The effects of secular change in the Earth's internal magnetic field on geomagnetic activity

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Aims and approach

AIMS

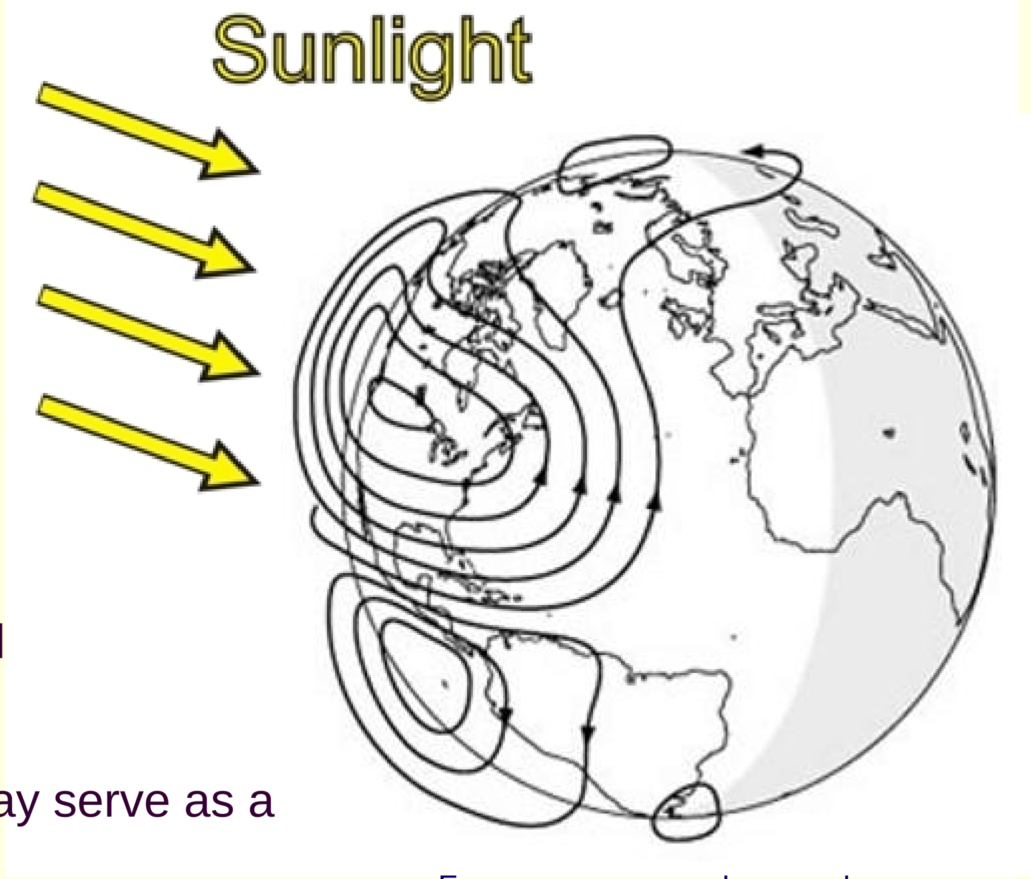
- Quantify and understand the effects of magnetic field changes on the Sq current system
- Find out which parts of the world are least affected by magnetic field changes

APPROACH

- Use simulations with the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model
- Idealized studies:
  - Changes in dipole moment
  - Changes in dipole tilt
- Realistic simulations
  - International Geomagnetic Reference Field (IGRF) or GUFM-1 (Jackson et al., 2000) to specify the magnetic field
  - Real solar wind conditions
  - 1858, 1908, 1958, 2008

The solar quiet (Sq) current system

- Geomagnetic activity = perturbations to the main magnetic field produced by currents flowing in the magnetosphere and ionosphere
- The solar quiet (Sq) current system is located at low-middle latitudes 90-200 km
- Quiet geomagnetic conditions
- Mainly affected by the ionospheric wind dynamo
- Thermospheric neutral winds driven by solar heating
- Ionospheric dynamo also depends on conductance and therefore on the solar cycle
- Sq magnetic perturbations may serve as a proxy for solar activity

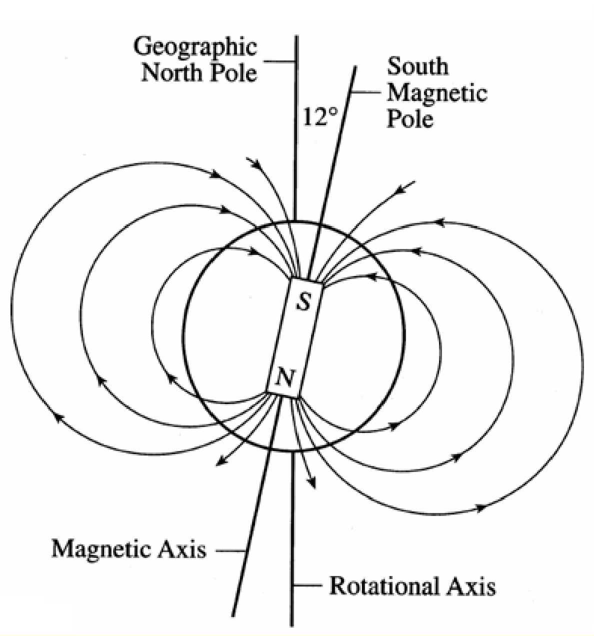


From www.geomag.bgs.ac.uk
(British Geological Survey)

But Sq can be affected by internal magnetic field changes too…

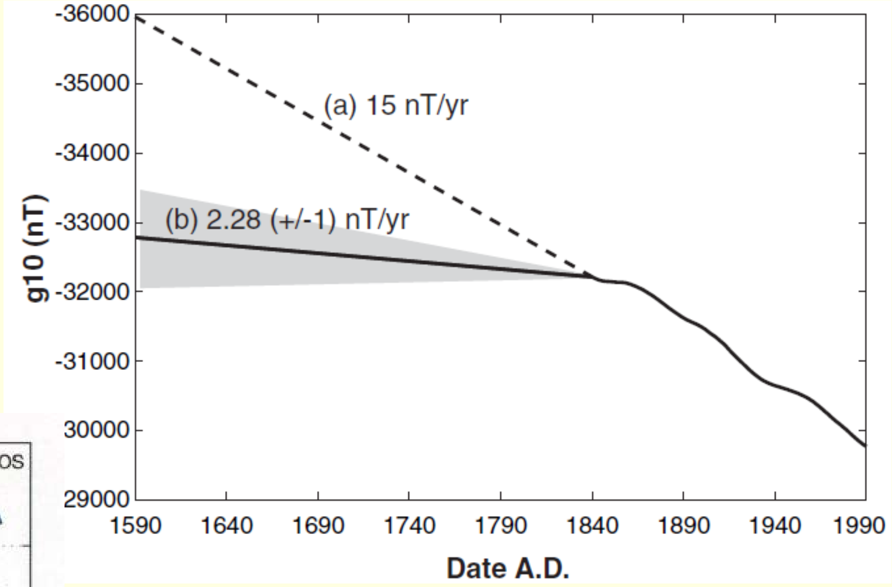
- A change in magnetic field strength
  - Changes the ionospheric conductivity
  - Affects the ionospheric wind dynamo
  - Also affects the magnetosphere and coupling with the ionosphere, but this probably plays a minor role at low to mid-latitudes under quiet conditions

- Changes in the orientation of the field
  - Changes the mapping of geomagnetic to geographic coordinates, e.g. changes in the location of the magnetic equator
  - Geographic shift of the Sq system?



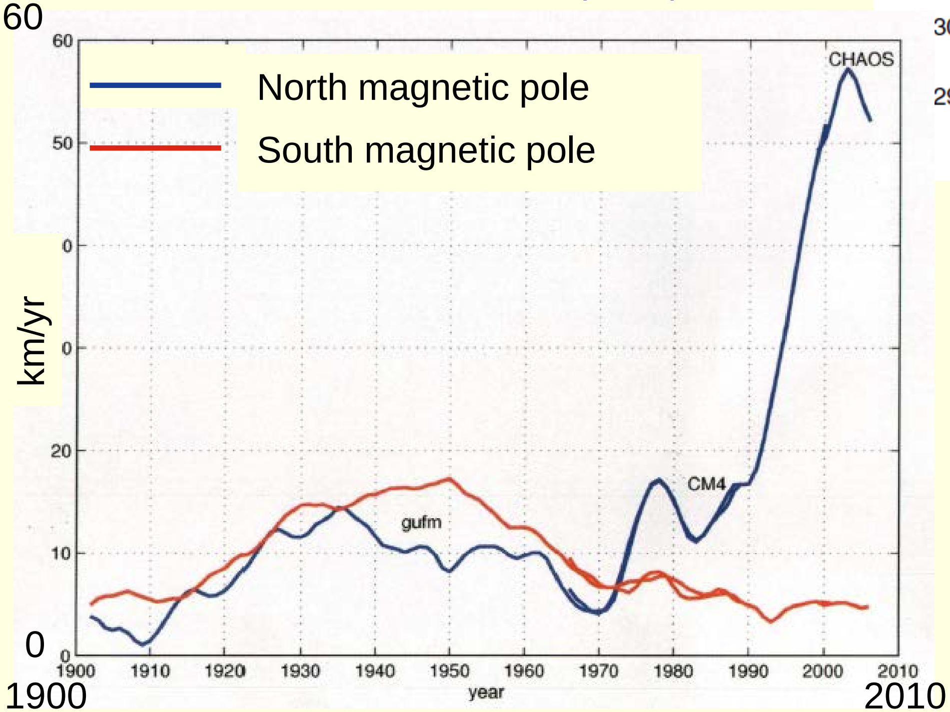
Changes in the Earth's magnetic field

- Decrease in magnetic field strength over the past 170 years at 5-7% per century



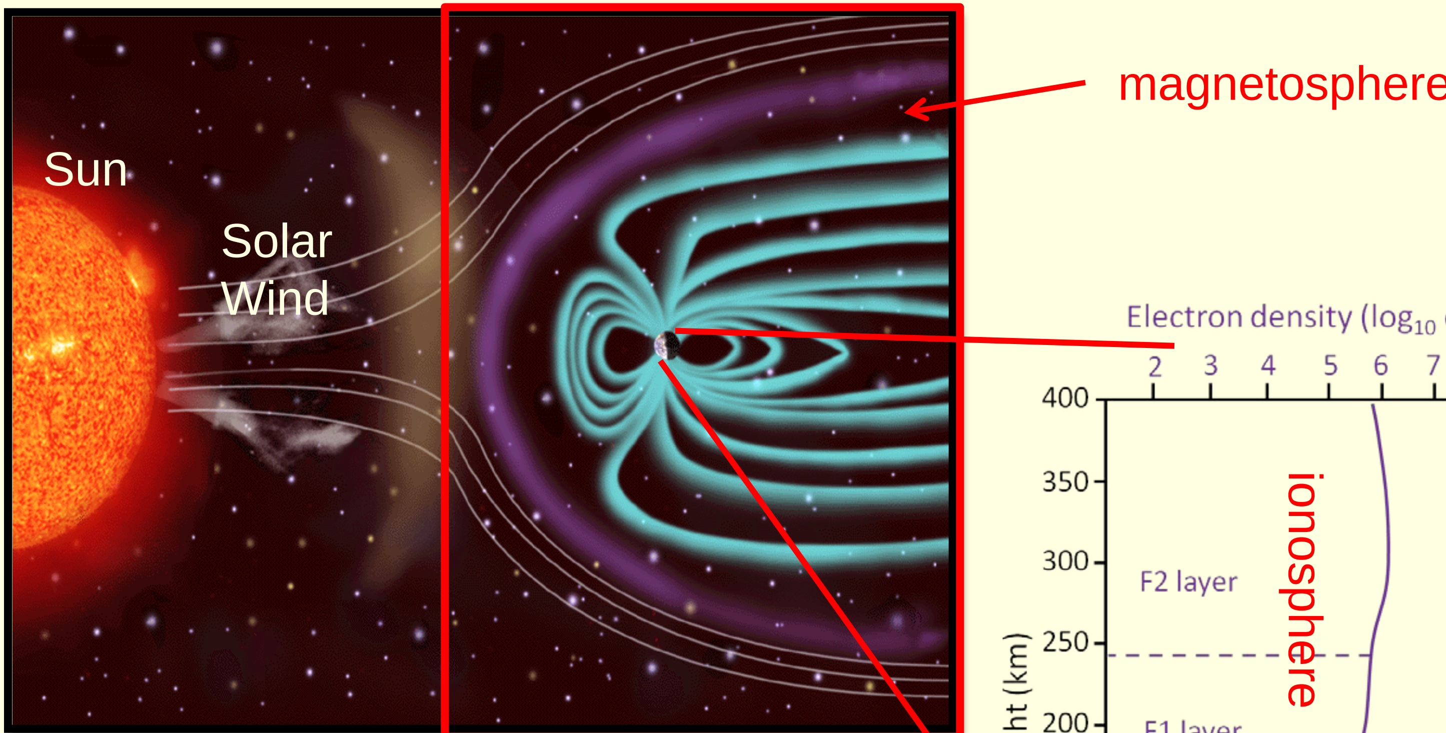
From Gubbins et al. (2006)

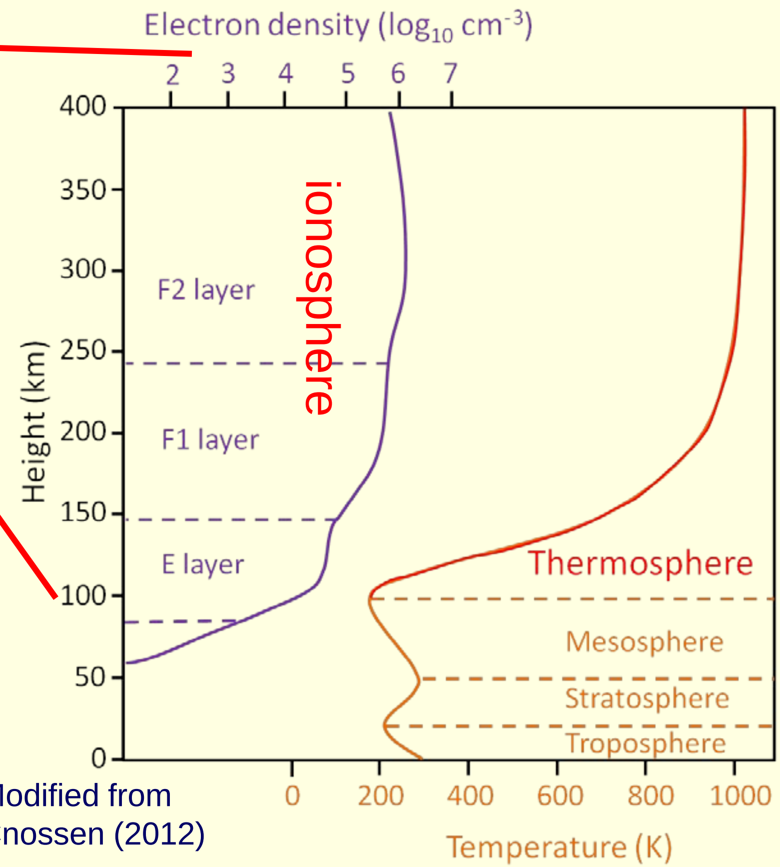
From Olsen and Mandea (2007)



- Magnetic poles are moving
- The northern hemisphere pole has been speeding up!

The Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model



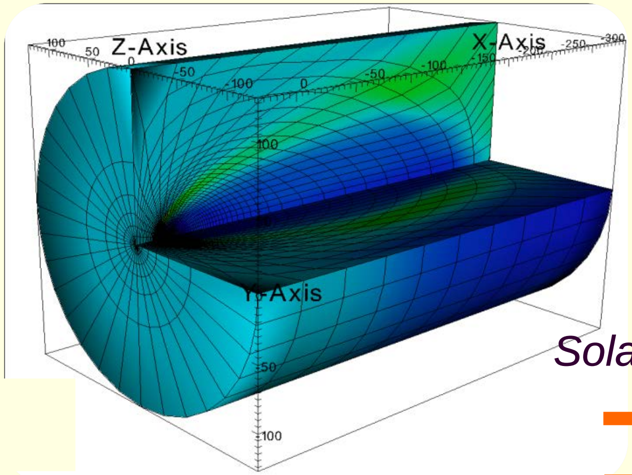


Modified from Cnossen (2012)

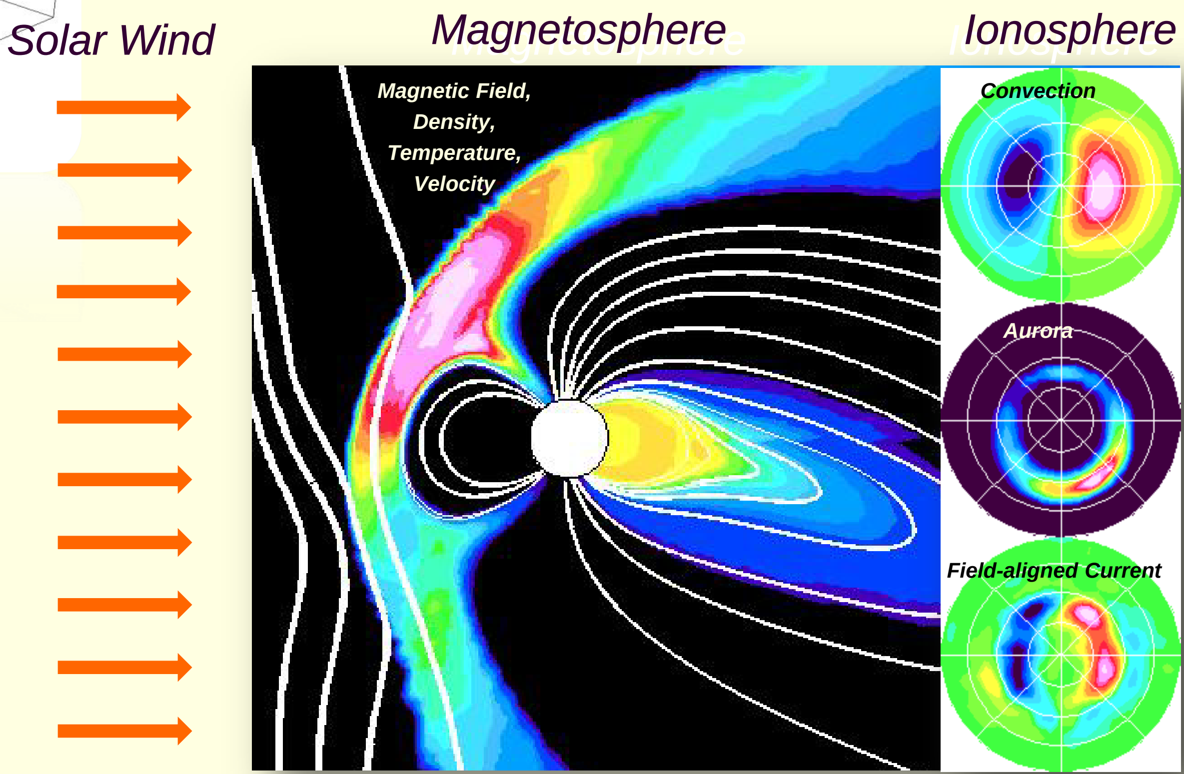
- LFM = Lyon-Fedder-Mobarry MHD code (**M**agnetosphere)
- TIEGCM = **T**hermosphere-**I**onosphere-Electrodynamics General Circulation Model

The LFM magnetospheric model

- LFM = Lyon-Fedder-Mobarry MHD code
- 3D Ideal MHD equations
- Upstream solar wind and IMF conditions
- Ionospheric inner boundary conditions



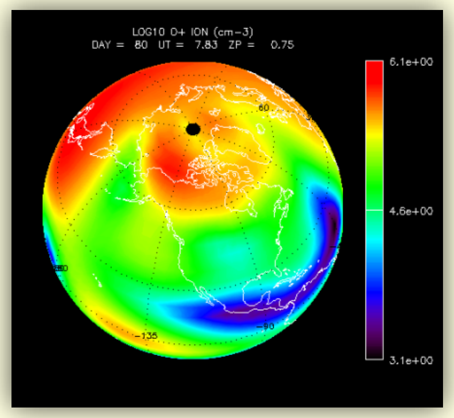
- Distorted spherical grid with azimuthal symmetry

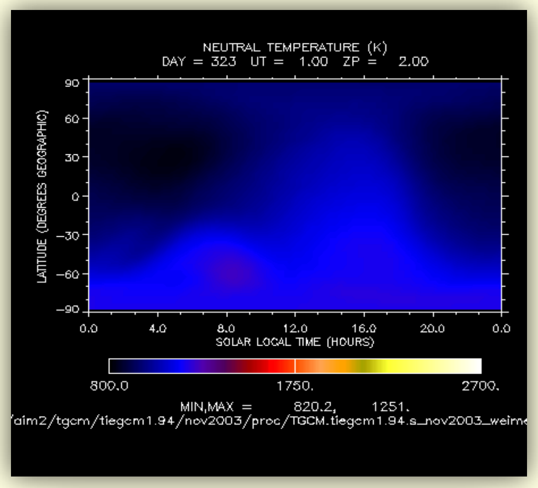


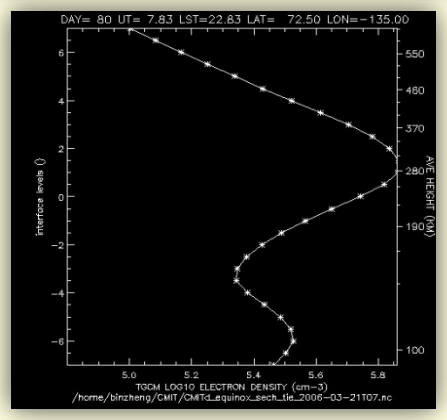
Graphics courtesy of Binzheng Zhang

The TIE-GCM

- TIE-GCM = Thermosphere-Ionosphere-Electrodynamics General Circulation Model
- Solves 3D equations of
  - Momentum
  - Continuity
  - Energy
- 5°x5° global grid
- ~97-500 km
- Includes the low/mid-latitude ionospheric wind dynamo
- Requires
  - Solar radiative forcing, parameterized by F10.7
  - High-latitude electric potential
  - Energetic particle precipitation (energy and flux)

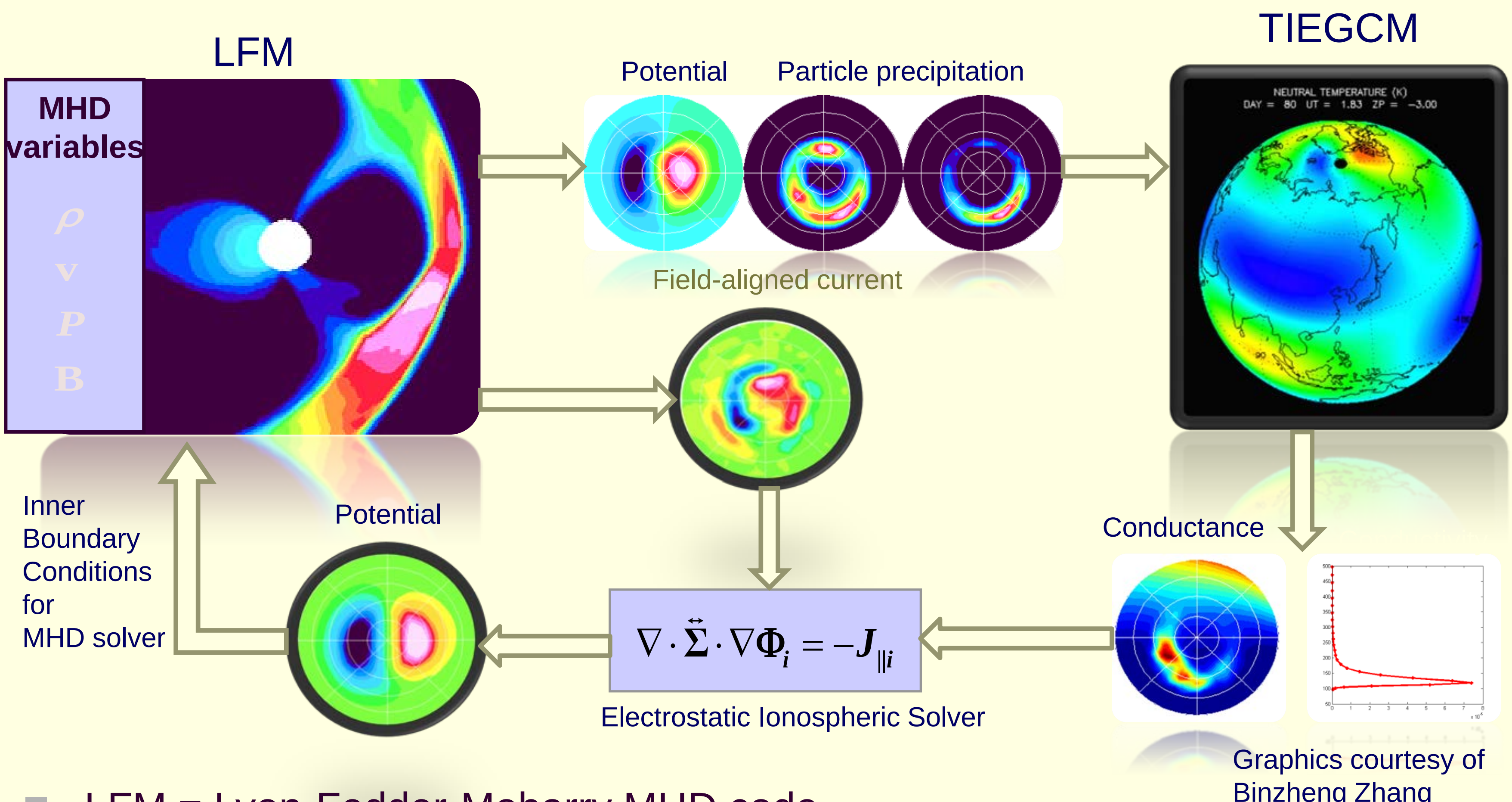






Graphics courtesy of Binzheng Zhang

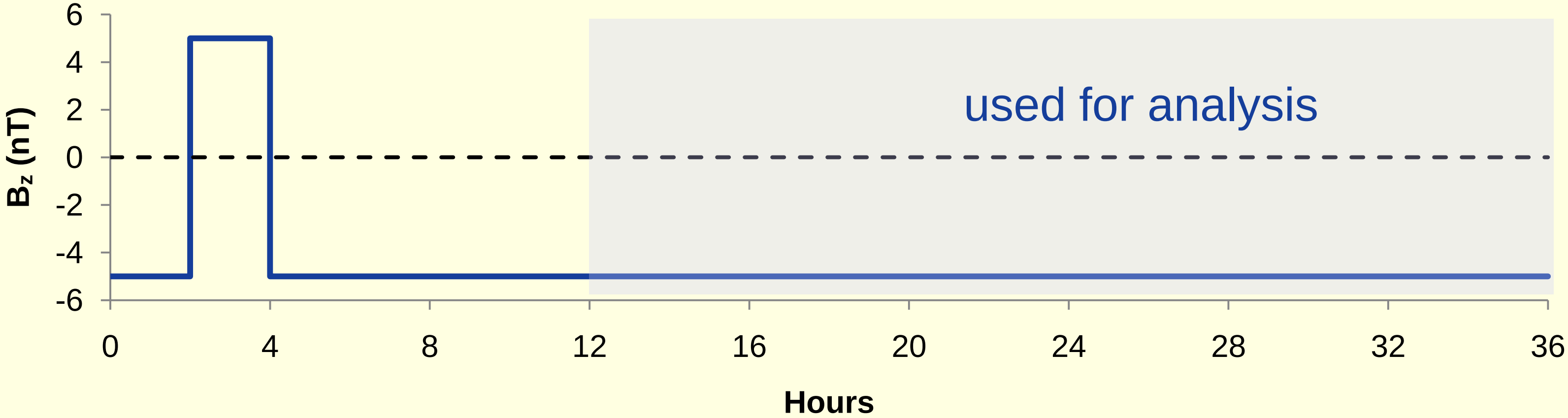
The Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model



- LFM = Lyon-Fedder-Mobarry MHD code
- TIEGCM = Thermosphere-Ionosphere-Electrodynamics General Circulation Model

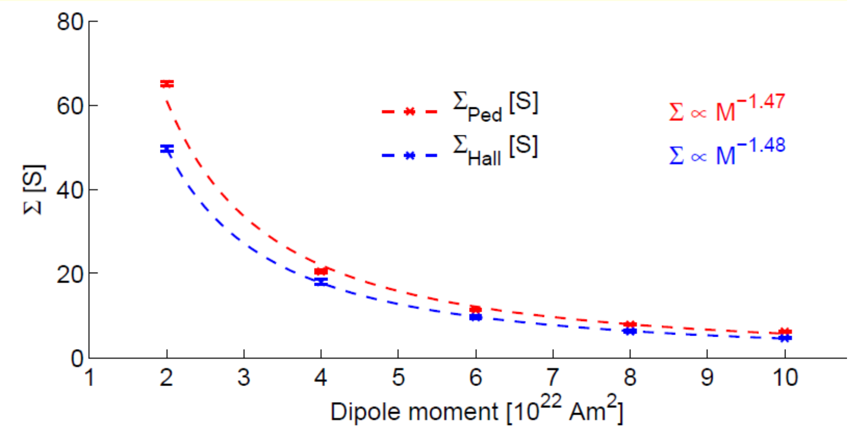
Idealized studies: setup

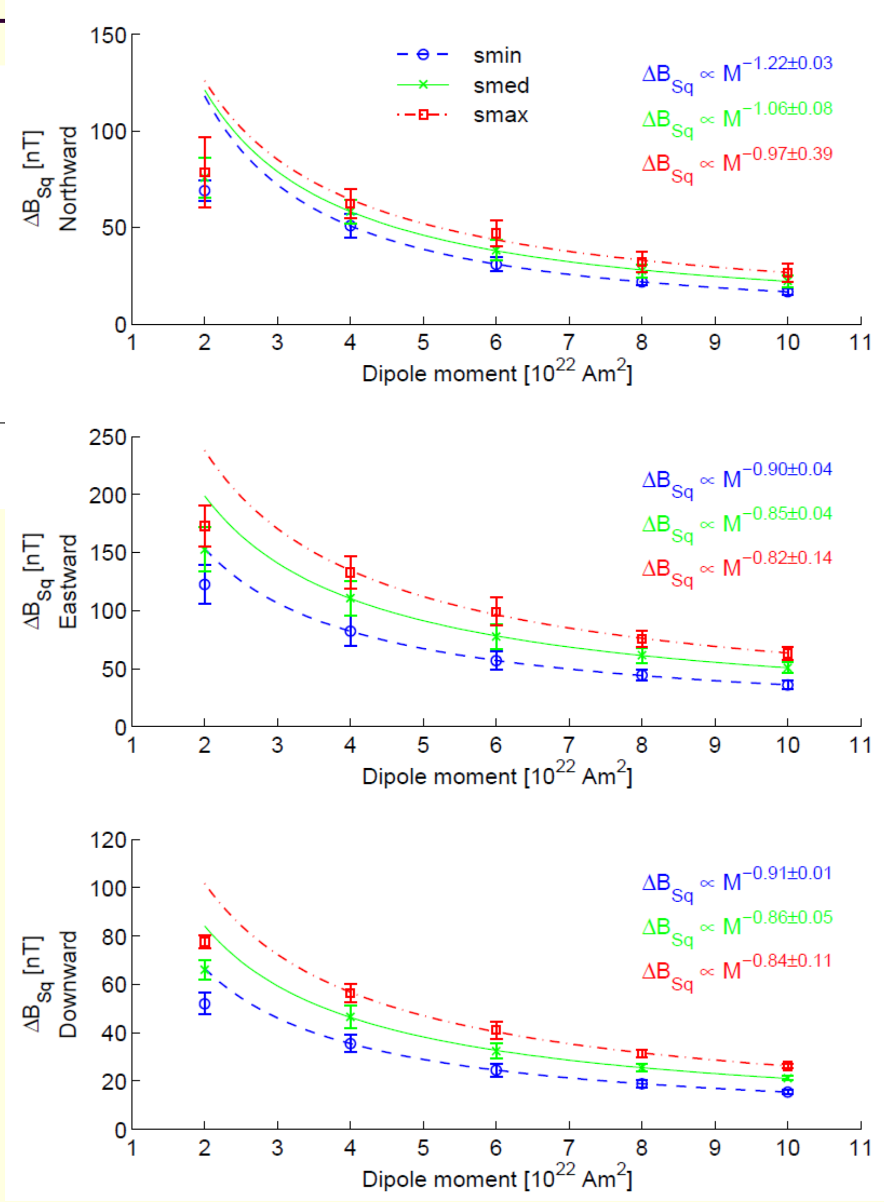
- Study 1: vary the dipole moment: 2-10 $\times 10^{22}$ Am^2
- Study 2: vary the dipole tilt (angle with rotation axis): 0, and 20°
- 36 hour simulations
- March equinox
- Solar wind conditions:
  - v_x = -400 km/s ($v_y = v_z = 0$)
  - density = 5 cm^{-3}
  - $B_x = B_y = 0$



Varying the dipole moment

From Cnossen et al. (JGR, 2012)

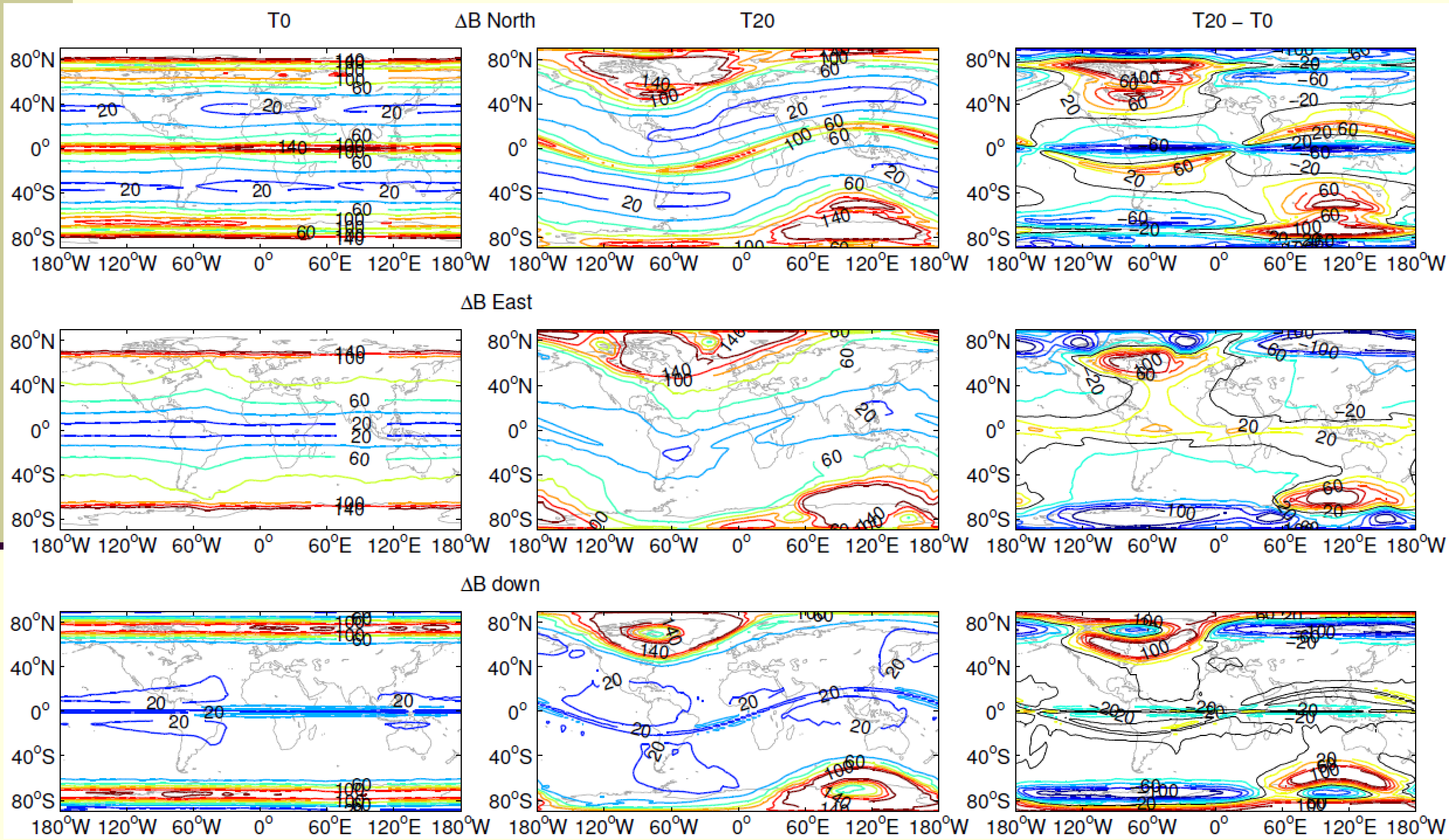




- Ionospheric conductance increases with decreasing dipole moment
- Sq magnetic perturbations also increase with decreasing dipole moment
- Power law relations derived
- No significant dependence of power laws on solar activity

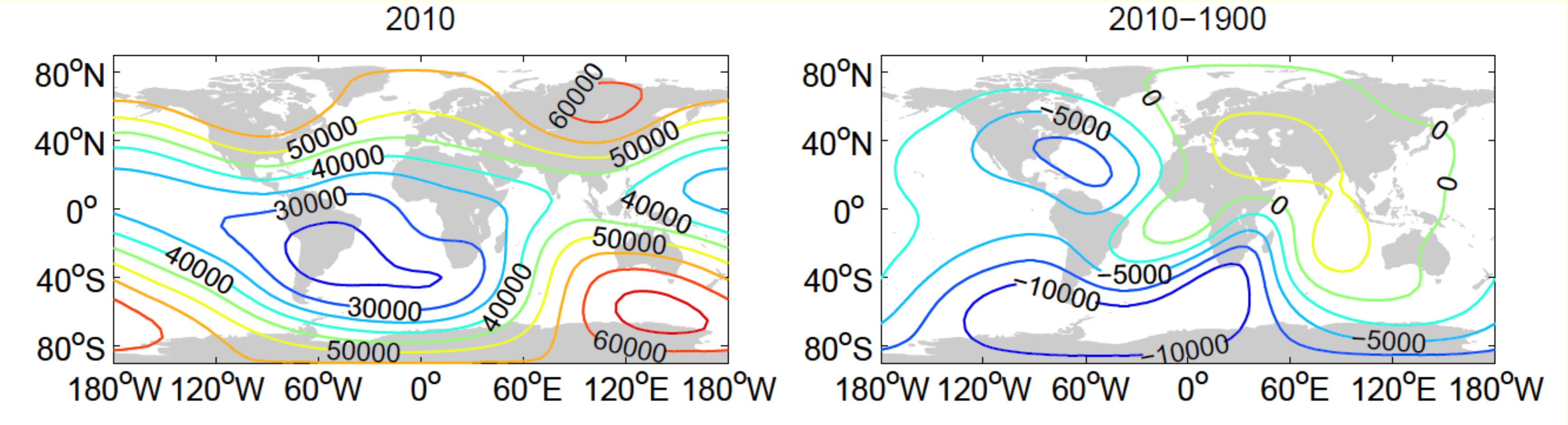
Varying the dipole tilt: Sq amplitude maps

No tilt | 20° tilt | 20° – 0° tilt



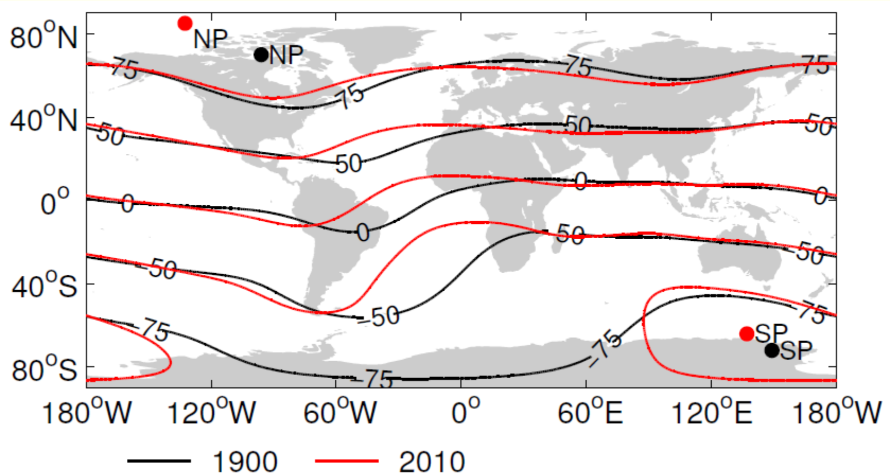
Changes in the Earth's magnetic field 1900-2010

Magnetic field strength (nT) in 2010 and the difference between 2010 and 1900



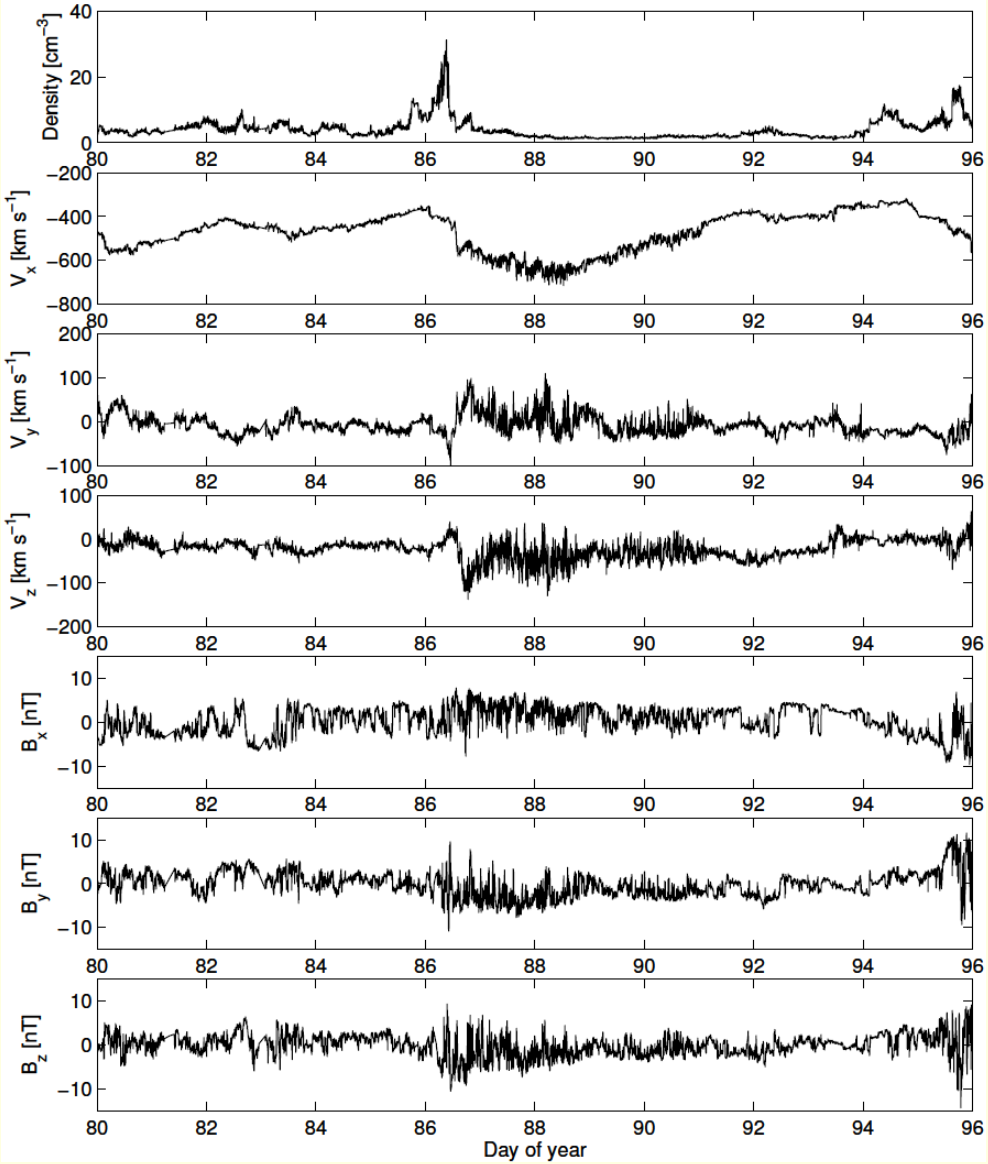
- The strongest changes in magnetic field strength occur in a region that has already a weak magnetic field, called the **South Atlantic Anomaly**
- Also changes in orientation of the field, such as the inclination (angle with the Earth's surface)
- The magnetic equator and magnetic poles have changed position

Inclination contours of 0° (magnetic equator), ±50° and ±75° for 1900 and 2010



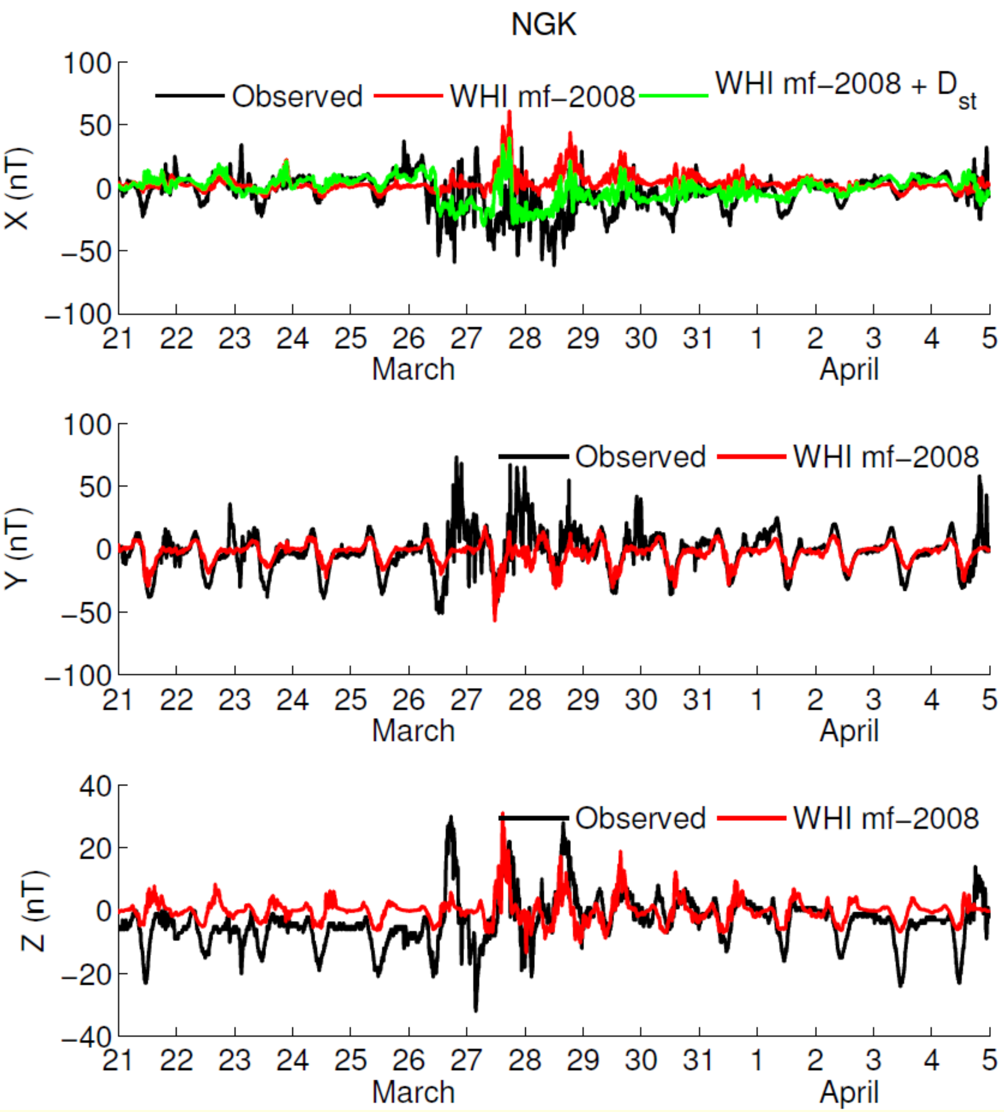
Realistic simulations: 2008 Whole Heliosphere Interval (WHI)

- WHI 2008 interval: 21 March – 5 April (15 days)
- Real solar wind conditions
- Magnetic fields of 1858, 1908, 1958 and 2008
- All simulations are identical apart from the magnetic field used!
- Compare 2008 simulation to observations
- Compare 15-day mean amplitudes of Sq variation between simulations with different magnetic fields

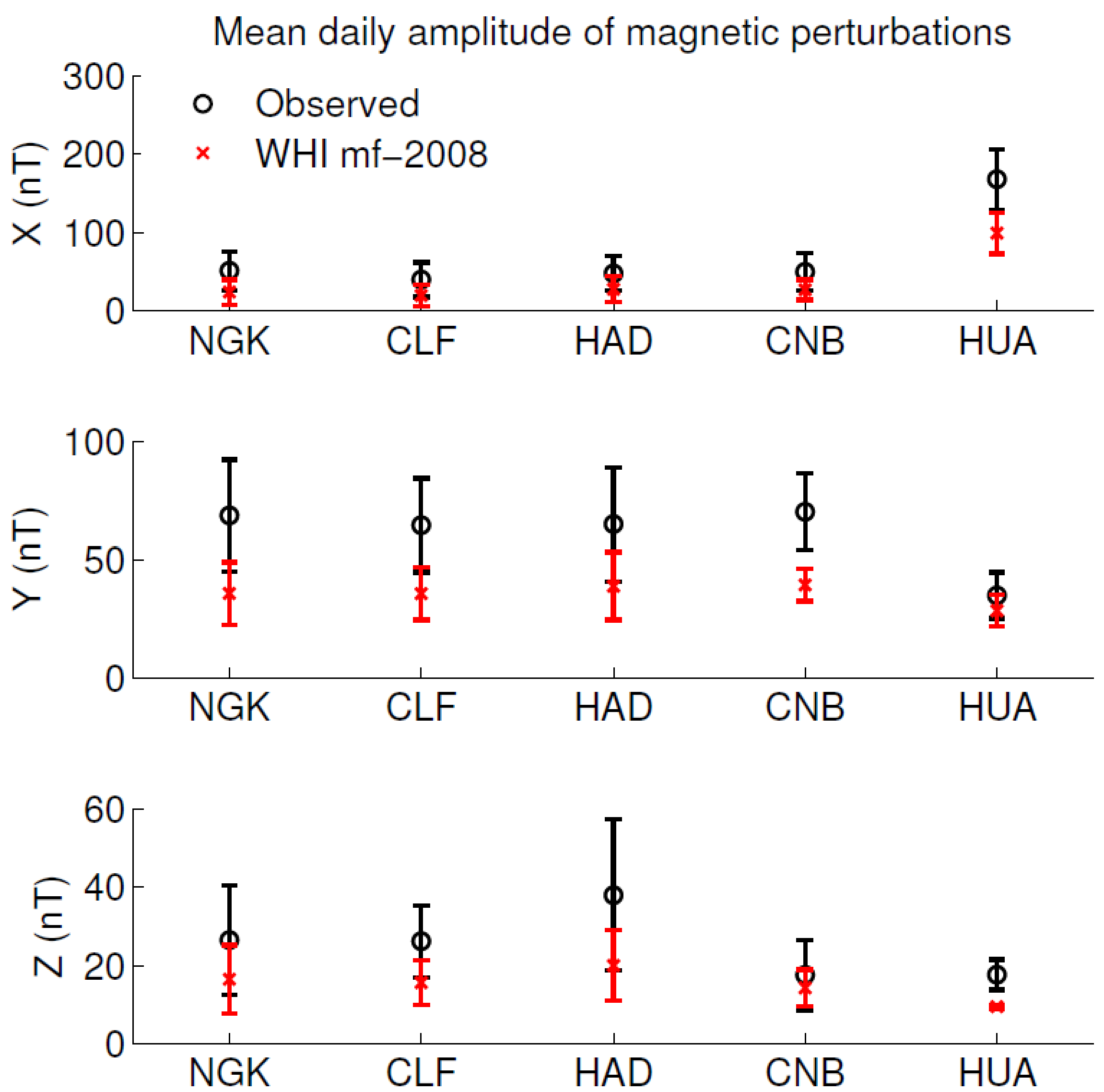


WHI 2008 timeseries comparison with observed magnetic perturbations: Niemegk (NGK)

- The ring current produces a negative signal in the northward component (X) during disturbed times, which is not captured well by CMIT
- Better agreement when observed D_{st} is added to model result
- Perturbations during quiet time captured fairly well, although there can be an offset
- Observed amplitudes of Sq variation do tend to be larger than simulated

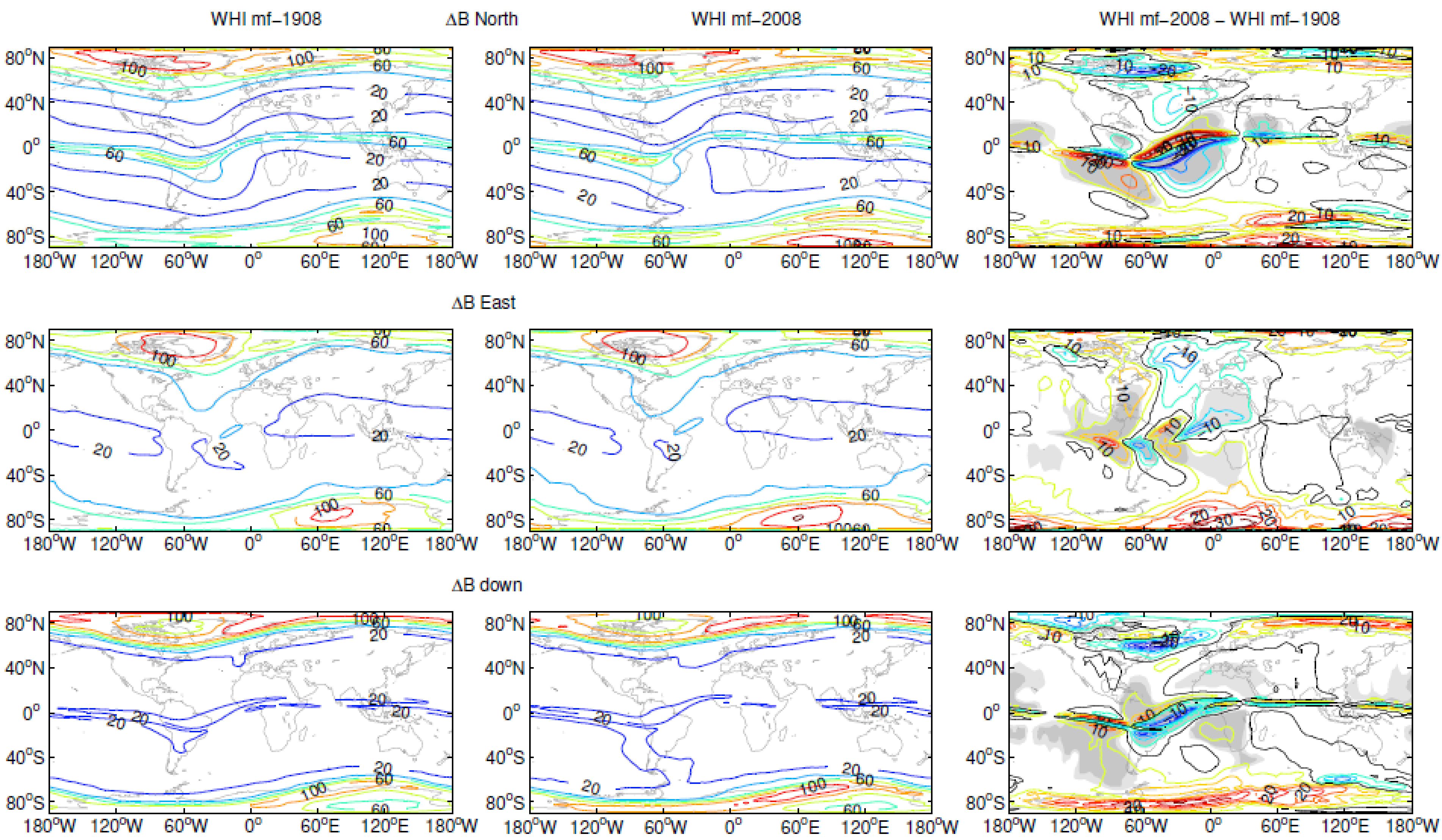


WHI 2008 daily amplitude comparison with observed magnetic perturbations

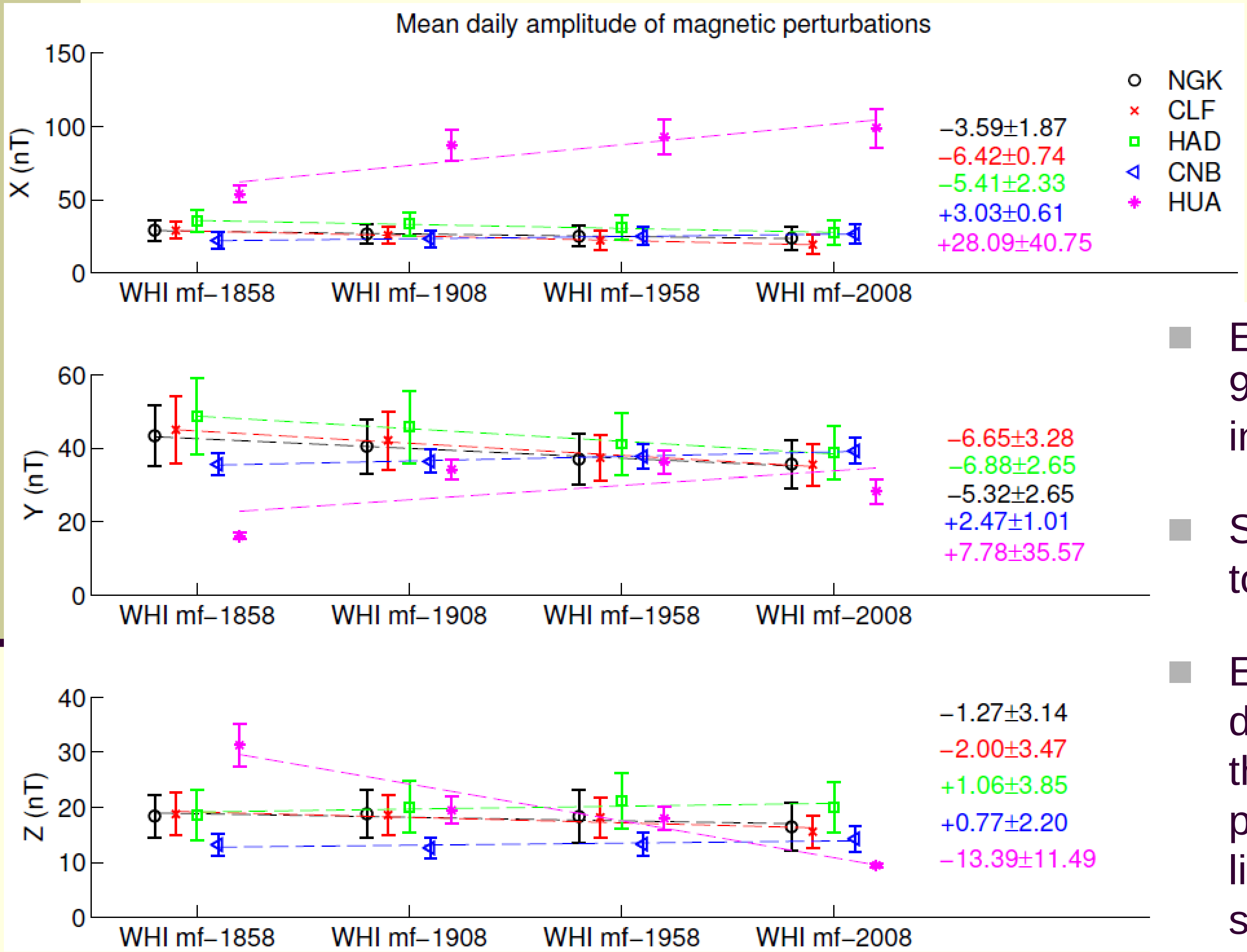


- For all five stations studied the mean daily amplitude is larger in observations
- But observed and modelled values are mostly within one standard deviation of each other

Differences in Sq amplitude (max-min) between 1908 and 2008: a global picture



Differences in daily mean amplitude from 1858 to 2008 at selected stations



- Error bars are 95% confidence intervals
- Straight lines fitted to calculate trends
- Errors on trends describe how well the mean data points can be linked with a straight line

Conclusions

- A decrease in the Earth's magnetic field strength causes stronger magnetic perturbations
- Rule of thumb: $Sq_{east} \propto M^{-0.85}$
- A change in dipole tilt causes a change in the mapping of magnetic to geographic coordinates, which can change magnetic perturbations at fixed geographic locations (such as magnetic observatories)
- The strongest changes in the magnetic field over the past 150 years have taken place in the South Atlantic Anomaly region
- This is where the strongest changes in the Sq current system occur, and they are significant
- Changes in the Earth's magnetic field do not cause significant changes in the Sq amplitude at many geomagnetic stations, such as Niemegk (Germany), Canberra (Australia) and Hartland (England)

- There are other sources of long-term change in the upper atmosphere (e.g. increasing CO_2 concentration) that could potentially cause long-term changes in geomagnetic perturbations – this should be checked