Simulated trends in ionosphere-thermosphere climate due to predicted main magnetic field changes from 2015 to 2065

Ingrid Cnossen\textsuperscript{1}

Astrid Maute\textsuperscript{2}

\textsuperscript{1}NERC Independent Research Fellow (NE/R015651/1), British Antarctic Survey
\textsuperscript{2}National Center for Atmospheric Research
Why do we care about high-altitude climate?

- Managing space debris
  - Satellites operate in the upper atmosphere (~90-500 km)
  - Population of space debris is growing – collisional hazard
  - Satellite orbit and space debris lifetime depend on upper atmosphere density

- Remote sensing signals can be distorted by the ionosphere
  - Stability of long-term measurements can be affected by long-term ionospheric changes

- Connections to lower atmosphere climate change
Drivers of upper atmosphere climate change

- Solar and geomagnetic activity variations
- Increase in CO$_2$ concentration
  - Cools upper atmosphere
  - Thermal contraction
  - Indirect changes via altered lower boundary forcing?
- Magnetic field changes
  - Important for ionosphere
  - Regionally varying
Geomagnetic field changes and effects

- Decreasing main field strength
  - Causes increase in ionospheric conductivity
- Changes in field orientation
  - Causes changes in plasma transport processes, electron density
- Change in position of magnetic pole / auroral oval
  - Causes change in geographic distribution of high-latitude current systems, Joule heating
- Change in position of magnetic equator
  - Causes changes in low-latitude current systems, electron density

From Cnossen & Maute (2020), based on prediction by Aubert (2015)
Methodology

- Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM)
- 2.5° x 2.5° grid, ¼ scale height
- Two full-year simulations with magnetic field of 2015 (mf2015) and 2065 (mf2065)
- Includes effects of the magnetic field on conductivity and electrodynamics, and changes in mapping from magnetic to geographic coordinates
- Observed solar and geomagnetic forcing for 2015 used for both
  - High-latitude forcing is fixed in magnetic coordinates – only mapping effects included
- Hourly data
- Analyze average differences
Joule heating power and neutral density

- Small increase in neutral density
- Largest and most significant for high geomagnetic activity
- Probably due to increase in Joule heating – expected for reduced main field strength
- Larger effect in SH due to larger decrease in main field strength

Cnossen & Maute (2020)
Global mean total electron content (TEC)

- Global mean TEC changes depend on UT and season, varying from -4% to +3% or -0.5 to +0.3 TECU
- Due to spatial and local time variations

Cnossen & Maute (2020)
Total electron content (TEC) – spatial variations

- Largest changes occur in South Atlantic Anomaly region during daytime

Cnossen & Maute (2020)
Total electron content (TEC) – spatial variations

- TEC response is partly a mapping effect

Cnossen & Maute (2020)
Cause of TEC response: vertical transport terms

Vertical \textbf{ExB} drift

Vertical movement due to horizontal winds pushing plasma up/down magnetic field lines

Vertical component of diffusion along the magnetic field

- Changes in vertical \textbf{ExB} drift are the most important driver of the TEC response

Cnossen & Maute (2020)
Electron density changes at Jicamarca

- Increase in daytime peak electron density at Jicamarca
- Appears inconsistent with reduced upward $\mathbf{E}_\perp \mathbf{B}$ drift

Cnossen & Maute (2020)
Electron density changes at Jicamarca

- Increase in daytime peak electron density at Jicamarca
- Appears inconsistent with reduced upward $\text{ExB}$ drift
- But makes sense as entire EIA structure weakens!

Cnossen & Maute (2020)
Summary and conclusions

- Predicted main magnetic field changes from 2015 to 2065 cause minor effects on the thermosphere
  - Very small increase (1-2%) in thermosphere density – too small to be reliably detectable; unimportant compared to CO₂ effect on density
  - Due to minor increase (2-4%) in Joule heating, mainly coming from SH
- But they cause substantial effects on the ionosphere
  - Changes in TEC of up to ±10 TECU or ±35% during daytime between ~45°S-45°N, 110-0°W
  - Mainly driven by changes in vertical ExB drift
  - In the Jicamarca longitude sector reduced ExB drifts weaken the EIA, causing an increase in the daytime electron density at Jicamarca
- Effects of predicted magnetic field changes on TEC should be observationally detectable and could make a significant contribution to long-term trends in TEC, depending on spatial and temporal averaging