The limited contribution from outer core dynamics to global deformations at the Earth's surface

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Summary

- Recent studies suggest that interannual changes in the Earth surface deformations and gravity field may be related to the dynamics within the Earth's core [1,2,3]. They highlight in particular a signal of period 6-yr for spherical harmonic coefficients of degree 2 and order 2, of millimetric amplitude, in link with geomagnetic field changes [1].
- We consider the dynamical pressure field at the base of the mantle, associated with core flow models deduced from magnetic data [4]. Following [5,6] we then calculate its signature in term of surface deformations, considering an elastic mantle. Decadal deformations changes are at most of the order of 0.3 mm, while interannual variation are smaller than 0.05 mm, at least an order of magnitude smaller than the reported observations.
- Surface deformations induced by dynamical pressure changes in the core are below the detection level at present-day. Alternative geophysical sources must be sought to explain the observed millimetric interannual variations of the planetary scale topography, and its associated gravity variations. We currently see no justification for a physical relationship between interannual fluctuations of the geomagnetic field and of Earth's observed deformations.
- The largest gravity signal of core origin is potentially associated with decadal longitudinal oscillations of the inner core [7]. It might be detectable as longer series will become available.
- reference: Gillet, Dumberry & Rosat, Geophys. J. Int. (2020)

Dynamical fluid pressure at the core–mantle boundary

- Because deriving the pressure requires the knowledge of the force balance, estimating the pressure is not straightforward when using topological constraints for the kinematic core flow inverse problem (e.g. such as the quasi-geostrophic hypothesis).
- The pressure can be approximated using the tangentially geostrophic (TG) balance between the Coriolis force and the pressure gradient [8]:

$$2\rho\Omega\mathbf{1}_z \times \mathbf{u} = -\nabla p \Rightarrow \mathbf{u}_h = \frac{\mathbf{1}_r \times \nabla_h p}{2\rho\Omega\cos\theta}\,. \qquad (1)$$

- Using a spherical harmonics expansion of the pressure field at the CMB,

$$p(\theta,\phi) = \sum_{n=1}^{N}\left[p_n^0 P_n^0(\cos\theta) + \sum_{m=1}^{n}\left[p_n^{mc}\cos(m\phi) + p_n^{ms}\sin(m\phi)\right]P_n^m(\cos\theta)\right]\,, \qquad (2)$$

we relate the pressure coefficients $p_n^{mc,s}$ to the toroidal–poloidal flow coefficients $t_n^{mc,s}$, $s_n^{mc,s}$ [9]:

$$\text{for } m=0\text{: } p_n^0 = K\left(\alpha_n^- t_{n-1}^0 + \alpha_n^+ t_{n+1}^0\right)\,, \qquad (3a)$$

$$\text{for } m\neq 0\text{: } p_n^{ms,c} = K\left(\beta_{nm}^- s_{n-2}^{m\ \ c,s} + \beta_{nm} s_n^{mc,s} + \beta_{nm}^+ s_{n+2}^m\right)\,. \qquad (3b)$$

Deformations at the Earth's surface

- We use a Love number formulation to estimate deformations at the Earth's surface [5,6]:

$$\text{for } (n,m)\neq(2,0)\text{: } d_n^{mc,s} = \frac{h_n}{\overline{\rho}g}p_n^{mc,s}\,, \qquad (4a)$$

$$d_2^0 = \frac{h_2}{\overline{\rho}g}p_2^0\left(1 - \frac{h_2^\Omega}{h_2}\frac{\overline{\rho}}{\rho}\frac{I_c}{I_m}\left(\frac{a}{c}\right)^2\right)\,. \qquad (4b)$$

- The h_n are Love numbers based on the PREM model. See the table for the definitions of variables.

name	symbol	value	units
Earth radius	a	6.371×10^6	m
outer core radius	c	3.485×10^6	m
inner core radius	b	1.280×10^6	m
Earth rotation rate	Ω	7.292×10^{-5}	s^{-1}
outer core density at the CMB	ρ	9.903×10^3	$kg\ m^{-3}$
mean density of Earth	$\overline{\rho}$	5.515×10^3	$kg\ m^{-3}$
core moment of inertia	I_c	0.908×10^{37}	$kg\ m^2$
mantle moment of inertia	I_m	7.129×10^{37}	$kg\ m^2$
gravitational acceleration at the surface	g	9.820	$m\ s^{-2}$
Mass of Earth	M	5.972×10^{24}	kg
gravitational constant	G	6.674×10^{-11}	$m^3\ kg^{-1}\ s^{-2}$

Table: Geophysical parameters used to estimate surface deformations and Stokes coefficients.

The limited topography changes from outer core dynamics

- If the pressure spectrum is rather flat at the CMB, the spectrum for surface deformations is steep (see Fig. 1) due to the steep decrease of the h_n with harmonic degrees.

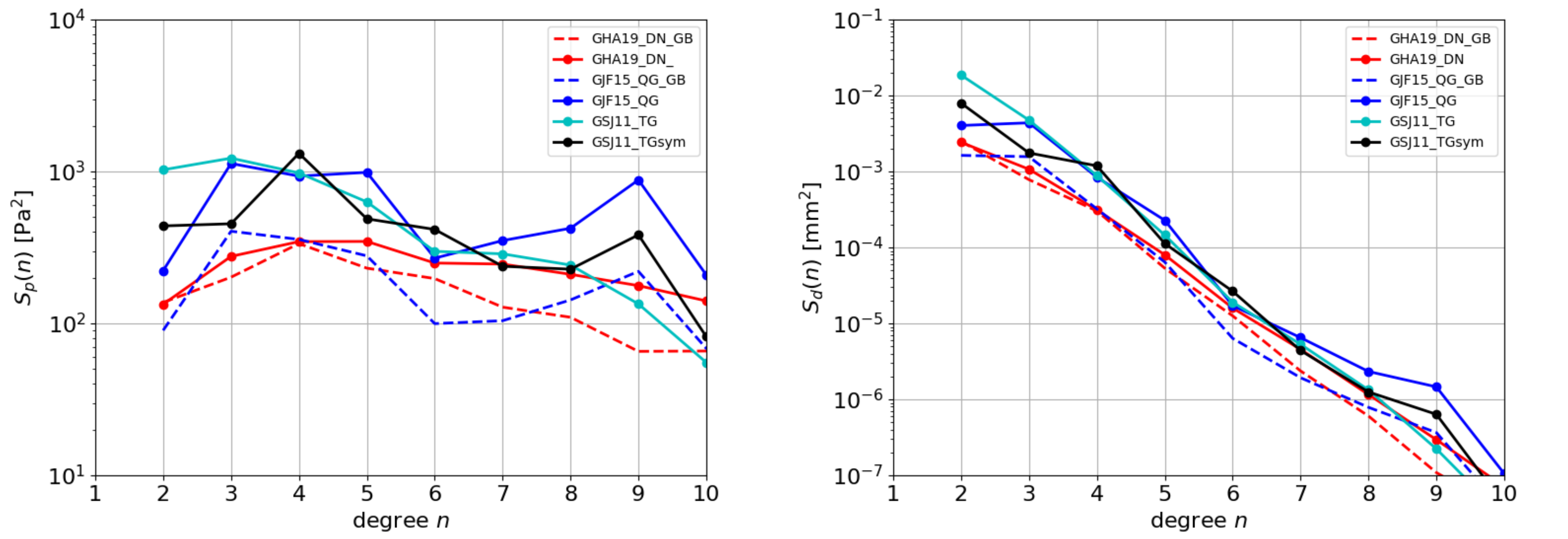

Fig. 1- Spatial spectra for the deformations at the Earth's surface (right) and the fluid pressure anomaly at the CMB (left), obtained for several core flow models.

- Global deformations are at most 0.3 mm for both zonal and non-zonal motions. They are one order of magnitude weaker at interannual periods (Fig. 2), because the temporal power spectrum of core motions decreases towards short period [4].

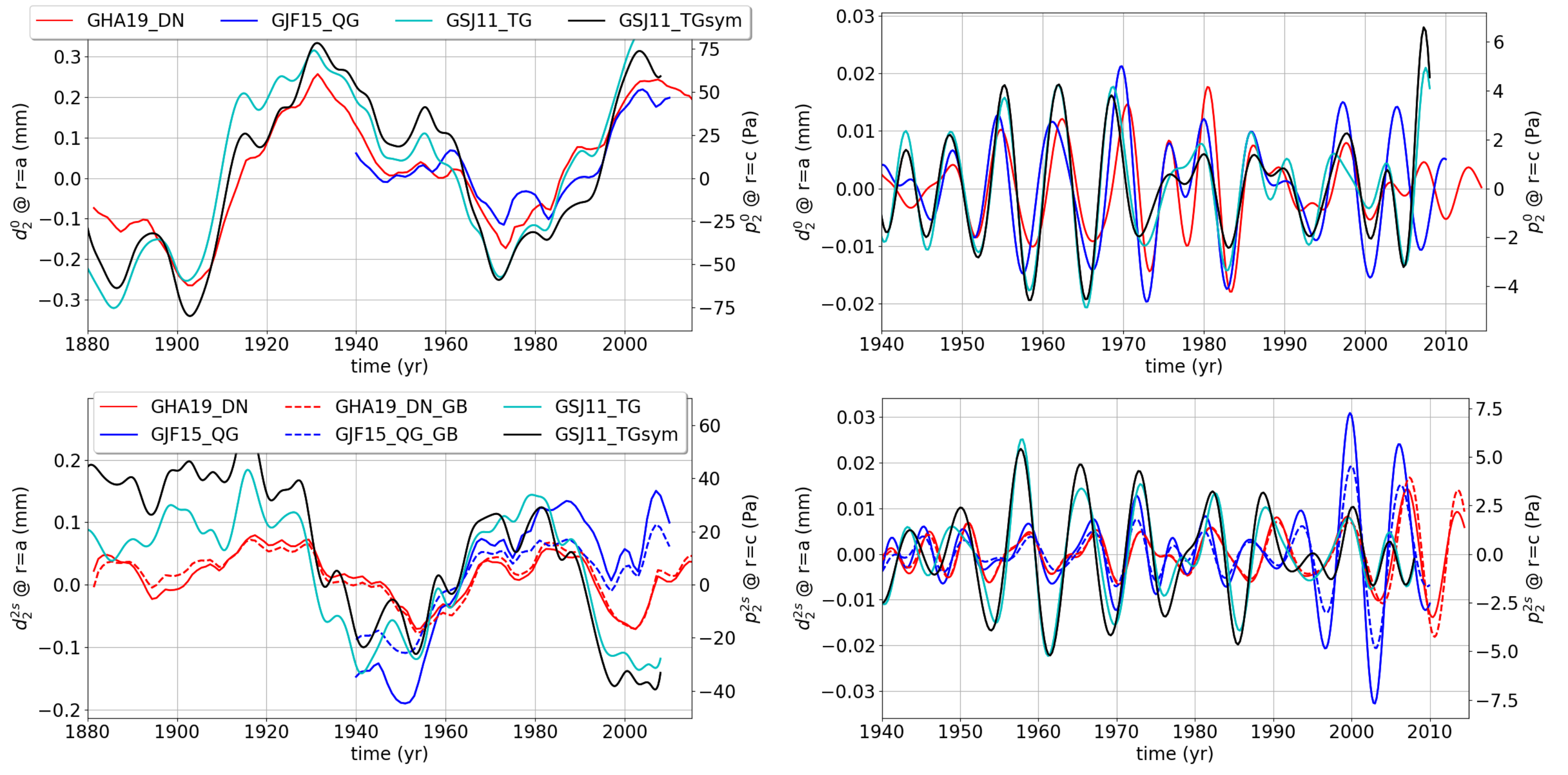

Fig. 2- Left: time series of the vertical deformation at the Earth's surface (left y-axis, in mm) for coefficients d_2^0 (top) and d_2^{2s} (bottom), for different flow models. The change in the associated coefficients of pressure at the CMB p_2^0 and p_2^{2s} is indicated on the right y-axis (in Pa). The extension '_GB' indicates a projection of the flow model onto a TG basis. Right: time series band-pass filtered between 4 and 9.5 yr. The legend is common to all 4 panels. .

- At interannual periods we miss about two orders of magnitude to reach the level of measured deformations at Earth's surface (see Fig. 3).

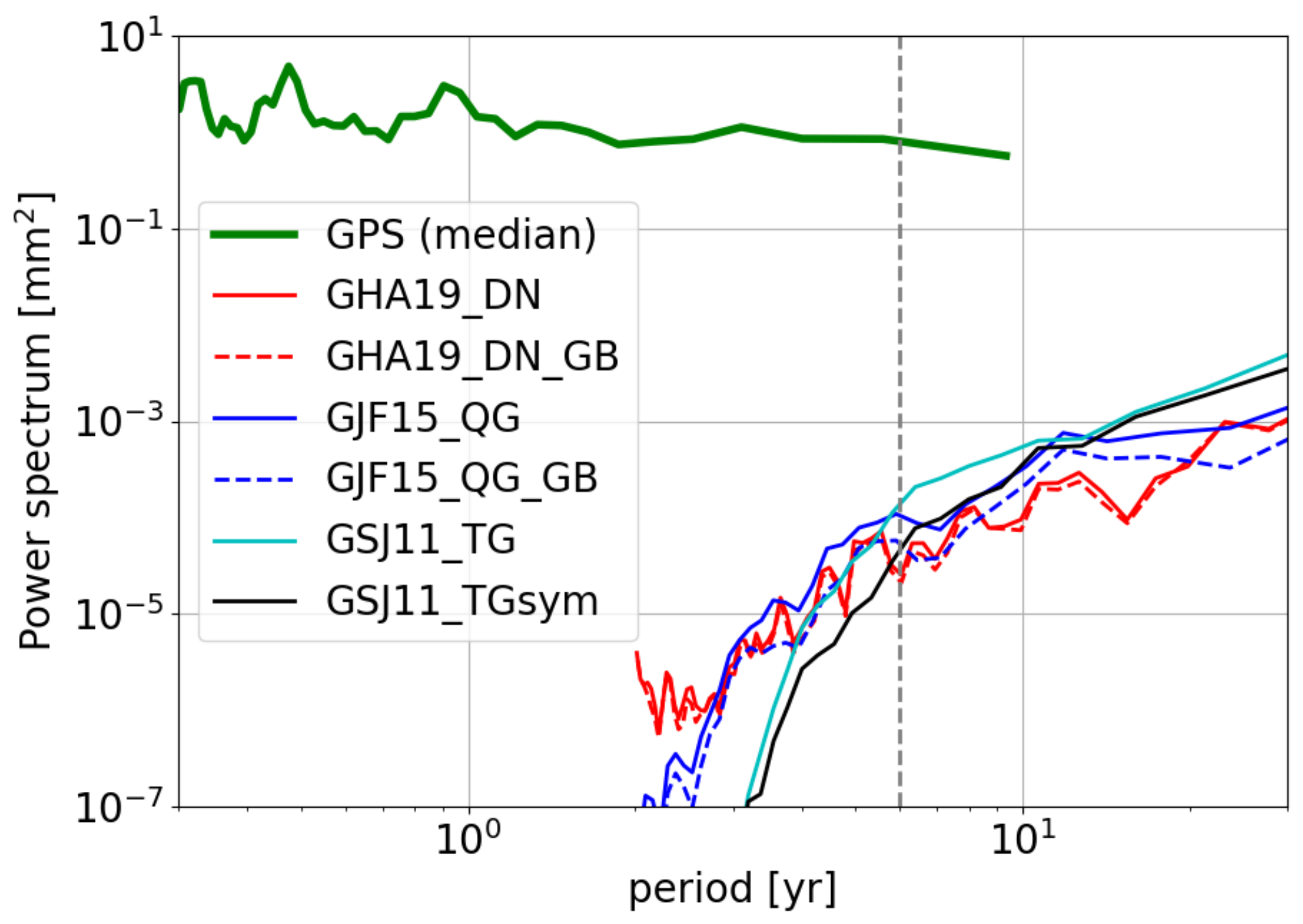

Fig. 3- Power spectra of deformation series at the Earth's surface, in mm^2. In bold green the median power spectrum level taken over the set of 63 GPS stations (from the International GNSS Service) covering a time-period longer than 18 yr. Other series represent the r.m.s. power at the Earth's surface), for predictions from the several core surface flow models. The vertical dotted line indicates the 6-yr period.

The lack of evidence for a connection between surface deformations and geomagnetic field changes

- Lets consider the simplest possible TG flow. If responsible of 1.7 mm Y_2^2 deformations as in [1], it would induce a geomagnetic signal ways too large (see Fig. 4).

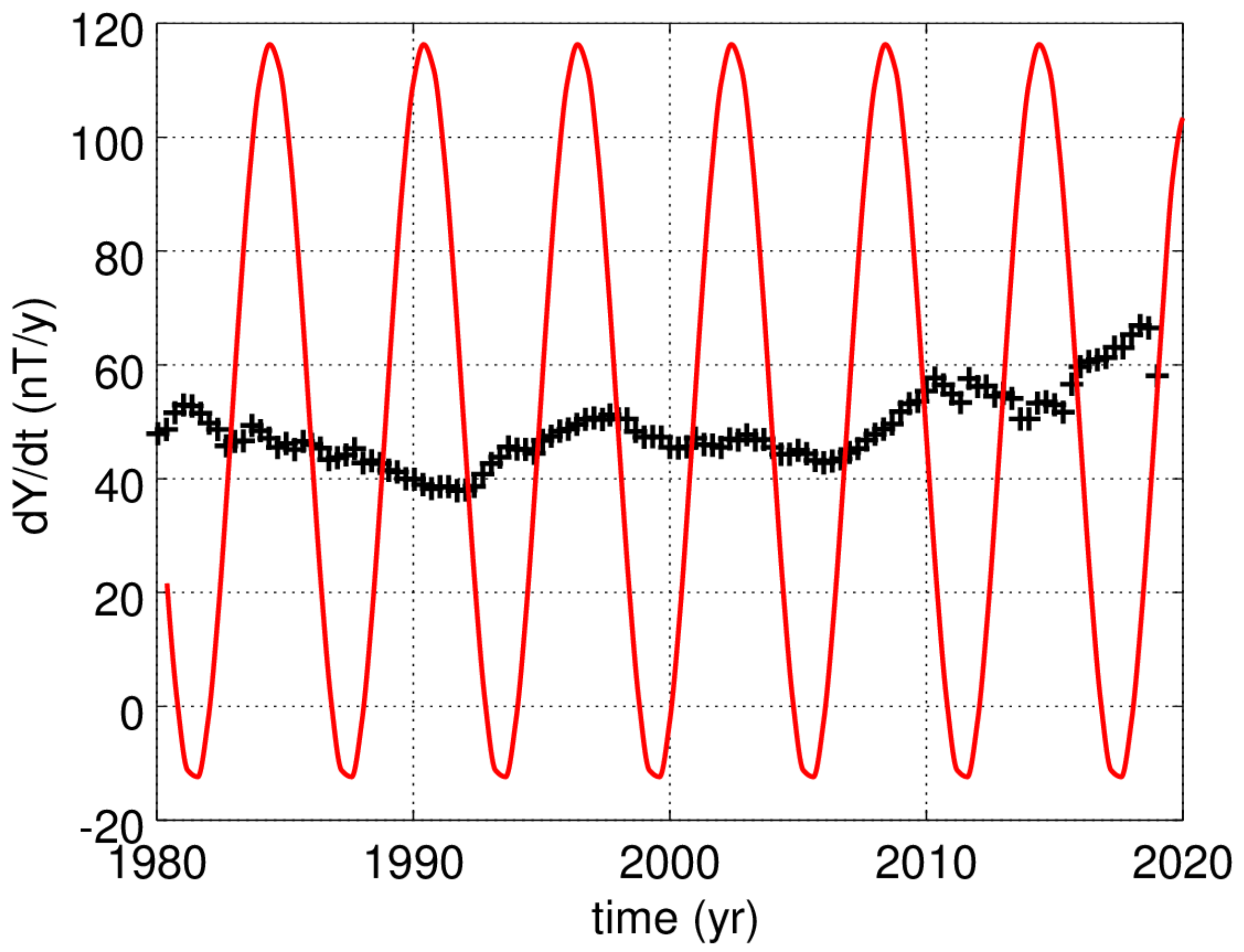

Fig. 4- Eastward component of the rate of change of the magnetic field, dY/dt, at the ground-based observatory of Chambon-la-Forêt in France (in nT yr^{-1}): annual difference of 4-monthly means (black crosses), and prediction (red solid line) for a simple TG core surface flow.

Gravity field variations induced by fluid motions at the core surface

- Stokes coefficients for the gravity field are directly related to pressure coefficients through [10]

$$\left(\Delta C_{nm}, \Delta S_{nm}\right) = \frac{k_n}{\sqrt{2n+1}}\frac{a}{GM\overline{\rho}}\left(p_n^{mc}, p_n^{ms}\right)\,, \qquad (5)$$

- For degree 2, 50 Pa decadal changes in p_2^2 (see Fig. 2) lead to $\Delta C_{22} \approx 4 \times 10^{-12}$. This is one order of magnitude weaker than observed variations [11].
- 4 Pa interannual changes in p_2^2 correspond to $\Delta C_{22} \approx 4 \times 3 \times 10^{-13}$, again much weaker than the observed variations.

Gravity field variations induced by an oscillating inner core

- because of the density drop at the inner–core boundary ($\Delta\rho \sim 600$ kg/m^3), for a Y_2^2 topography the inner core of height $h \sim 15$ m (from the degree-2 CMB geoid), an oscillation of the inner core of amplitude ϕ_0 and period T will induce gravity changes [7]

$$\Delta S_{22} \propto \frac{b^4}{Ma^2}h\Delta\rho\phi_0\sin(2\pi t/T)\,. \qquad (6)$$

- Supposing motions invariant along the ortation axis, ϕ_0 can be approximated from the zonal flow $\overline{v}_\phi$ at the core surface at the cylindrical radius $s=b$, as $\phi_0 = T\overline{v}_\phi/(2\pi b)$.
- Core flow models indicate $\overline{v}_\phi \approx 2$ km/yr at 30 yr period and ≈ 0.4 km/yr at 6-yr periods [4]. This corresponds to $\Delta S_{22} \approx 1.5 \times 10^{-11}$ and $\approx 5 \times 10^{-13}$, respectively.

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