Geomagnetic Storm and Its Impact on the Ionosphere-Thermosphere System

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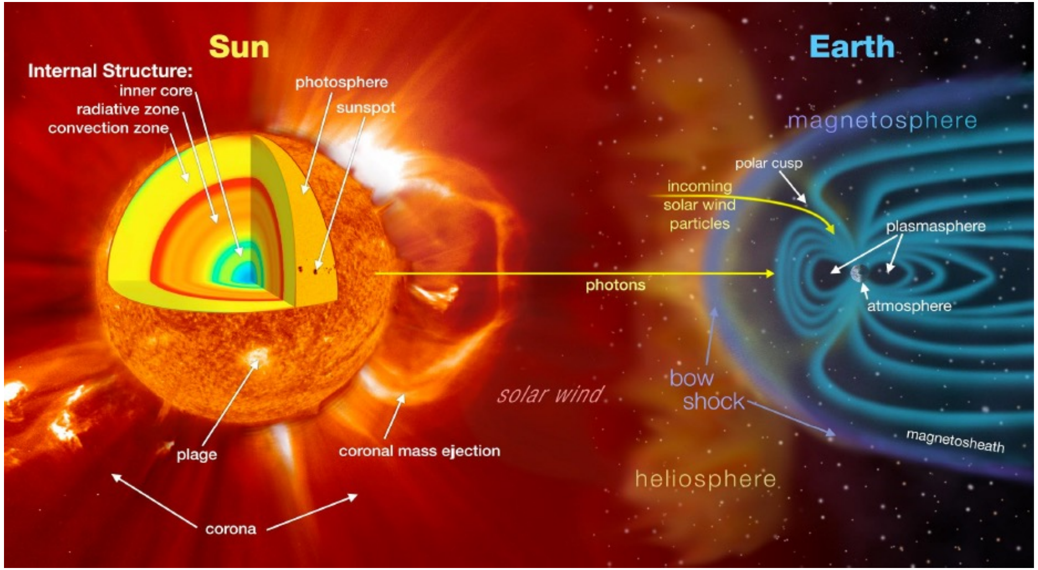
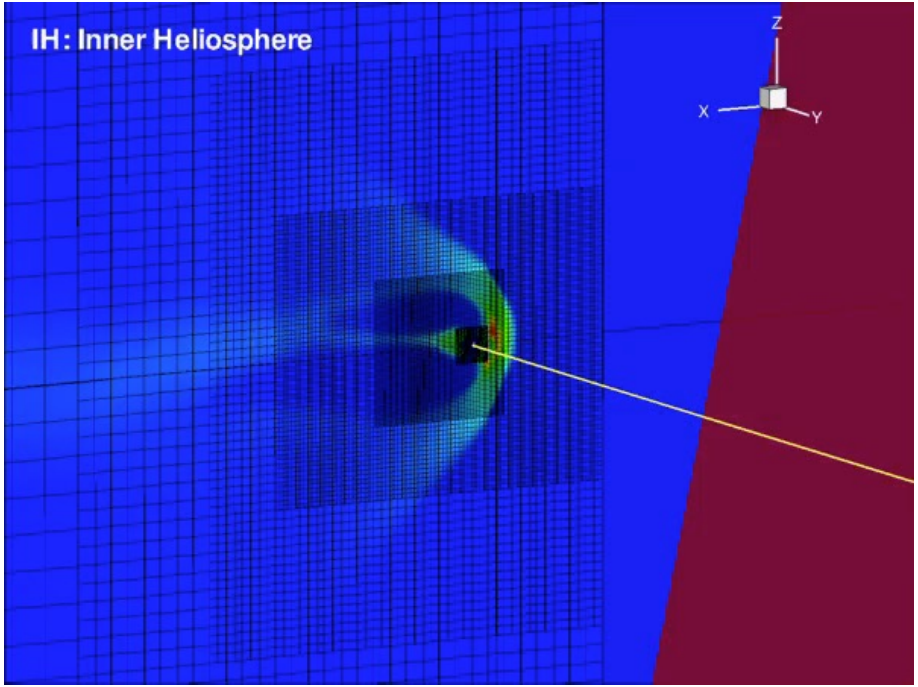
Solar-Terrestrial Relations



- Solar radiation and solar wind are the two ultimate energy sources provided by the Sun to the geospace system.
- The Earth's intrinsic magnetic field deflects much of the solar wind. The solar wind energy entering the magnetosphere drives the dynamics of the geospace system.

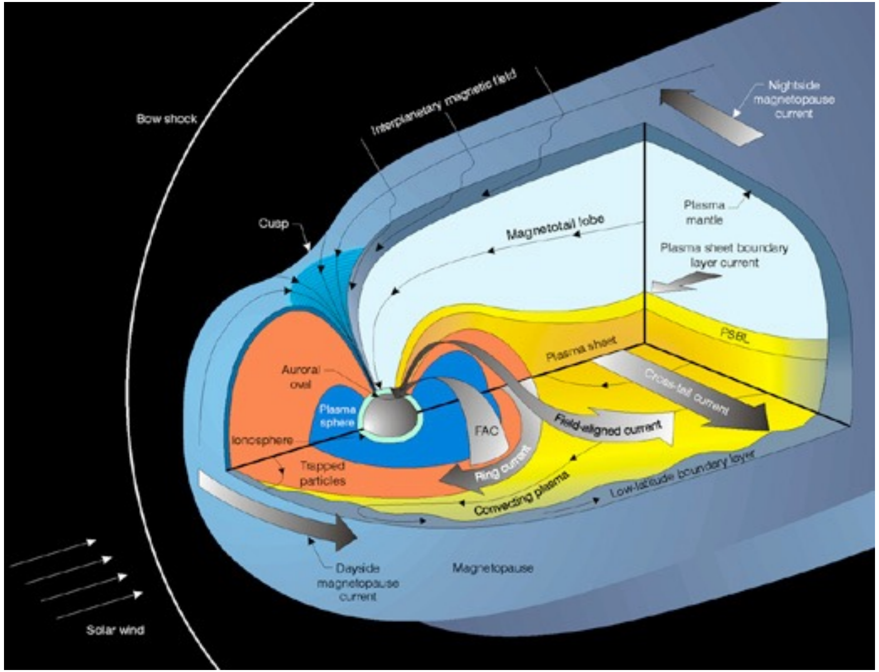
Interaction between Solar Wind and the Earth

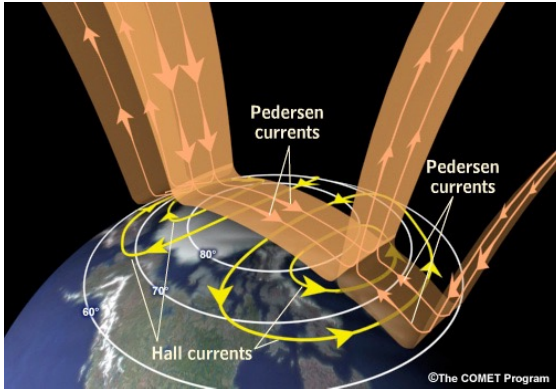


Plasma pressure and magnetic fields simulated using University of Michigan Space Weather Modeling Framework (SWMF)

- The geospace system dynamically respond to varying solar wind.

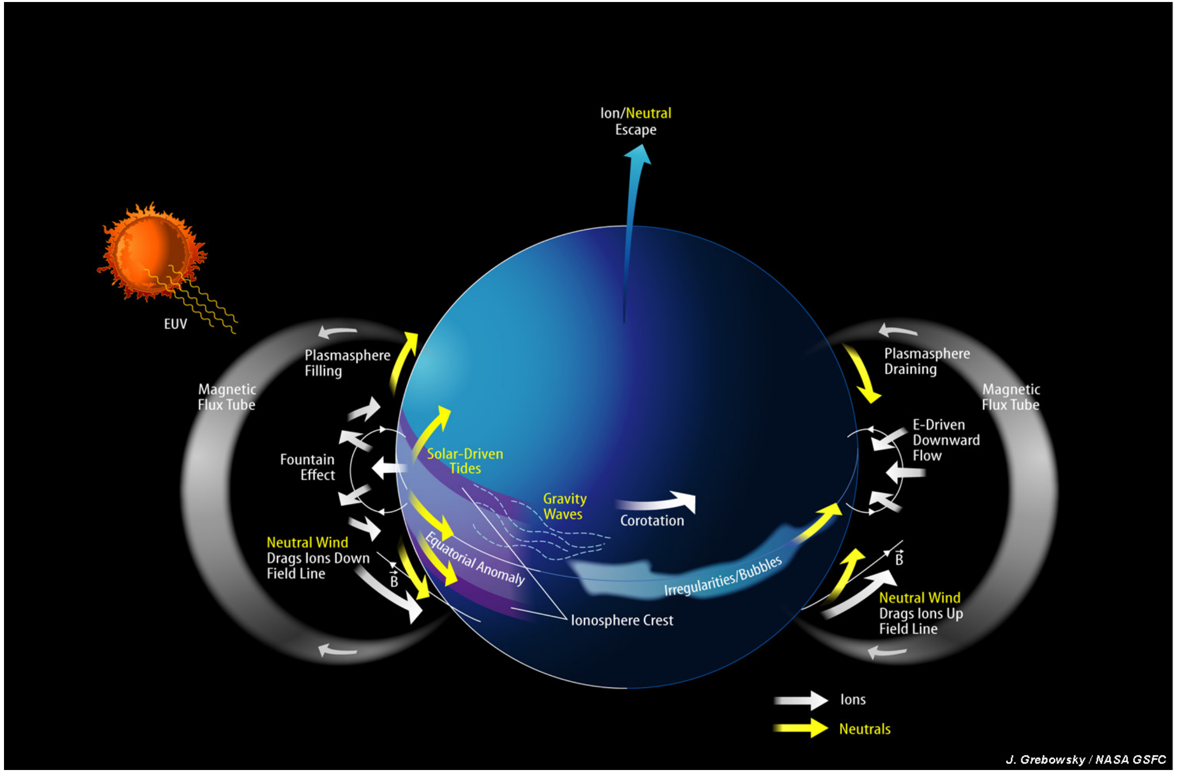
Currents in the Geospace System





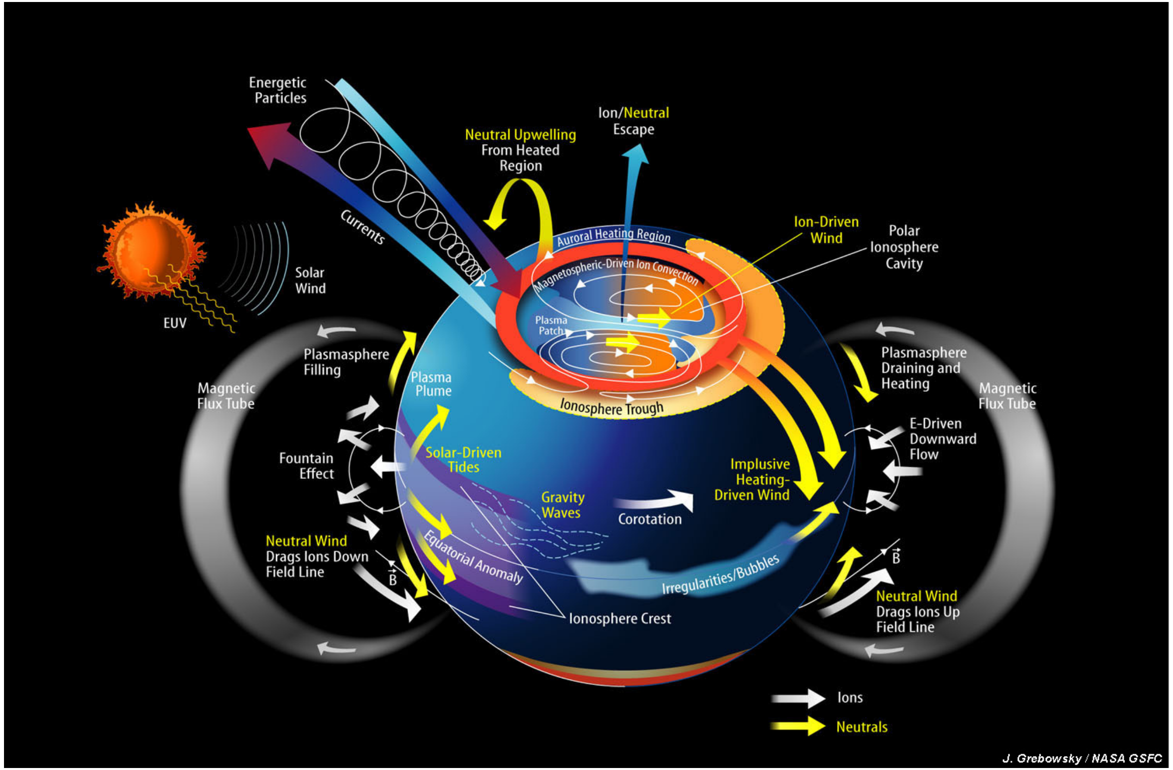
- Energies entering the magnetopause are temporarily stored in the magnetosphere, powering several large-scale current systems.
- Field-aligned currents (FACs) communicate between the magnetosphere and ionosphere and vast majority of the energy deposition occurs in the FAC region.

IT System with Solar EUV Forcing Only



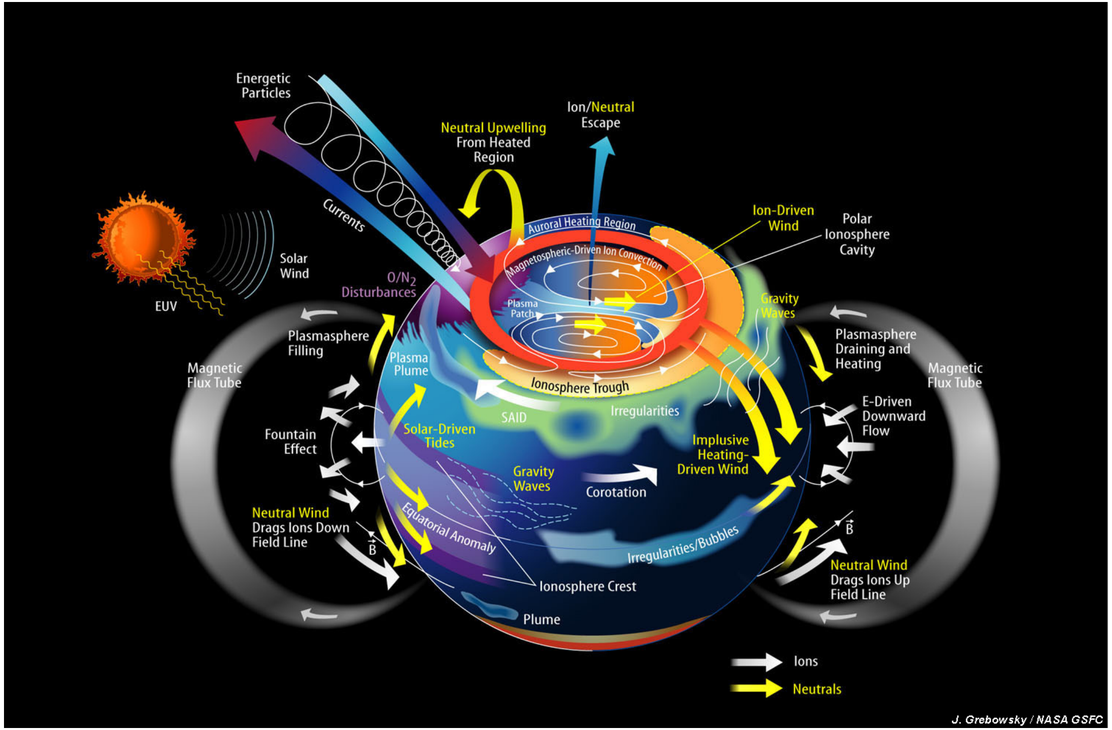
If the solar EUV is the only energy source, most of the IT dynamics would occur in the equatorial to low latitude region.

Adding Solar Wind Forcing



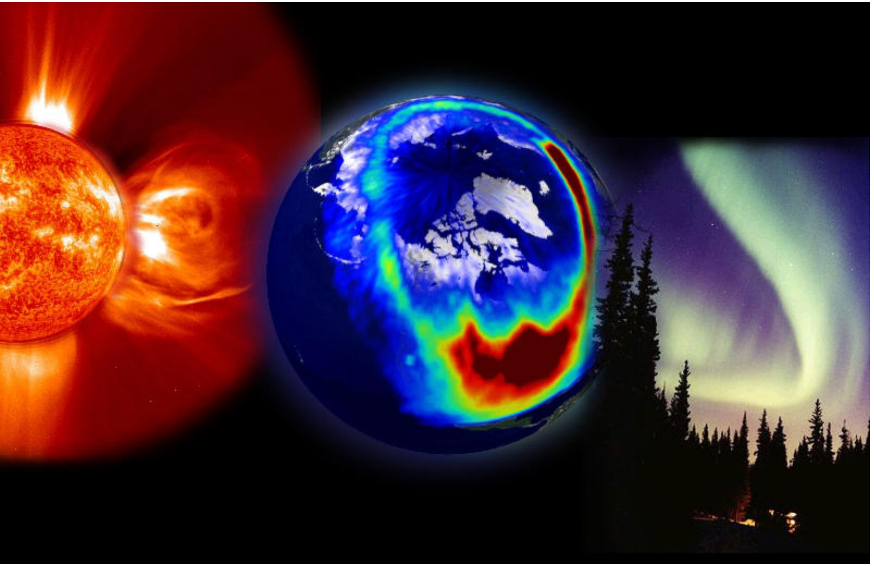
- Adding the solar wind forcing would create various high-latitude dynamics, including convection pattern, FACs and auroral zone.
- During geomagnetic quiet times, the low and high-latitude systems do not interact strongly with each other.

When the Sun "Sneezes"



- Both the solar wind and the solar EUV are highly variable and create "space weather".
- When they drive the geospace more strongly, for example, during geomagnetic disturbances, the high-latitude system would expand equatorward. At the same time, the equatorial system also expands to higher latitudes. Thus, cross-latitude coupling enhances.

Geomagnetic Disturbances

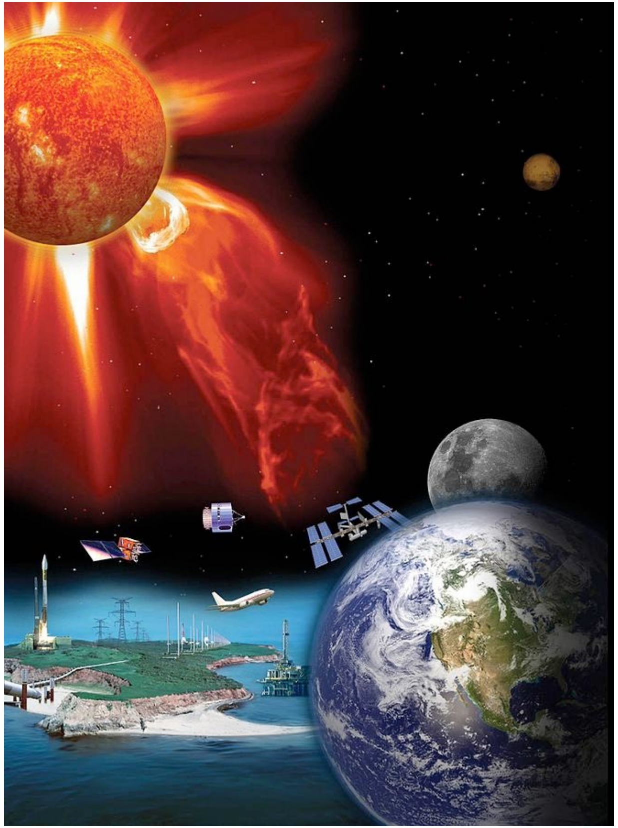


Geomagnetic disturbances are driven by transient solar wind and interplanetary magnetic field structures, such as Coronal Mass Ejection (CME) and Corotating Interaction Region (CIR).

Three major geomagnetic disturbances:

1. **Storm**: largest disturbance; global scale; last a couple of days
2. **Substorm**: nightside disturbance; last a couple of hours
3. **Shock compression**: transient but global disturbance; last several minutes

Space Weather



"Conditions on the Sun and in the space environment that can adversely influence the performance and reliability of space-borne and ground-based technological systems. "

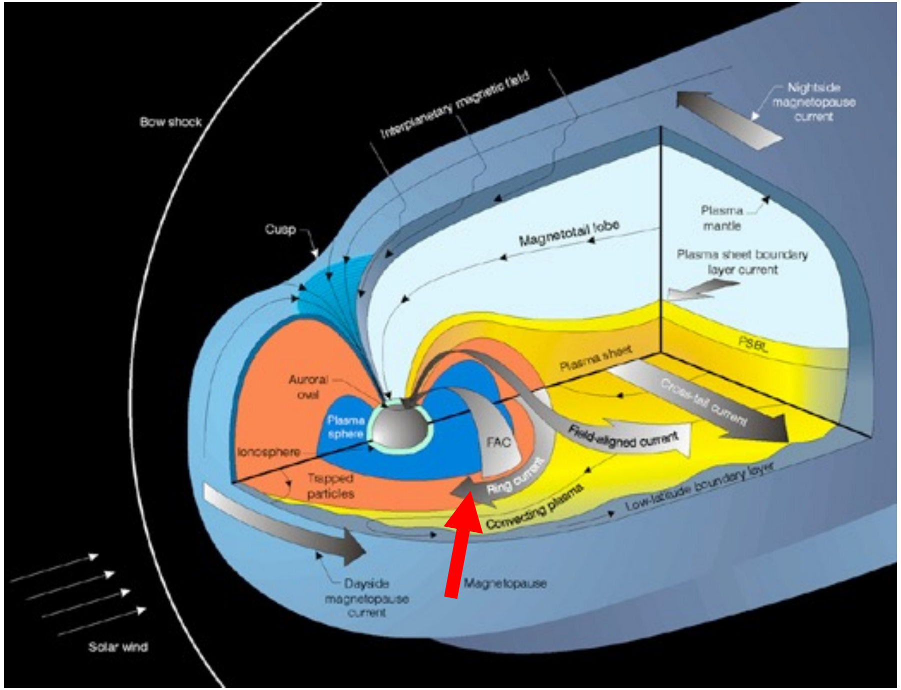
From "Space Weather: A Research Perspective", National Academy of Science, 1997.

Five major threats highlighted in the National Space Weather Strategy and Action Plan (2015):

- Induced Geo-Electric Fields
- Ionizing Radiation
- Ionospheric Disturbances
- Solar Radio Bursts
- Upper Atmospheric Expansion

Geomagnetic Storm

- A geomagnetic storm is a major disturbance of Earth's magnetosphere that occurs when there is a very *efficient energy exchange* from the solar wind into the space environment surrounding Earth.
- There are major changes in the currents, plasmas, and fields in the Earth's magnetosphere.
- Geomagnetic storms are defined by worldwide average of the low-latitude disturbance in the horizontal magnetic field due to *ring current* in the inner magnetosphere.

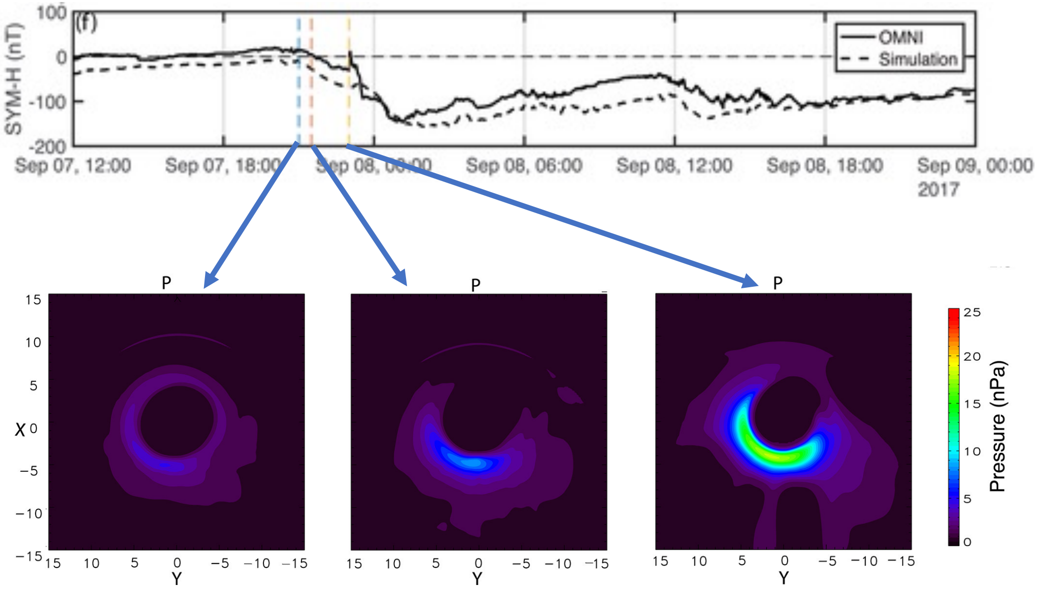


Geomagnetic Storm Identification

- An hourly index D_{st} (disturbance storm-time index) is traditionally used to identify storm and define its magnitude.
  - High temporal resolution version (1-min): Sym-H
  - SuperMAG symmetric ring current index: SMR (Newell and Gjerloev, 2012, JGR)

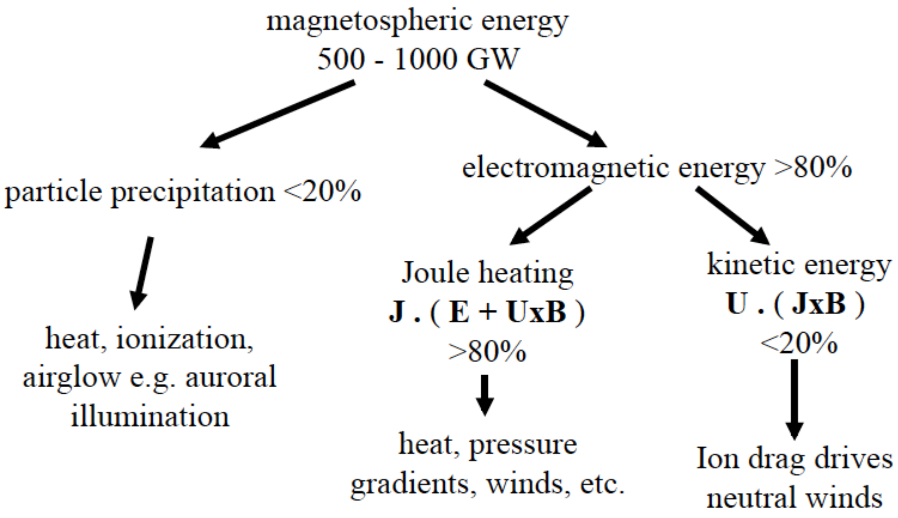
- Geomagnetic storm classification:
  - Minor: -20 nT > D_{st} > -50 nT
  - Moderate: -50 nT > D_{st} > -100 nT
  - Intense: -100 nT > D_{st} > -250 nT
  - Super: -250 nT > D_{st}

Sym-H and ring current evolution



Wang et al. (2019). *GRL*, 46, 7920– 7928.

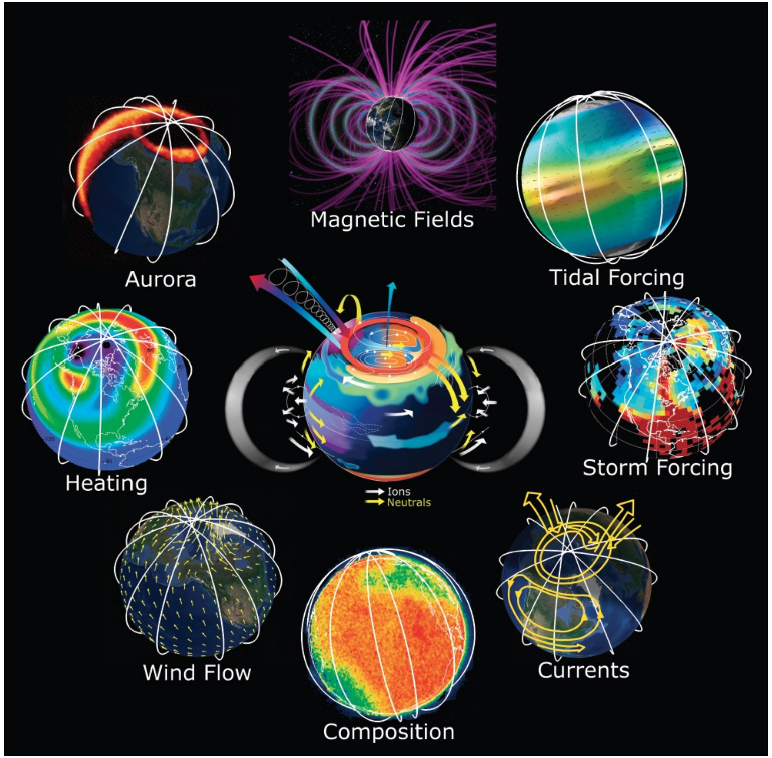
Energy Flow During Storm



See Lu et al., 1995

- Several hundreds GW energies flow into the IT system in the form of electromagnetic energy (Poynting flux) and particle precipitation.
- Electromagnetic energy (Poynting flux) is the dominant energy source.
- Majority of the electromagnetic energy goes to Joule heating.

Complexity of Geospace Responses During Storm

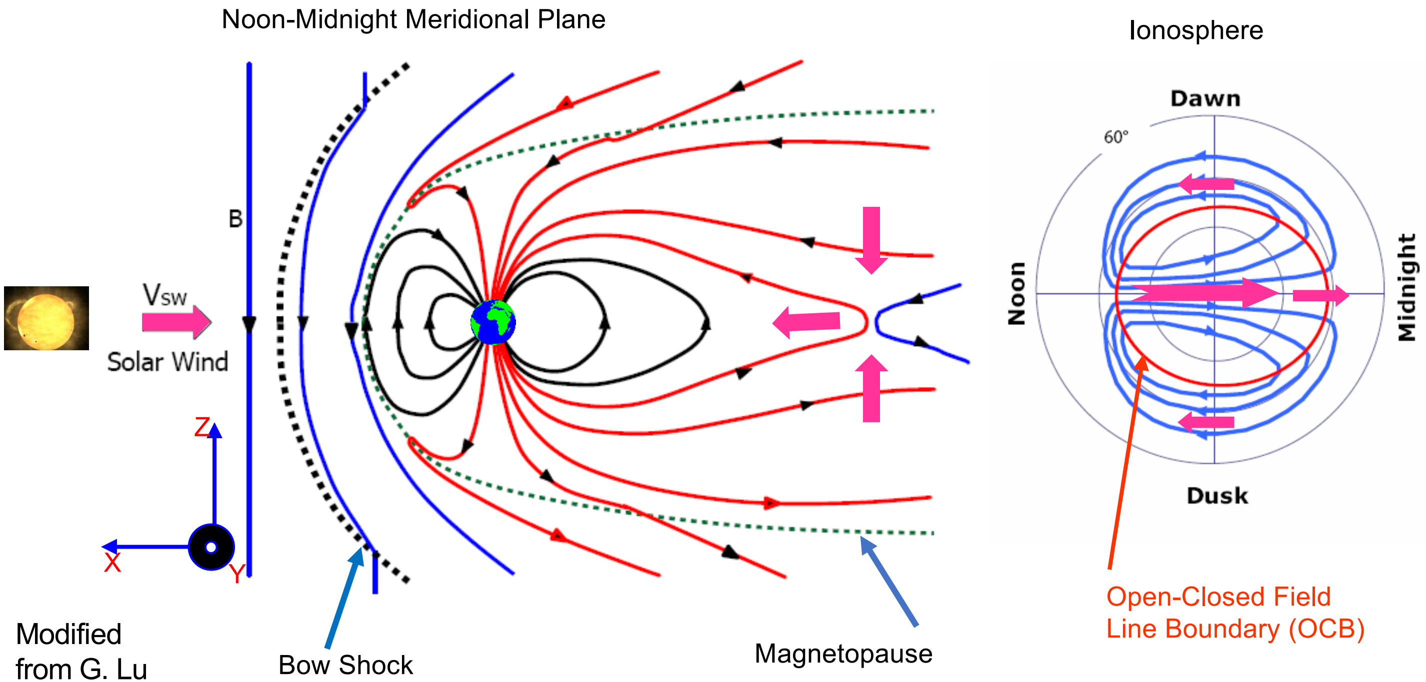


2013 Solar and Space Physics decadal survey

- Storm-time forcing from the magnetosphere drives global responses of multiple physical quantities.

- Physical quantities highlighted in this lecture:
  - Electric field
  - Ionosphere plasma content
  - Thermospheric wind
  - Thermospheric composition

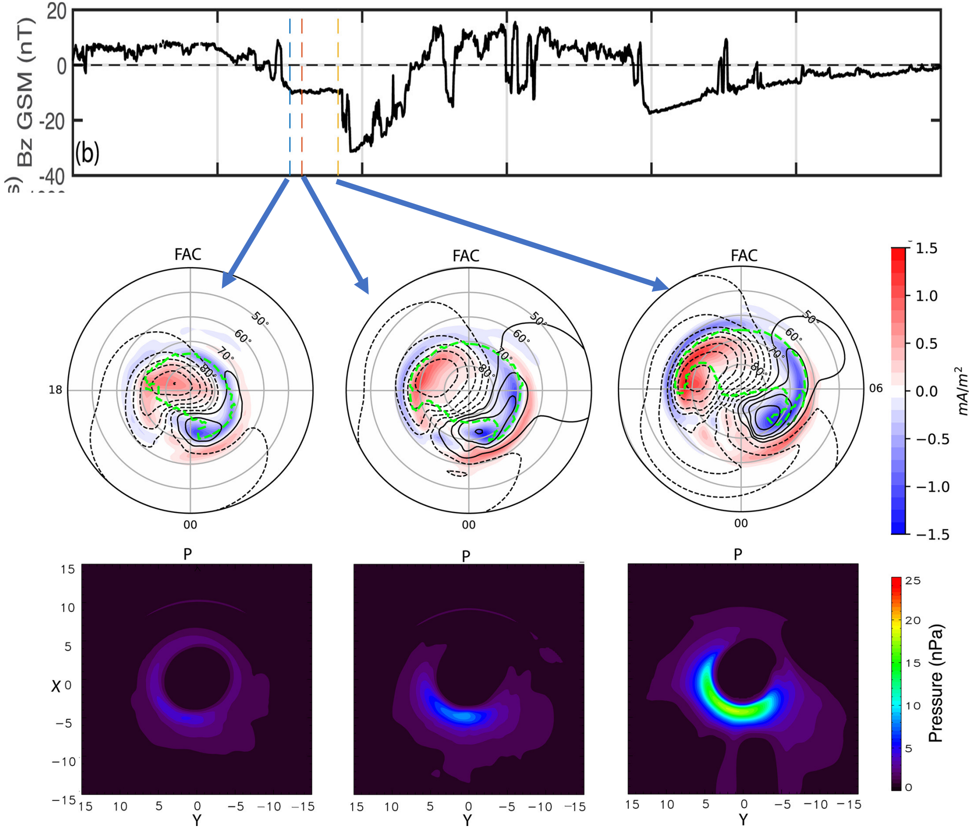
Magnetospheric and Ionospheric Convection: Fluid Description



Modified from G. Lu 2005 GEM Tutorial

- Reconnection model proposed by J. Dungey [1961]
- Major energy and momentum coupling mechanism between the solar wind and magnetosphere.

Storm-time Expansion of Ionospheric Convection



- Dayside reconnection enhances after strong IMF southward turning during storm and efficiently transfers energies into the magnetosphere.
- High-latitude ionospheric convection and FACs expand to lower latitudes.
- Mis-match between convection pattern and FACs => penetrating or shielding electric field
- Penetration electric fields can be established globally nearly simultaneous.
- Ring current evolution modulates the convection and FAC patterns.

Wang et al. (2019). *GRL*, 46, 7920– 7928.

Ionospheric Storm

- Ionospheric storm refers to ionospheric density disturbances during geomagnetic storm.
- Positive and negative phases refer to ionospheric density/total electron content (TEC) increase or decrease comparing with quiet values, respectively.
- Low- and mid-latitude ionospheric density increase is also referred to as storm-enhanced density (SED) (Foster et al., 1993, JGR).

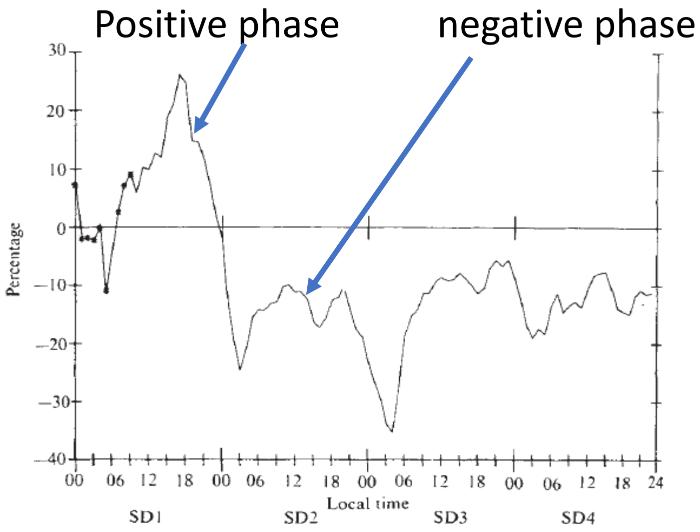
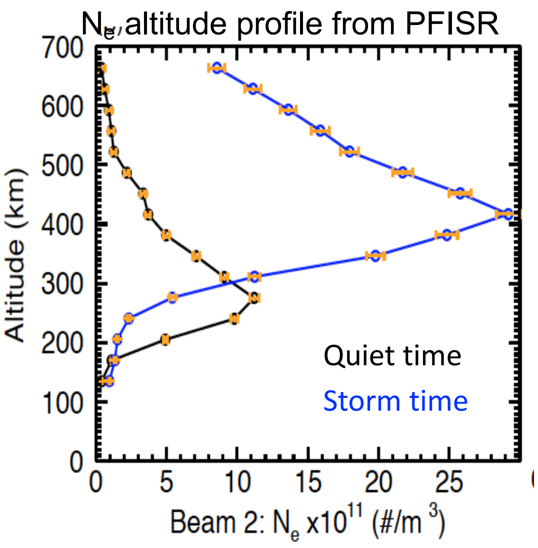


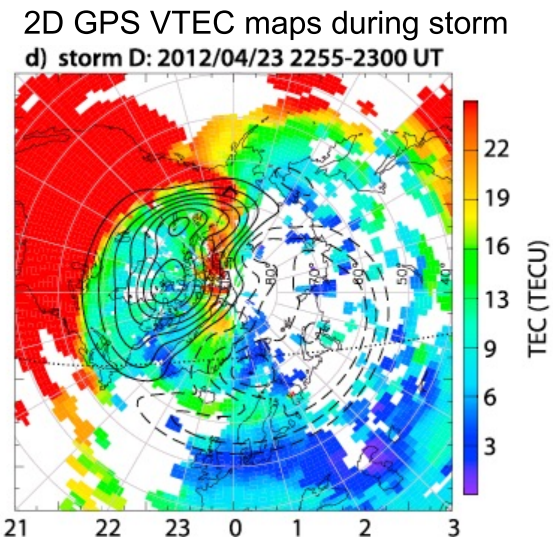
Fig. 2 The average disturbed daily variation (SD) of total electron content (N_T) obtained from twenty-eight storm periods. The asterisks denote mean hourly values averaged from less than fourteen data points.

Mendillo, M. (1971), Ionospheric total electron content behavior during geomagnetic storms, Nature.

F-region Density within SED



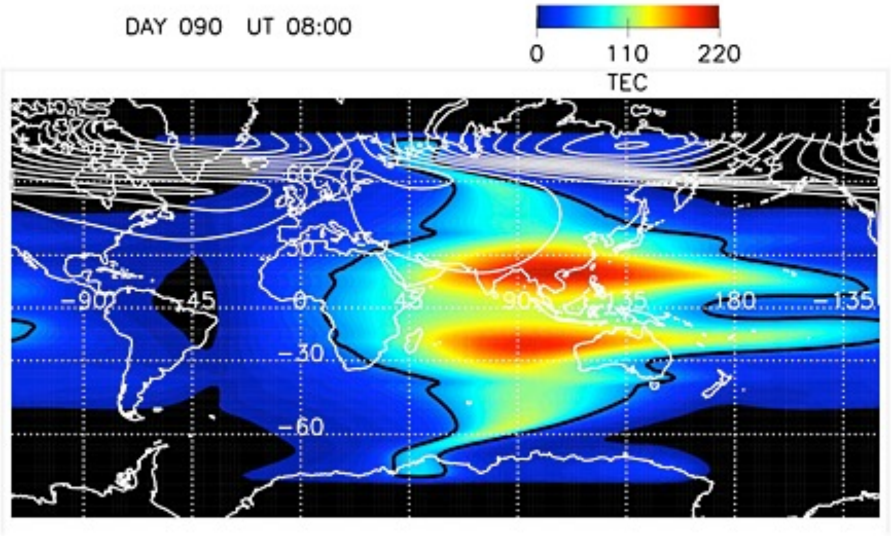
Zou et al. 2013



Zou et al. 2014

- Important mechanism for transporting solar produced high density plasma into low density polar cap and nightside auroral region.
- Strong vertical lifting within SED is evident and is a result of magnetosphere-ionosphere-thermosphere coupling processes.

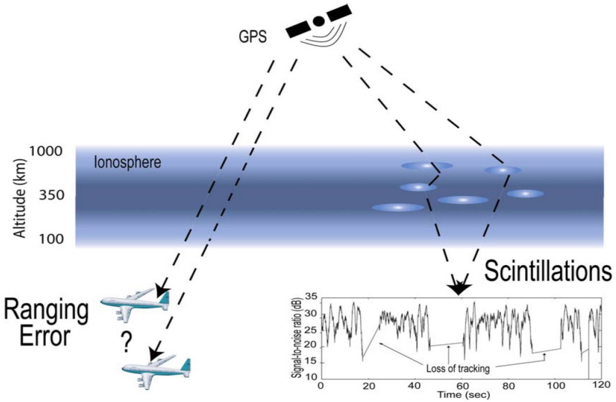
Coupled SAMI3-RCM Simulation of SED



Huba and Sazykin, 2014, GRL

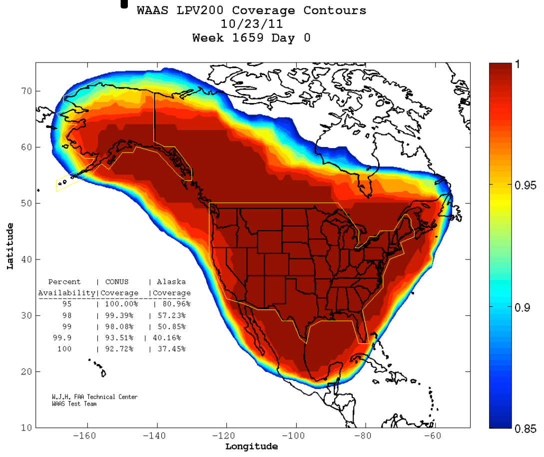
- Minimum D_{st} during March 31, 2001 storm reached -387 nT.
- Plasma from the expanded Appleton anomaly may also contribute to the formation of SED plume during superstorms.

Space Weather Impact of Ionospheric Storm

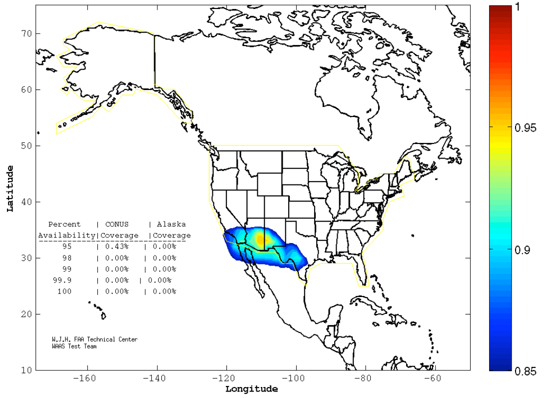


Kintner, 2006

Quiet time



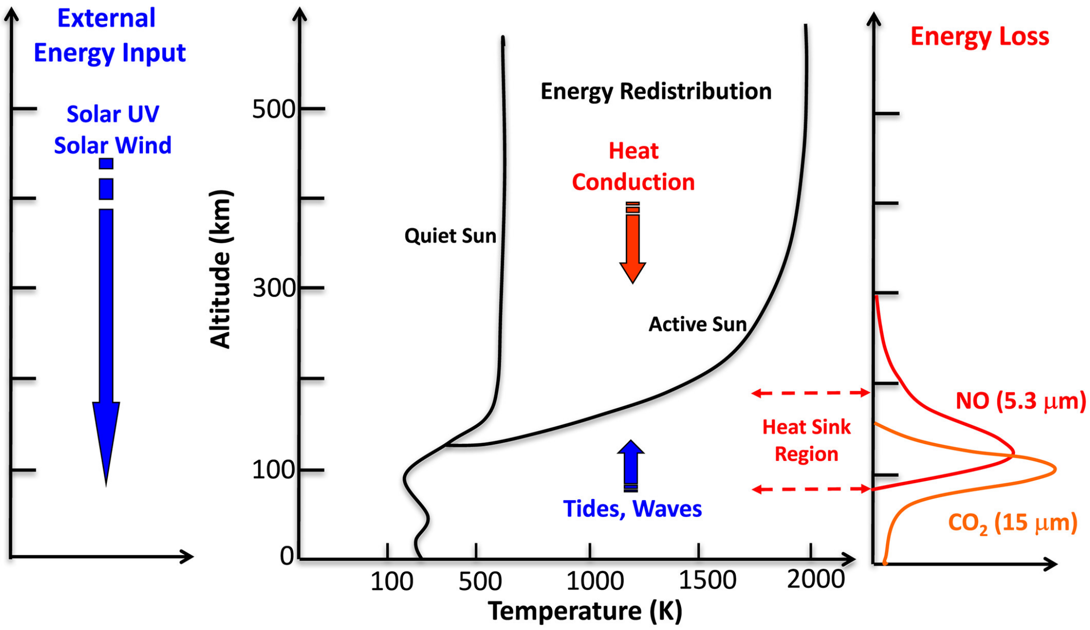
Storm time



- The Global Positioning System (GPS) is a U.S.-owned utility that provides users with positioning, navigation, and timing (PNT) services.
- The Wide Area Augmentation System (WAAS) is an air navigation aid developed by the Federal Aviation Administration to augment GPS.
- WAAS performance can be affected by storm-time density structures.

Thermosphere Thermal Structure and its Energy Budget

Energy is input to the thermosphere externally from the Solar radiation and solar wind, as well as from the atmosphere below in the form of tides and waves.



The primary loss mechanism of the energy in the upper atmosphere is through Nitric Oxide (NO) and Carbon Dioxide (CO2) radiative cooling.

Mlynczak et al., 2018, Space Weather, 16, 363-375.

Thermospheric Wind Circulation during Storm

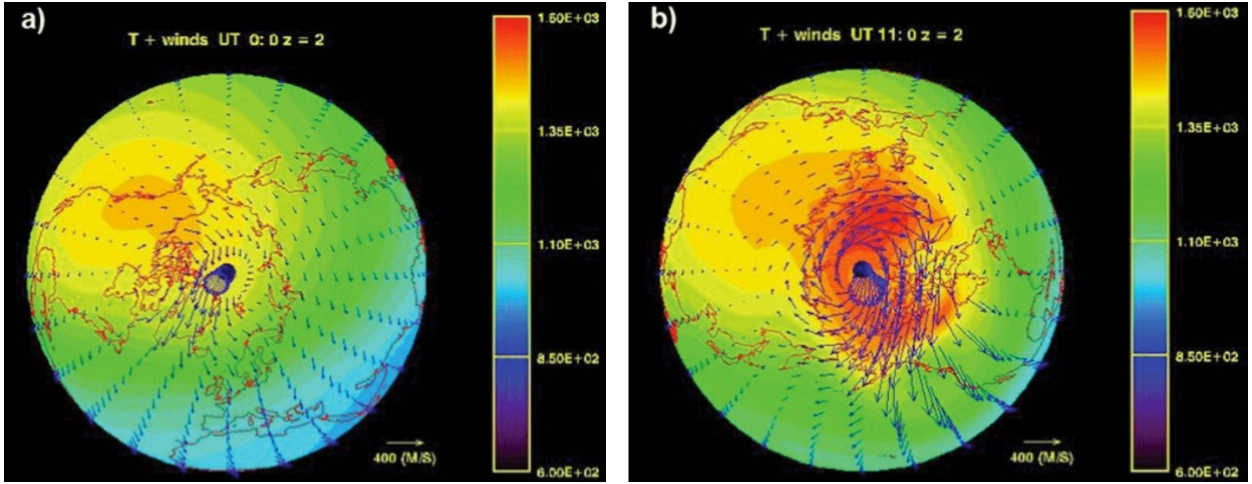
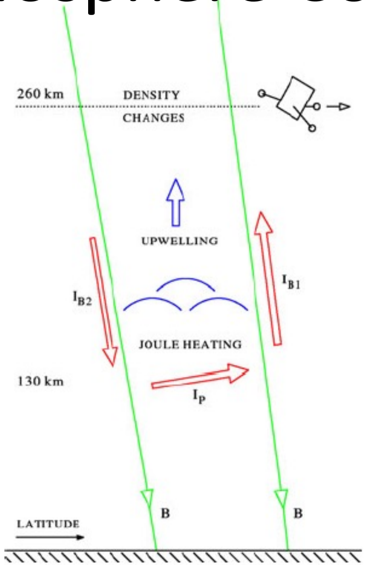
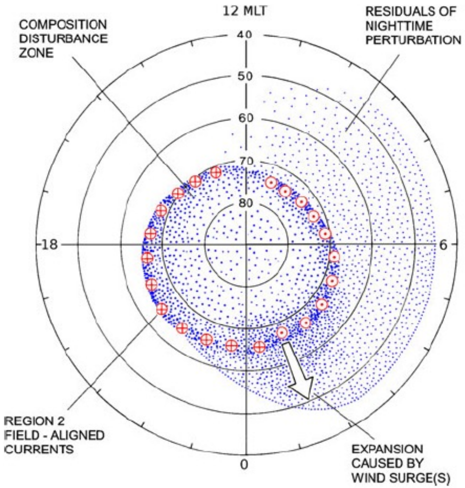


Figure 12-24, “Understanding space weather and physics behind” by Delores Knipp.

- Convecting ionosphere is a significant source of momentum and energy for the thermosphere via ion–neutral collisions during storms.
- High-latitude thermospheric wind pattern mimics the ionospheric convection pattern and modifies the quiet time solar heating driven wind pattern. Large equatorward wind can be generated on the nightside.
- Evident thermosphere heating in the auroral zone.

Thermosphere Composition Change during Storm

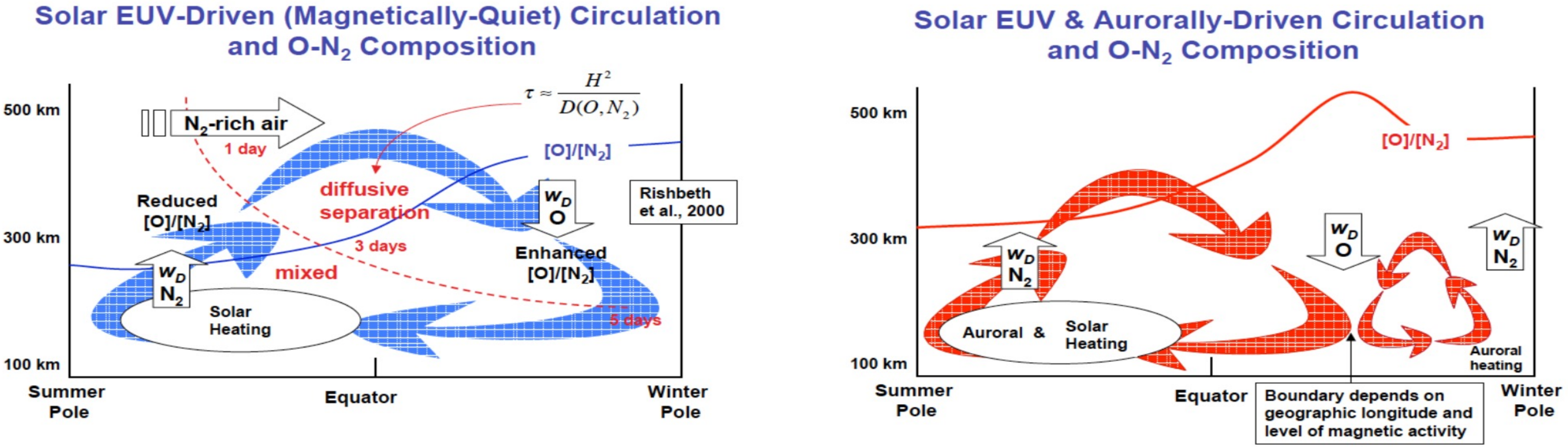




Prölss, 2006,
Survey of Geophysics

- Enhanced joule heating and particle precipitation in the auroral zone leads to upwelling of molecular rich neutral particles and thus composition perturbations.
- These composition perturbations expand to lower latitudes due to the enhanced equatorward wind and to the dayside due to corotation.
- Thermosphere composition (O/N_2) is critical in determining the density of the ionosphere, since the O controls the production rate of ions, while N_2 controls the loss rate.

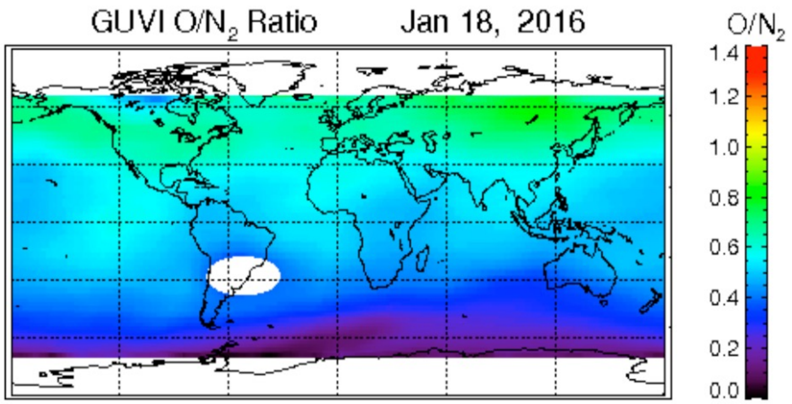
Superposition of Season and Storm Effects



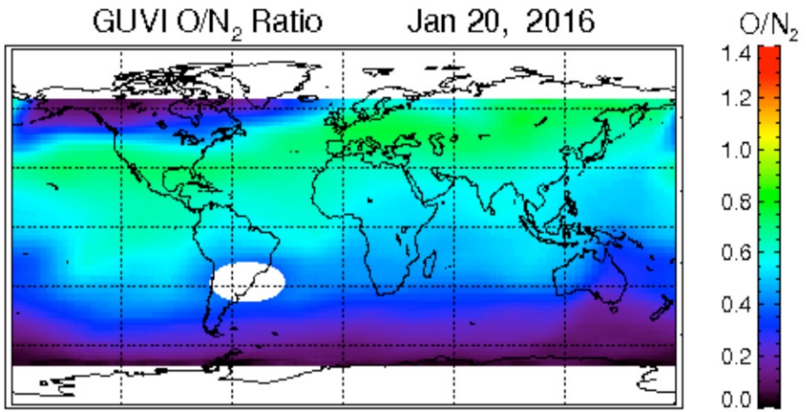
- These storm time thermospheric wind and composition changes are superposed on top of the seasonal variations.
- Due to the differential heating of the thermosphere in solstice, the O/N_2 ratio is increased in the winter hemisphere and decreased in the summer hemisphere.
- Storm-time auroral latitude Joule heating modifies this circulation and the O/N_2 ratio distribution.

GUVI O/N_2 Ratio Observations during Storm

Quiet day O/N2 ratio



Storm time O/N2 ratio

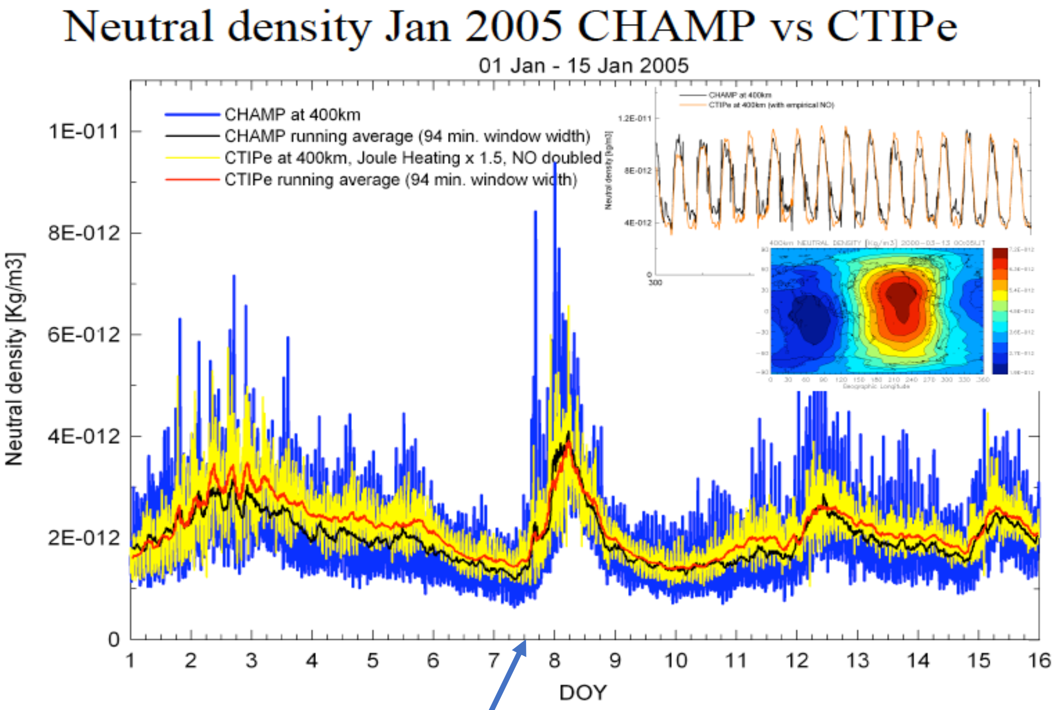


- Column integrated O/N2 ratio is often used as a disturbance proxy of the thermosphere.
- Decrease of O/N2 ratio is the major reason for storm-time ionosphere negative phase.

GUVI images from APL GUVI website
Dst from WDC Kyoto center

Thermosphere density increase during storms

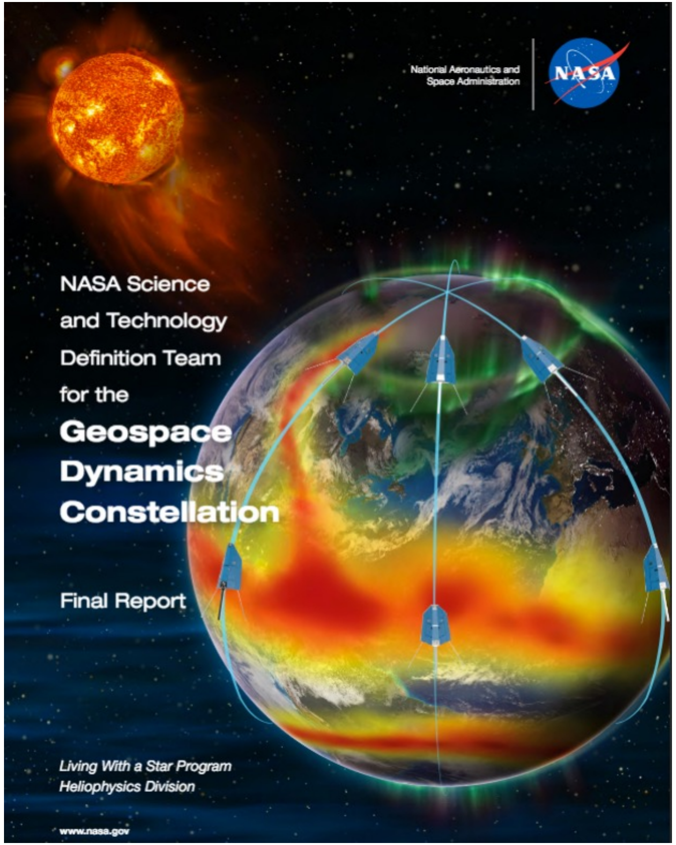
- Neutral mass density increases significantly during storms due to heating and scale height change.
- Thermosphere density variations significantly change the satellite drag and affect satellite orbit prediction.



Storm onset

From T. Fuller-Rowell

Geospace Dynamics Constellation (GDC)



The GDC mission will meet the critical observational needs of the complex IT system by employing a multi-satellite architecture sufficient to cover the relevant temporal and spatial scales, thereby transforming our understanding of this critically-under sampled region.

Goal 1: Understand how the high latitude ionosphere-thermosphere system responds to variable solar wind/magnetosphere forcing.

Goal 2: Understand how internal processes in the global ionosphere-thermosphere system redistribute mass, momentum and energy.

Summary

- A geomagnetic storm is the most severe geomagnetic disturbances of Earth's magnetosphere that occurs when there is a very efficient energy exchange from the solar wind into the space environment surrounding Earth. There are major changes in the currents, plasmas, and fields in the Earth’s magnetosphere.
- Several hundreds GW energies flow into the IT system in the form of electromagnetic energy (Poynting flux) and particle precipitation, and lead to global and complex IT system responses.
- Ionosphere-Thermosphere responses highlighted in this lecture include
  - Expansion of high-latitude convection pattern and penetration to mid- and low-latitudes;
  - Large-scale ionospheric density structure formation and dynamics during ionospheric storm;
  - Thermosphere energy budget and composition change.