Reporter Reviews: Division V

Summary of Session A36: **Planetary Magnetic Fields and Geomagnetic Secular Variation**

Chris Finlay (DTU Space)

With thanks to: Susan Macmillan, Vincent Lesur, Kathy Whaler, Nicolas Gillet, Ciaran Beggan, Julien Aubert, Colin More, Phil Livermore, Henri-Claude Nataf, Thomas Gastine, Foteini Vervelidou, Erwan Thebault

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Sunday 28th June 2015

Outline

1. Introduction to secular variation

2. Advances from observational studies of secular variation

2. New developments in the theory of secular variation

3. News from the planets

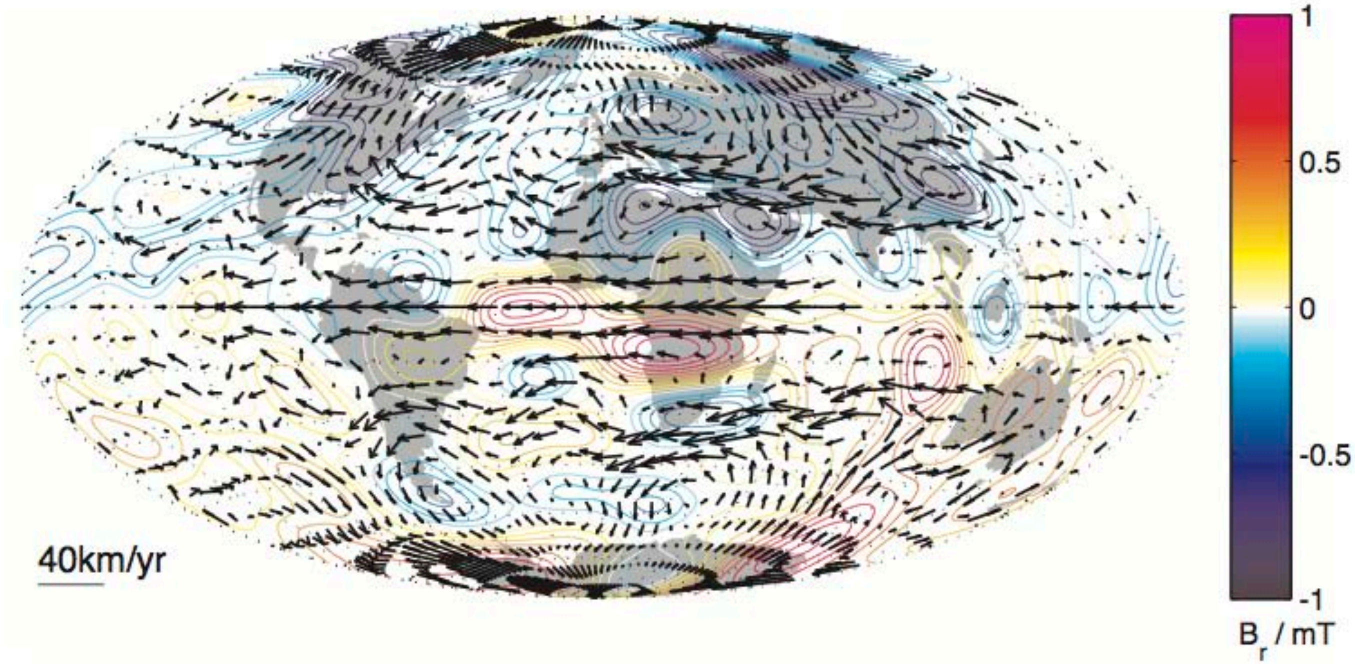
4. Summary

1. Introduction

What is Secular Variation?

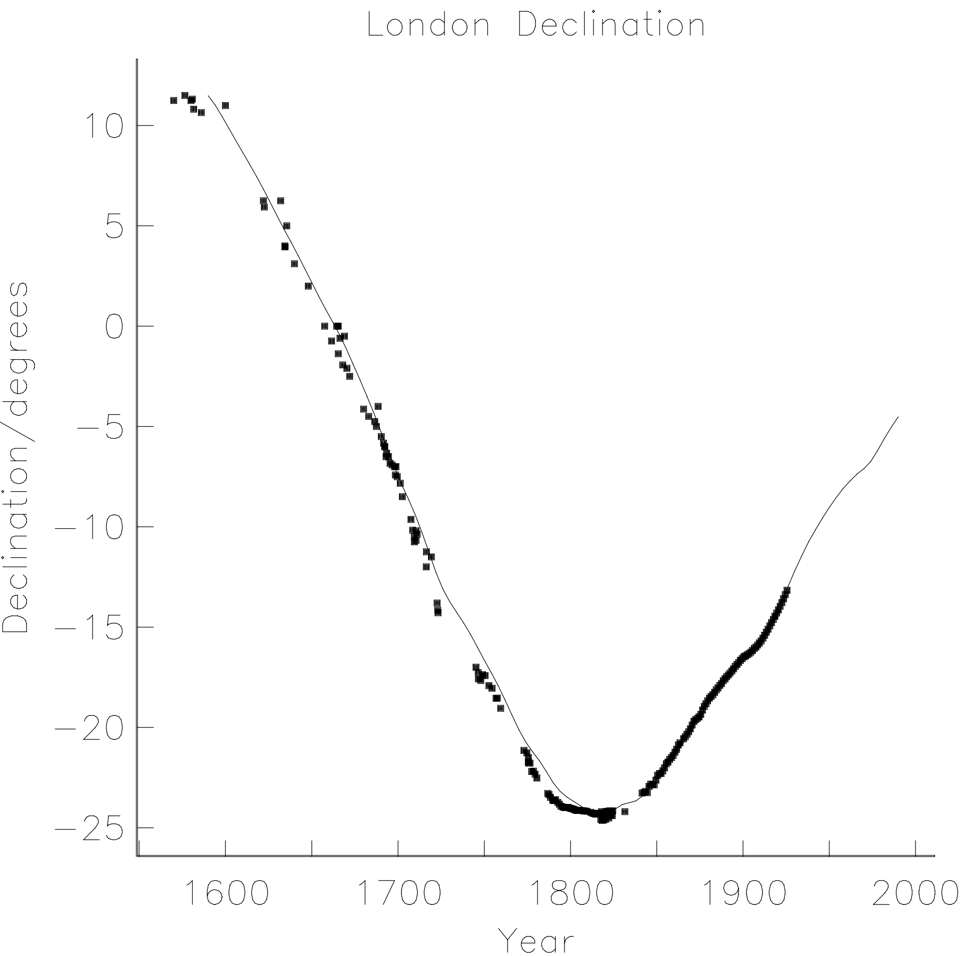
- Here we take SV to be the slow change of the main field produced by core processes:

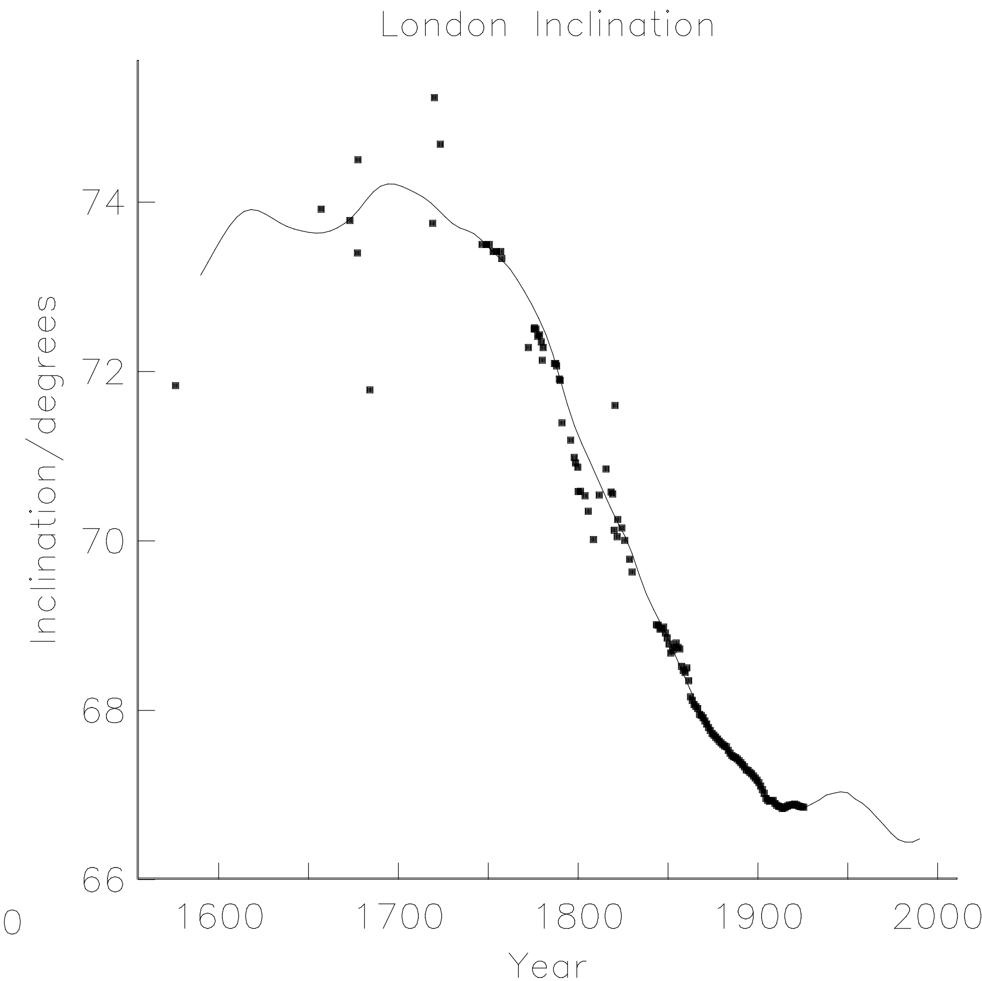
$$\underbrace{\frac{\partial \mathbf{B}}{\partial t}}_{\text{Secular variation}} = \underbrace{\nabla \times (\mathbf{u} \times \mathbf{B})}_{\text{Advection \& stretching by core flow}} + \underbrace{\eta \nabla^2 \mathbf{B}}_{\text{Ohmic diffusion}}$$



[Example core flow from Gillet et al., 2015]

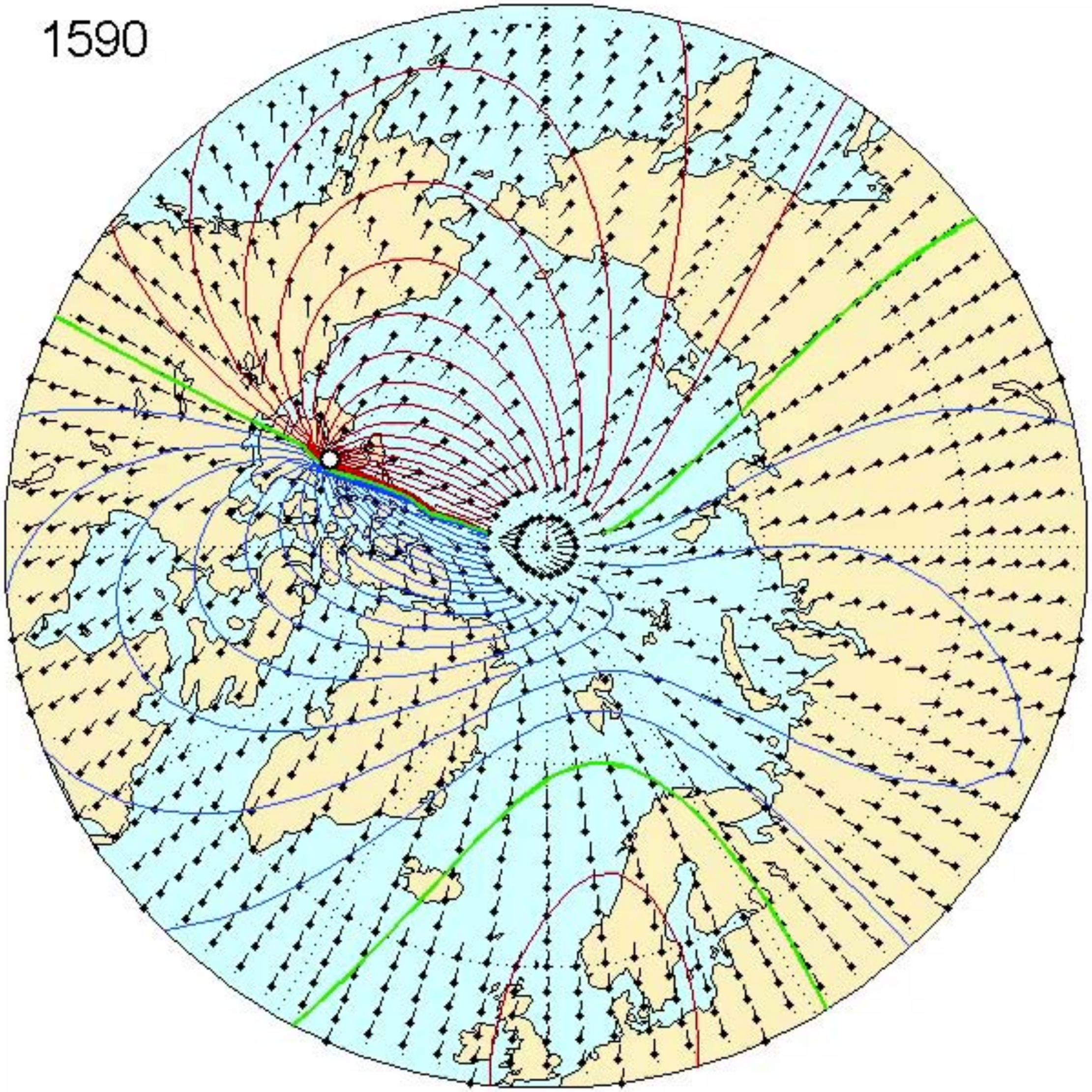
Historical field evolution



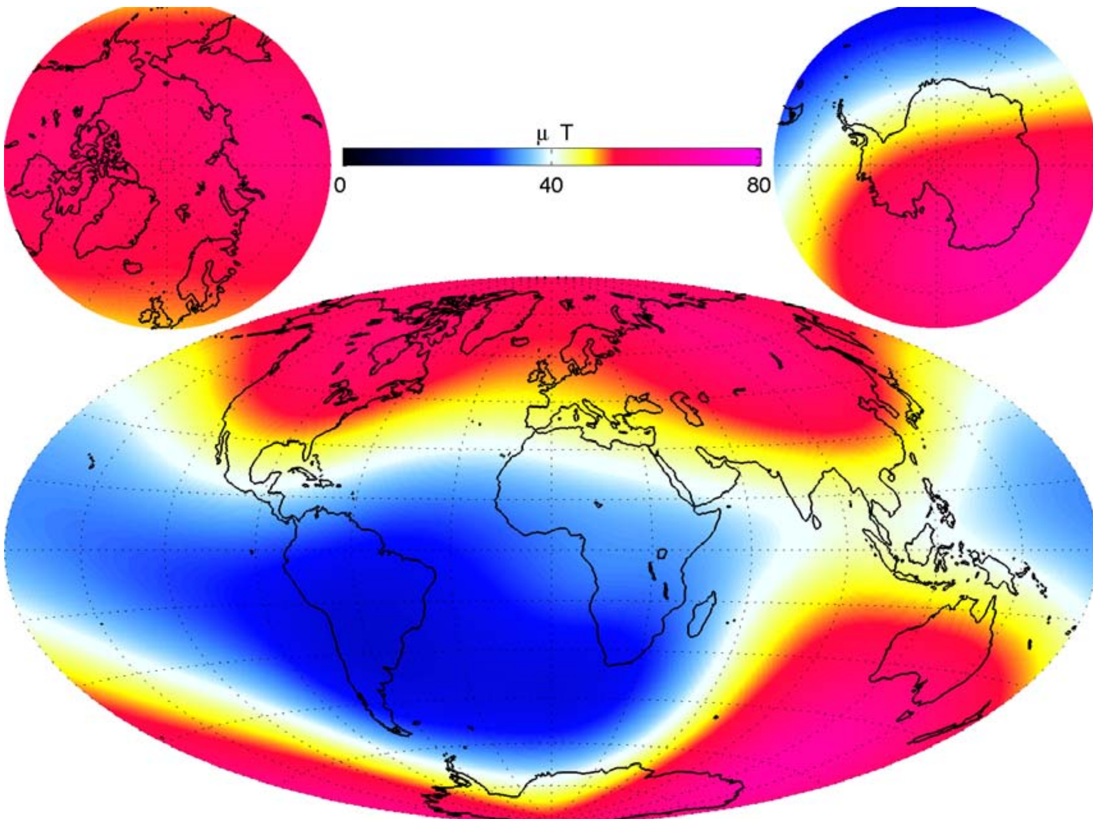


[From Jackson et al., 2000]

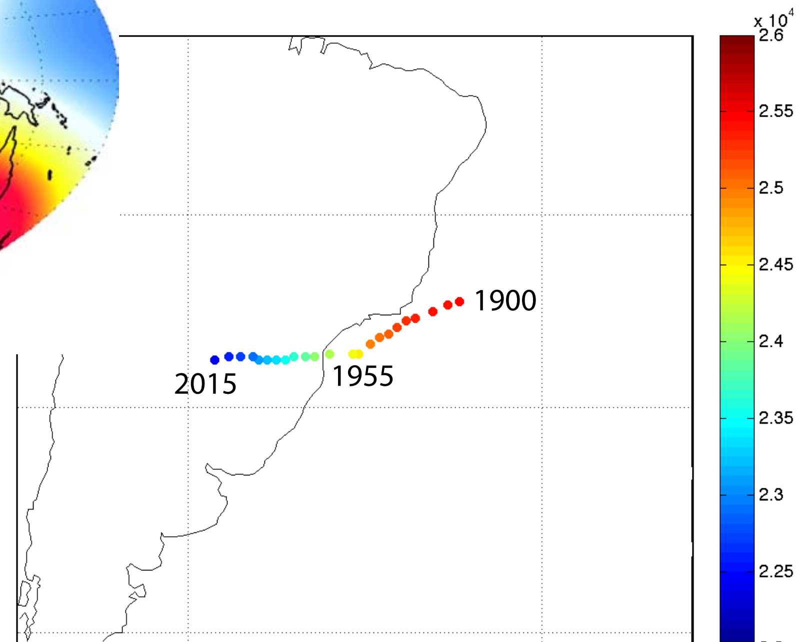
Historical field evolution



Historical field evolution: SAA

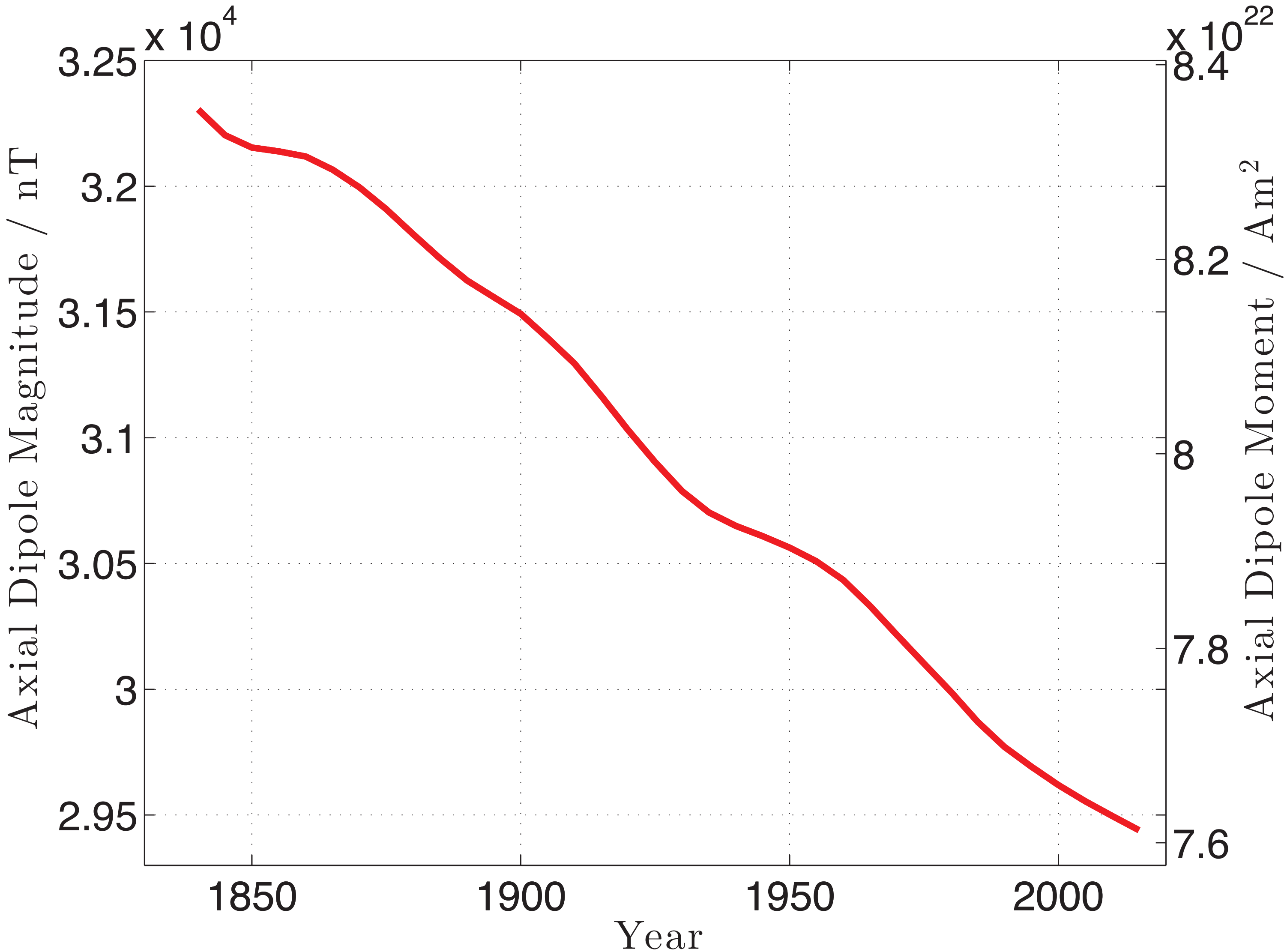


SAA: South Atlantic Anomaly
in field intensity F



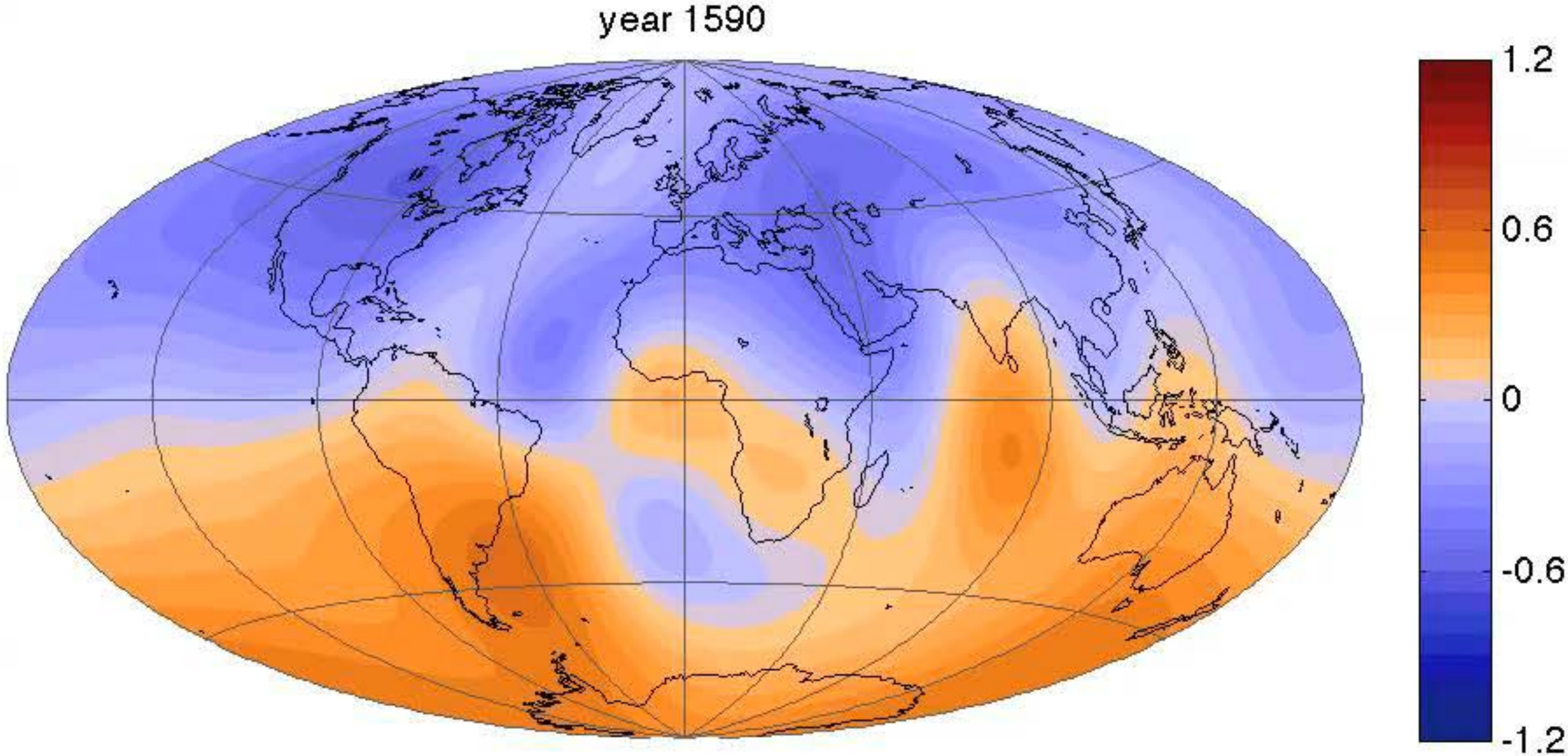
[From IGRF-11;
Finlay et al, IUGG 2015]

Historical field evolution: Dipole Decay



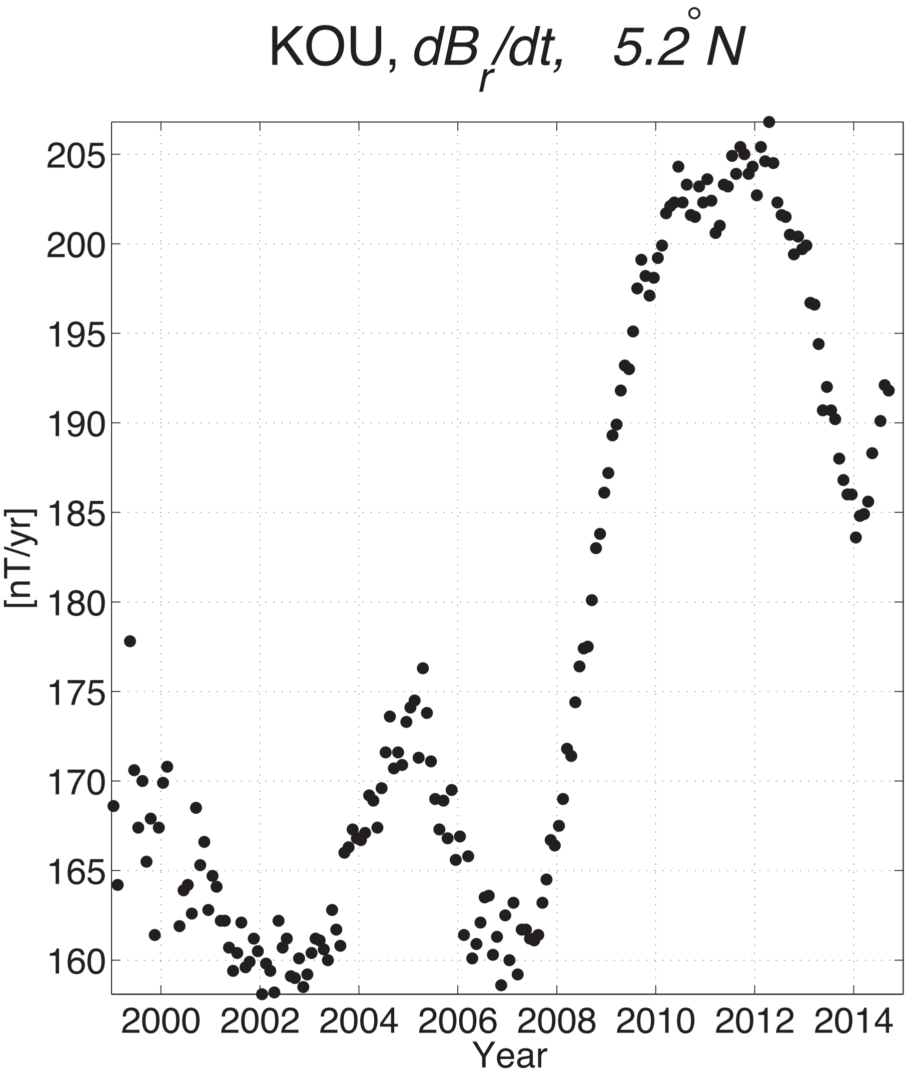
[From COV-OBS model of Gillet et al., 2013]

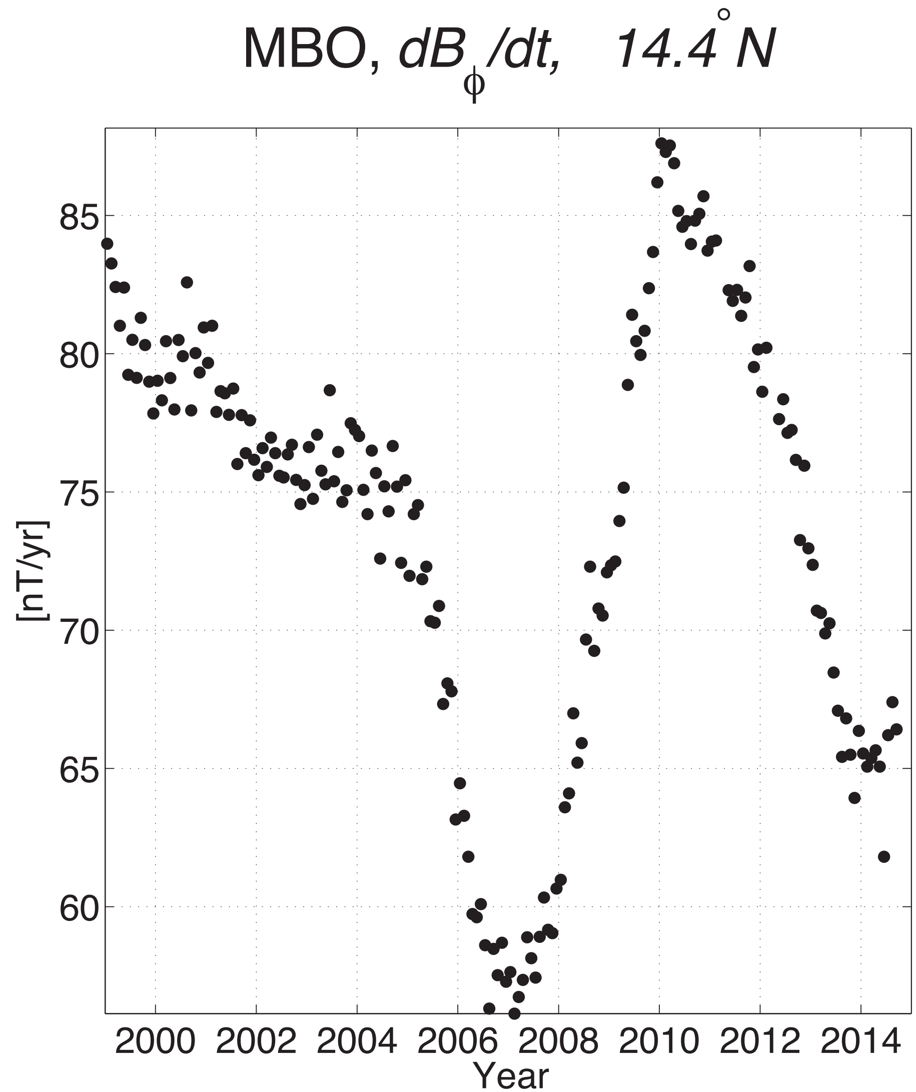
Historical field evolution: B_r at CMB



[From *gufm1* model of Jackson et al., 2000]

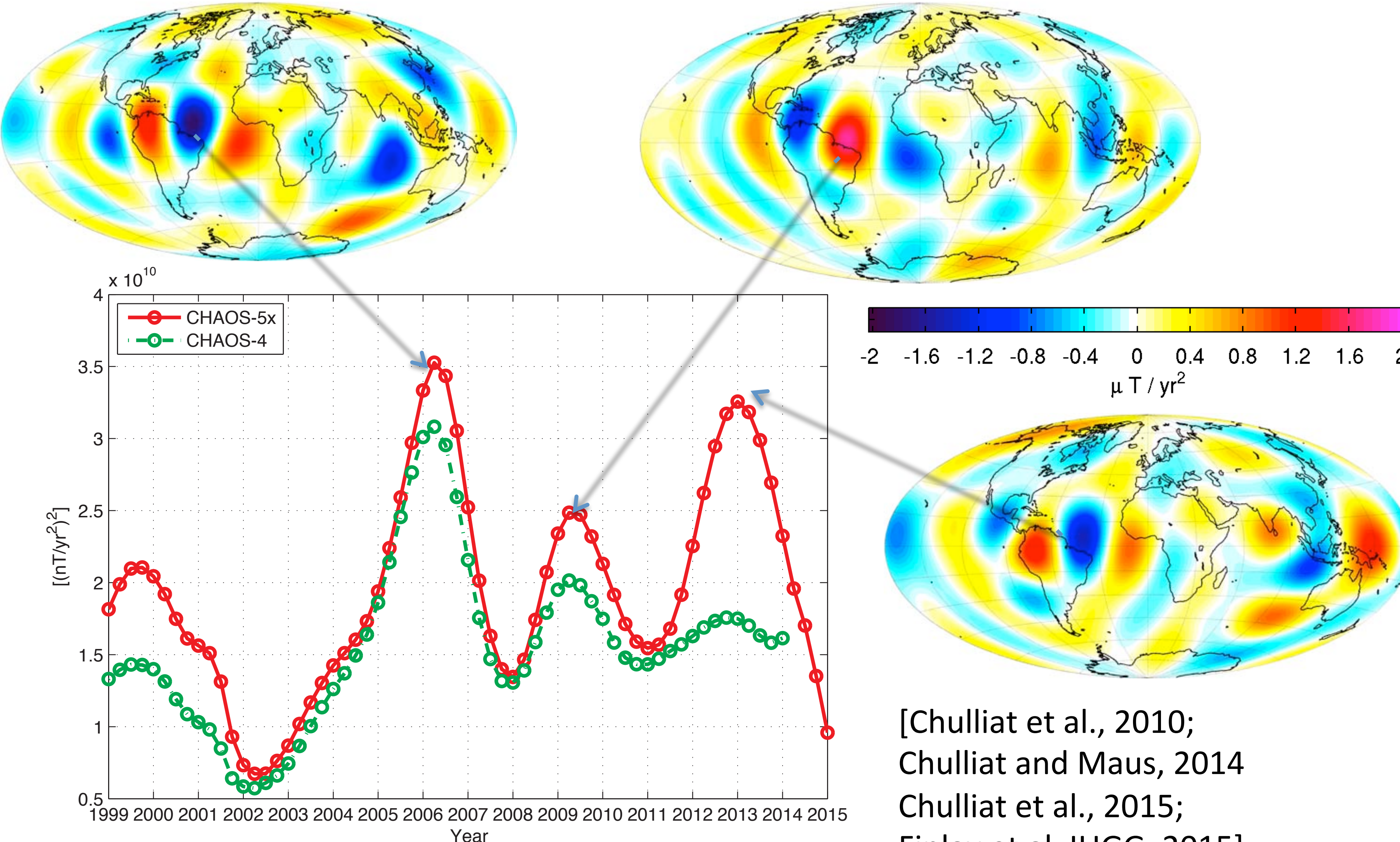
Rapid (Sub-decadal) SV





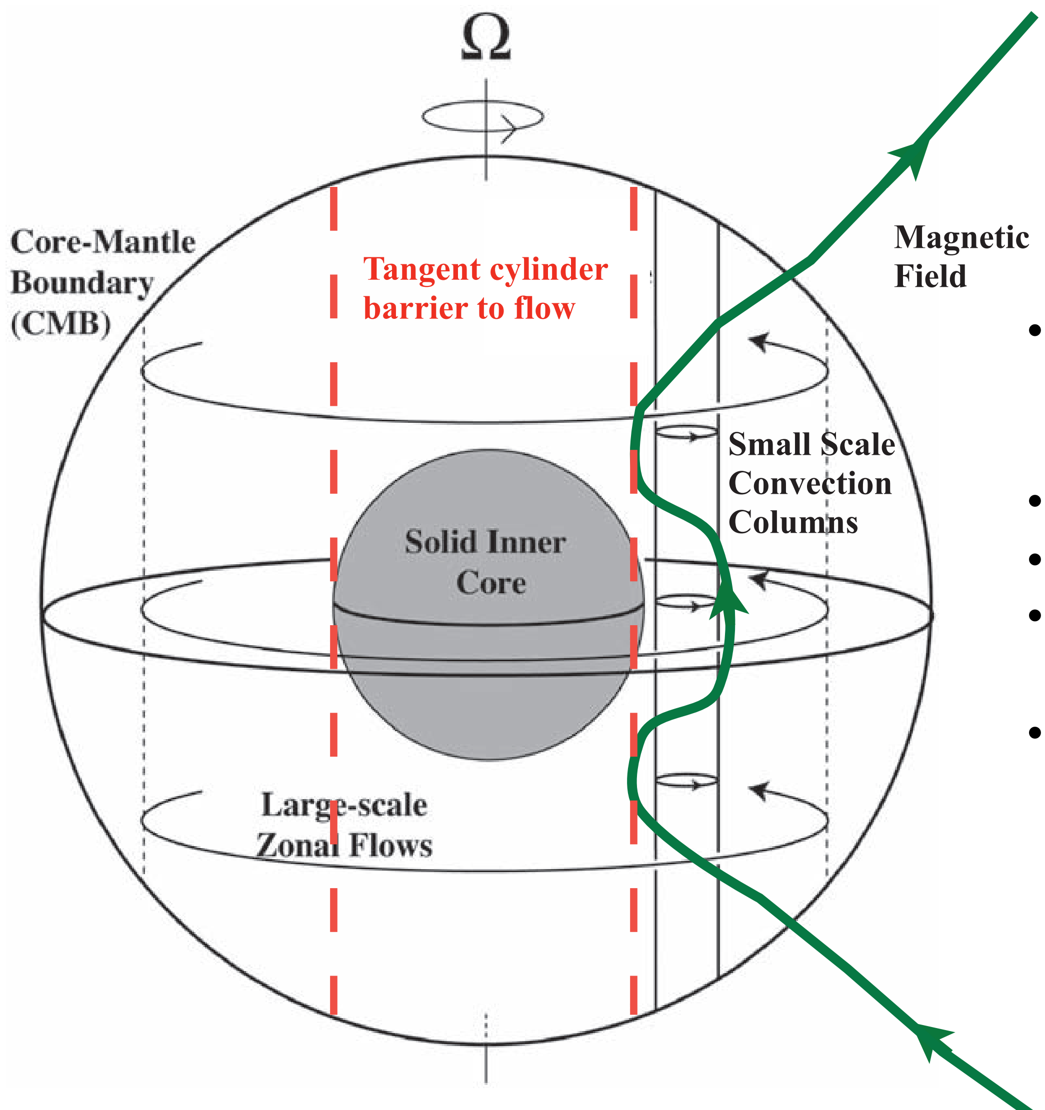
[From Finlay et al., IUGG, 2015]

Pulses of SA at the Core Surface



[Chulliat et al., 2010;
Chulliat and Maus, 2014
Chulliat et al., 2015;
Finlay et al, IUGG, 2015]

Responsible core dynamics



(Modified from Aurnou, 2007)

- Spherical shell of electrically conducting liquid metal

- Rapid Rotation
- Motions driven by convection
- Strong magnetic fields

- Boundary coupling at ICB and CMB

Scientific challenges

- What is the origin of the westward drift?
- What is the origin of the geomagnetic dipole decay?
- What is the origin of the South Atlantic Anomaly?

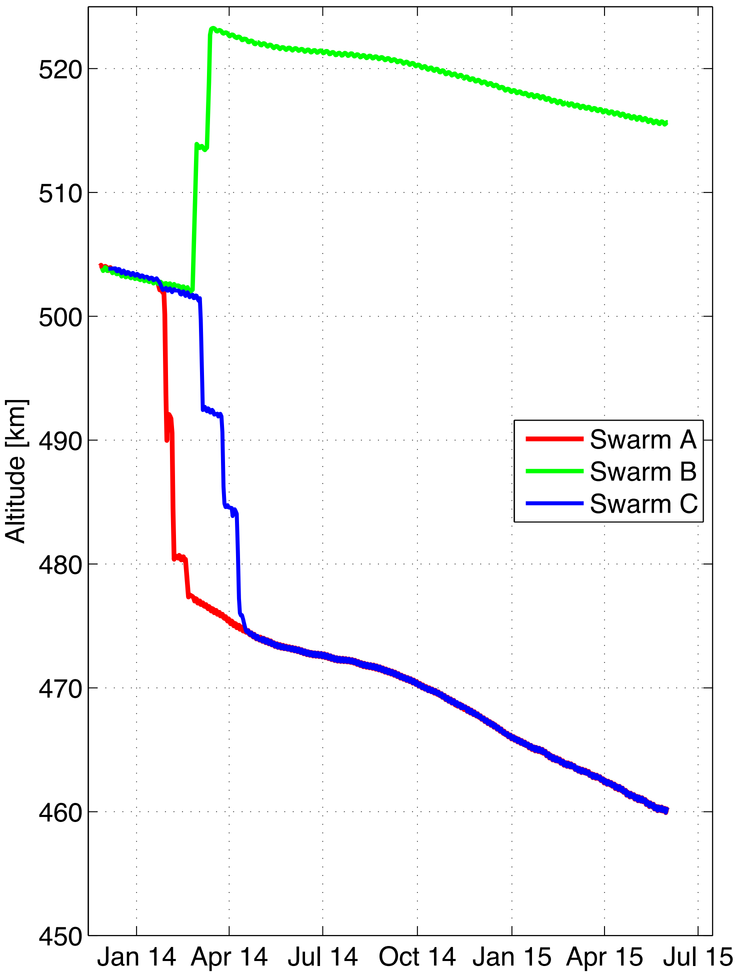
- How will these features evolve in the future?

- Can we better characterize and understand rapid core field changes?

- How can we better model the underlying core dynamics?

2. Observation-based studies of secular variation and inference of core flows

Swarm satellite trio



- Launched by ESA 22nd November 2013

Swarm

- Data is well suited for field modelling:
  Used by for IGRF-12, epoch 2015 and SV 2015-2020.

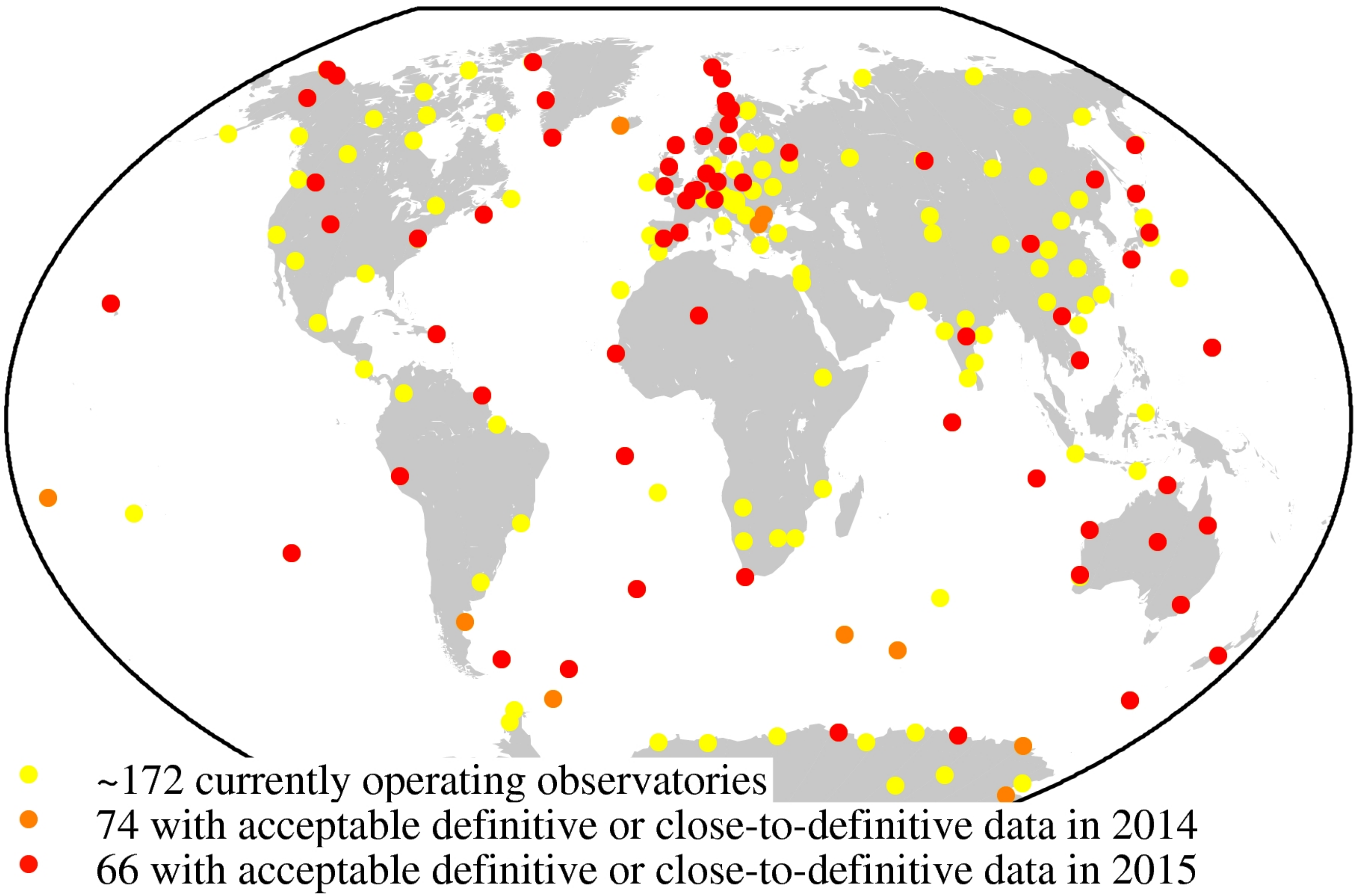
- Has been used to derive high resolution field models
  (e.g. Swarm Initial Field Model, Olsen et al., 2015, GRL)

- Data is freely available from ESA

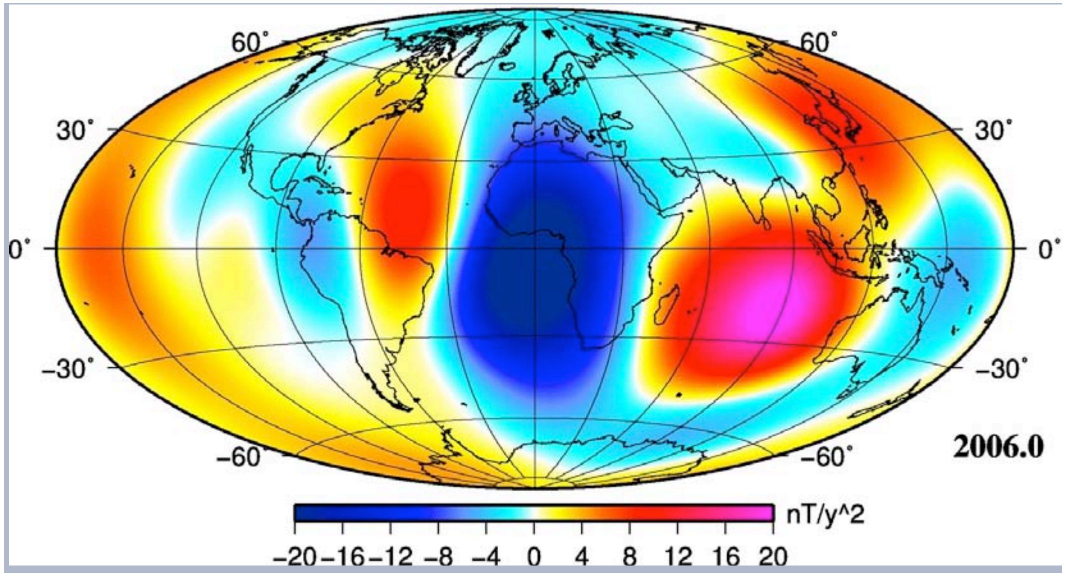
- For the latest operational updates on status of satellites, data releases etc. see ESA's Swarm webpage

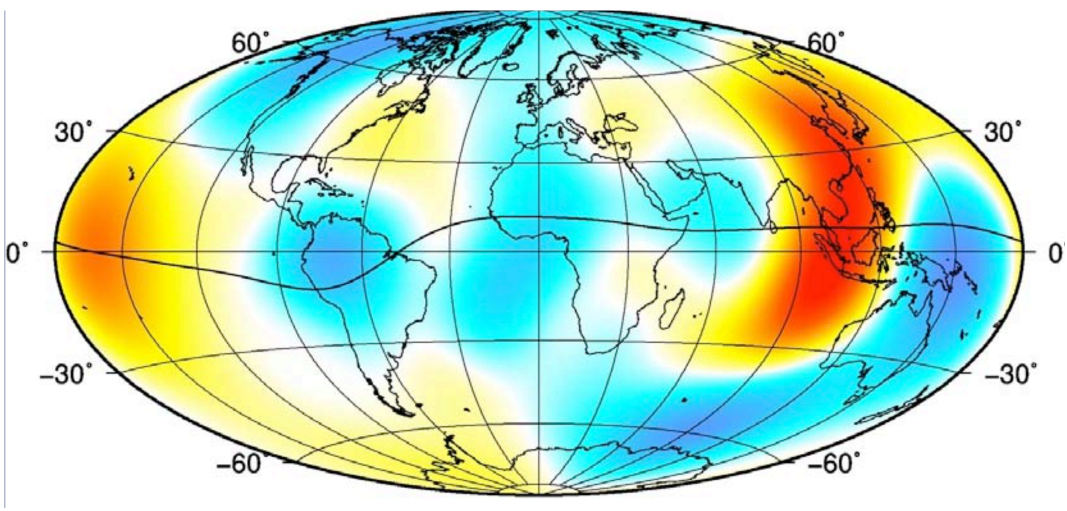
https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/swarm

Ground observatory locations and timeliness of data release



GRIMM-42 field model



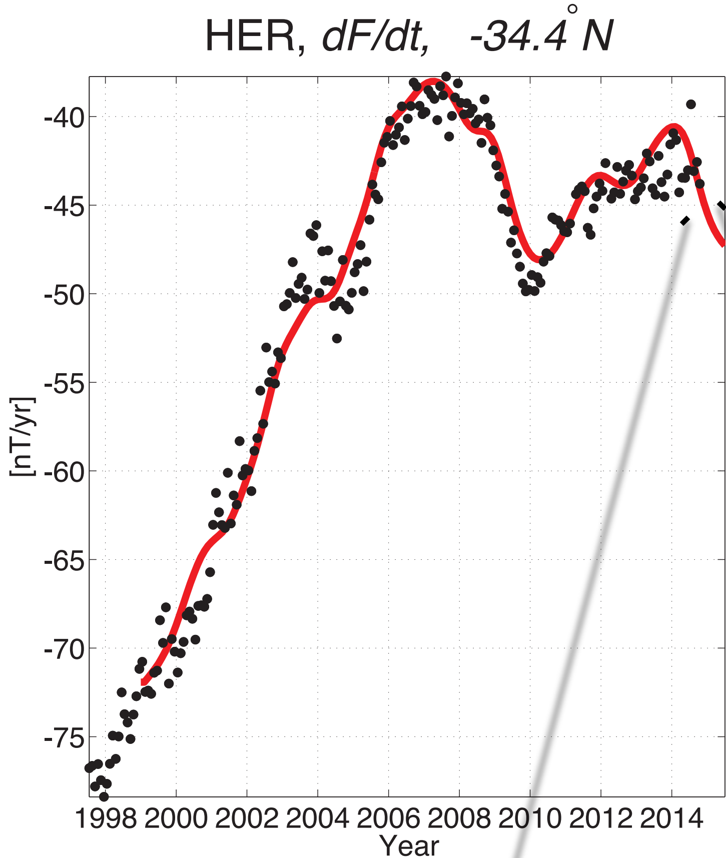


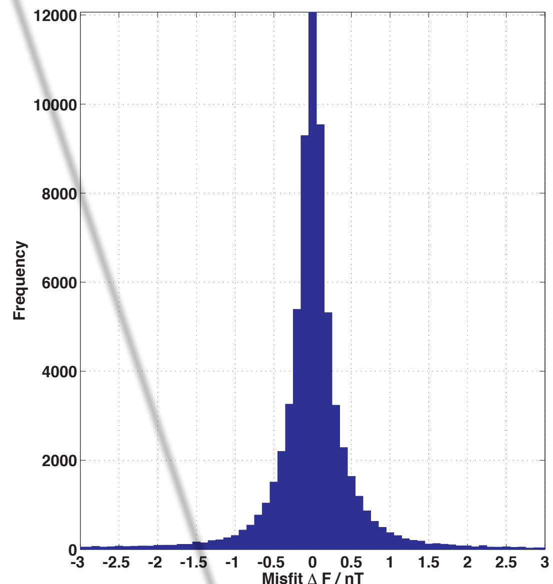
Time- averaged SA 2004-2014

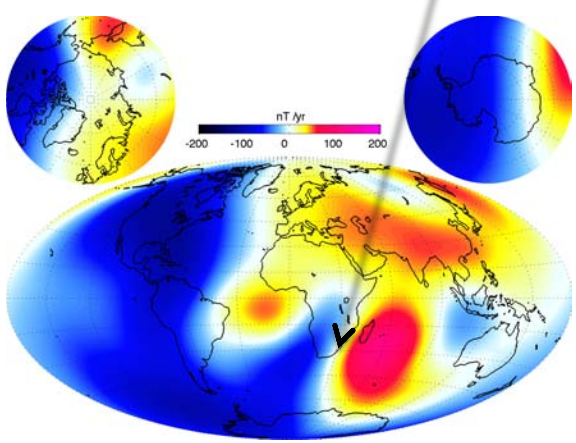
- Derived from CHAMP, Swarm and ground observatory data from 2004-2015
- Finds large variations in SA, especially in the low latitude Atlantic and Indian sectors (up to 37 nT/yr^2)
- Averaging over 10 years the amplitude of the SV is much weaker (< 8 nT/yr^2)
- Suggests a slow long-term SV associated with a nearly steady core flow + rapid perturbations ontop of this.

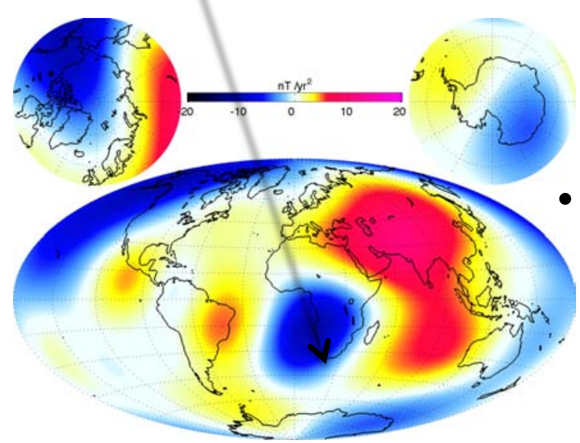
[Lesur et al., IUGG, 2015]

CHAOS-5x field model







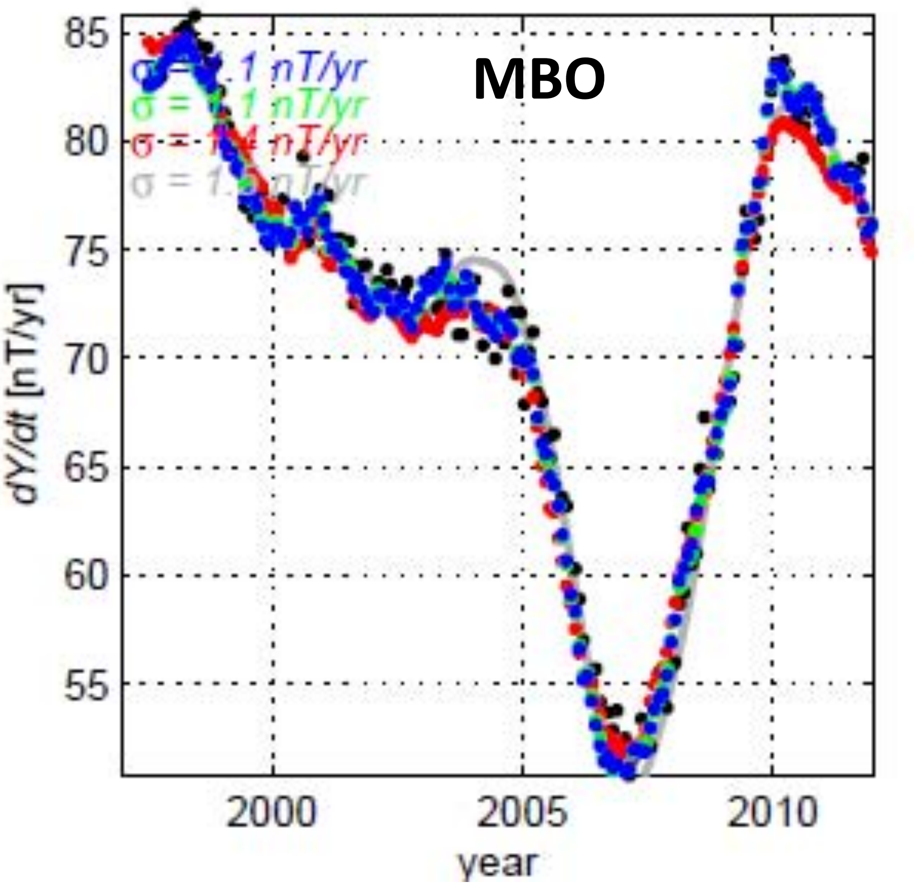


- Includes 20 months of *Swarm* data including along-track and EW diffs & ground obs MM to 05.15
- Good fit to Swarm data (misfit ~ 0.4 nT for scalar diff btw *Swarm* A and *Swarm* C)
- Preliminary evidence of field accelerations during Swarm-era (Nov '13 ->)
- For example acceleration of field strengthening in Asia/Indian ocean and of field weakening in Southern Africa.

[Finlay et al., IUGG, 2015]

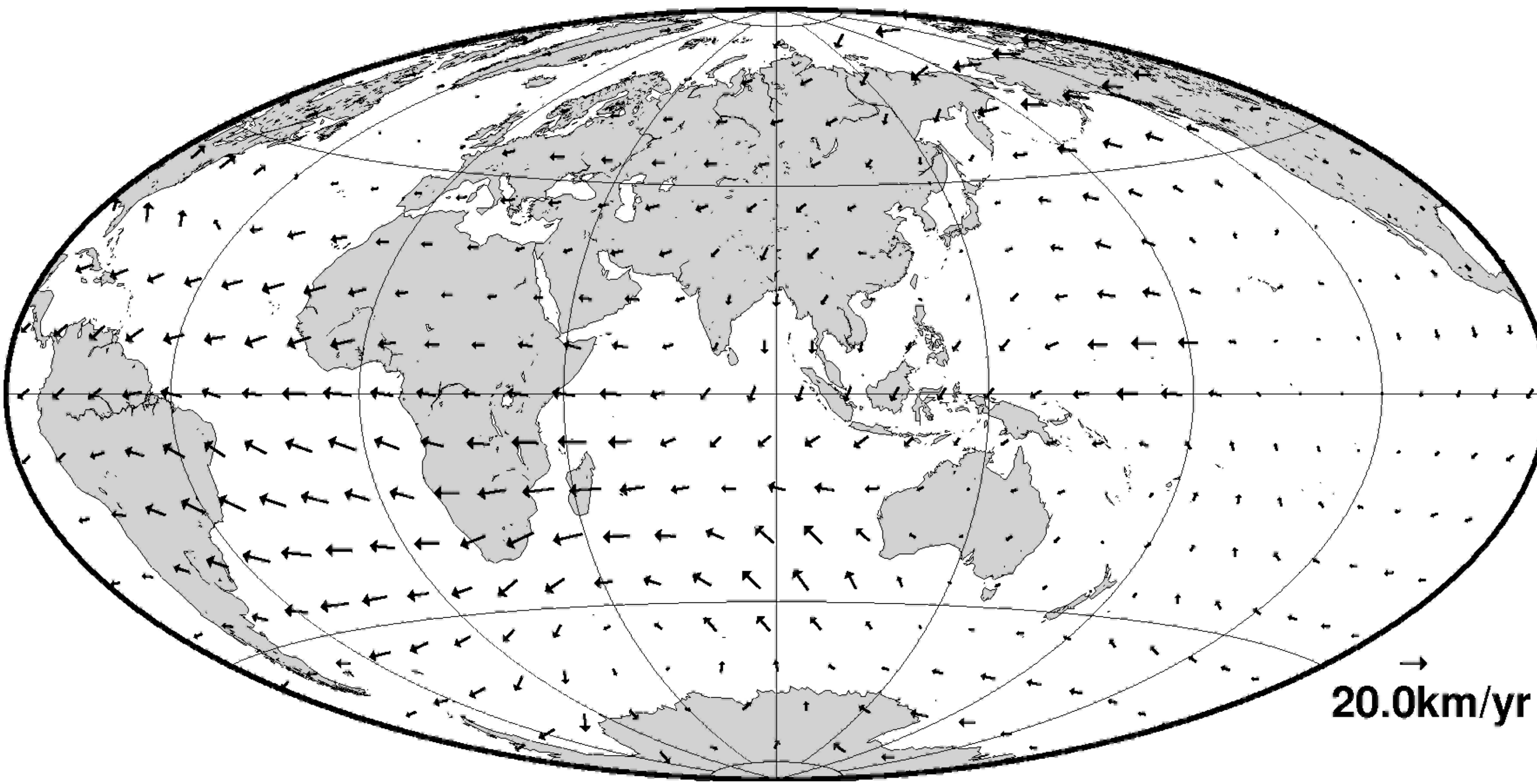
Relatively small flow changes need to explain rapid SV seen at observatories

[Whaler, et al., IUGG, 2015]



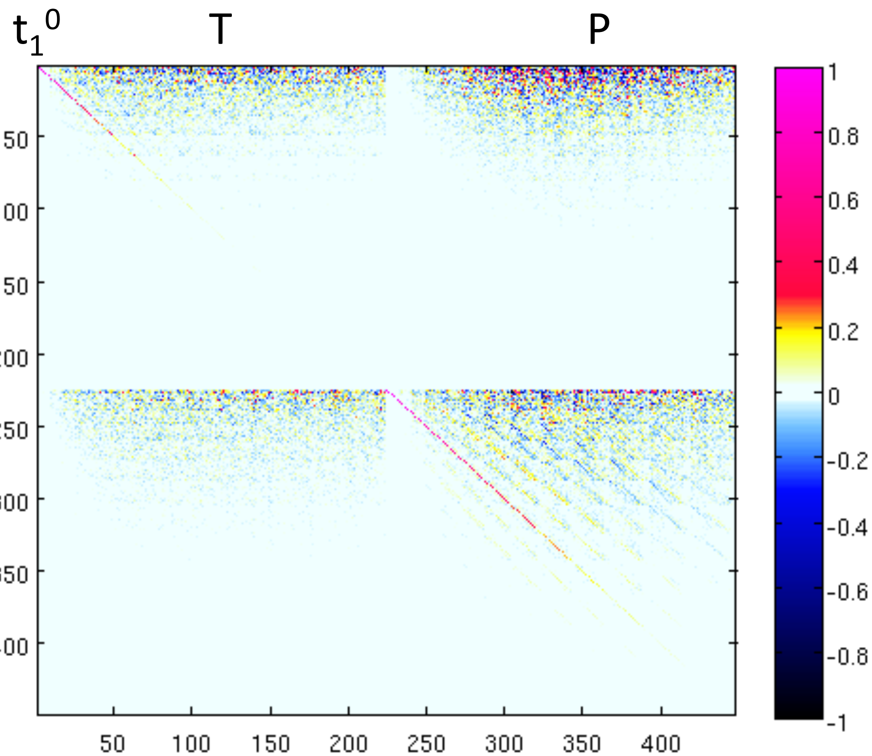
- All flows predict the data better than CHAOS-4
- Steady flow + TO not an adequate model
- Flows with time-variations penalized fit data as well as unpenalized case

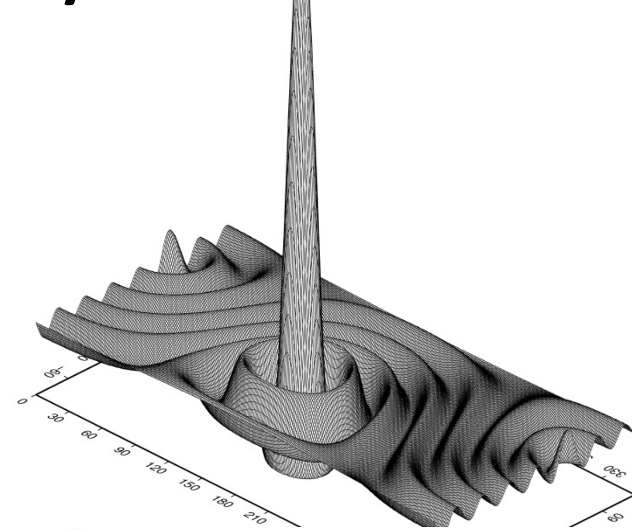
Relatively small flow changes need to explain observatory SV

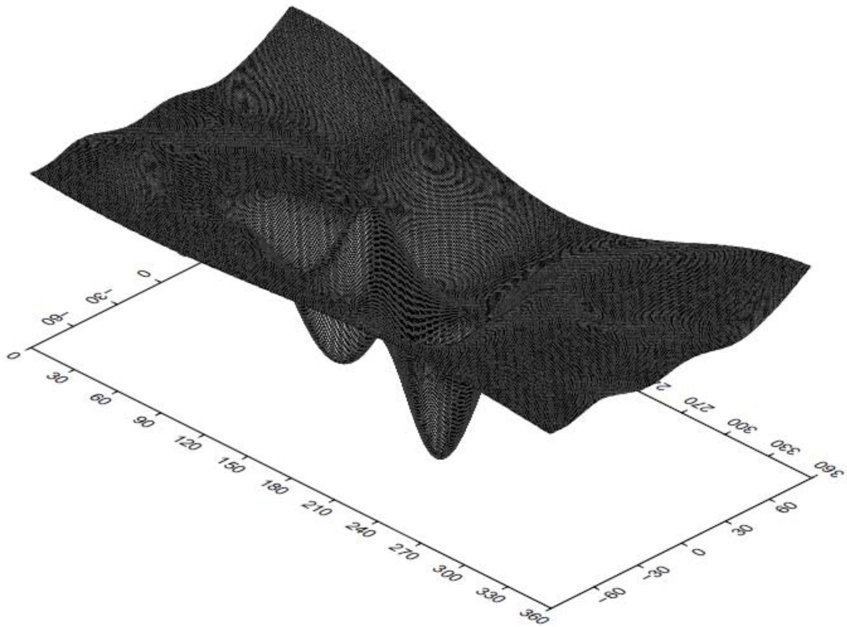


[Whaler, et al., IUGG, 2015]

Flow resolution is rather poor, when only using ground observatory data







[Whaler, et al., IUGG, 2015]

Importance of time-correlated errors in core flow modelling

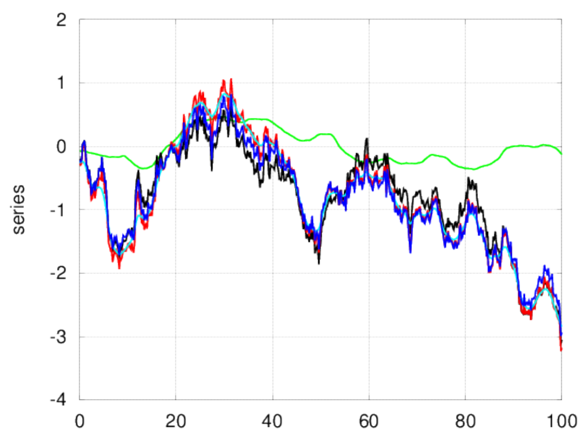
- only access to large length-scales $\overline{B}_r \Rightarrow$ SV model errors

$$\frac{\partial \overline{B}_r}{\partial t} = -\overline{\nabla_h \cdot (\mathbf{u}\overline{B}_r)} - \overline{\nabla_h \cdot (\mathbf{u}B_r')}$$

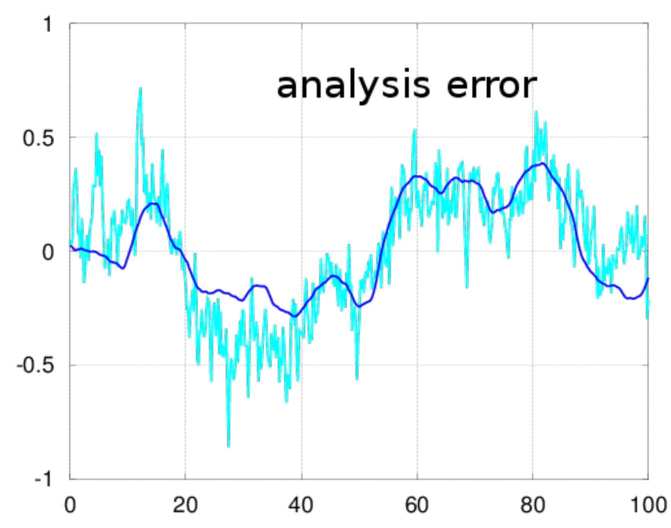
[Gillet, et al., 2015 ; and IUGG, 2015]

  - model errors $\gg$ observation errors (Pais & Jault, 2008)

- 1-D tutorial example, with time-correlated errors



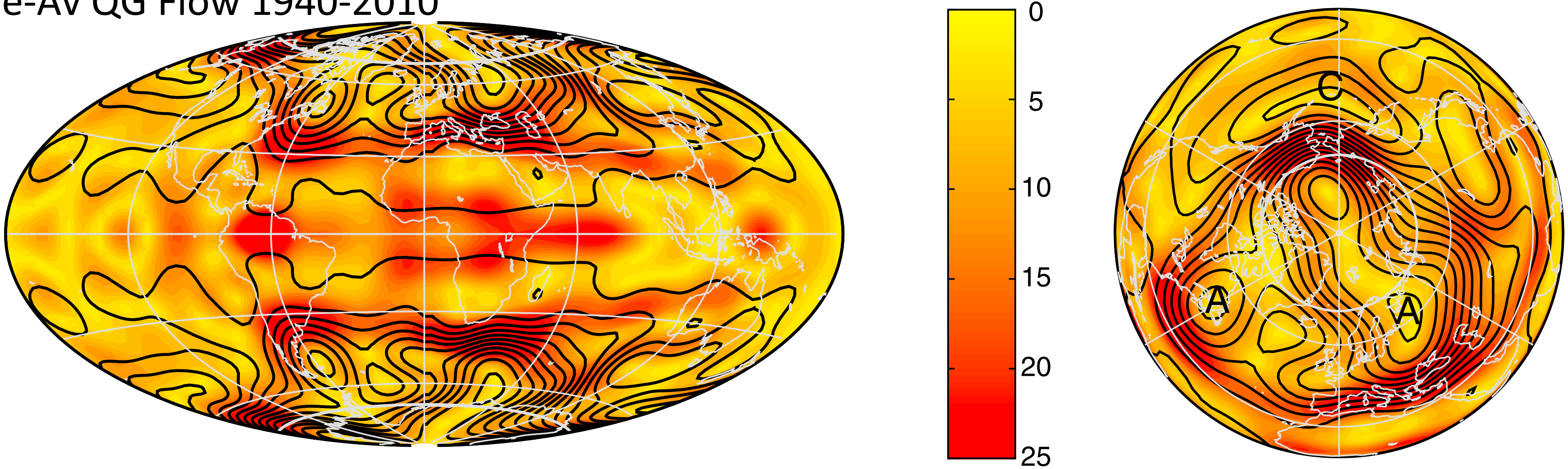
true state (order 1 process)
noise (order 2 process)
data
BLUE (considering correlations)
BLUE (ignoring correlations)



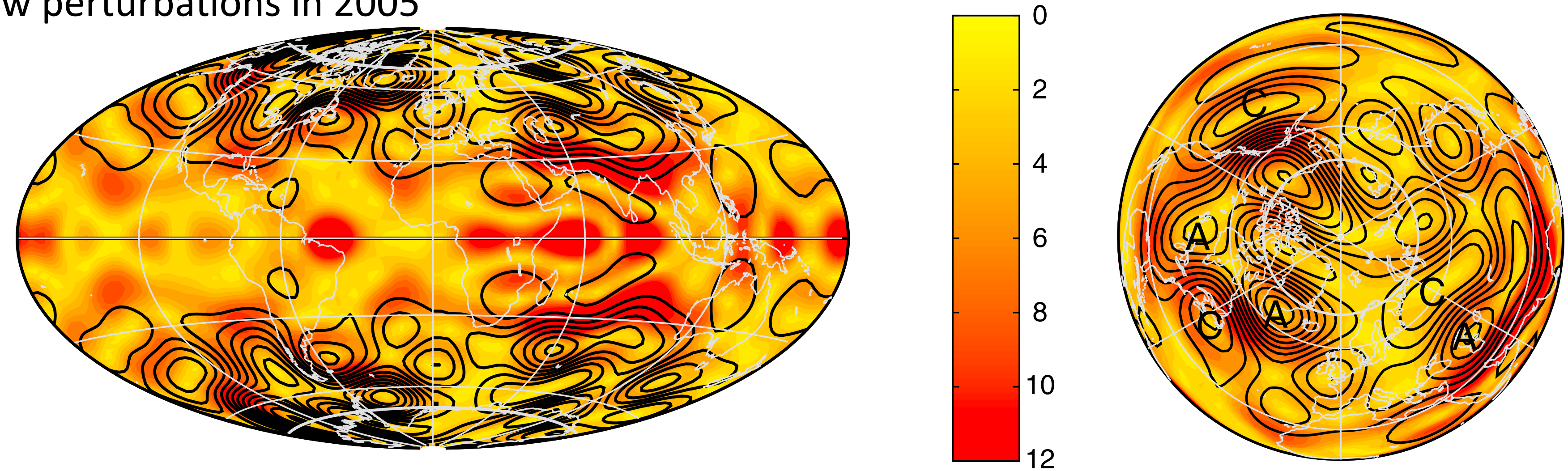
$\Rightarrow$ ignoring covariances = losing information on rapid changes

Steady flow including planetary gyre dominates over time-dependent eddies

Time-Av QG Flow 1940-2010

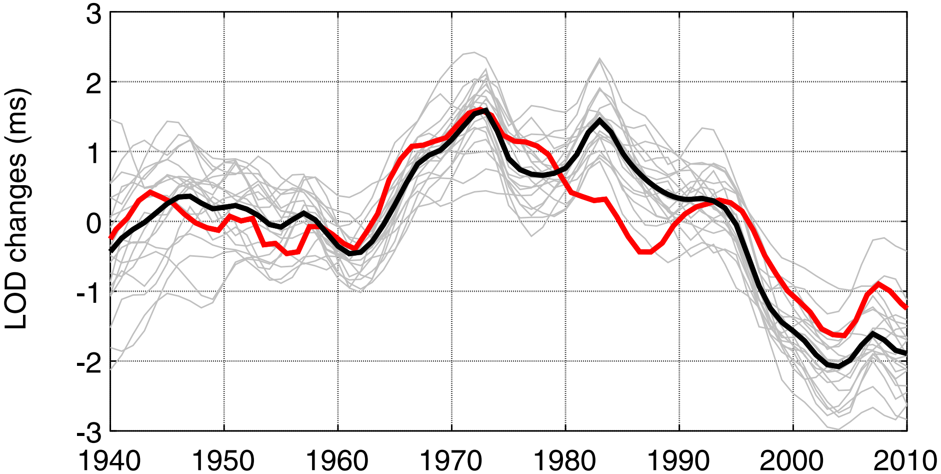


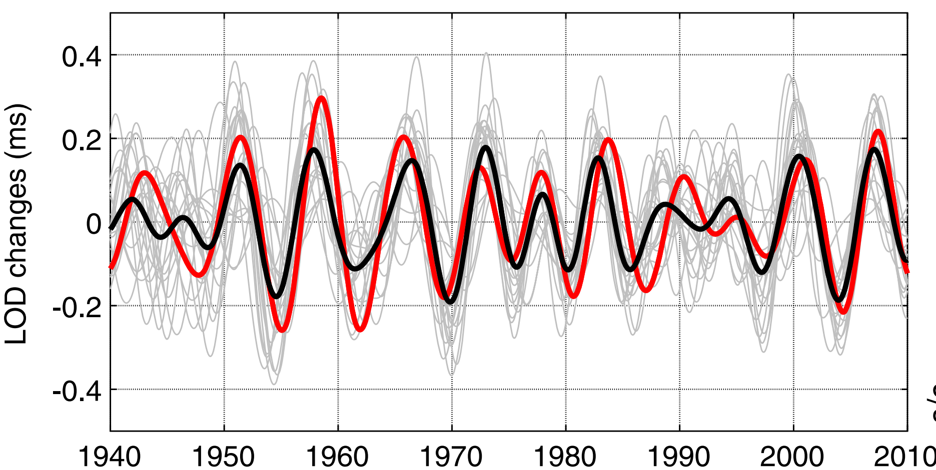
Flow perturbations in 2005



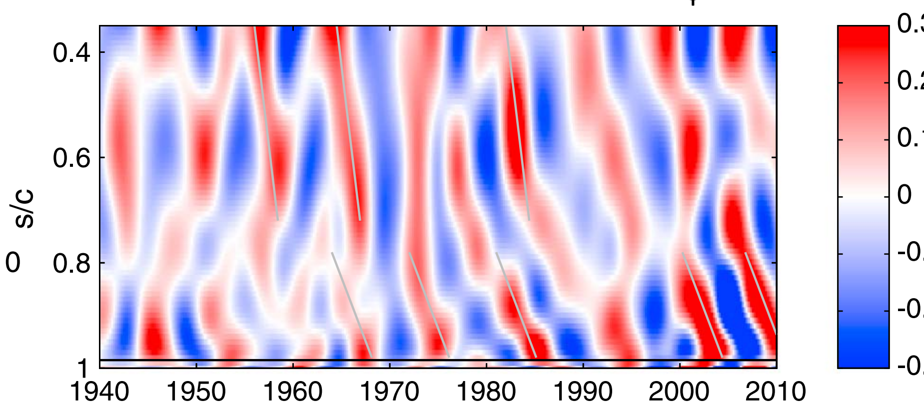
Zonal flow variations explain Δ LOD

[Gillet, et al., 2015 ; and IUGG, 2015]



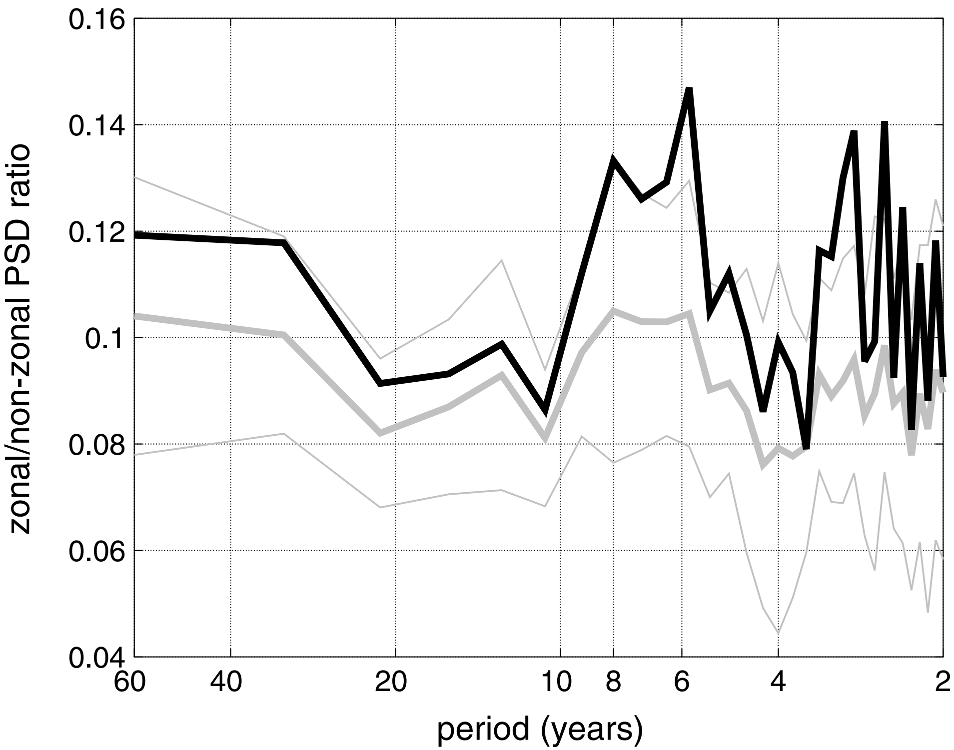


- QG flows accounting for time-correlated unmodelled scales **explains decadal LOD** 1940–2010
- Filtering btw 4-9.5 yrs, also **explains inter-annual LOD**
- Geostrophic flow: outward propagation of Torsional waves

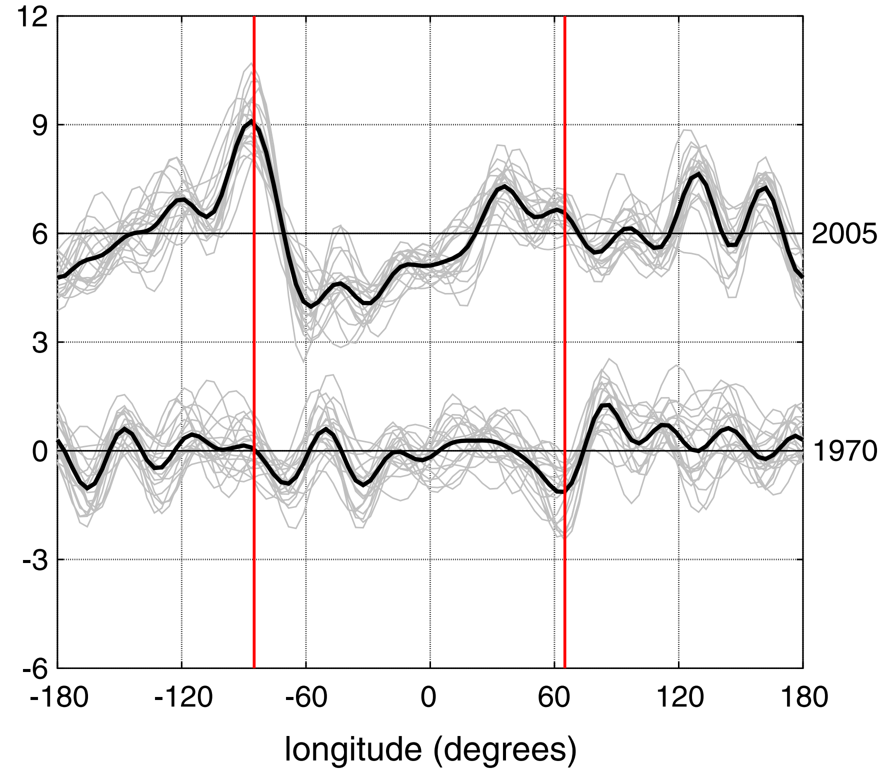


Non-zonal flows much stronger than zonal

[Gillet, et al., 2015 ; and IUGG, 2015]

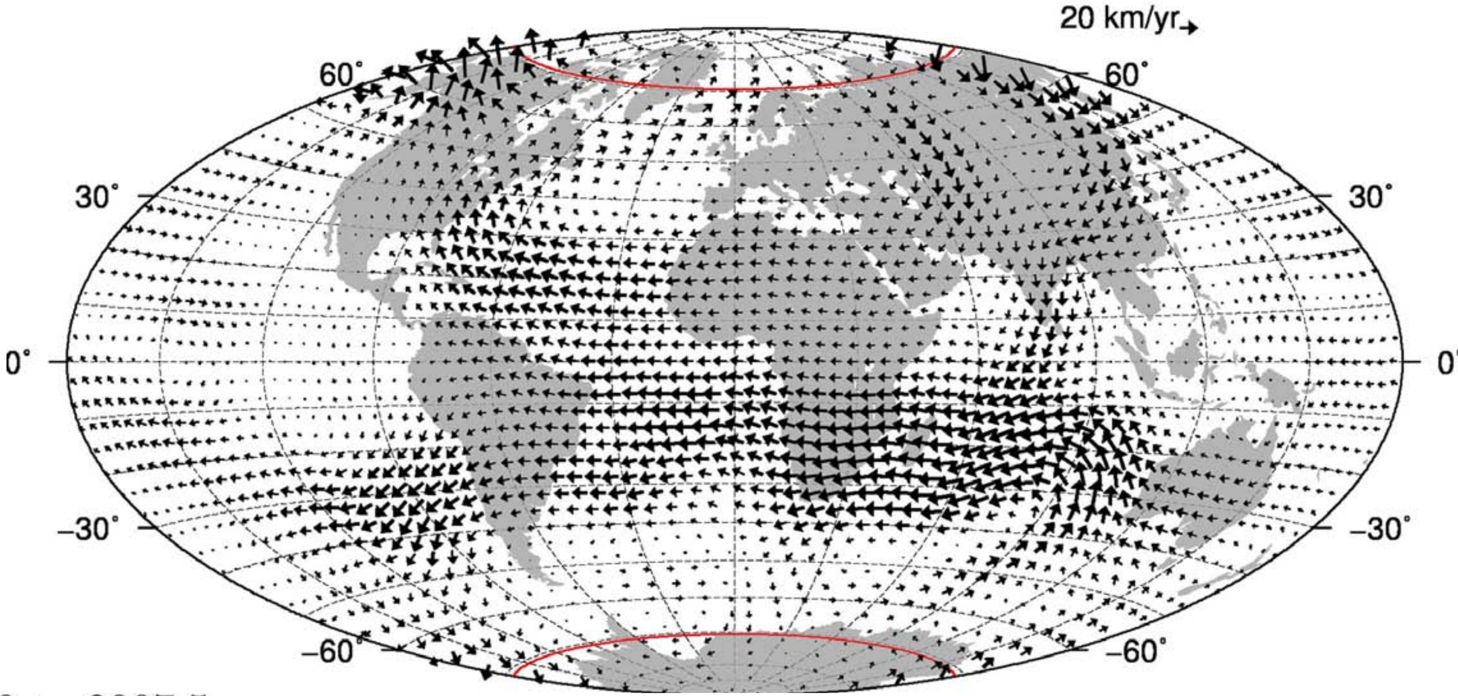


$u_\phi(s,\phi) - u_G(s)$ @ equator $(s=1)$

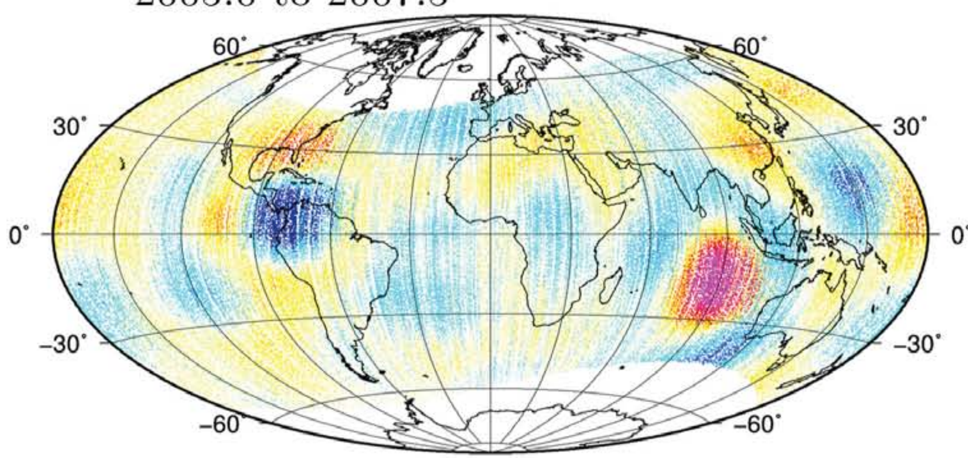


- Geostrophic torsional waves may be triggered by non-zonal flow fluctuations
- Longitudinally localized peaks in azimuthal flow perturbations, up to 6km/yr
- Peaks concentrated within 10 deg of equator
- Particularly clear in past decade, do we have enough resolution at earlier epochs?

Large scale toroidal flows insufficient to fit CHAMP satellite data



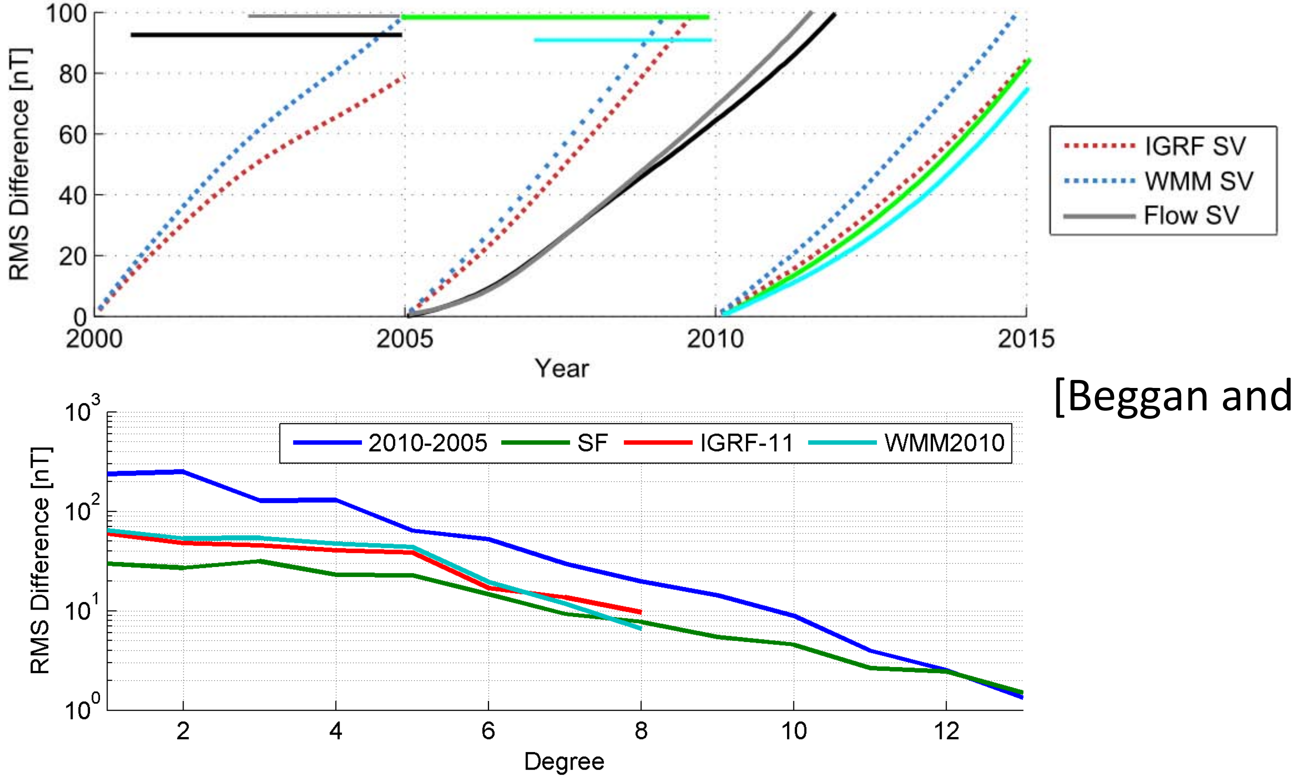
2005.0 to 2007.5



[Lesur, et al., 2015; and IUGG, 2015]

- Large scale toroidal flow cannot fit satellite data in Indian and American sectors
- Only a weak (< 2km/yr) , additional, large scale poloidal flow is need to fit the data

SV prediction using core flows

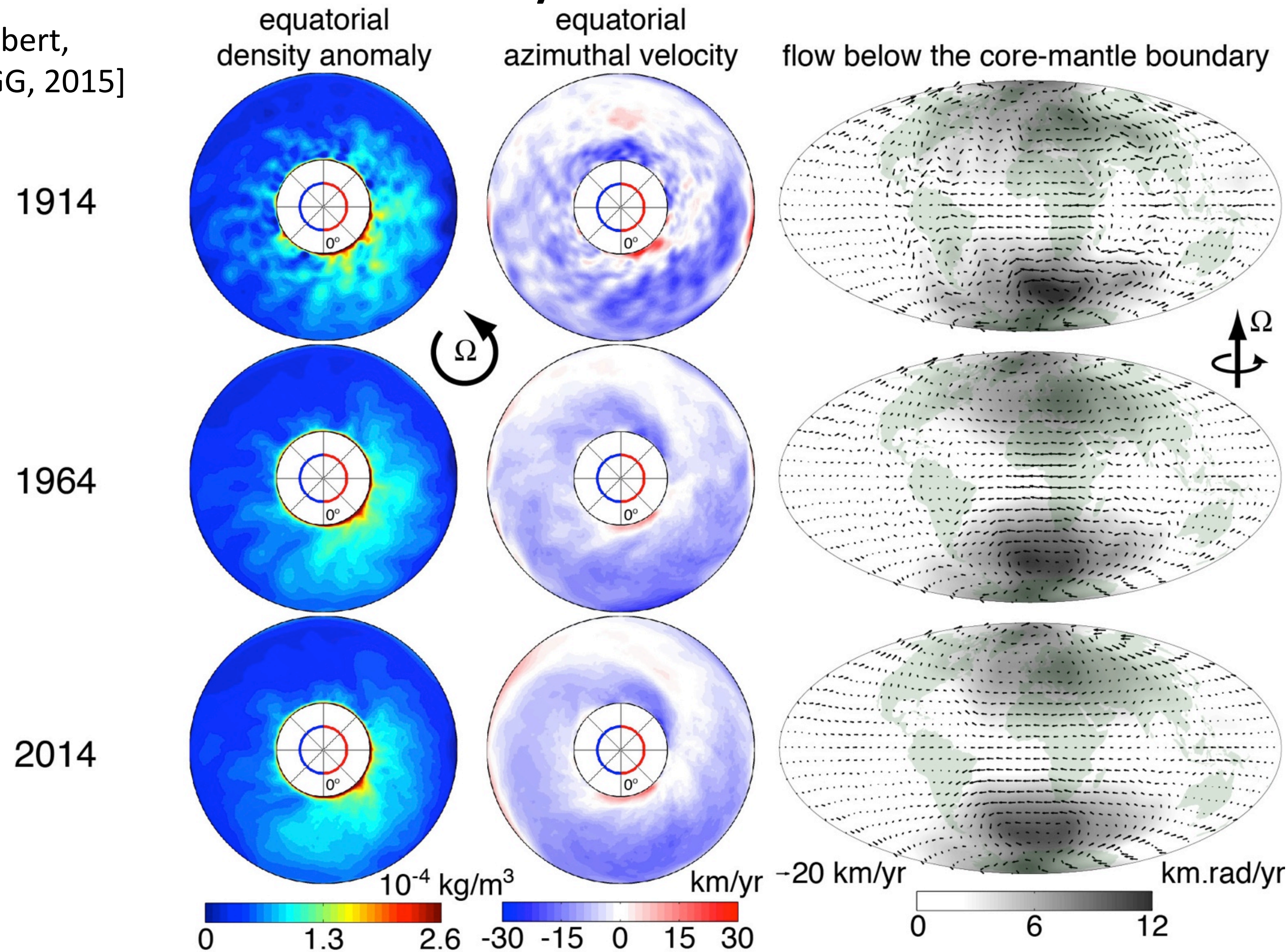


[Beggan and Whaler, IUGG, 2015]

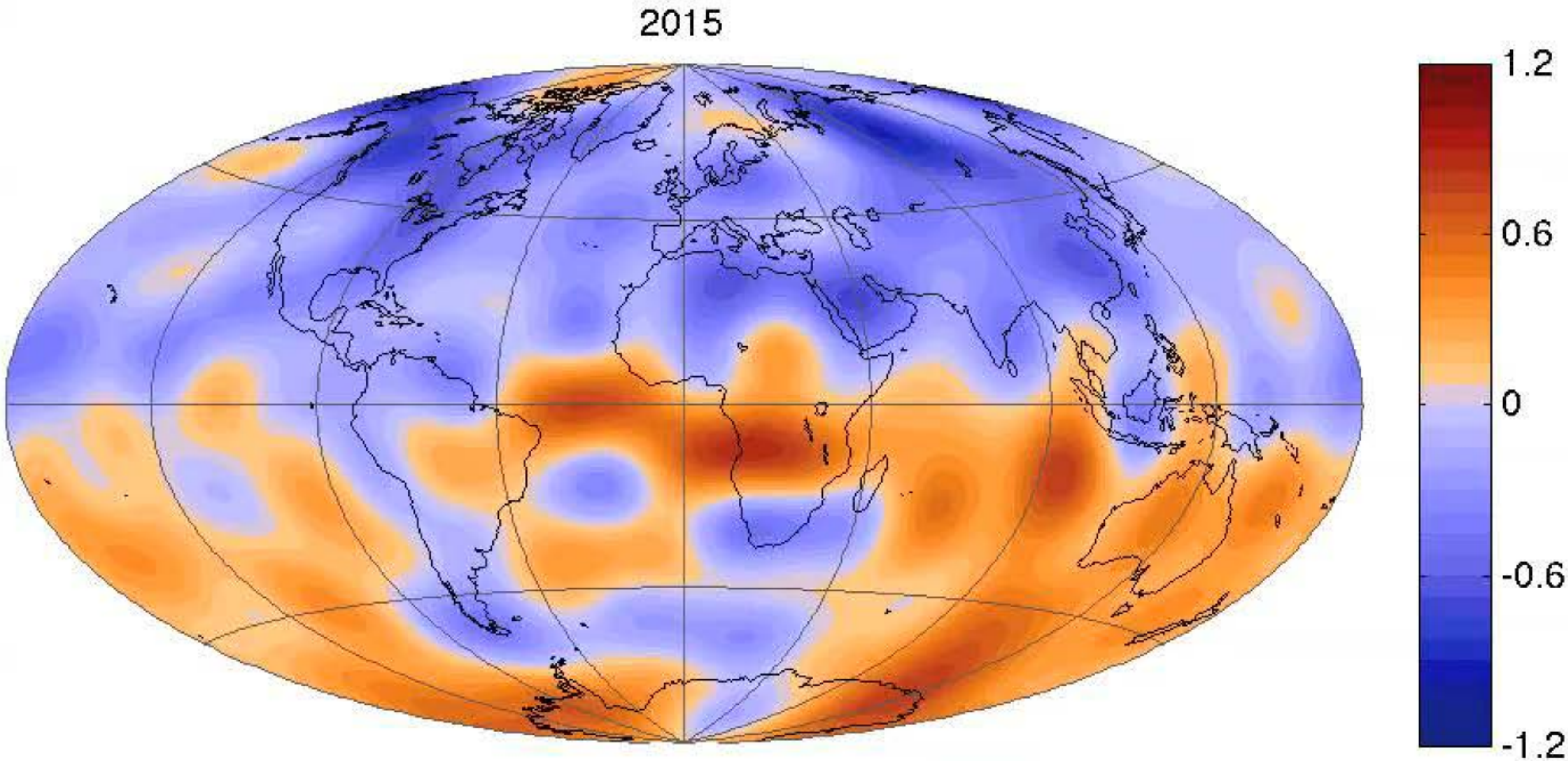
- Usually able to capture > 75% of the field change
- Jerks/accelerations are significant for goodness of forecast
- Core flows using 3-5 years of data are best
- *Slightly better* to *somewhat better* than standard instantaneous SV extrapolation

Inferred 3D density and flow within the core

[Aubert, IUGG, 2015]



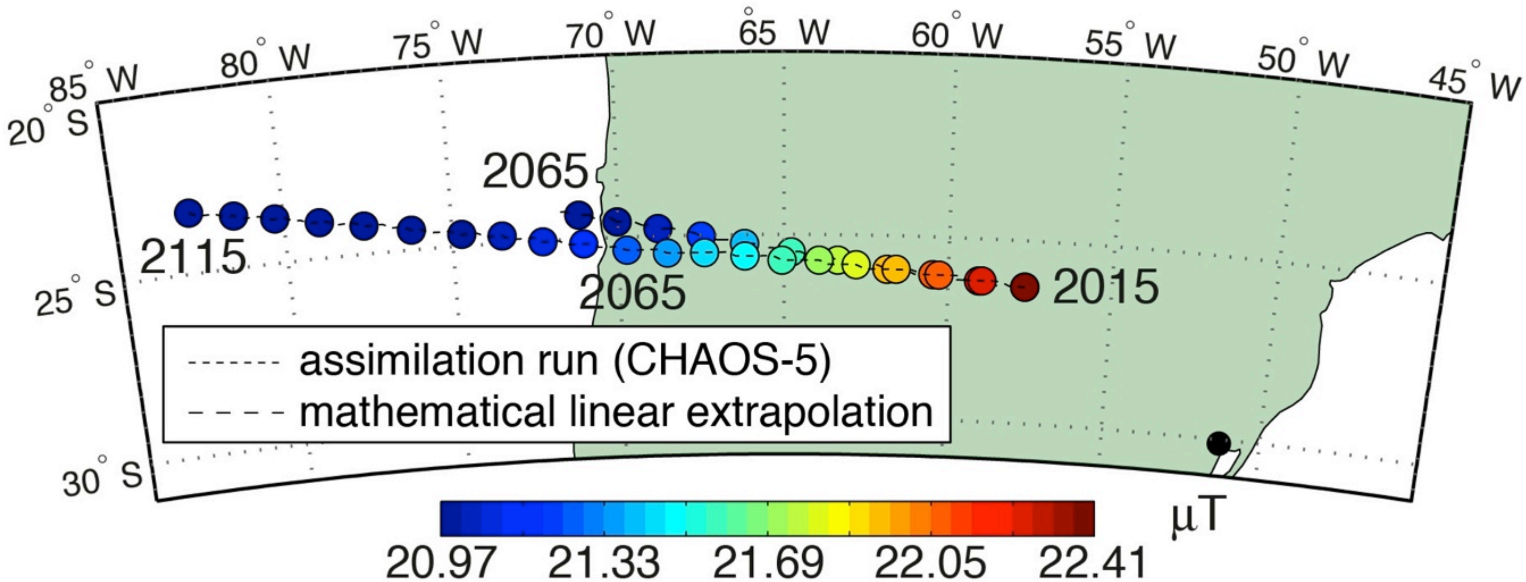
Predicted Future CMB Field evolution

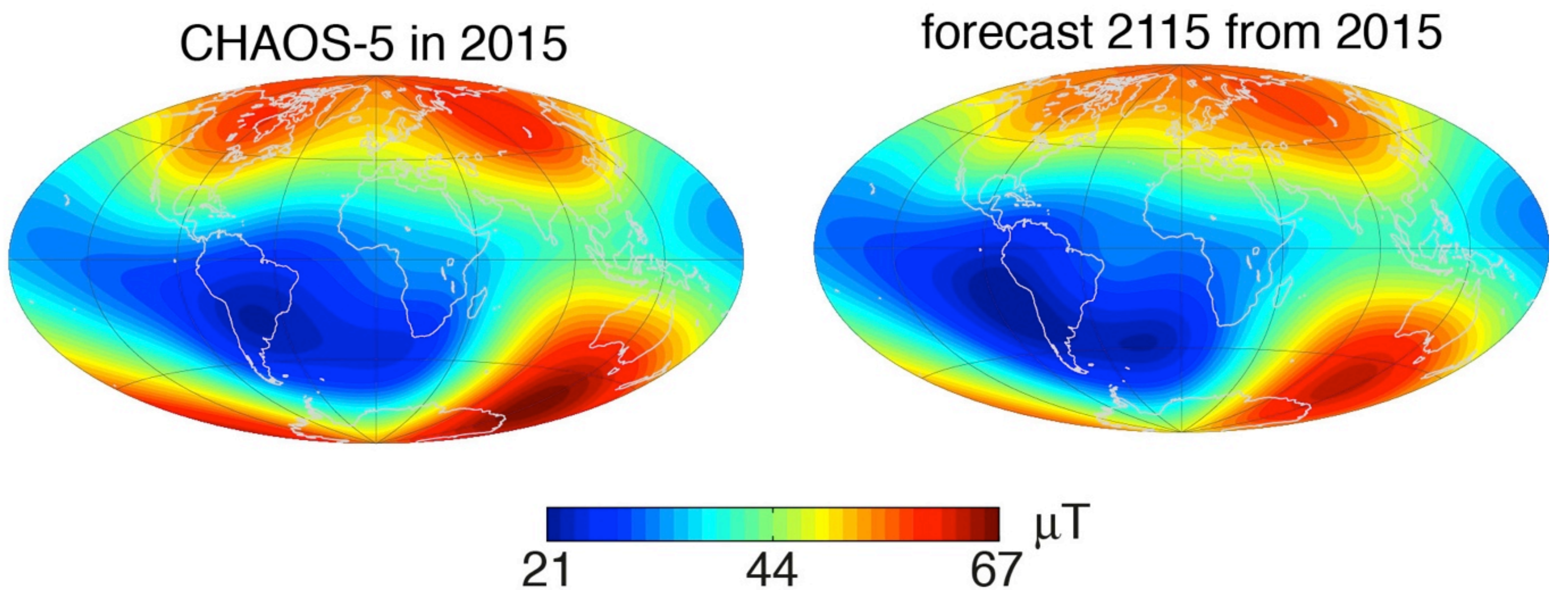


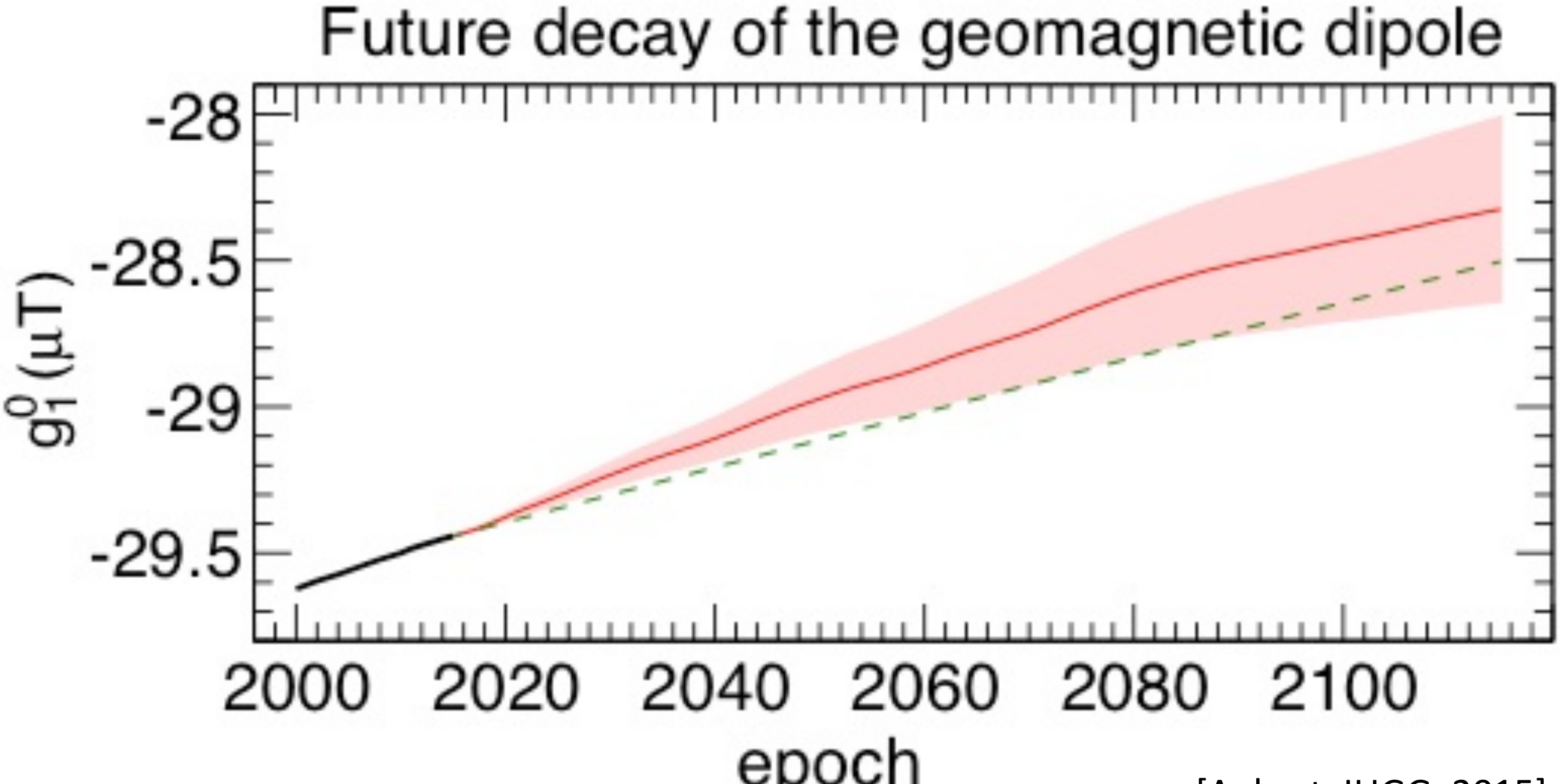
[Aubert, IUGG, 2015]

Future prediction of Earth-surface magnetic field intensity and South Atlantic anomaly

[Aubert, IUGG, 2015]





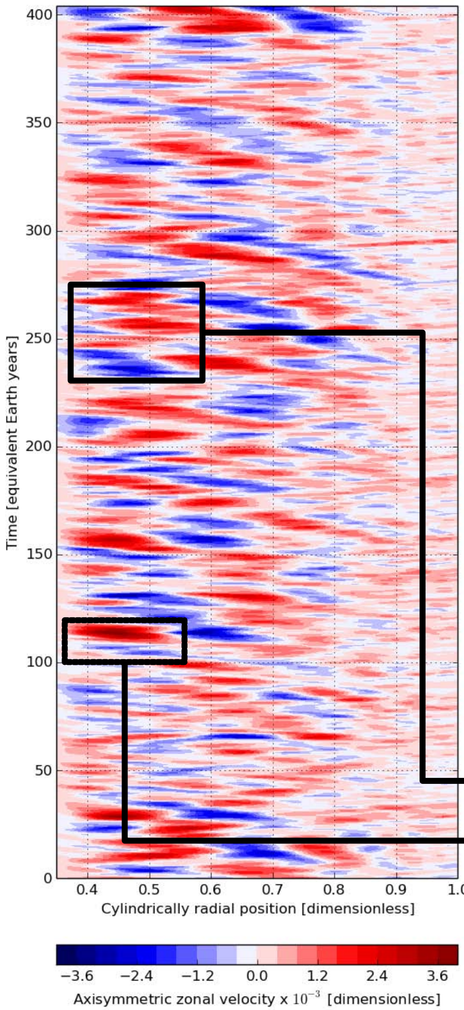


[Aubert, IUGG, 2015]

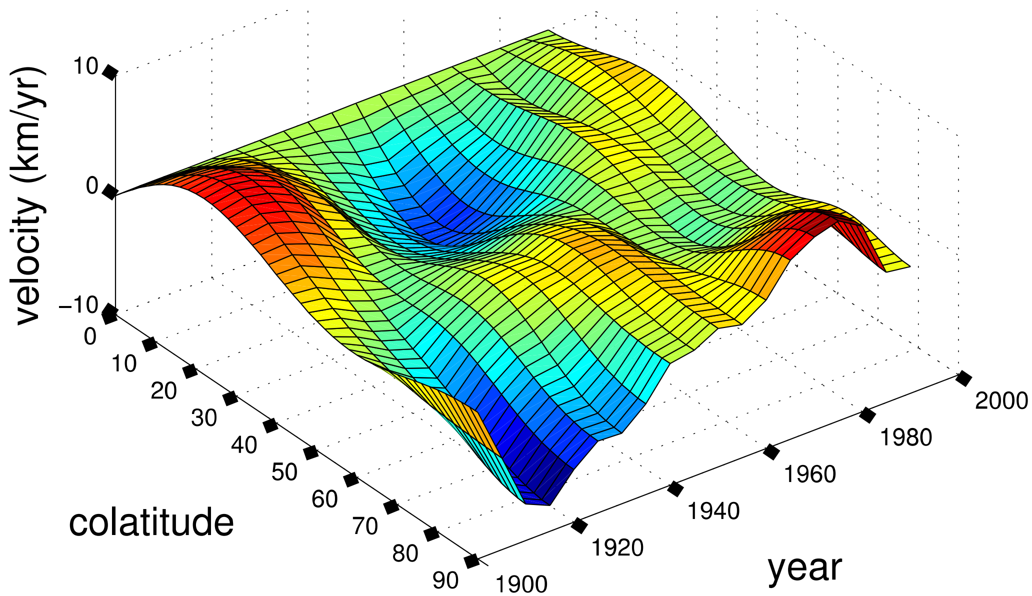
3. Theory of Secular Variation and new Core Dynamics Models

Quasi-Geostrophic numerical model of magneto-convection: two time-scales

Time-dependent zonal flows



Observed flows

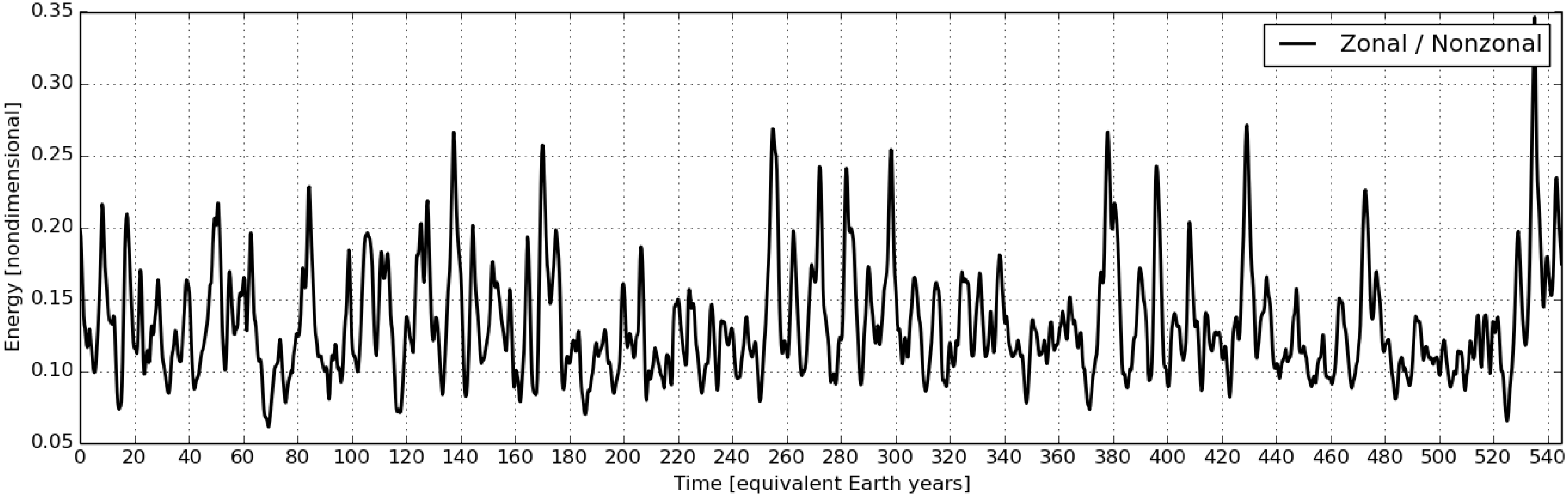


longer-timescale oscillations (multi-decade)

free Alfvén modes (6-year)

[More and Dumberry, IUGG, 2015]

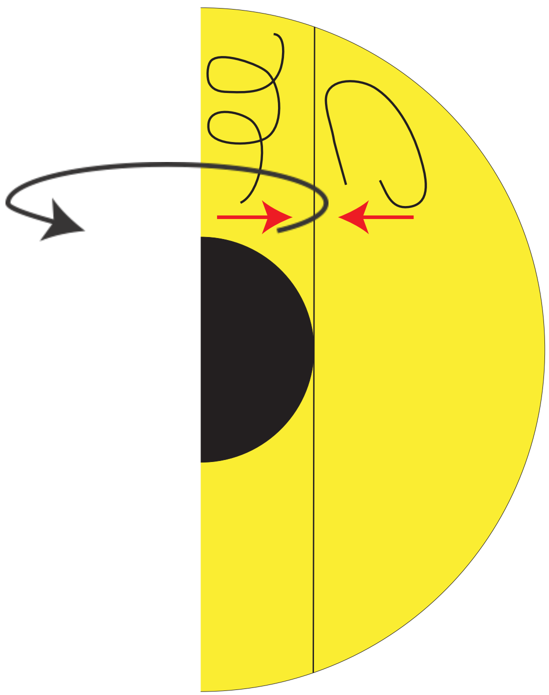
Non-zonal flows dominate over zonal flows

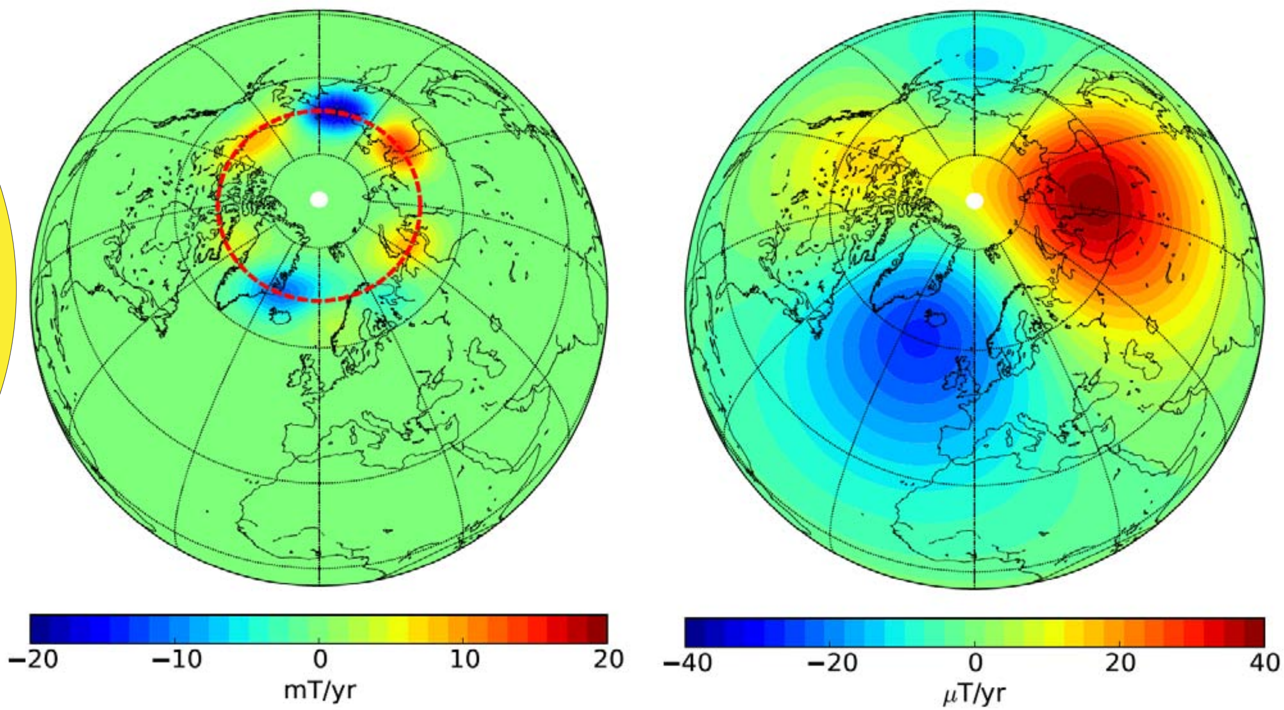


[More and Dumberry, IUGG, 2015]

Geomagnetic signatures of localised jets in the Earth's core

[Livermore and Hollerbach, IUGG, 2015]



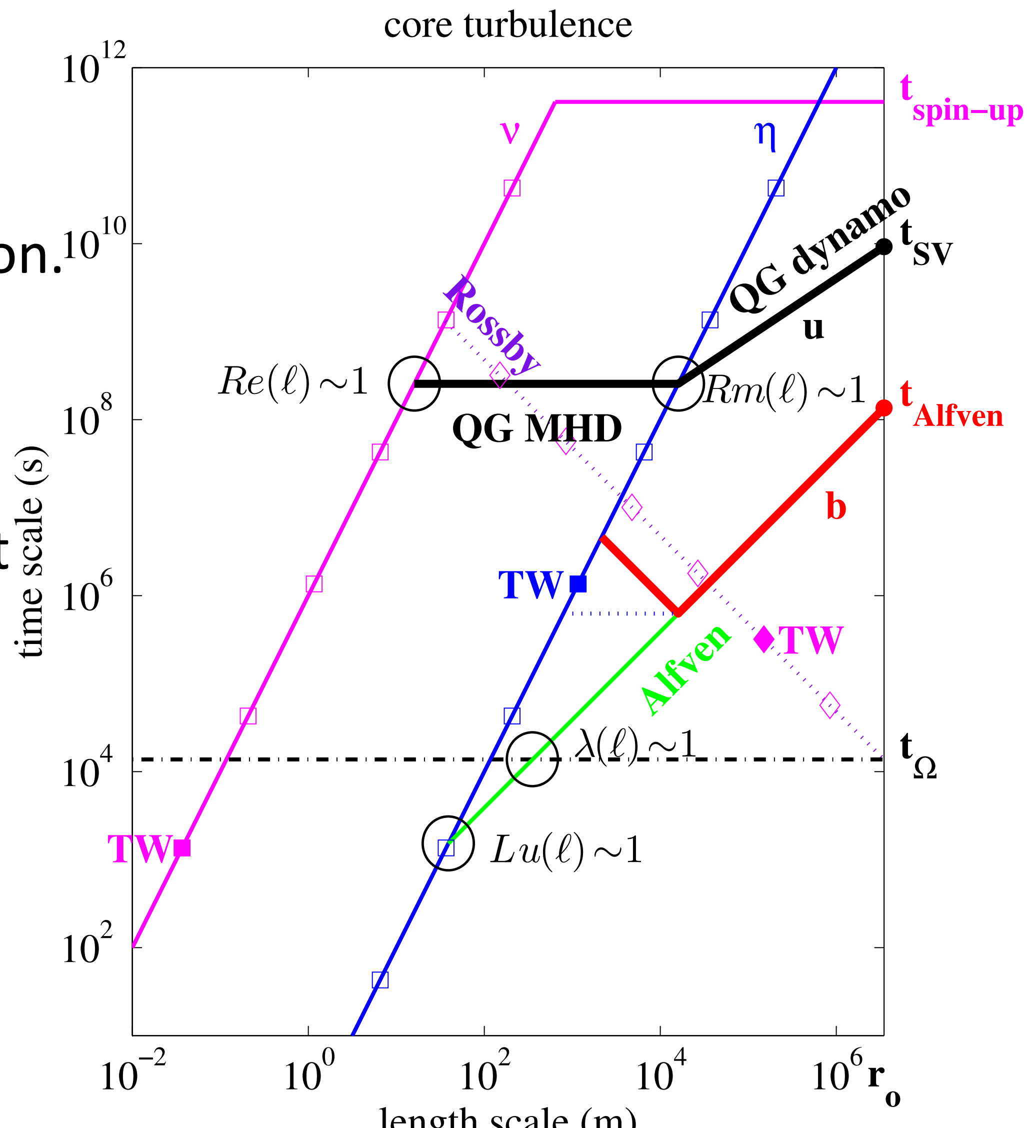


- Tangent cylinder may be an internal boundary
- Net influx of fluid driven into an azimuthal jet
- Such a jet could be as large as ~5 m/s (much larger than currently inferred flows)

Core turbulence: τ(l) diagrams

[Nataf and Schaeffer 2015;
& IUGG, 2015]

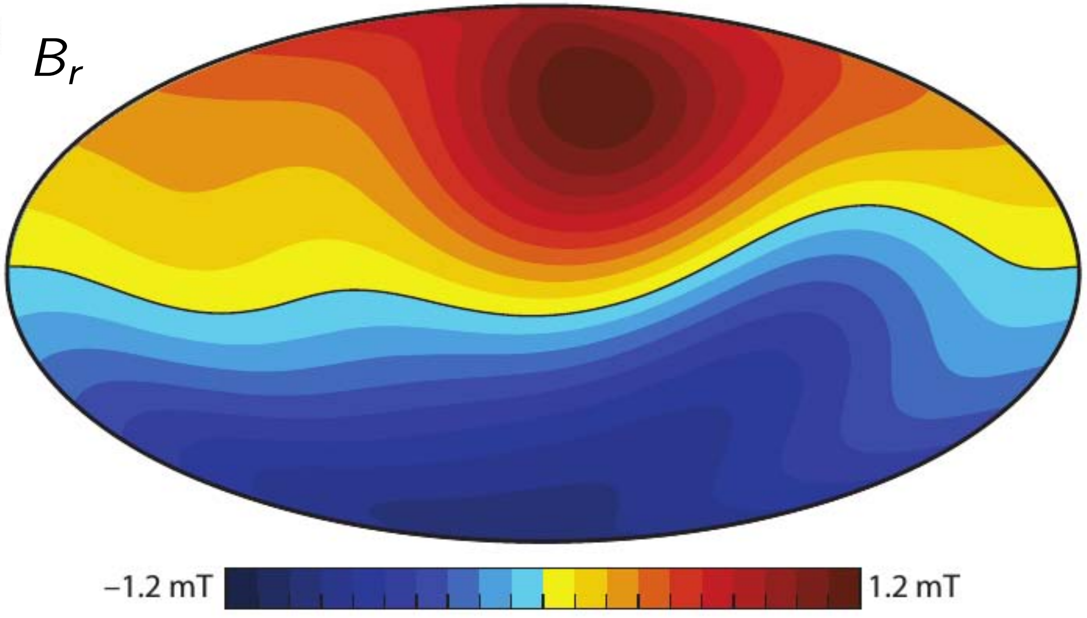
- τ(ℓ) is the typical time-scale at length-scale ℓ for given phenomenon.
- τ-ℓ regime diagrams are akin to the classical *E(k) vs k* spectra, but regime changes are more apparent
- Additional relevant information can be added (total dissipation, wave travel-times, etc)
- Main assumption: the shortest dynamical time-scale controls the turbulence regime.



4. News from the planets

Jupiter: Current knowledge of magnetic field

[Gastine et al., IUGG, 2015]

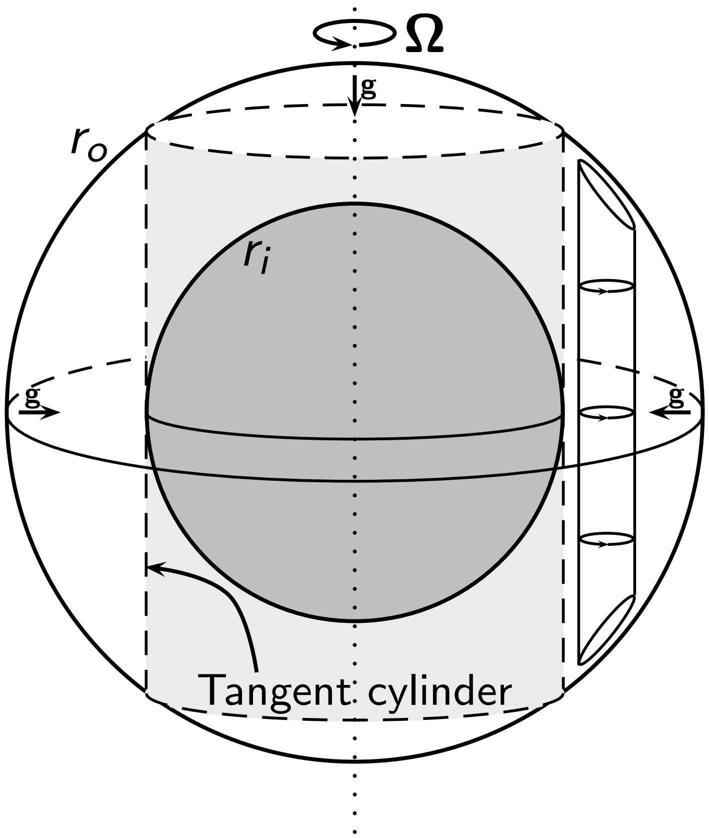


Connerney *et al.* 1998

- Flybys by Voyager, Pioneer + Galileo: **magnetic field up to $\ell_{\mathbf{max}} = 4$**
- Tilted dipole with $\Theta_d \sim 10^\circ$
- **Similar to the geodynamo?**

A dynamo model for Jupiter

[Gastine et al., IUGG, 2015]



Numerical developments

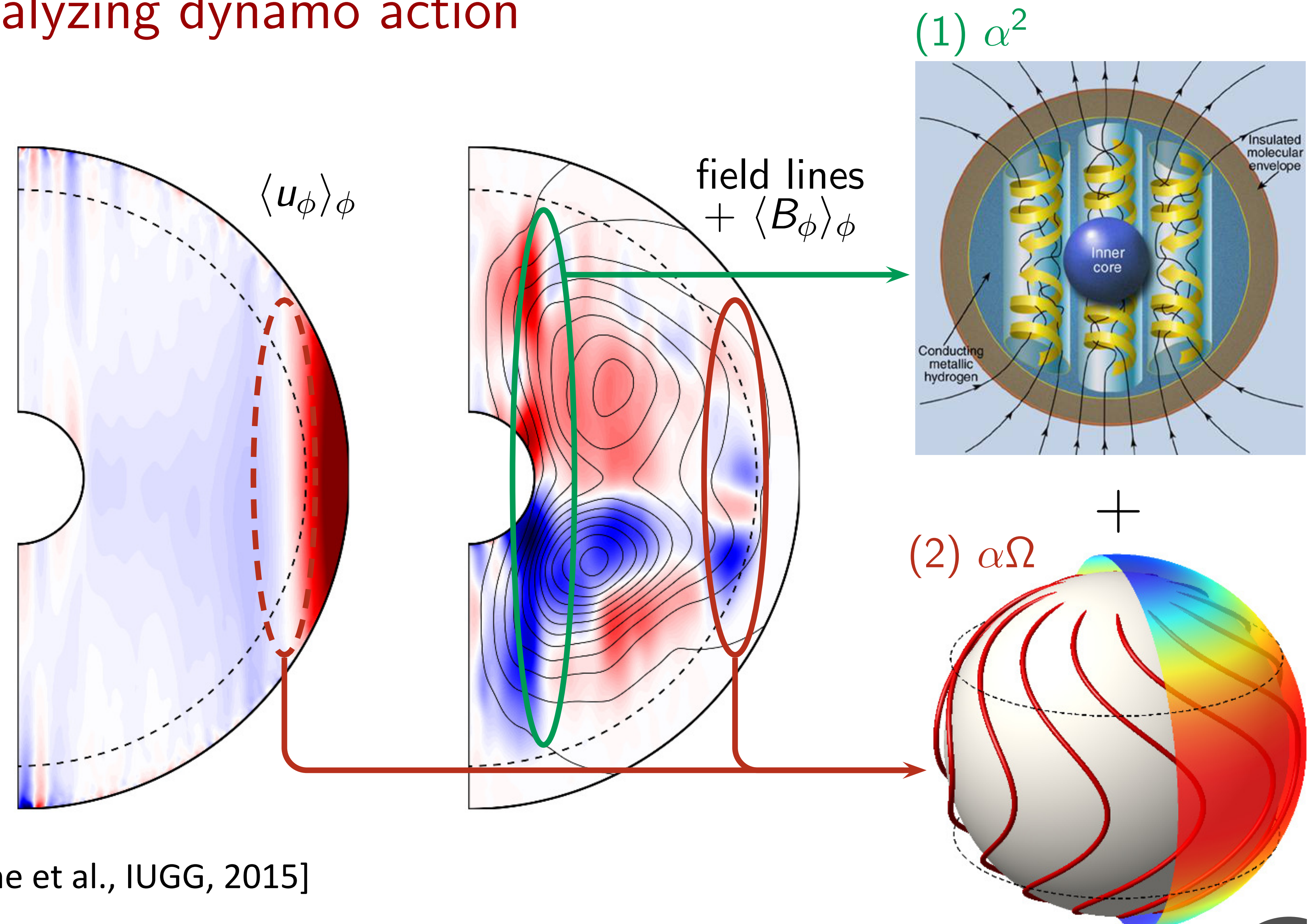
1. Transformation of a Boussinesq code into an **anelastic code**: fast acoustic waves are filtered out but **density stratification effects** are allowed
2. Validation of the numerical devs by an international Benchmark (Jones *et al.* 2011)

Numerical method

- Anelastic approximation: $\nabla \cdot \tilde{\rho}\mathbf{u} = 0$
- 3-D numerical simulations in rotating spherical shells: hydro and MHD
- Pseudo-spectral code: spherical harmonic decomposition

Jupiter's dynamo?

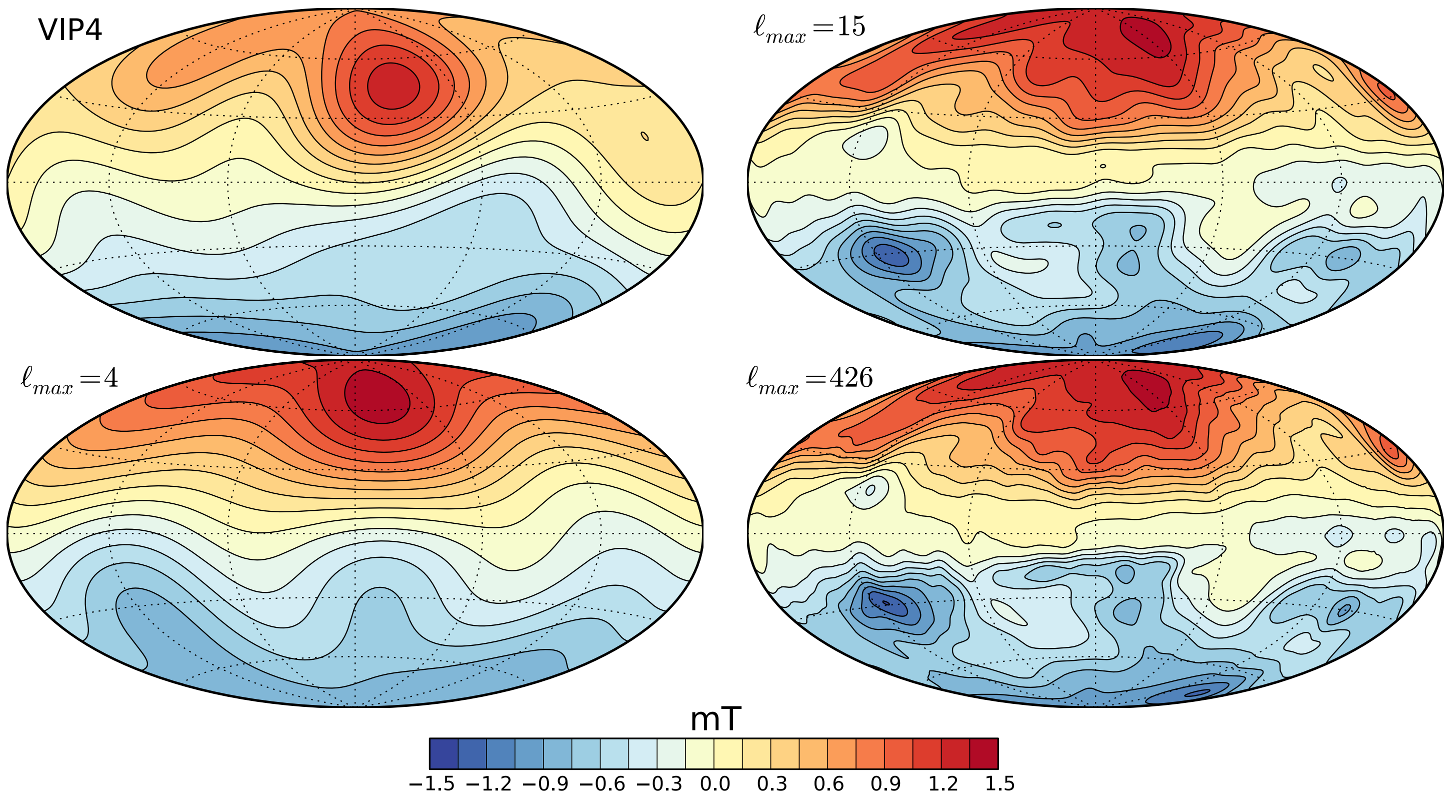
Analyzing dynamo action



[Gastine et al., IUGG, 2015]

Comparison to observed Jovian field

[Gastine et al., IUGG, 2015]



- Good agreement with VIP4 ($\ell \leq 4$)
- All the morphology is essentially captured for $\ell \leq 15$

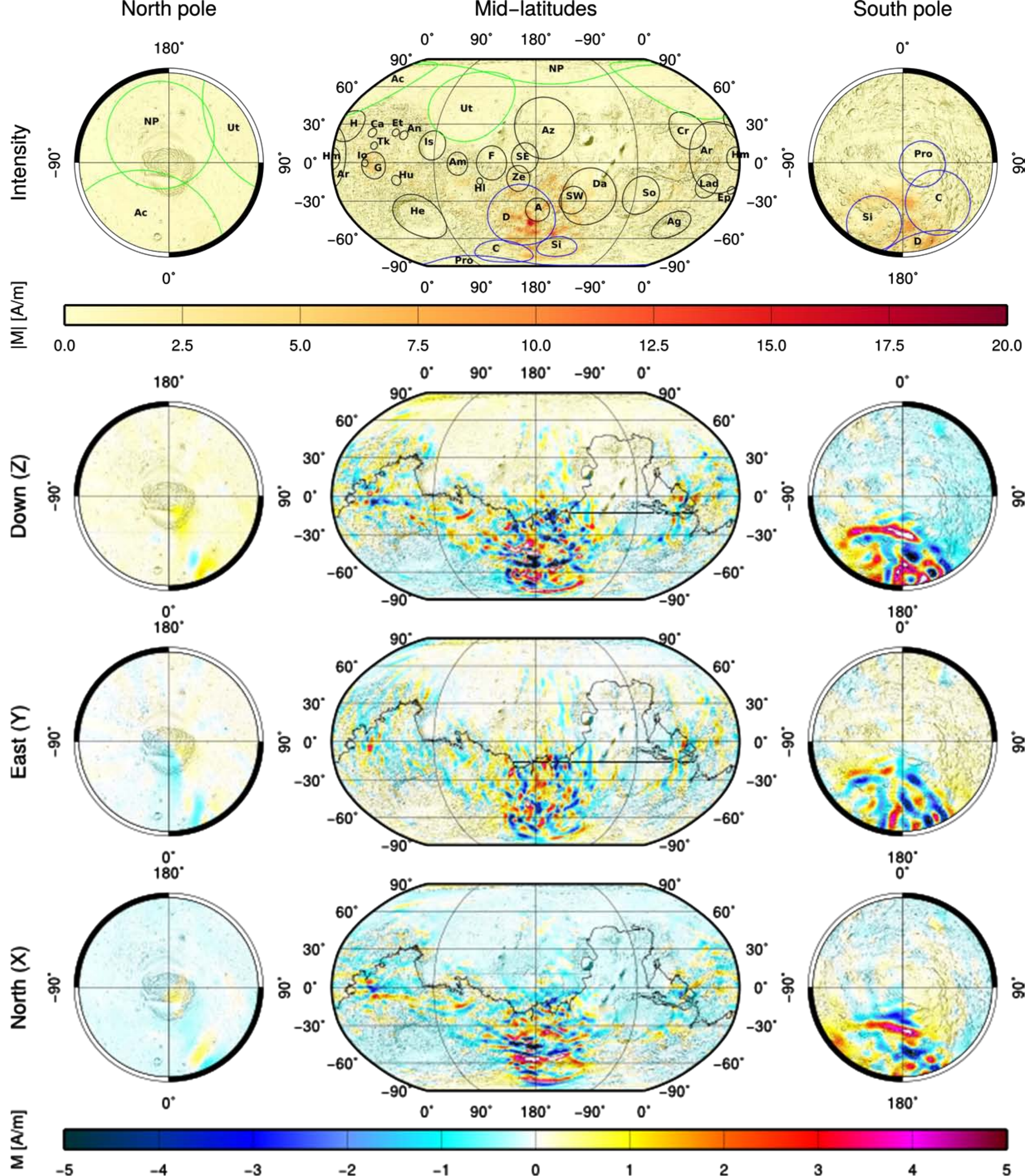
- Dynamo model also shows secular variation – might this one day be observed?

New observations on the way from NASA's JUNO mission

[Gastine et al., IUGG, 2015]

- **Juno**: NASA mission, launched on 5/08/2011
- It will orbit Jupiter in august 2016
- 32-34 polar orbits: 1.06 R_J to 39 R_J
- **Magnetometers**: magnetic field map up to $\ell_{\max} = 15$, secular variation?
- **Gravity experiment**: indirectly infer the jet's signature
- **Microwave radiometer**: help to re-construct the thermal emission of the planet up to 600 kms below the surface

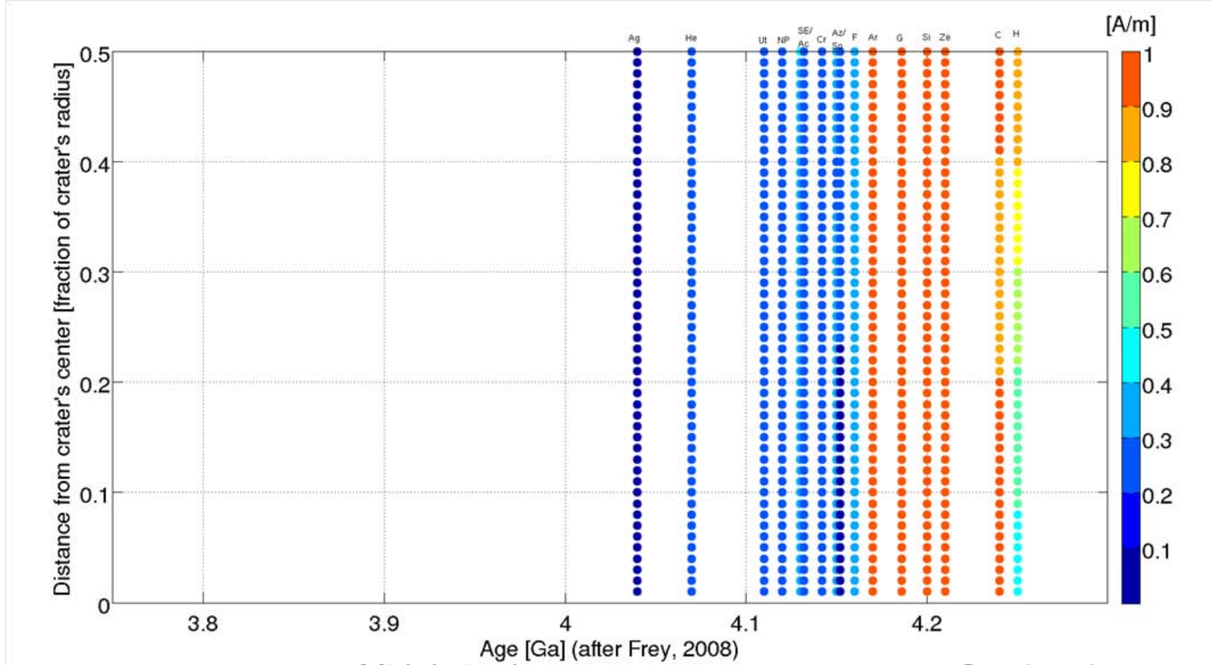
Mars: Observable part of magnetization mapped

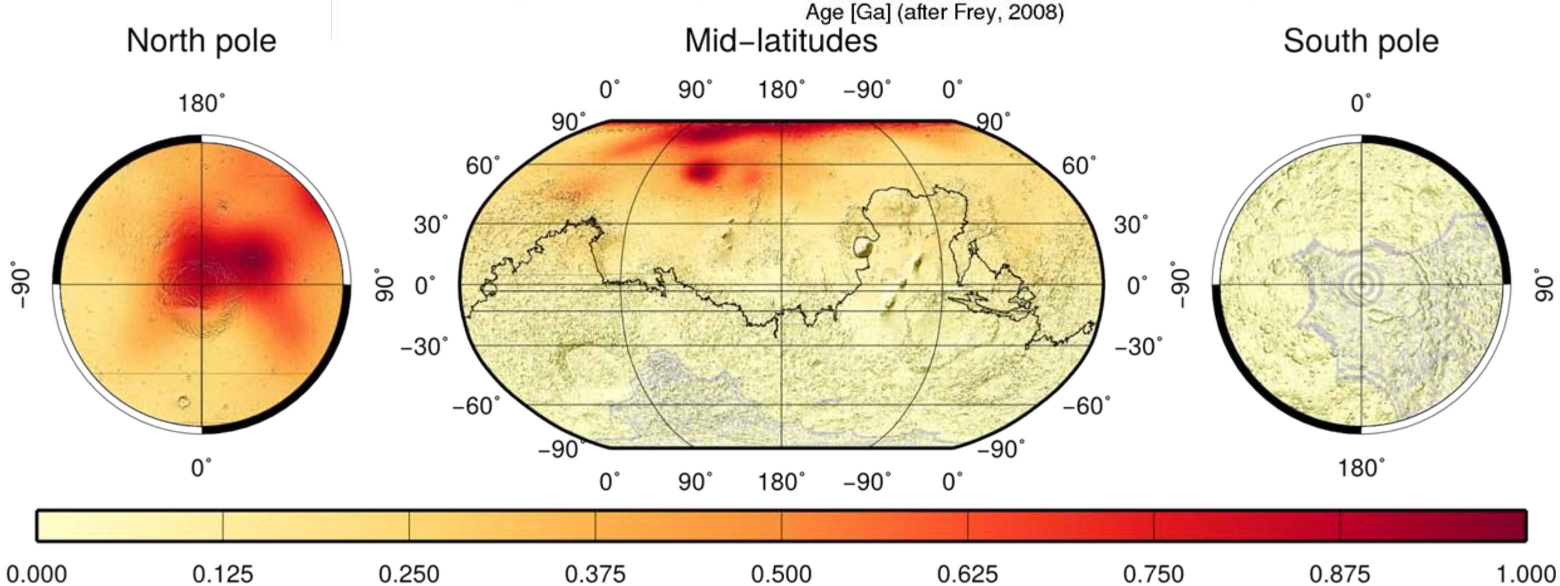


[Vervelidou et al.;
IUGG, 2015]

Mars: Onset of dynamo and paleopoles

[Vervelidou et al.;
IUGG, 2015]

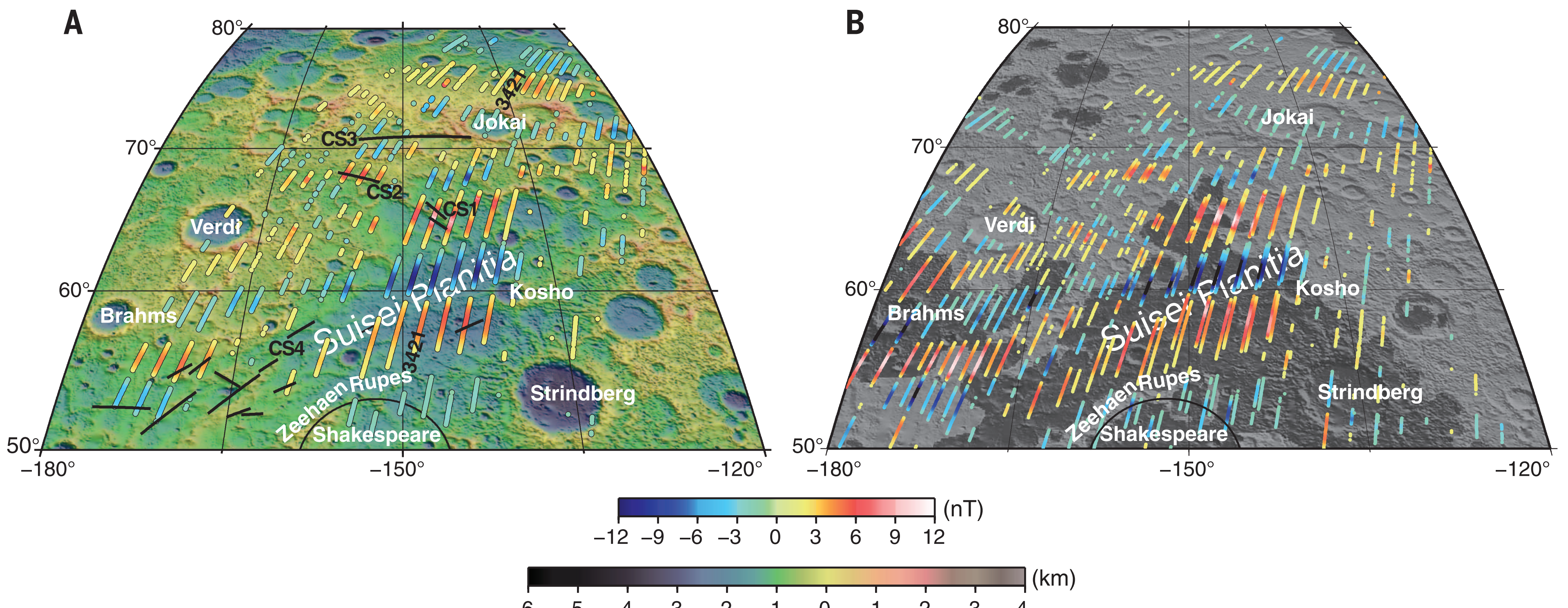




Mercury: Messenger finds possible evidence for a crustal field

[Johnson et al.; 2015]

- Very low altitudes < 150 km (down to 25km!)
- Report detection of remanent magnetization
- Indicates presence of ancient dynamo

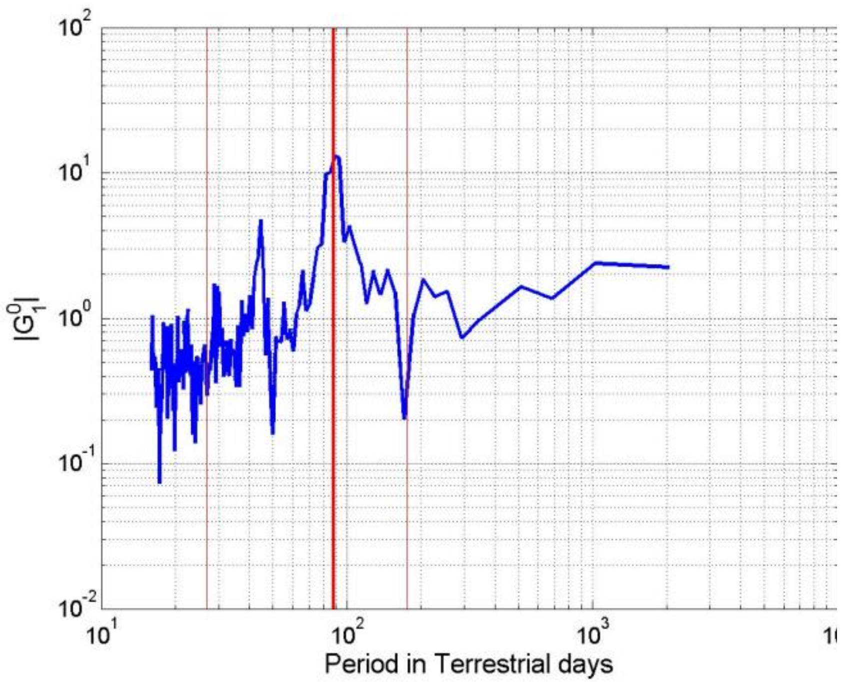


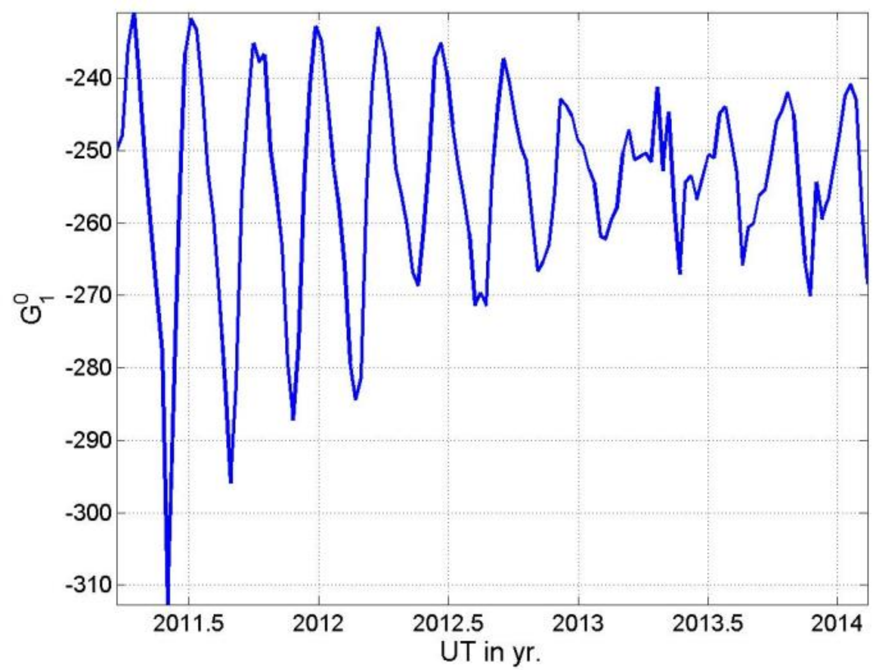
Mercury: Possible evidence of SV?

[Thebault et al., IUGG, 2015]

- Regional modelling of the Messenger data with high resolution in space (1000 km) and time (8 terrestrial days)

- Find evidence for a time variation of the axial dipole field coefficient although they cannot formally rule out that spectral leakage might have occurred.





5. Summary

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- It is an exciting time for our understanding of planetary magnetic fields and geomagnetic secular variation due to:

 (i) improving observations from ground and space
 (ii) new physics-based computational models

- Almost steady, planetary scale gyre(s) account for majority of the observed secular variation
- Physically consistent models of such flows within an EnKF means forecasts of future field behaviour are becoming possible
- Vigorous SA caused by weaker flow perturbations e.g. non-zonal azimuthal jets, especially at low latitudes. Need higher res OBS!
- Very weak torsional oscillations account for interannual ΔLOD

- Core dynamic models are still limited (control params, turbulence)
  New approaches are needed, especially to study rapid SV and SA

- Advances in knowledge of planetary fields (esp. Mercury, Mars, Jupiter) as old observations are re-interpreted with new methods, and new data slowly arrives