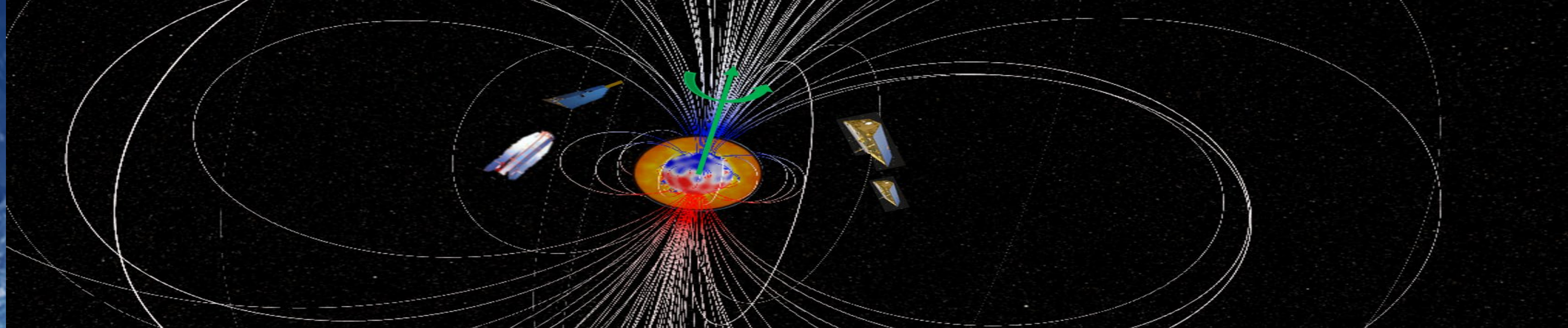

GRACEFUL PROBING THE DEEP EARTH INTERIOR BY SYNERGISTIC USE OF OBSERVATIONS OF THE MAGNETIC AND GRAVITY FIELDS, AND OF THE ROTATION OF THE EARTH

Mioara MANDEA [1], Anny CAZENAVE [2], Veronique DEHANT [3]

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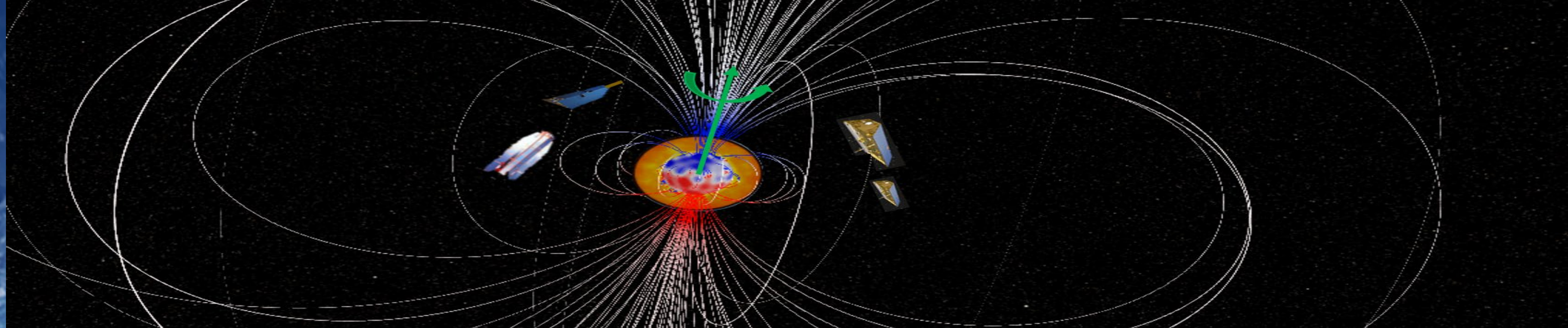

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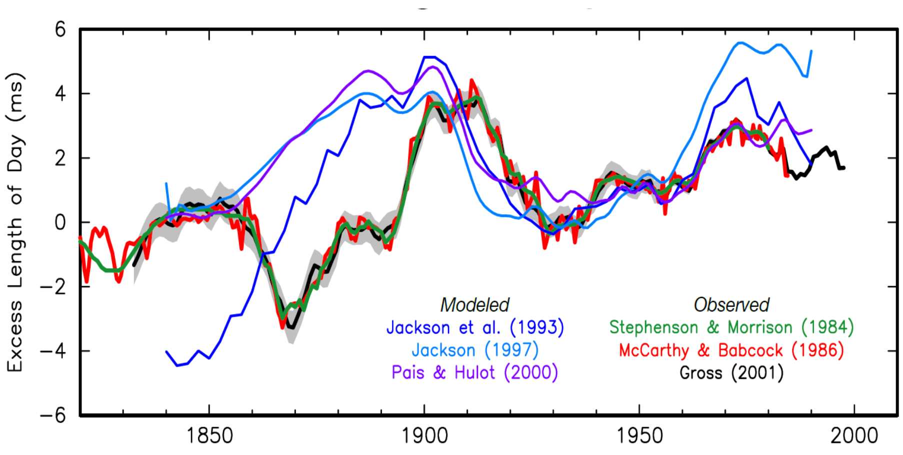
To improve our understanding of physical processes involved in the deep interior of the Earth

- the dynamics of the Earth's fluid iron-rich outer core and its impact on the Core Mantle Boundary (CMB)
- the interaction between the core and the mantle
- the rapid magnetic field variations and rapid flows in the core
- the impact of the core flow on the rotational properties of the Earth

Using in synergy observations of the magnetic and gravity fields of the Earth and of the Earth's rotation (length of day)

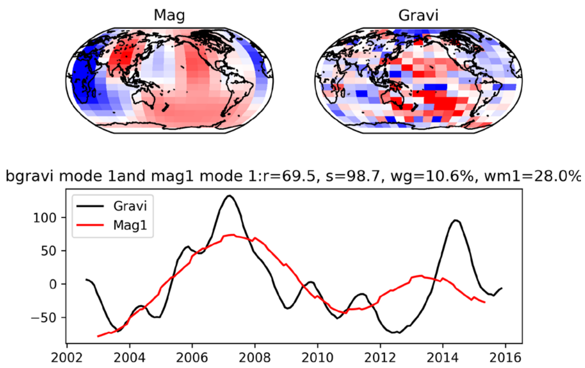
How magnetic, LOD, gravity series are correlated?

1. Decadal oscillations of the LOD are attributed to variations of the core angular momentum deduced from observations of the magnetic field



2. - Spatio-temporal correlation detected for the first time between the magnetic and gravity fields at interannual time scale *[Mandea et al. 2015]*

- Computation of an ACP / Varimax decomposition of the fields separately (trend and seasonal effects removed)



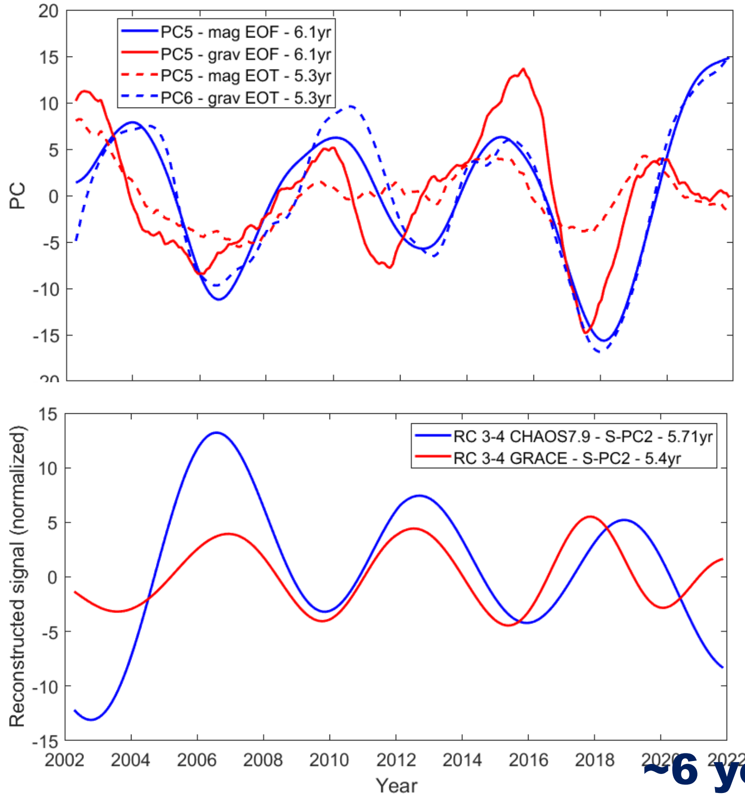
Gravity & magnetic anomalies

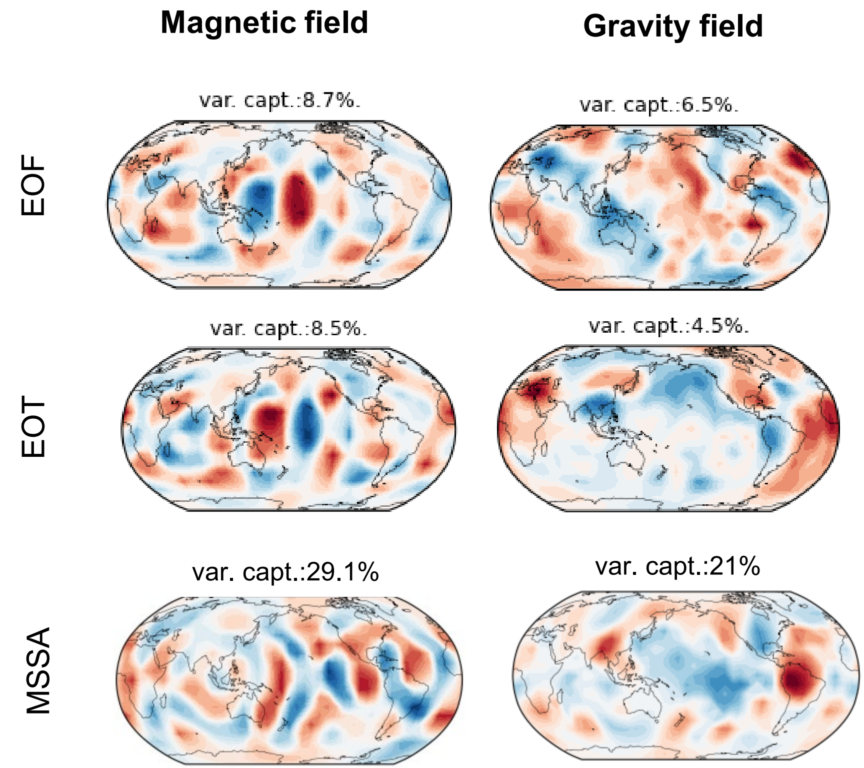
Secular acceleration of magnetic field: CHAOS 7.9 ***[Finley et al., 2020]***

Gravity anomaly field: GRACE/FO – COST-G solution

EOF & EOF

MSSA





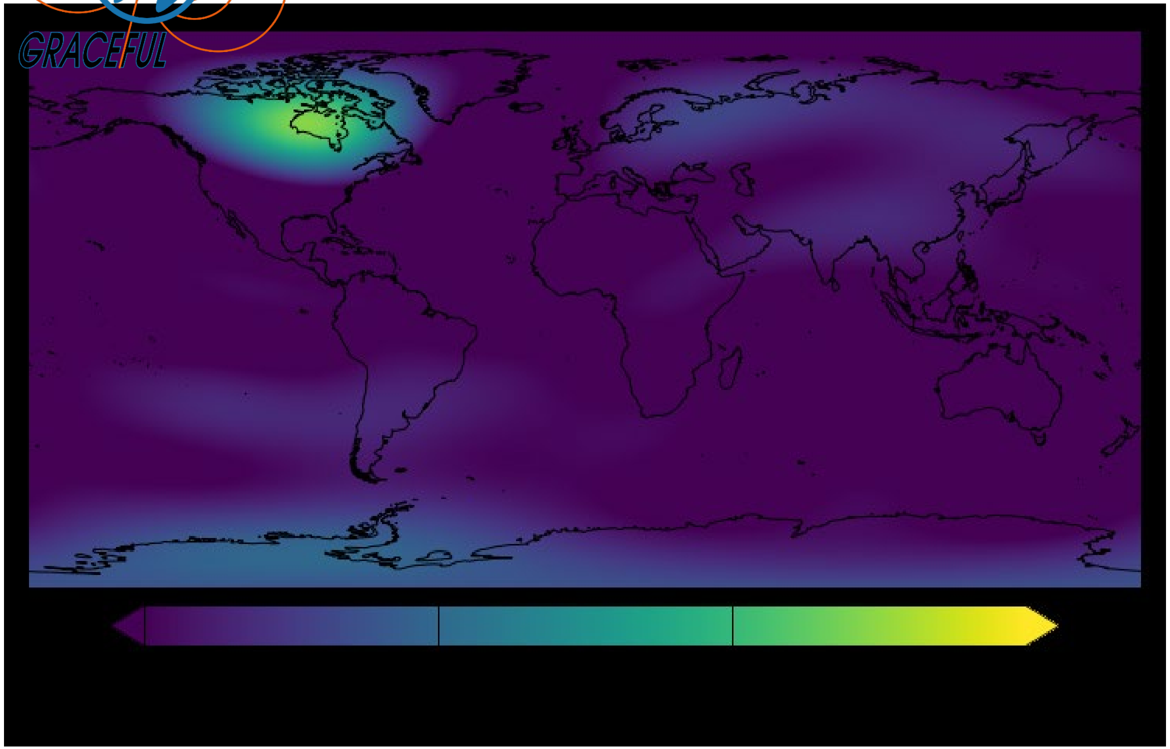
~6 years oscillations from magnetic and gravity field

Trend and seasonal signals are removed before
EOF (Empirical Orthogonal Function)
EOT (Empirical Orthogonal Teleconnection)
MSSA (Multivariate Singular Spectrum Analysis)

Work in progress [Saraswati et al., 2022]

Which **gravity** field contributions?

Work in progress [Lecomte et al., 2022; Pfeffer et al., 2022]



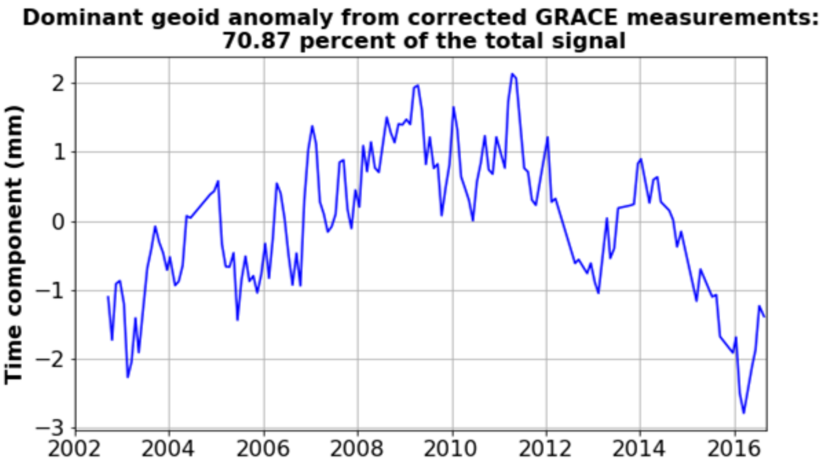
- Effects of Glacial Isostatic Adjustement (GIA) and hydrology loading => to be corrected with several models
- Effects of atmosphere, ocean loading and tides: to be corrected

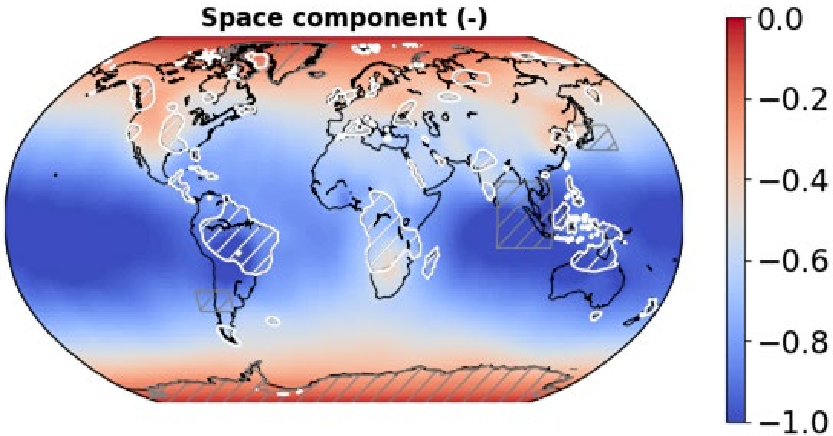
Four models considered: velocity of the GIA model ICE-6G_D VM5a for l<8 [Peltier et al., 2018]
Differences of 1cm/yr error on Antartica = 20% error on $S_{4,1}$, $S_{6,1}$, $S_{8,1}$

Which **gravity** field contributions?

- GRACE data are corrected for surface processes using empirical *[Pfeffer et al., 2022]* and process-oriented models. Masks (all hatches) are applied where models do not satisfactorily predict observations.
- Significant residual gravity anomalies are detected over some continental areas (white hatches) and attributed to slow hydrological processes misrepresented by models.
- Elsewhere, residual gravity anomalies display very large scale features, with remarkable continuity between the oceans and the continents and typical time-scales spanning from a few years to the decade.

MORE INFORMATION ON TUESDAY AT 15h55 talk by Julia Pfeffer during the session A10.02.3 Geodetic Satellite Missions and Their Applications - 3





[Pfeffer et al., 2022]

Which **gravity** field contributions?

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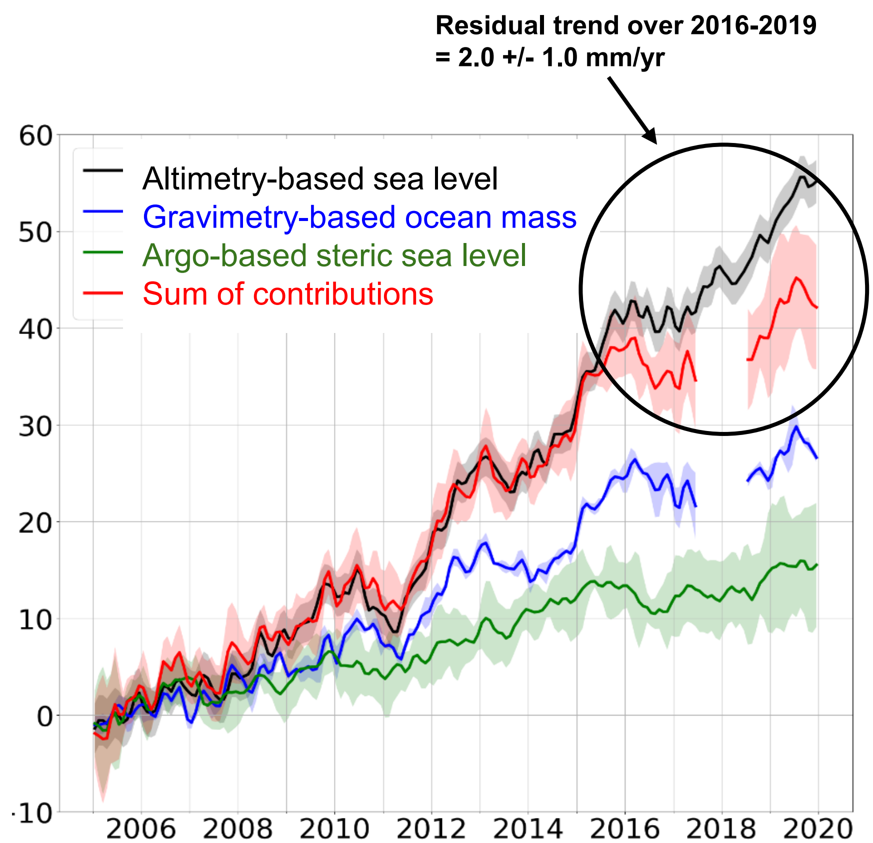
- The global mean sea level (GMSL) budget is no more closed since 2015, meaning that there are errors in any of the three observing systems: altimetry, satellite gravimetry and Argo oceanographic measurements.
- The non-closure was found to be due to:
  - errors in Argo salinity measurements (~40 % of the non-closure)
  - a drift of the radiometer measurements of Jason-3 altimetry satellite, launched in 2016 (~30 % of the non-closure)
- The remaining non-closure can be due to errors in the other components, including the GRACE and GRACE-FO-based ocean mass, or neglected contributions.

MORE INFORMATION ON TUESDAY AT 14h45 talk by Anne Barnoud during the session A10.02.2 Geodetic Satellite Missions and Their Applications - 2



[Barnoud et al., 2021]

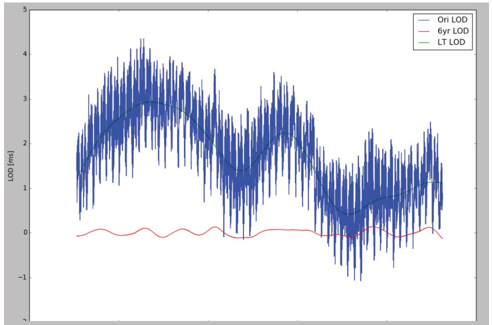
Length-of-day data analysis

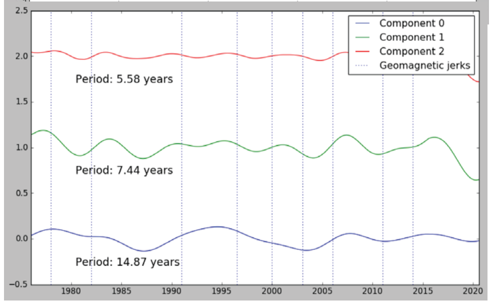
Length-of-day (LOD) IERS series

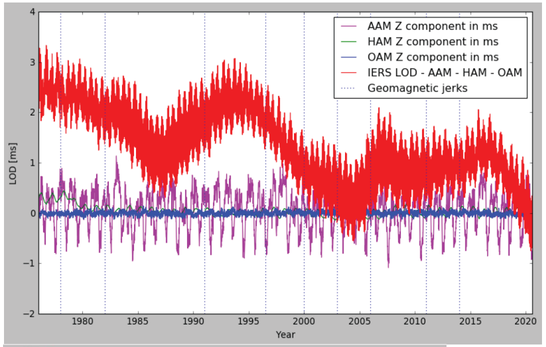
SSA singular spectrum analysis

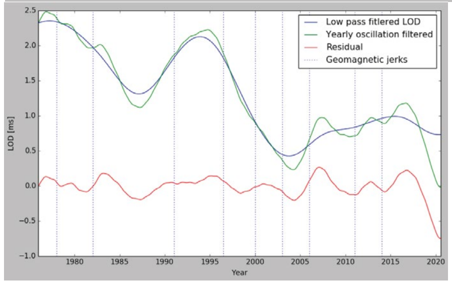
Or any filter

Modes around 6 years









Length-of-day (LOD) corrected for external geophysical fluids

SSA singular spectrum analysis

Or any filter

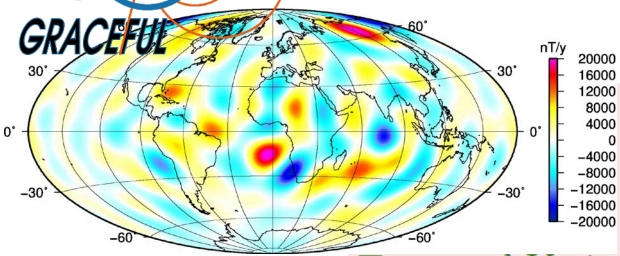
Modes around 6 years

Analyzing LOD variations with or without the external geophysical fluids (atmosphere, ocean, hydrology) indicates:

- observation of the 6-year oscillations, related to the core
- the amplitude seems not to be correlated with the geomagnetic jerks

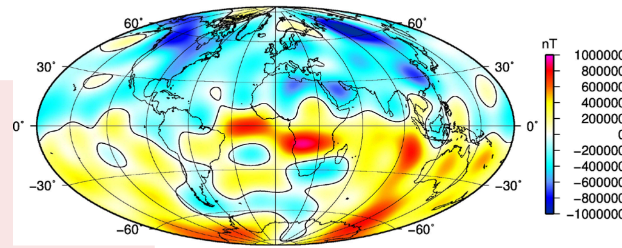
Work in progress *[Ping et al., 2022; Bodranghen et al., 2022]*

Complex processes at the CMB



$$\underbrace{\frac{\partial \mathbf{B}}{\partial t}}_{} = \underbrace{\nabla \times (\boldsymbol{u} \times \mathbf{B})}_{} + \underbrace{\eta \nabla^2 \mathbf{B}}_{},$$

Temporal Variation of B = Induction of B + Dissipation of B



$$\partial_t B_r = -\nabla_H \cdot (B_r \mathbf{u}_H)$$

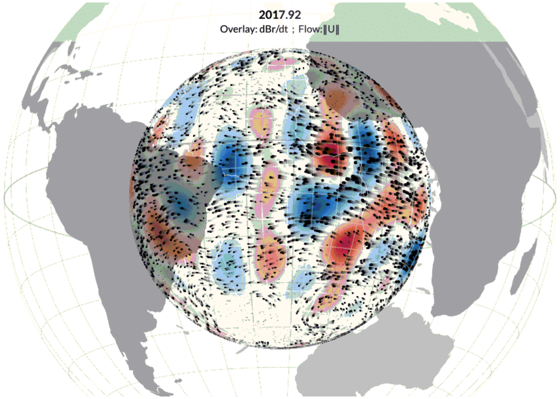
$$2\rho(\mathbf{\Omega} \times \mathbf{u})_H = -\nabla_H p$$

Classical approach

Surface velocity field

u as t_l^m and c_l^m

$$u_{\mathrm{H}} = \nabla \times (Tr) + \nabla_{\mathrm{H}} rS$$



New approach

Inversion for the quasi-geostrophic stream function in the fluid outer core from geomagnetic observations

Interior velocity field

u as q_l^m

$$\mathbf{u} = \nabla \psi \times \nabla\left(\frac{z}{H}\right)$$

Work in progress [Firsov et al., 2022]

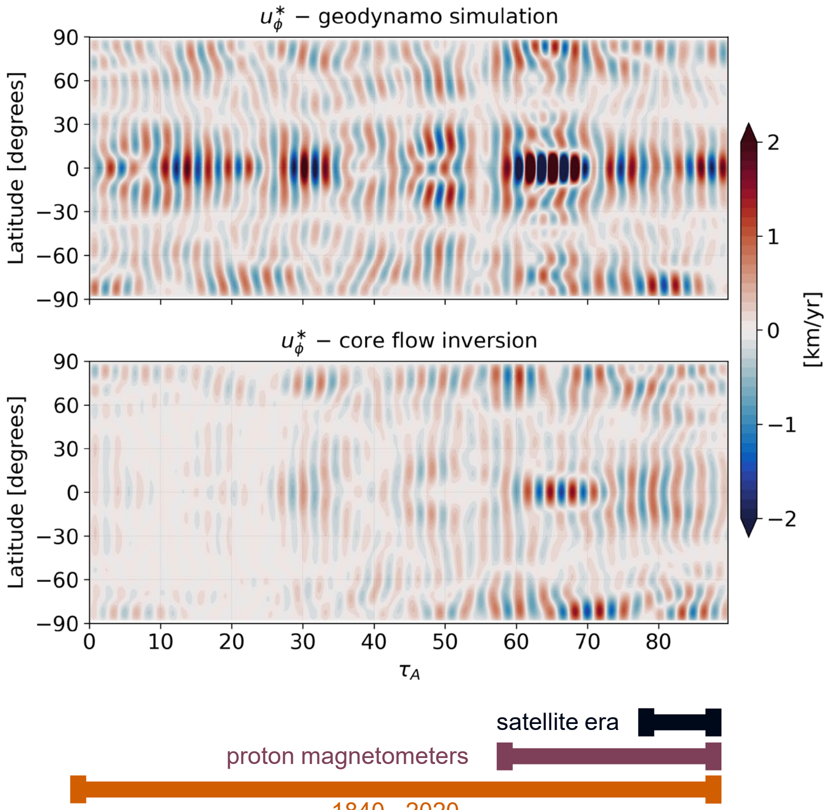
Complex processes at the CMB

Recovery of rapid core motions: a synthetic study

- use numerical geodynamo simulation 71%-path *[Aubert & Gillet, 2021]* to generate synthetic geomagnetic field observations mimicking observatory and satellite coverage
- construct geomagnetic field model from synthetic data, analogous to COV-OBS.x2 *[Huder et al., 2020]*
- invert field model for the flow at the simulated core surface using the data assimilation tool pygeodyn *[Huder et al. 2019]*

How well can we resolve wave-like motions on "decadal" and "interannual" periods?

recovery of axisymmetric flow on "interannual" periods



MORE INFORMATION ON MONDAY AT poster by Tobias Schwaiger during the session Our Solid Earth: From Core to Surface

Work in progress [Schwaiger et al., 2022]

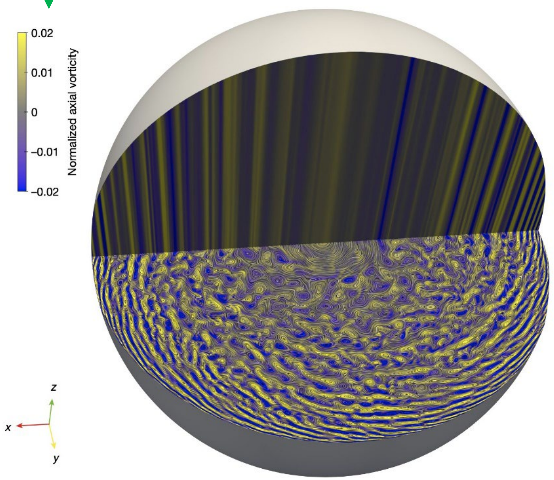
Complex processes at the CMB

Modelling of the core flow with quasi-geostrophic Magneto-Coriolis modes

Pressure gradient force

Geostrophic flow/current

Coriolis force



Reality: not perfect:

quasi-geostrophic

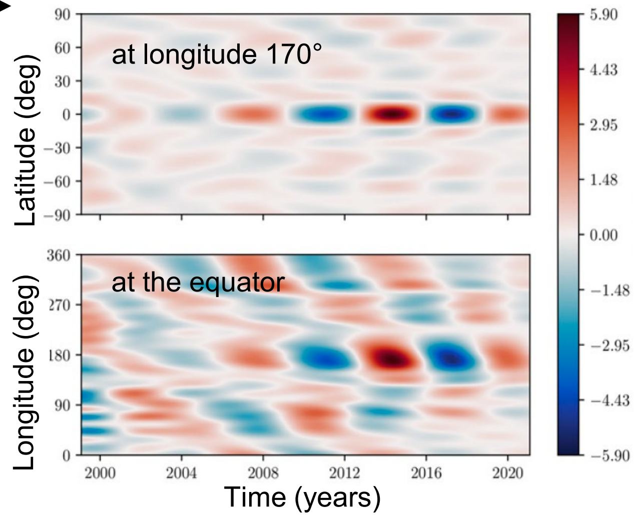
satellite data!

⇨ interannual timescale
(bandpass-filtered between 4 and 9.5

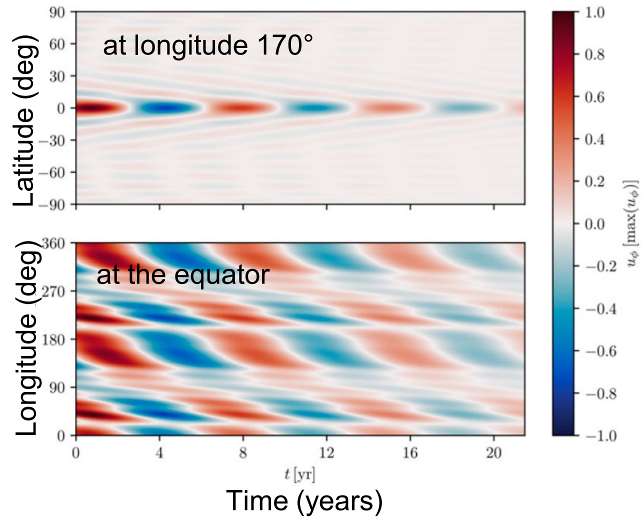
Observation supports axi-symmetry and non-axisymmetric wavelike patterns

= Alfvén torsional waves

Theory for quasi-geostrophic Magneto-Coriolis modes



[Gillet et al., 2022]



MORE INFORMATION ON MONDAY AT poster by Felix Gerick during the session Our Solid Earth: From Core to Surface

Complex processes at the CMB

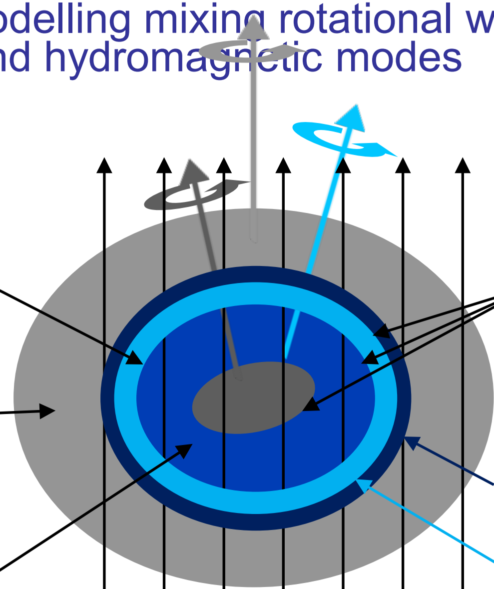
1. Numerical core modelling mixing rotational with gravito-inertial and hydromagnetic modes

"Kore" code

Numerical model where inner core-core-mantle are **fully coupled.**

Tidal forcing in terms of mantle librations, nutations, Length-of-day variations

Rotational normal modes such as FCN and **inertial modes**



Dissipation (ohmic and viscous) in the liquid core and at the core-mantle boundary or inner core boundary

conducting layer at the bottom of the mantle

possible stratified layer at the top of the core

Presence of a **magnetic field**

VLBI observed FCN period and damping

Turbulent viscosity of 10^{-2} m^2/s

Most of the dissipation at CMB

[Triana et al., 2020, 2021]

Work in progress [Triana et al., 2022]

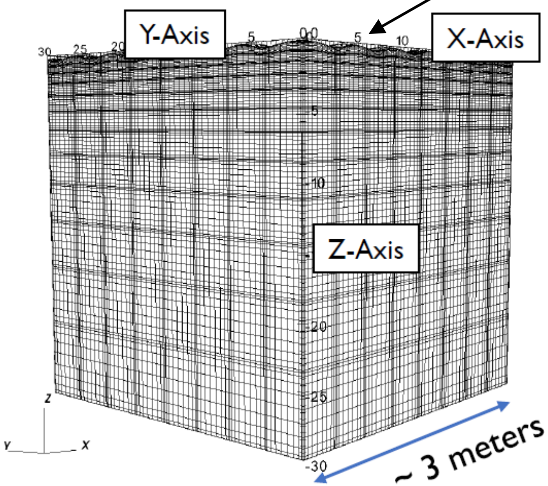
2. Numerical core modelling with stratified layer at top of the core

- Ongoing debate in seismology, thermodynamics, wave dynamics, geomagnetism, geodynamo on the existence of a stratified layer at the top of the Earth's core – PRO & CON
- the bulk of the flow remains unchanged but that for some of the values of the parameters, different types of waves may exist in the stratified layer

Work in progress [Seuren et al., 2022]

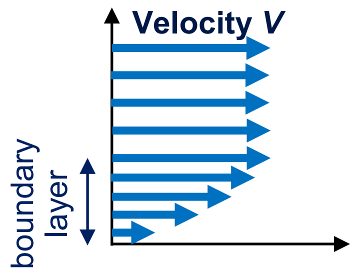
Complex processes at the CMB

1. Small-scale topography effects on core flow - numerical methods



Software Nek5000

Model with viscosity ν



Reynolds number

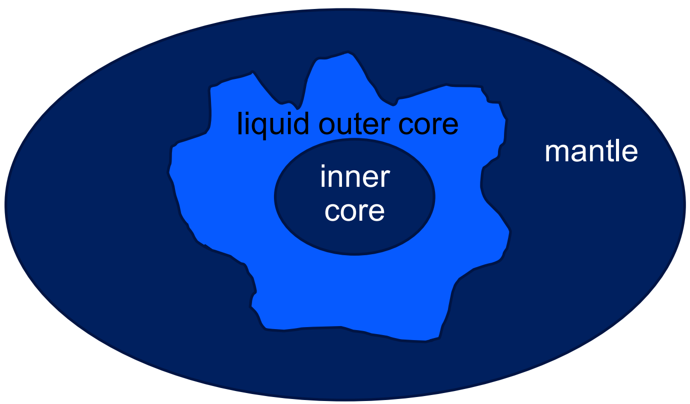
$$Re = \frac{V\,L}{\nu} = \frac{\text{inertia force}}{\text{viscous force}}$$

Earth's core: $Re_{Earth} \approx 500$

Work in progress *[Shih et al., 2022]*

Transition to turbulence $Re \approx 300$
below: laminar above: turbulent
< Re (Earth)
Small-scale topography can increase dissipation.

2. Large-scale topography effects on core flow – analytical method



Work in progress *[Dehant et al., 2022]*

Conclusions and future work

- ***GRACEFUL - already notable progresses***
  - *in analysis of gravity, magnetic field and Earth rotation data*
  - *in numerical and analytical modelling of the core*
- ***More work is needed on data analysis, core modelling, core-mantle topography – to name a few - for bridging the results in a synergistic way***

The research leading to these results has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (GRACEFUL Synergy Grant agreement No 855677).