EGU22-84

The future evolution of the auroral zones

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Outline

- Introduction
- Methodology
- Part 1: climatological forecasts
- Part 2: sensitivity study
- Conclusions

Objective and questions:

Research objectives:

- To estimate the future geomagnetic response to space weather phenomena, in particular:
- To estimate the future geographical exposure to extreme (i.e. Carrington like) space weather events.
- To explain the fundamental reason for the above temporal changes (if any).

Methodology:

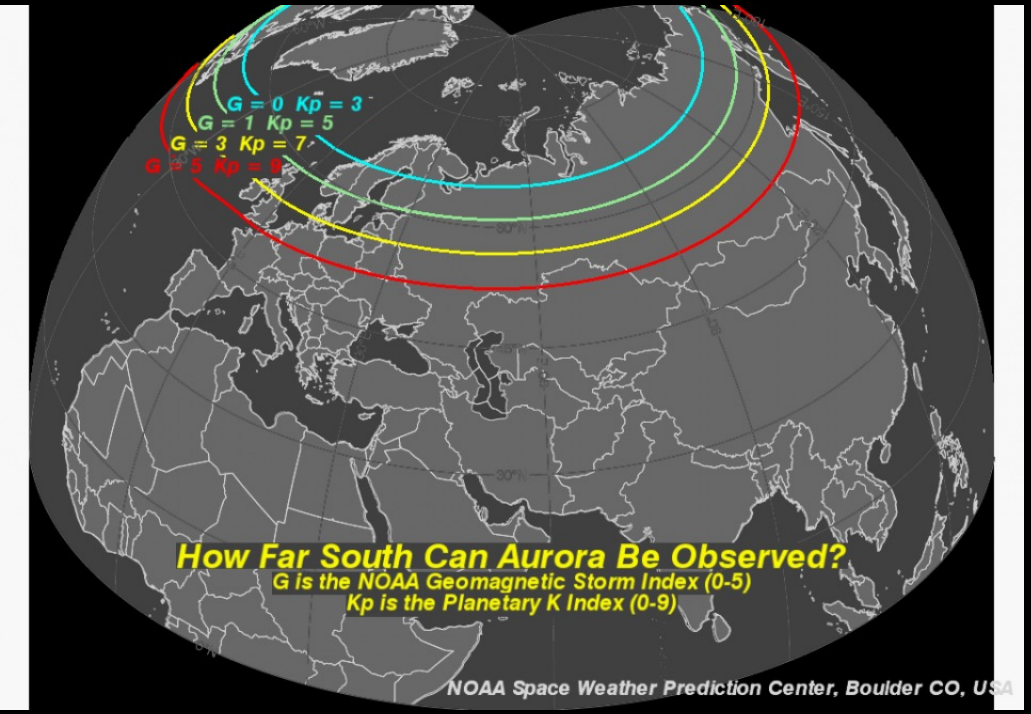
Link the decadal geomagnetic field changes with geographical exposure to space weather phenomena (to be appropriately defined).

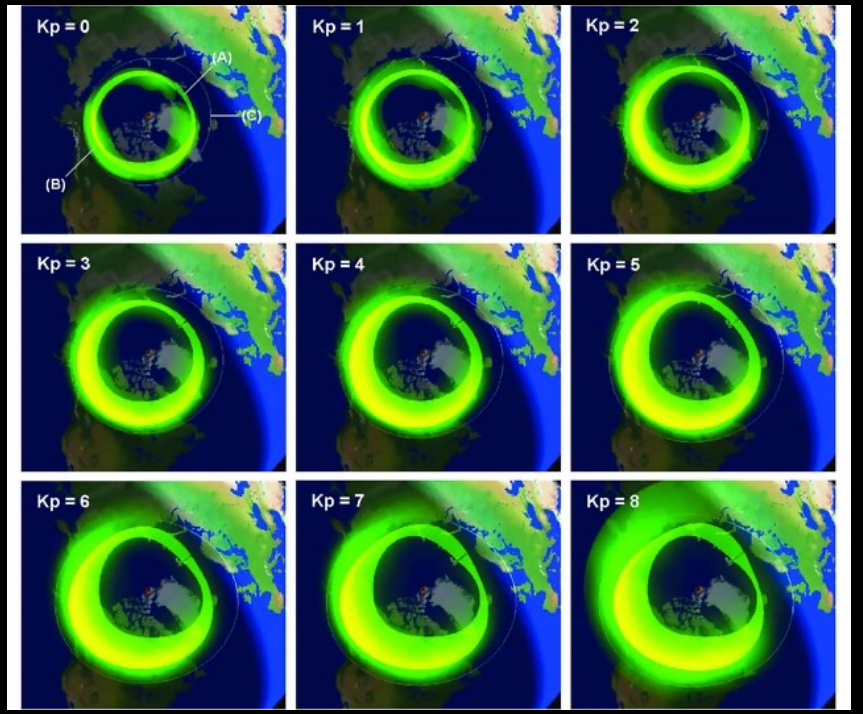
Some questions:

- Where can we expect aurorae to be most likely visible in the next decades?
- What cities are most exposed to the effect of extreme solar activity and how is that going to change in the next decades?
- How are these changes related to temporal changes in the geomagnetic field of internal origin?
- How precise must our knowledge of the geomagnetic field be to understand the geomagnetic response to solar activity?

Introduction

Auroral oval extension





Sigernes et al., 2011

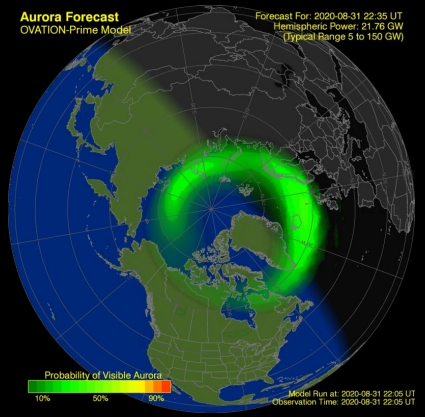
With more intense geomagnetic activity:

- the auroral oval oval expands and widens
- the northern aurorae can be visible further south

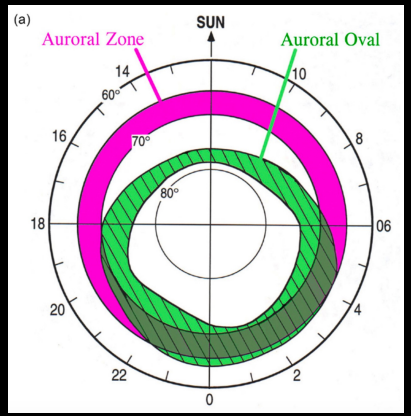
Definitions

Auroral oval - Space weather (Where are aurorae visible **now**?)

- Visually/energetically defined (i.e. Feldstein, 1963; Feldstein 2016)
- As solar activity increases, the ovals expands equatorward
- The oval location depend on many factors (solar wind speed, IMF, time-of-day, etc…) and its link with the internal geomagnetic field is difficult to establish



www.spaceweatherlive.com



Akasofu, 2015

Auroral zone - Space climate (Where are aurorae visible, **on average**?)

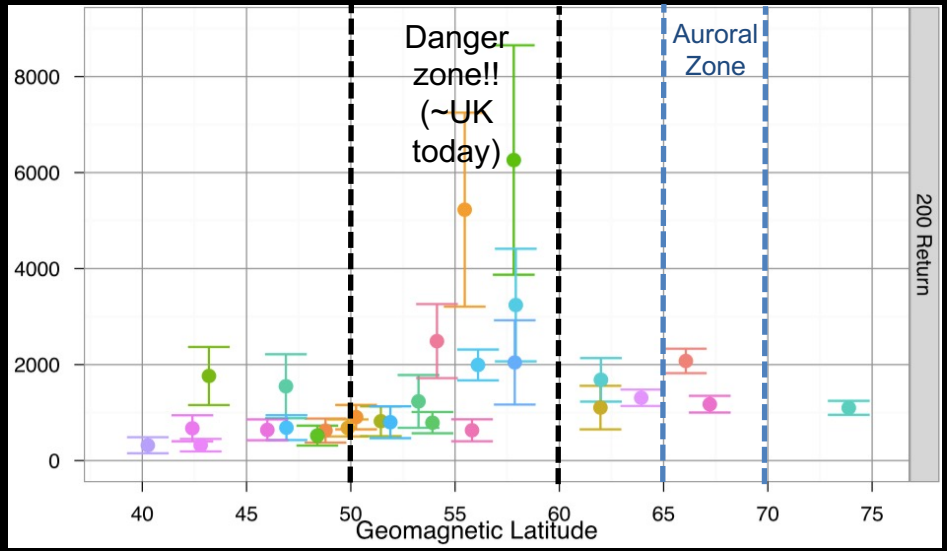
- Typically defined as **the 65 to 70 deg band** in geomagnetic coordinates
- Pro: Easy to track its decadal evolution as geomagnetic field evolves
- Con: This definition does not tell us anything about the impact of severe space weather events, only on moderate ones (Kp<3)

Definitions

- For extreme solar activity the auroral oval expands equatorward.
- The corresponding magnetic field variations drive GIC (ground induced currents) that can damage ground-based technology.
- We need a climatological definition for the geographical locations of the regions that are most exposed to severe (Carrington like) space weather events.

Danger zone - Space climate (Where are the most severe GIC to be expected, **on average**?)

- Extreme events analysis (*Thomson et al., 2011*) suggests a band **between 50 and 60 deg** in geomagnetic latitude for a 200-year return event.
- Bounds are somewhat arbitrary, but they include the maximum temporal variation in horizontal magnetic field on the ground.
- See later for validation.

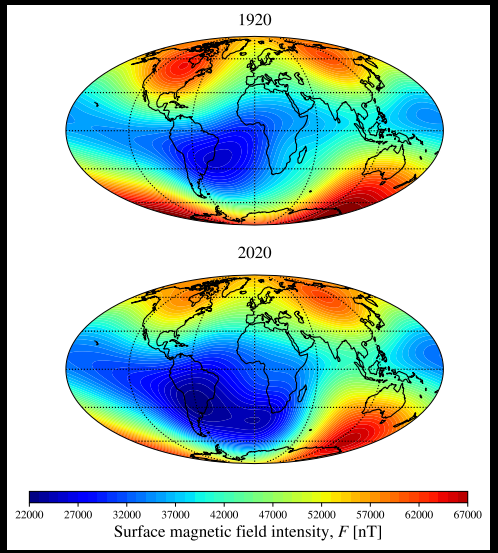


Thomson et al., 2011. Estimated 200-return-time-extreme dH/dt values

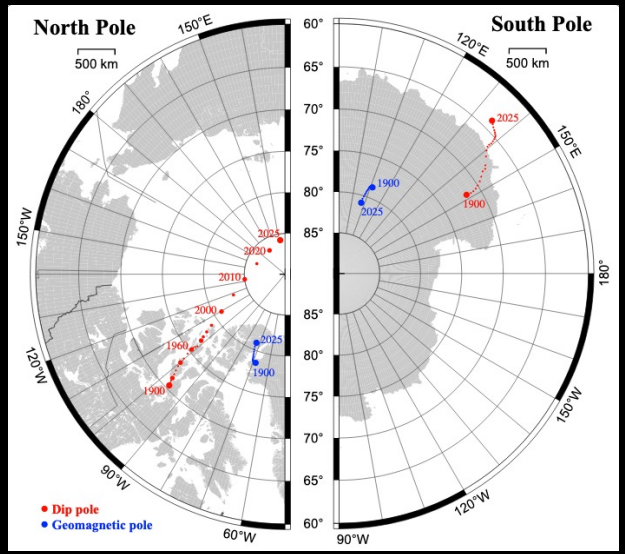
Geomagnetic field variations

- The above definitions can be linked to temporal variations of the geomagnetic field of internal origin to estimate temporal evolution of auroral zones and danger zones.
- Over decades the geomagnetic field evolves in a non-trivial manner:

Geomagnetic field intensity evolution (IGRF13)



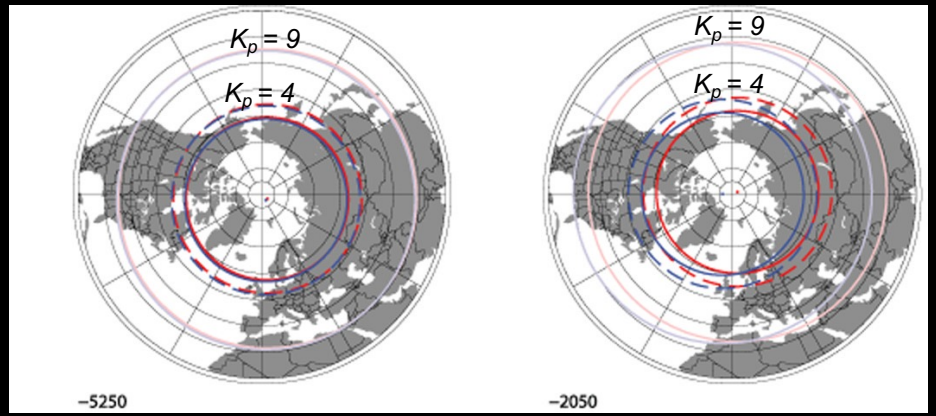
Geomagnetic and dip poles evolution (IGRF13)



What are the corresponding temporal variations of auroral and danger zones locations?

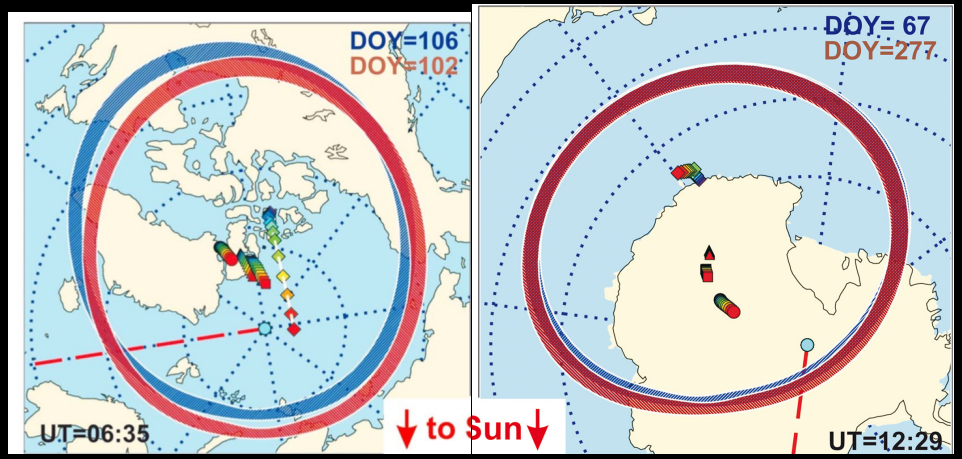
Existing studies: past evolution

Dipole-based prediction of auroral zones *(Korte and Stolze, 2014)*



Red: geomagnetic pole-centered
Blue: virtual geomagnetic pole-centered

Auroral zones in 1965 and 2020, from an empirical magnetospheric model *(Tsyganenko, 2019)*



Circles: centered dipole
Squares: eccentric dipole
Triangles: corrected geomagnetic pole
Diamonds: dip poles

- **Non-dipolar magnetic field components have a first order effect on the location of the auroral zones:**
- **Dipole-based predictions are limited by the need to chose a pole definition and miss the non-dipolar deformation of the auroral zones**

Existing studies: Auroral zone forecast

(Oguti, 1993)

Method:

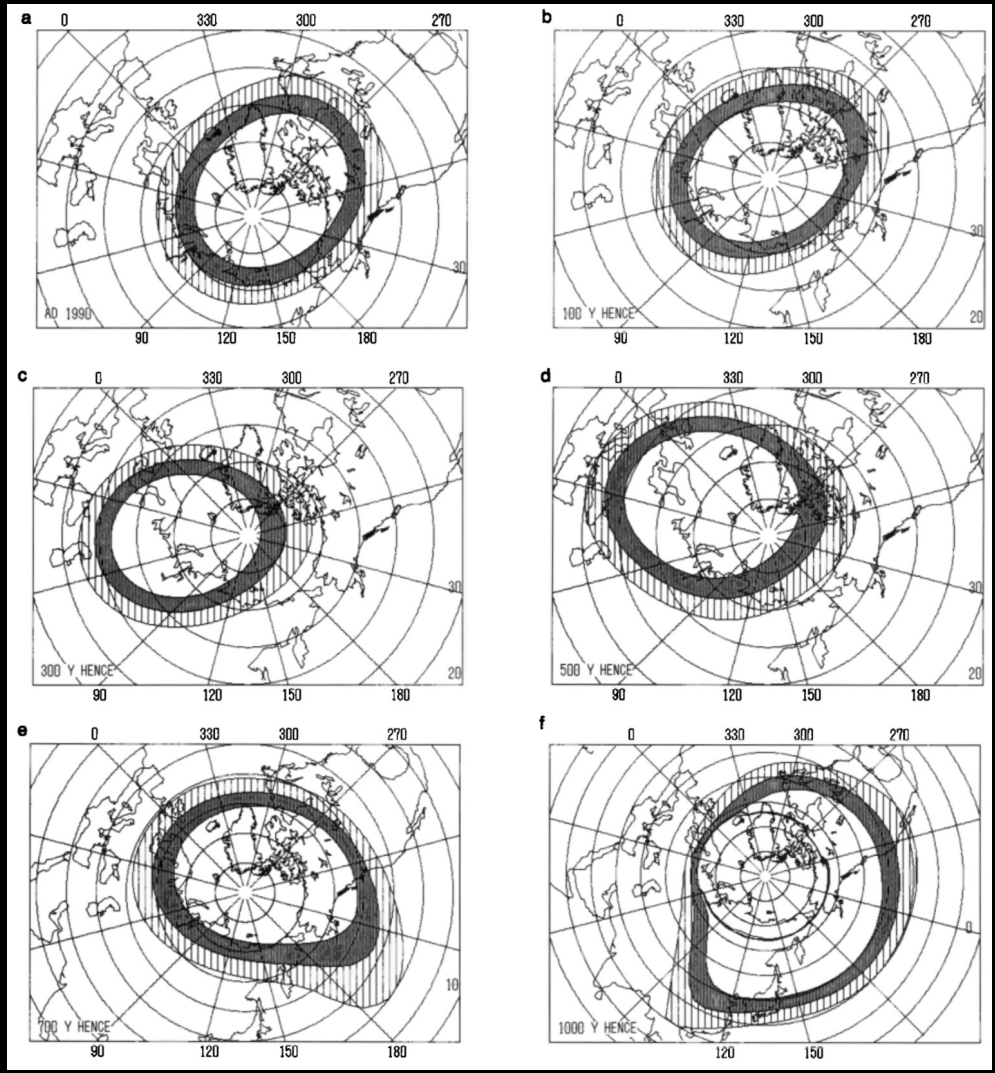
- Define today's auroral zone as:
  65° < dipole latitude < 70°
- Use the same field line apex intensity to define the auroral zone as the magnetic field is changed
- Use ad-hoc, long-term forecasts to change the magnetic field in time

Observations:

- The initial auroral zone is not a circle
- As the dipole decays, multipolar components distort the zone even further

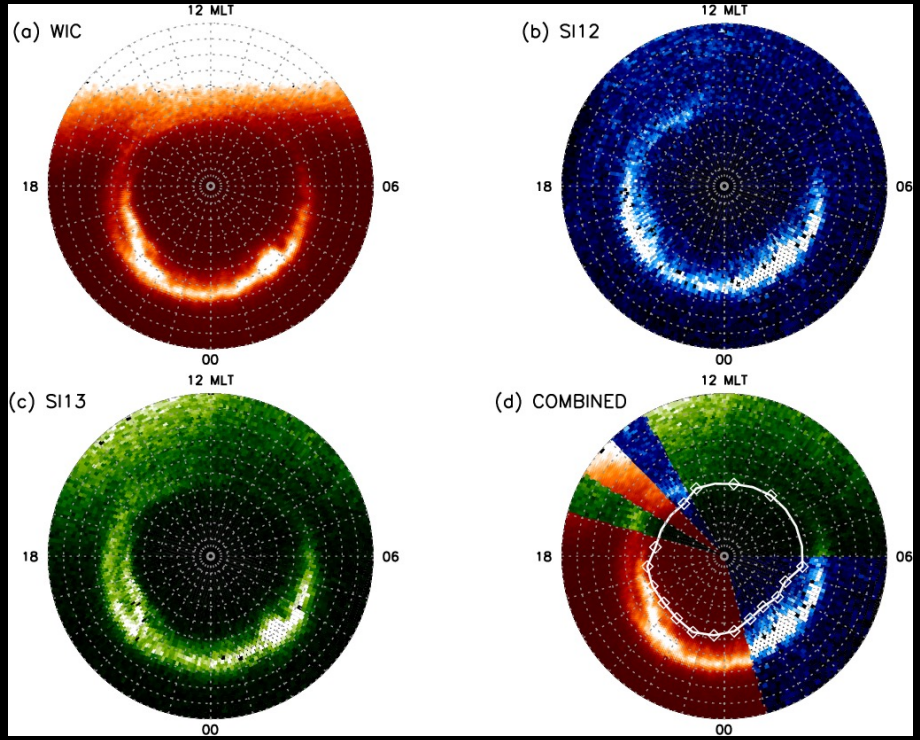
Limitaion:

- Today's forecasts allow more detailed analysis over decadal time-scales

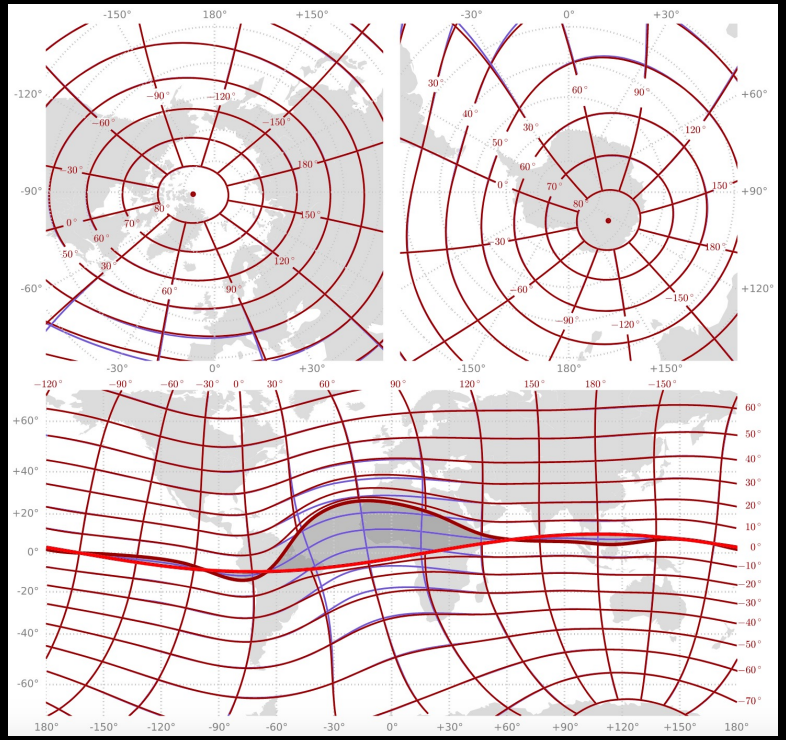


Methodology

Auroral zones in geomagnetic coordinates



Longden et al., 2010: IMAGE in AACGM coordinates (~circular contours)



Laundal and Richmond,2017: AACGM vs QD coordinates

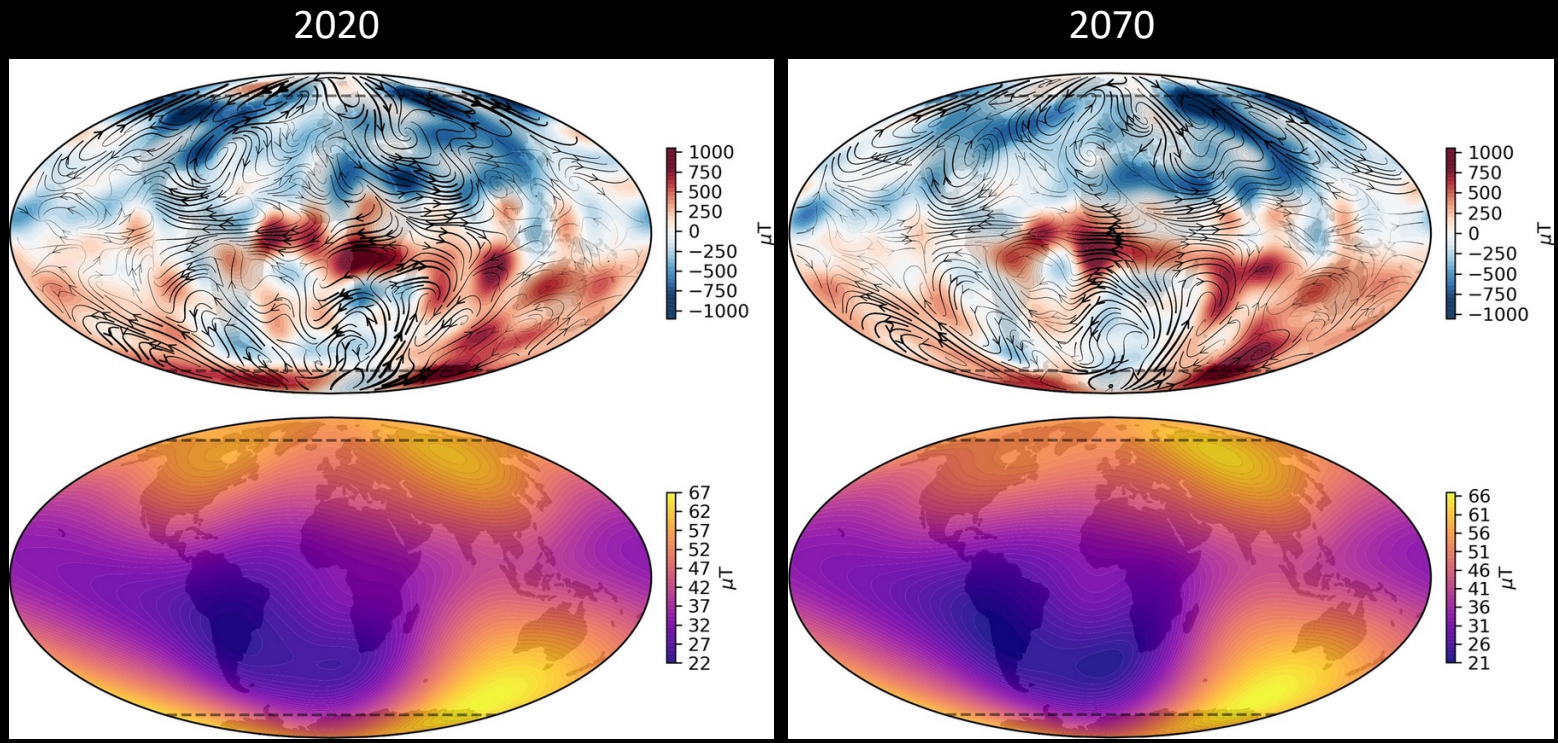
Procedure:

- **Calculate AACGM coordinates from past, present and predicted geomagnetic field configurations.**
- **Auroral zones: 65 to 70 magnetic latitude. Danger zones: 50 to 60 magnetic latitude.**

Geomagnetic field forecasts

State-of-the-art: geomagnetic data assimilation (Sanchez et al., 2020 – MPG model)

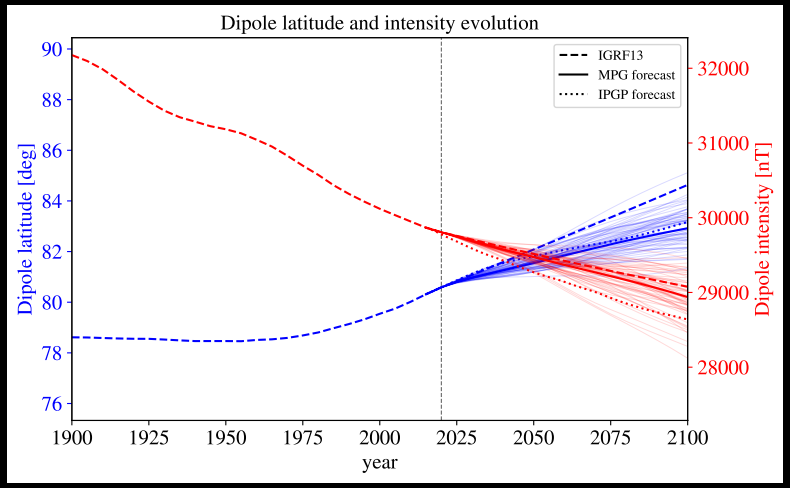
- Combine numerical models of core-dynamics with geomagnetic field observations
- Main limitation: the extreme parameters of Earth's core are yet computationally unreachable

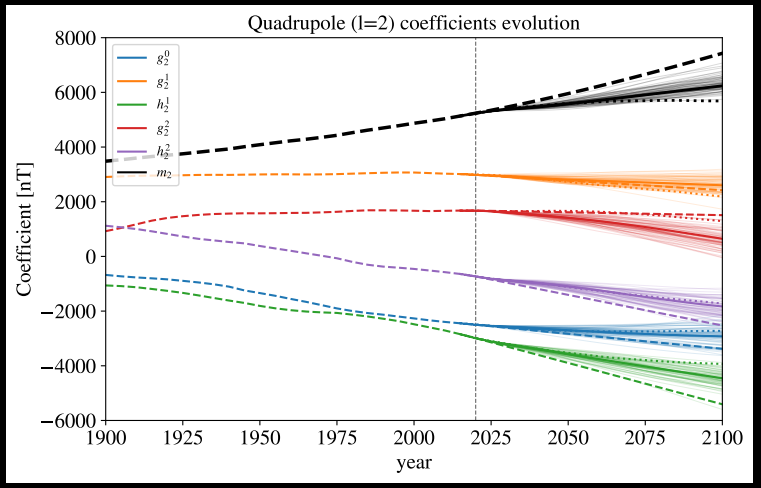


Geomagnetic field forecasts

We consider the following forecasts:

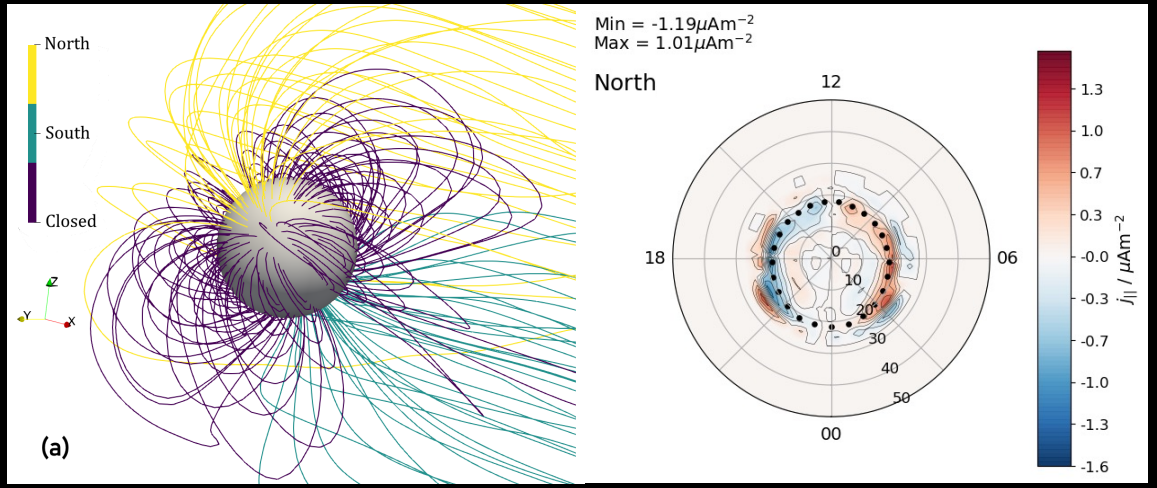
- MPG forecast mean and ensemble *(Sanchez et al., 2021)* – data assimilation
- IGRF-13 *(Alken et al., 2021)* extrapolated in time– no dynamics
- IPGP Forecast *(Aubert, 2015)* – single epoch inversion





And estimate the corresponding evolution of auroral zones and danger zones
We calculate AACGM coordinates using the *aacgmv2* Python wrapper
https://github.com/aburrell/aacgmv2/tree/main/aacgmv2.

Auroral zones: validation with Gorgon



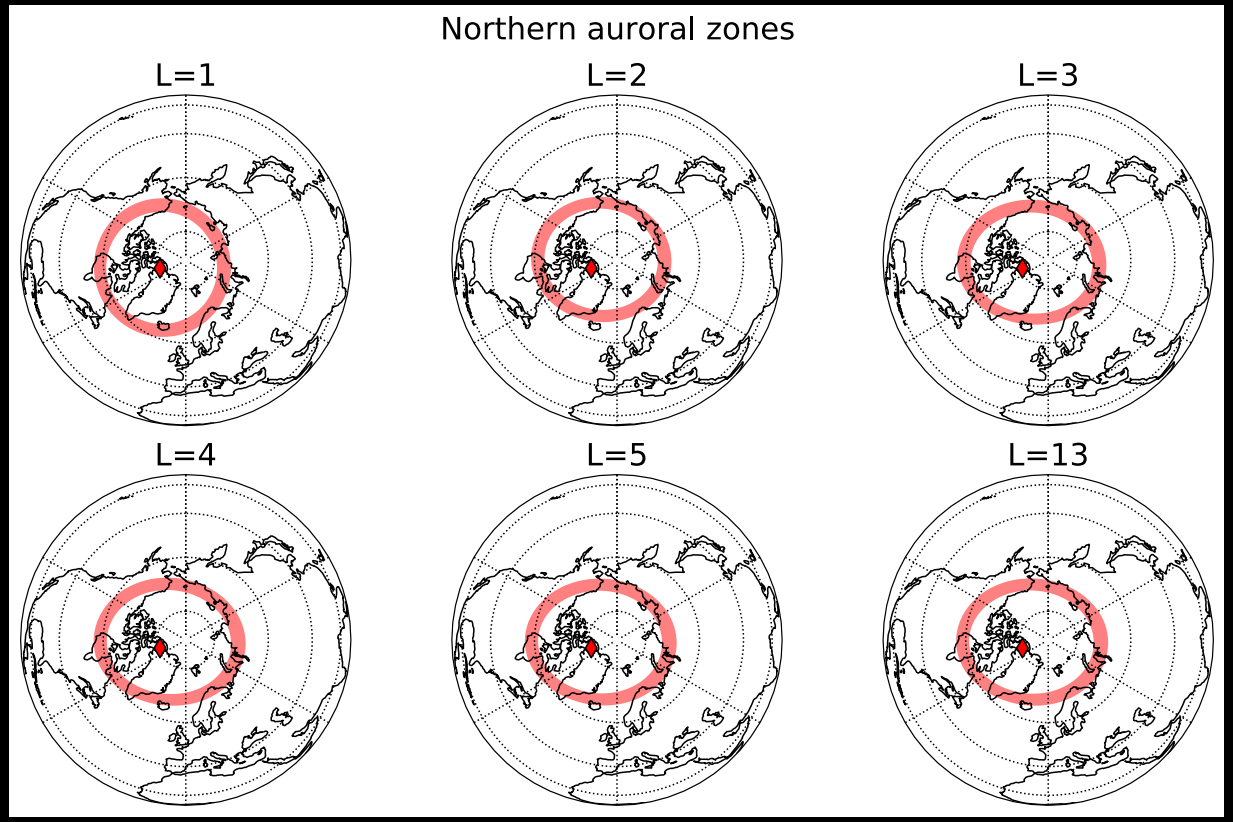
- Prescribe solar wind conditions (v_x=400 km/s, n=5/cm^3, variable IMF) and geomagnetic dipole Simulate magnetospheric response with the GORGON code (*Mejnertsen et al., 2018; Eggington et al., 2020*)
- Sample the OCB (poleward edge of auroral zone)
- Can we approximate the OCB with a circle of constant geomagnetic latitude of 70 deg, under weak to moderate IMF conditions?

IMF Bz / nT	Min. OCB Lat. / °	Max. OCB Lat. / °	Avg. OCB Lat. / °
-2	69.3	75.2	72.5
-4	68.6	72.9	70.8
-6	67.3	71.4	69.5
-8	66.7	70.0	68.4
-10	66.7	69.3	67.8
-20	62.7	70.7	65.8

→ **YES**

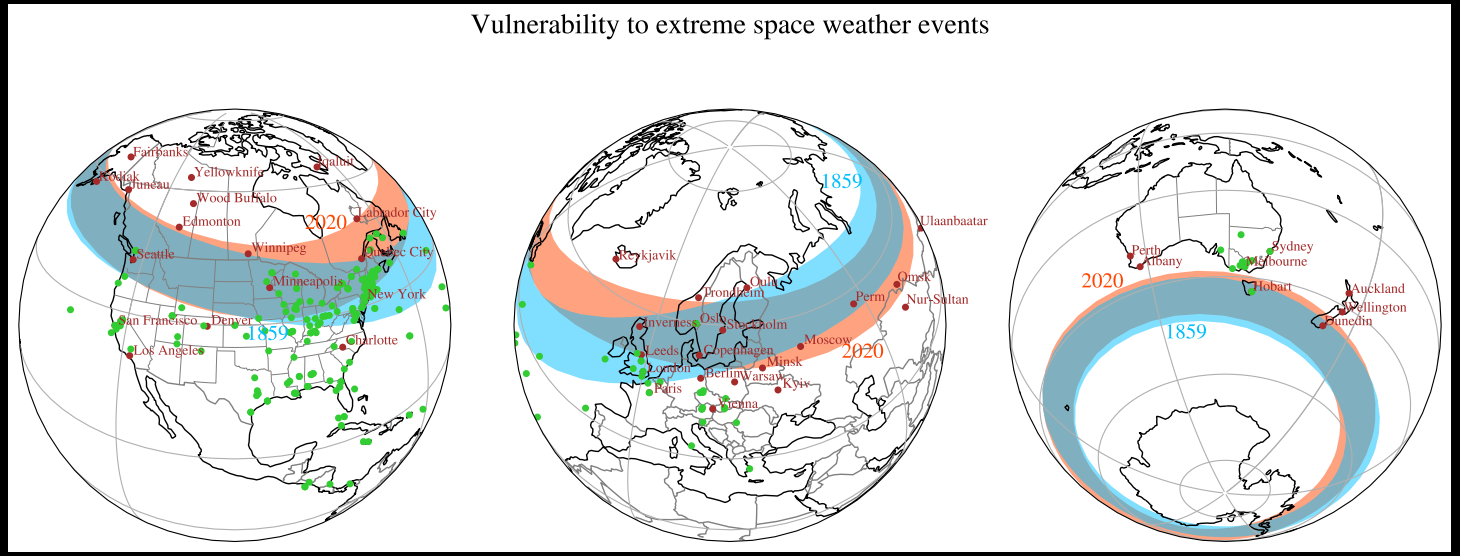
Beyond dipolar contributions

Northern auroral zone for 2020 (IGRF-13)



Significant contribution for up to L = 3 - 4 (same for southern auroral zone)

Danger zones: validation



2020 (today, IGRF) and 1859 (Carrington's event, GUFM1)

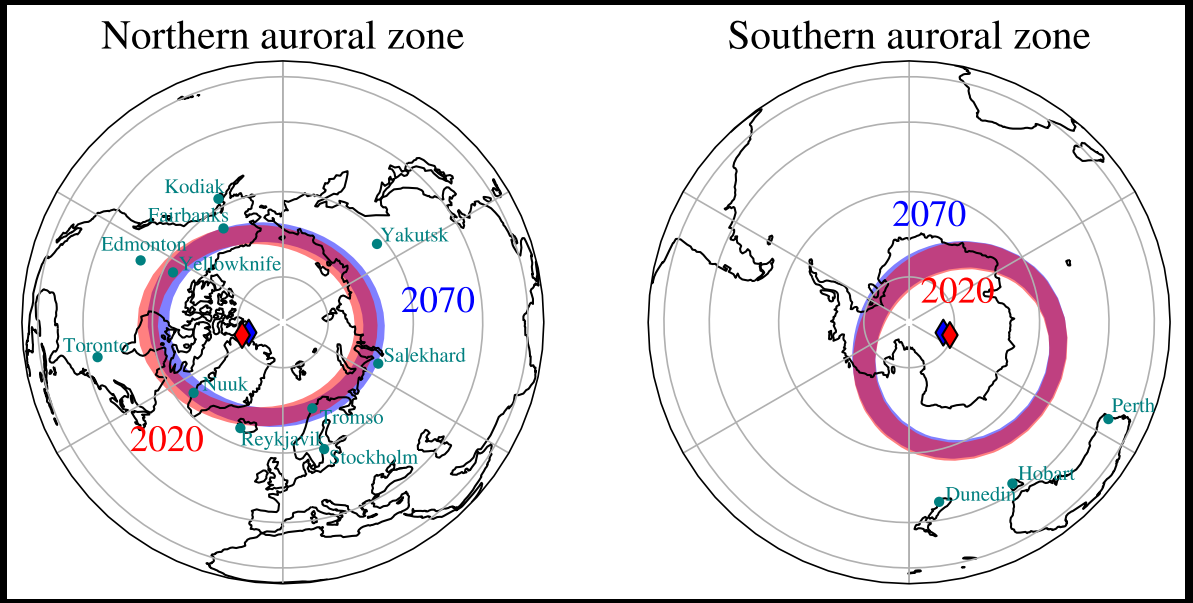
Green: aurorae sightings during the 1859 Carrington event (*Green and Boardsen, 2006*)

Some observations useful to extreme space weather events mitigation:

- **Carrington event: 60 deg N is a good measure for the poleward bound. There are exceptions.**
- **No apparent equatorward bound.**
- **This suggests that (e.g.) Quebec City is exposed to a Carrington-like event today (see 1989 Quebec blackout).**

Part 1: forecasts

Auroal zone forecasts

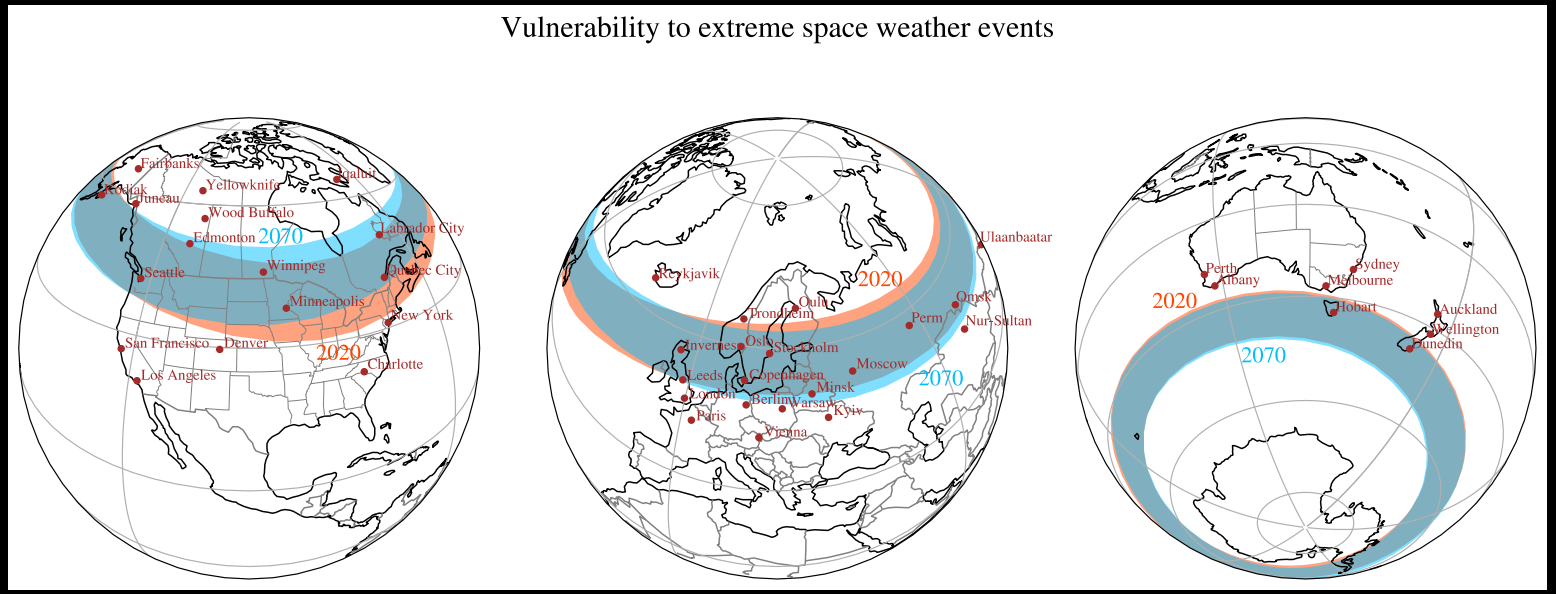


Aurorae will be:

- **more likely to be visible at lower latitudes in Russia**
- **Less likely to be visible at Edmonton latitudes in North-America**
- **Little change in Europe, Australia and New Zealand**

Note: different evolution of Northern and Southern zone: non-dipolar field effect

Danger zone forecasts

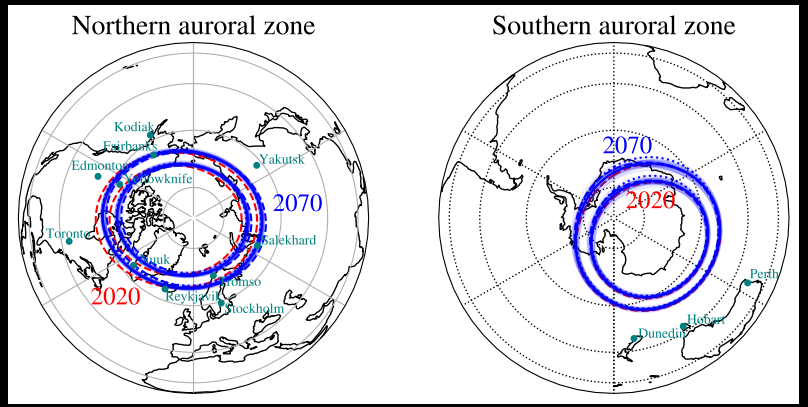


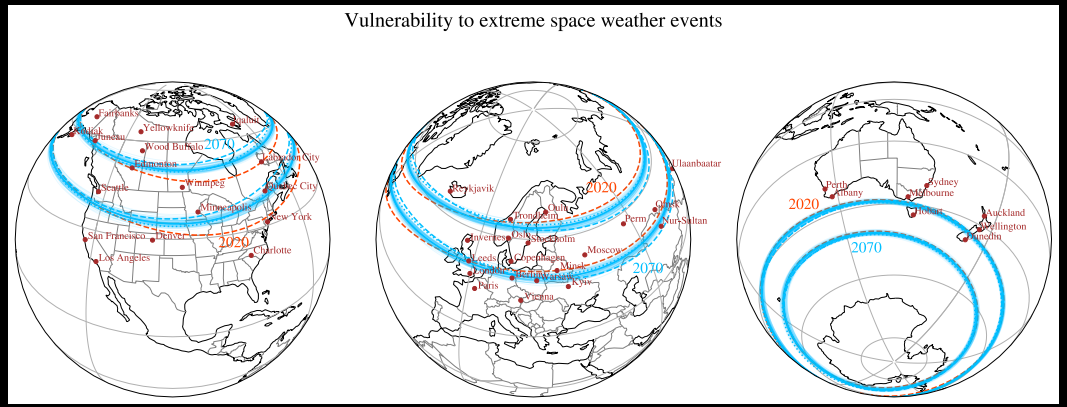
Some observations useful to extreme space weather events mitigation:

- **Northern Europe, Tasmania and New Zealand will likely still be in the danger zone in 50 years from now**
- **High risk region moves northward in North-America: Newfoundland, Quebec City and Montreal will be out / at the edge of the danger zone (today they are inside); Edmonton will be inside the danger zone**

Forecast uncertainty estimation

- The full ensemble of the MPG forecast and other available forecasts (IPGP, IGRF) allow to estimate the uncertainty on the above estimates.
- Plot the poleward and equatorward boundaries of the auroral/danger zones for all available forecasts:



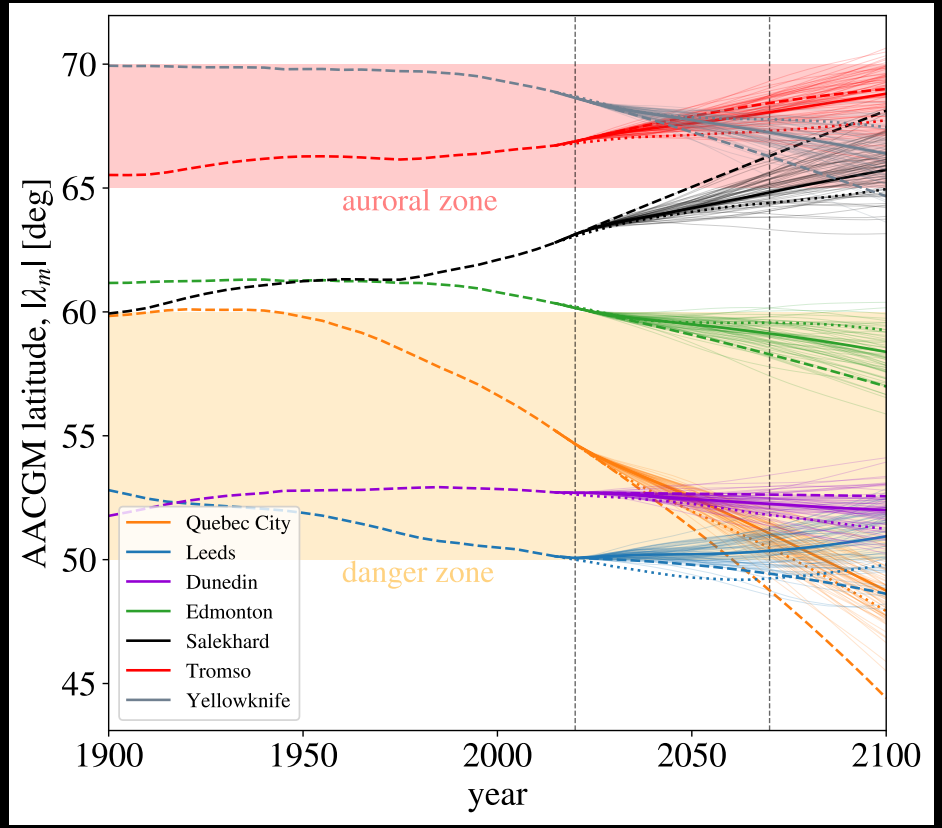


- **An uncertainty of about 2 degrees is estimated in the estimation of all boundaries locations**
- **The MPG ensemble contains other forecasts: climatological predictions are meaningful (akin to atmospheric climate predictions)**

Forecast uncertainty estimation

Same estimate is possible for selected cities:

- An uncertainty of about 2 degree is confirmed for the AACGM latitude determination in 2070
- Western/Eastern hemisphere cities have decreasing/increasing AACGM latitude
- Edmonton: increased severe space weather exposure
- Dunedin/Leeds: same high exposure to severe space weather events
- Salekhard: increased likelihood of aurorae spotting
- Tromso/Yelloknife: same high likelihood of aurorae spotting

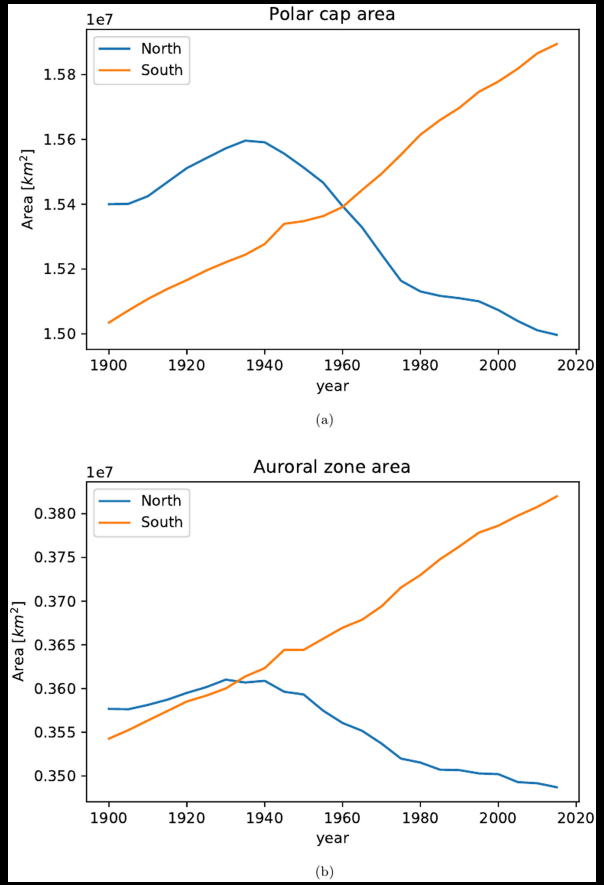


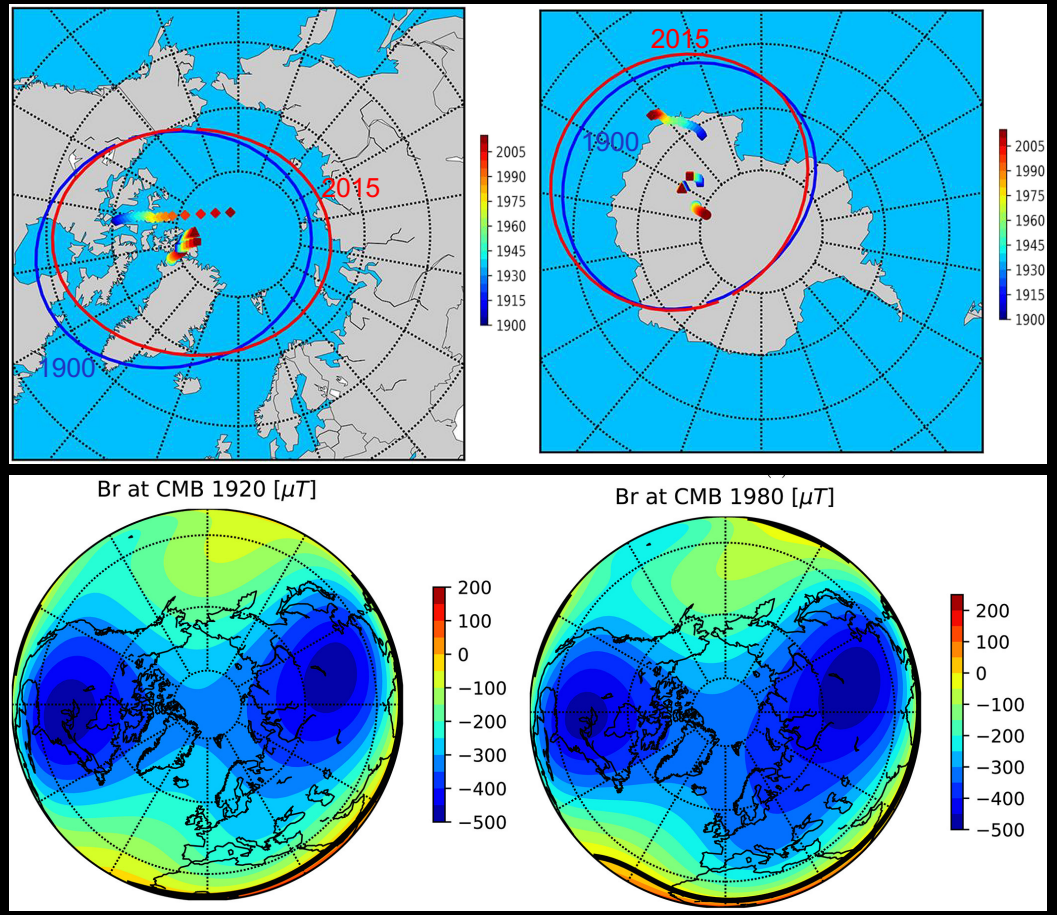
Part 2: Green’s functions (work in progress)

Sensitivity study:

- Can we link the present/future evolution of auroral and danger zones to specific spatio-temporal feature of the geomagnetic field?
- Approach: Green's functions.
- Need to choose specific diagnostics: fitting an ellipse to the zones would be easy but limited.
- Focus on auroral zones. Diagnostics: surface area, centroid latitude, distance from selected cities.
- Example/motivation: the auroral zones surface areas and location evolution has been traditionally linked to high latitudes geomagnetic field variations. Is it true? Can we validate this (logically acceptable) view?

Geomagnetic Field Model Indicates Shrinking Northern Auroral Oval *(Zossi et al. 2020)*

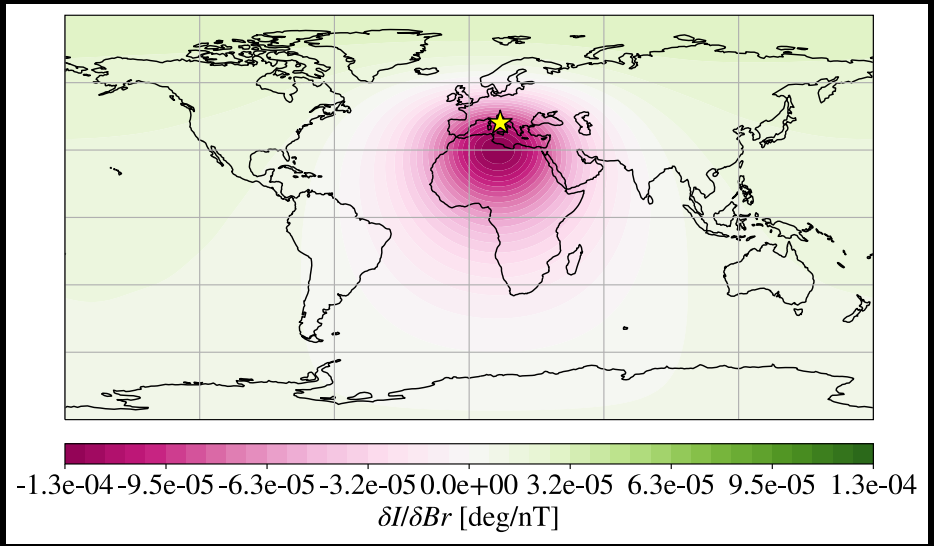




Green's functions – an example: geomagnetic inclination

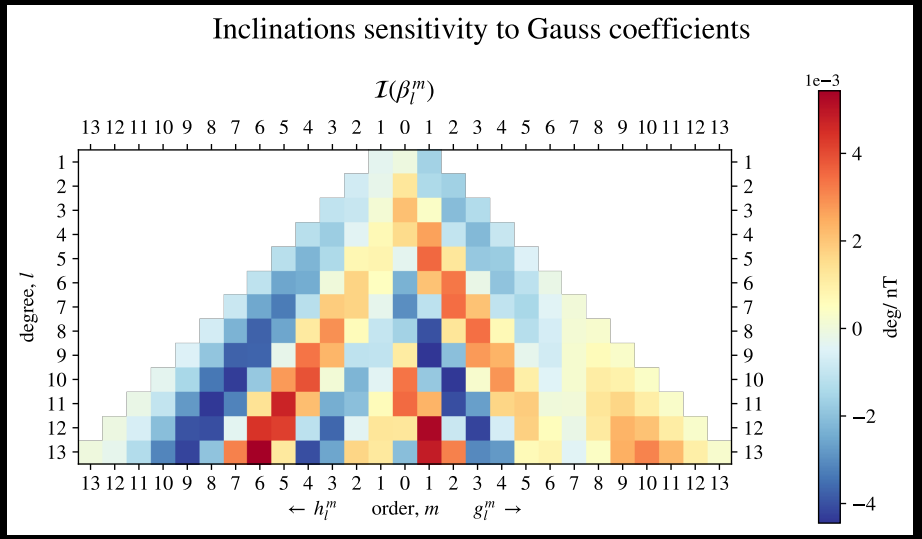
Green's function wrt CMB radial field variations

$$I(\mathbf{r}) = \int_{CMB} \frac{\delta I(\mathbf{r})}{\delta B_r(\mathbf{r}')} B_r(\mathbf{r}') dS'$$



Green's function wrt Gauss coefficients variations

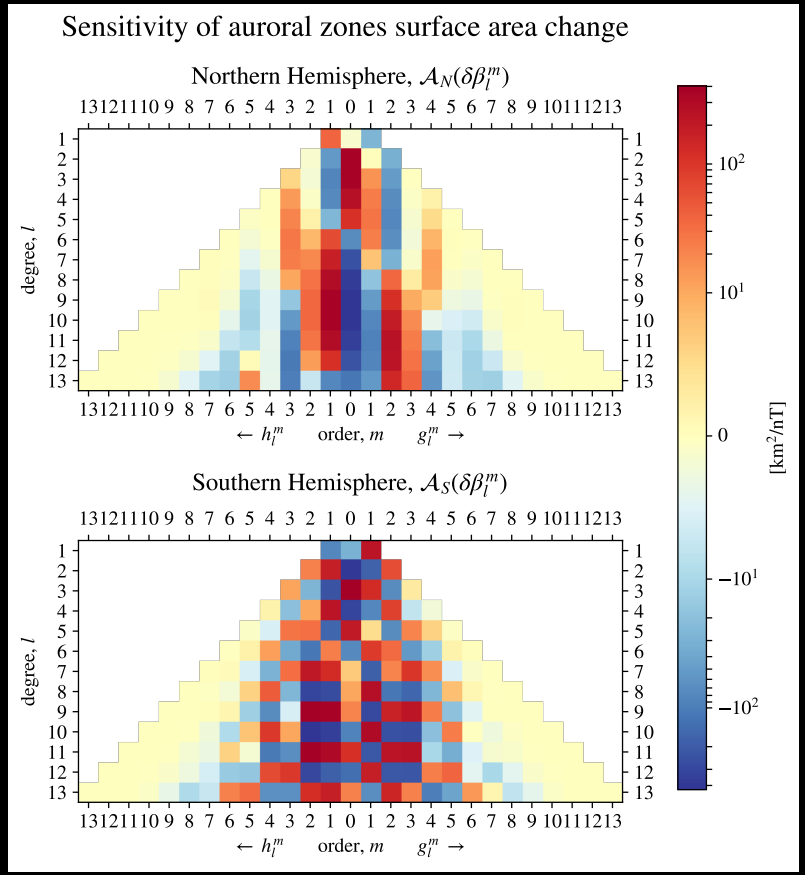
$$\mathcal{I}(\delta\beta_l^m) \equiv \frac{\delta I}{\delta \beta_l^m}$$



$$\frac{\delta I}{\delta B_r} = \sum_{l,m} \mathcal{I}(\delta\beta_l^m) \left(\frac{\delta B_r}{\delta \beta_l^m}\right)^{-1}$$

Green's functions: auroral zone's surface area

$$\mathcal{A}_i(\delta\beta_l^m) \equiv \frac{\delta A_i}{\delta\beta_l^m}$$



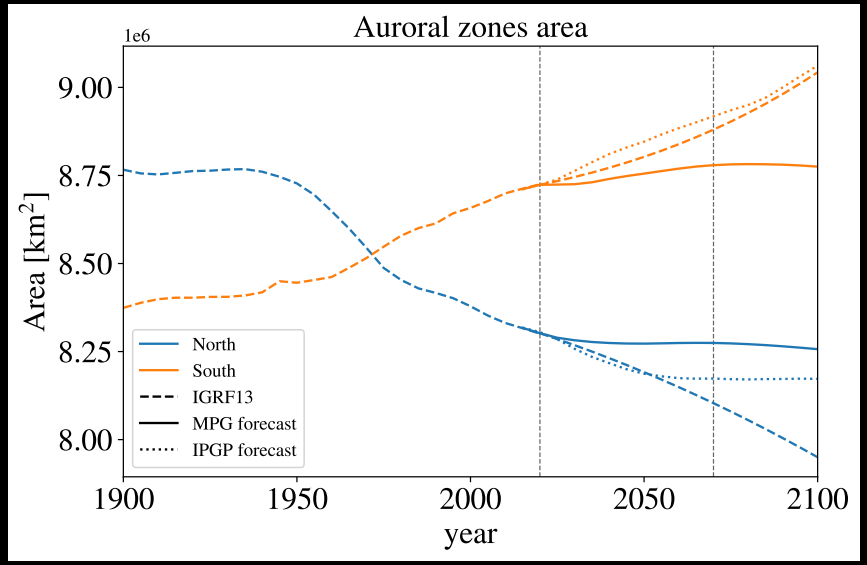
- **Significant contributions beyond the dipole (remember: L=3 is significant)**
- **North ≠ South**

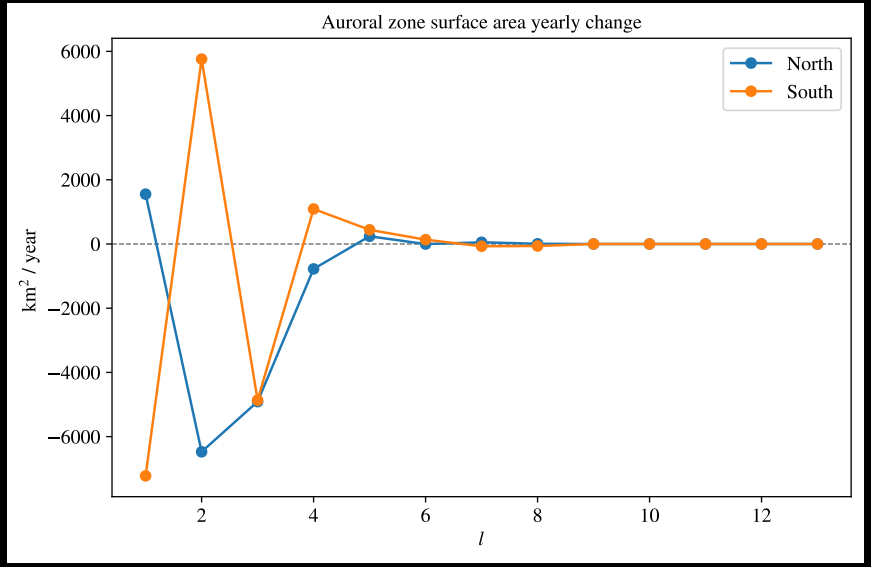
Green's functions: auroral zones surface area

Auroral zone's surface area. North-South dichotomy. First pointed out in Zossi et al., 2020

Temporal changes in auroral zones' areas from Gauss coefficients temporal changes (IGRF-13, 2020)

$$\frac{\partial A_i}{\partial t}(l) = \sum_{m=0}^{l} \mathcal{A}_i(\delta\beta_l^m)\frac{\partial \beta_l^m}{\partial t}$$



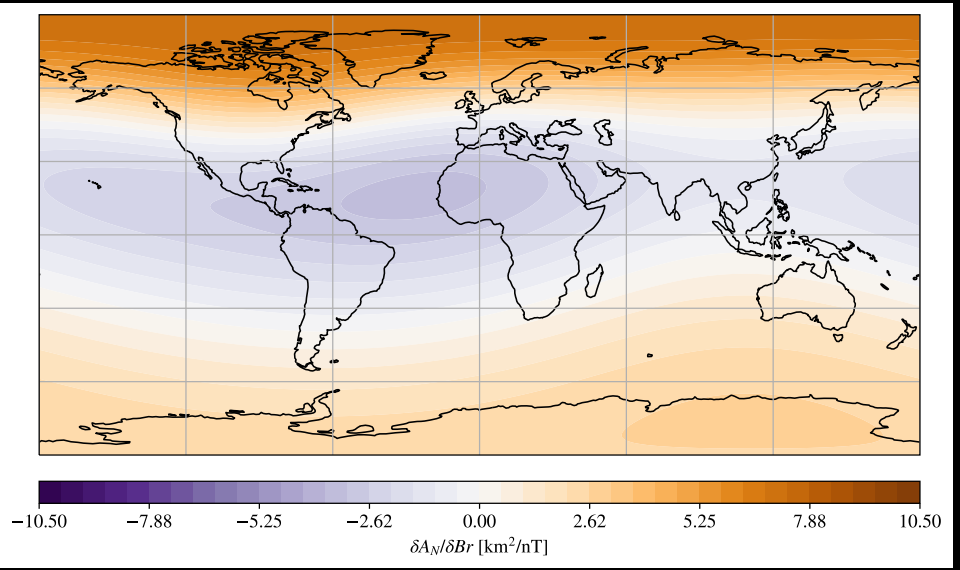


- **Significant contributions beyond the dipole**
- **Dipole contributions alone know that North ≠ South**

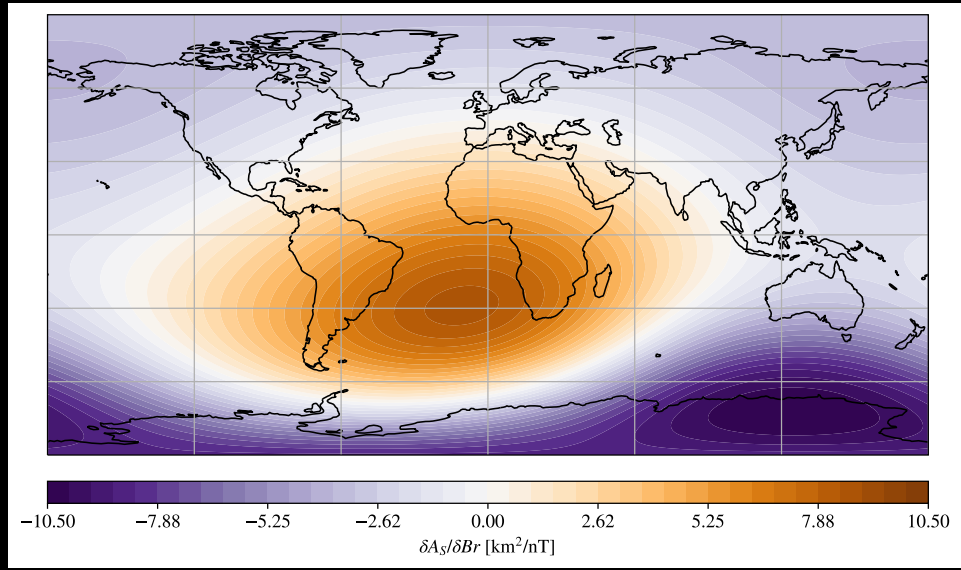
Auroral zones area: sensitivity to CMB field changes.

$$\frac{\delta A_i}{\delta B_r} = \sum_{m,l} \mathcal{A}_i(\delta\beta_l^m) \left(\frac{\delta B_r}{\delta \beta_l^m}\right)^{-1}$$

Northern auroral zone



Southern auroral zone

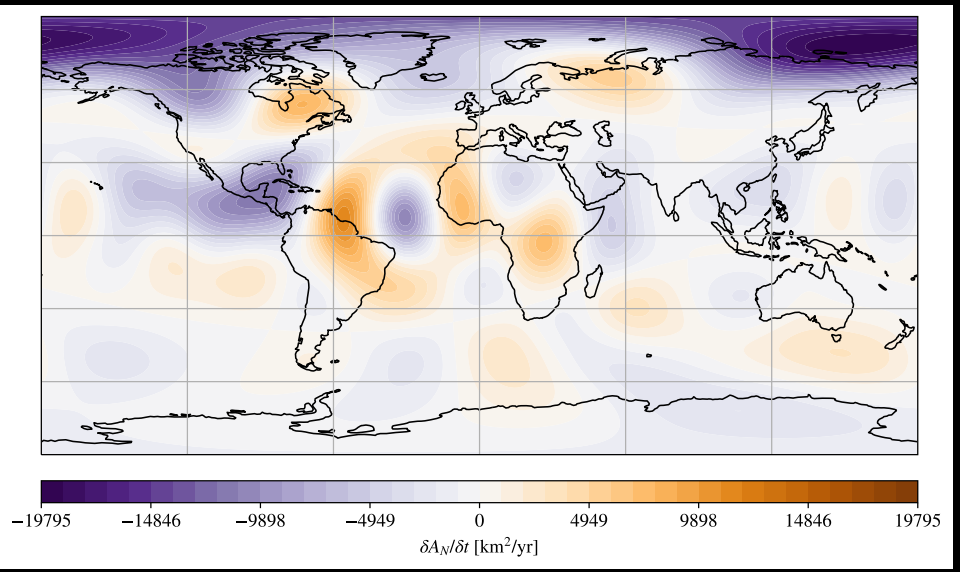


- The auroral zone's surface area is sensitive to both the polar field and the mid-latitude, Atlantic CMB field.
- Actual contributions are found multiplying the sensitivity maps by the secular variation maps.

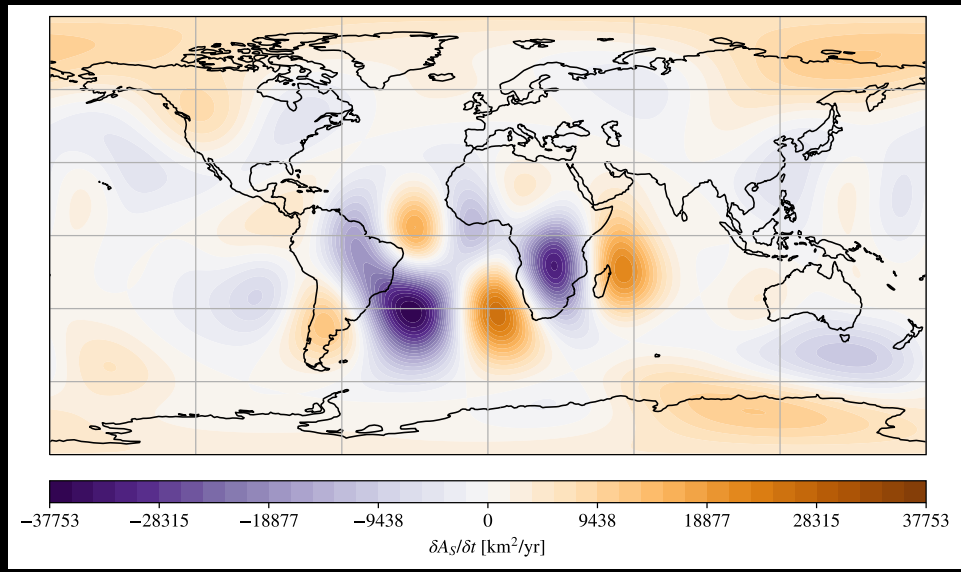
Auroral zones area changes: CMB contributions.

$$\frac{\partial A_i}{\partial t} = \frac{\delta A_i}{\delta B_r}\frac{\partial B_r}{\partial t}$$

Northern auroral zone



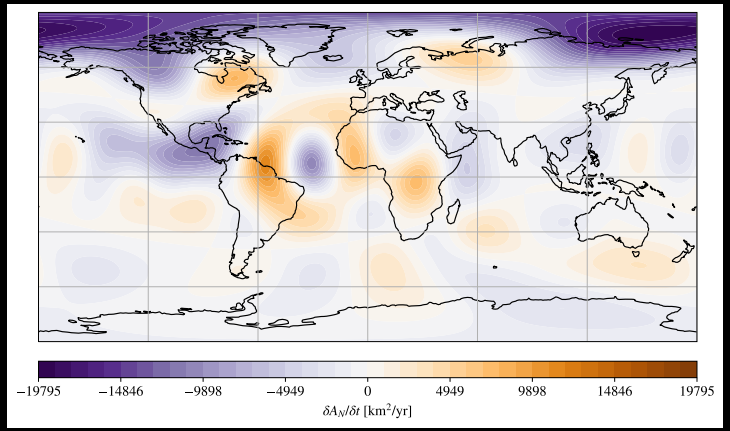
Southern auroral zone



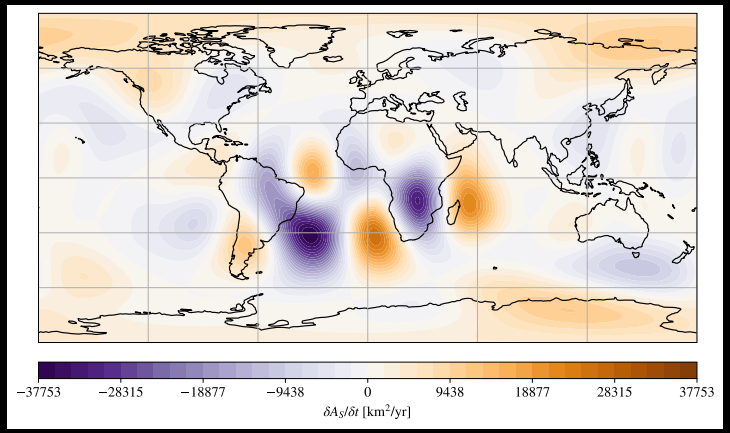
- It is commonly accepted that the high latitude geomagnetic field controls the auroral zones.
- However, we find a great part of variability is controlled by the EQUATORIAL CMB field.

Auroral zones area changes: CMB contributions

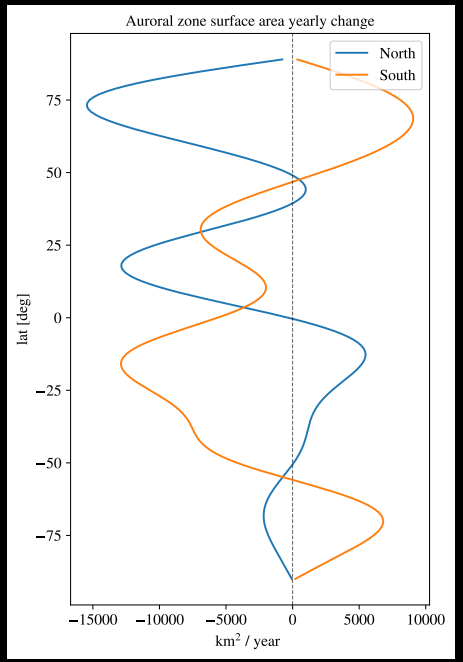
Northern auroral zone



Southern auroral zone



$$\frac{\partial A_i}{\partial t}(\theta) = \int_0^{2\pi} \frac{\delta A_i}{\delta B_r} \frac{\partial B_r}{\partial t} \sin\theta d\phi$$

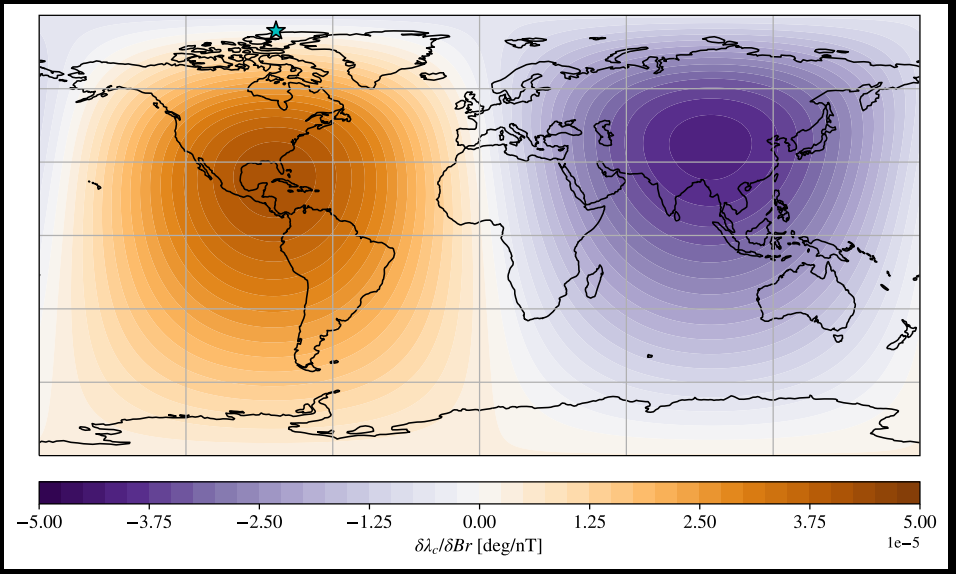


The azimuthally integrated contribution reveal strong equatorial control of auroral zones surface areas

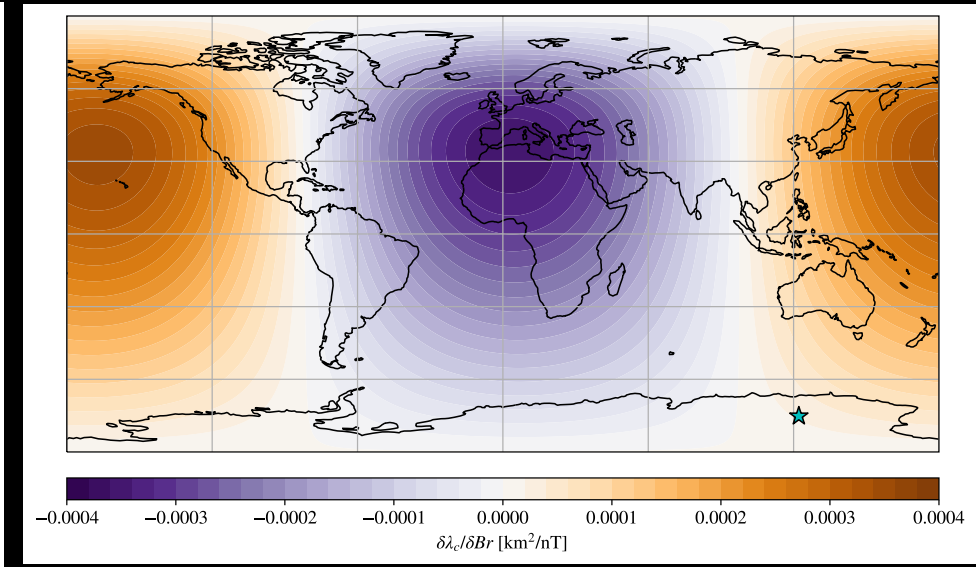
Auroral zones centroid: sensitivity to CMB field changes

Repeat the same analysis for the northern/southern auroral zones centroids (blue stars).

Northern auroral zone



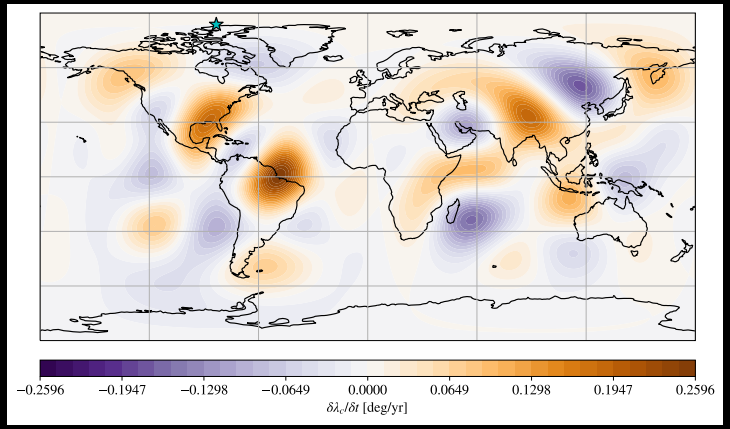
Southern auroral zone



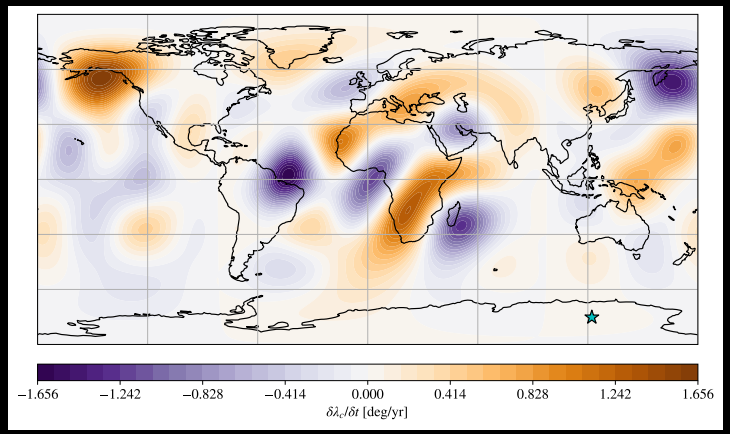
- **The auroral zone centroid is sensitive middle/low latitudes field changes.**
- **Geometry of Green's function suggests high sensitivity to dipole tilt.**

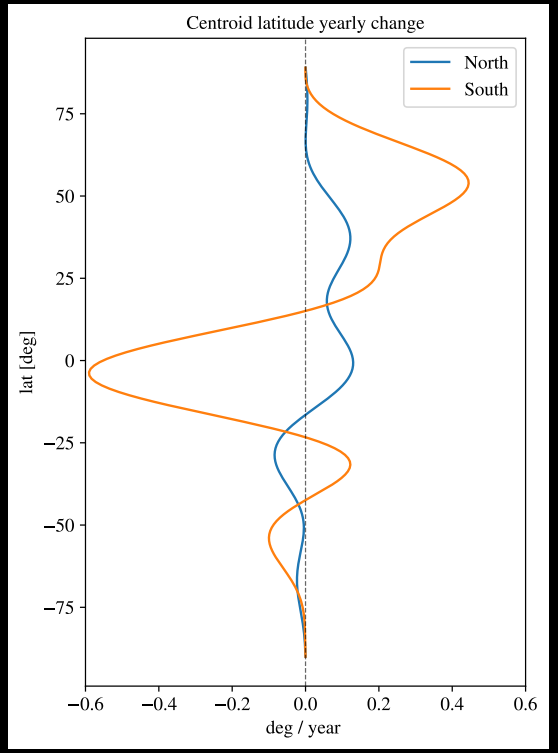
Auroral zones centroid latitude changes: CMB contributions

Northern auroral zone



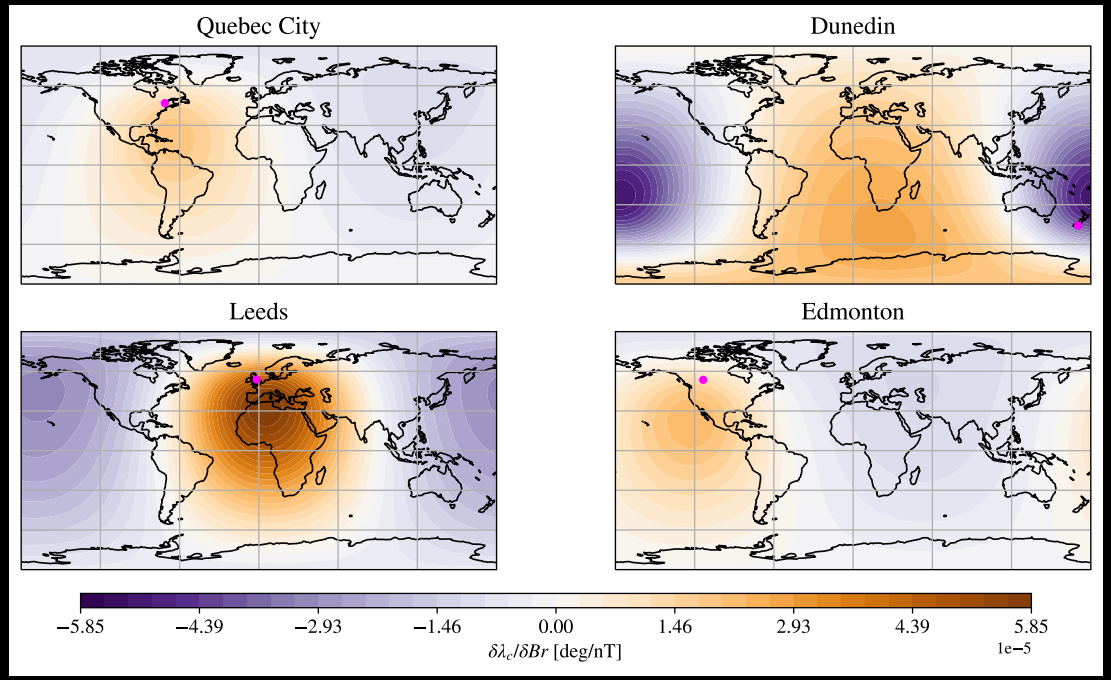
Southern auroral zone





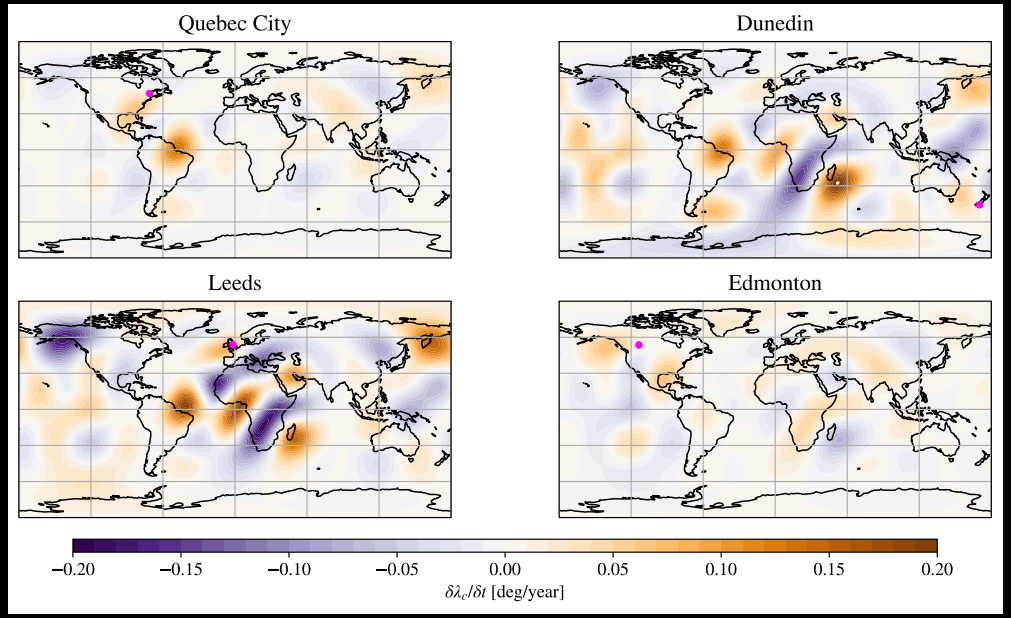
Strong equatorial control of the centroid latitude, particularly for the southern zone

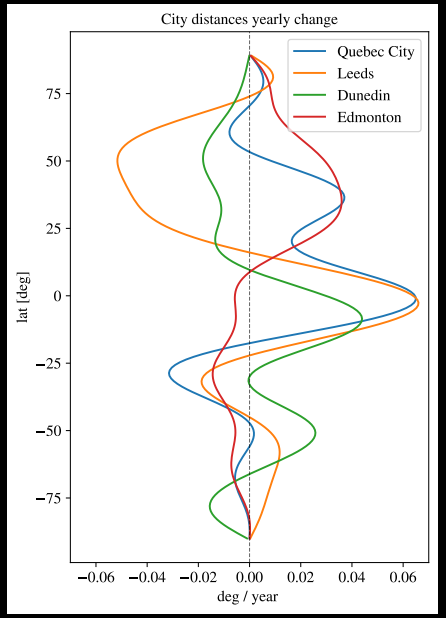
Auroral zones distance from selected locations: sensitivity to CMB field changes



- Local nature: highest sensitivity is equatorward with respect to the selected location
- Strong dipolar contributions hints at high sensitivity to dipole tilt

Auroral zones distance from selected locations: temporal changes CMB contributions





- **Strong equatorial/mid latitude control**
- **Small contributions from polar regions**

Conclusions

Summary and conclusions

Part 1 (forecasts):

- Northern and Southern auroral zones have different behavior
- Increased exposure to severe space weather events North America (i.e. Edmonton)
- No significant changes in Australia, New Zealand and Europe

Part 2 (Green's functions):

- High order Gauss coefficients $(l<5)$ contribute significantly to the auroral zone surface area and location
- Equatorial magnetic field structures contribute significantly to the extent and location of the auroral zones, contrary to the accepted view that only high-latitude changes do.