Ionospheric response to geomagnetic storm over Africa:

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Outline

- Introduction and history of Adverse space weather
- Why we are interested in space weather?
- Ionospheric Electrodynamics:
- Basic principles and Fundamental equations
- Quiet time
- Disturbed time
- Storm-time electric fields
- Ionospheric Response to storm time dynamics over Africa:
  - Case 1: Ionospheric Disturbance Dynamo
  - Case 2: Mid-Low-Coupling due to storm
- Summary

History of Space Weather

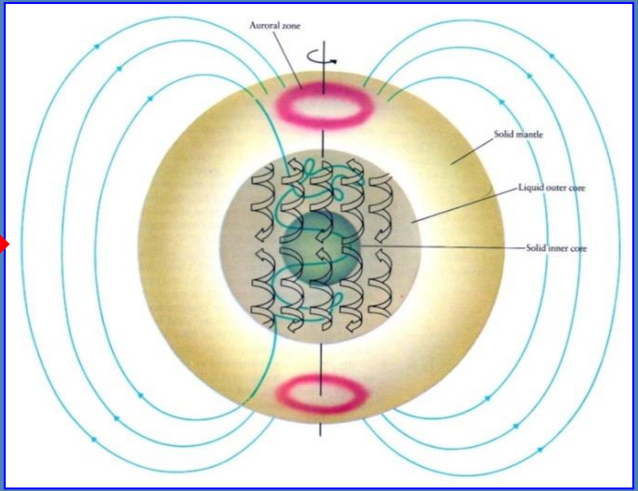
- **September 1, 1859** – Carrington observed a "solar flare" and two days later Magnetic disturbances in London.
  "One swallow does not make a summer."

- **November 30, 1892** - Royal Society Presidential Address
  "It seems as if we may also be forced to conclude that the supposed connexion* between magnetic storms and sunspots is unreal, and that the seeming agreement between periods has been a mere coincidence." Lord Kelvin (* = "old" British spelling)

- **November, 1905** - Monthly Notices of the Royal Astronomical Society "The origin of our magnetic disturbances lies in the Sun" Prof. Maunder

- **Outstanding Question:** What kind of stuff from the Sun causes Magnetic Storms and Aurora?

Sun and Earth as a system of two magnetized bodies in motion



The Sun

- Releases energy packaged as: Protons, particles, magnetic fieldssular solar wind

Major disturbance comes from:

- Coronal hole
- Coronal mass Ejection
- Solar Flares
- Solar Particles Emission

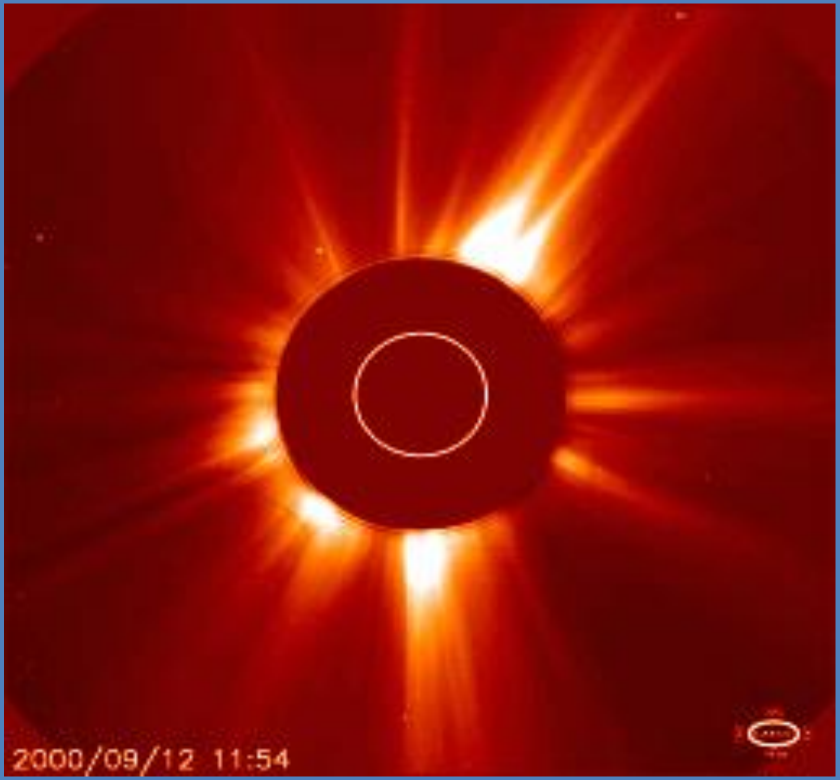
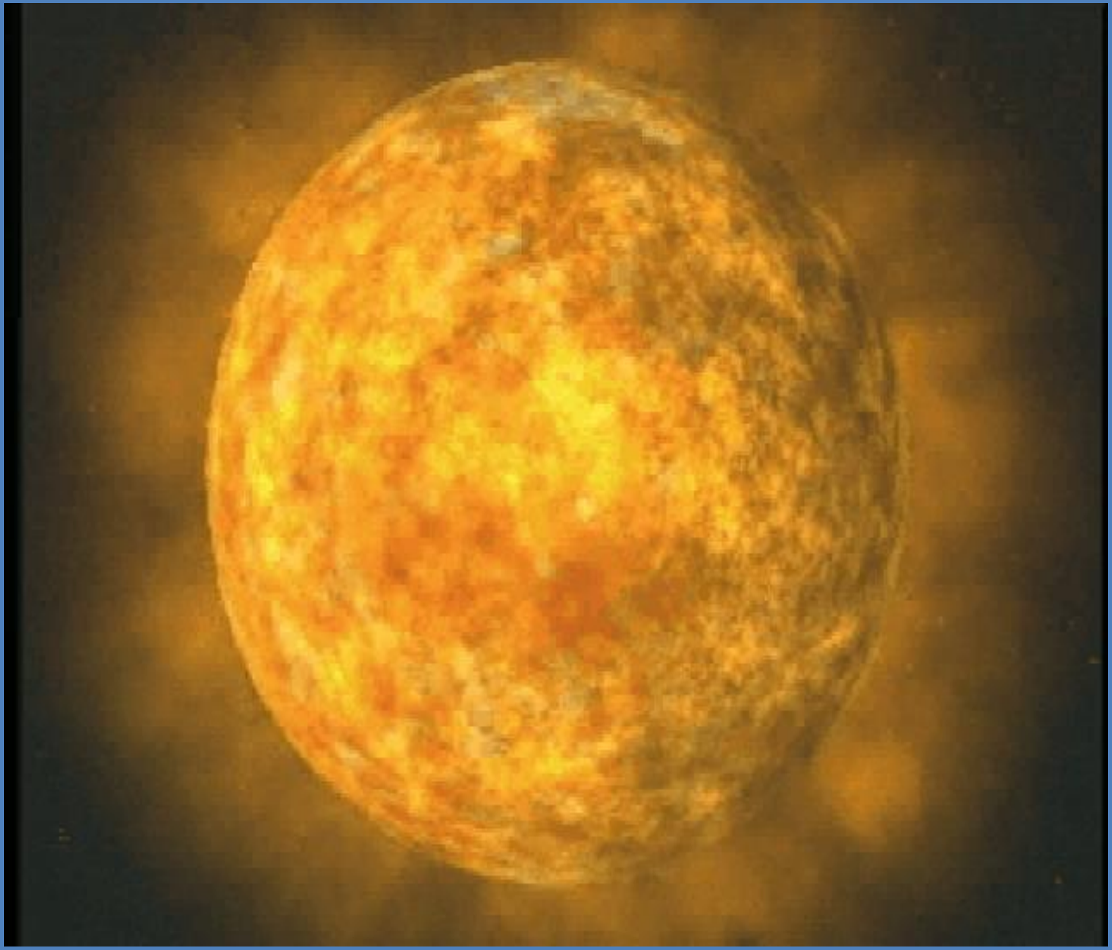


Image credits: SOHO

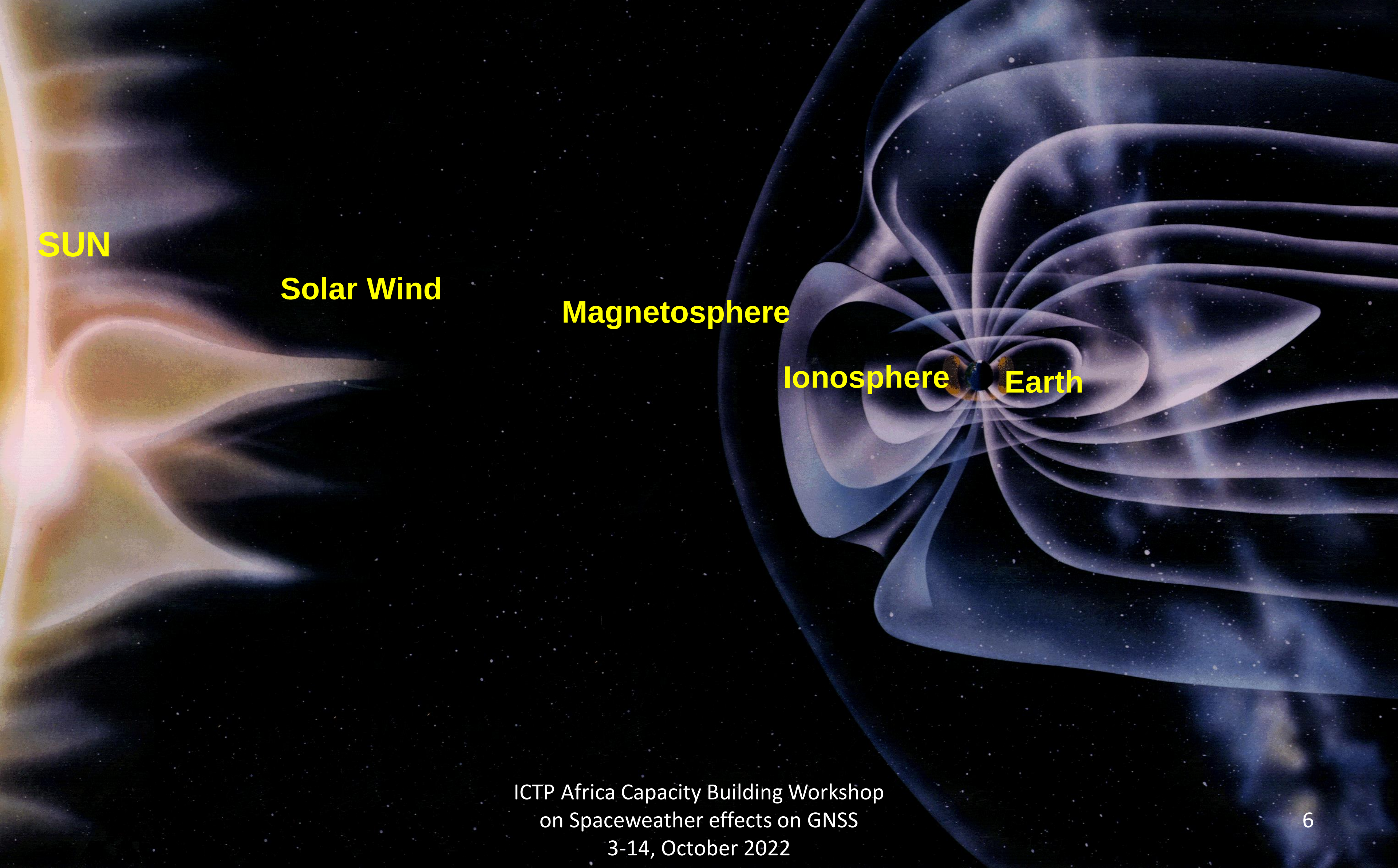
The Sun: The space weather driver



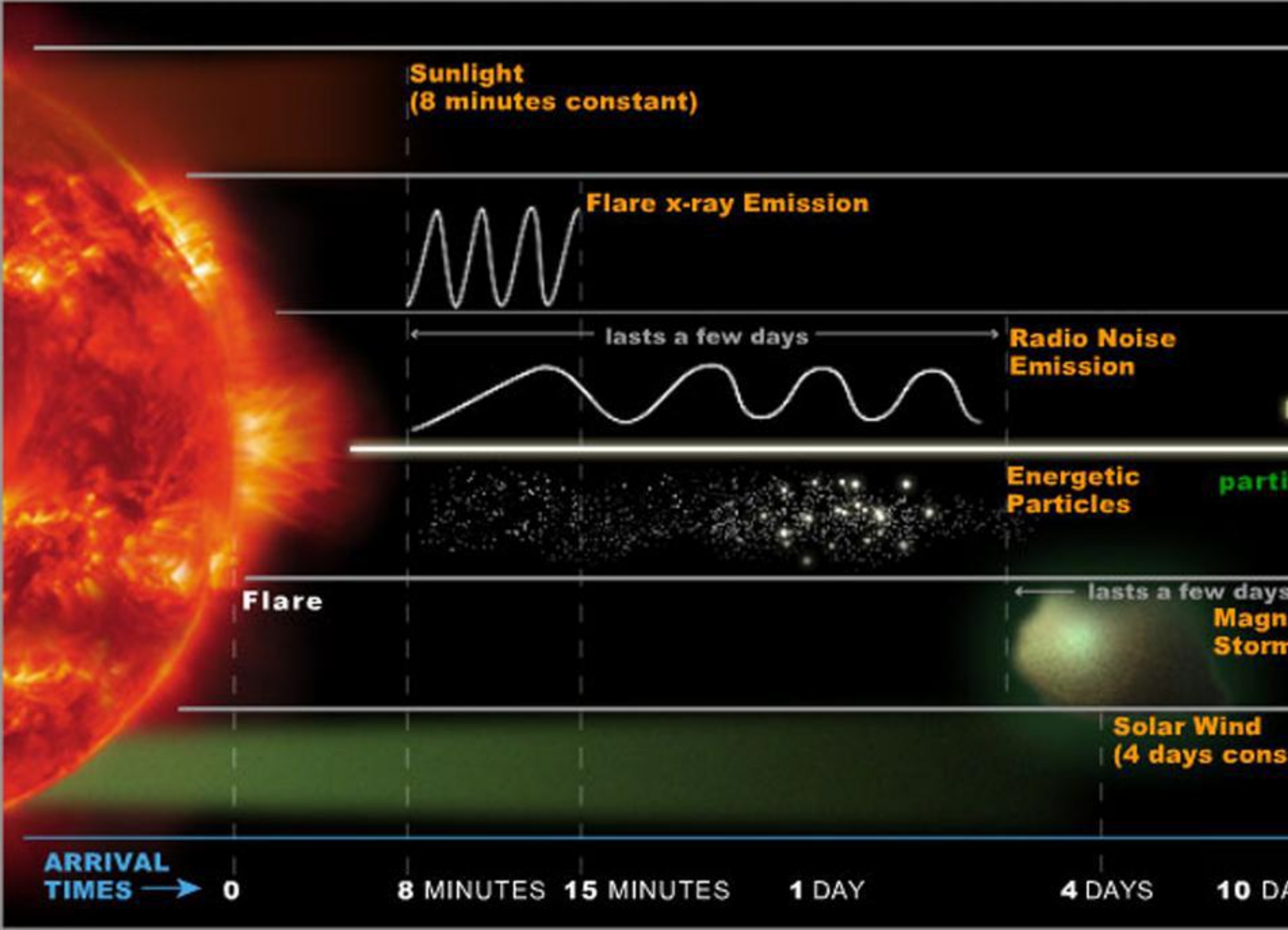
Interplanetary Space:

- Solar wind
- Disturbance from the sun makes shocks and waves in the solar wind.

Space Weather refers to events on the Sun and in the space environment that can influence performance and reliability of space borne and ground-based technological systems, and can also endanger human life or health.



DYNAMIC AND CONSTANT SOLAR EFFECTS ON EARTH



Sunlight
(8 minutes constant)

Flare x-ray Emission

lasts a few days

Radio Noise
Emission

Energetic
Particles

parti

Flare

lasts a few days

Magn
Storm

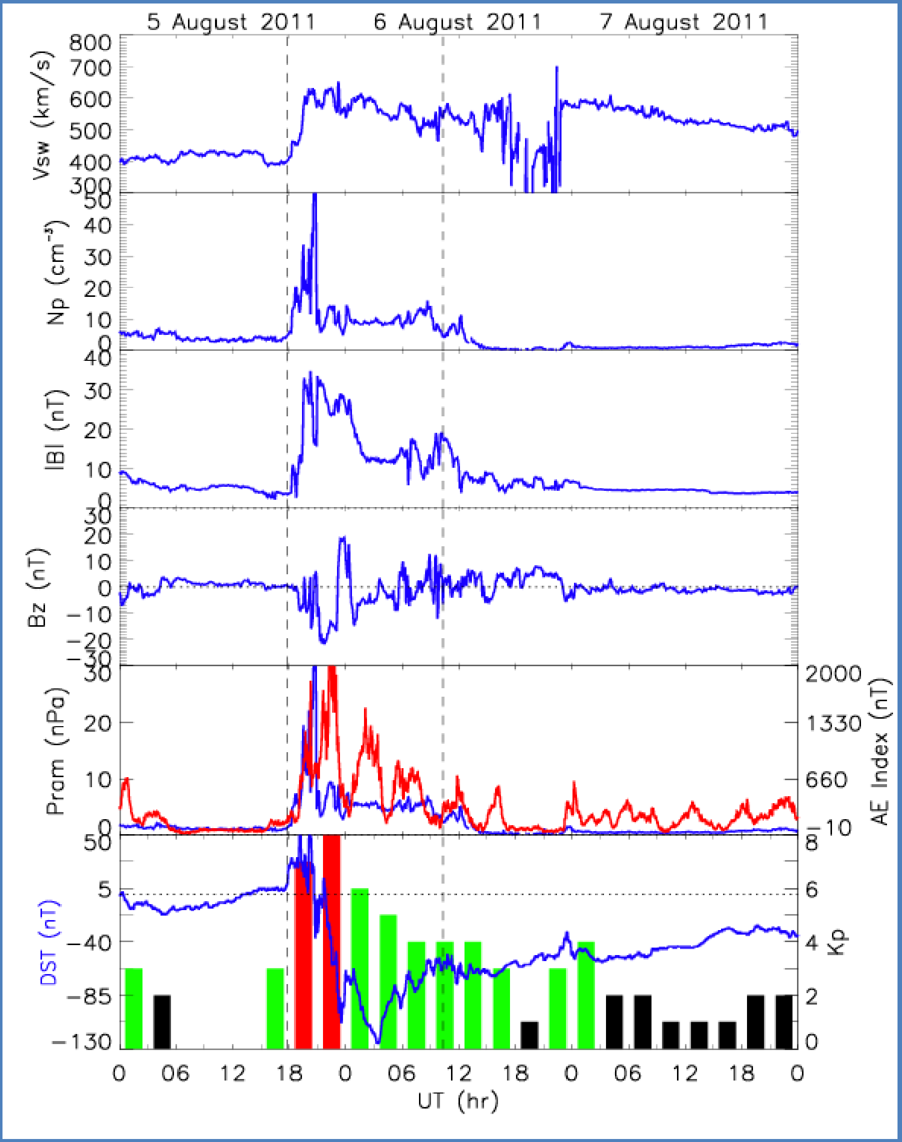
Solar Wind
(4 days cons

ARRIVAL TIMES → 0 | 8 MINUTES | 15 MINUTES | 1 DAY | 4 DAYS | 10 DA

How do we measure space weather storms?

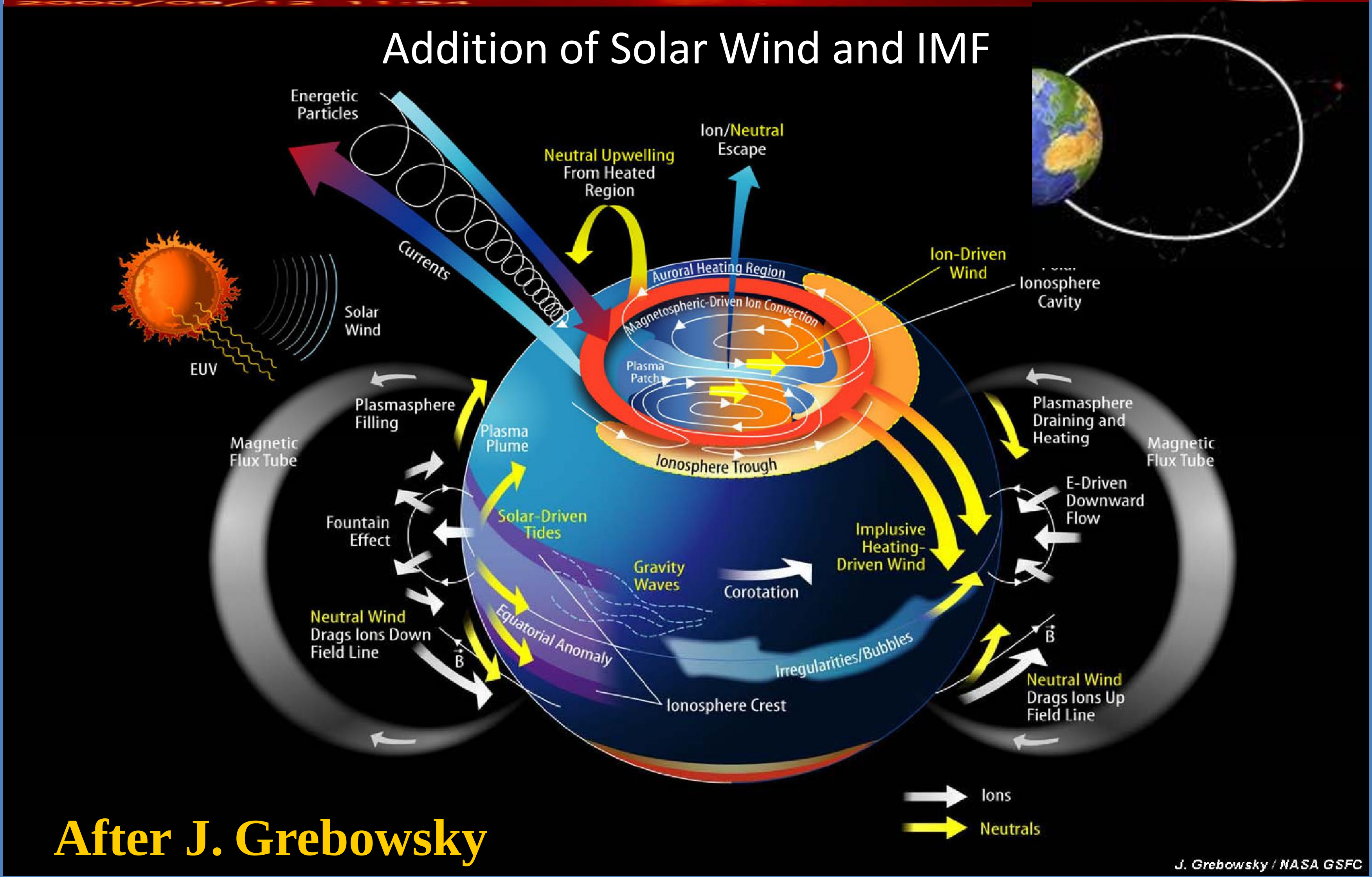
- Indices (like Richter Scale - earthquakes, Saffir-Simpson-hurricanes) - Kp, Dst for space weather storms
- Kp - planetary magnetic field disturbance index (logarithmic from 0 to 9)
- Dst – disturbed stormtime index - also a magnetic index that examines the strength of the ring current.

Courtesy: Endawoke, ICTP, 2016



M-I coupling gets messy

Addition of Solar Wind and IMF

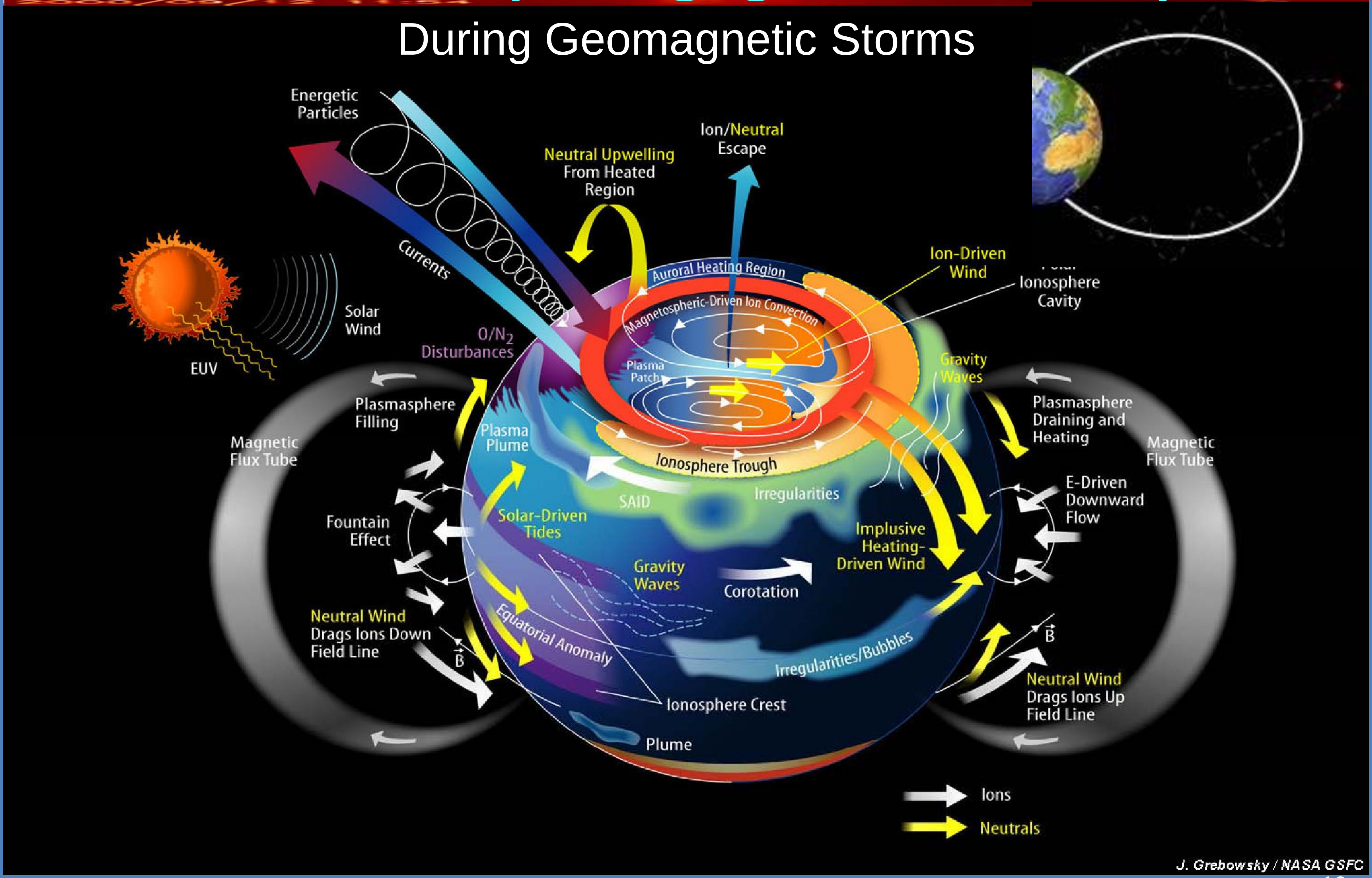


After J. Grebowsky

J. Grebowsky / NASA GSFC

M-I coupling gets messy

During Geomagnetic Storms



J. Grebowsky / NASA GSFC

Ionospheric Electrodynamics: Fundamental equations and Basic principles.

- The ionosphere is a plasma with an embedded magnetic field-partially ionized plasma

$$\nabla.\left[\delta.\left(E\left(r,t\right)+U\left(r,t\right)\times B\right)\right]=0$$

- In a partially ionized plasma in a magnetic field the motion of the charged particles is anisotropic and is determined by the distribution of charged and neutral particles.

THUS

- Forces may drive ions and electrons at different speeds producing a current that may have a divergence.

BUT

- Polarization electric fields are produced to make the total current divergence free everywhere

THEN

- Modified electric fields redistribute the ionization and change the anisotropic motion.

Source: Heelis Tutorial 2004..

Equations of Motion

Parallel equation of motion

$$qE = m_i \nu_{in} u_i$$

$$-eE = m_e \nu_{en} u_e$$

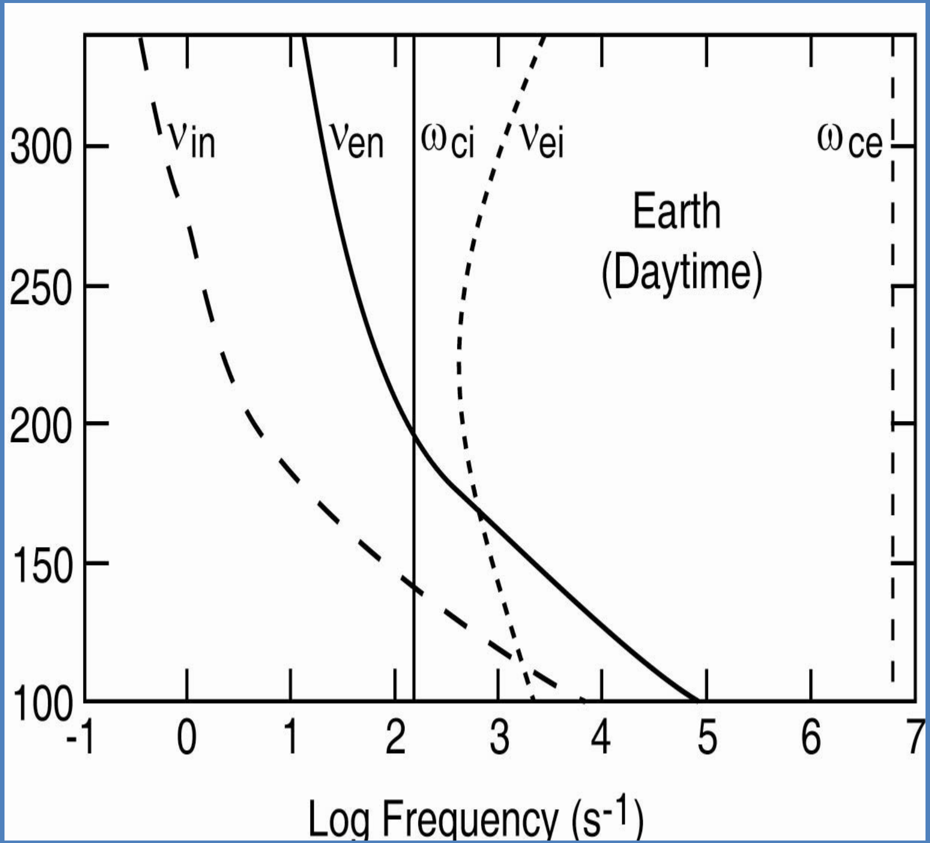
Perpendicular equation of motion

$$q(E + u_i \times B) = m_i \nu_{in} u_i$$

$$-e(E + u_e \times B) = m_e \nu_{en} u_e$$

Collision frequencies:

- The movement of ions and electron in their response to electric fields depends on the collision frequency relative to the yrofrequency.



Ionospheric conductivity

Multi-fluid Theory: neutral and charged species are treated as separate fluids that interact through collisions and charged fluids are assumed to be in force balance.

$$N_e e\left(E + v_i \times B\right) - N_i m_i \nu_{in}\left(v_i - v_n\right) - N_e m_i \nu_{ie}\left(v_i - v_e\right) = 0$$

$$-N_e e\left(E + v_e \times B\right) - N_e m_e \nu_{en}\left(v_e - v_n\right) + N_e m_e \nu_{ei}\left(v_i - v_e\right) = 0$$

Using this relation

$$J = N_e e\left(v_i - v_e\right) = \delta_{II} E_{II}$$

$$\delta_{II} = \frac{N_e e^2}{m_e\left(\nu_{en_{II}} + \nu_{ei_{II}}\right)}$$

$$m_i \nu_{ie} = m_e \nu_{ei}$$

$$m_i \nu_{in}\left(v_i - v_n\right)_{II} + m_i \nu_{ie}\left(v_i - v_e\right)_{II} = eE_{II}$$

$$m_e \nu_{en}\left(v_e - v_n\right)_{II} - m_e \nu_{ei}\left(v_i - v_e\right)_{II} = -eE_{II}$$

$$\delta_1 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\nu_{en}^2}{\nu_{en}^2 + \Omega_e}\right) + \frac{1}{m_i \nu_{in}}\left(\frac{\nu_{in}^2}{\nu_{in}^2 + \Omega_i^2}\right)\right] n_e e^2$$

Pedersen Conductivity

$$\delta_2 = \left[\frac{1}{m_e \nu_{en}}\left(\frac{\Omega_e \nu_{en}}{\nu_{en}^2 + \Omega_e}\right) + \frac{1}{m_i \nu_{in}}\left(\frac{\Omega_i \nu_{in}}{\nu_{in}^2 + \Omega_i^2}\right)\right] n_e e^2$$

Hall conductivity

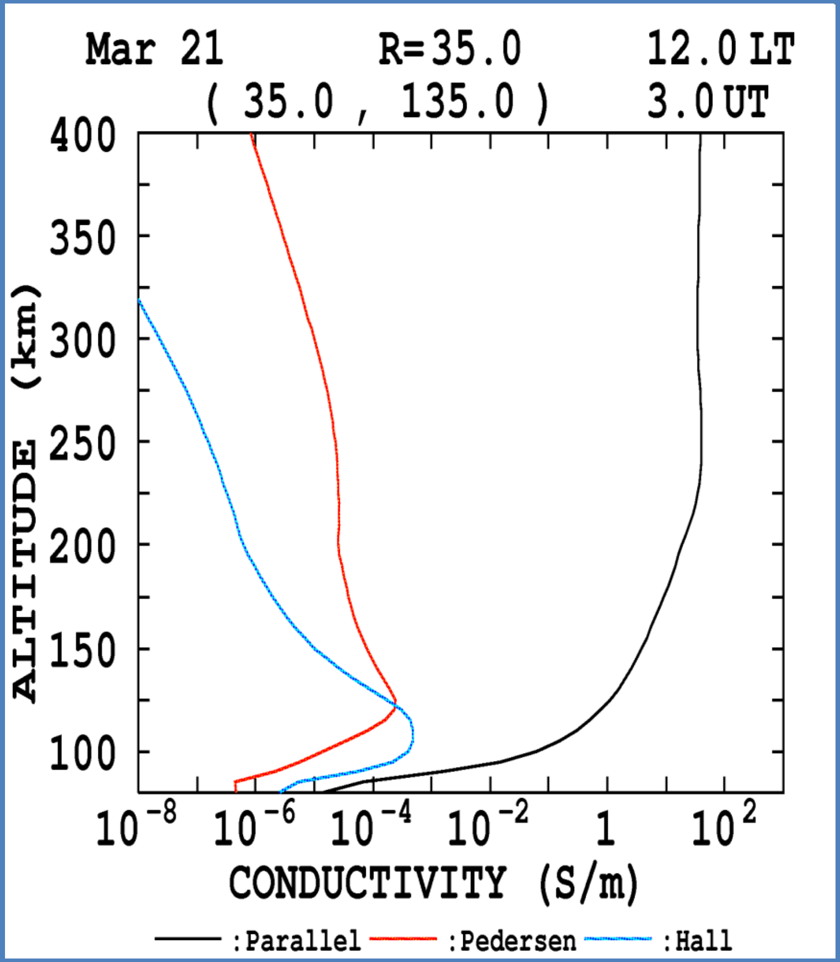
$$\delta_1 = \left[\frac{1}{m_e \nu_{en}} + \frac{1}{m_i \nu_{in}}\right] n_e e^2$$

Parallel conductivity

$$J = \begin{pmatrix} \delta_1 & \delta_2 & 0 \\ -\delta_2 & \delta_1 & 0 \\ 0 & 0 & \delta_2 \end{pmatrix}\begin{pmatrix} E_x \\ E_y \\ E_z \end{pmatrix}$$

Conduction Tensor

Ionospheric conductivity (continued)



http://wdc.kugi.kyoto-u.ac.jp/ionocond/exp/icexp.html

- Hall conductivity is essentially removed at night in a layer near 125 km.
- Pedersen conductivity is distributed in two regions: With E region much greater than F-region during daytime and F-region much greater than the E region at night.
- Direct conductivity much greater than the transverse conductivities everywhere above 90 km.

Ionospheric Dynamo or Ionospheric Wind Dynamo:

- This effect is produced by the movement of charged particles in the ionosphere across B.
- The motion is driven by the tidal effect of the sun, the moon and the solar heating.
- From Ohm’s law the total current density J in terms of electric field that exists in the frame of reference of the moving neutral gas is:

$$J = \delta_P\left(E + v_n \times B\right) + \delta_H b \times \left(E + v_n \times B\right) + \delta_{II} E_{II} b$$

- Neutral Winds drive dynamo current leading to the building up of polarization charges responsible for the electric fields.
- The Dynamo is controlled by:

  - distribution of winds
  - Distribution of electrical conductivities

Ionospheric electric fields and Currents:

- If distribution of the thermospheric winds and ionospheric conduction are known then the electric fields and current generated by the dynamo effect can be calculated.
- The condition for current continuity and electrostatic fields must be satisfied:

$$\nabla . J = 0$$

$$E = -\nabla . \Phi$$

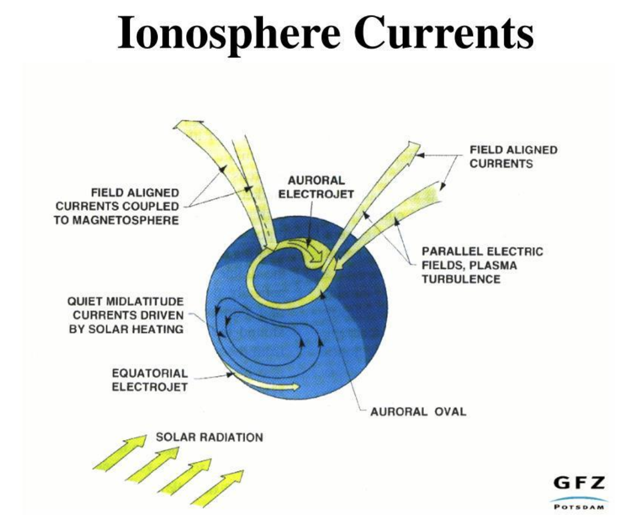
- We solve this equation with the correct boundary condition that represents coupling with the magnetosphere.

$$\nabla . \left[\delta_P (\nabla \Phi) + \delta_H b \times \nabla \Phi + \delta_{II} (\nabla \Phi) \right] = \nabla . \left[\delta_P v_n \times B + \delta_H b \times (v_n \times B) \right]$$

- Atmosphere below 80 km is a very poor conductor and the electric current coupling between ionosphere and lower atmosphere is negligible. Coupling with the magnetosphere is however not negligible.

Quiet time vs Disturbed time Dynamics

- Under quiet, steady magnetospheric conditions, there is a tendency for ionospheric electrodynamics at middle and low latitude to be significantly DECOUPLED from magnetospheric electrodynamics.



- Energetic plasma in the middle magnetosphere at the inner edge tends to adjust itself so as to produce polarization electric fields that counters the strong electric fields at the outer magnetosphere.

- This shields the inner magnetosphere and the middle and low latitude ionosphere from magnetospheric effects - Quiet time

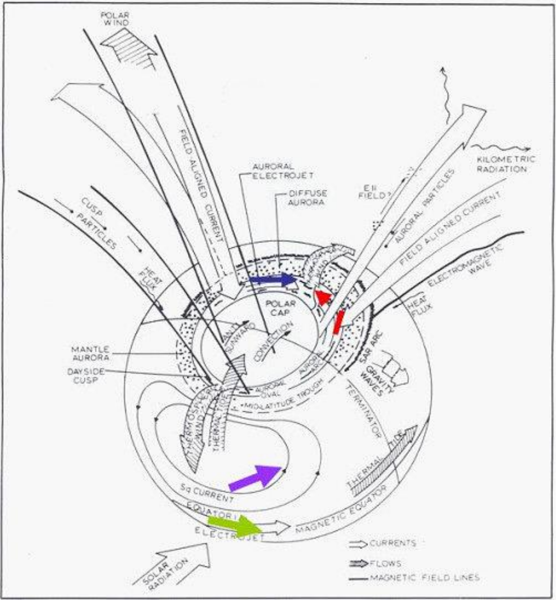
- Changes in thermospheric winds associated with magnetospheric energy inputs can produce significant dynamo effect at high latitude but also on global scale – Disturbed Time

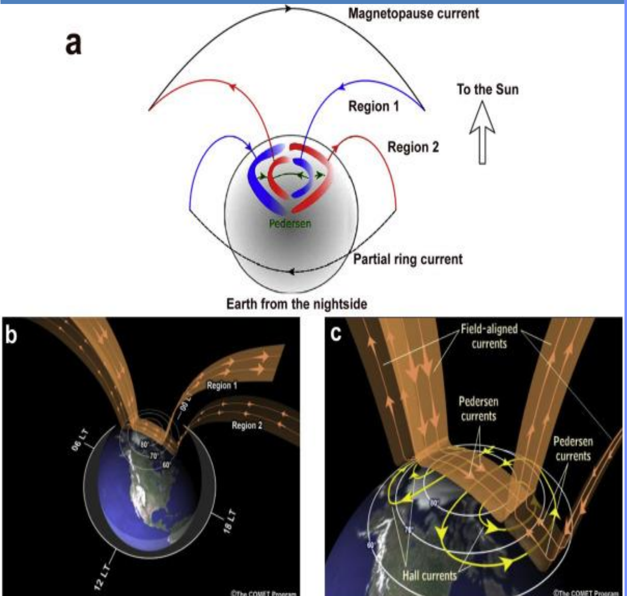
Disturbed time electrodynamics:

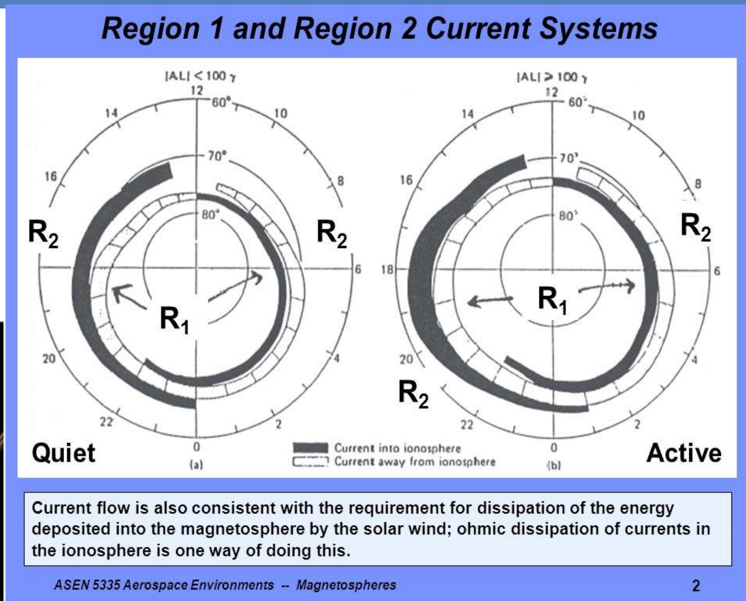
- Disturbed times are mainly linked to geomagnetically active times.
- During disturbed times the ionospheric electric fields are thought to come from:
  - a) Disturbed Wind dynamo
  - b) Magnetospheric origin:
    - -Penetration Electric field-PEF
    - -Subauroral Polarization stream
- The direct penetration of the high-latitude electric fields to lower latitudes and the disturbances dynamo, both play a significant role in restructuring the storm-time equatorial ionosphere and thermosphere.
- Both PEF and neutral disturbance dynamo electric field occur at low latitude during magnetic storms.
- PEF can cause ionospheric disturbance at all latitudes and does dominate the dayside ionospheric evolution.

Disturbed time electrodynamics (continued):

- Magnetospheric convection is enhanced following a southward turning of the interplanetary magnetic field (IMF). initial high-latitude electric field will penetrate to the equatorial latitudes.
- Storm-time penetration eastward electric field uplifts equatorial ionosphere and enhances the Equatorial anomaly.
- Cross-tail electric fields energize and inject particles into the inner magnetosphere forming the disturbance Ring Current.






Region 1 and Region 2 Current Systems

▬ Current into ionosphere
▭ Current away from ionosphere

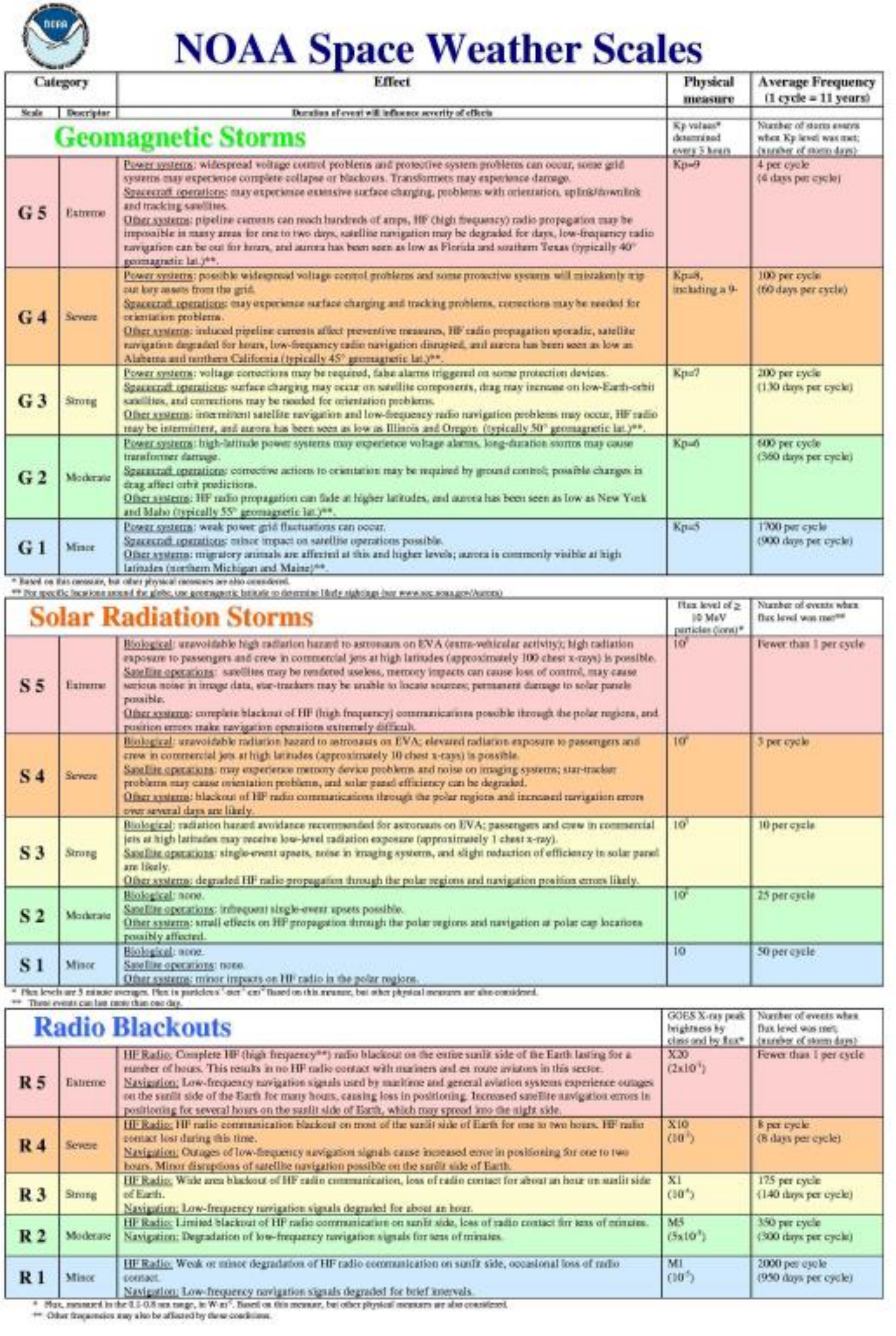
Current flow is also consistent with the requirement for dissipation of the energy deposited into the magnetosphere by the solar wind; ohmic dissipation of currents in the ionosphere is one way of doing this.

ASEN 5335 Aerospace Environments -- Magnetospheres 2

Categories and Space Weather Scales for Geomagnetic storms

- 3 Categories
  - Geomagnetic Storms (CMEs)
  - Solar Radiation Storms (Particle Events)
  - Radio Blackouts (Solar Flares)

http://sec.noaa.gov



NOAA Space Weather Scales

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	Power systems: widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. Spacecraft operations: may experience extensive surface charging, problems with orientation, uplink/downlink and tracking satellites. Other systems: pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp=9	4 per cycle (4 days per cycle)
G 4	Severe	Power systems: possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. Spacecraft operations: may experience surface charging and tracking problems, corrections may be needed for orientation problems. Other systems: induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp=8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	Power systems: voltage corrections may be required, false alarms triggered on some protection devices. Spacecraft operations: surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. Other systems: intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp=7	200 per cycle (130 days per cycle)
G 2	Moderate	Power systems: high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. Spacecraft operations: corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. Other systems: HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp=6	600 per cycle (360 days per cycle)
G 1	Minor	Power systems: weak power grid fluctuations can occur. Spacecraft operations: minor impact on satellite operations possible. Other systems: migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp=5	1700 per cycle (900 days per cycle)

* Based on this measure, but other physical measures are also considered.

** For specific locations around the globe, use geomagnetic latitude to determine likely sightings (see www.sec.noaa.gov/Aurora)

Solar Radiation Storms			Flux level of ≥ 10 MeV particles (ions)*	Number of events when flux level was met**
S 5	Extreme	Biological: unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); high radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 100 chest x-rays) is possible. Satellite operations: satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. Other systems: complete blackout of HF (high frequency) communications possible through the polar regions, and position errors make navigation operations extremely difficult.	10^5	Fewer than 1 per cycle
S 4	Severe	Biological: unavoidable radiation hazard to astronauts on EVA; elevated radiation exposure to passengers and crew in commercial jets at high latitudes (approximately 10 chest x-rays) is possible. Satellite operations: may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. Other systems: blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S 3	Strong	Biological: radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in commercial jets at high latitudes may receive low-level radiation exposure (approximately 1 chest x-ray). Satellite operations: single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. Other systems: degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S 2	Moderate	Biological: none. Satellite operations: infrequent single-event upsets possible. Other systems: small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S 1	Minor	Biological: none. Satellite operations: none. Other systems: minor impacts on HF radio in the polar regions.	10	50 per cycle

* Flux levels are 5 minute averages. Flux in particles·s^{-1}·ster^{-1}·cm^{-2} Based on this measure, but other physical measures are also considered.

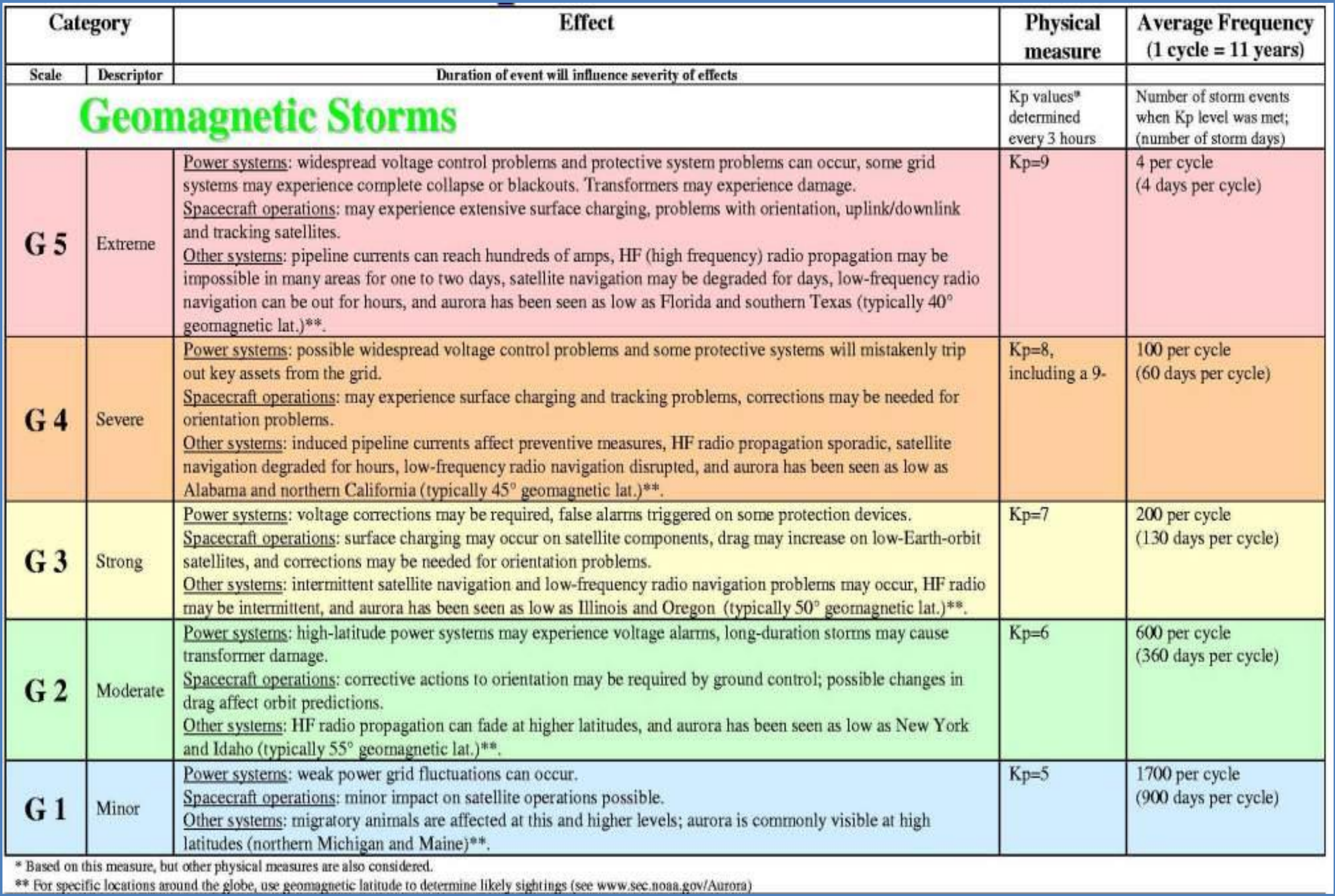
** These events can last more than one day.

Radio Blackouts			GOES X-ray peak brightness by class and by flux*	Number of events when flux level was met; (number of storm days)
R 5	Extreme	HF Radio: Complete HF (high frequency**) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. Navigation: Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 ($2x10^{-3}$)	Fewer than 1 per cycle
R 4	Severe	HF Radio: HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. Navigation: Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R 3	Strong	HF Radio: Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. Navigation: Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R 2	Moderate	HF Radio: Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. Navigation: Degradation of low-frequency navigation signals for tens of minutes.	M5 ($5x10^{-5}$)	350 per cycle (300 days per cycle)
R 1	Minor	HF Radio: Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. Navigation: Low-frequency navigation signals degraded for brief intervals.	M1 (10^{-5})	2000 per cycle (950 days per cycle)

* Flux, measured in the 0.1-0.8 nm range, in W·m^{-2}. Based on this measure, but other physical measures are also considered.

** Other frequencies may also be affected by these conditions.

Geomagnetic Storm Scales



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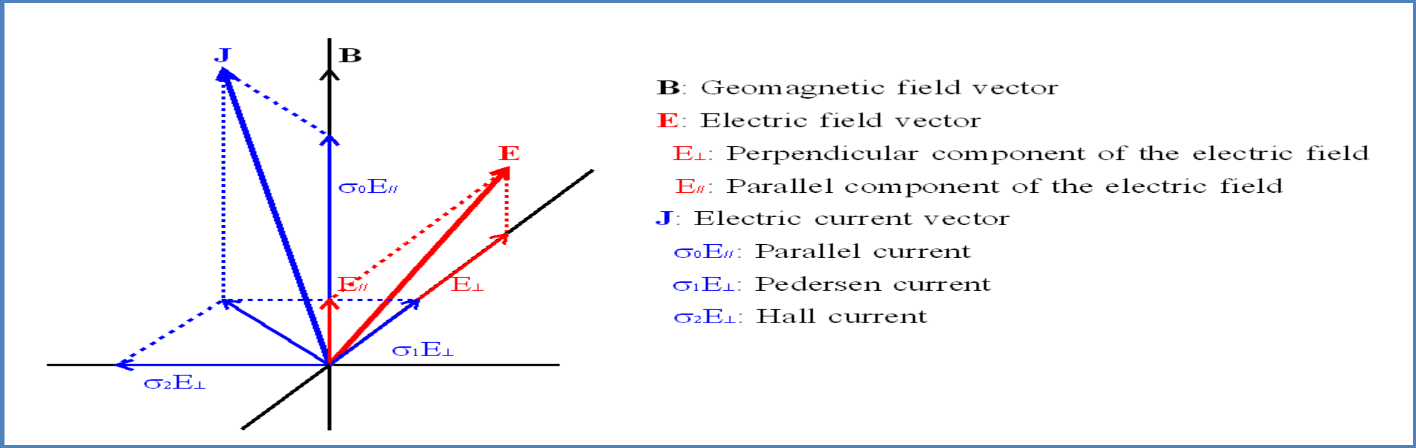
Magnetic variations and measurements



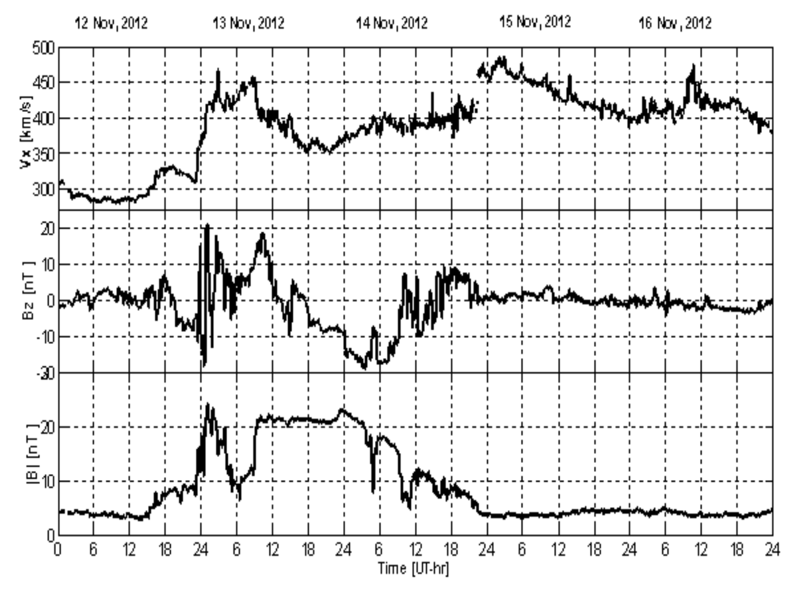
Magnetic indices for storm time dynamics diagnostics:

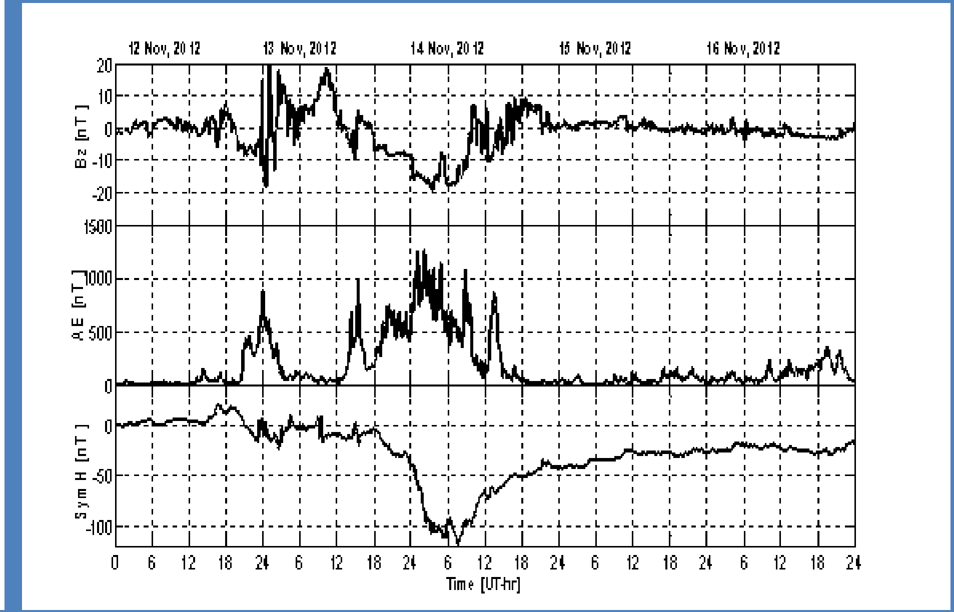
- AU and AL (AE)- superposed H-perturbation from auroral zone magnetometers.
- Bz(northward) – Component of Interplanetary magnetic field, IMF.
- -Bz(southward)-This component tend to produce magnetic activity in the auroral zone.
- Dst- Disturbed Storm time index- negative excursion depicts ring currents at low latitude.
- Kp- Global magnetic measure.
- In addition to the fluctuations in magnetic field, the average ExB drifts are altered during disturbed periods.

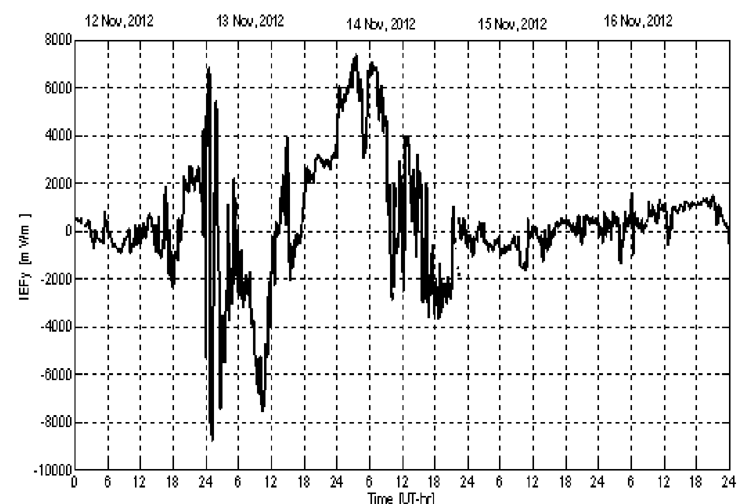
Case 1: ionospheric Disturbance Dynamo

Case Study 1: **Geomagnetic storm of November 13, 2012.**

Interplanetary magnetic parameters associated with the storm were:







$$IEF_y = V_x \times B_z$$

Olwendo et al., 2015

Criteria for identifying ionospheric dd:

Criteria for Detection of Ionospheric disturbance dynamo:

- Dawn to dusk interplanetary electric filed (IEF)

$$IEF_y = V_x \times B_z$$

- The variations of the Earth's magnetic dH

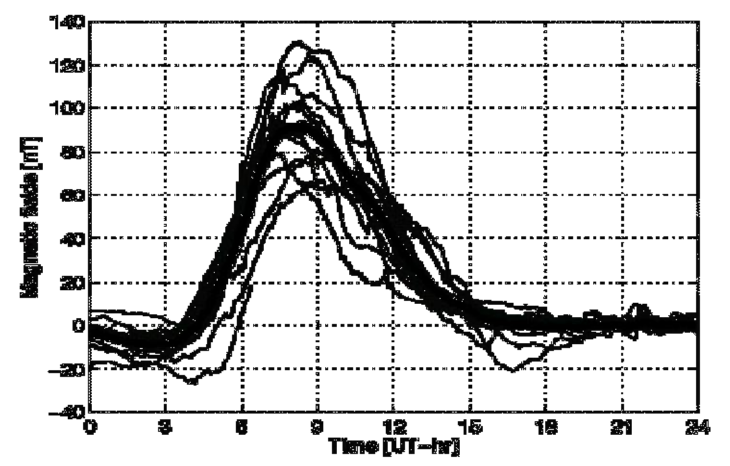
$$dH = Sq + D_R + D_{dyn}$$

- In the absence of magnetospheric currents into the ionosphere then;

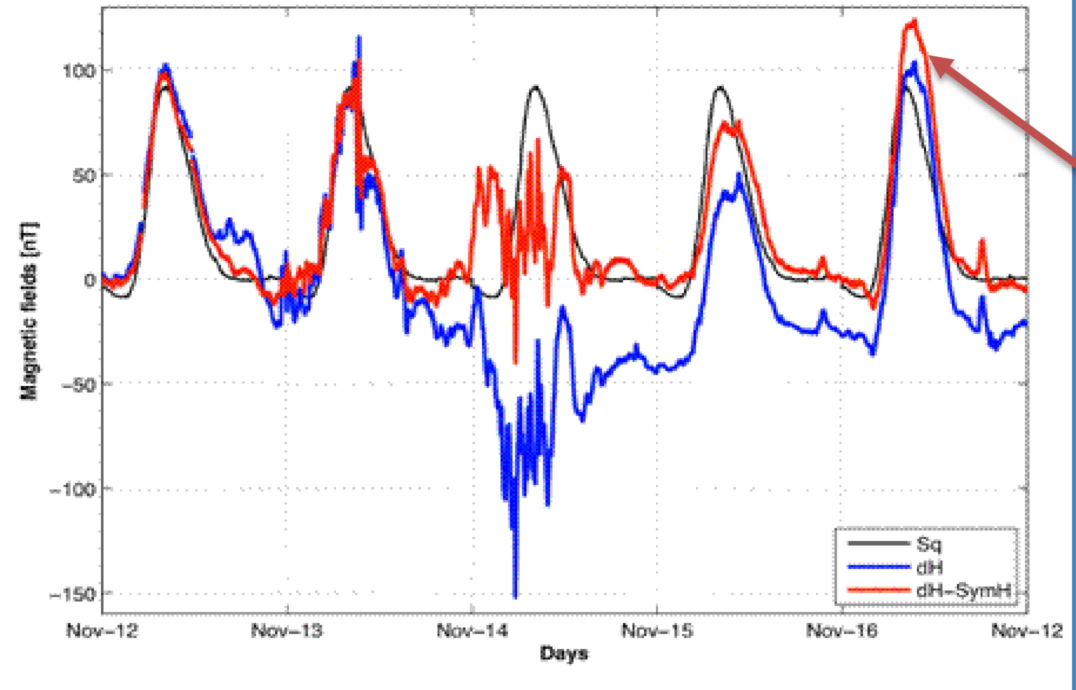
$$dH - SymH = D_{dyn} + Sq$$

- Taking away the Sq term of the RHS should leave us with a term equivalent to the Ionospheric disturbance dynamo.

Signatures of Ionospheric disturbance dynamo



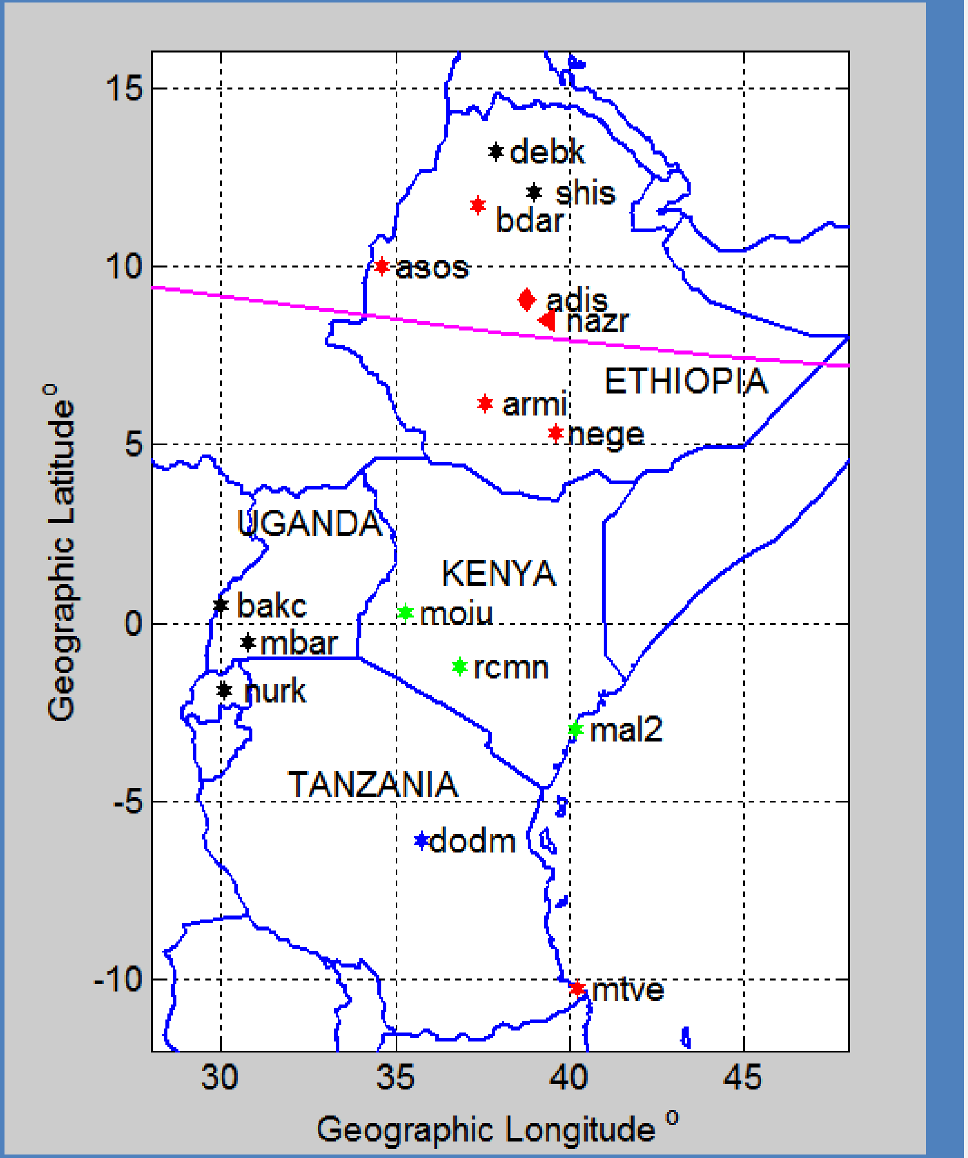
Quiet-day daily variations of geomagnetic field at Addis Ababa for November 2012. Green curves show geomagnetic daily variations for individual quiet days (Kp < 2), while the black curve shows the average (i.e. Sq)

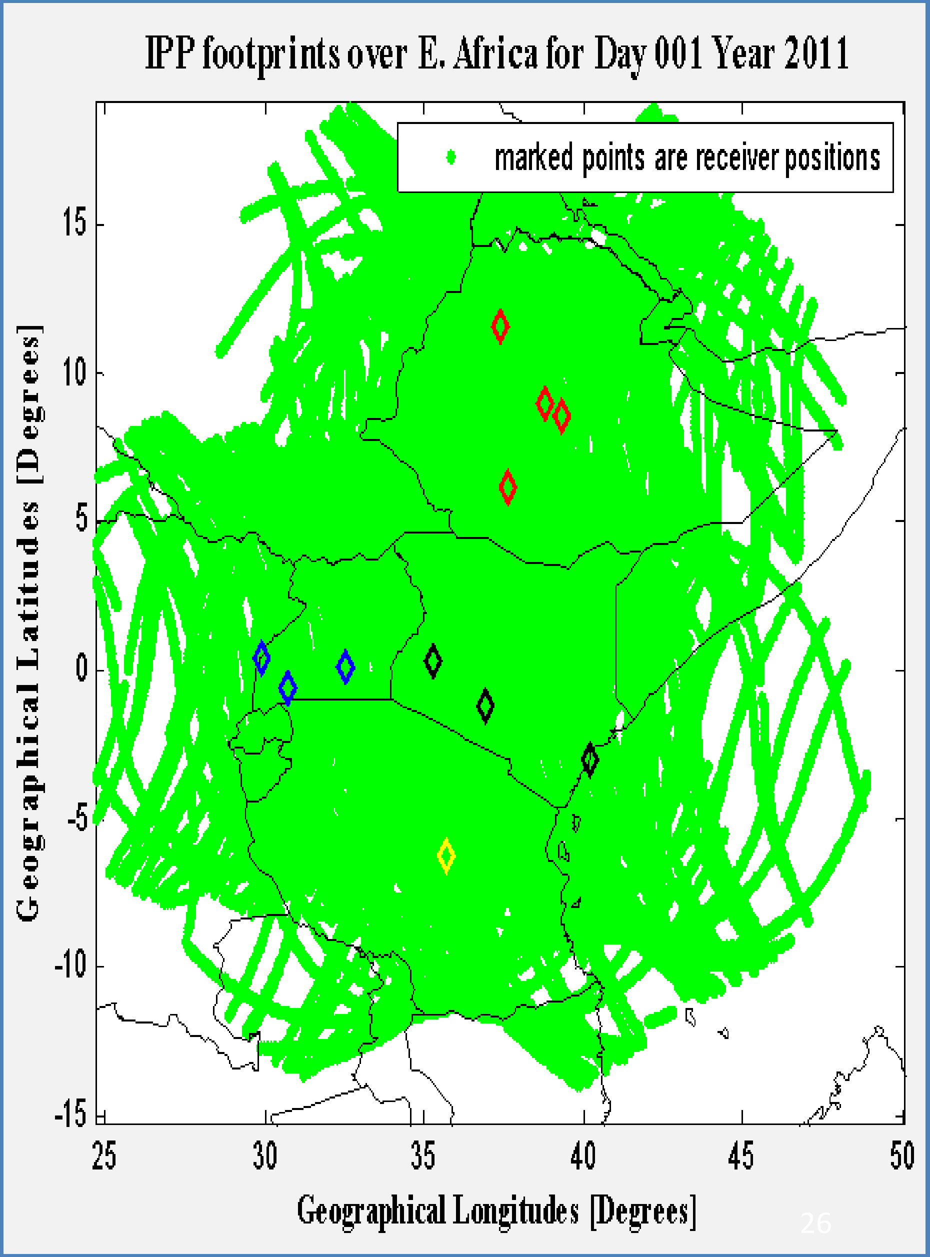


Ionospheric disturbance Dynamo effects given as dH-SymH

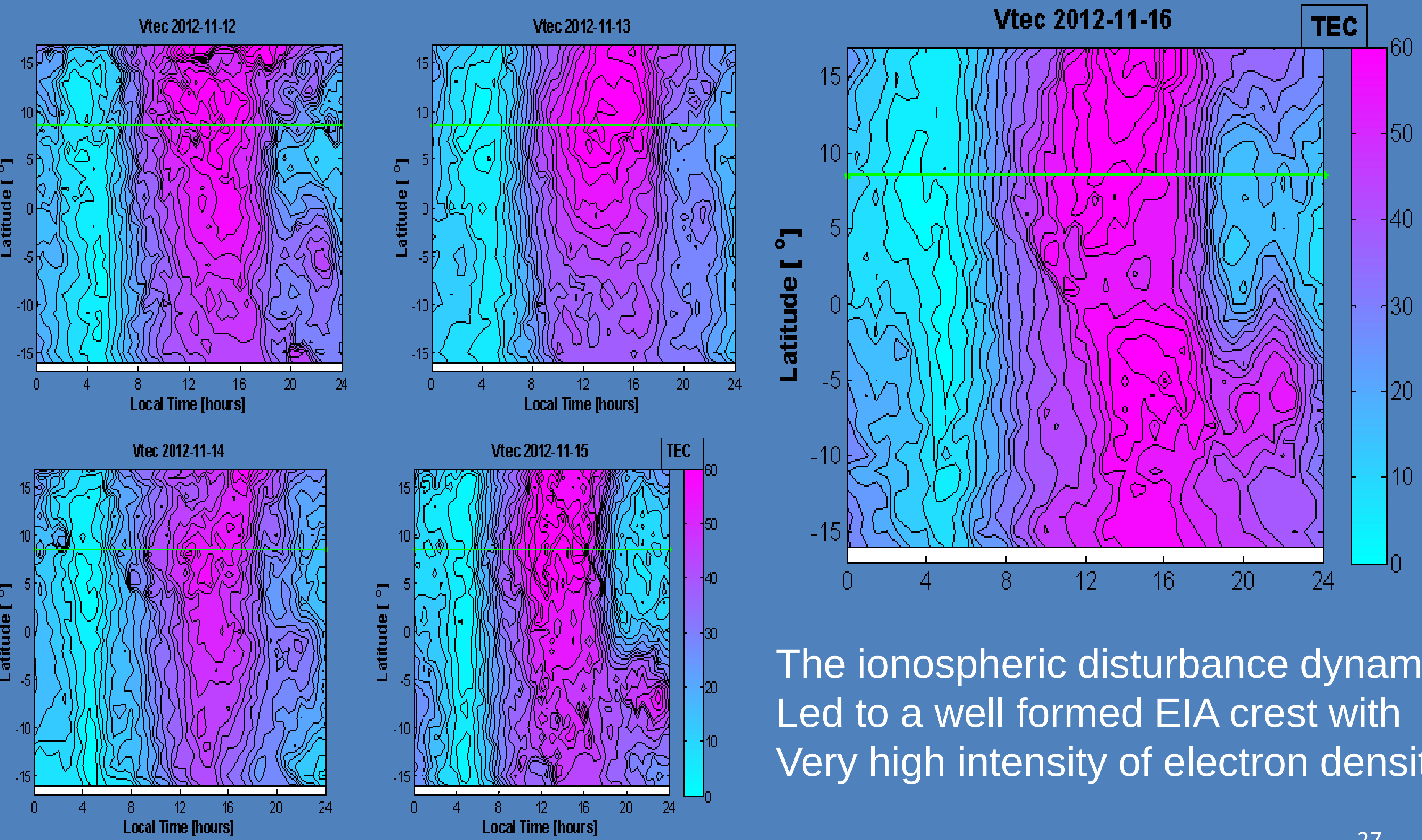
Ionospheric response to storm time dynamics

Locations of the GNSS stations



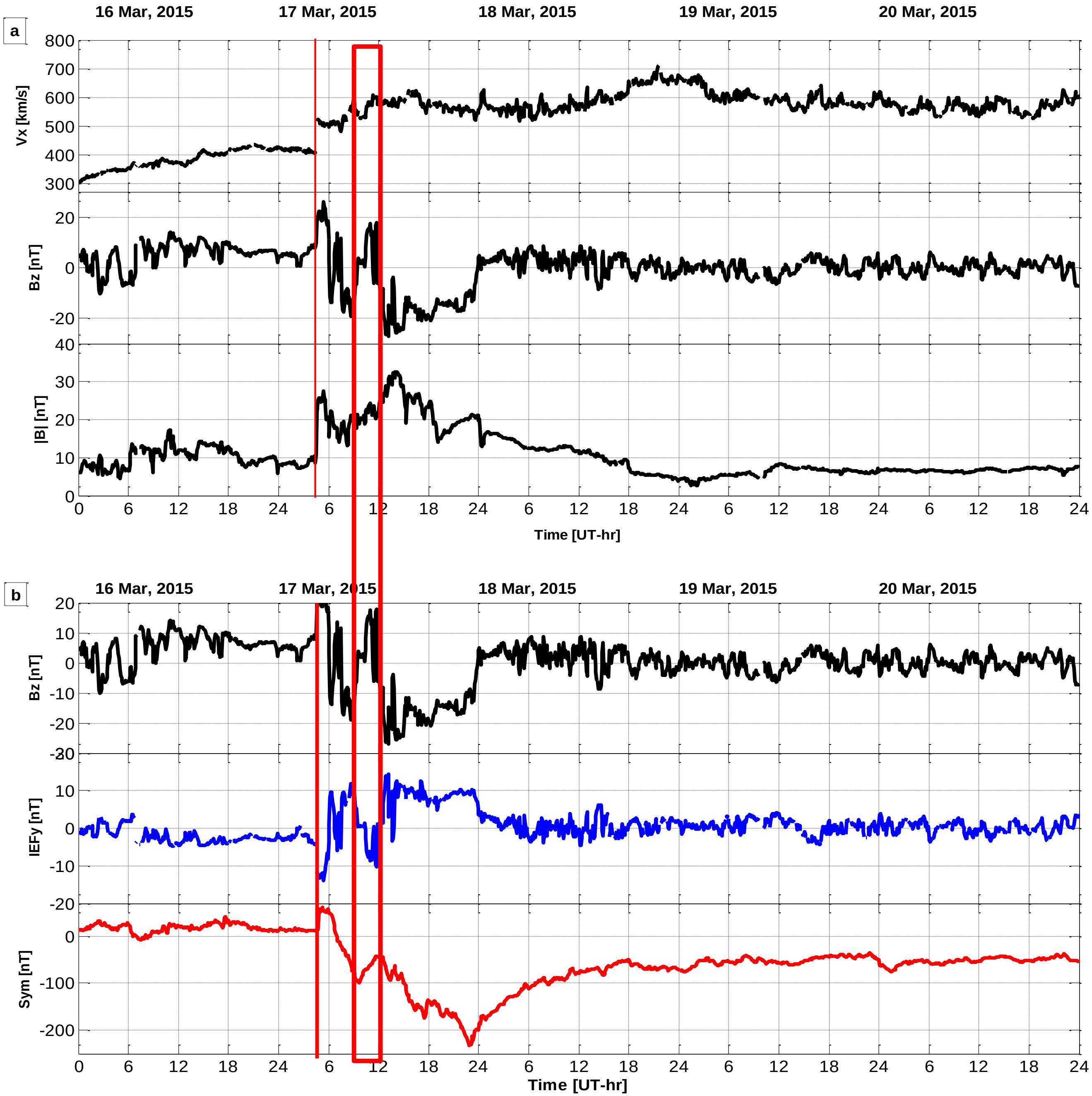


EIA response due to the Ionospheric disturbance dynamo fields



The ionospheric disturbance dynamo
Led to a well formed EIA crest with
Very high intensity of electron density

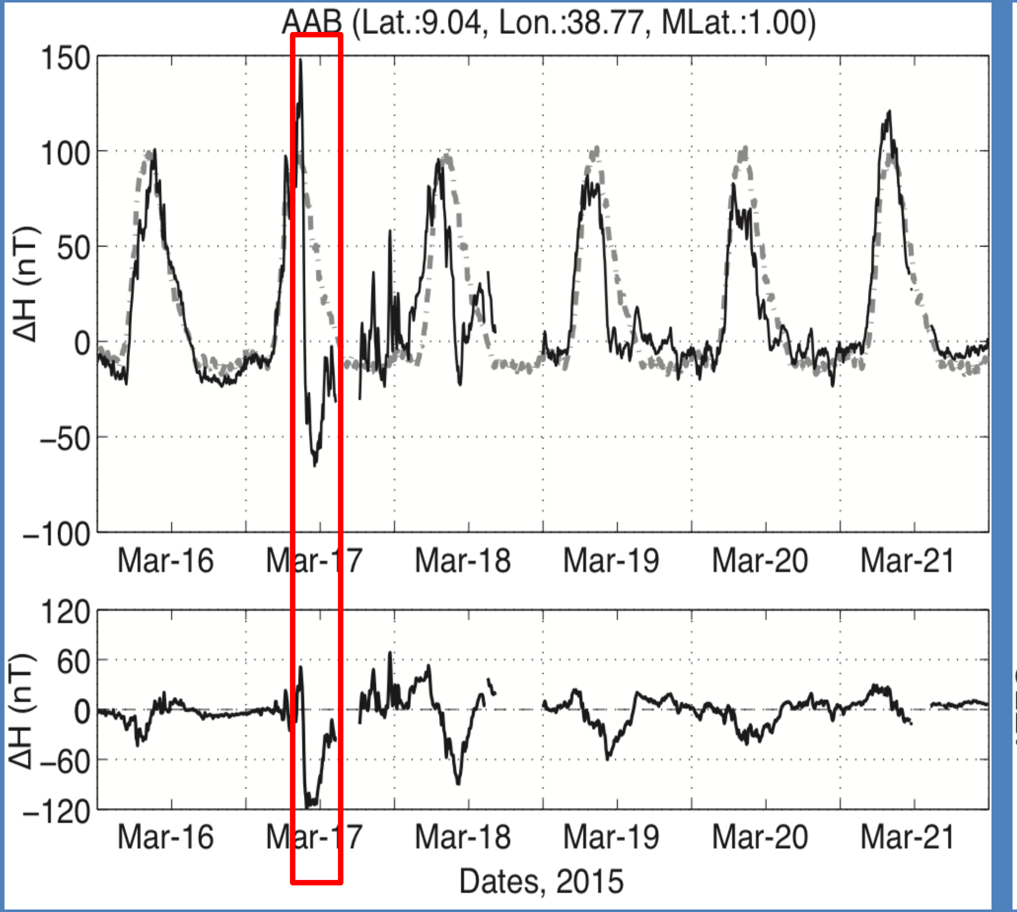
Case study 2: Geomagnetic storm March, 17-2015

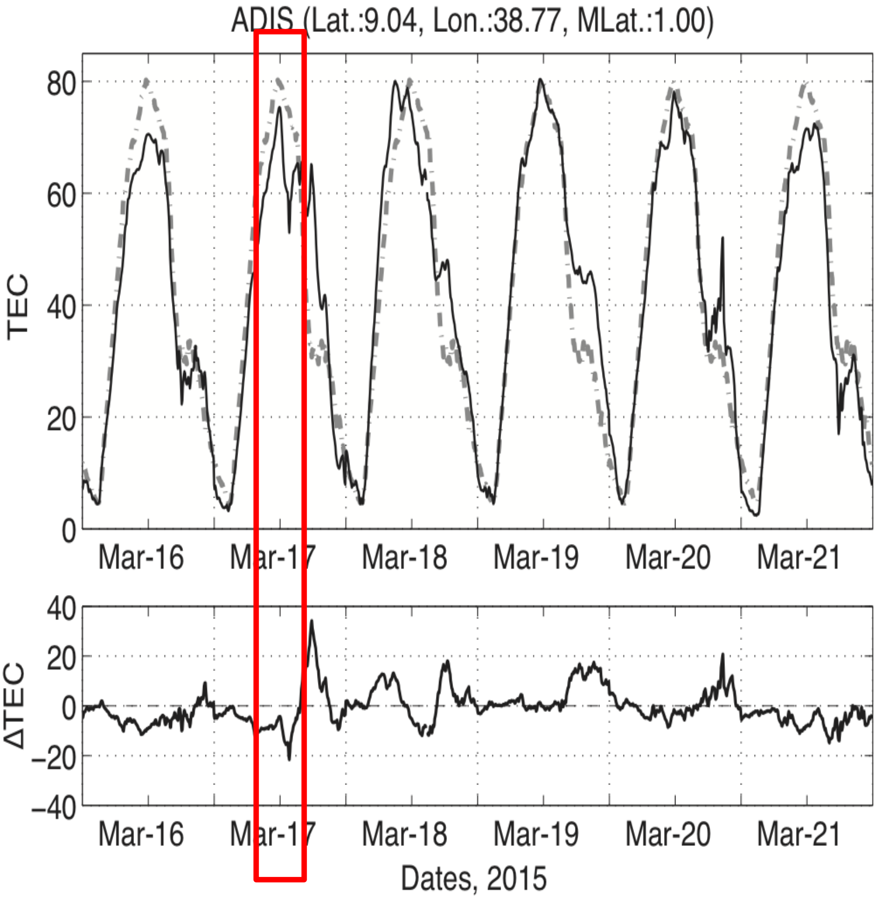


Magnetic Field Variations and on the geomagnetic storm day.

Magnetic fielld in Addis Abeba

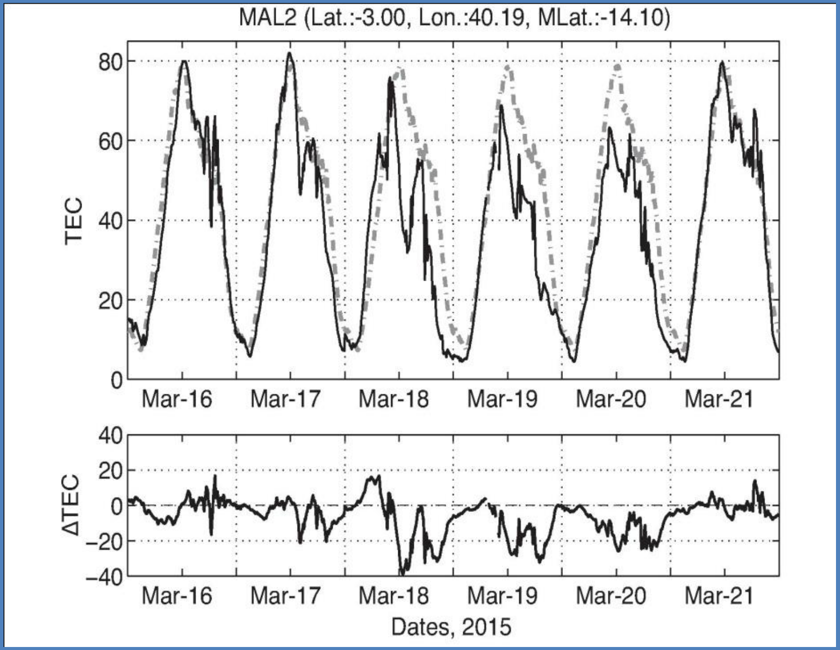
TEC response from Ethiopia

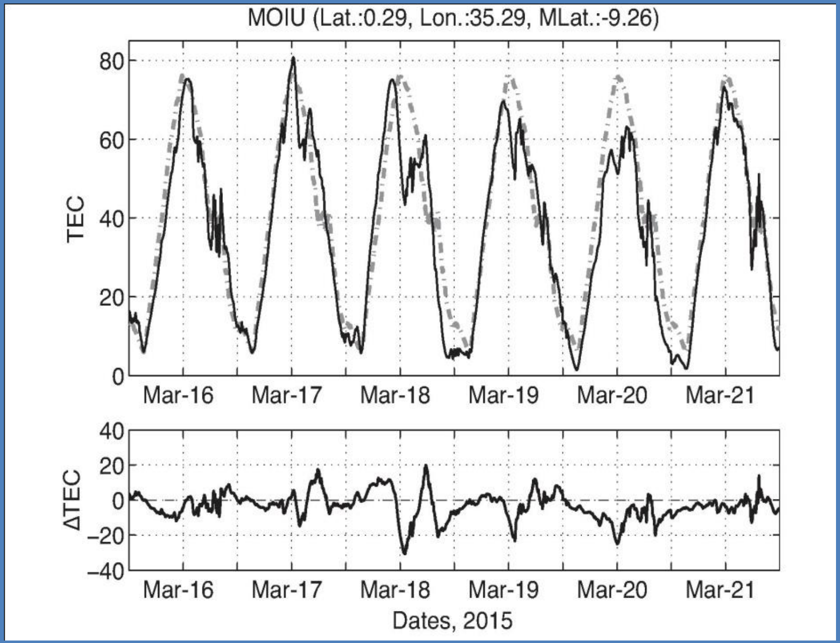


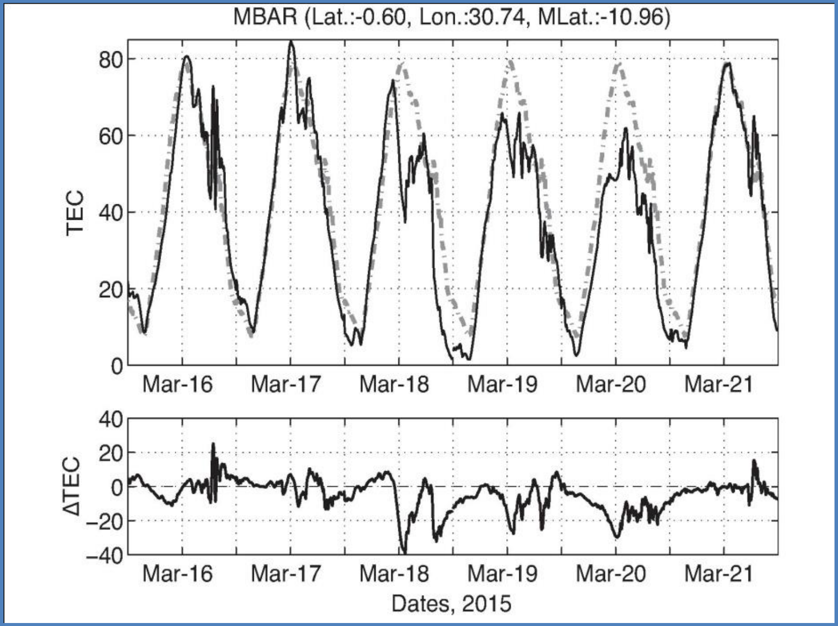


Marked region: Counter EEJ on 17 Mar 2015 between 09:00 and 12:00 causes TEC depletion over all the stations. Recovery phase of the storm starting at 09:00 is marked by a negative ionospheric storm effect.

TEC response from Kenyan region to the Geomagnetic storm


MAL2 (Lat.:-3.00, Lon.:40.19, MLat.:-14.10)


MOIU (Lat.:0.29, Lon.:35.29, MLat.:-9.26)

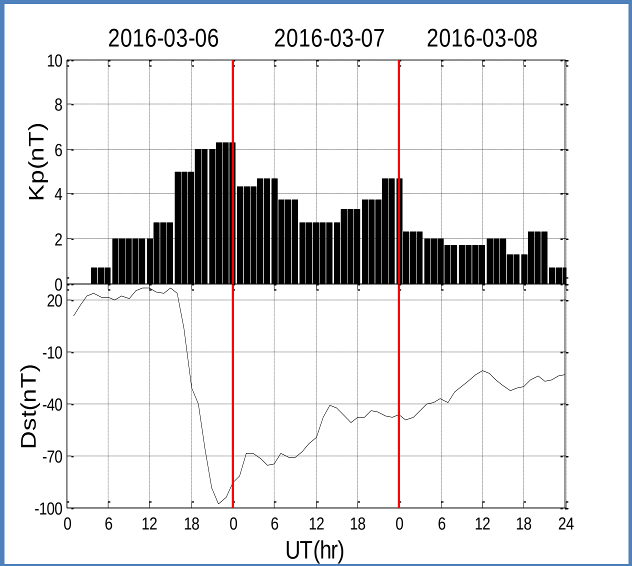

MBAR (Lat.:-0.60, Lon.:30.74, MLat.:-10.96)

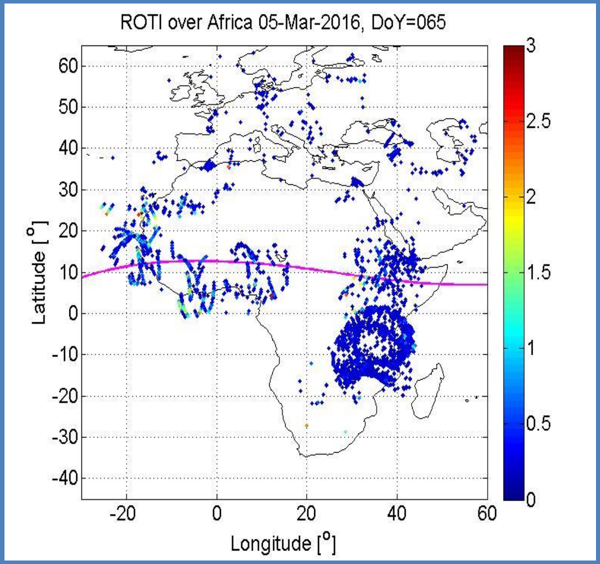
There was a positive storm effect over Ethiopia and a negative storm effect in Kenya and Uganda. (A distance of about 2000 km)

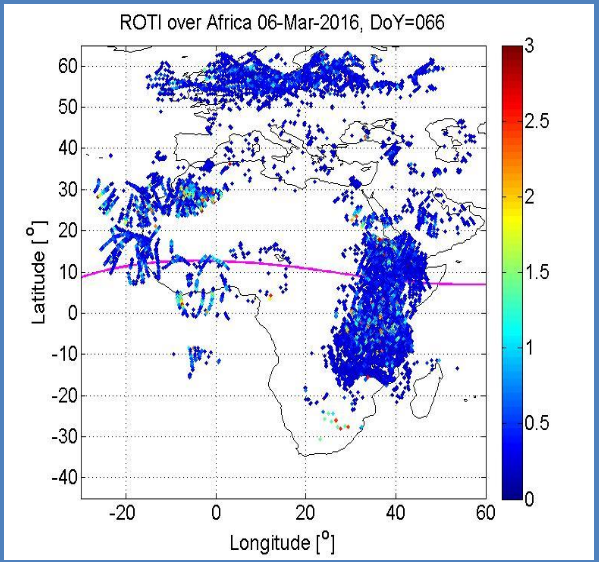
Its interesting that the effects related to storm are localized and are local time dependent.

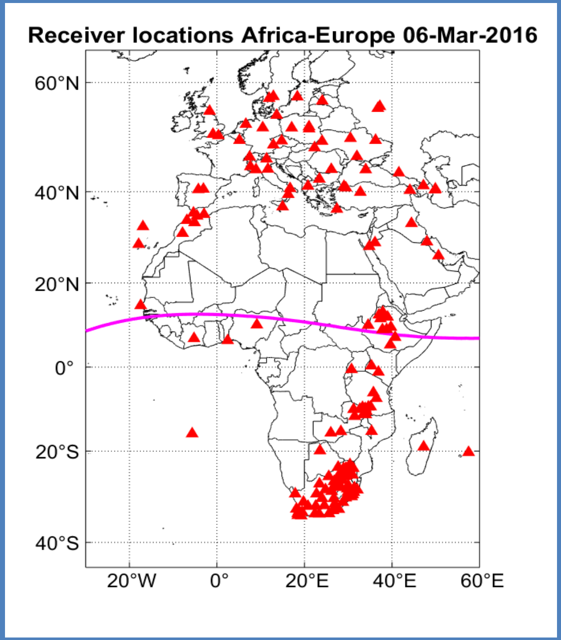
What are the causes!! We are working on investigating this interesting event!

Ionospheric Irregularities during storm: High-mid latitude coupling

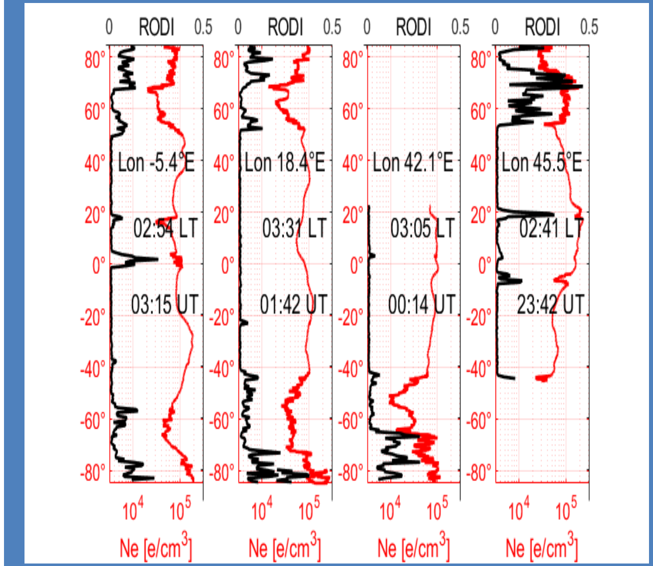




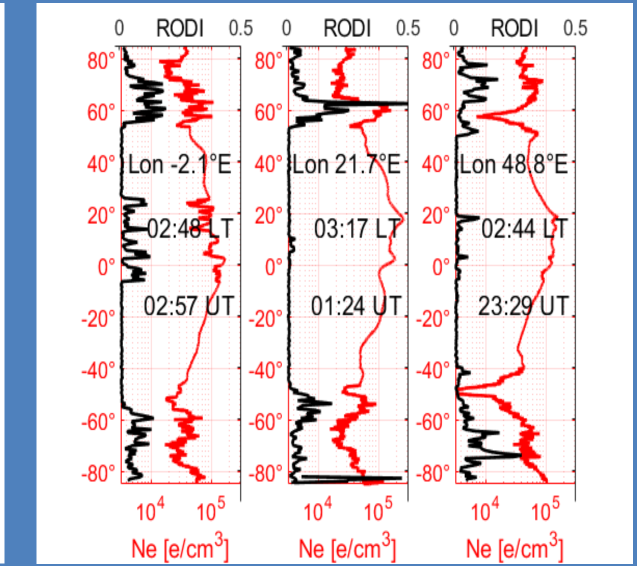




From Swarm B 06-Mar-2016



From Swarm B 07-Mar-2016



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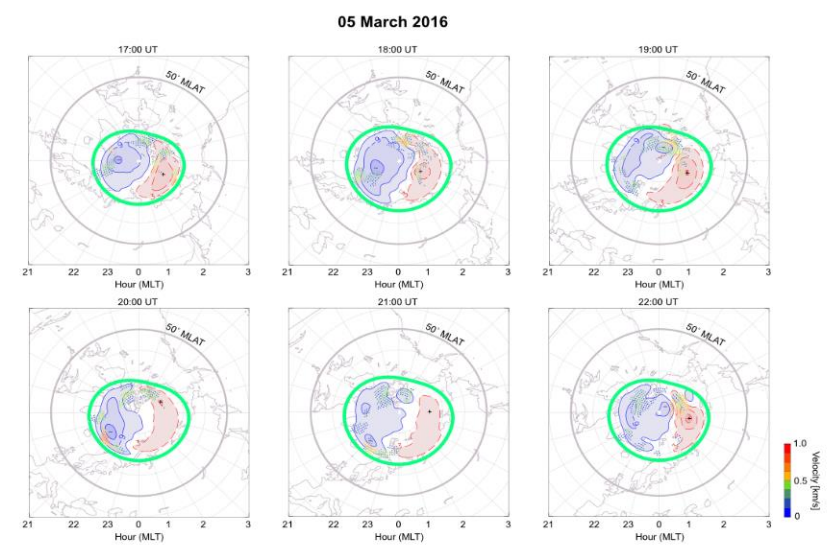
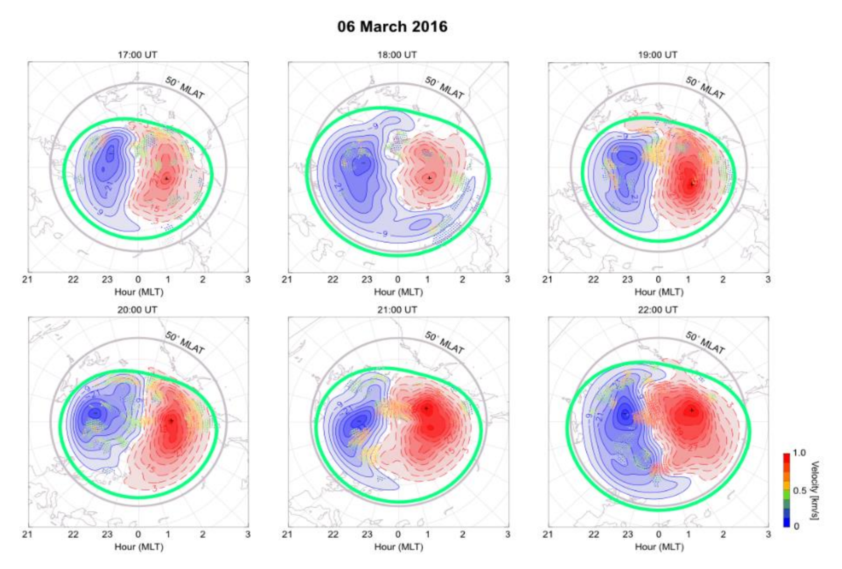
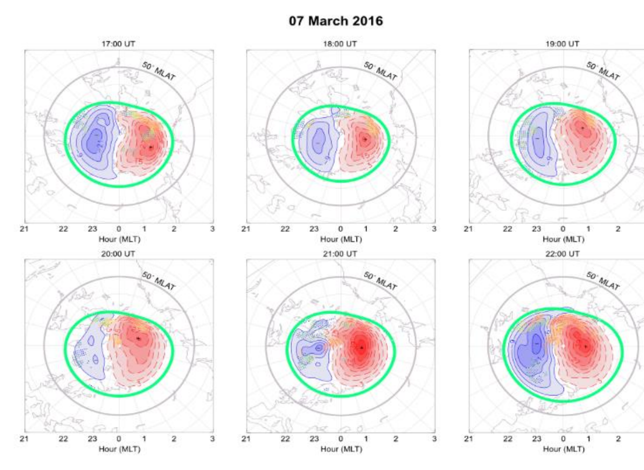
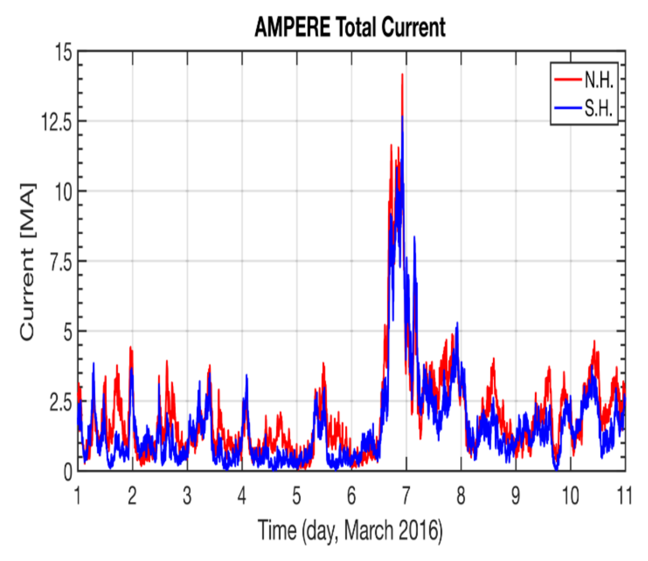
Where did the Mid Latitude irregularities come from?
Coupling Expansion of Auroral oval during storm









AMPERE current intensity in the Northern Hemisphere (red) and Southern Hemisphere (blue) during the period 1−11 March 2016.

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Conclusions

- Work on space weather specification, modeling and forecasting remains a basic research need with great public purpose and societal benefits across many sectors of our modern economies.

- The GNSS infrastructure remains vital in system science studies of the atmosphere. We however must combine GNSS observations with other data sets mainly of meteorological origin to understand the lower atmosphere-Ionosphere-Magnetosphere coupling during adverse space weather events.

- Derivation of the equivalent current system using ground-based magnetometers remains a very good estimation of the real upper atmospheric electric current, but it is important to try and relate this observation of the magnetic signatures of the storm wind dynamo physical process to in-situ measurements and model predictions.

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THE END

THANKS FOR LISTENING

ANY QUESTIONS?