Recent secular variation and core motions: Complementary constraints from ground observatories and the Swarm satellite constellation

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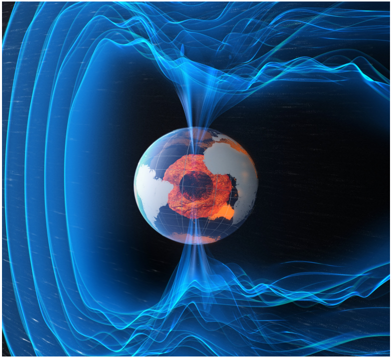
Exploring core motions using geomagnetic secular variation

- $> 98\%$ Earth's $\mathbf{B}$ field originates in the core
- Provides protection from the solar wind
- Generated by **dynamo action** in the core
- Not steady; continuously changing
  -> Secular Variation (SV)



[Image credit: ESA]

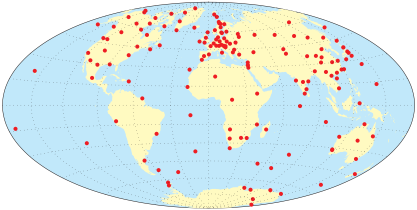
Outstanding scientific questions

- Structure of flows responsible for generating, and driving the evolution, of the field?
- Origin of core field changes on timescales of decades and less?

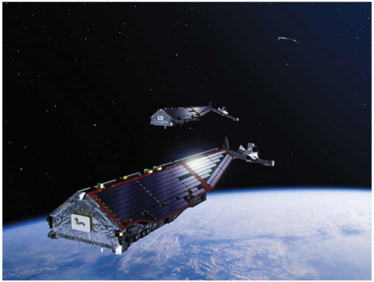
This talk: recent findings using latest ground observatory and *Swarm* data

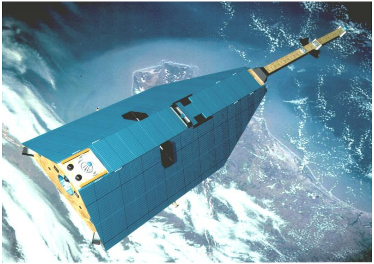
Geomagnetic field observations

- **Ground observatories:**



- **Low Earth Orbit Satellites (*Swarm*, CHAMP Ørsted, SAC-C)**





Talk Outline

1. Field modelling with observatory and satellite data

2. Recent secular variation 1999-2016.5

3. Downward continuation to the core-mantle boundary

4. Inferred core motions and the geodynamo process

5. Summary

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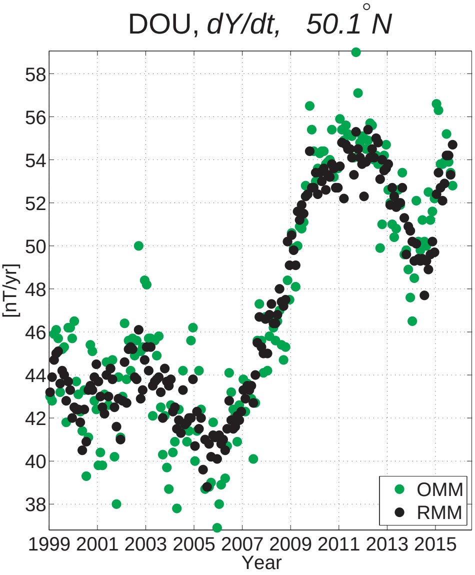
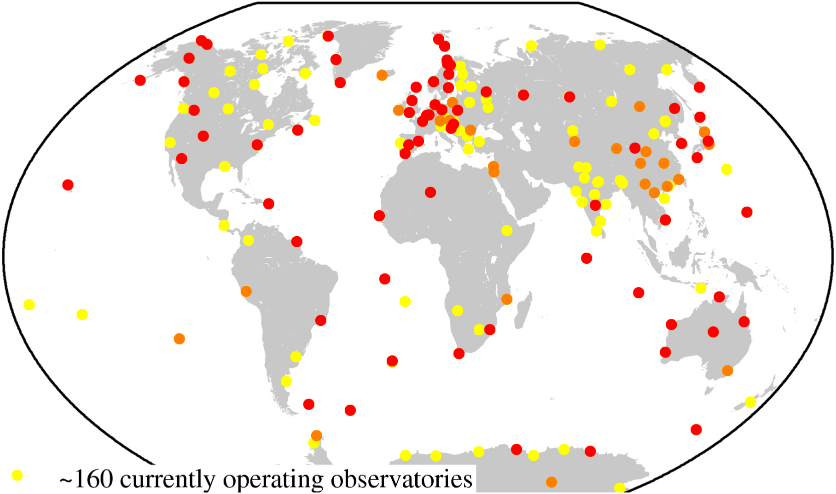
Observatory data: Revised Monthly Means (RMM)



- AUX_OBS_2 data product, derived from WDC hourly means ($\sim$ 160 active observ.)
- Manually checked and corrected for known baseline changes (Macmillan and Olsen 2013)
- Estimates of large-scale magnetospheric (Olsen et al., 2014) and Sq (Sabaka et al., 2004) fields removed
- Compute Huber-weighted monthly mean, considering all local times

Availability of close to definitive (or QD) data



- ~160 currently operating observatories
- 93 with acceptable definitive or close-to-definitive data in 2015
- 70 with acceptable definitive or close-to-definitive data in 2016

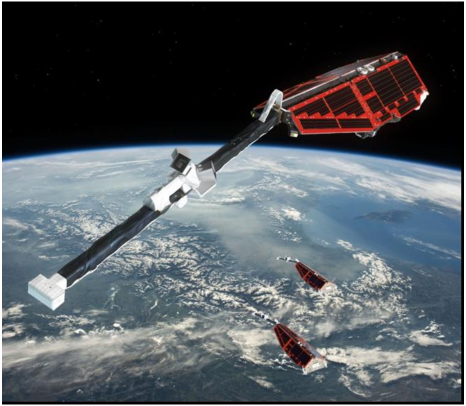
[Courtesy S.Macmillan, BGS]

Selection of satellite data: vector and scalar

- Night side: data from dark regions, sun 10 deg below horizon
- Vector data below 55 deg geomagnetic latitude
- Quiet-time, based on observatory-data derived indices:
  - $Kp \leq$ 2o
  - $|dRC/dt| \leq$ 2nT/hr
- Quiet-time, based on IMF and solar wind parameters (for scalar data in polar regions)
  - IMF $B_z > 0$, averaged over preceding 1 hr
  - $E_m = \leq 0.8$mV/m, averaged over preceding 1hr

The *Swarm* satellite constellation and field gradients

- A pair of satellites (*Alpha*, *Charlie*), flying close together at altitude approx. 460 km
- A third satellite (*Bravo*) higher ~ 500 km, and separated in LT (now by 3hrs)



- Use field differences (approx. gradients) btw satellites and along-track
- Relax selection criteria *Kp* $\leq$ 3o, $|dRC/dt| \leq$ 3nT/hr
- Consider scalar gradient also in sunlit polar region (-> more uniform data coverage)

Parameterization of Internal Field

- **Potential field approach:** $\mathbf{B} = -\nabla V$ where $V = V^{\text{int}} + V^{\text{ext}}$.

- The internal part of the potential takes the form

$$V^{\text{int}} = a \sum_{n=1}^{N_{\text{int}}} \sum_{m=0}^{n} \left(g_n^m \cos m\phi + h_n^m \sin m\phi\right) \left(\frac{a}{r}\right)^{n+1} P_n^m\left(\cos\theta\right)$$

- For $n \leq 20$, expand in 6th order B-splines

$$g_n^m(t) = \sum_{k=1}^{K} {}^k g_n^m B_k(t). \tag{1}$$

Parameterization of External Field

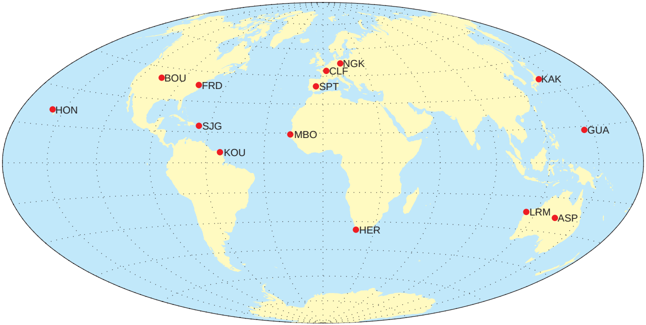
- For the external potential, expand in SM and GSM co-ordinate systems, with θ_d and T_d being dipole co-lat. and dipole local time

$$\begin{aligned} V^{\mathrm{ext}} &= a \sum_{n=1}^{2} \sum_{m=0}^{n} \left(q_n^m \cos mT_d + s_n^m \sin mT_d \right) \left(\frac{r}{a} \right)^n P_n^m(\cos\theta_d) \\ &+ a \sum_{n=1}^{2} q_n^{0,\mathrm{GSM}} R_n^0(r,\theta,\phi). \end{aligned}$$

- Degree-1 coefficients in *SM* coords dependent on the RC disturbance index

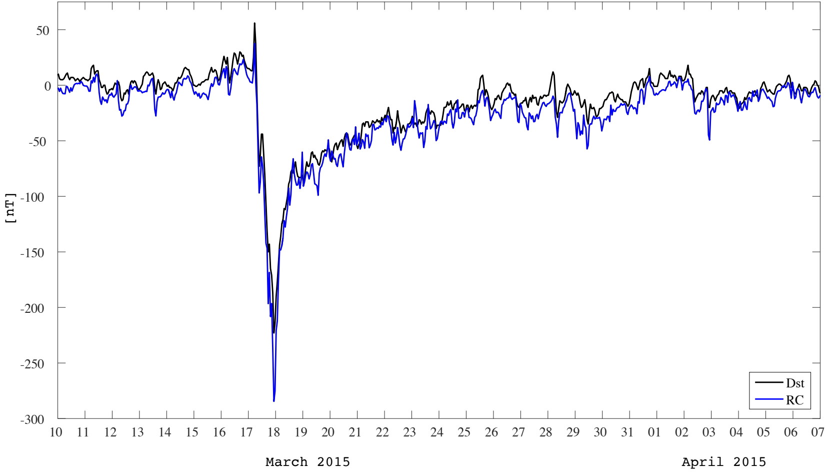
The RC Index

- **Similar to *Dst* but stable on months to year time-scale**
- Based on hourly means from 14 mid/low latitude obs reporting up-to-date QD data



- Baseline: core field from latest CHAOS field model
- Only night-side data, no explicit Sq correction
- Hour-by-hour spherical harmonic analysis of horizontal components
- Separated into internal and external components using a 1D mantle conductivity model
- An 'experimental' index, mostly for field modelling purposes. Under development....

Example: RC Index during the St. Patrick's day storm



- Small offset compared to Dst (due to different definition of baseline)
- Amplitude slightly different, especially during storms, due to different selection of contributing observatories

Global field modelling: Estimation

- Work with satellite vector data in **magnetometer frame**, co-estimate Euler angles
- 7,873,156 data in all (3 x 24583 from Observatory Revised Monthly Means)

- **Robust non-linear least squares including regularization**, iteratively minimizing

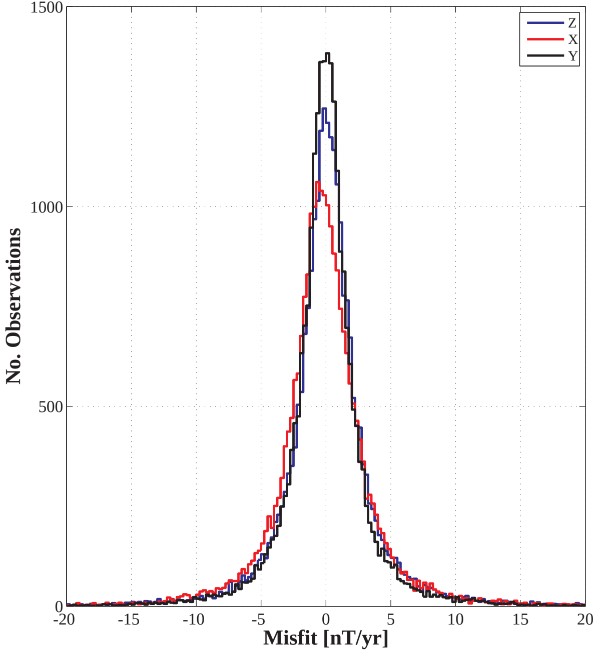
$$[\mathbf{d} - F(\mathbf{m})]^T \underline{\underline{\mathbf{W}}}^{-1} [\mathbf{d} - F(\mathbf{m})] + \lambda_2 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_2 \mathbf{m} + \lambda_3 \mathbf{m}^T \underline{\underline{\mathbf{\Lambda}}}_3 \mathbf{m}$$

  $\underline{\underline{\mathbf{W}}}$ is a Huber weighting matrix, $\underline{\underline{\mathbf{\Lambda}}}_2$ and $\underline{\underline{\mathbf{\Lambda}}}_3$ are regularization matrices

- **Latest model, CHAOS-6 (Finlay et al., 2016), now updated to Aug 2016**
  `http://www.spacecenter.dk/files/magnetic-models/CHAOS-6/`
- Weighted rms misfit to non-polar, dark *Swarm* scalar data is **2.14 nT**,
  For scalar field differences, **0.26 nT** along-track and **0.45 nT** cross-track,

  For obs RMM, **3.66 nT/yr, 3.08 nT/yr, 3.80nT/yr** for dX/dt, dY/dt, dZ/dt

Histograms of residuals to observatory RMM



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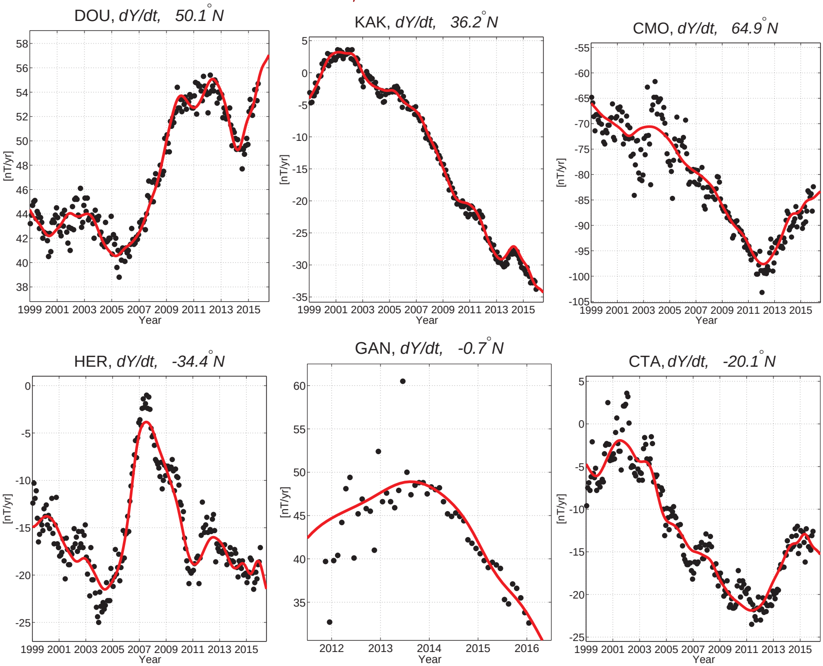
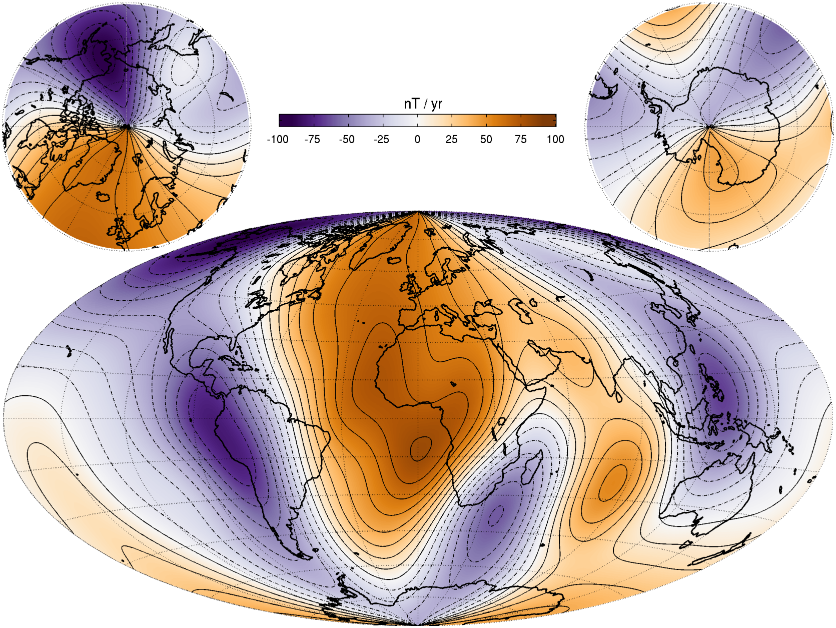
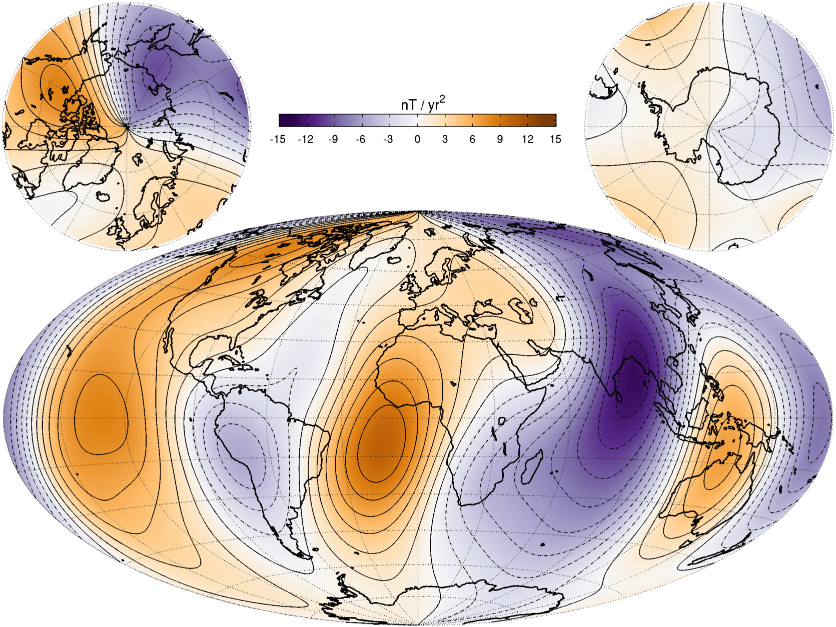
Fit to observatory data, dY/dt



Rate of change of Eastward field dY/dt in 2016.5



Acceleration of Eastward field d^2Y/dt^2 in 2015



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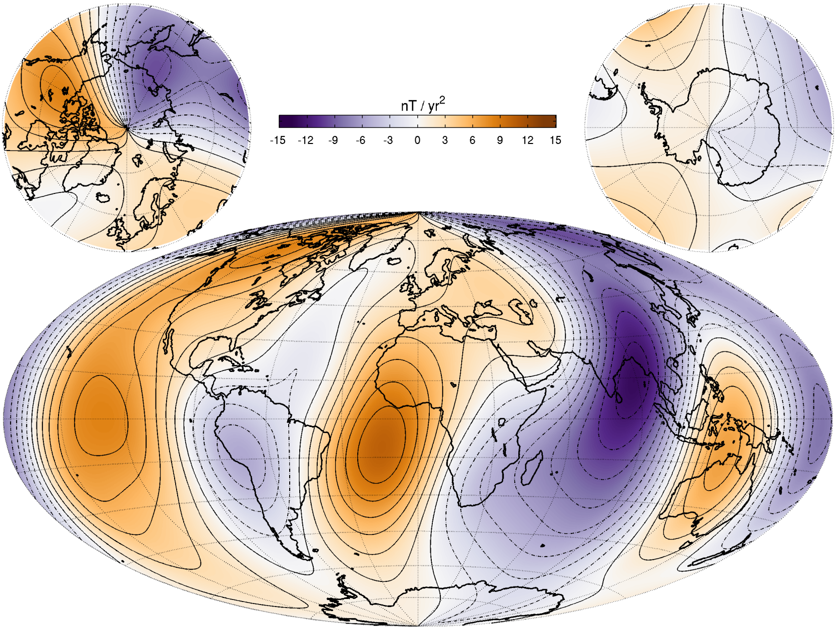
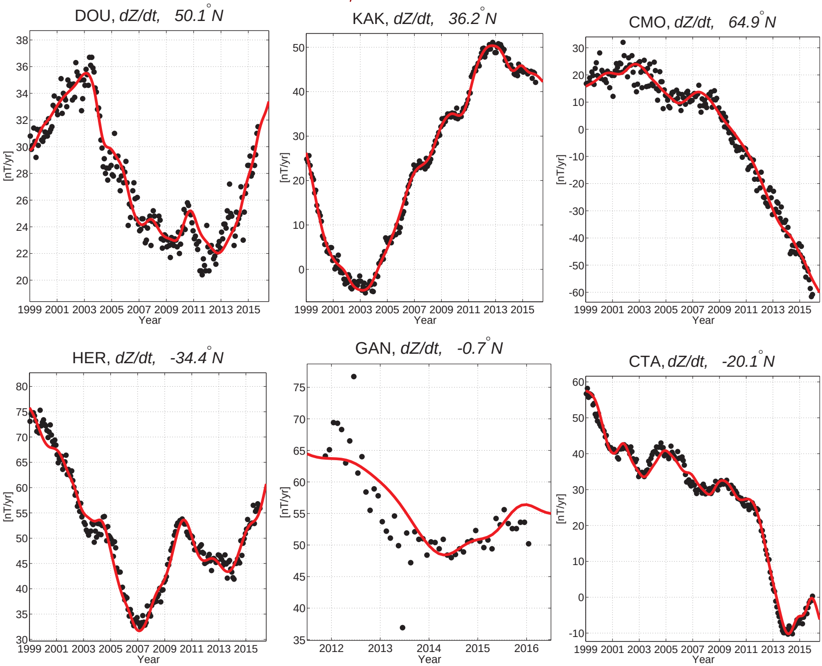
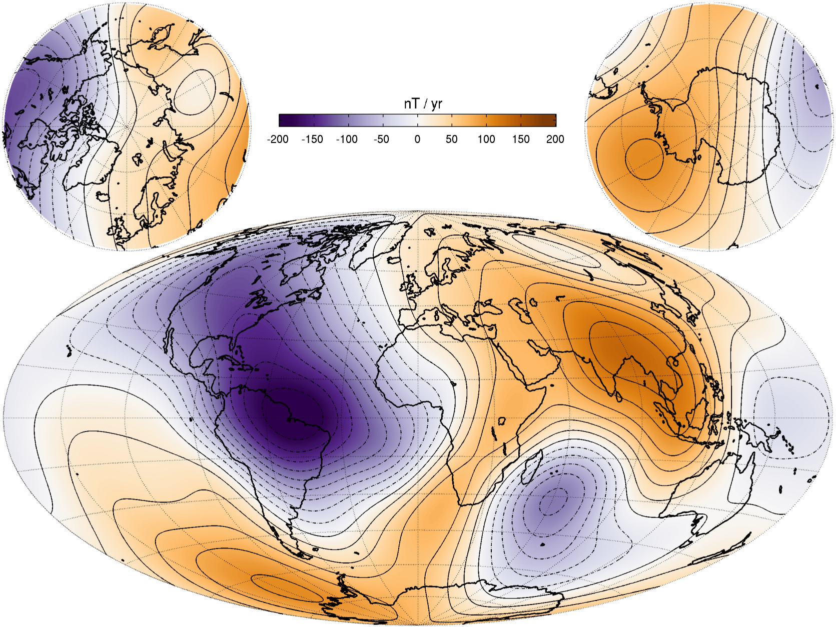


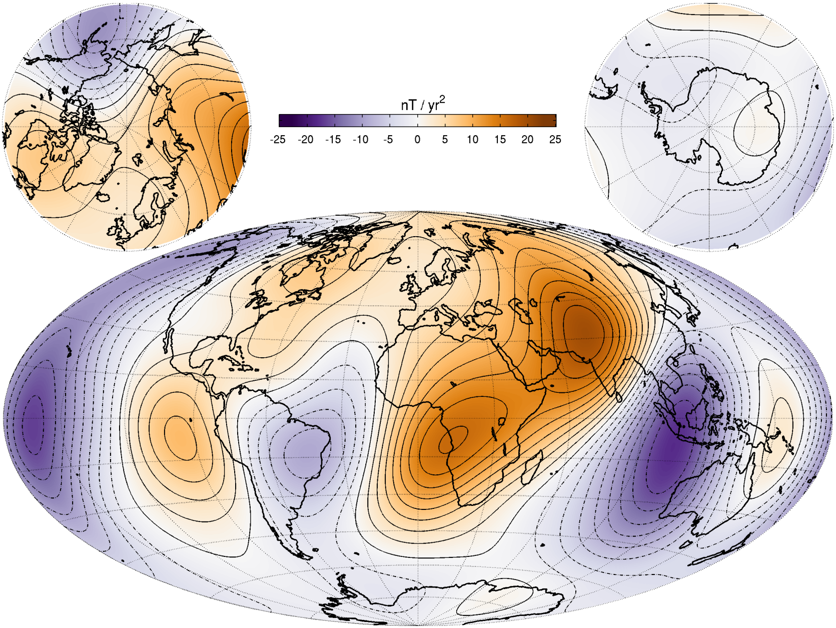
Fit to observatory data, dZ/dt



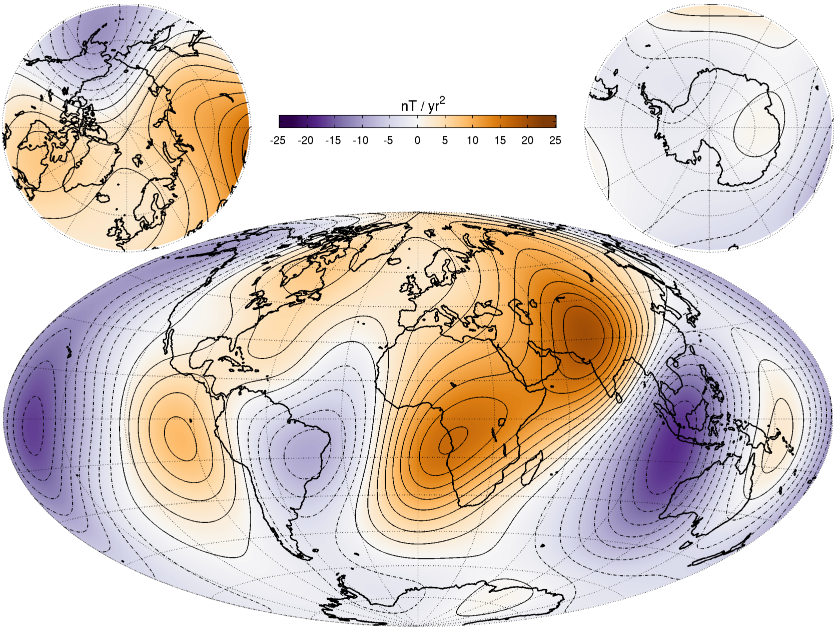
Rate of change of vertical field dZ/dt in 2016.5



Acceleration of Eastward field d^2Z/dt^2 in 2015



Acceleration of Eastward field d^2Z/dt^2



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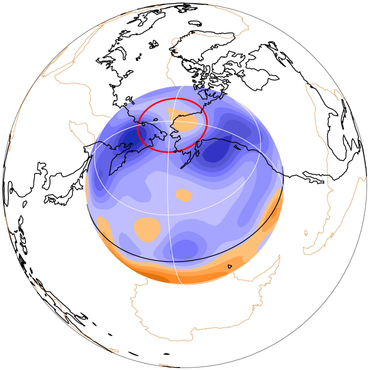
Downward continuation to the core-mantle boundary

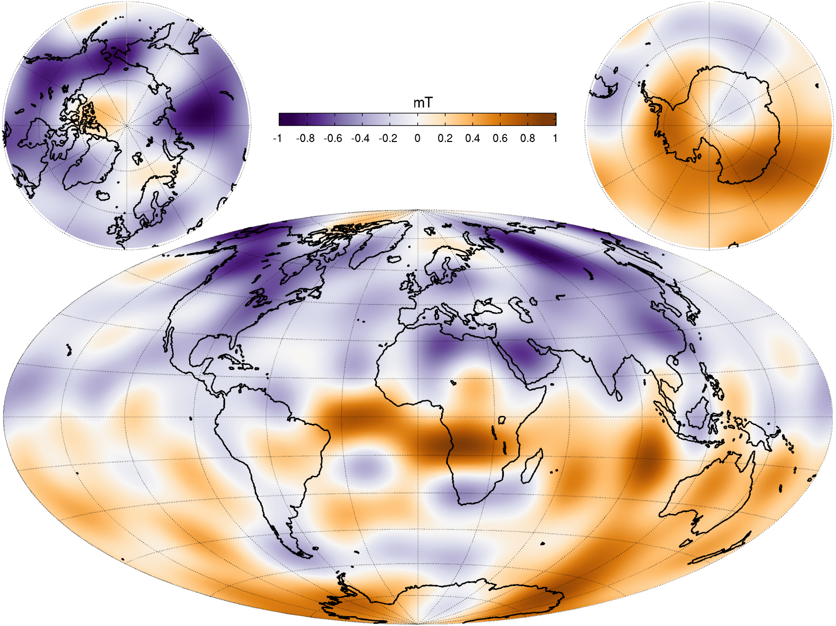
- Wish to understand origin of changes
  -> need to descend to core
- Possible to downward continue through mantle
  (Neglecting currents there on timescales > 1 yr)
- Small scales amplified as approach source
- Field at core surface stable to degree 13
  (above this crust dominate)
- Field change (SV) stable to degree 18



[Image credit: A. Jackson]

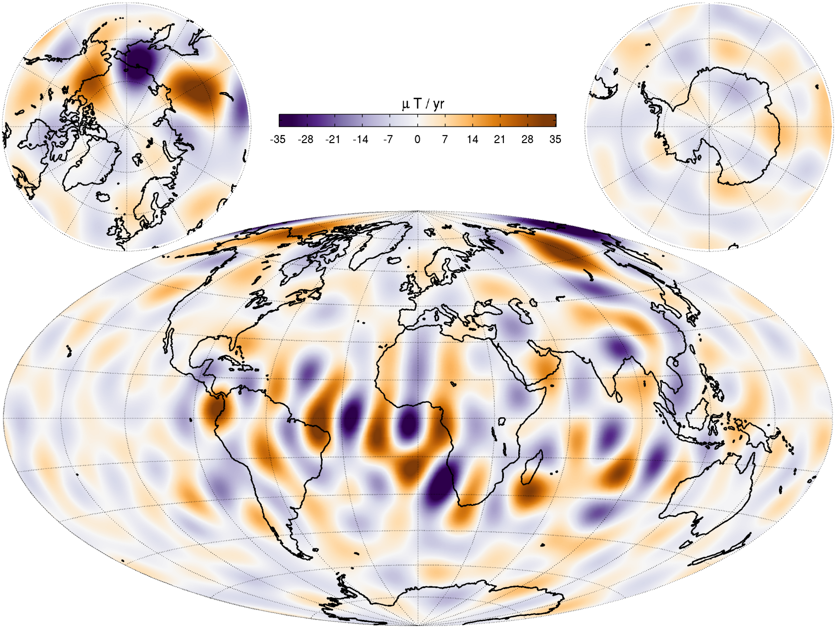
$$B_r = \sum_{n=1}^{N} \sum_{m=0}^{n} (n+1) \left(g_n^m \cos m\phi + h_n^m \sin m\phi\right) \left(\frac{a}{r}\right)^{n+2} P_n^m (\cos\theta)$$

Radial field B_r at core surface in 2015



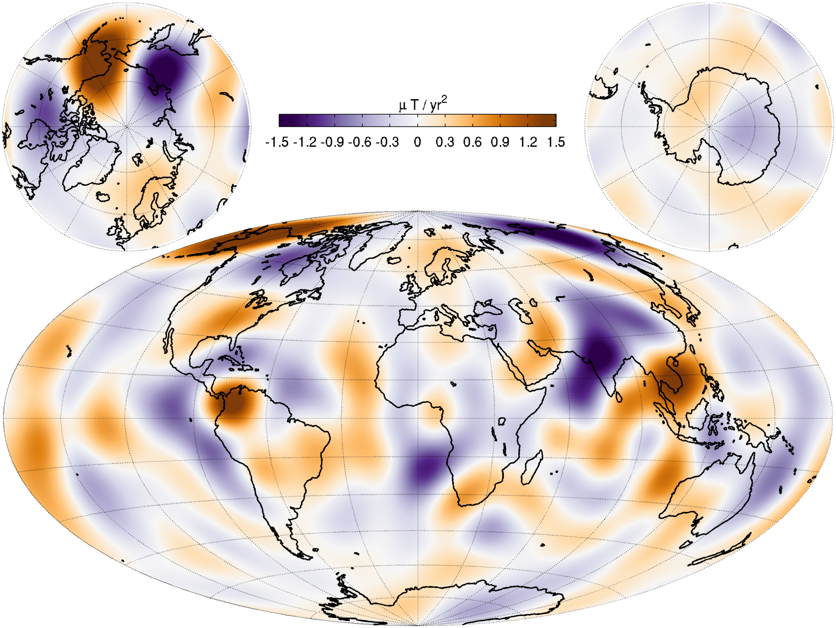
[CHAOS-6, truncated degree 13]

Radial field SV dB_r/dt at core surface in 2015

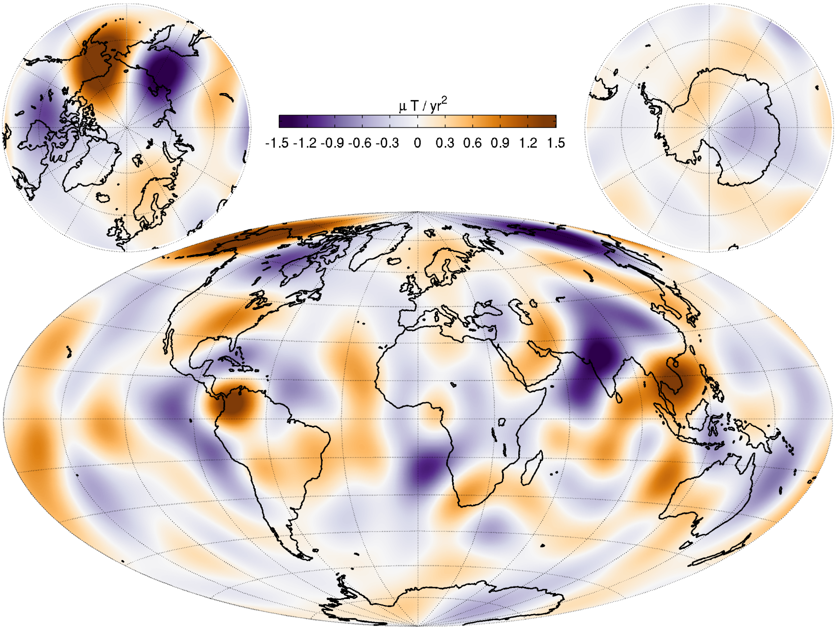


[CHAOS-6, truncated degree 18]

Radial field SA $d^2 B_r / dt^2$ at core surface in 2015



Radial field SA d^2B_r/dt^2 at core surface



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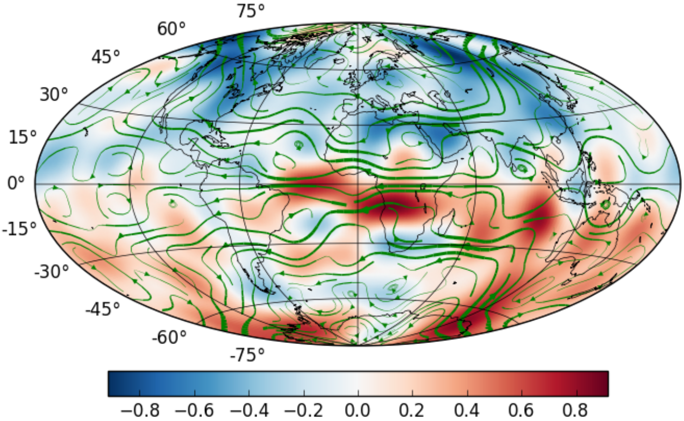
Inferred quasi-geostrophic core flow in 2015

- Assume rotation dominates the core flow (quasi-geostrophy)
- Invert for flow producing observed field changes, using the frozen flux induction eqn:

$$\frac{\partial B_r}{\partial t} = -\nabla_H \cdot (\mathbf{u} B_r)$$

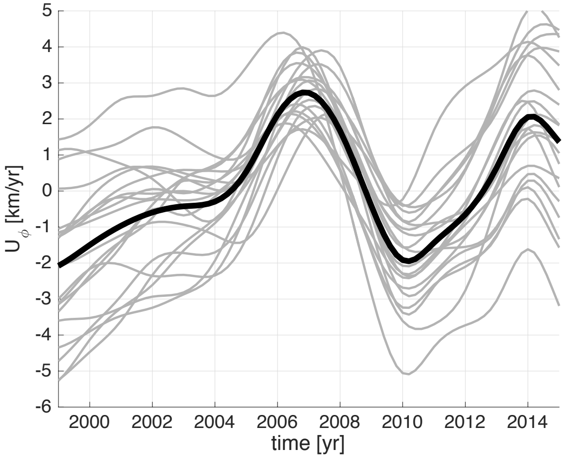
- Ensemble approach: random realizations of unknown small scale field



- Planetary scale anticyclonic gyre, westward at mid/low latitudes under Atlantic

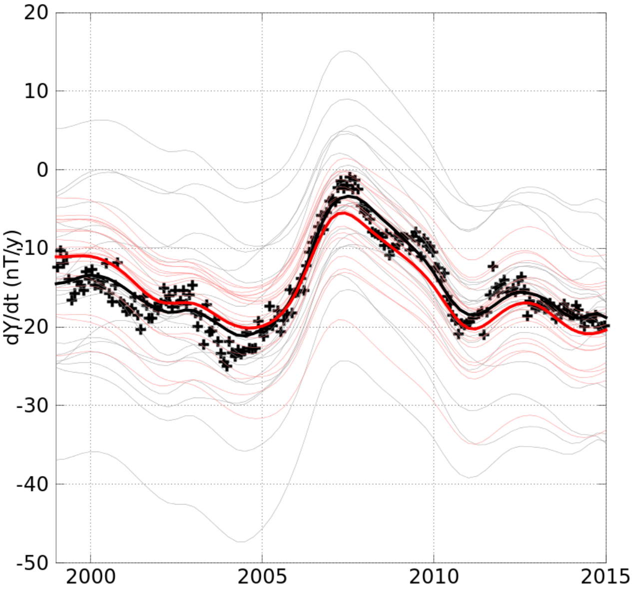
Time-dependent (oscillating) core flow

- Find non-axisymmetric flow **oscillations** at low latitudes e.g. -15°N, 0°E

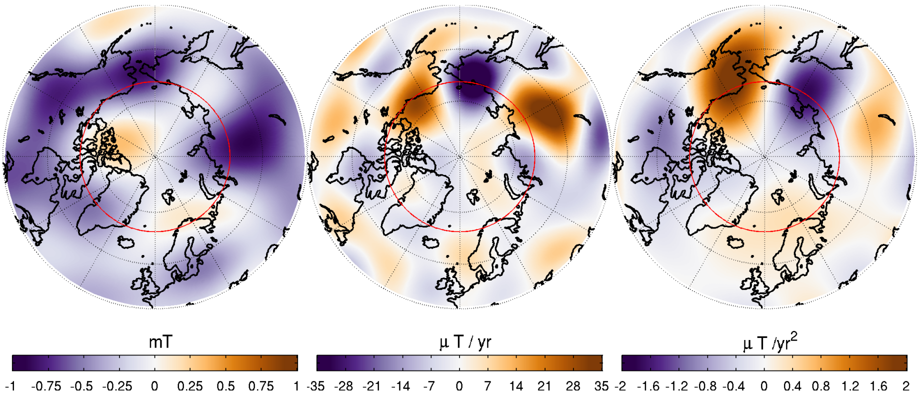


- Times of azimuthal flow acceleration, correspond to times of rapid field change
- Dynamical origin of oscillations presently unknown

Predictions from time-dependent core flow: HER

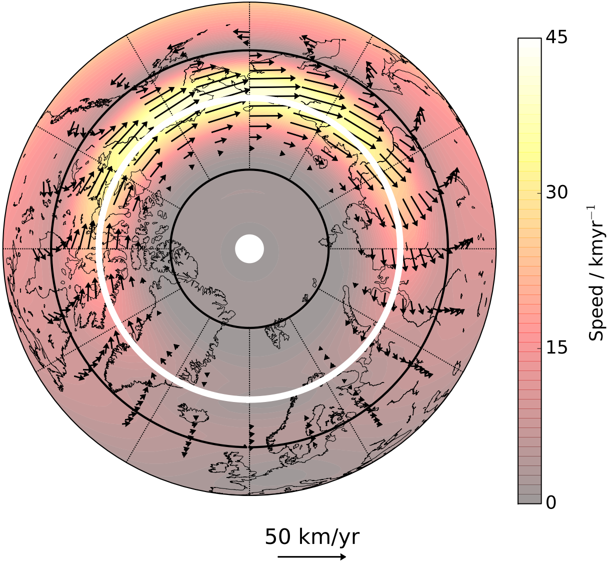


Evolution of B_r close to the tangent cylinder in 2015



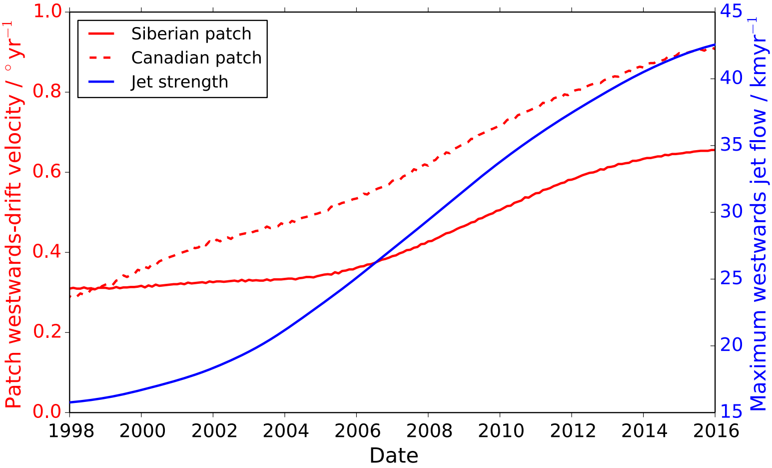
[CHAOS-6 model at CMB]

A localized jet at the tangent cylinder



[Livermore et al. (submitted)]

Accelerating of tangent cylinder jet



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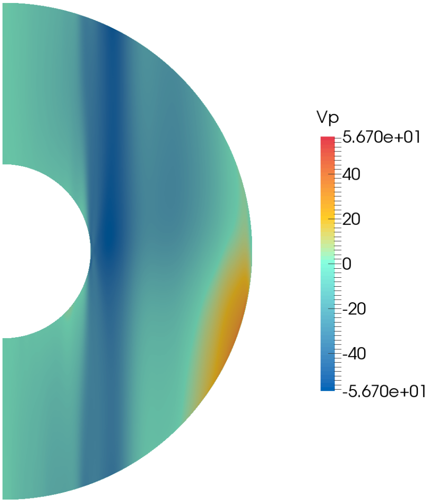
Role of shear at tangent cylinder in geodynamo process



- Shear at tangent cylinder is important for dynamos in rapidly-rotating regime
- Fundamental for building toroidal field within core
- Underlies dynamo oscillations and reversals

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(1) Close-to-definitive (QD) observatory AND *Swarm* data provide the basis for monitoring today's geodynamo

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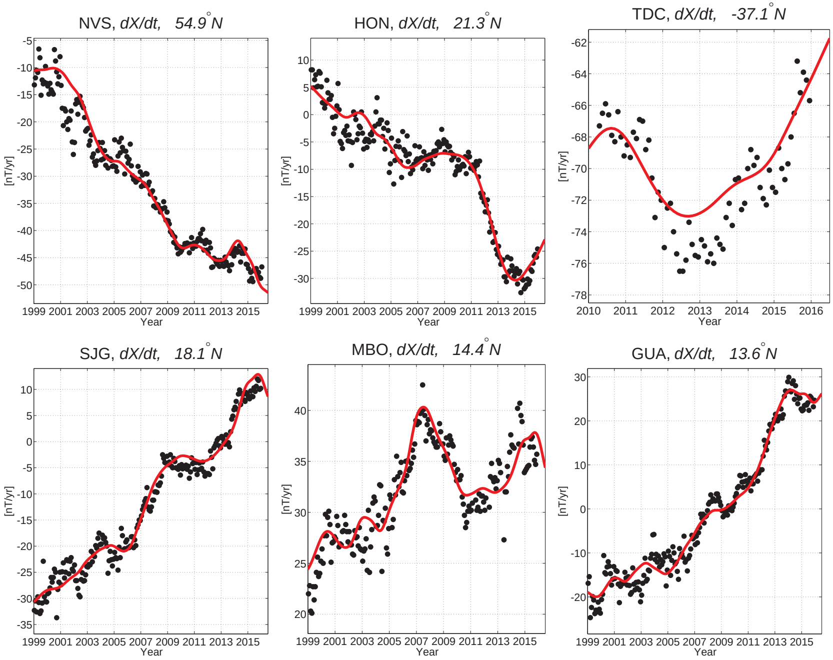
(1) Close-to-definitive (QD) observatory AND *Swarm* data provide the basis for monitoring today's geodynamo

(2) Dynamic and localized secular variation observed on sub-decadal time scales

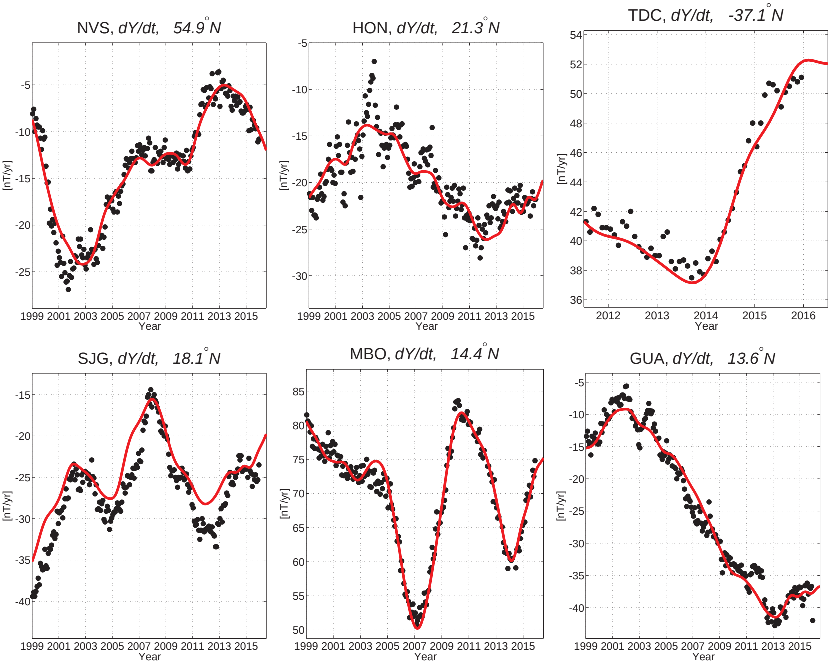
(3) Underlying core flow : Planetary-scale gyres, oscillations and localized jets

(4) Up-to-date and long-term stable observatory data is essential to improve our understand of the geodynamo and for real-time reference model applications

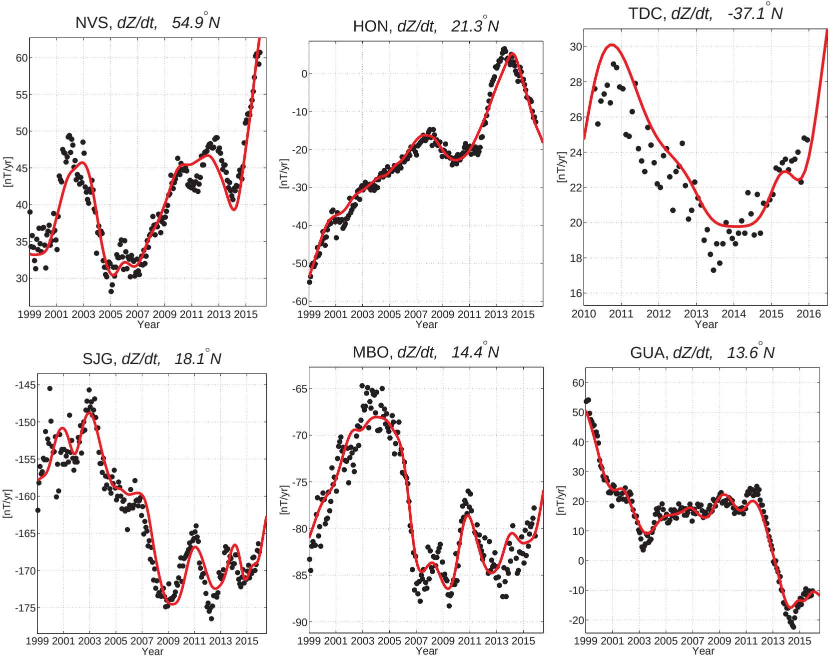
Fit to observatory data, X



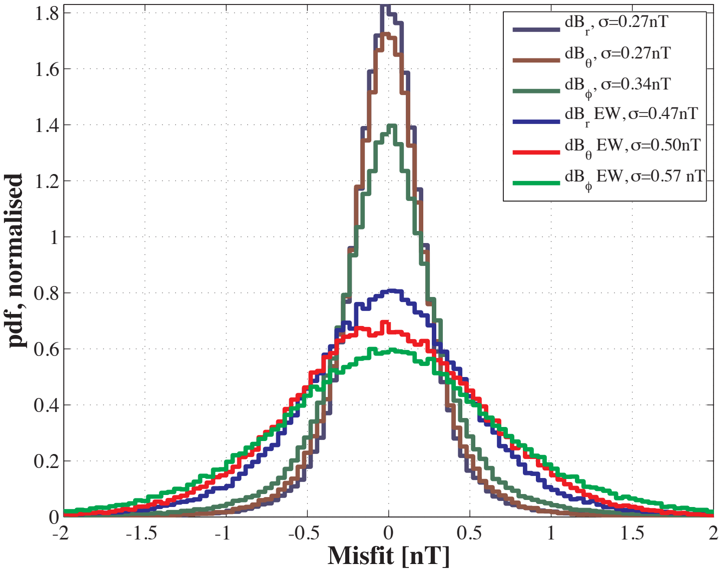
Fit to observatory data, Y



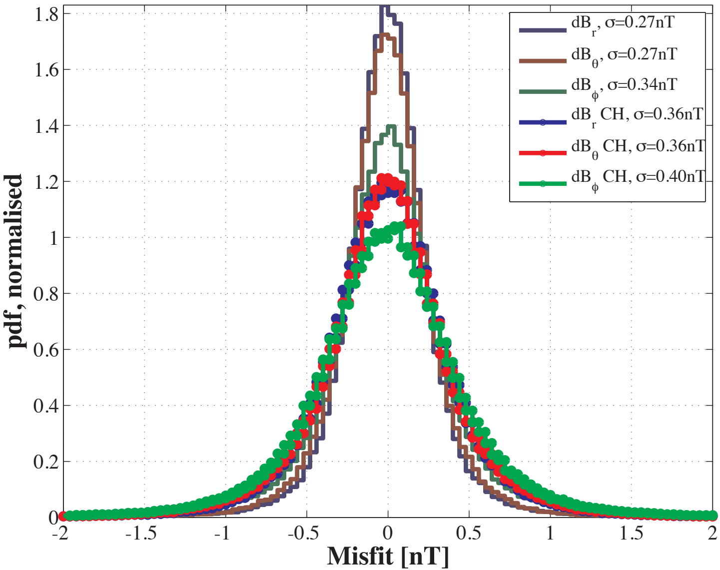
Fit to observatory data, Z



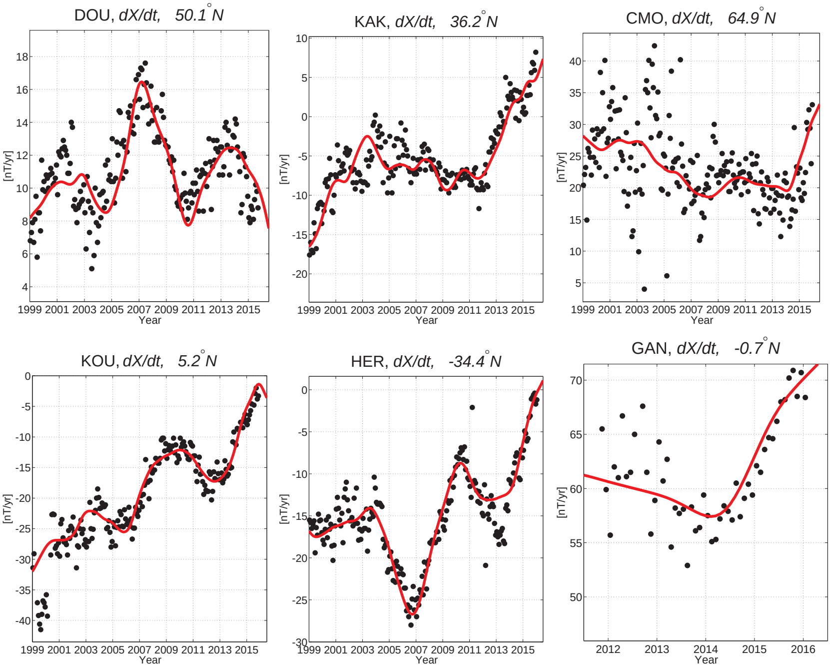
Swarm vector difference residuals, Along vs Cross track



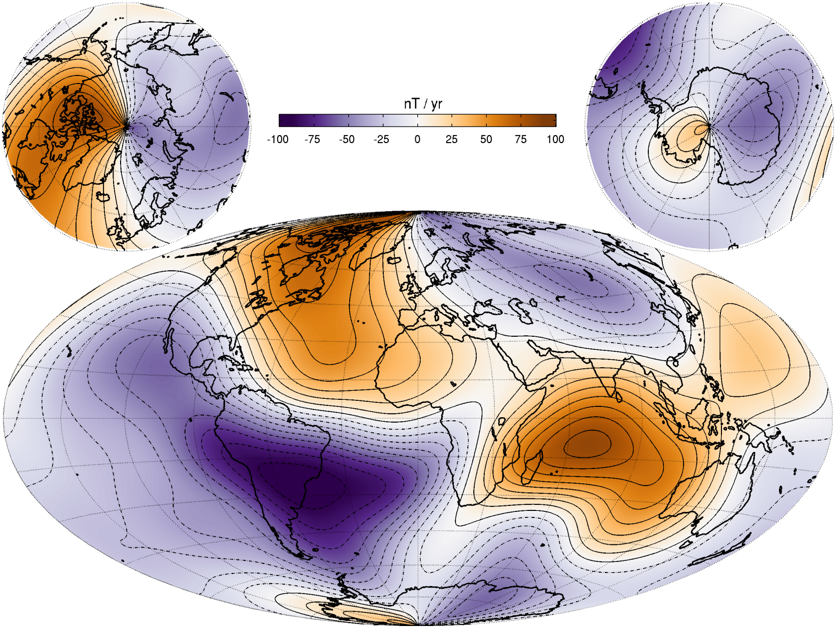
Vector difference residuals, Swarm vs CHAMP



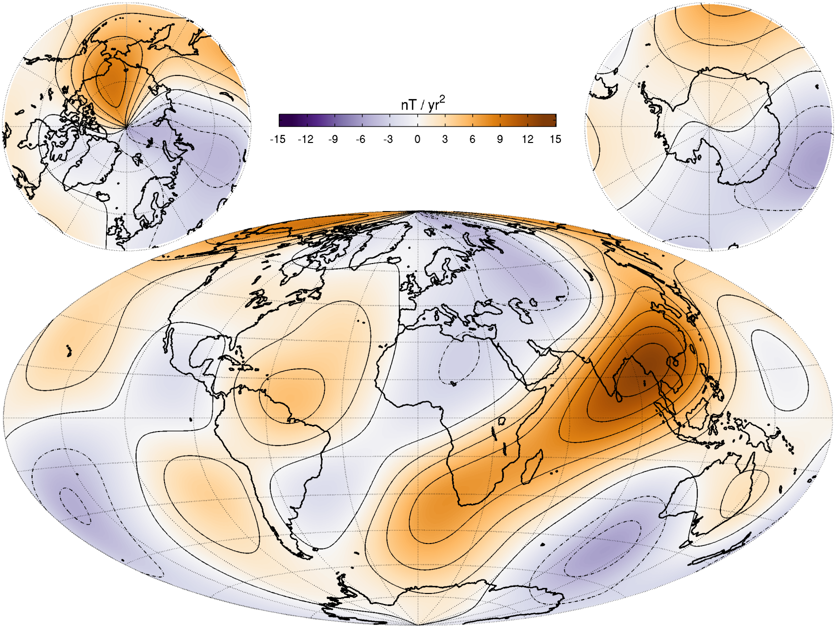
Fit to observatory data, dX/dt



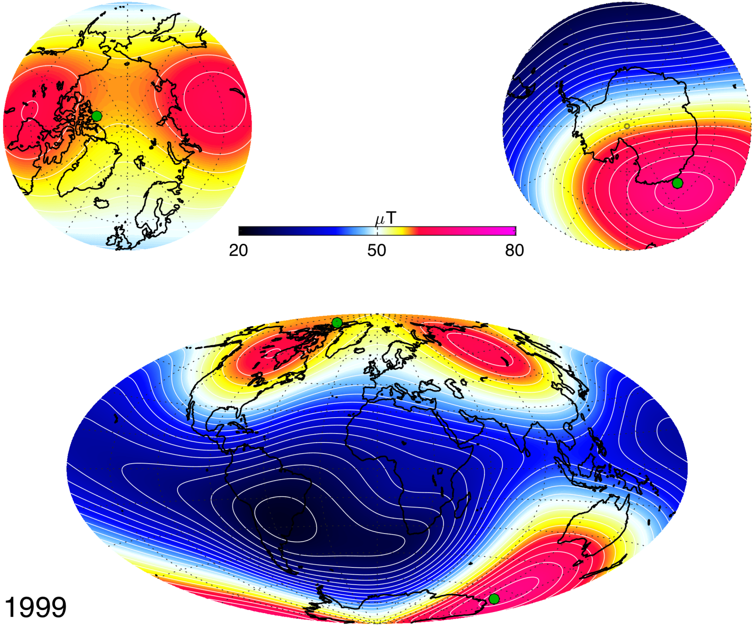
Rate of change of Northward field dX/dt in 2016.5



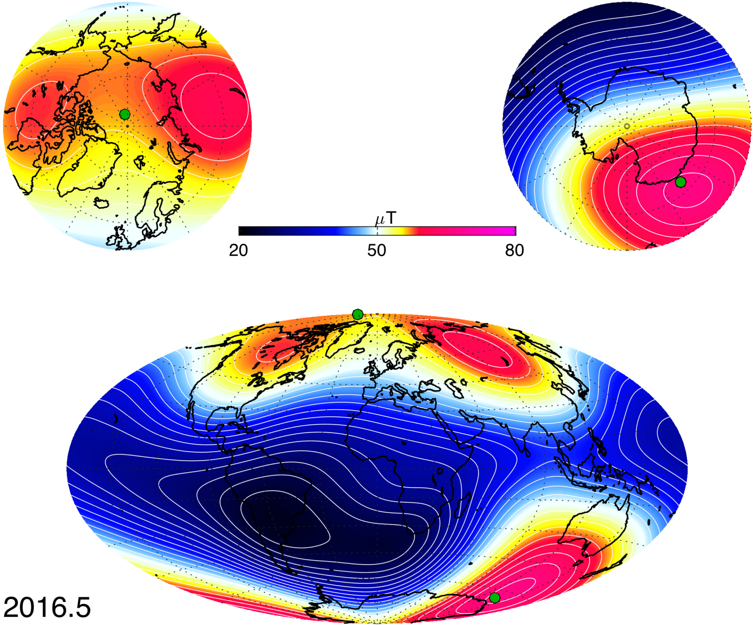
Acceleration of Northward field d^2X/dt^2 in 2015



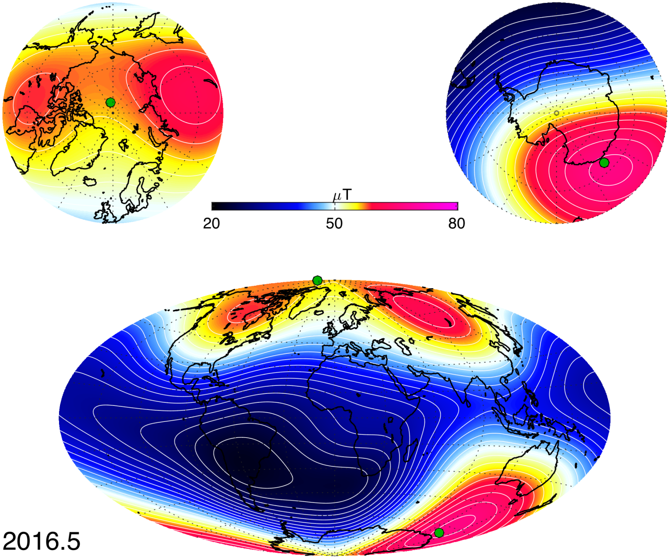
Field strength and magnetic pole position in 1999



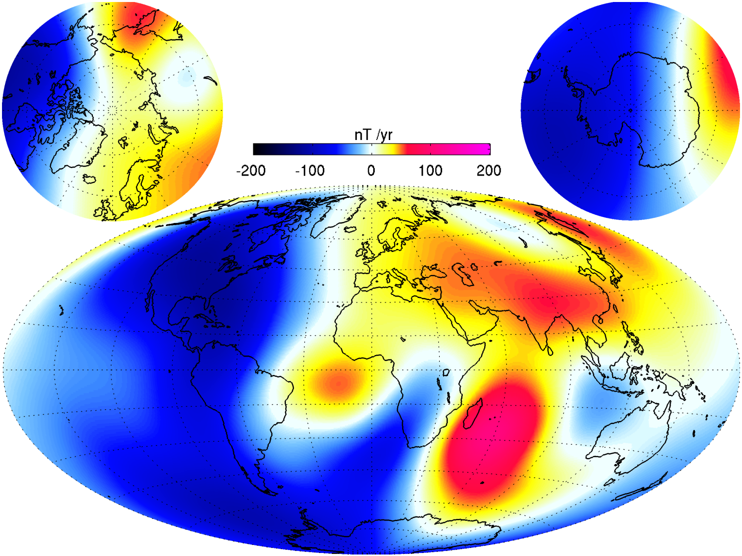
Field strength and magnetic pole position in 2016.5



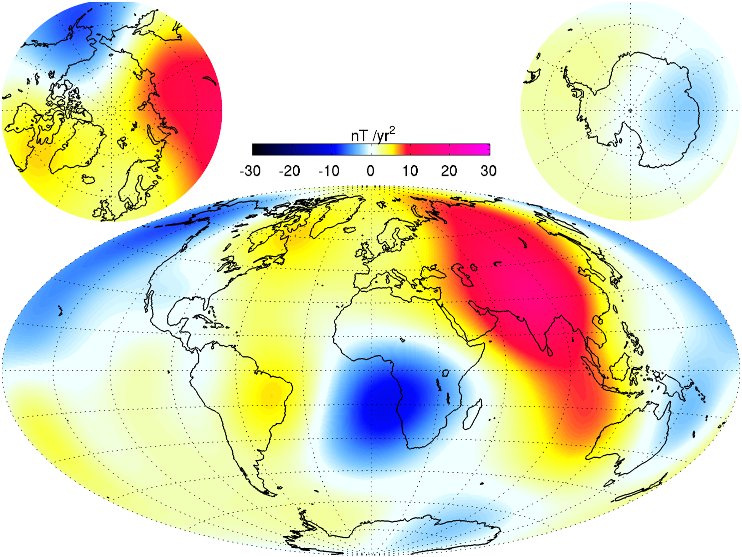
Evolution of field intensity



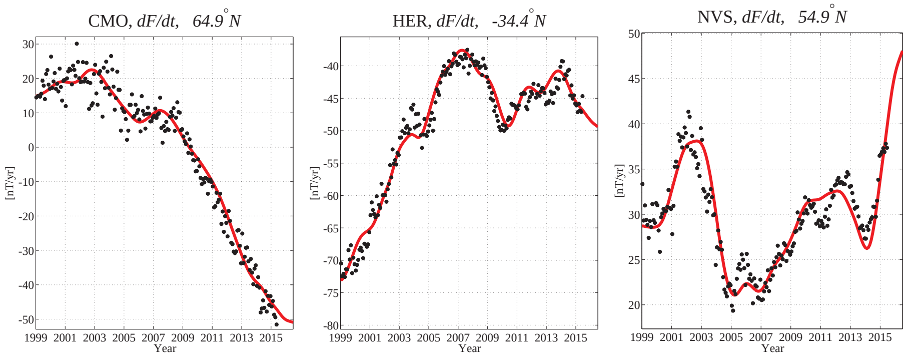
Field strength strengthening and weakening in 2015



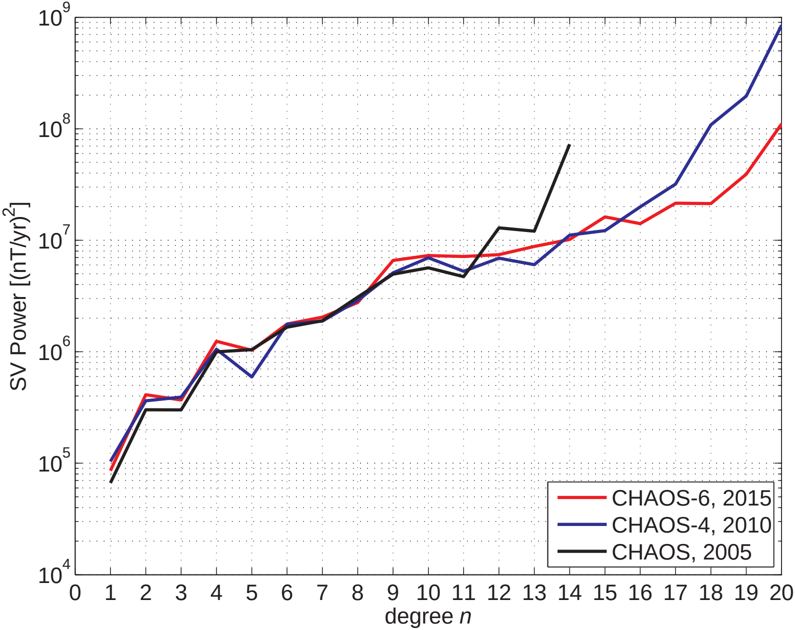
Rate of change of field strengthening/weakening 2015



Ground observatory series of field strength change

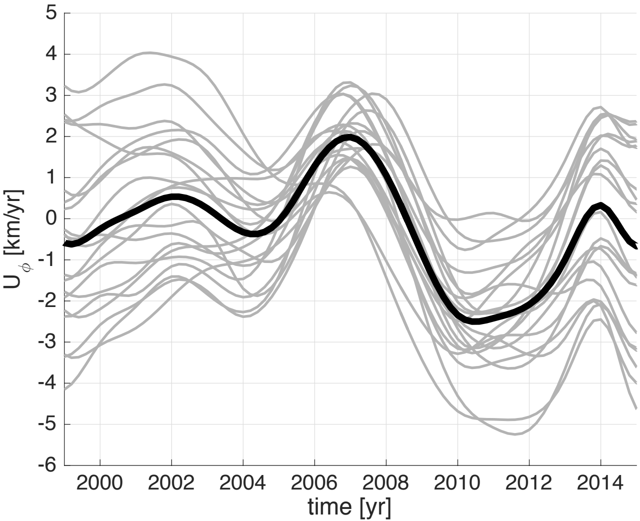


Power spectrum of SV at core surface



Time-dependence of core flow (another example)

- Also find non-axisymmetric flow **oscillations** at low latitudes e.g. 0°N, 40°W



Predictions from time-dependence of core flow: KOU