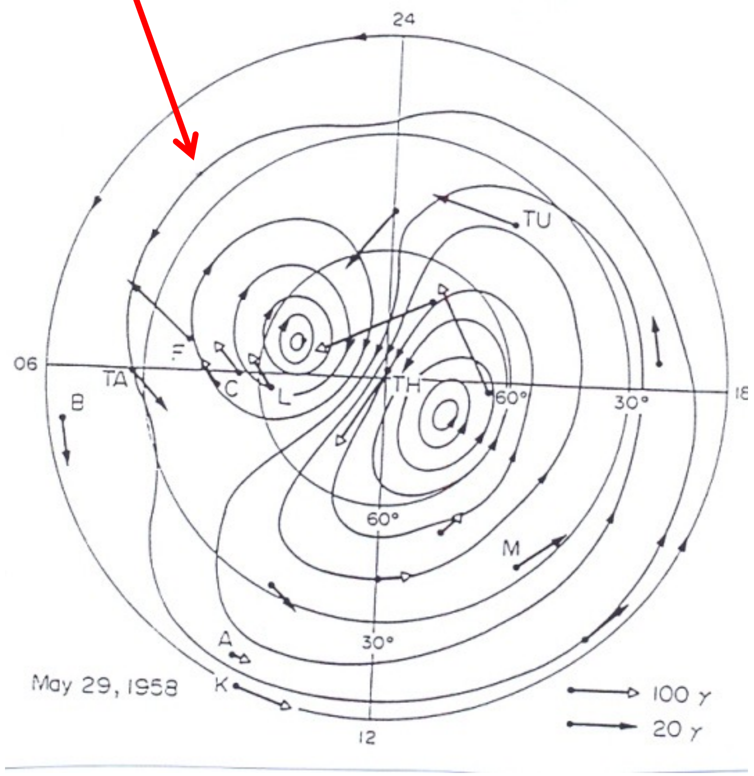
*Magnetic disturbance **Ddyn** (large scale disturbed ionospheric electric current)*

COUPLING between AURORAL and EQUATORIAL regions
THE MAGNETIC EQUIVALENT CURRENT SYSTEM DP2

DP_2, Nishida, 1968, JGR, Ce système de courant s'étend vers les basses latitudes (perturbation magnétique [Nishida et al., 1966]

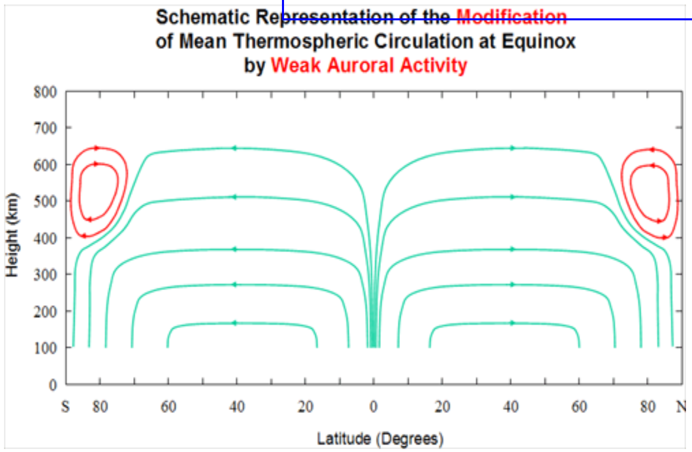


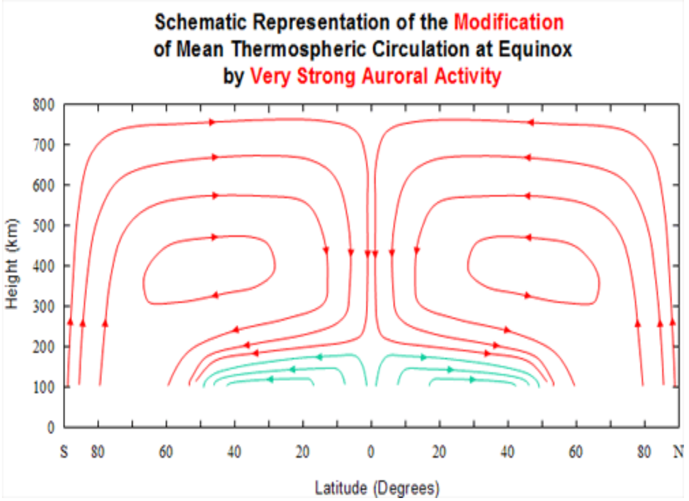
Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and —89.1 (Vostok).

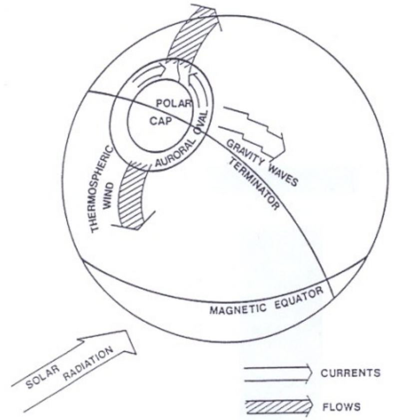


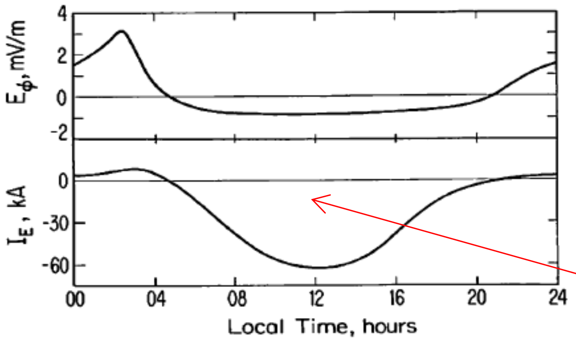
Magnetic disturbance from the Pole to the Equator : D_{dyn}

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

Thermal expansion of the atmosphere: Travelling Atmospheric disturbance (TAD's) => disturbed TEC [Theory Fuller Rowell et al., (1994), (1996)]

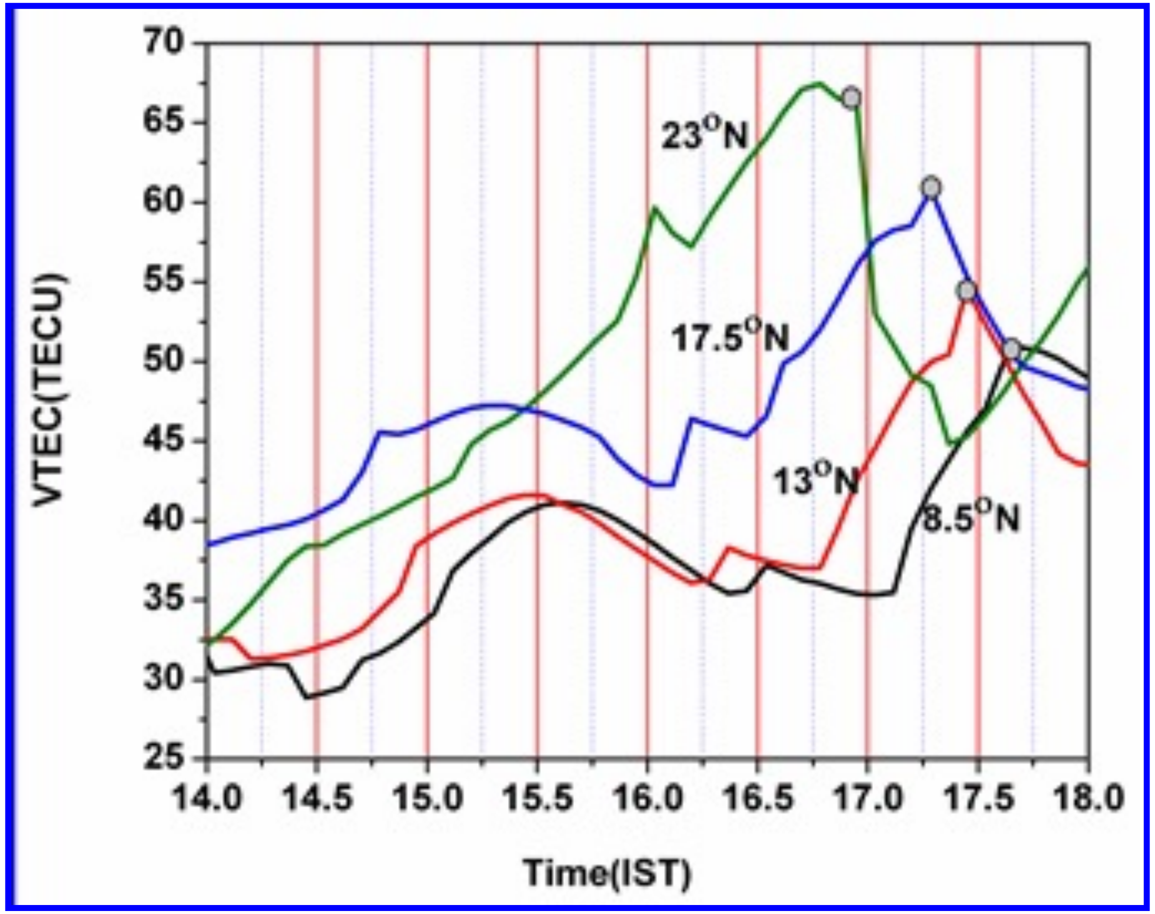
24/08/2005

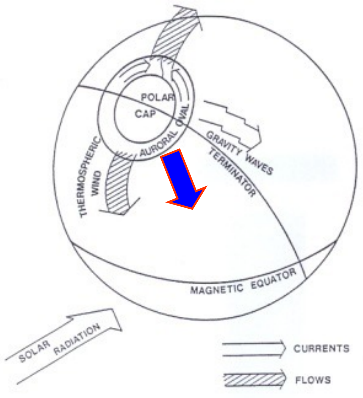
SSC : 13.00 UT
Main Phase : 16 00 UT

INDIA
77-78°E meridian

V~750m/s

Sreeja et al.,
JGR vol 114, A12307, 2009

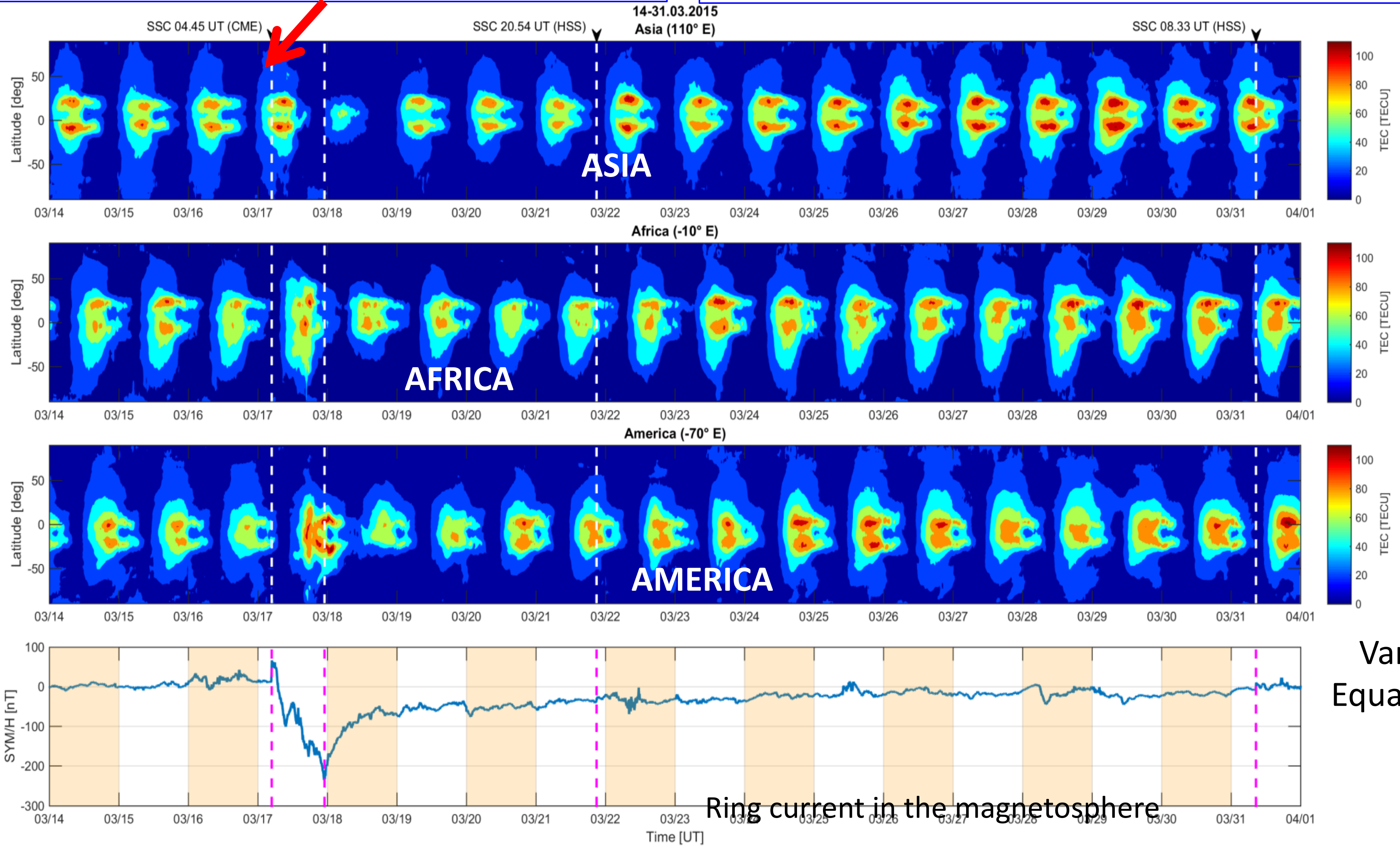


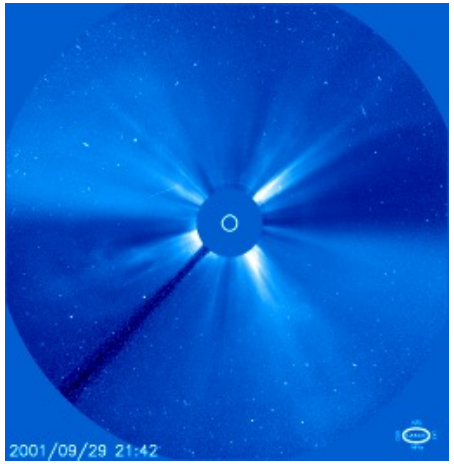


A time delay in the VTEC variations over the different latitudes indicates a propagation of TAD's Velocity 750m/s

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

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

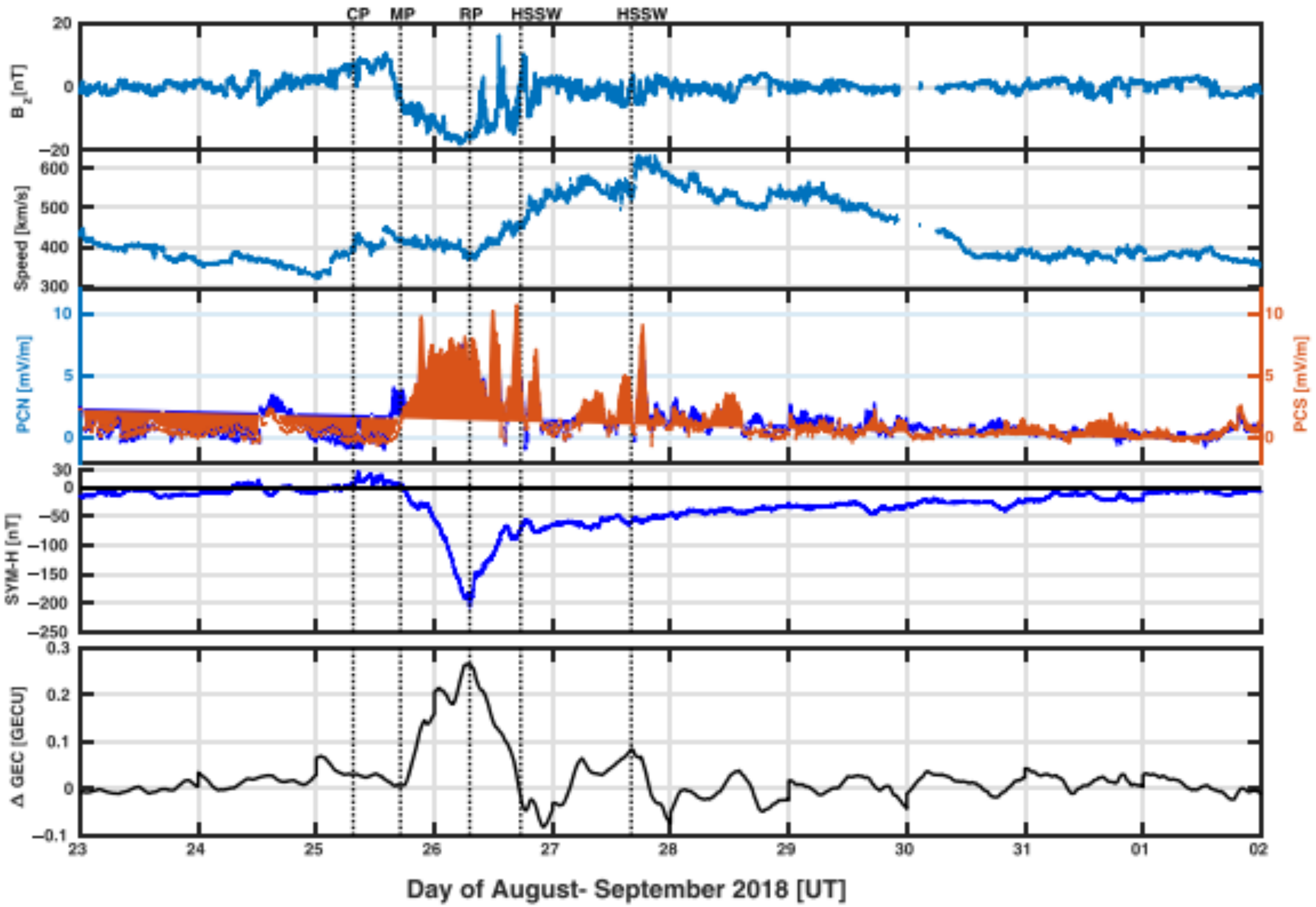




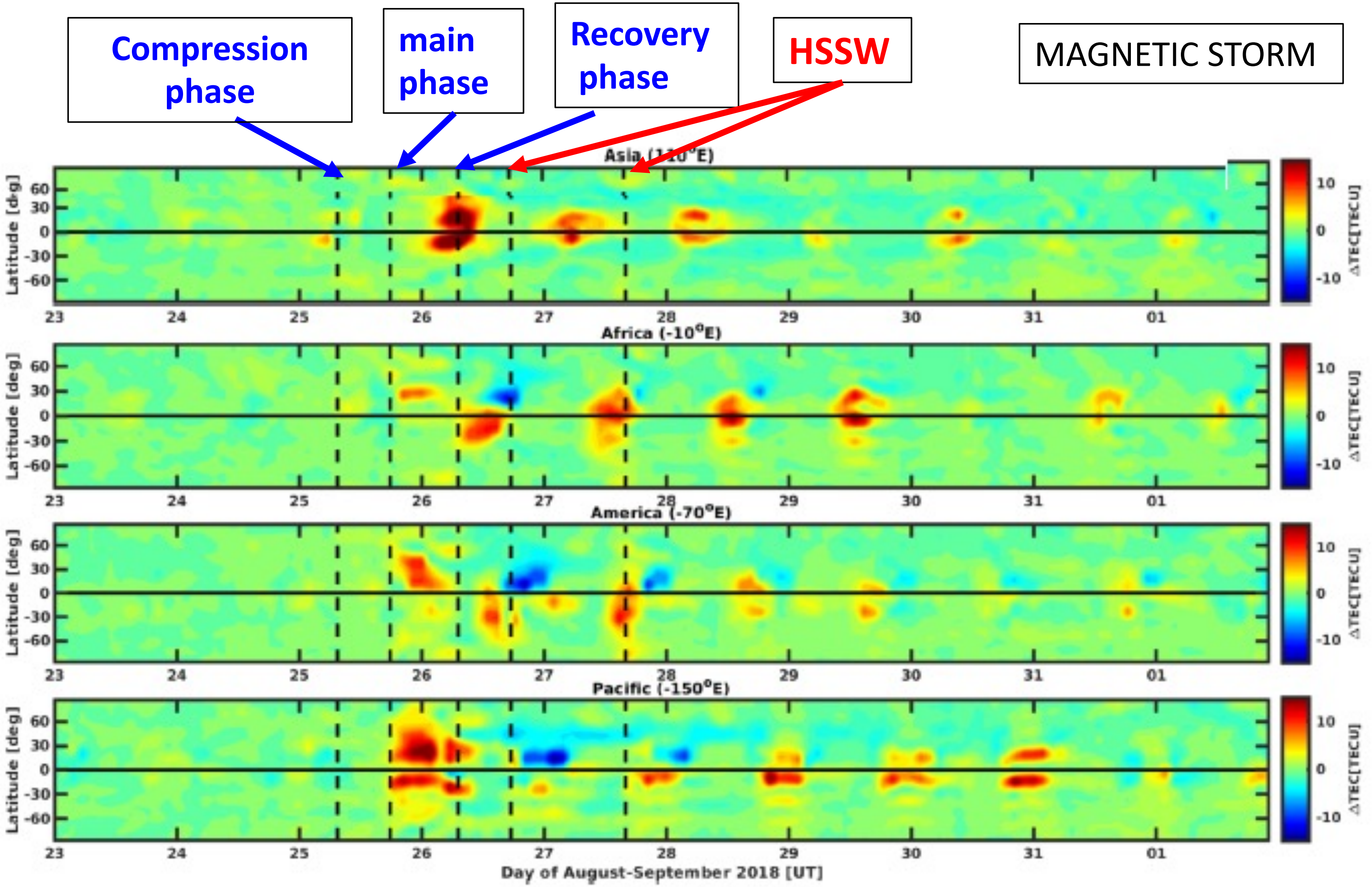
Variations near the magnetic Equator due to a CME (~200 GPS stations)

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.

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



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

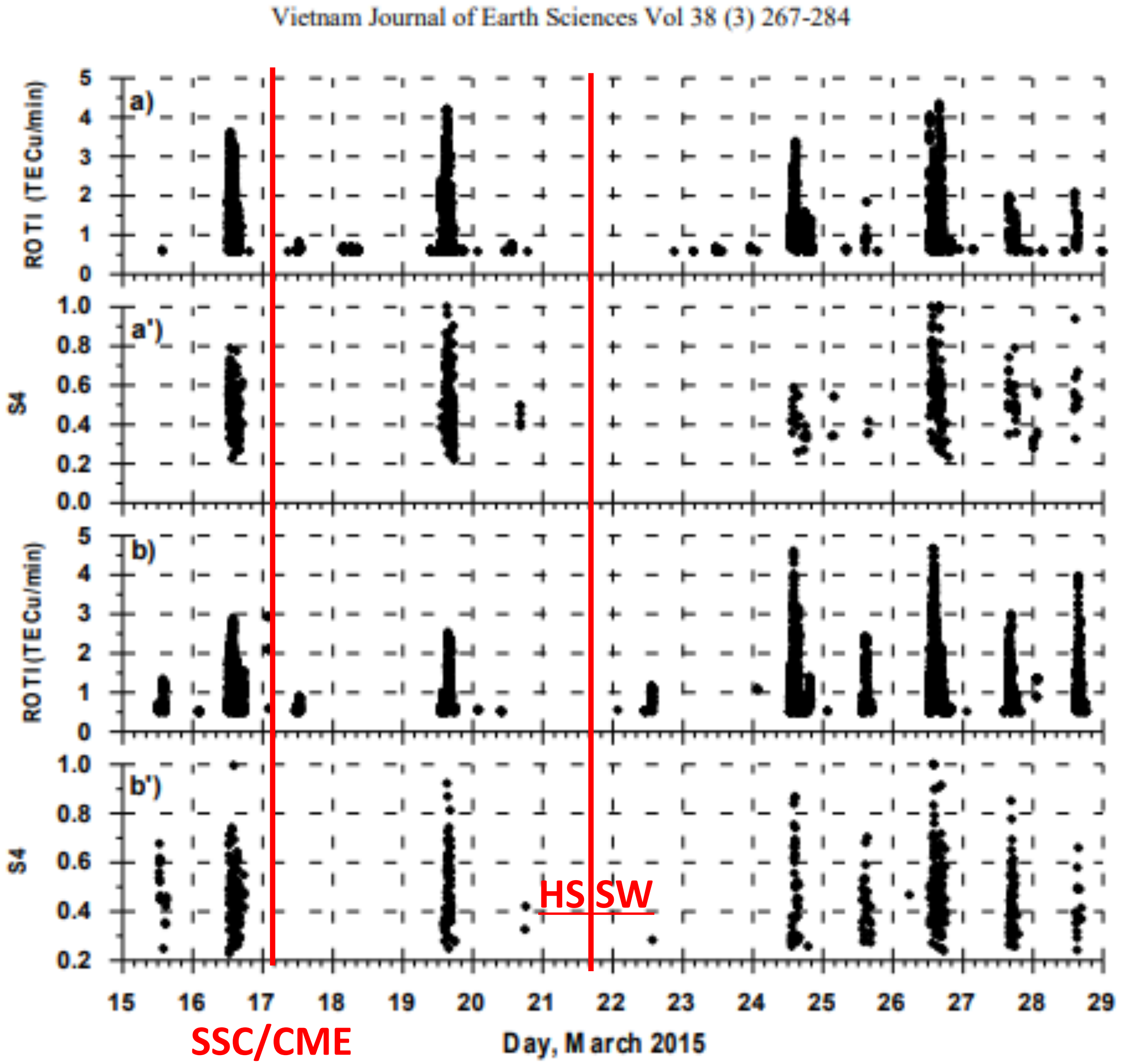
Younas,W et al., Journal of Geophysical Research, Space Physics, 125, e2020JA027981. https://doi.org/10.1029/2020JA027981

ROTI and S4 Indices

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

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

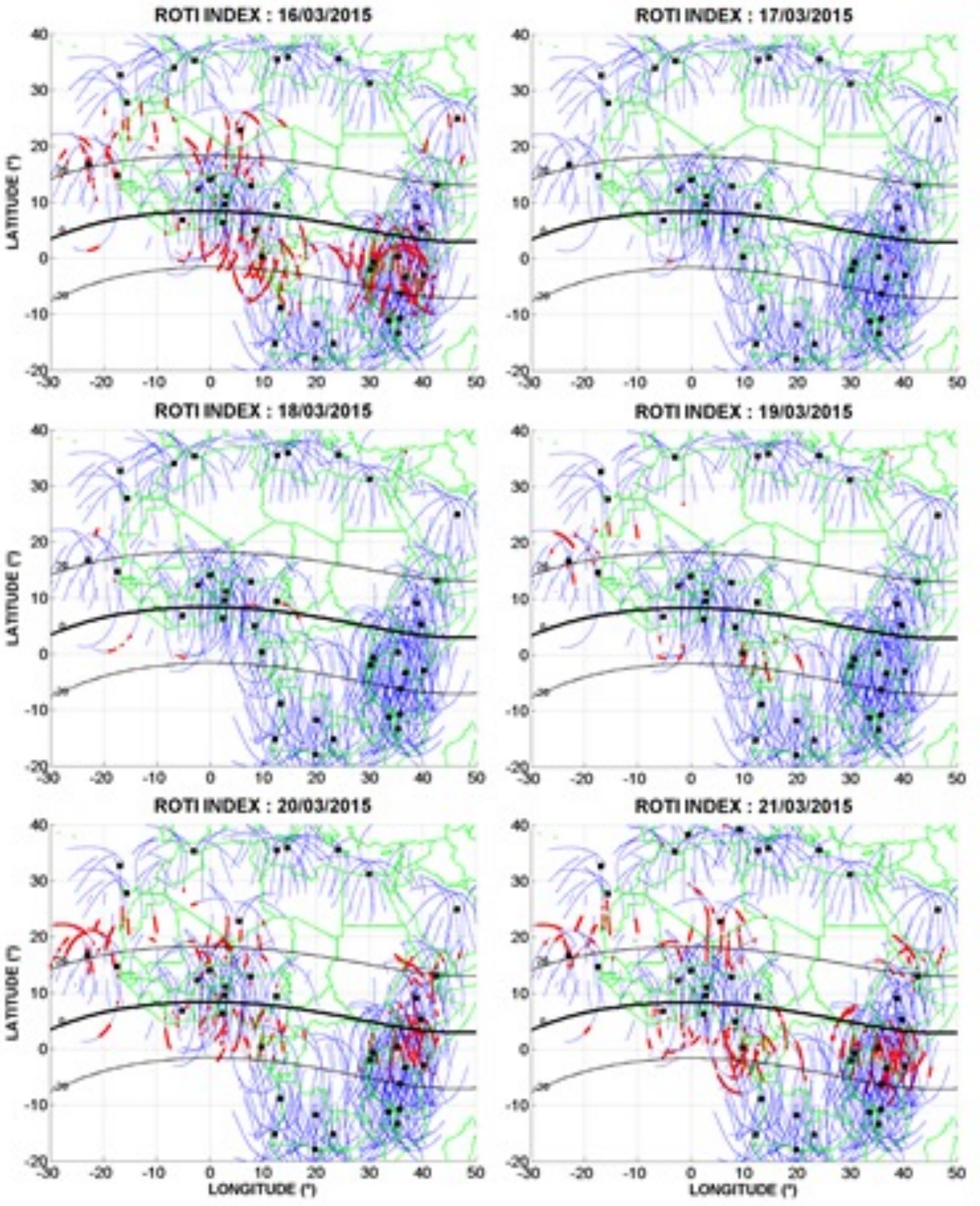
I : intensity of the signal



Le Huy Minh, et al., 2016. TEC variations and ionospheric disturbances during the magnetic storm on March 2015 observed from continuous GPS data in the Southeast Asian region, *Vietnam J. Earth Sciences*, ISBN 0866-7187, **38(3)**, 287-305, doi:10.15625.0866-7187/38/3/8714

Storm March 17, 2015 /equinox

Dst < -200 nT, storm started at 04.45 UT



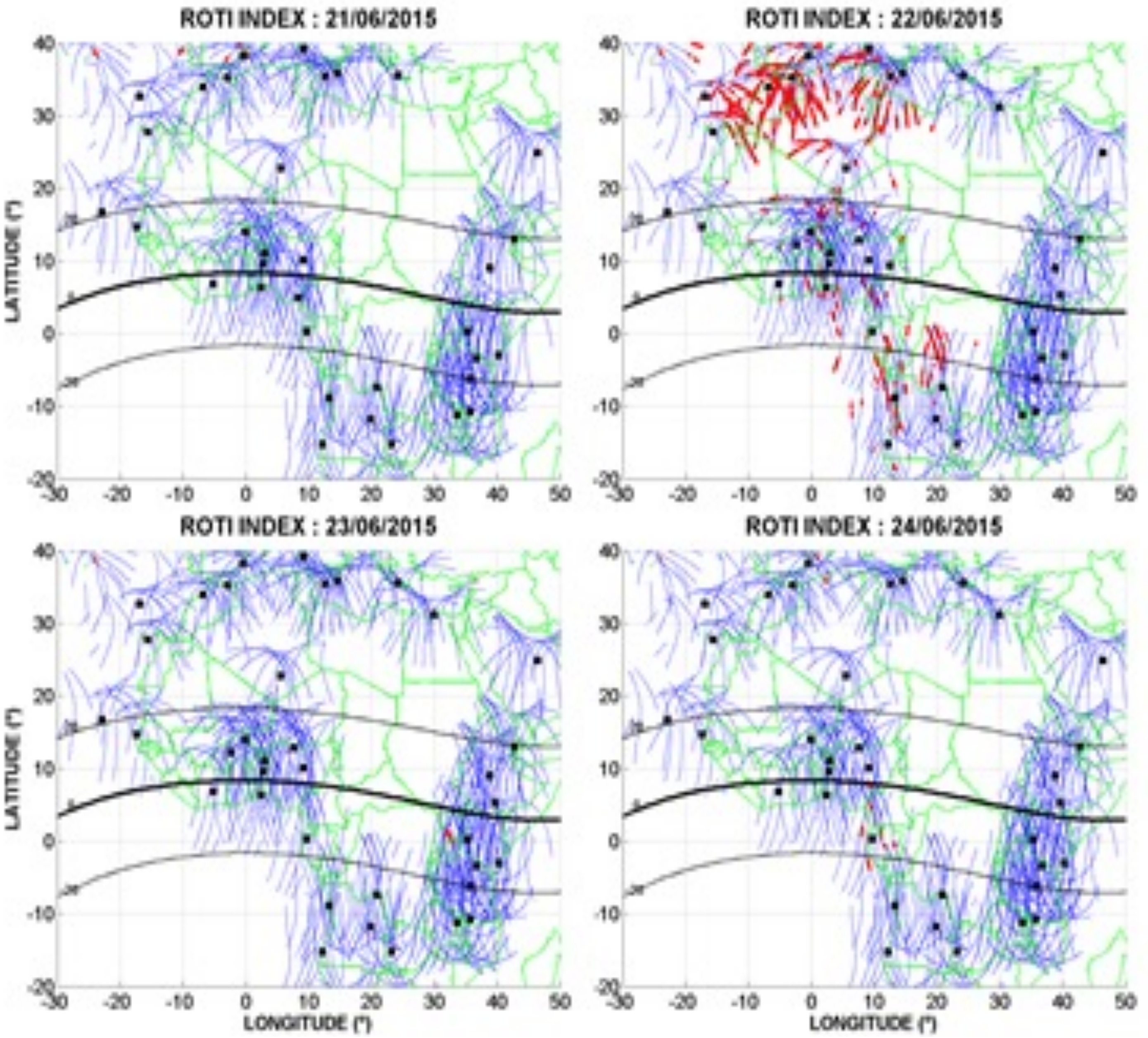
Rate of change of total electron content index (ROTI) maps over African region during St. Patrick's Day storm, 16– 21 March 2015. Thin blue lines show ROTI ≤1.5 TECU/min, while red squares represent ROTI >1.5 TECU/min. Black squares indicate Global Navigation Satellite System station used to produce ROTI maps

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

Inhibition of scintillations over the whole earth during several days : DDEF effect long duration

Kashcheyev, A., 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 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, it is the time of the Pre reversal enhancement of the eastward electric field

Increase of scintillations
PPEF effect short duration

Kashcheyev, A et al., Journal of Geophysical Research: Space Physics, 123. https://doi.org/10.1029/2017JA024900

Disturbed magnetic field

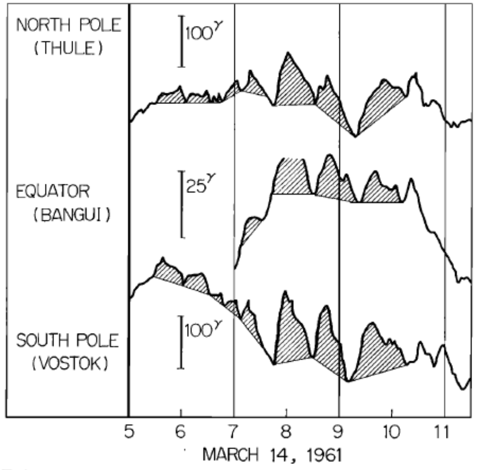


Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

Model of Fejer et al.,(2008)

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

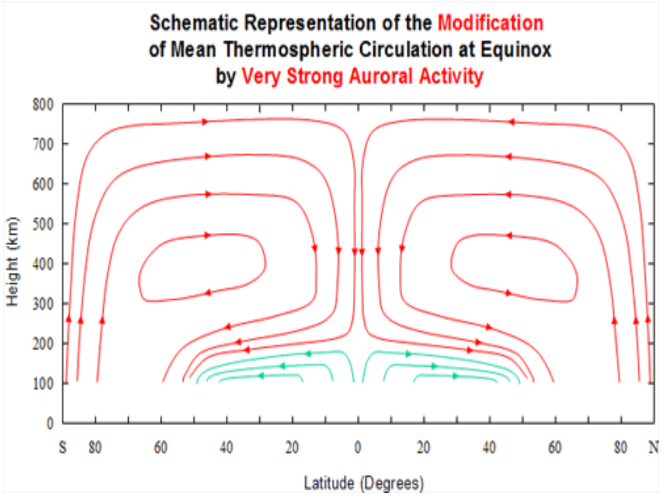
PPEF is an eastward Ey, increases the PRE

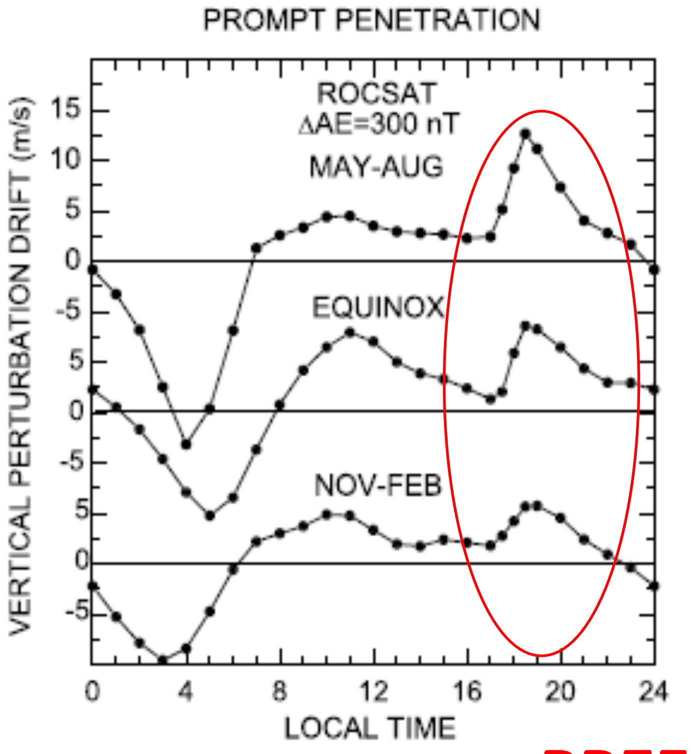
DDEF is a westward Ey, decreases the PRE

Eastward electric field => moves up

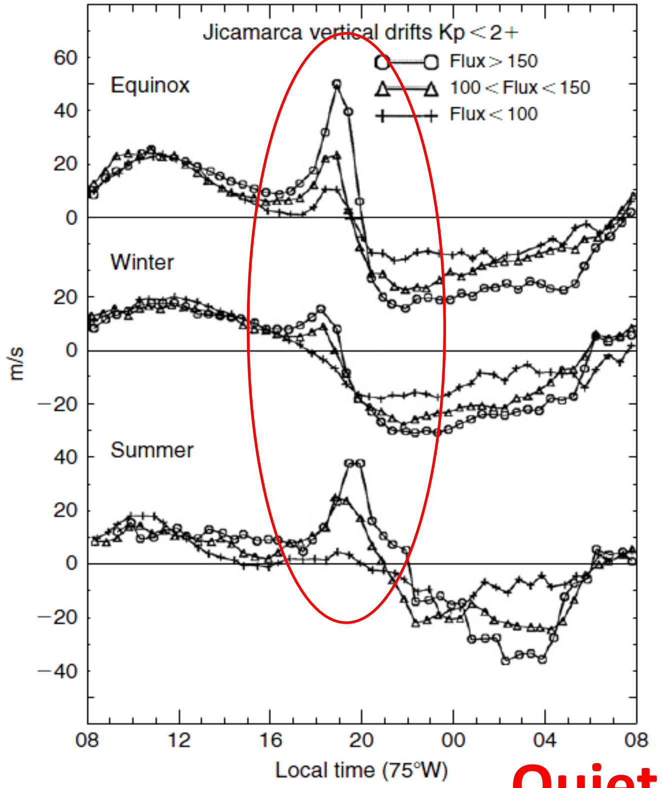
Westward electric field => moves down

Disturbed thermospheric wind

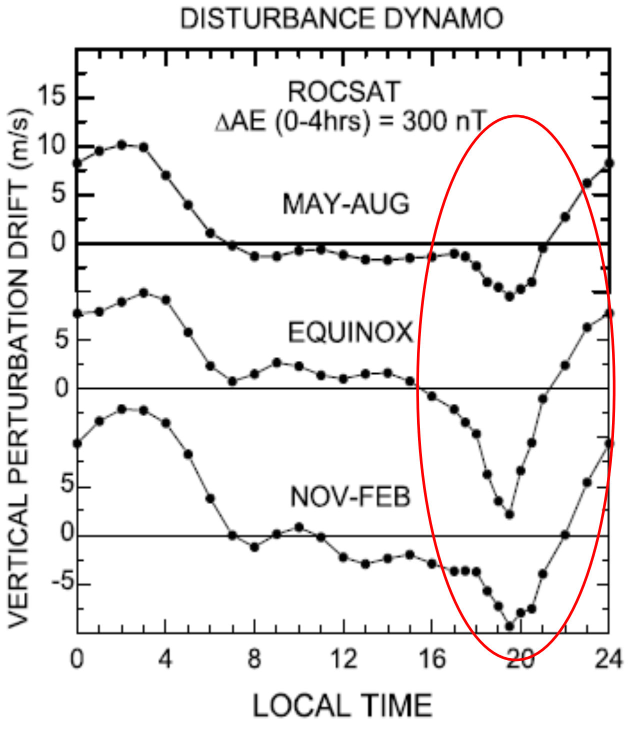




PPEF



Quiet day



DDEF

Magnetic signatures [PPEF and DDEF]

Law of Biot and Savart

$$\Delta H = Sq + D_{iono} + D_{mag}$$

ΔH: H component of the Earth's magnetic field measured by magetometers

Sq : regular variation of the Earth's magnetic field during magnetic quiet days

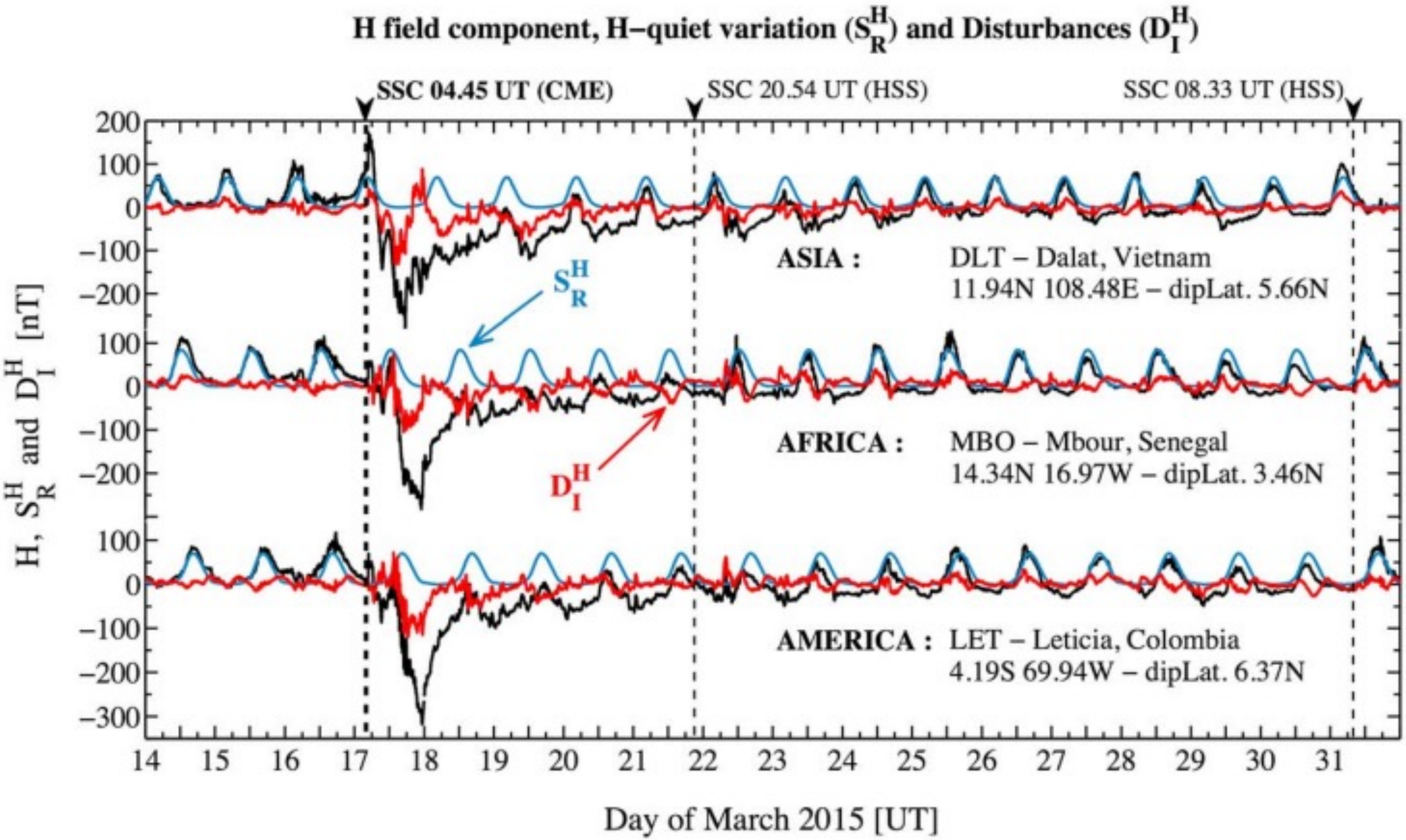
D_{iono} : magnetic disturbance due to the ionospheric electric currents

D_{mag} : magnetic disturbance due to the ionospheric electric currents (SYM-H, ASYM-H)

Disturbed ionospheric electric current

$$D_{iono} = \Delta H - Sq - D_{mag}$$

$$D_{iono} = DP_2 + D_{dyn}$$

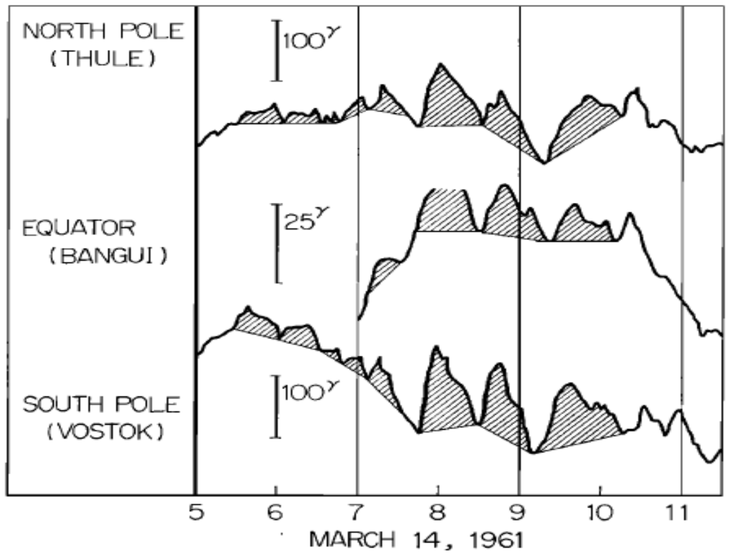


blue : the Regular variation Sq, black : ΔH measured, red :Diono disturbance

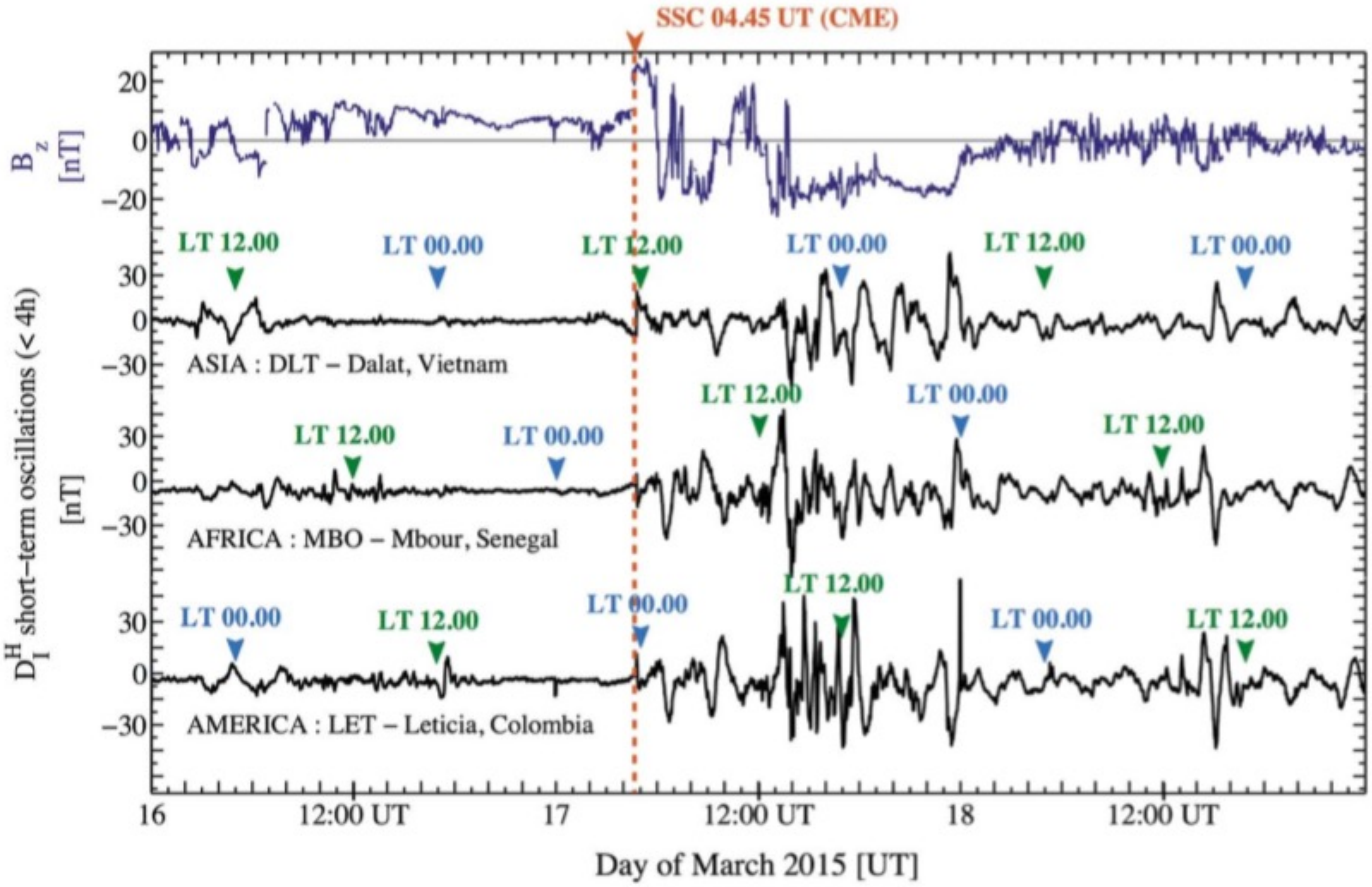
Magnetic signature of PPEF / DP_2

WORLD WIDE DISTURBANCE

(Nishida ,1968)

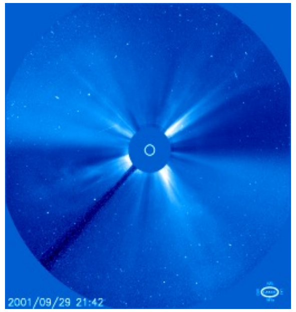


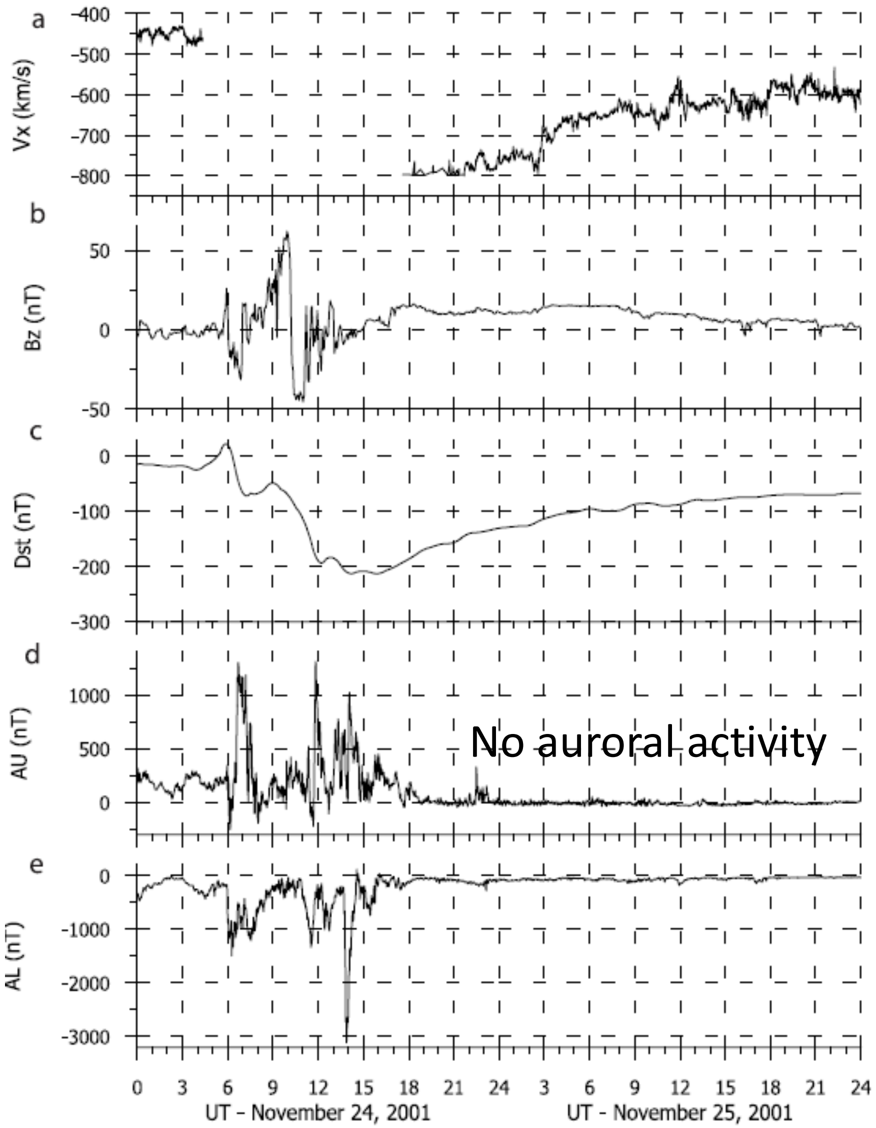
Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations a (Thule), 05.0 (Bangui), and —89.1 (Vostok).

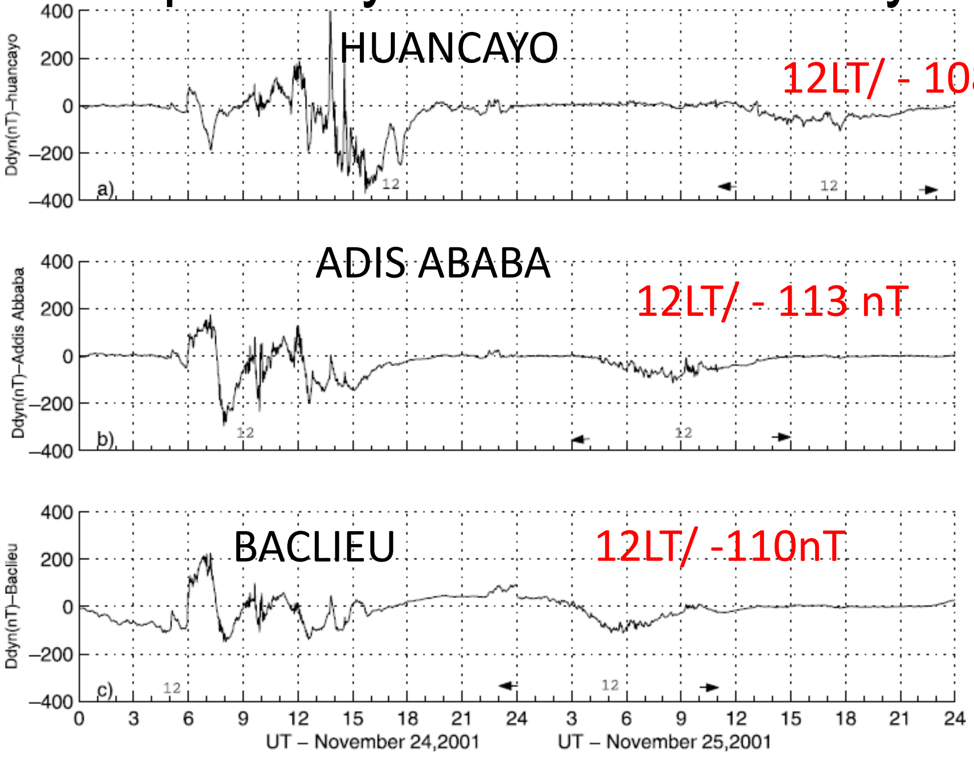


Magnetic disturbance of the H component due to PPEF at specific longitudinal sectors, from 16 to 18 March, from top to bottom are plotted the Bz component of IMF, ssectors. (Nava et al., JGR 2016)

Magnetic signature of DDEF D_{dyn} (simple case : a quiet day after a storm / only CME)





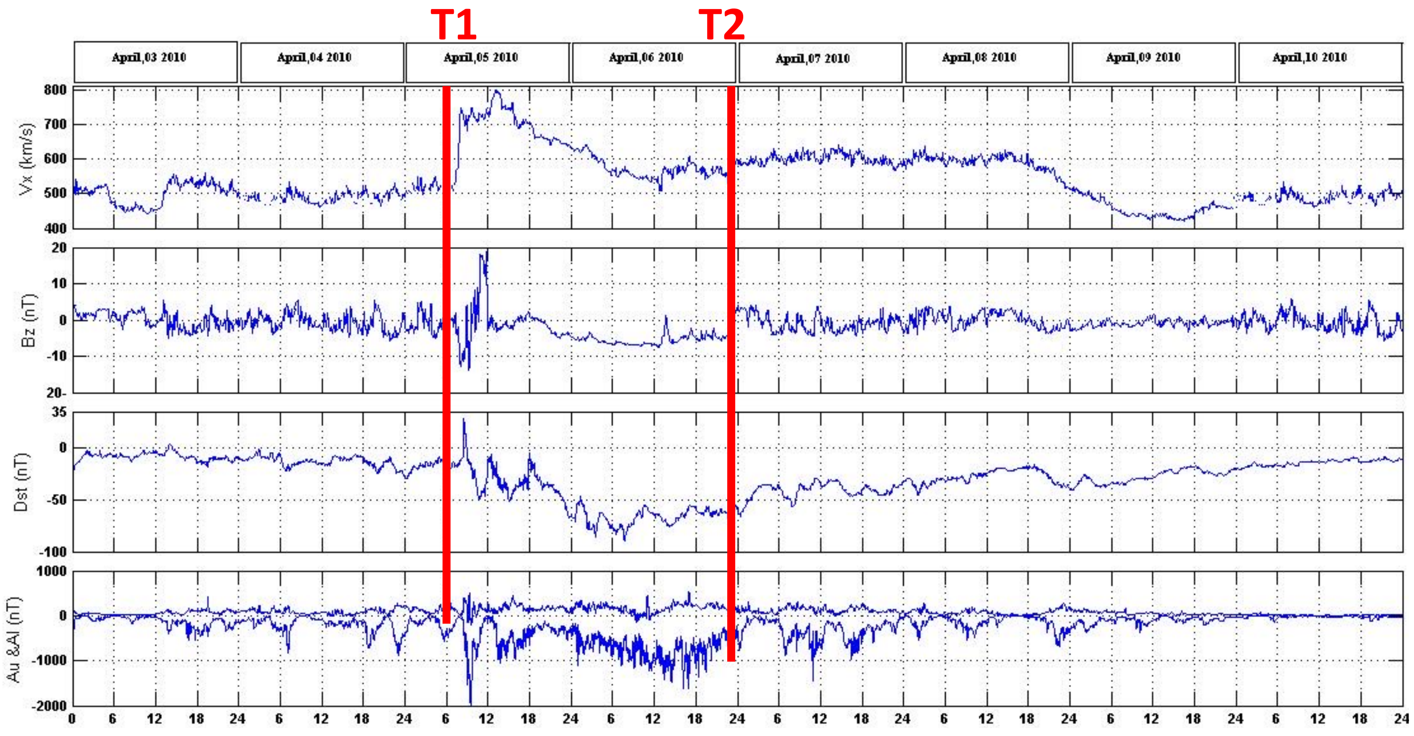


$$D_{iono} = DP_2 + D_{dyn}$$

To isolate the magnetic Ddyn due to the ionospheric disturbance dynamo at the equator, we selected magnetic quiet days just after the storm => DP2 ~ 0

$$D_{iono} = D_{dyn}$$

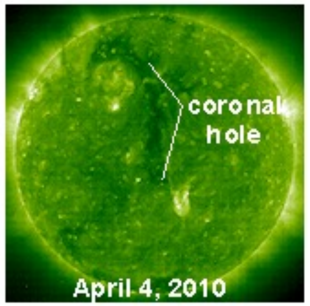
Le Huy and Amory-Mazaudier, JGR 2005, 2008
Zaka et al., Annales Geophysicae 2009/ Zaka et al., JGR 2010 [modelling with TIEGCM]



T1 : Shock of CME on April 5 at 08h25

T2 : arrival of High Speed Solar Wind on April 6 around 24h00

Coronal Holes:

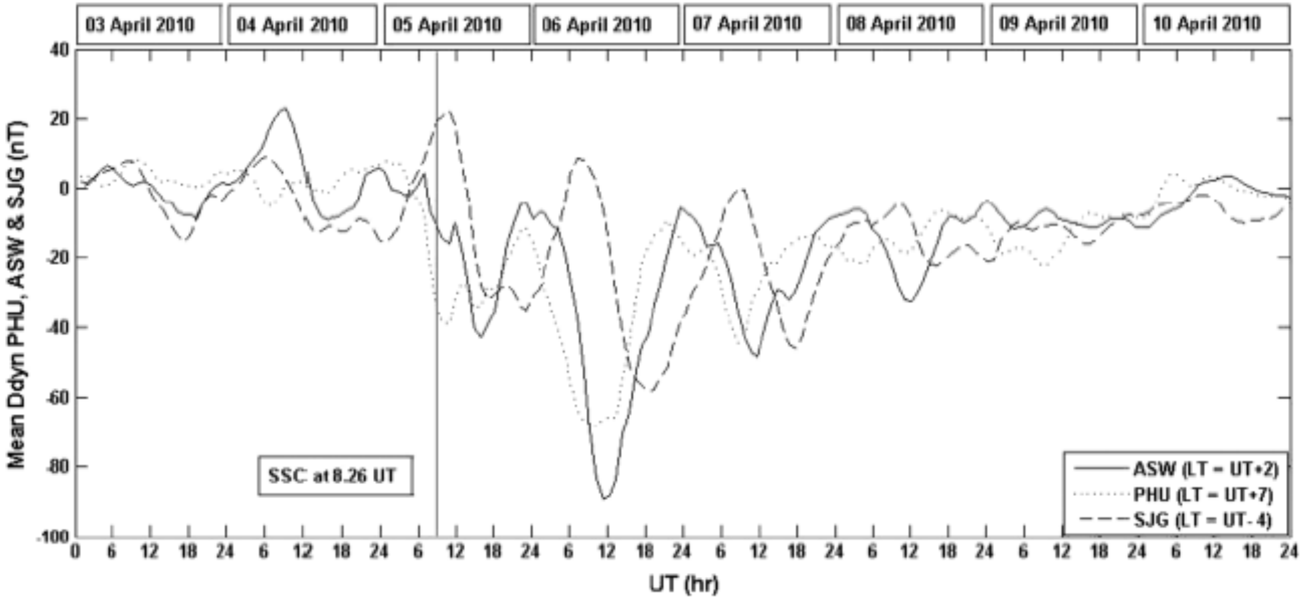


A solar wind stream flowing from the indicated coronal hole should reach Earth on April 6th or 7th. Credit: SOHO Extreme UV Telescope

To separate the effect of the DP2 signal from the disturbance dynamo (Ddyn) signal, **we take the average value of 4 h with sliding of 1 h for the whole period**

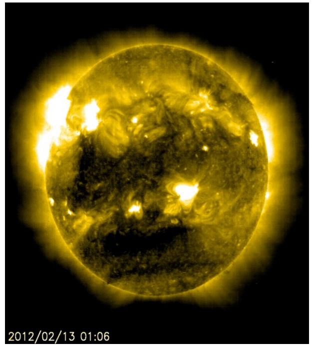
magnetic disturbance of DDEF, Ddyn, observed in the three longitude sectors : Asia, Africa , America , due to a CME followed by a high speed solar wind [April 2010],

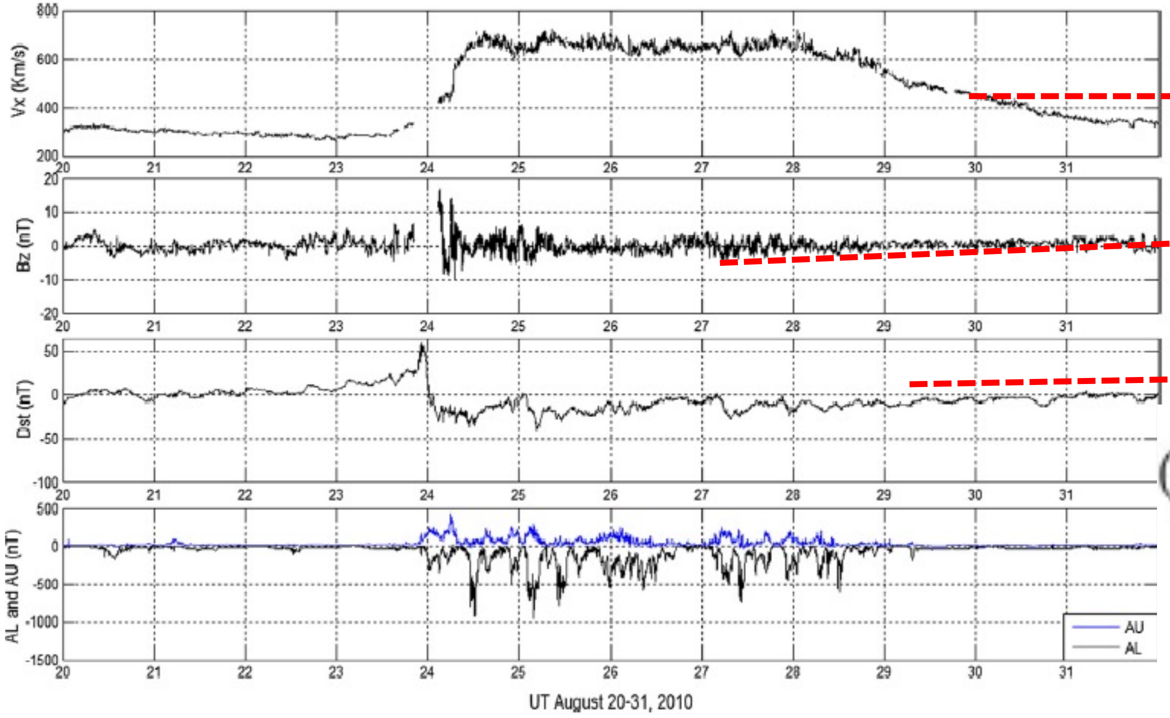
Fathy, I., C. Amory-Mazaudier, A. Fathy, A. M. Mahrous, K. Yumoto, and E. Ghamry (2014), Ionospheric disturbance dynamo associated to a coronal hole: Case study of 5–10 April 2010, J. Geophys. Res. SpacePhysics, 119, 4120–4133, doi:10.1002/2013JA019510



HIGH SPEEED SOLAR WIND

Features od HSSW

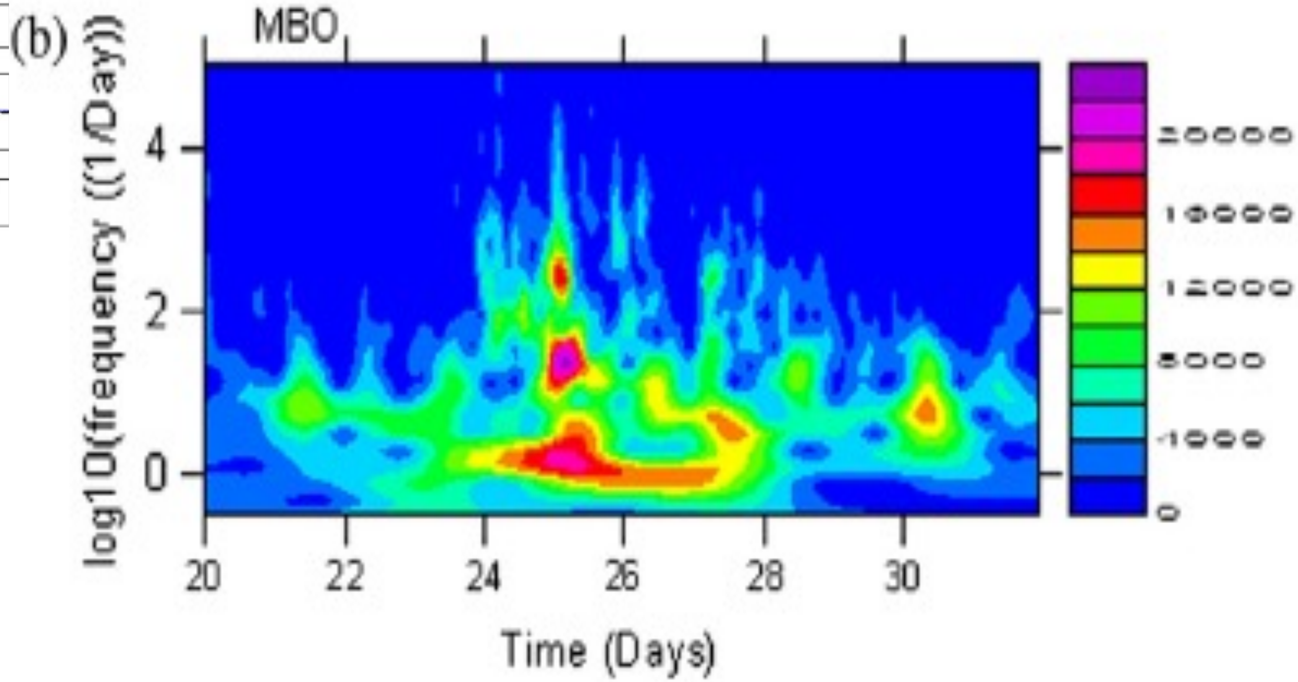




Large solar wind speed

Oscillating Bz

No large Dst



Scalograms revealing the amplitude **wavelet coefficients** of D_{iono} at MBO

Zaourar, N. , C. Amory-Mazaudier and R. Fleury, ، Hemispheric asymmetries in the ionosphere response observed during the high-speed solar wind streams of the 24-28 August 2010 (2017), Advances in Space Research, doi.org/10.1016/j.asr.2017.01.048.

Magnetic variations at three observatories located in three regions (from top to bottom): GUA (Asia), MBO (Africa), and KOU (America) from April 4-10, 2010. /**Law of Biot and Savart /**

Disturbed ionospheric current $D_{iono} = \Delta H - S_q - D_{mag}$

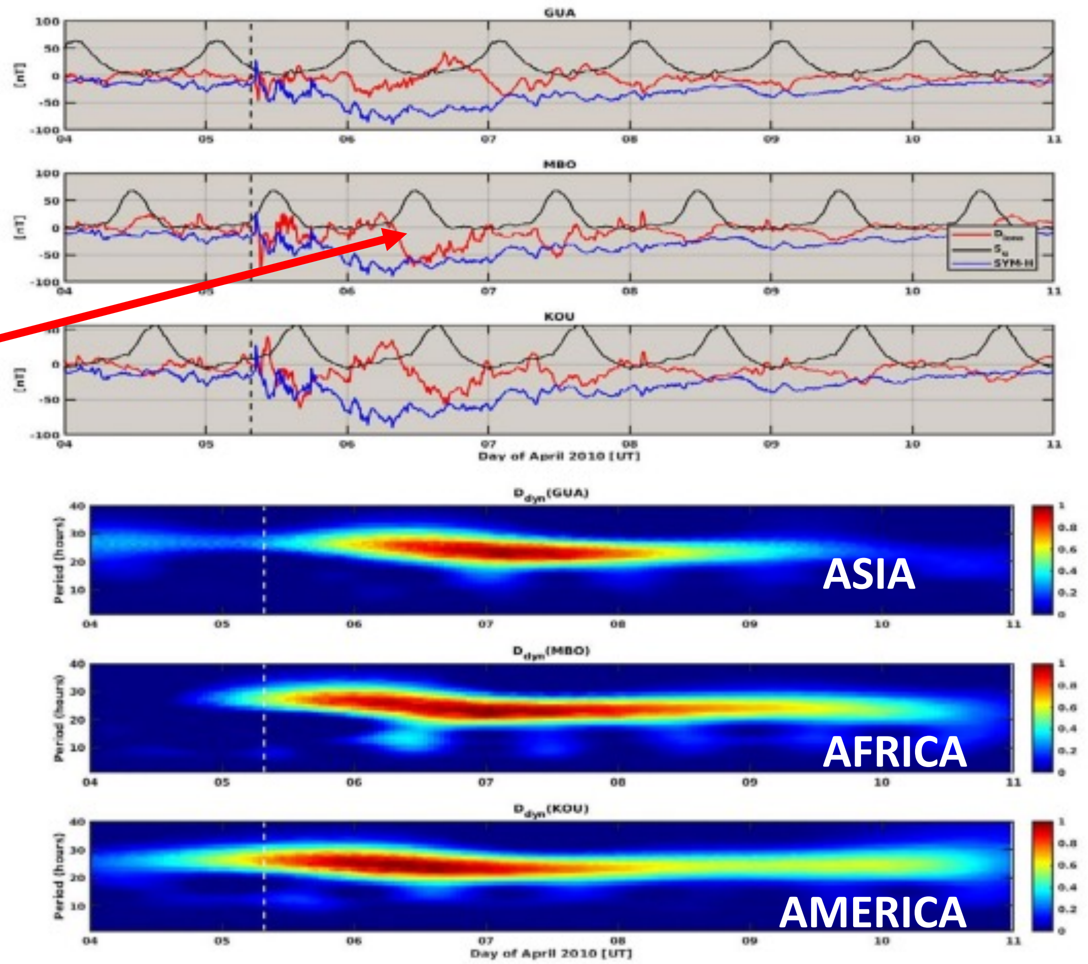
<u>Top figure</u>

ΔH measured (black),

Regular S_q variation (blue)

Diono = $DP_2 + D_{dyn}$ (red)

reversed from their observed normal quiet-day variation.



ASIA/GUA

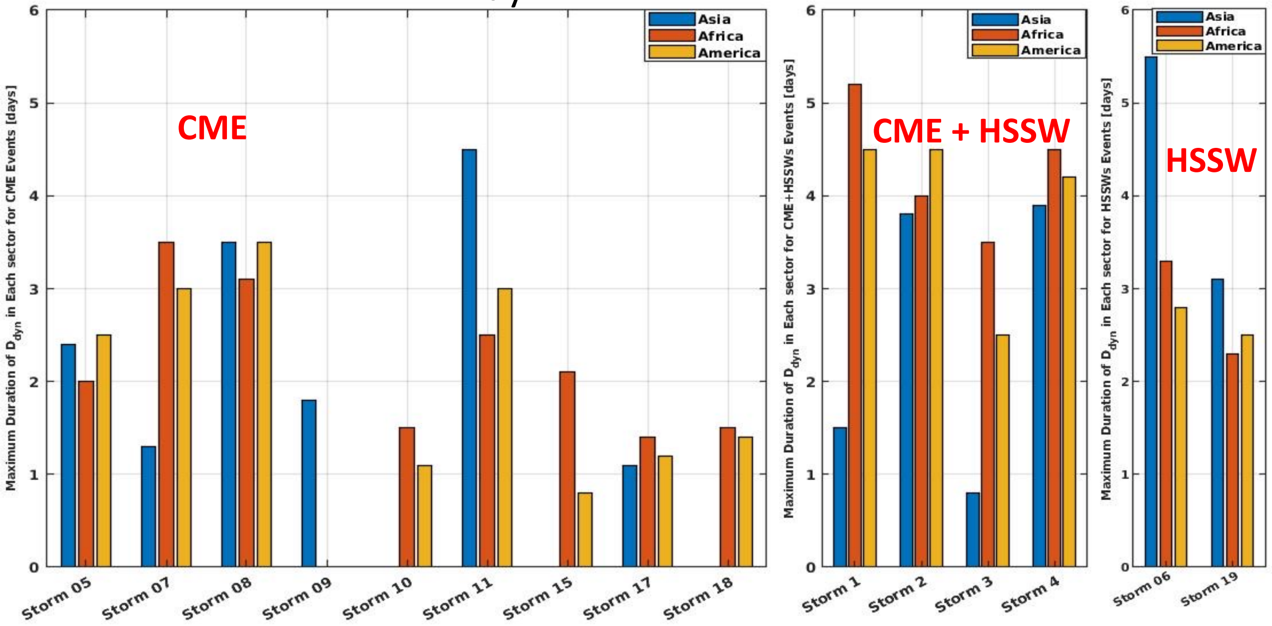
AFRICA/MBO

AMERICA/KOU

<u>Bottom figure</u>

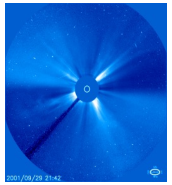
Disturbance dynamo (Ddyn) estimated using wavelet based semblance analysis. The vertical dashed line corresponds to the arrival of CME

D_{dyn} DURATION

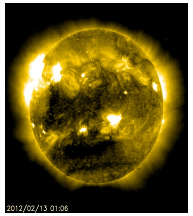


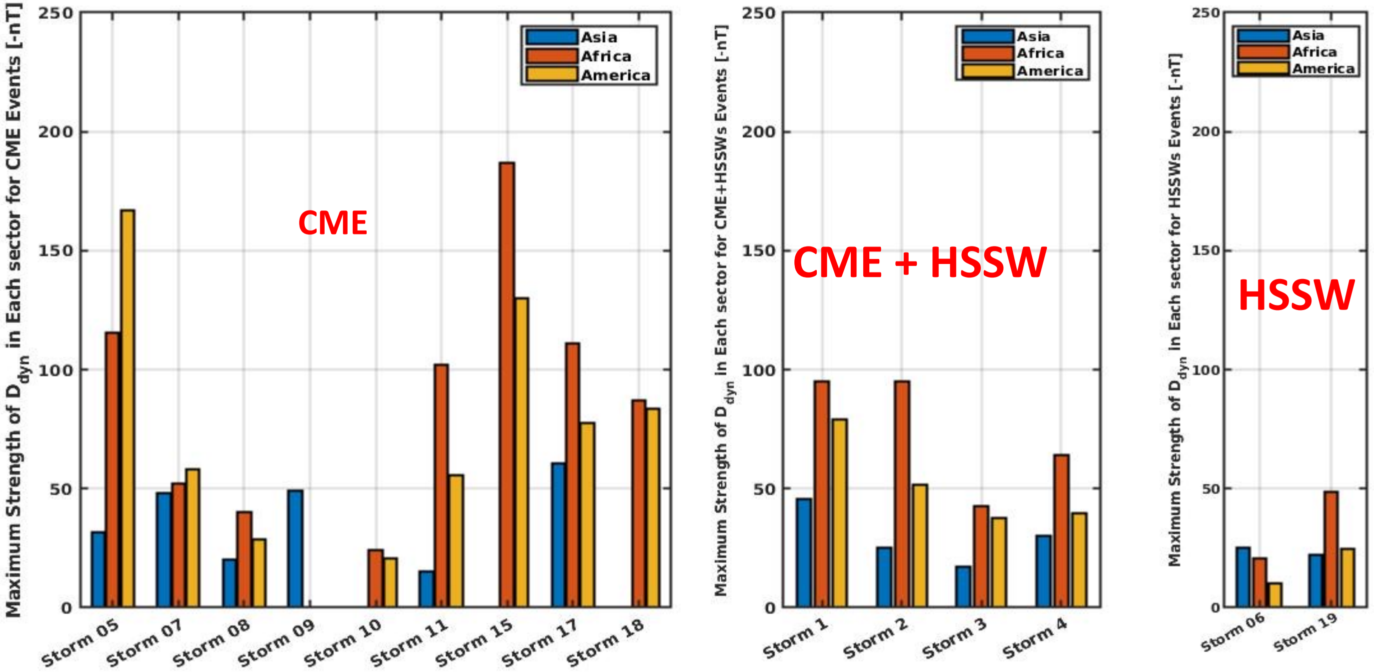
STUDY OF 19 STORMS

D_{dyn} Magnetic signature of DDEF



D_{dyn} STRENGTH





*Longest duration for HSSW
*Greater strength for CME
*HSSW => All longitude sectors are disrupted
*CME => 1, 2 or all longitude sectors disturbed

Younas, W. et al., Magnetic signatures of ionospheric disturbance dynamo for CME and HSSWs generated storms , Earth and Space Science, https://doi.org/10.1029/2021SW002825

Conclusion

The results presented concerns some direct impacts of Sun on the Earth.

It is a tiny part of space weather concerning certain relations between the Sun and the Earth. We have shown results obtained mainly with GNSS receivers and magnetometers. There are many other works using satellite data and models (IRI NeQuick, TIEGCM,

Studies are currently being developed on the effect of earthquakes, stratospheric warming or QBO on the variations of the Ionosphere, and GNSS receivers are again very useful.

There are a lot of data sets on the web, and this give opportunity to many students to do PhD and contribute to built this new systemic approach of the Sun Earth system needed for Space Weather.

The GNSS receivers can be also used to study the motions tectonic plates, the vapor water in the troposphere.