The response of the ionosphere to the changing terrestrial magnetic field

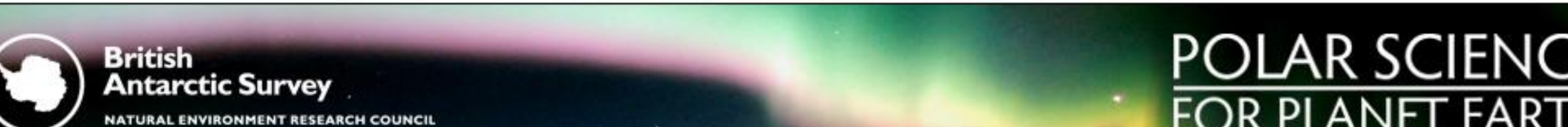
Ingrid Cnossen[1]

with contributions from

Arthur Richmond[2] and Michael Wiltberger[2]

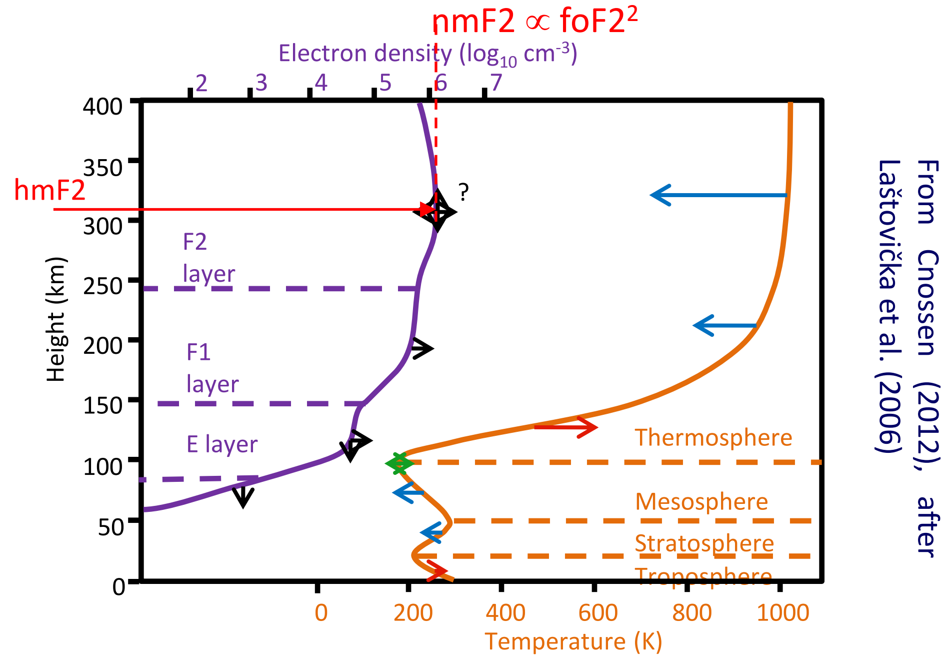
[1]British Antarctic Survey, Cambridge, UK

[2]High Altitude Observatory, NCAR, Boulder, USA



Motivation and approach

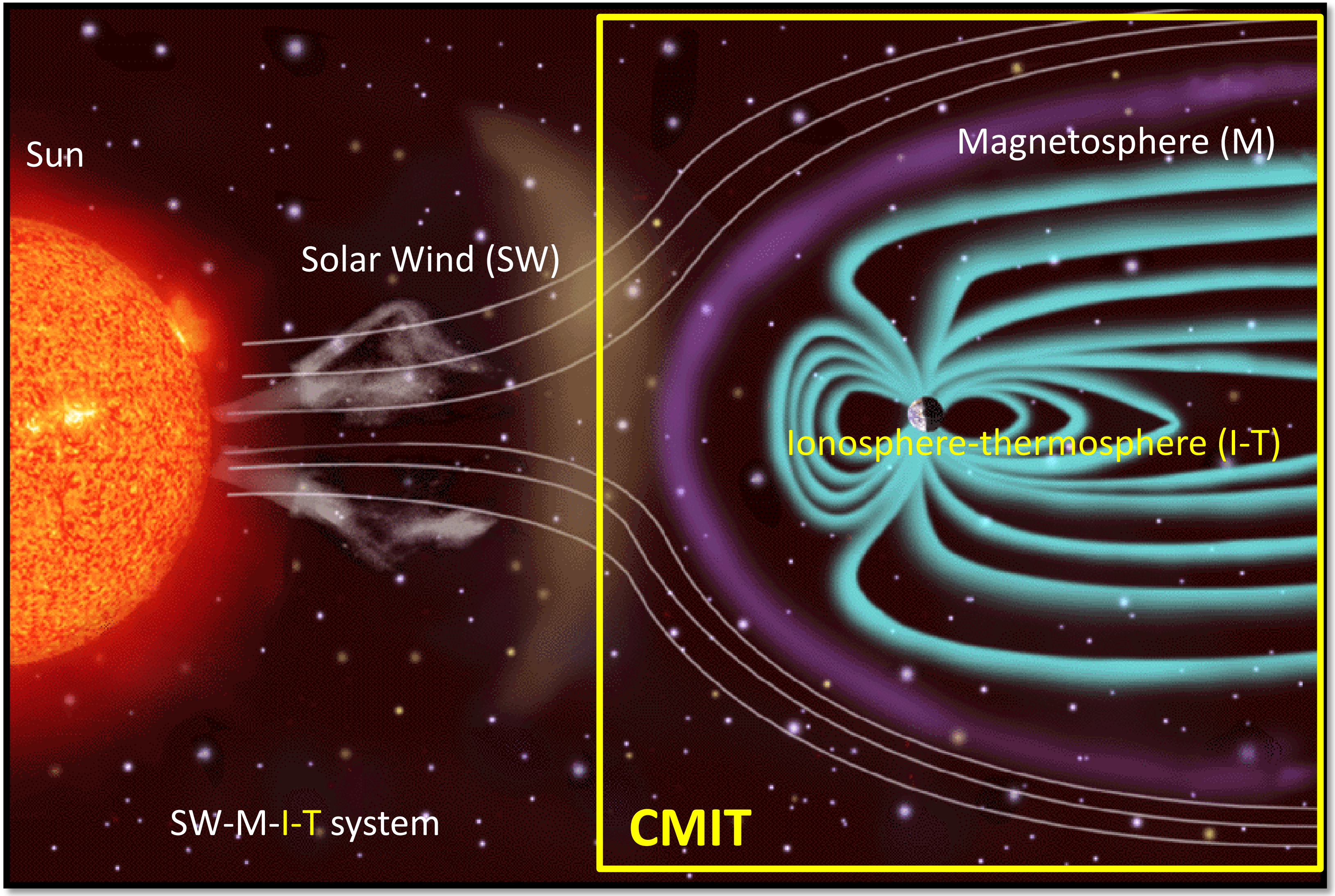
- Noticeable changes in the magnetic field take place on decadal timescales and longer
- These can affect the coupled magnetosphere-ionosphere-thermosphere system
- To what extent are they responsible for observed long-term trends?



Approach:

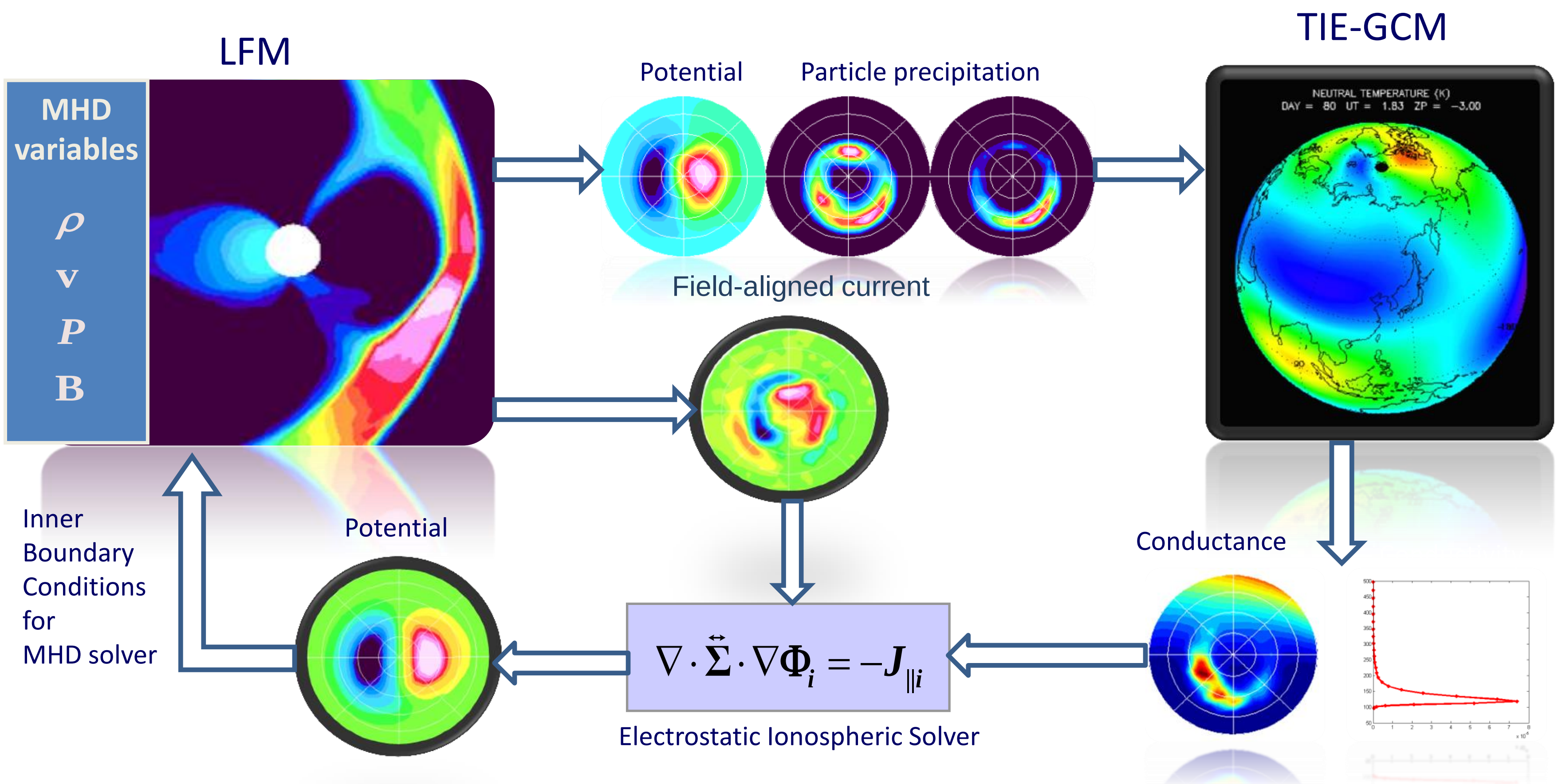
- Simulations with the Coupled Magnetosphere-Ionosphere-Thermosphere (CMIT) model
- To understand mechanisms, perform idealized studies:
  - Changes in magnetic field intensity
  - Changes in dipole orientation
- To compare with observed trends, perform realistic simulations:
  - IGRF changes from 1908 to 2008

Coupled Magnetosphere-Ionosphere-Thermosphere model



Coupled Magnetosphere-Ionosphere-Thermosphere model

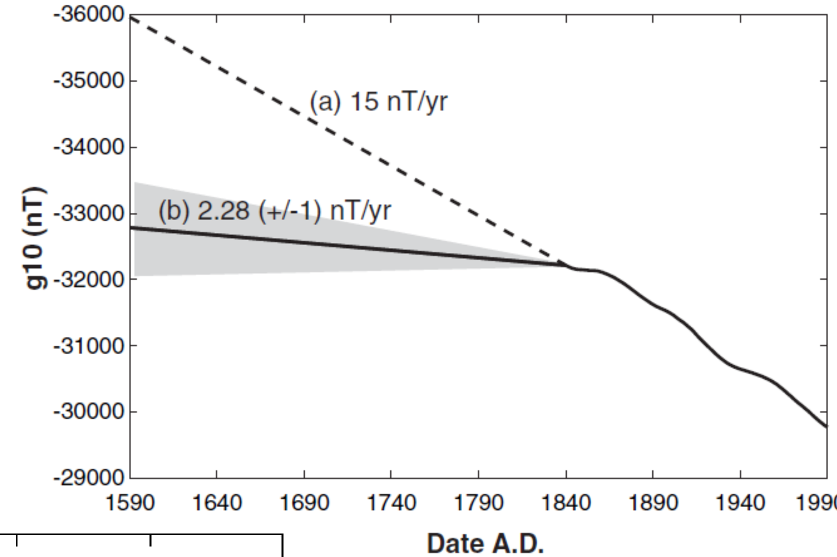
- CMIT = LFM + TIE-GCM
- LFM = Lyon-Fedder-Mobarry MHD code (magnetosphere model)
- TIE-GCM = Thermosphere-Ionosphere-Electrodynamics General Circulation Model



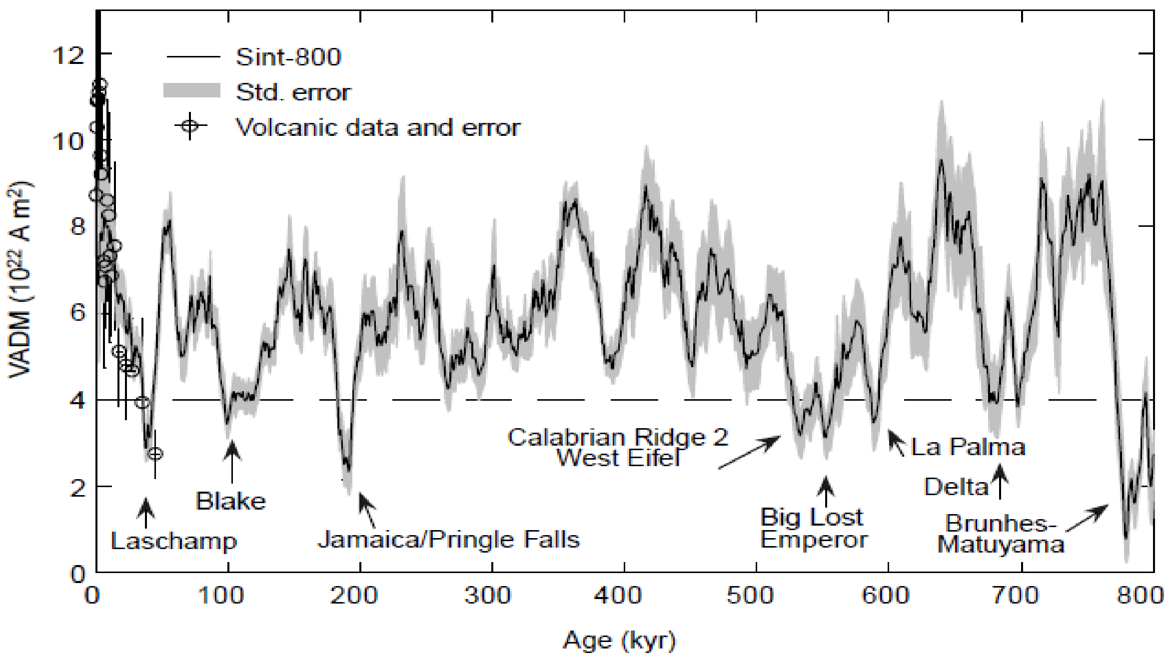
Graphics courtesy of Binzheng Zhang

Changes in dipole moment

- The Earth's magnetic field intensity has decreased by 5-7% per century since 1840 (Gubbins et al., 2006; Mandea and Purucker, 2005)
- Larger changes on geological timescales



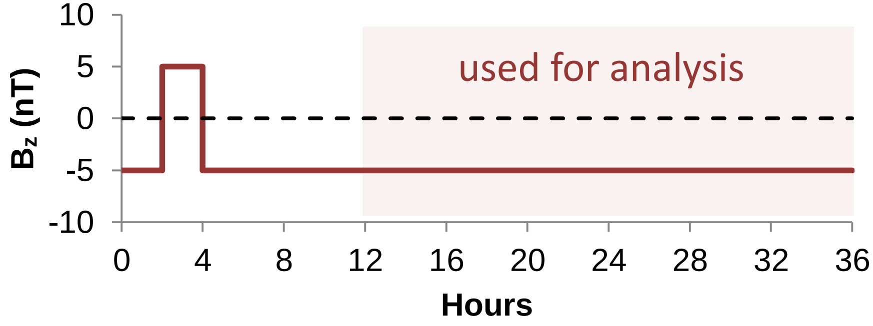
From Gubbins et al. (2006)



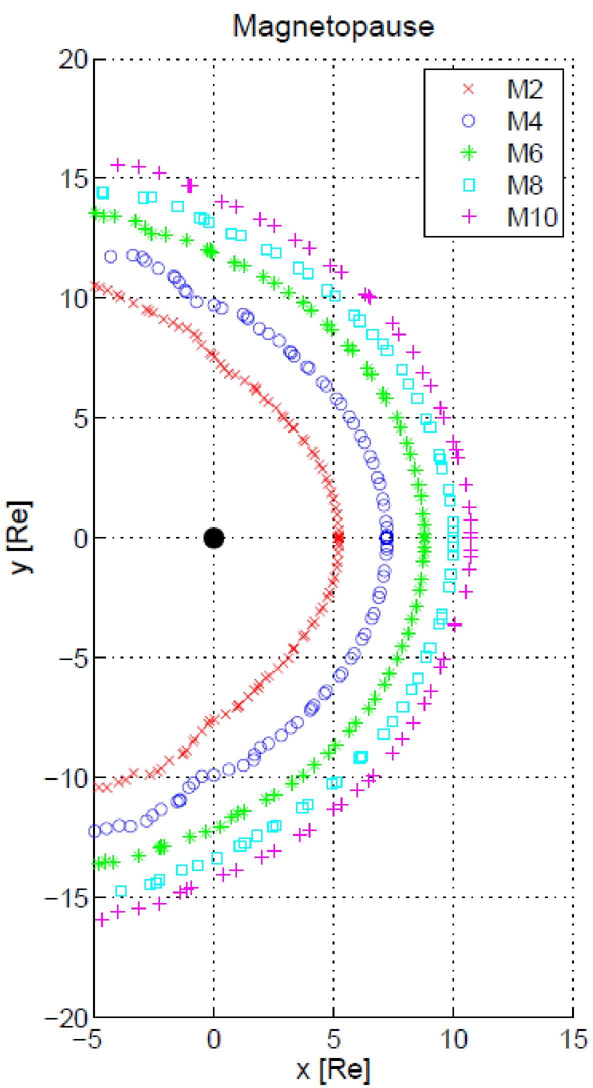
From Guyodo and Valet (1999)

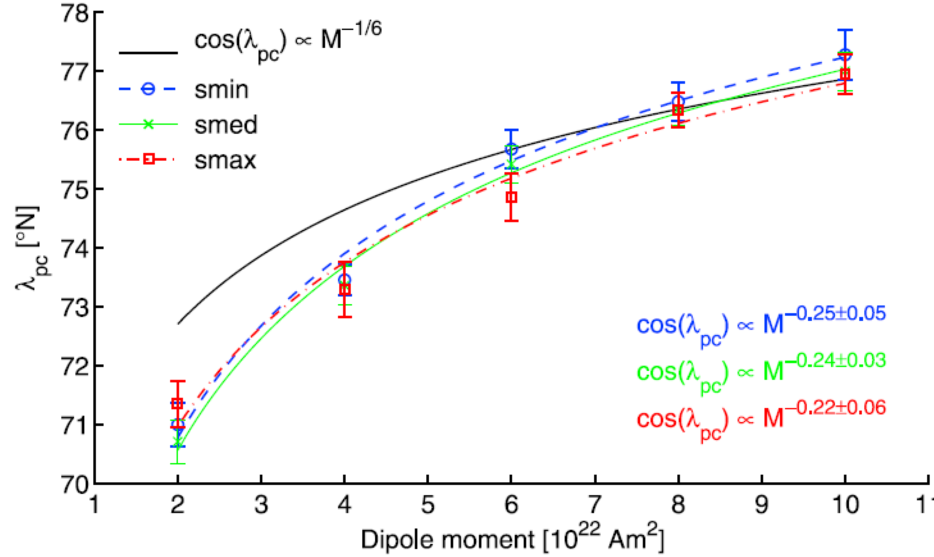
Simulation setup

- Series of simulations with dipole moments of 2, 4, 6, 8, and 10 $\times$ 10^{22} Am^2: M2, M4, M6, M8 and M10
- 36 hour duration (use last 24 h)
- March equinox (some also June solstice)
- Solar minimum, medium and maximum conditions (F10.7 = 80, 150, 220),
  - Focus on solar medium
- Idealized solar wind conditions:
  - v_x = -400 km/s (v_y = v_z = 0)
  - density = 5 cm^{-3},
  - $B_x = B_y = 0$



Magnetosphere and polar cap size

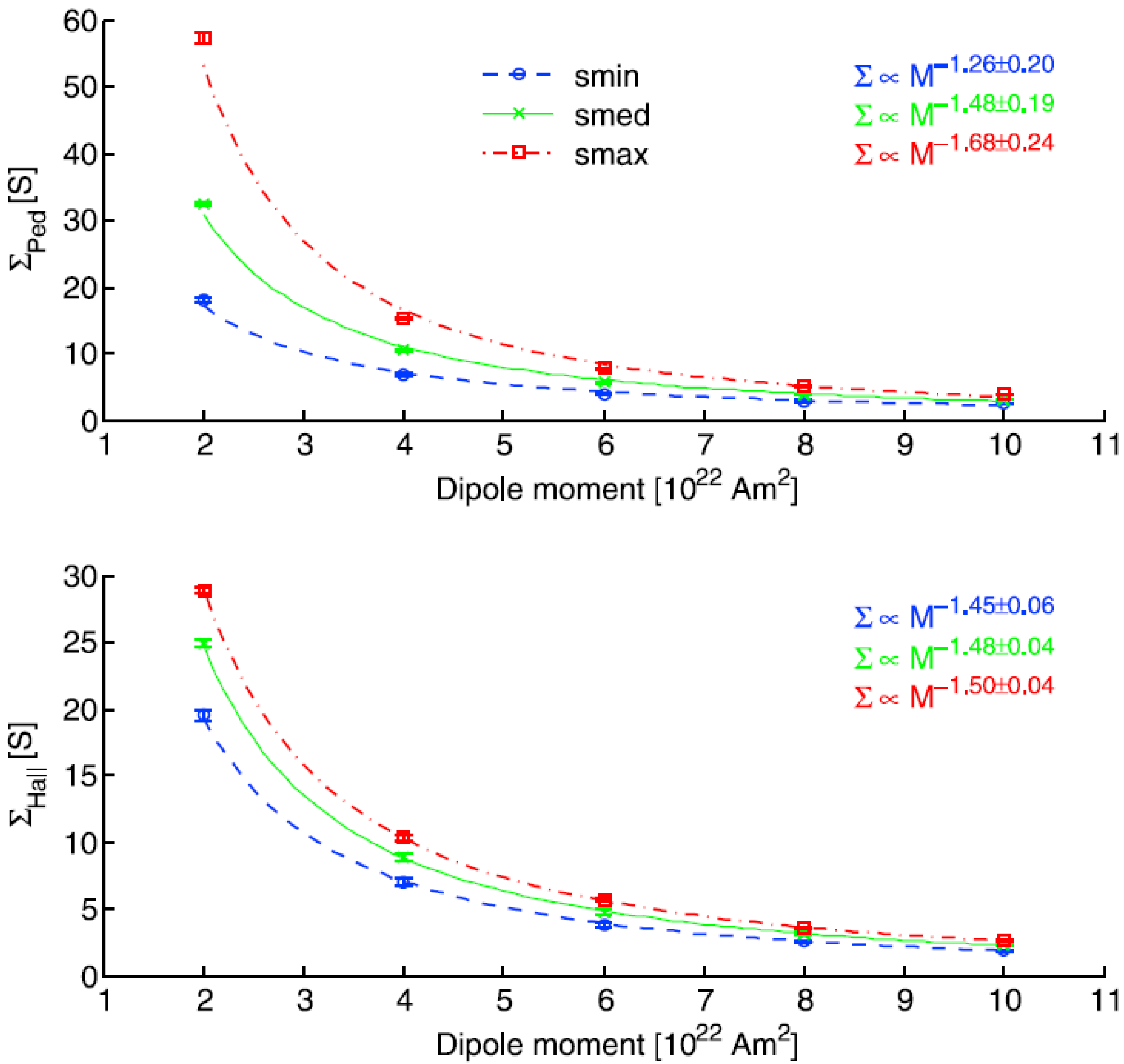




- Magnetosphere becomes larger with increasing *M*
- Polar cap boundary latitude increases with *M*
- Polar cap size decreases with *M*
- Dependence on *M* is stronger than predicted from theoretical scaling by Siscoe and Chen (1975)

Cnossen, Richmond and Wiltberger, JGR, 2012

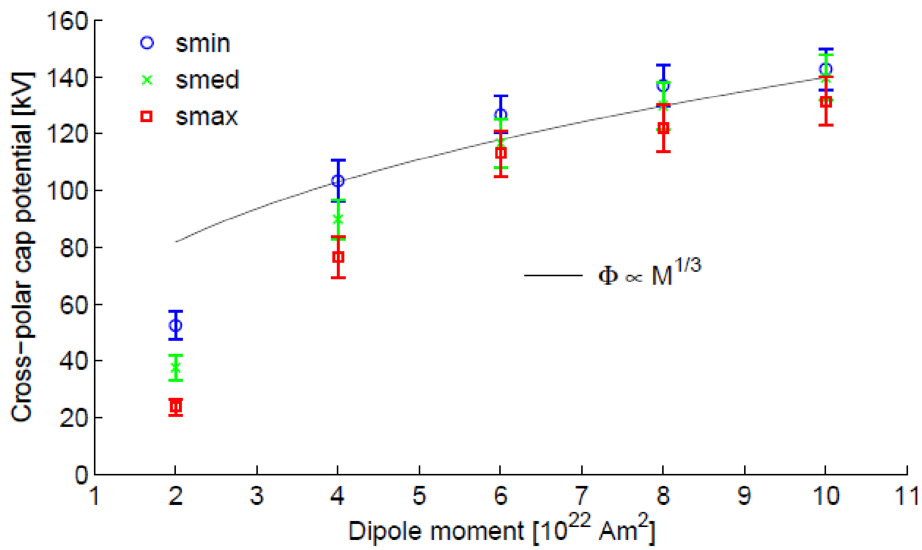
Mean ionospheric conductance versus dipole moment



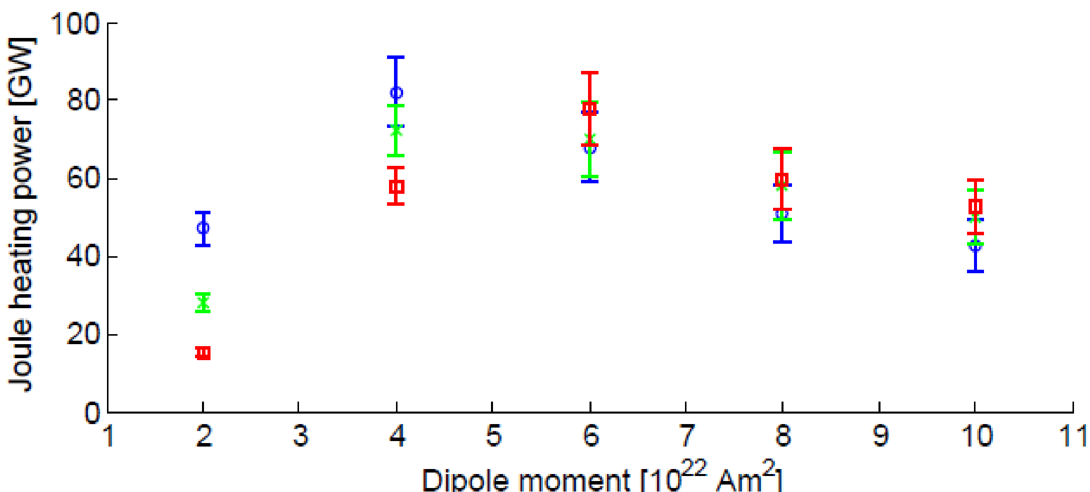
- Dependence of Σ on *M* is stronger than $\Sigma \propto M^{-1}$
- Scaling of Pedersen conductance is influenced by solar activity level
- Hall conductance scaling is robust

Cnossen, Richmond and Wiltberger, JGR, 2012

Cross-polar cap potential and Joule heating



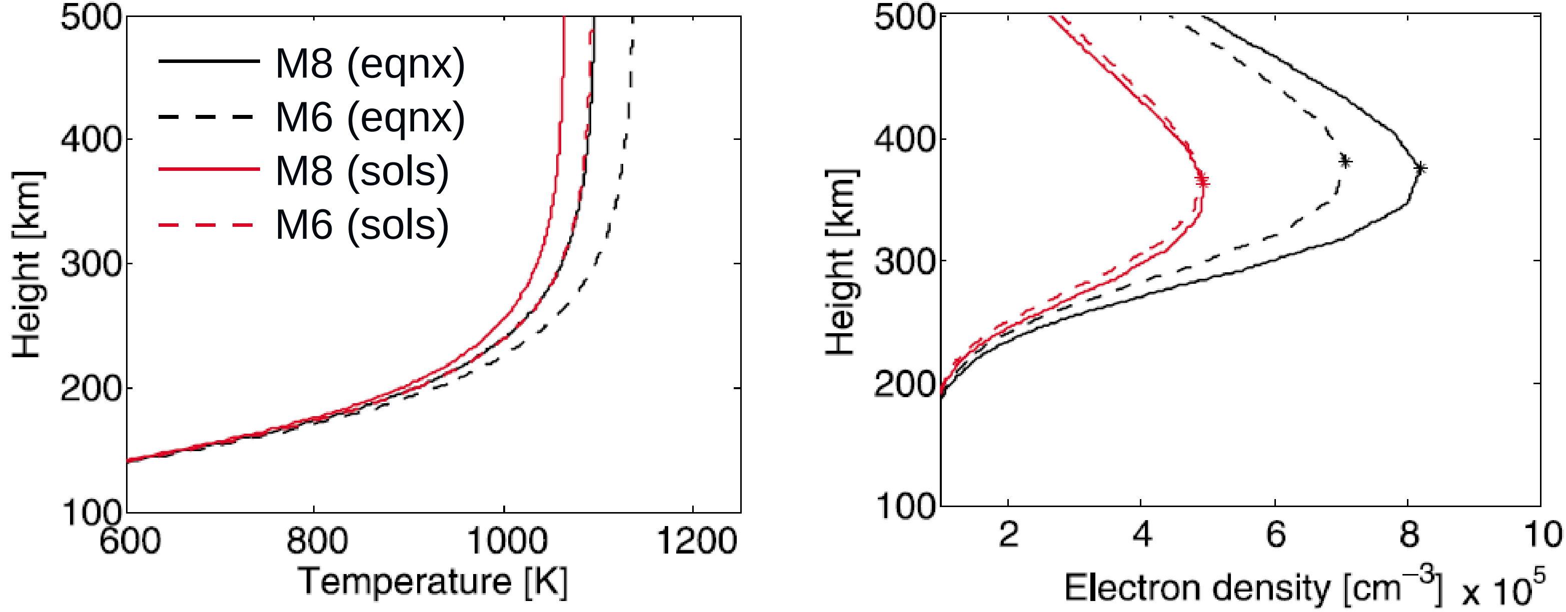
- Cross-polar cap potential decreases with decreasing *M*
- Deviates from theoretical relationship by Glassmeier et al. (2004) for large change in *M*



- Electric field *E* scales as potential/distance, e.g. $\Phi/\cos(\lambda_{pc})$
- **ExB** drifts scale as *E/B*
- Joule heating follows *E/B* scaling

Cnossen, Richmond and Wiltberger, JGR, 2012

Temperature and electron density

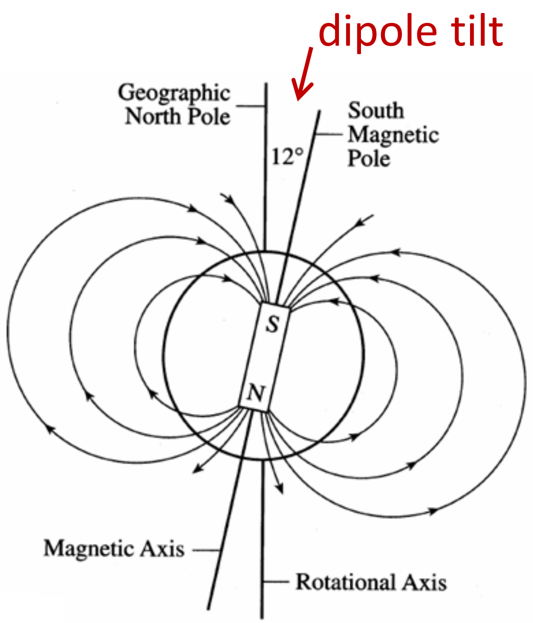


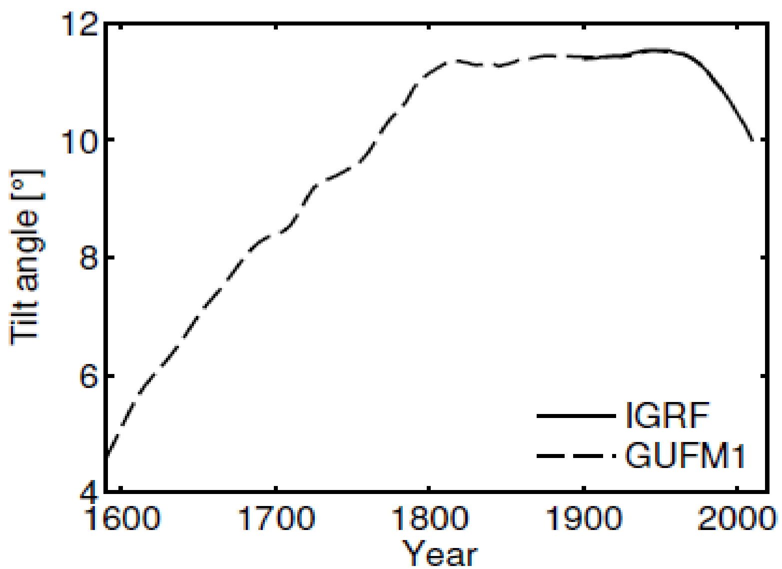
- Decrease in Joule heating leads to
  - Decrease in global mean temperature; lowering of F_2 peak
  - Less upwelling → increase in O/N_2 ratio → increase in electron density

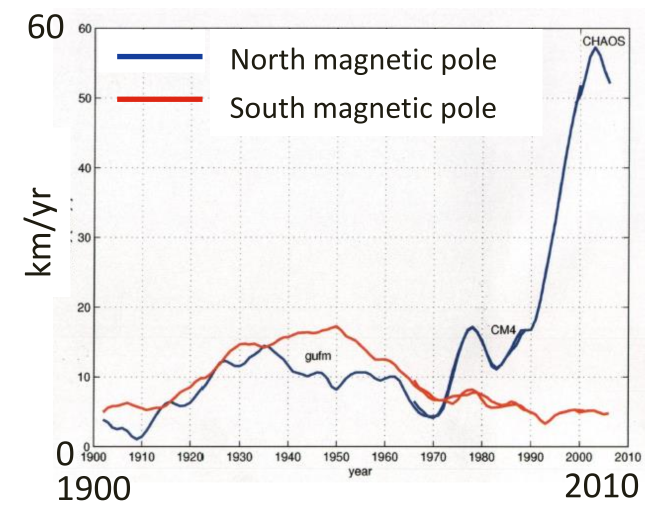
Cnossen et al., JGR, 2011

Changes in dipole orientation (tilt angle)

- The tilt angle of the best-fitting dipole has been decreasing since the 1950s after being stable at ~11.5° for 150 years
- The tilt angle was only ~5° in 1600
- The movement rate of the North magnetic pole has been very high recently
- The offset between the geographic and magnetic invariant poles in the SH is currently about twice as large as in the NH



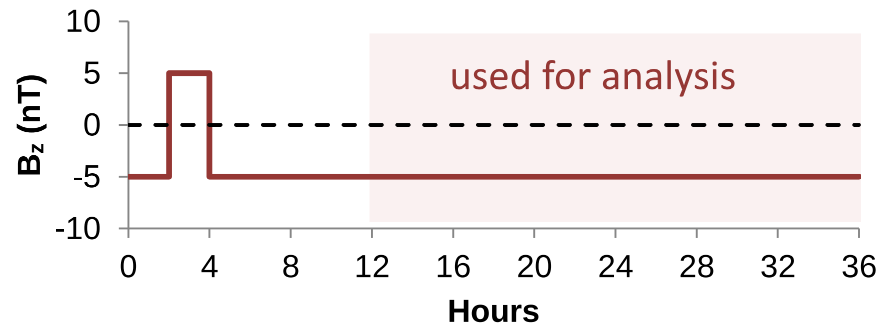




Olsen and Mandea (2007)

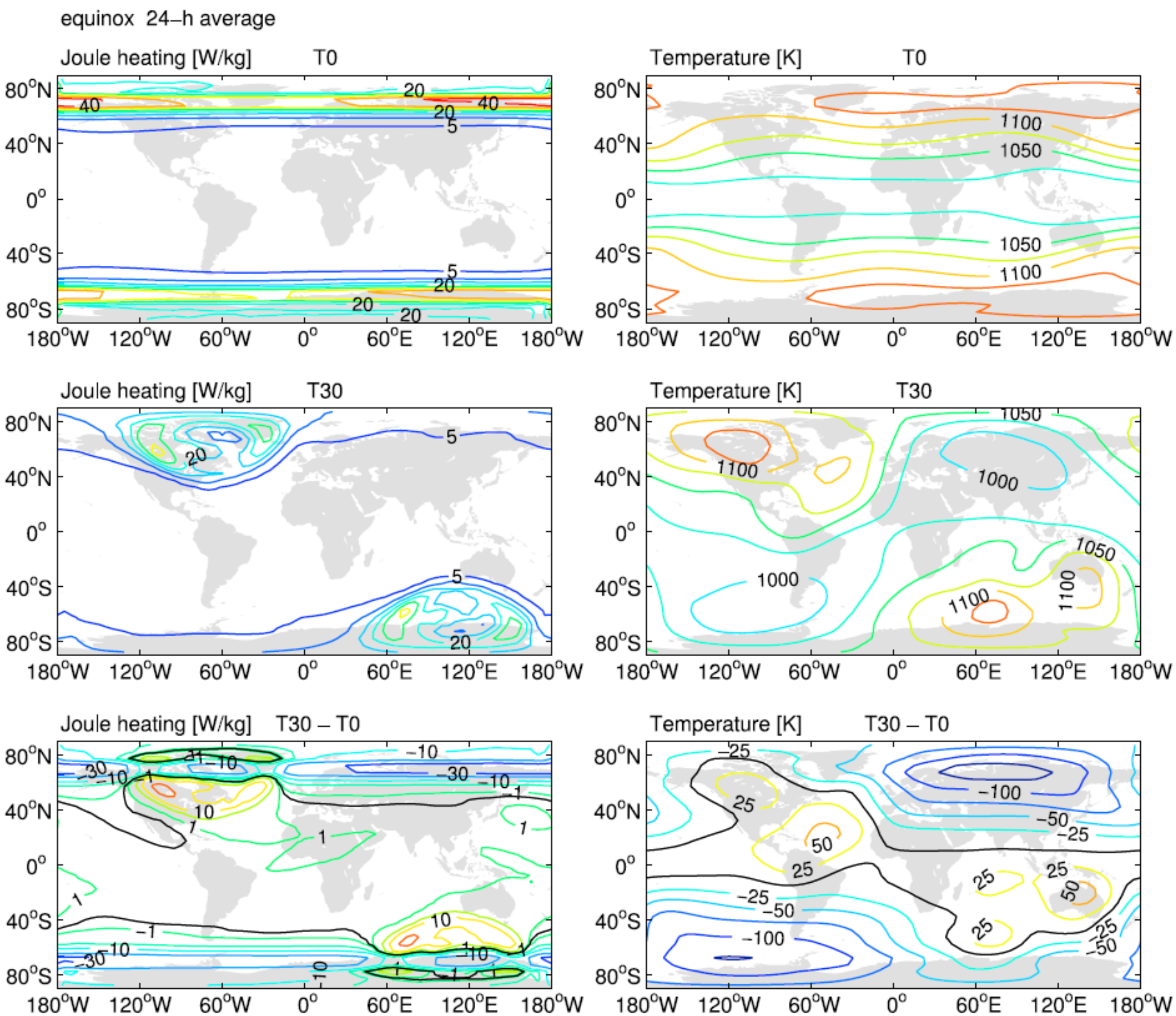
Simulation and analysis setup

- Series of simulations with dipole tilt angles of 0, 10, 20, 30, 40, 50, and 60°: T0, T10, T20, etc.
- 36 hour duration (use last 24 h)
- March equinox / June solstice
- Solar medium conditions (F10.7 = 150)
- Idealized solar wind conditions:
  - v_x = -400 km/s
  - $v_y = v_z = 0$
  - density = 5 cm^{-3},
  - $B_x = B_y = 0$



- Additional simulations with northward IMF (B_z = 5 nT) for T0 and T30
- Focus on differences in the ionosphere-thermosphere system between T0 and T30 for equinox

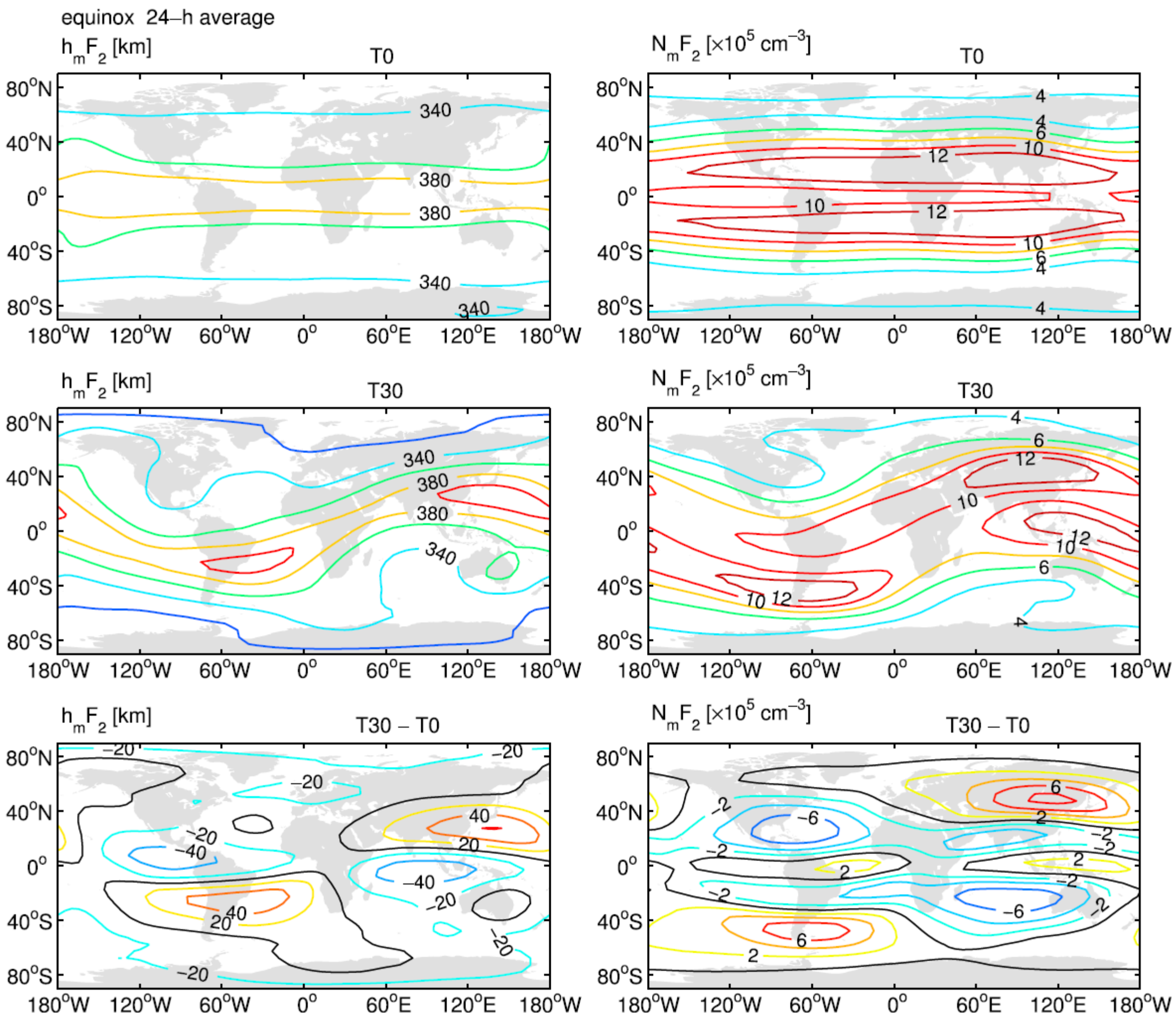
T0 vs. T30: Joule heating and temperature



- T30 gives less Joule heating than T0
- Changes in geographic distribution of Joule heating
- Changes in temperature structure more or less follow

Cnossen and Richmond (JGR, 2012)

T0 vs. T30: h_mF_2 and N_mF_2

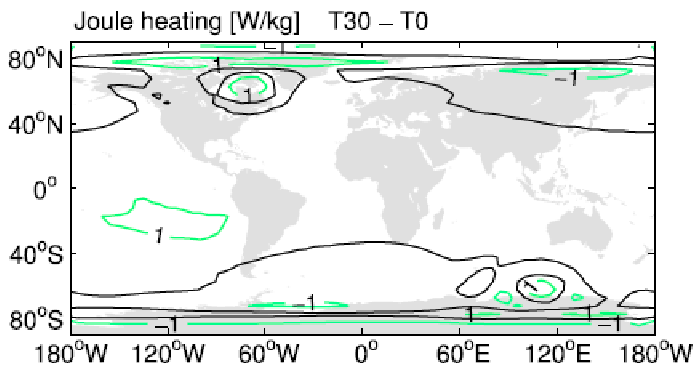


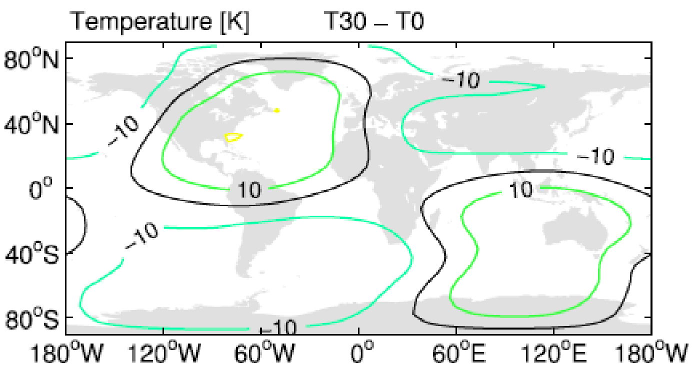
Cnossen and Richmond (JGR, 2012)

- h_mF_2 and N_mF_2 structures follow magnetic latitude structure
- Changes in N_mF_2 are due to changes in O/N_2 ratio and changes in the vertical component of diffusion along the magnetic field
- Changes in vertical diffusion are also the main cause for changes in h_mF_2

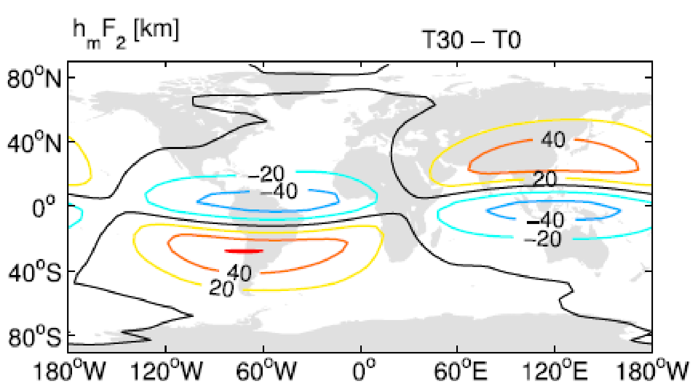
T0 vs. T30: northward IMF

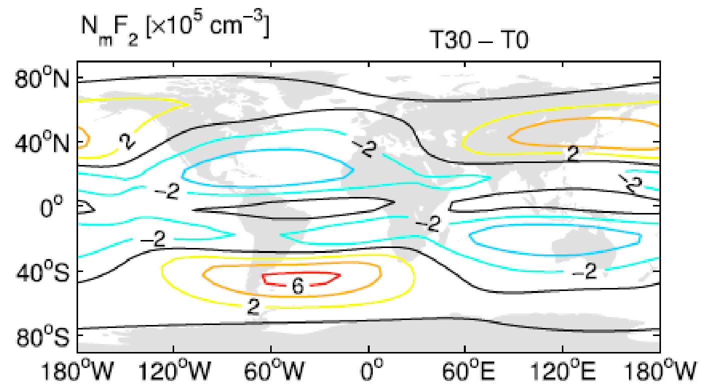
- Changes in Joule heating and neutral temperature are much smaller compared to southward IMF





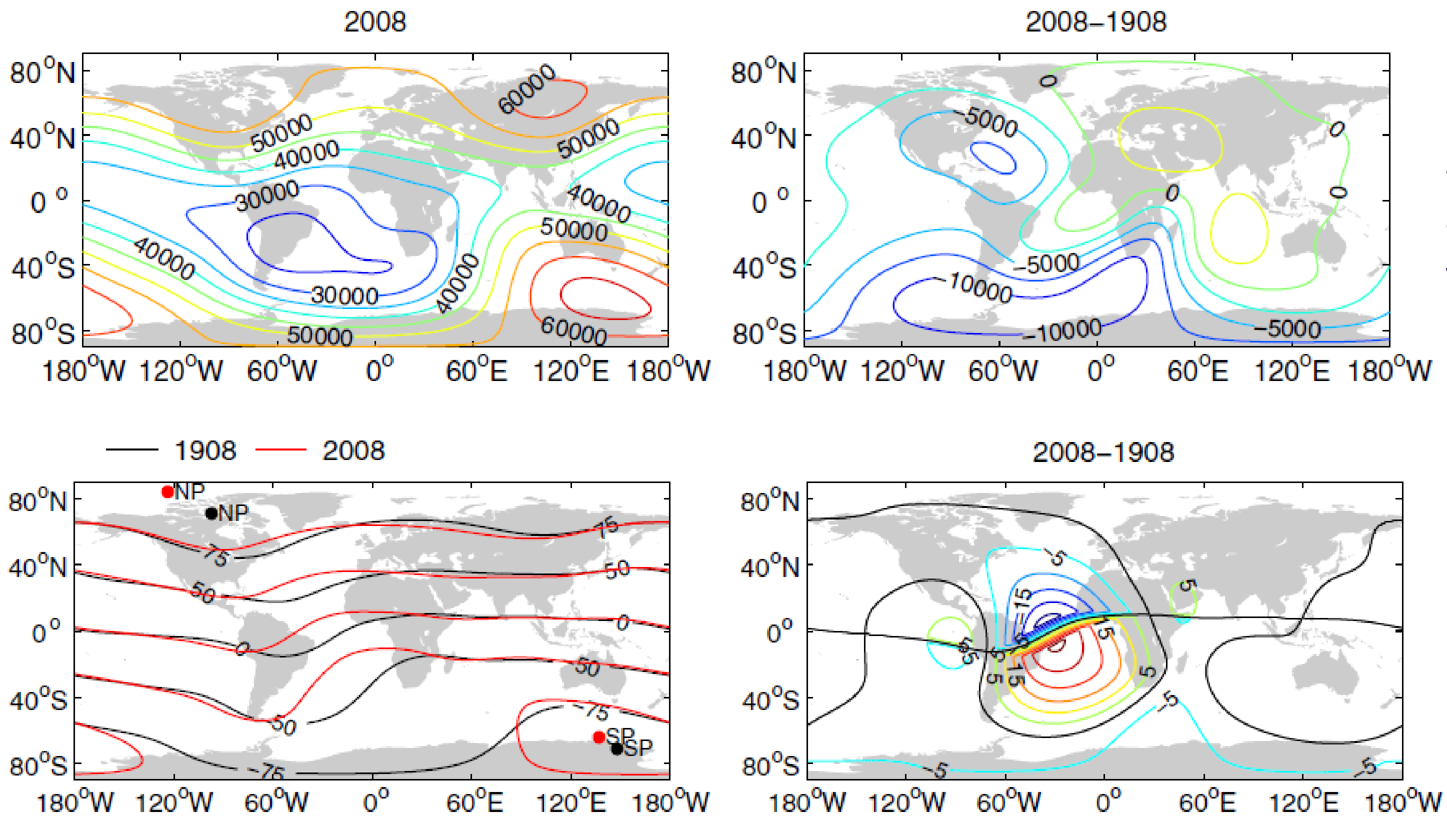
- Changes in h_mF_2 are similar in strength and spatial pattern, while changes in N_mF_2 are smaller by ~a third but similar in structure as well





Crossen and Richmond (JGR, 2012)

Realistic magnetic field changes 1908-2008



Magnetic field strength in 2008 and difference with 1908 (nT)

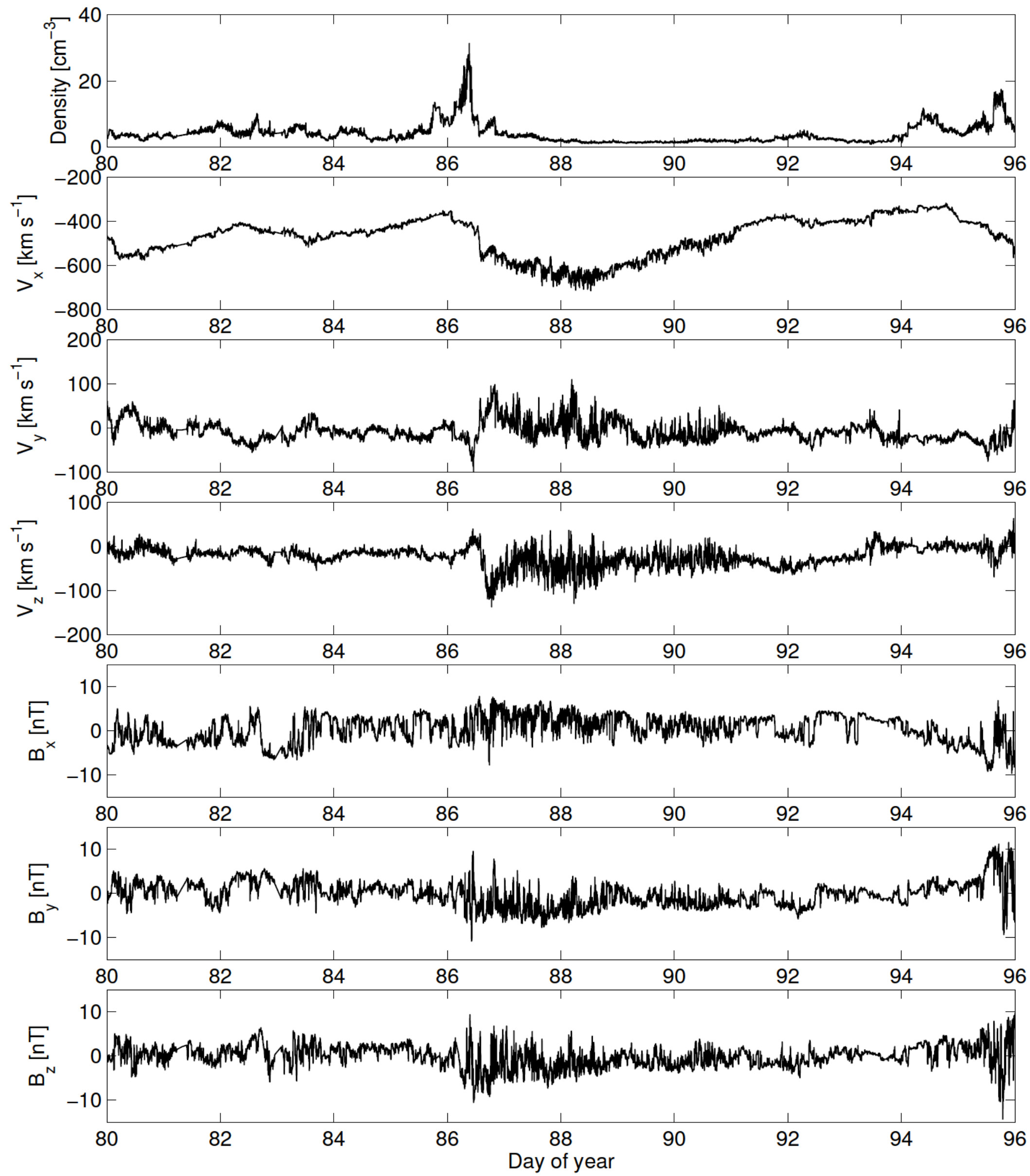
Inclination angle contours of 1908 and 2008 and differences in inclination (°)

- Expansion and intensification of the South Atlantic Anomaly region of low magnetic field strength
- Northward and westward movement of magnetic field structures
- Strongest inclination angle changes in Atlantic region (~100°W-50°E; ~40°S-40°N)

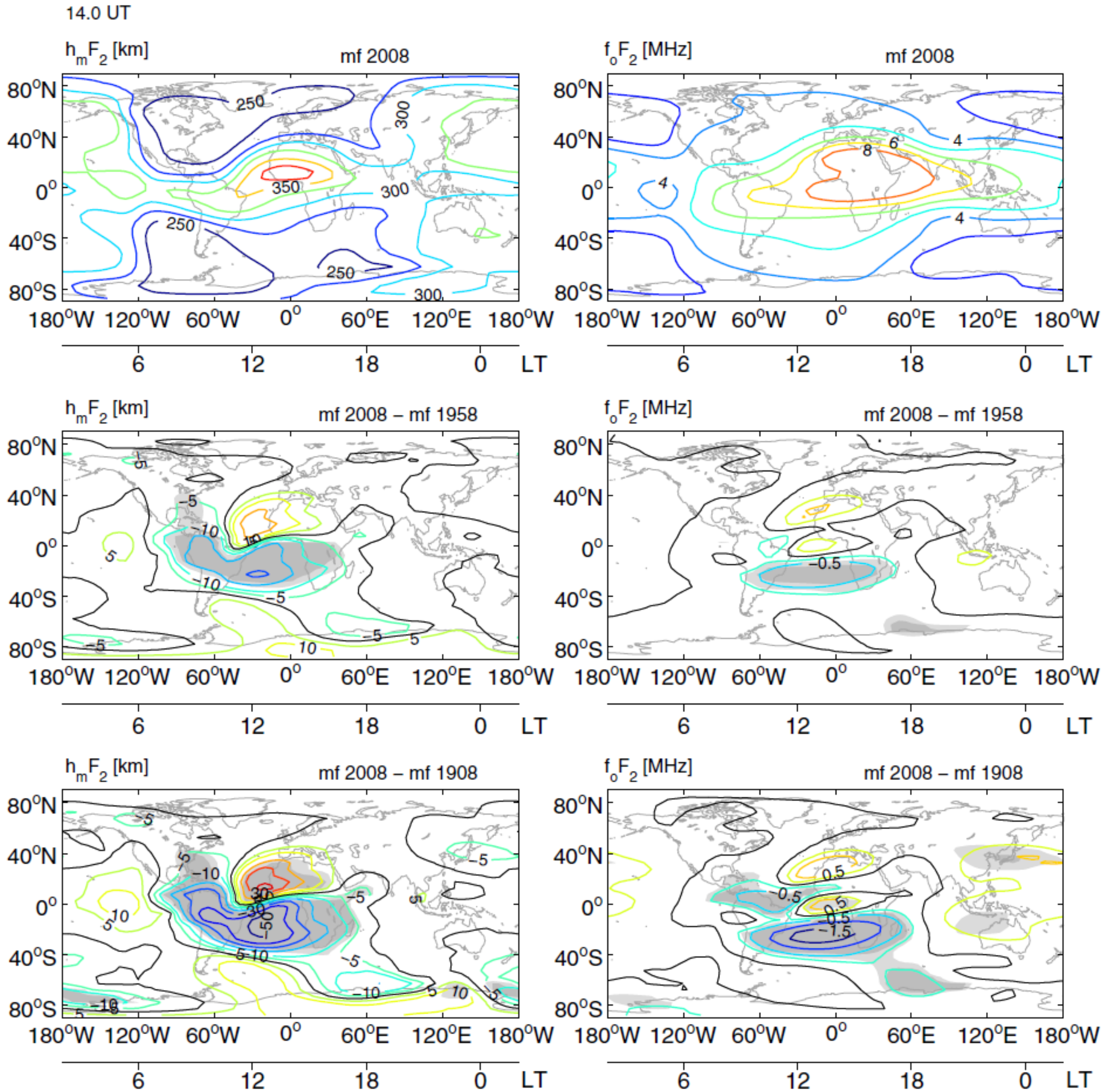
Cnossen and Richmond (JGR, 2013)

Simulation and analysis setup

- Simulations with the International Geomagnetic Reference Field (IGRF) of 1908, 1958 and 2008
- 15-day duration
- 20 March, 0 UT – 4 April, 0 UT (March equinox)
- Solar minimum conditions (F10.7 ≈ 70)
- Realistic solar wind conditions: used observed values for 2008
- Low geomagnetic activity (Kp < 5; mostly ~2)
- Test significance of differences against day-to-day variability with *t*-test



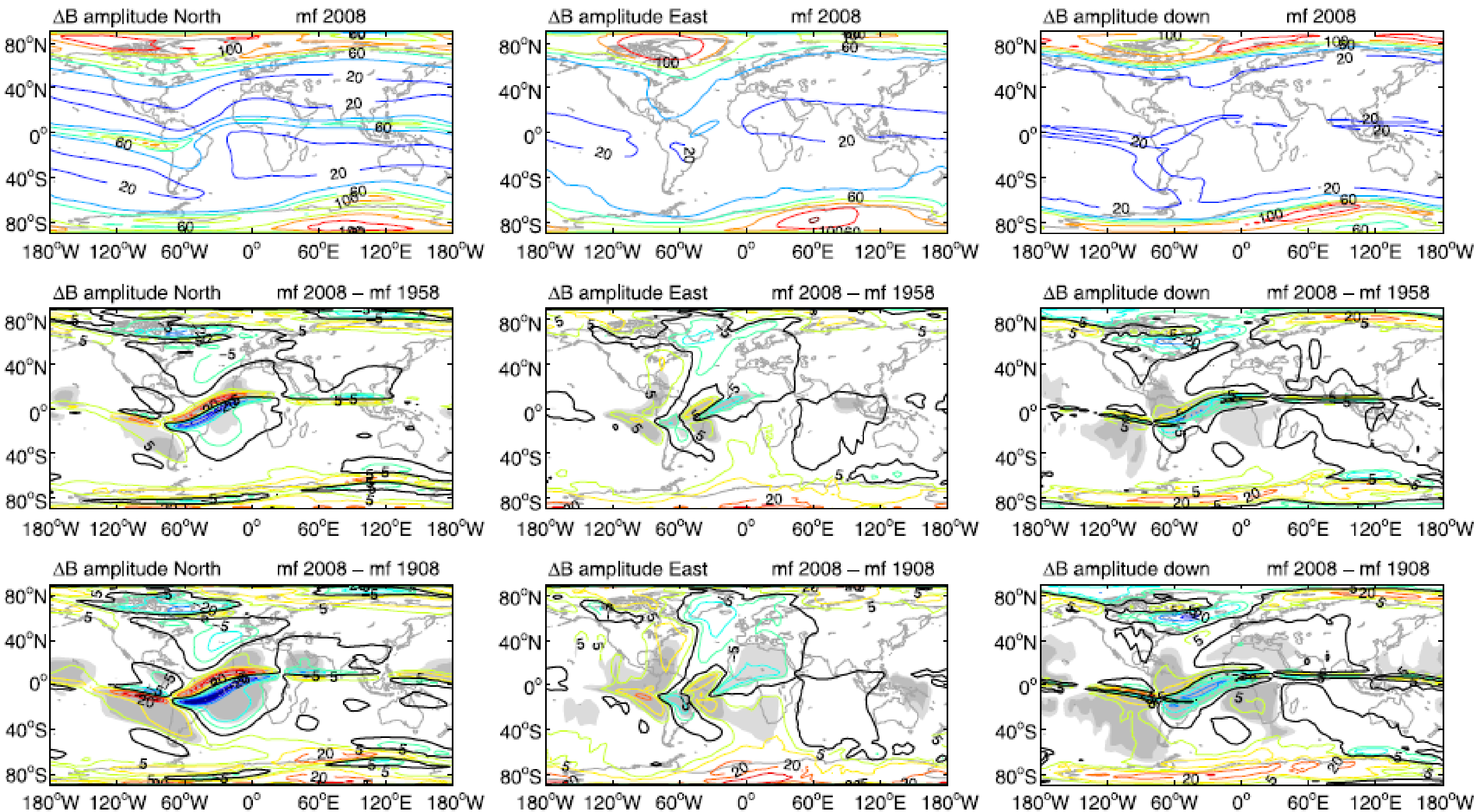
2008 vs. 1958 vs. 1908: h_mF_2 and f_oF_2 (14 UT)



- Significant changes (shaded) occur mostly in the "Atlantic region": ~100°W-50°E; ~40°S-40°N
- Mostly due to changes in plasma transport terms:
  - Vertical **ExB** drift
  - Vertical plasma transport induced by horizontal neutral wind
  - Vertical component of diffusion along magnetic field

Cnossen and Richmond (JGR, 2013)

2008 vs. 1958 vs. 1908: amplitude of Sq variation



- Significant differences in all components
- Mainly near magnetic equator; especially in Atlantic sector

Cnossen and Richmond (JGR, 2013)

Contribution of magnetic field changes to observed trends

- Ion temperature
  - Long-term decrease observed at Millstone Hill (43°N; 72°W) may be explained by up to 8% by long-term change in the magnetic field (Zhang and Holt, JGR, accepted)
- Sq daily amplitude
  - Good quantitative agreement between observed and simulated trends at Apia, Bangui and Hermanus, while trends at Frederickburg and Trivandrum were not significant (De Haro et al., JGR, accepted) – magnetic field changes important at *some* locations
- h_mF_2 and f_oF_2
  - New trend analysis (by me) of the Damboldt and Suessmann (2012) database (259 stations), using trend detection and significance testing methods by Franzke (2009, 2012)
  - Further work needed to make quantitative model-observation comparisons possible

Conclusions

- Changes in magnetic field strength affect the ionosphere via changes in ionospheric conductivity and changes in polar cap size, which cause subsequent changes to the high-latitude electric field, **E**x**B** drifts and Joule heating, which then lead to changes in h_mF_2 and N_mF_2
- Changes in dipole tilt angle affect the ionosphere through changes in the amount and geographic distribution of Joule heating and through changes in (the vertical component of) plasma transport processes as inclination and declination angles change
- Realistic magnetic field changes from 1908 to 2008 have had a significant effect on h_mF_2 and f_oF_2, as well as the amplitude of Sq magnetic variation, in particular in the Atlantic region (~100°W-50°E; ~40°S-40°N), where the strongest magnetic field changes have occurred
- Comparisons with observed trends so far indicate that magnetic field changes can be an important contributor to those trends, at least in some parts of the world
- Further comparisons are needed

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