SUN-EARTH CONNECTIONS
Impacts of Space Weather events at Low Latitudes

Christine Amory-Mazaudier

Sorbonne Université, Ecole polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris, CNRS, Laboratoire de Physique des Plasmas (LPP), Paris France

christine.amory@lpp.polytechnique.fr

United Nations / Germany ISWI Workshop, 10-14 June 2024, Neustrelitz, Germany

OUTLINE

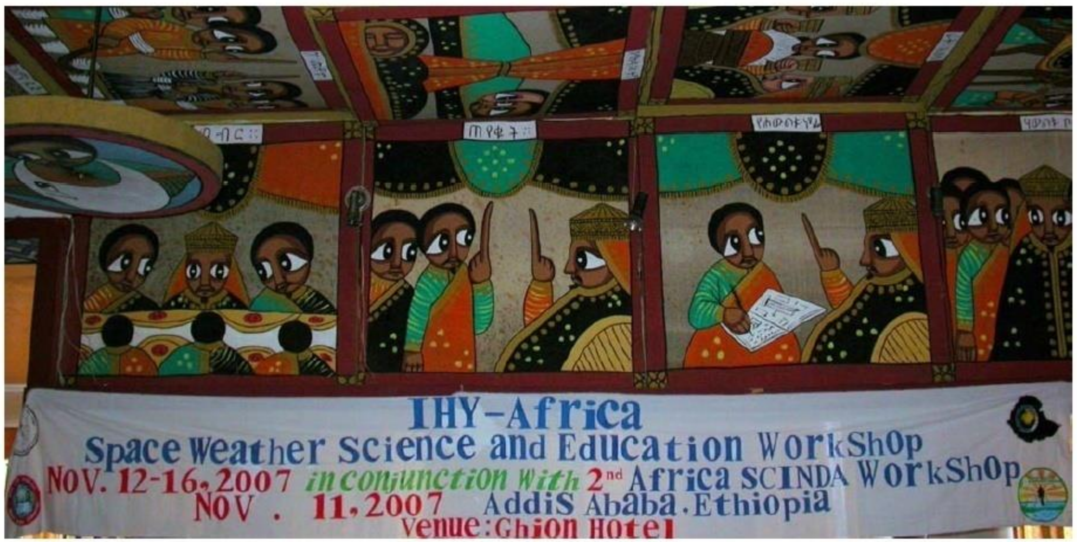
1. IHY and ISWI projects - UNBSSI
2. From Geophysics to Helio physics
3. Characteristics of the low latitudes :
   - EIA, Equatorial Ionization Anomaly
   - EEJ, Equatorial Electrojet
   - PRE, Pre Reversal Enhancement
   - EPB, Equatorial Plasma Bubble
4. TEC measurements => Ionosphere
5. Quiet magnetic time :
   - Ionization (VTEC), irregularities (ROTI and S4)
6. Electrodynamics coupling between High and Low-latitudes:
   - CME (VTEC), Coronal Hole (GTEC)
   - Equivalent electric current of PPEF and DDEF
   - Impact of PPEF and DDEF on irregularities
   - Impact on PPEF and DDEF on the Earth's magnetic field
7. Conclusion

International Heliophysical Year 2007-2009

a turning point in the participation of African countries

WHOLE AFRICA

IHY-Africa
Space Weather Science and Education
Workshop Report



The Ethiopian Physical Society

in conjunction with

Addis Ababa University and Bahir Dar University

African Countries Represented (20): (72 representatives)

Algérie
Bénin
Burkina Faso
Cameroon
Cape Verde
Côte d'Ivoire
Démocratique République du Congo
Egypt
Ethiopia
Kenya
Liberia
Libya
Mozambique
Namibia
Niger
Nigeria
République du Congo
Sénégal
South Africa
Uganda

Other Nations Represented (9): (56 representatives)

Australia
Austria
Canada
France
India
Italy
Japan
UK
USA

Distribution of inexpensive instruments GPS and magnetometers

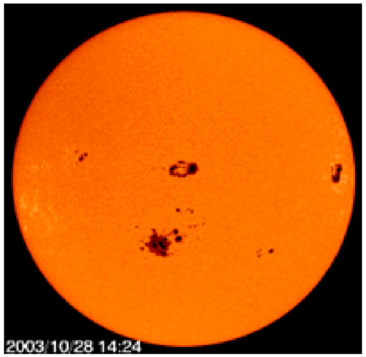
ISWI project 2010-2012
ISWI network: http://www.iswi-secretariat.org

1. Distribution of scientific tools
2. Training schools / Space Weather
3. PhD => position in the country
4. Curricula in Universities

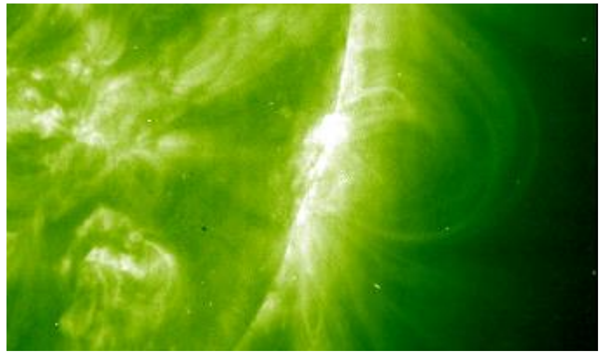
GLOBAL APPROACH OF OF THE SUN-EARTH SYSTEM

Electromagnetic emissions and particles [some large scale phenomena]

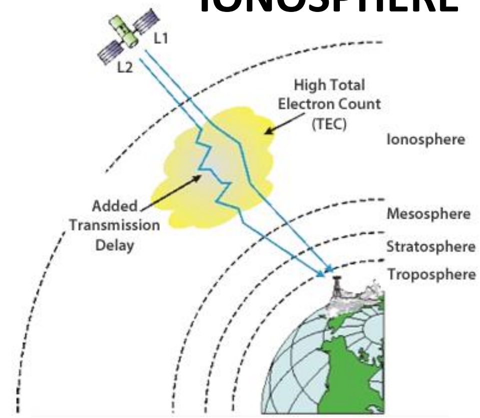
Sunspots

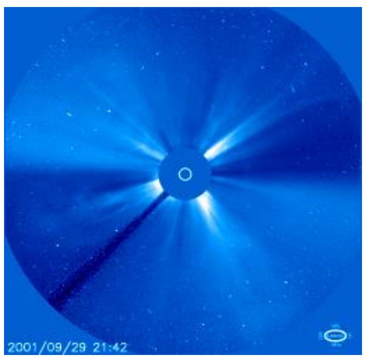


Big solar flare of November 2003



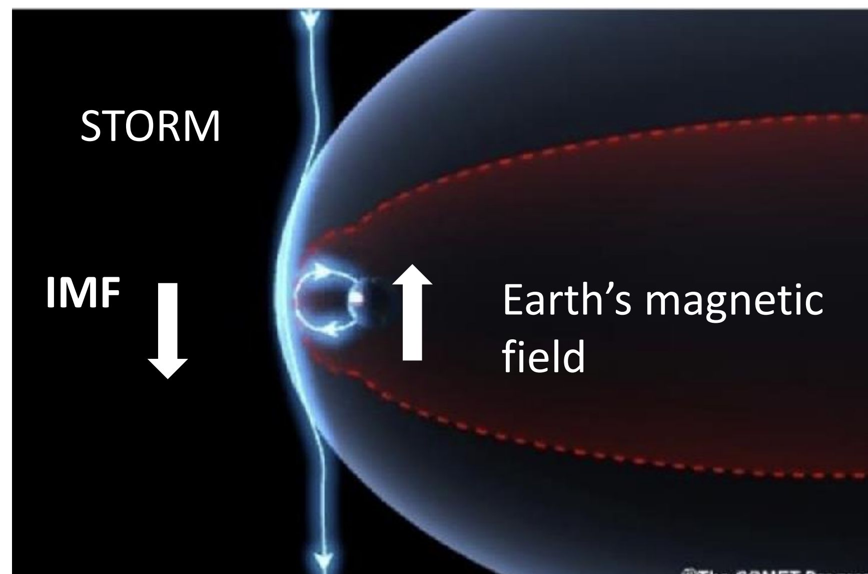
IONOSPHERE

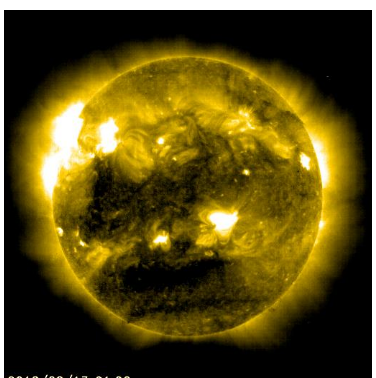




CME: Coronal Mass Ejection
Magnetic cloud
Billions of tons of solar mass

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)

The two main channels

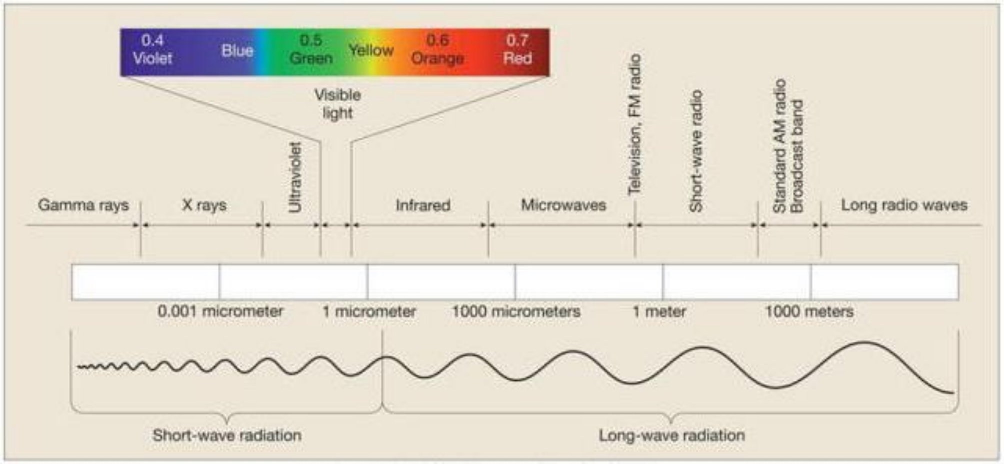
Electromagnetic emissions [8’]

*Regular

**Disturbed

Solar flare: X rays

Solar bursts : Radio emissions



SOLAR WIND - PARTICLES [1-4 days]

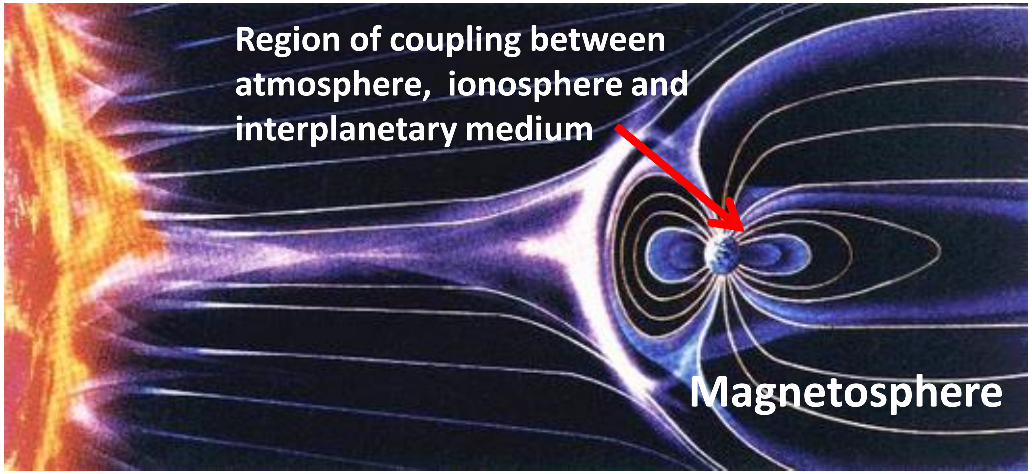
*Regular

**Disturbed by

Coronal Mass Ejection

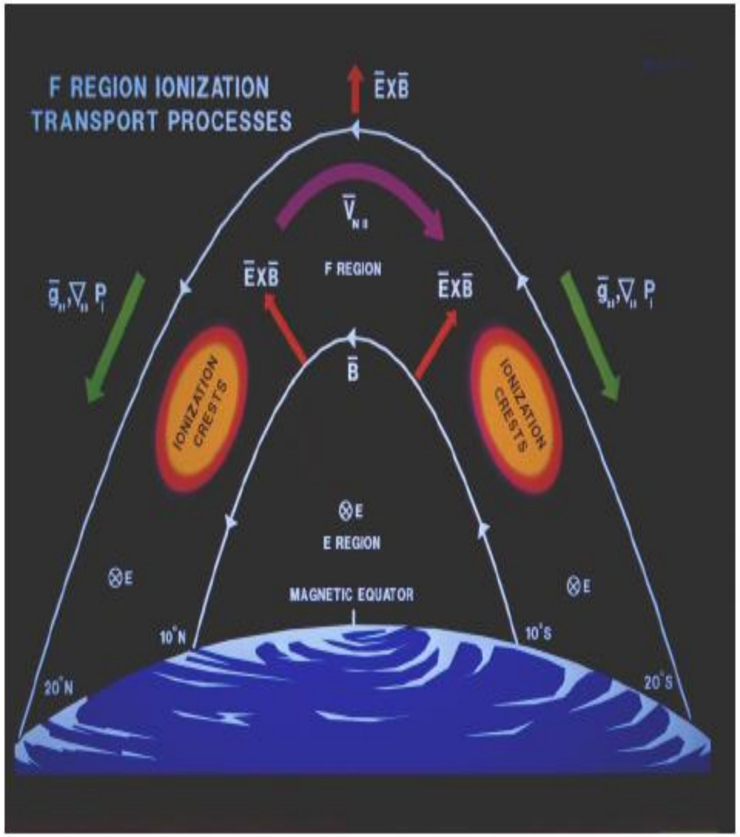
High speed solar wind from coronal hole, etc…

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

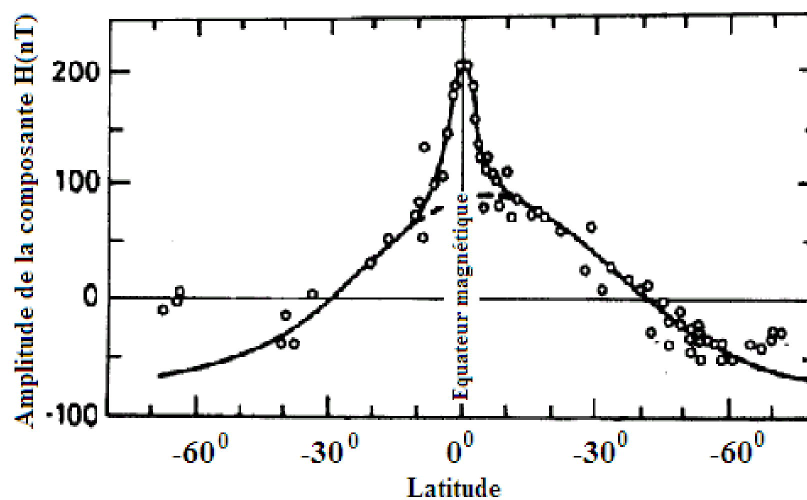
PHYSICS of Low latitudes



At equator the Earth's magnetic field is horizontalDuring 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

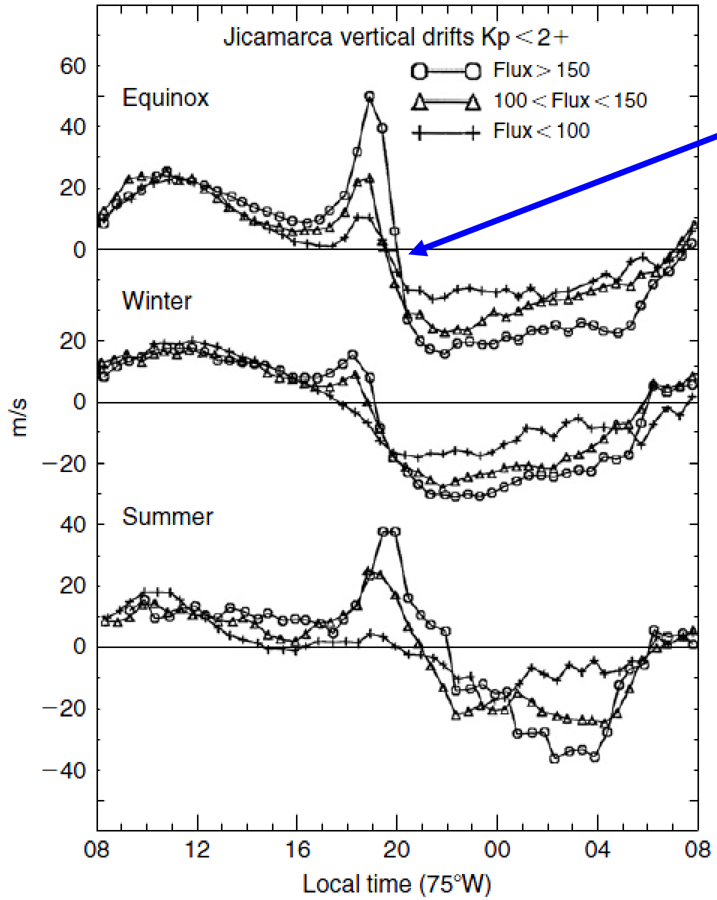
Equatorial Fountain

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



The Equatorial Electrojet (Jacobs, 1990)

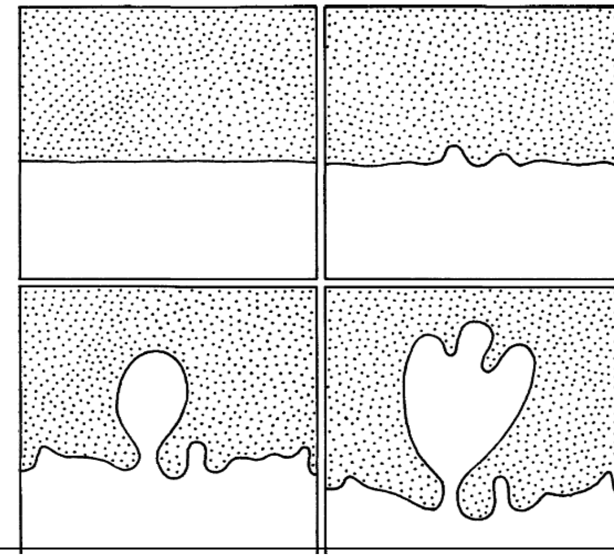
PRE : Pre Reversal Enhancement



Equatorial Plasma Bubbles

Magnetic quiet time

ExB drift 25m/s ⇔ 1 mV/m

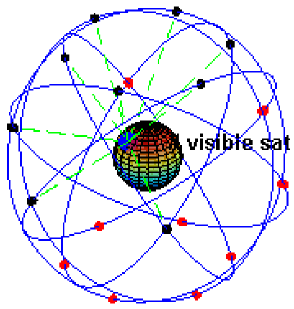


Sequential diagram, from photos, of the development of a Rayleigh Taylor instability. The heaviest fluid [... ..], over a lighter and more transparent fluid (Kelley, 2009)

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)

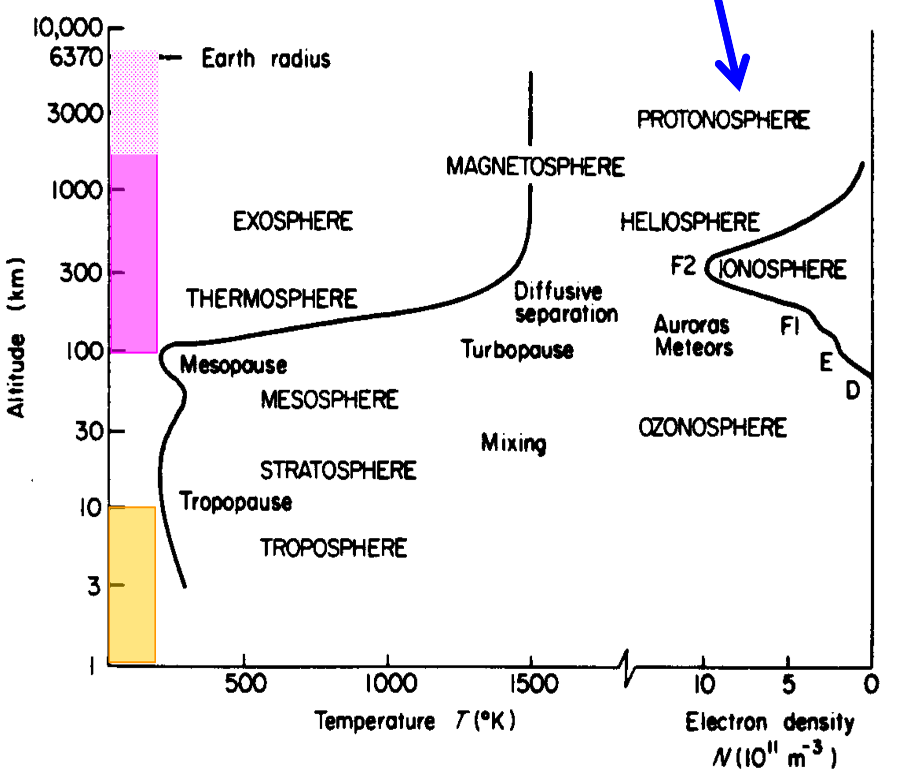
Equatorial plasma bubble s: a Review d'Archana Bhattacharyya jn special issue ionospheric and magnetic signatures of Space Weather events https://www.mdpi.com/journal/atmosphere/special_issues/Space_Weather_Events

Use of GNSS :The satellite signal is strongly modified by ionosphere and troposphere



TEC

Total electron content



LAYERS

> 600 km EXOSPHERE
few collisions, Particles follow balistic orbit

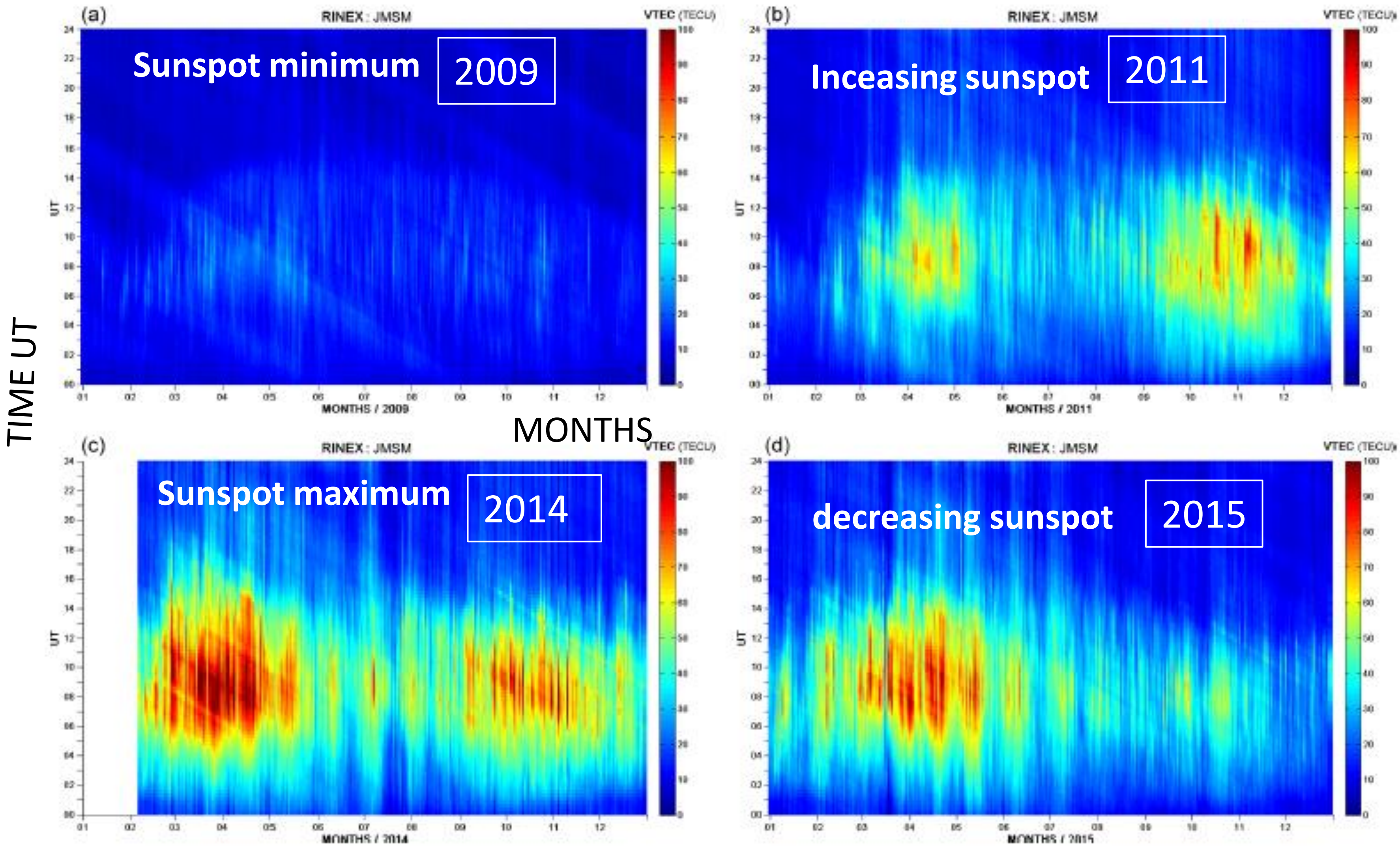
80-600 km THERMOSPHERE
Ionization by the solar X-EUV radiation **IONOSPHERE**

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

11-30 km STRATOSPHERE
Turbulence

0-11 km TROPOSPHERE
Meteorological phenomena

Station GPS JOMSON (JMSM) **NEPAL**



A two-dimensional (2D) variation in vertical TEC according to UT at the JMSM station

Pandit et al., Ann. Geophys., 39, 743–758, 2021 https://doi.org/10.5194/angeo-39-743-2021

STUDY of IONOSPHERIC IRREGULARITIES IN EAST AFRICA using the ROTI index derived from the TEC

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

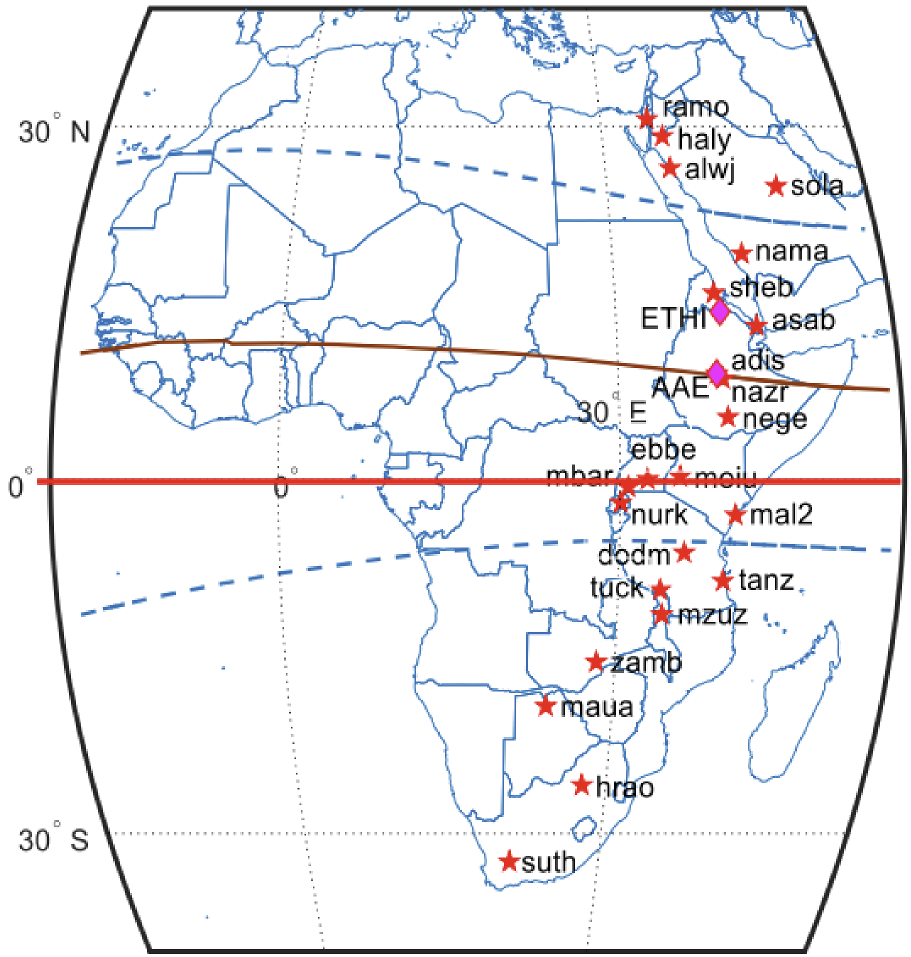
$$\mathrm{roti} = \sqrt{\langle \mathrm{rot}^2 \rangle - \langle \mathrm{rot} \rangle^2}$$

Magnetic equator

± 15° dip latitude

GNSS station

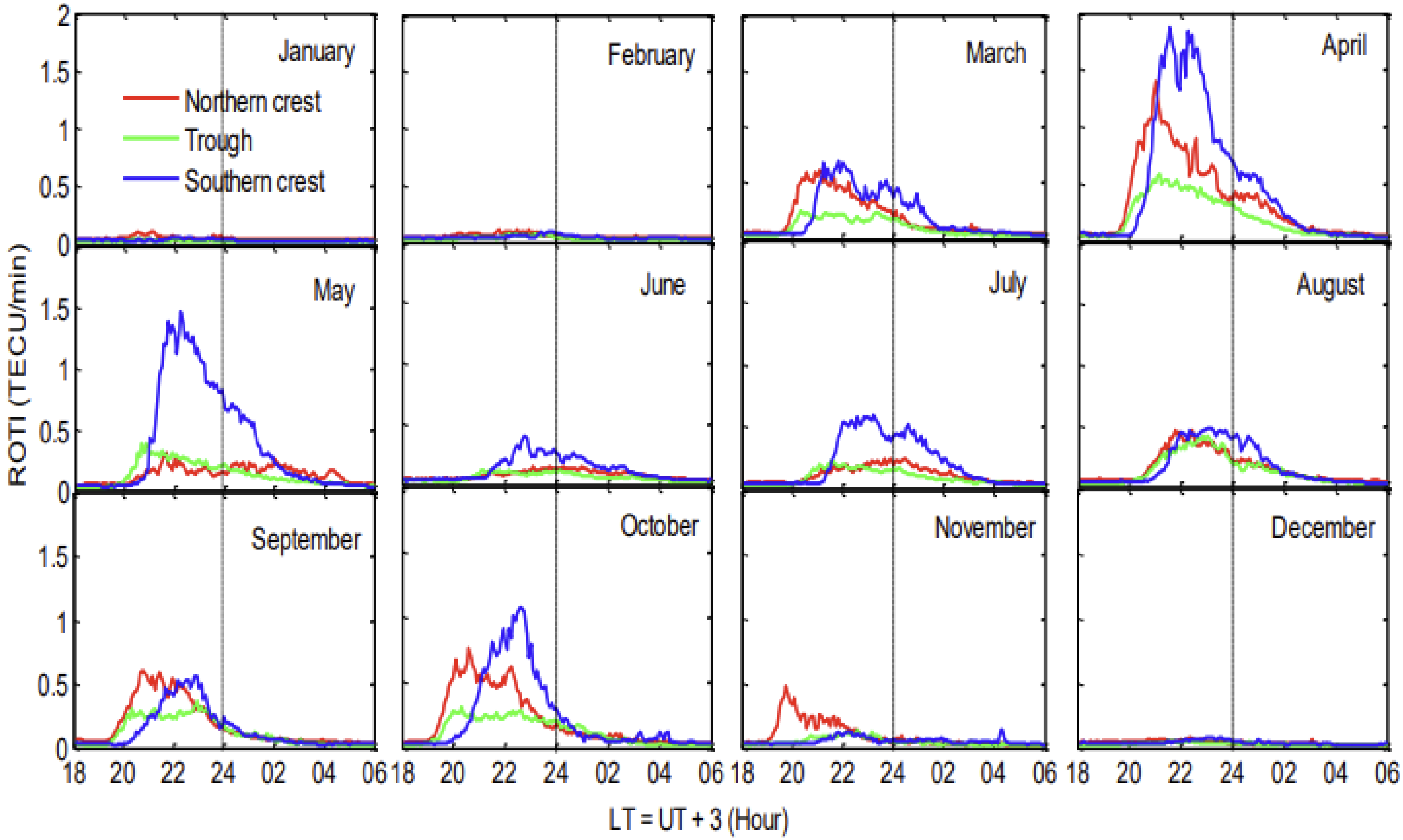
Magnetometer station



NIGERIA

Amaechi, P.A., E.O. Oyeyemi, A.O. Akala, E.O. Falayi, M. Kaab, Z. Benkhaldoun, C. t al., , Quiet-time ionospheric irregularities over the African Equatorial Ionization Anomaly (EIA) region, Radio Science, 55, e2020RS007077. https://doi.org/10.1029/2020RS007077

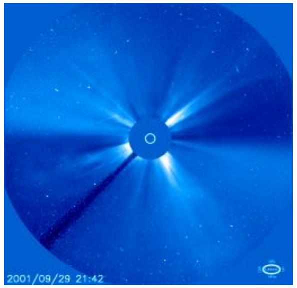
Asymmetry between the Northern and Southern crests of the EIA Due to configuration between the geographic and geomagnetic equators



Monthly mean variation of quiet time irregularities over Northern crest (red line), trough (green line) and Southern crest (blue line), in 2013 (Amaechi et al., 2020)

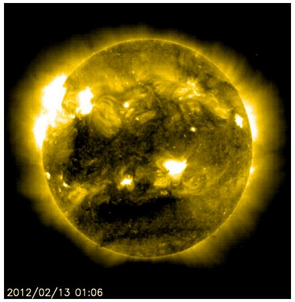
CME: Coronal Mass Ejection
Magnetic cloud

Coronal hole HSSW -CIR



SUN-EARTH CONNECTIONS

Solar wind from the Sun to the Earth



Coupling between high and low latitudes

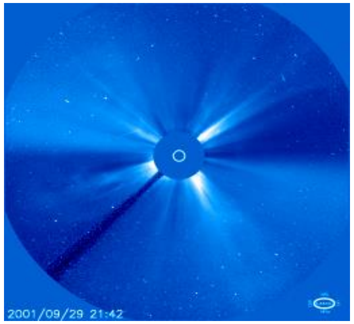
1. Transmission of an electric field PPEF
Magnetic disturbance ***DP_2*** *(large scale disturbed ionospheric electric current)*

2.a Thermal expansion of the atmosphere

Changes in pressure, temperature , motions , composition

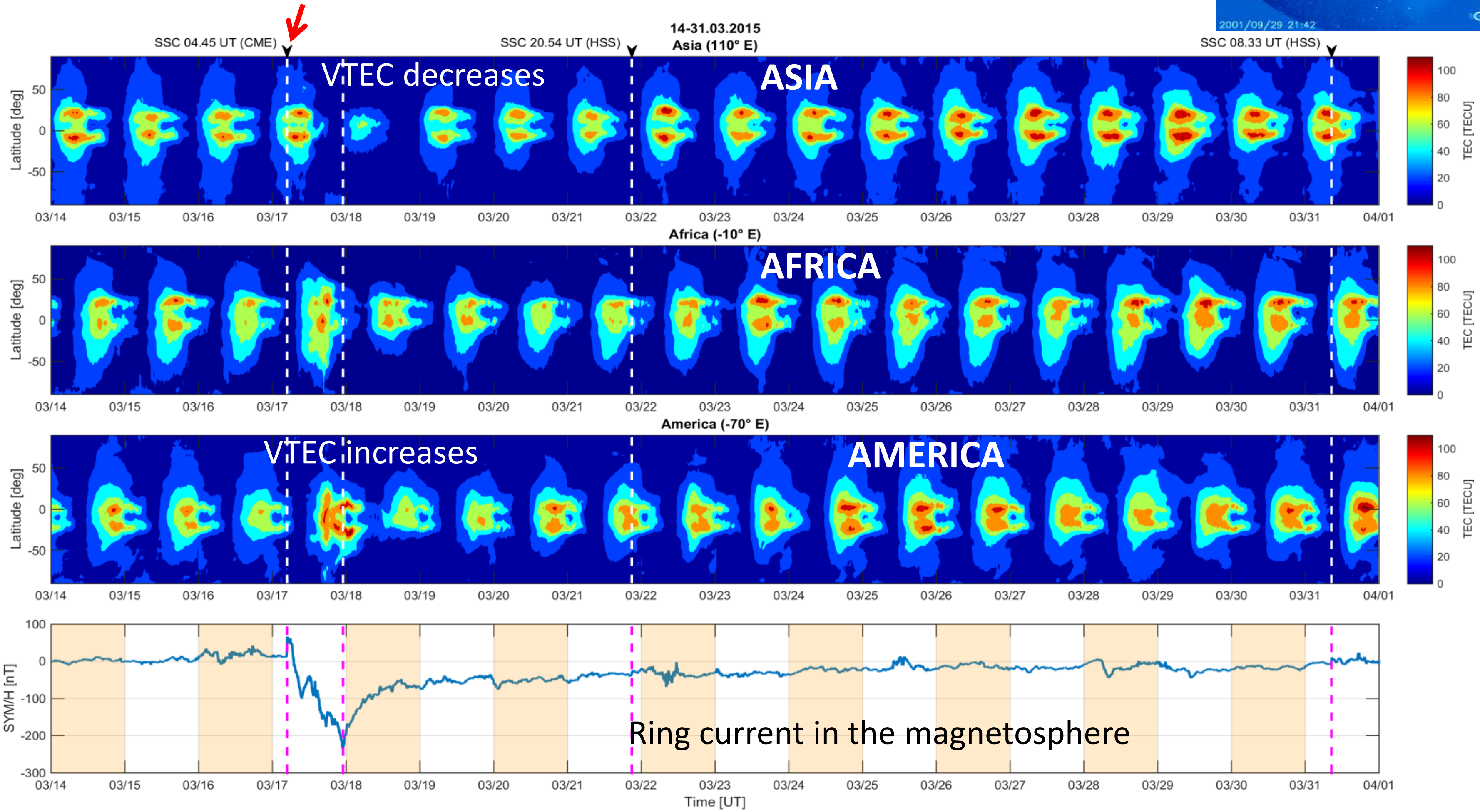
2.b Transmission of a disturbance electric field dynamo DDEF by the disturbed atmospheric motions in the dynamo layer
Magnetic disturbance ***Ddyn*** *(large scale disturbed ionospheric electric current)*

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, on March 15 ~ 04.45 - 02.00UT)



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. **TEAM ICTP**

CORONAL HOLE

GEOPHYSICS => HELIOPHYSICS

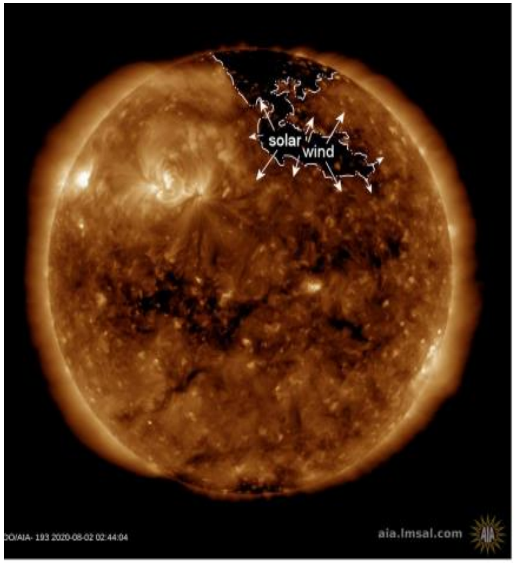
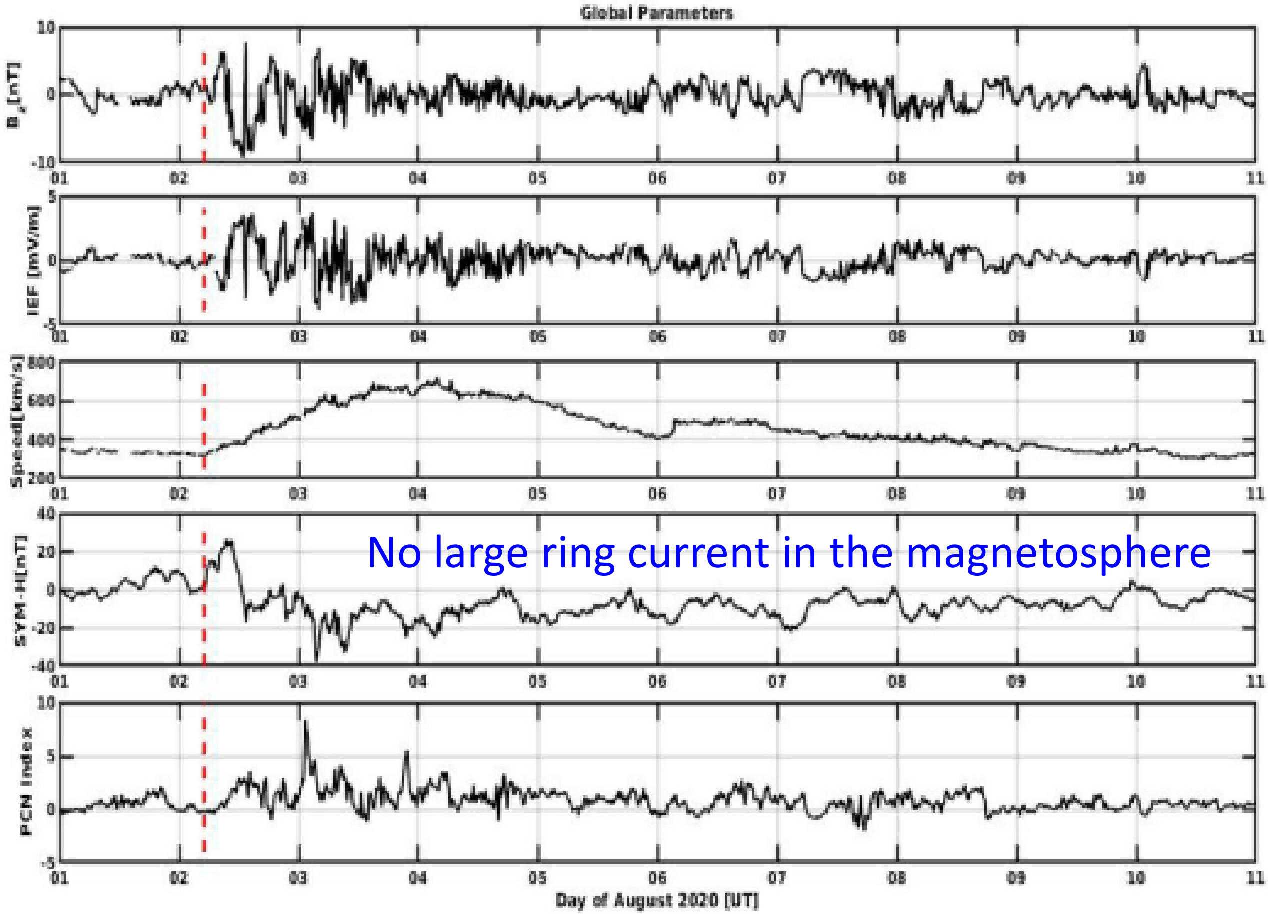


Figure 1. (a) Coronal hole in the northern part of sun as observed by AIA-193 on board Solar Dynamics Observatory (SDO) (Courtesy of NASA/SDO and the AIA, EVE, and HMI science teams)

PAKISTAN

Figure 1.(b) Variations of interplanetary and geophysical parameters, from top to bottom, Bz component of interplanetary magnetic field, solar wind speed, pressure, and SYMH index from 01 August 2020–10 August 2020



Younas, W., Khan, M., Amory-Mazaudier, C., & Amaechi, P. O., Ionospheric response to the coronal hole activity of August 2020: A global multi-instrumental overview. Space Weather, 20, e2022SW003176. https://doi.org/10.1029/2022SW003176

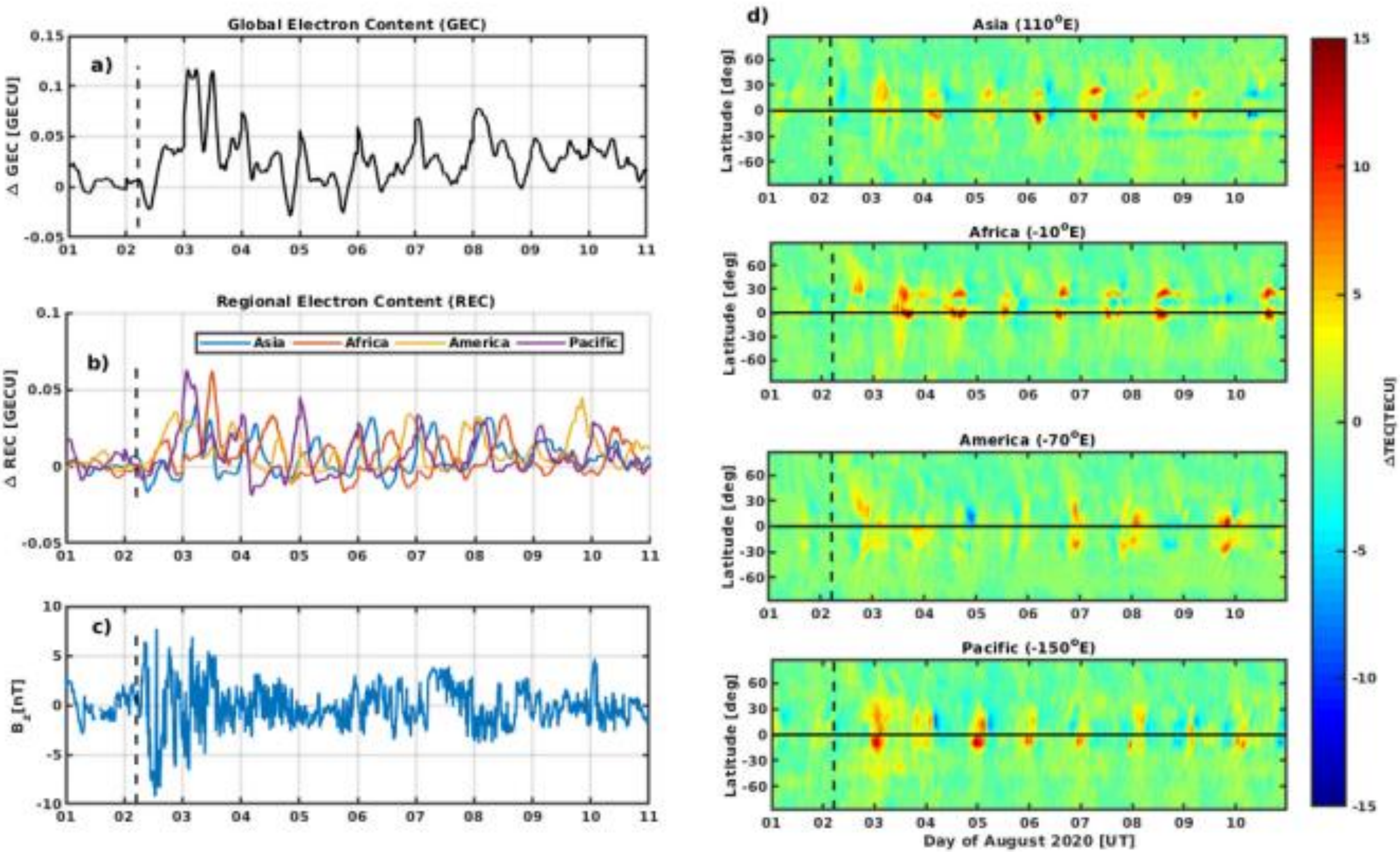


Figure 2. (a) ΔGEC (b) ΔREC in four longitudinal sectors Asia, Africa, America, and Pacific (c) Bz component of interplanetary magnetic field and (d) ΔvTEC at fixed longitudes, from top to bottom, Asia, Africa, America, and Pacific during 01 August–10 August 202

ELECTRODYNAMICS COUPLING BETWEEN HIGH AND LOW LATITUDES

Equivalent electric current systems

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

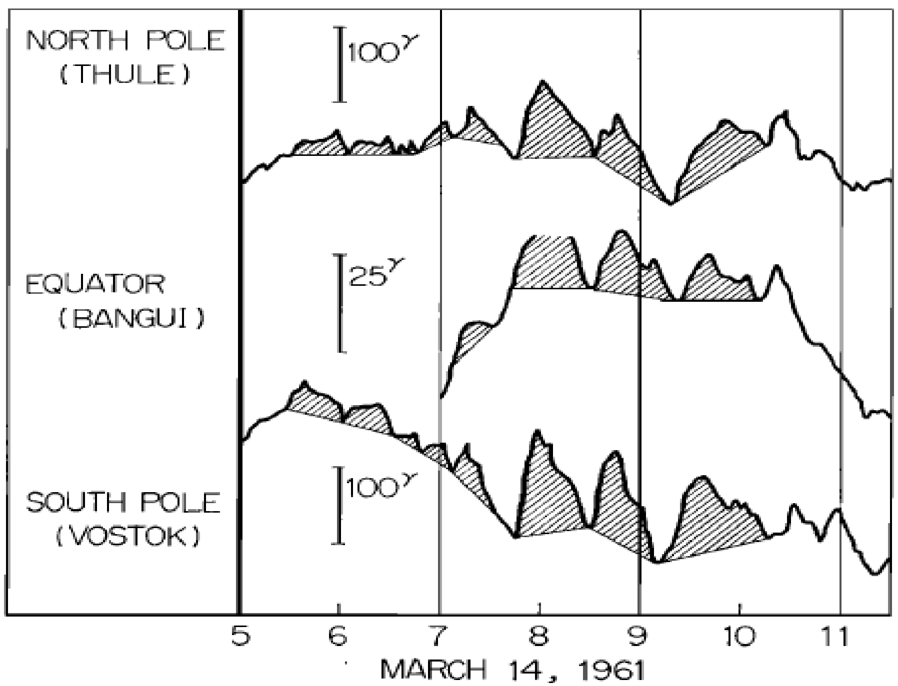
Magnetic disturbance ***Ddyn*** *(large scale disturbed ionospheric electric current)*

DISTURBED IONOSPHERE [PPEF]

Prompt penetration of the magnetospheric convection electric field

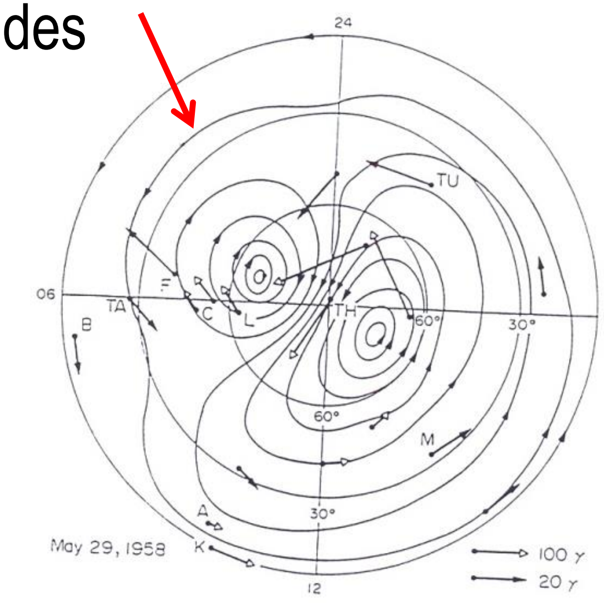
Electrodybnamic oupling between AURORAL and EQUATORIAL regions

The magnetic equivalent current system DP_2



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

DP_2, Nishida, 1968, Ce système de courant s'étend vers les basses latitudes



Nishida, A. (1968), J. Geophys. Res., 73, 1795–1803, doi:10.1029/ JA073i005p01795

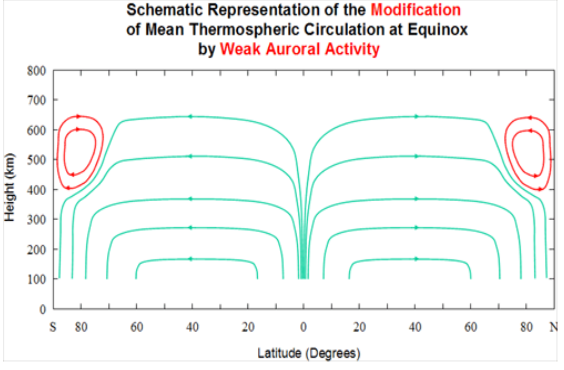
Vasyliunas, V. M. (1970), Mathematical models of magnetospheric convection and its coupling to the ionosphere, in Particles and Fields in the Magnetosphere, edited by M. McCormac, pp. 60–71, Springer, New York.

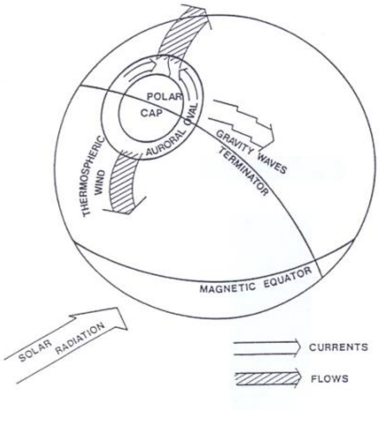
Kobea A.T., et al., , J. Geophys. Res , Vo1105, N° A10, pages 22979-22989, October, 1, 2000.

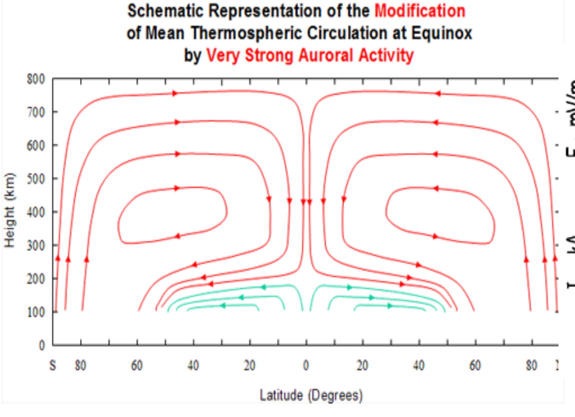
IONOSPHERIC DISTURBED DYNAMO [DDEF]

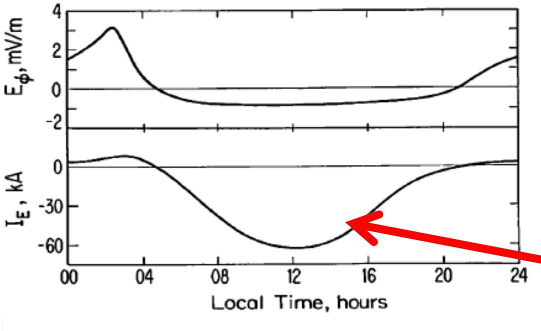
Magnetic disturbance from the Pole to the Equator : D_{dyn}

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









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

Blanc, M., and A. D. Richmond (1980), J. Geophys. Res., 85(A4), 1669–1686, doi:10.1029/ JA085iA04p01669.

Scintillations a regular phenomenon

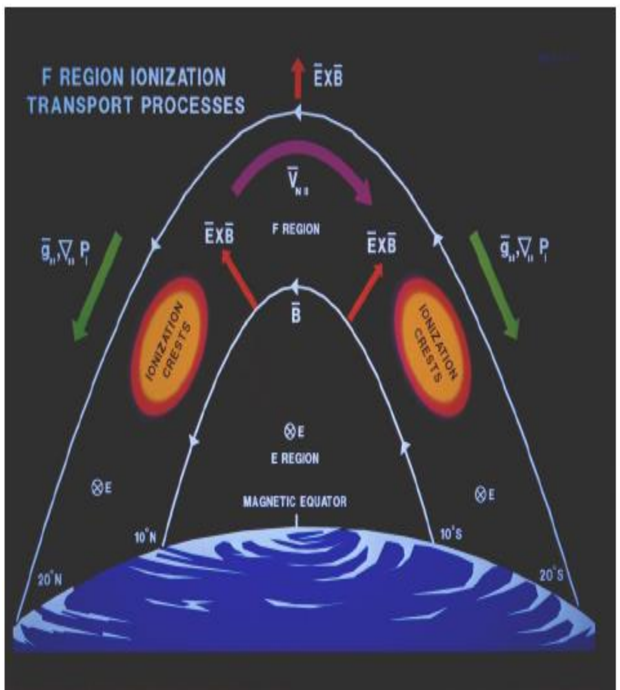
Ionospheric scintillation is the rapid modification of radio waves caused by small scale structures in the ionosphere **: Plasma Instabilities**

S_4 and ROTI indices derived from GNSS data

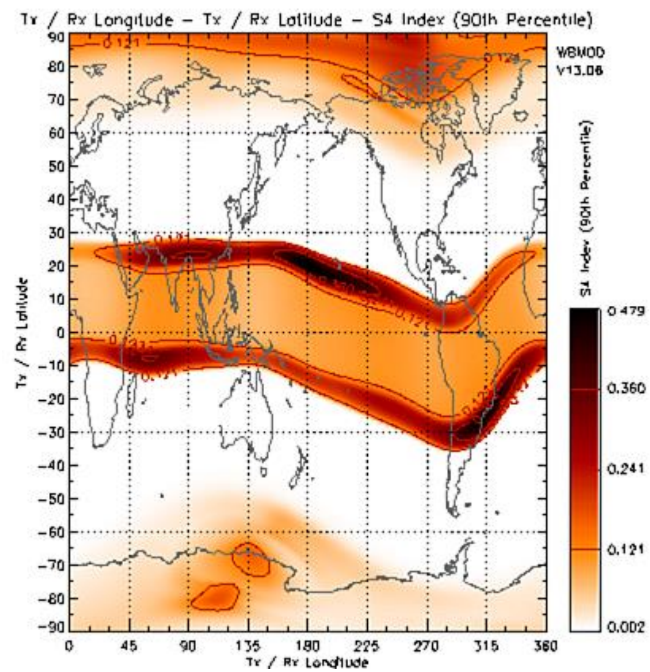
$$S_4 = \sqrt{\frac{<I^2> - <I>^2}{<I>^2}}$$

I : intensity of the signal

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



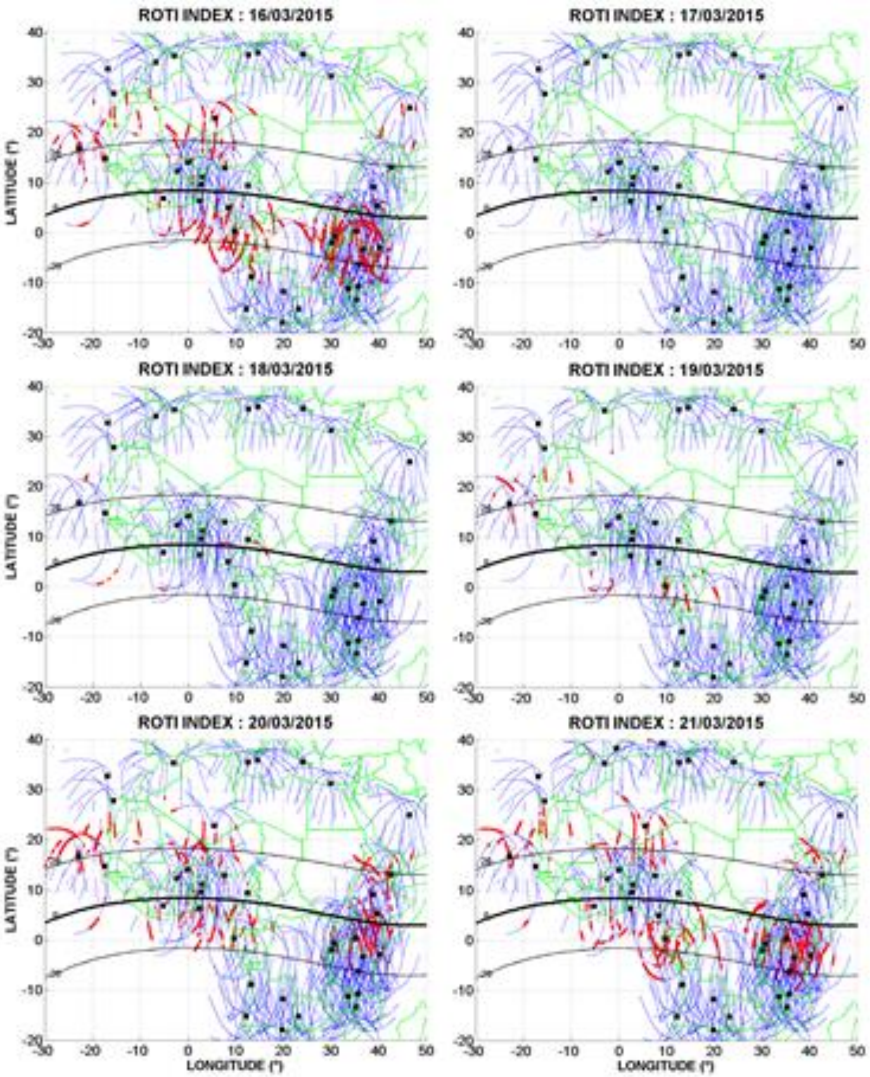
Equatorial Fountain



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

DISTURBED IONOSPHERE [DDEF]

Storm March 17, 2015 /equinox Dst < -200 nT, SSC at 04.45 UT



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

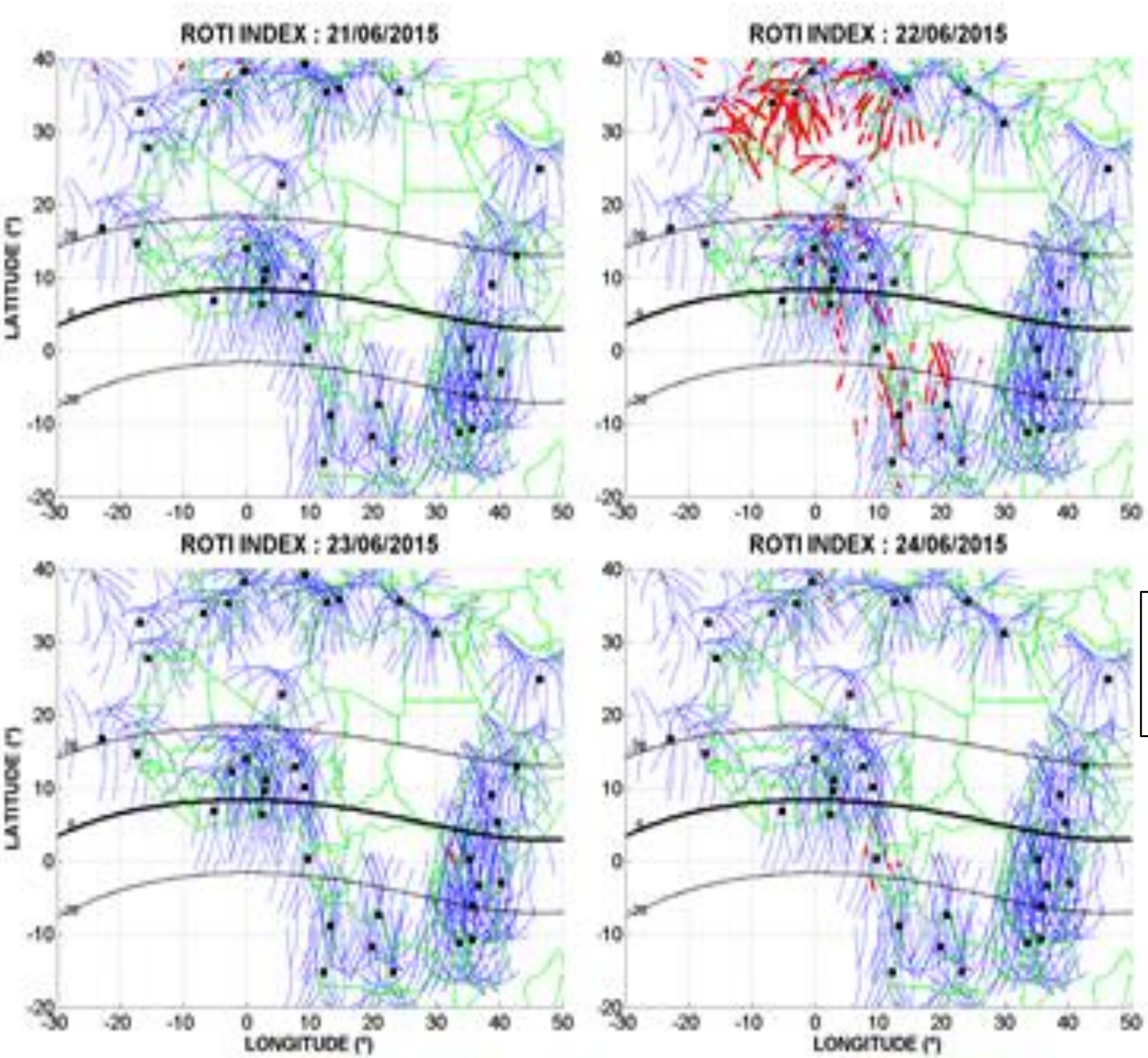
Rate of change of total electron content index (ROTI) maps over African region during St. Patrick's Day storm, 16– 21 March 2015. Thin blue lines show ROTI ≤1.5 TECU/min, while red squares represent ROTI >1.5 TECU/min. Black squares indicate Global Navigation Satellite System station used to produce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

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 TEAM ICTP

DISTURBED IONOSPHERE [PPEF]

Storm June 22, 2015 / solstice / Dst < -200 nT, SSC at 18h33



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

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

Storm started at 18.33 UT,
it is the time of the PRE

Increase of scintillations
PPEF effect
short duration

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

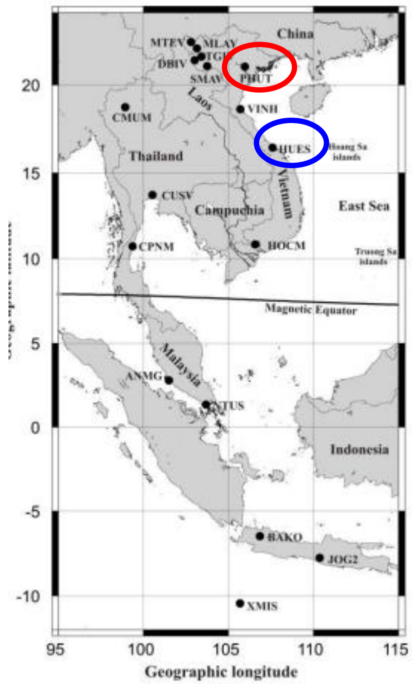
ICTP TEAM

S_4 and ROTI index during storm event in VIETNAM

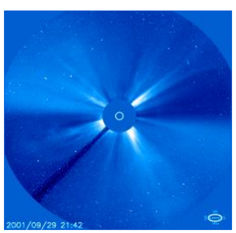
$$rot = \frac{STEC_{k+1} - STEC_k}{time_{k+1} - time_k} * 60$$

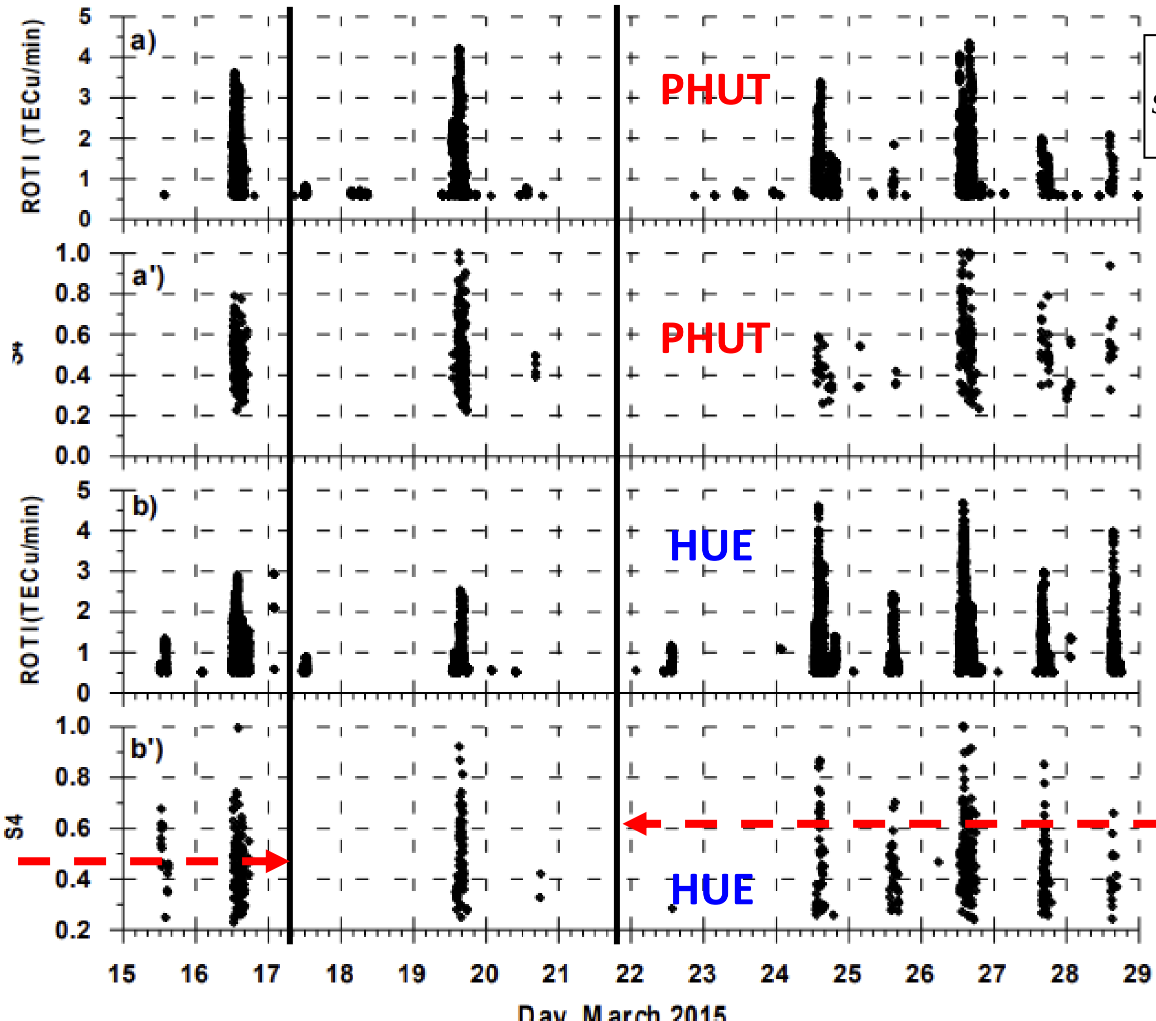
$$roti = \sqrt{\langle rot^2 \rangle - \langle rot \rangle^2}$$

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

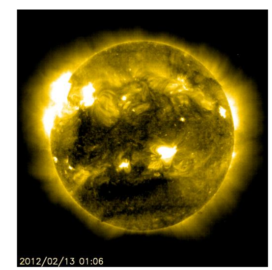


CME





HSSW



STORM SSC
March 17, 04.45UT

Arrival HSSW
March 21, 20.54UT

Le Huy Minh et al.,. 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, https://doi:10.15625.0866-7187/38/3/8714

Disturbed magnetic field

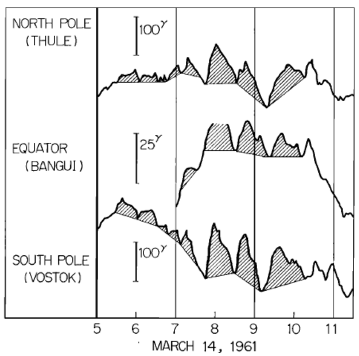


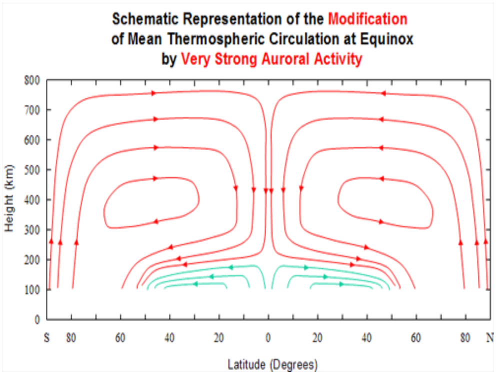
Fig. 1. Train of D_P 2 fluctuations (shaded). Geomagnetic latitudes of these stations are 88.9 (Thule), 05.0 (Bangui), and −89.1 (Vostok).

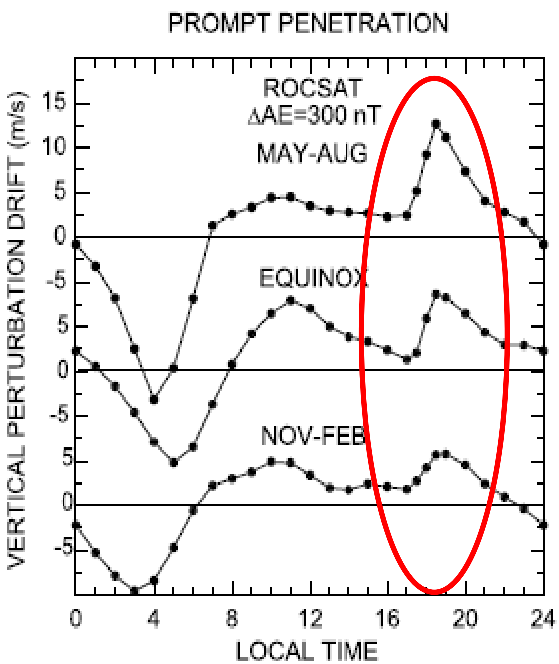
Model of Fejer et al.,(2008)

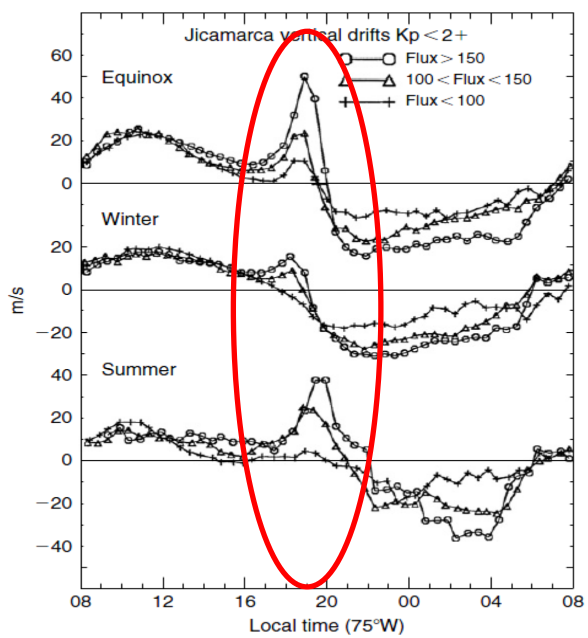
Geophysical Research Letters, 35, L20106.
https://doi.org/10.1029/2008GL035584

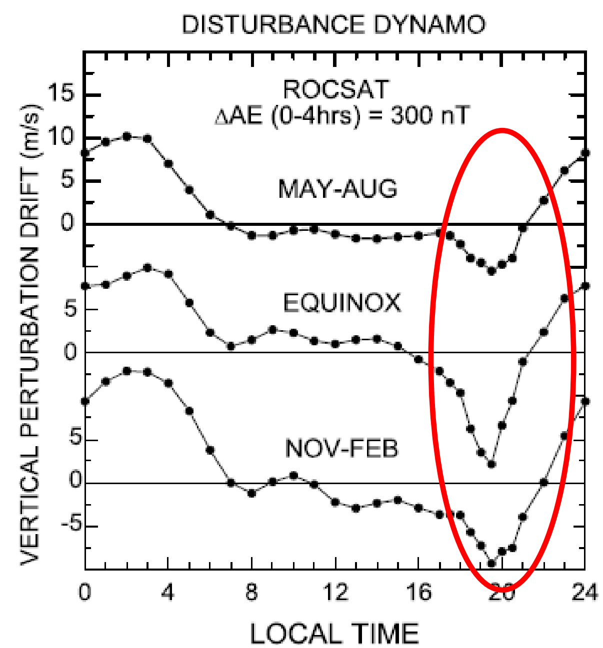
PPEF is an eastward Ey, increases the PRE
DDEF is a westward Ey, decreases the PRE
Eastward electric field => moves up
Westward electric field => moves down

Disturbed thermospheric wind









PPEF : Increase of PRE

Quiet day

DDEF: Inhibition of PRE

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

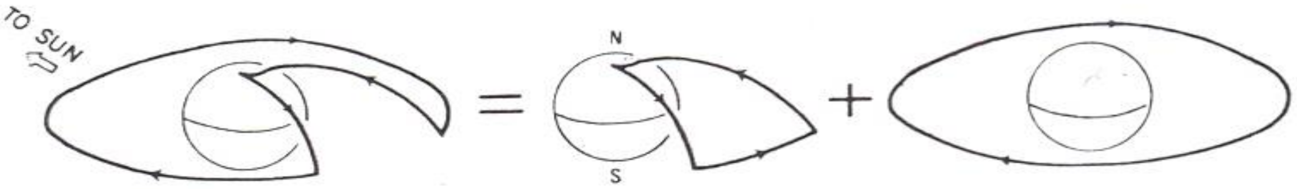
D_{iono} : magnetic disturbance due to the ionospheric electric currents

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

Disturbed ionospheric electric current

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

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

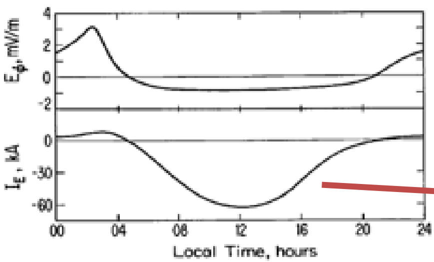


ASYM-H

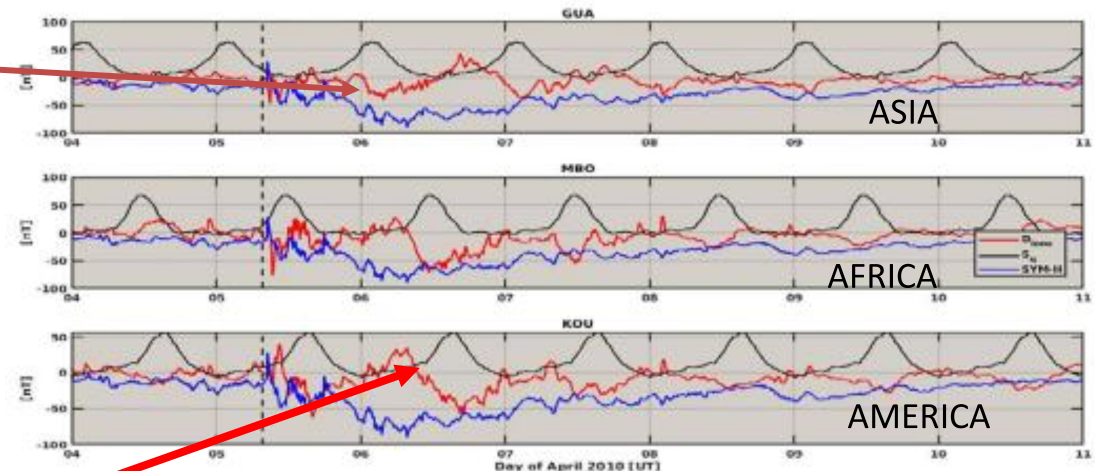
SYM-H

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 $D_{iono} = \Delta H - S_q - D_{mag}$**



Blanc and Richmond, 1980



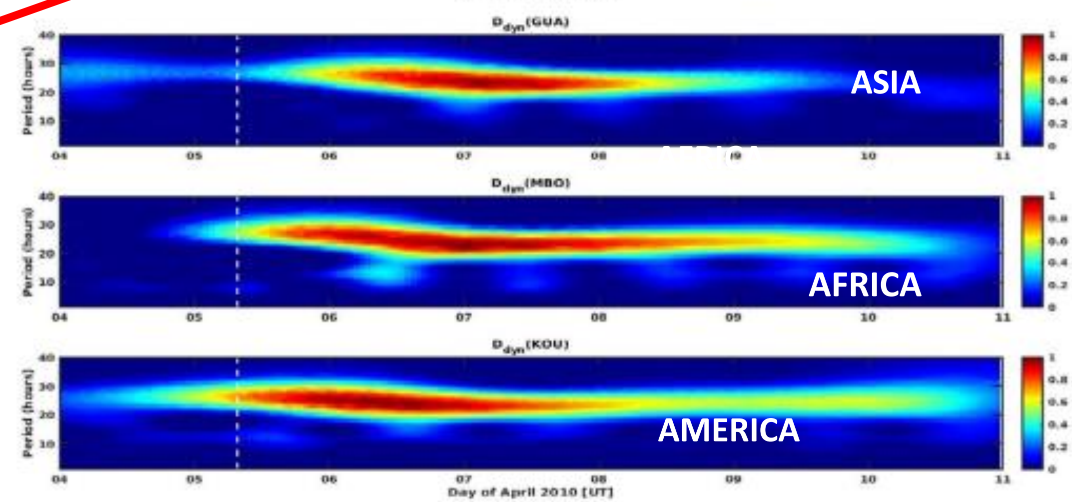
<u>Top figure</u>

ΔH measured (blue),

Regular S_q variation (black)

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

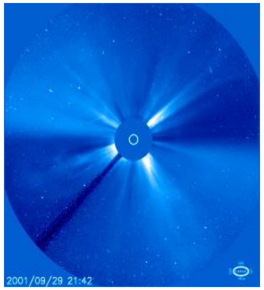
reversed from their observed normal quiet-day variation.



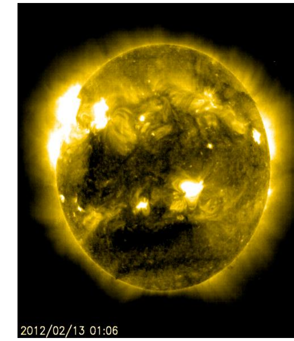
<u>Bottom figure</u>

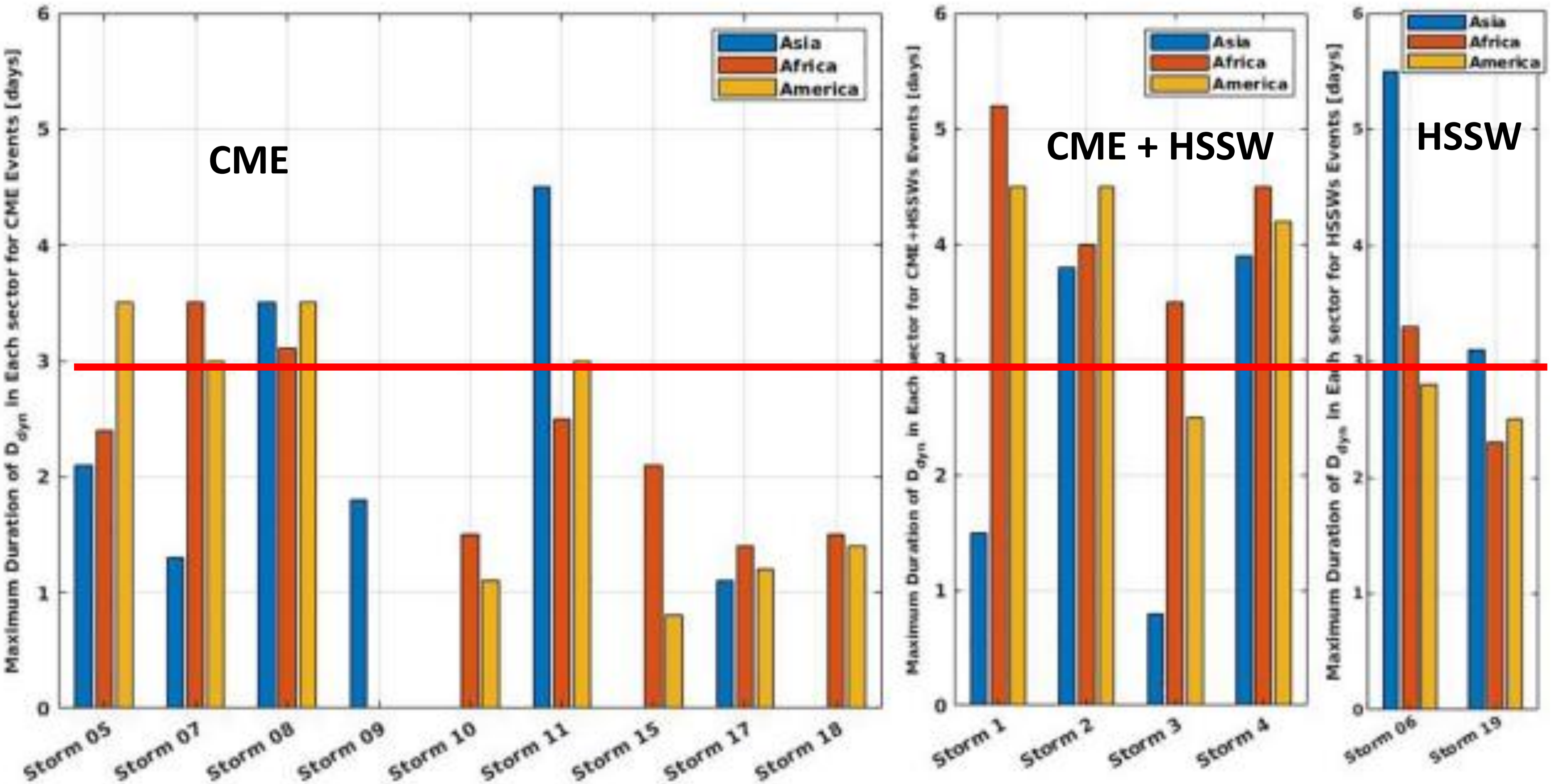
Disturbance dynamo (Ddyn) estimated **using wavelet based semblance analysis**. The vertical dashed line corresponds to the arrival of CME

Younas, W., et al, Earth and Space Science, https://doi.org/10.1029/2021SW002825

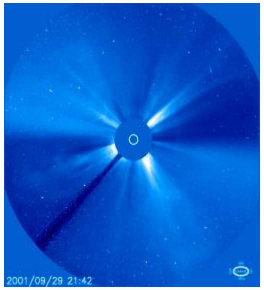


Maximum duration of Ddyn in days during each of the selected storm:

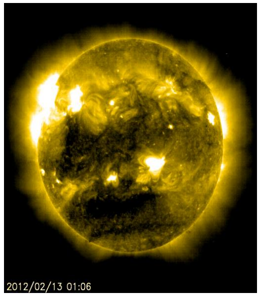


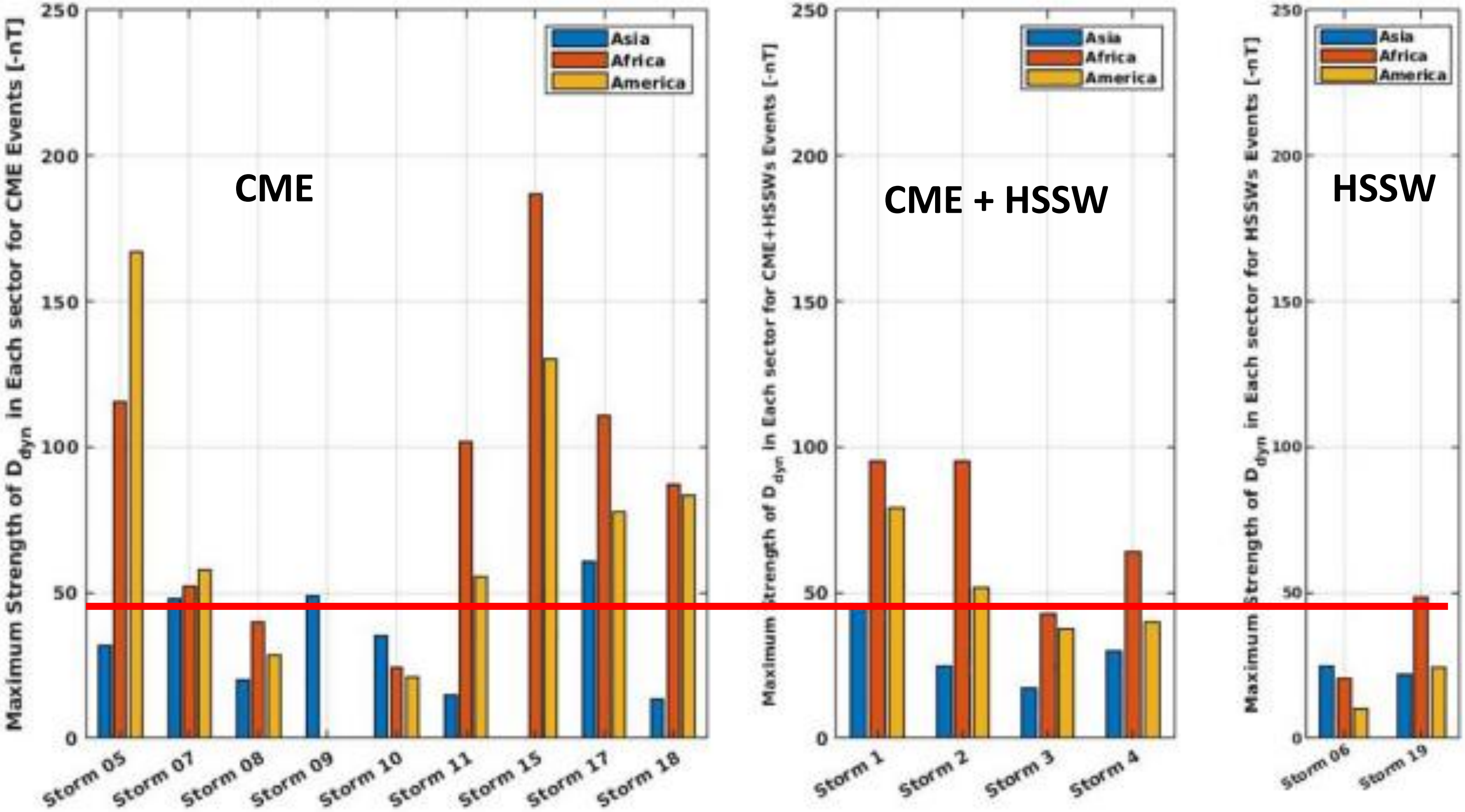


Younas, W., C. Amory-Mazaudier, M. Khan, M. Le Huy, Magnetic signatures of ionospheric disturbance dynamo for CME and HSSWs generated storms , Earth and Space Science, https://doi.org/10.1029/2021SW002825



Maximum strength of Ddyn in nT observed during each storm





Younas, W., et al, Earth and Space Science, https://doi.org/10.1029/2021SW002825

CONCLUSION

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.

In Africa there were 10 PhD theses defended during the first decade (1991–2001), while 84 PhD theses were defended during the period 2001–2023. Presently, there are 68 PhD theses in progress

Baki, P. et al., The Status of Space Weather Infrastructure and Research in Africa 2023, *Atmosphere* **2023**, *14*(12), 1791; https://doi.org/10.3390/atmos1412179