ON THE POSSIBLE SOURCES TO INTERANNUAL DEFORMATIONS AT THE EARTH'S SURFACE

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ABSTRACT. Signals of period around 6 years were recently observed in GNSS observations, and tentatively attributed to the dynamics of the fluid core. Fluid core motions may indeed induce changes in the fluid pressure acting at the core boundaries, and thus in the Earth's surface topography when considering an elastic mantle. However, we find unlikely the possibility for an interannual deformation of some mm at the Earth's surface due to core flows. We perform a spectral as well as a spherical harmonic analysis of more than 18 years of GNSS observations and confirm the existence of the 6-year signal previously detected. We also find a significant amplitude of hydrological loading effects at such periods. These should be considered when interpreting interannual deformations.

1. INTRODUCTION

Accessing the Earth's deep interior from surface observations is challenging. Constraining fluid flows acting in the Earth's core is possible using geomagnetic data (in particular through the rate of change of the core field). However, core flow models obtained this way suffer of non-unicity and are limited to large length-scales (e.g. Holme, 2015) and periods longer than a couple of years, due to ambiguities between core and external magnetic fields towards higher frequencies (see Gillet et al. 2015). Fluid core motions possibly induce global elastic deformations through changes in the non-hydrostatic pressure acting on the core-mantle boundary (CMB) (see Dumberry 2010).

Flows near the core boundaries may result in torques acting on the mantle and inner-core (e.g. Roberts & Aurnou, 2012). If we apply a torque at the CMB, the angular momentum conservation between the fluid core and the mantle will result in perturbations of the Earth's rotation (Jault et al., 1988; Jault & Finlay, 2015). Decadal variations in the length-of-day (LOD) have been observed and attributed to the core fluid motions (e.g. Gillet et al., 2019). On interannual time-scales, a 6-year periodic oscillation in LOD has been isolated (Abarca del Rio et al., 2000; Chao et al., 2014), which is not attributed to external fluid envelopes (Gross et al., 2004). This interannual signal was later on confirmed by Holme & De Viron (2013), who proposed a correlation with geomagnetic jerks.

Fluctuations of period about 6 yr were also detected in GNSS data (GPS data only), and related to magnetic field changes by Ding & Chao (2018), who postulate that a non-zonal (degree-2 and order-2) pressure wave travels within the core. A potential link between this 6-year GPS signal and axisymmetric core flows was proposed by Watkins et al. (2018). A possible interpretation involves the libration of the solid inner core under its gravitational coupling with the mantle (Mound & Buffett, 2003, 2006; Davies et al., 2014). Axi-symmetric motions at the core surface, imaged from independent magnetic observations, explain the above subdecadal LOD oscillations if interpreted as the signature of geostrophic (i.e. axially invariant) motions, as are torsional Alfven waves (Gillet et al., 2010, 2015). Their excitation mechanism remains an open issue. Aubert & Finlay (2019), analysing high resolution geodynamo simulations, put forward the possibility of jerks triggerred by localized (non axisymmetric) quasi-geostrophic Alfvén waves, also associated with Lorentz torques and thus to inflections into LOD series.

In this paper we recall the equations relating surface deformation and pressure changes at the CMB. We then present our analysis of GNSS data in the search for subdecadal oscillation, confronted with surface hydrological mass processes. Finally, we discuss our results.

2. CORE FLOW AND SURFACE DEFORMATION

Core flow velocities at the CMB can be reconstructed from geomagnetic observations. However, to access the non-hydrostatic pressure field p acting at the CMB, we need to know the forces at stake. This can be done under some hypothesis, like the tangentially geostrophic approximation (Gire & Le Mouël, 1990). Under this assumption, any horizontal gradient in pressure is compensated by the horizontal component of the Coriolis force

$$2\rho_c \left(\vec{\Omega} \wedge \vec{U}\right)_H = -\vec{\nabla}_H p \,, \tag{1}$$

with ρ_c the outer core density, $\vec{\Omega}$ the Earth's rotation vector, $\vec{U}$ the fluid core velocity in the rotating frame, and where $\vec{\nabla}_H$ stands for the horizontal gradient. The pressure at the CMB can be decomposed by means of spherical harmonics of degree n and order m as

$$p(\theta,\phi) = \sum_{n=0}^{\infty}\sum_{m=0}^{n} p_{nm} Y_n^m(\theta,\phi) \,,$$

where we have introduced the spherical harmonic functions Y_n^m at colatitude θ and longitude ϕ.

Using the Love number formalism (Love, 1909), the radial displacement at the Earth's surface induced by a pressure field acting at the CMB is given by

$$u_r(\theta,\phi) = \sum_{n=2}^{\infty}\sum_{m=0}^{n} \overline{h}_n \frac{p_{nm}}{\rho g_0} Y_n^m(\theta,\phi), \tag{2}$$

where ρ is the averaged density of the Earth, g_0 is the mean surface gravity value. $\overline{h}_n$ is the degree-n Love number. We refer e.g. to Crossley (1975) for the elasto-gravitational equations permitting to compute these Love numbers in the case of an isotropic Earth. We adopt below the value $\overline{h}_2 = 0.2302$ (Dumberry & Bloxham, 2004). Fang et al. (1996) and Greff-Lefftz et al. (2004), using the constraint from (1), estimated to a couple of mm the decadal changes in the Earth's surface topography, induced by the fluid pressure at the top of the core (some 100 Pa). For the degree-2 zonal components, Dumberry & Bloxham (2004) have introduced a correction (perturbation of the mantle and inner core rotation rates by the zonal flow, due to centrifugal effects) that reduces by a factor ≈ 2 the amplitude of the surface deformation. This leads to decadal changes in the zonal harmonic coefficient of the radial displacement of the order of only a fraction of mm. Given the red temporal spectrum of core motions (longer periods display larger fluctutations, see Gillet et al., 2015), we then expect significantly less deformation on interannual time-scales due to dynamical fluid pressure at the CMB.

3. GNSS DISPLACEMENT OBSERVATIONS AND ANALYSIS

Ding & Chao (2018) have used GPS data from the JPL website release[1]. Among all these datasets, they have selected 38 records of timespan longer than 18 years (between 1995/01/01 and

[1] `https://sideshow.jpl.nasa.gov/post/series.html`.

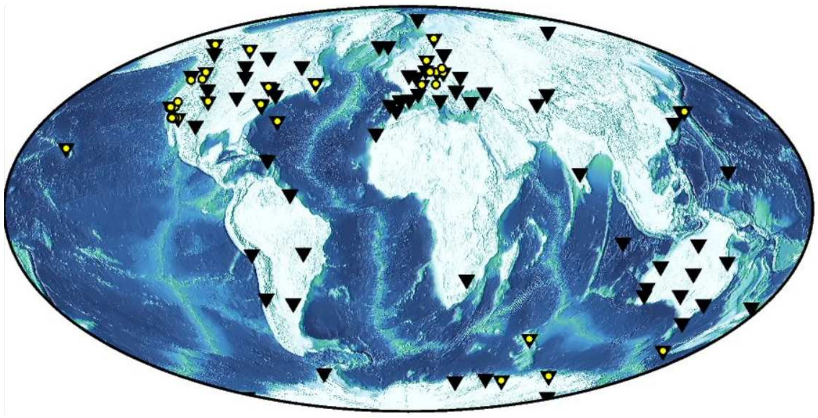

Figure 1: Map of the selected 83 GPS stations with time duration 19.8 years (Network 1, black triangles), and of the 38 GPS stations used by Ding & Chao (2018) (Network 2, yellow circles).

2015/04/02) for the vertical component. The JPL-released solutions are already corrected for the solid and ocean tidal signals. They further removed spikes and prominent steps in the timeseries as well as pole tide effect. However, they have not corrected for hydrological loading effects. Using the Optimal Sequence Estimation (OSE), which is an array-processing method based on the spherical harmonic decomposition in complex form (see Ding & Shen, 2013), they have extracted a degree-2 order-2 periodic oscillation at a period of 5.9 year. They obtained a vertical surface displacement of 1.7 ± 0.7 mm. Ding & Chao (2018) mention instead 4.3 ± 1.7 mm, but this was once normalized by the Y_2^2 value at $(\theta, \phi) = (90°, 0°)$ (Greenwhich equator), so the actual amplitude at the surface is obtained by multiplying by 0.386 (Ben Chao, personal communication).

Watkins et al. (2018) also used JPL residual time-series spanning 2002-2014 (12 years). They considered 523 stacked GPS radial time series and found a ∼6-year deformation signal that they compared with hydrological loading data from the GFZ (Dill & Dobslaw, 2013). They claim that the surface loading does not account for the ∼6-year deformation signal. However, in the amplitude spectra of their Figure 1, a strong spectral peak exists at sub-decadal time scales in loading data.

In the following we analyze ∼20 years of GPS vertical displacement time series and hydrological loading data in the search for such ∼6-year deformation signal.

3.1 Stacked GPS vertical time-series

From the JPL solutions reprocessed for the 2018 International GNSS Service campaign (IGS Repro2018a), we select stations with duration longer than 18 years (that is about three periods of 6 yr). We finally keep 83 time-records of duration 19.8 years with a homogeneous geographical distribution ('Network 1'). We also consider for a 'Network 2' the same 38 stations as in Ding & Chao (2018), with time duration of 21 years. The two networks are shown in Figure 1.

We perform two kinds of stacking on these residual time-series: a sum of the Fourier transform amplitude spectra and an Optimal Sequence Estimation (OSE) as in Ding & Chao (2018) for extracting degree-2 spherical harmonic components. The resulting amplitude spectra are respectively plotted in Figure 2 for the stacked FFTs, Figure 3 for OSE applied on Network 1 and Network 2.

3.2 Hydrological loading effect

We compare GPS vertical displacements to deformation models due to continental hydrology loading estimated at each individual station of the two networks (Figure 1) provided by the EOST loading service[2]; more details regarding the loading computation can be found in Petrov & Boy (2004) and Gegout et al. (2010). Loading estimates (in millimeters) are provided in the Center-

[2] http://loading.u-strasbg.fr/.

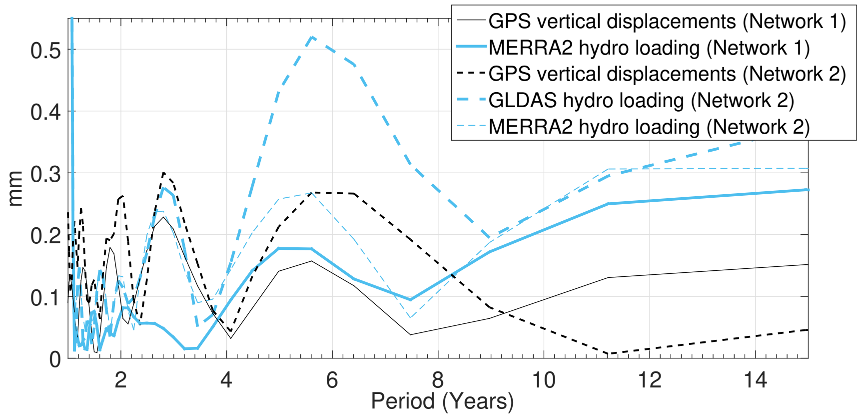

Figure 2: Stacked amplitude spectra of 83 (solid lines) and 38 (dashed lines) vertical GPS displacements of ∼20-year duration from JPL residuals. Hydrological loading for MERRA2 and GLDAS models from EOST loading service are also shown in blue.

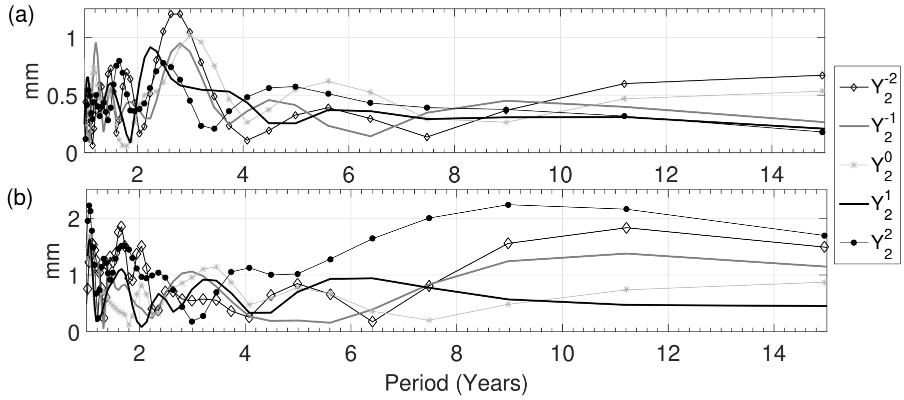

Figure 3: Optimal Sequence Estimation on (a) 83 vertical displacements of ∼20-year duration (Network 1) and (b) 38 vertical displacements of ∼20-year duration (Network 2) from JPL residuals. The Y_n^m denote the degree-n order-m components retrieved from the OSE.

of-Figure reference frame. We have tested two different hydrological models: soil moisture, snow and canopy water from GLDAS/Noah v1.0 model (Rodell et al., 2004, 3 hours, 0.25 degree) ; soil moisture and snow from MERRA2 (Modern Era-Retrospective Analysis) reanalysis (Gelaro et al., 2017, 1 hour, 0.50x0.625 degree). In both cases, permanent ice-covered regions have been masked out.

Resulting stacked FFT spectra are plotted on Figure 2, showing 3-year and 6-year spectral peaks for both hydrological models (larger for GLDAS than for MERRA2). We have also applied the OSE on the hydrological loading predictions. Results for the stations of Network 2 are shown in Figure 4. We recover a broad peak around 6 years on the components of degree-2 and order-2.

4. DISCUSSION AND CONCLUSION

Both FFT stacking method and OSE show a spectral peak around ∼6 years with an amplitude less than 1.5 mm on GPS time-series spanning ∼20 years of continuous measurements. Radial deformation due to hydrological loading also exhibits a spectral peak around ∼6 years with an am-

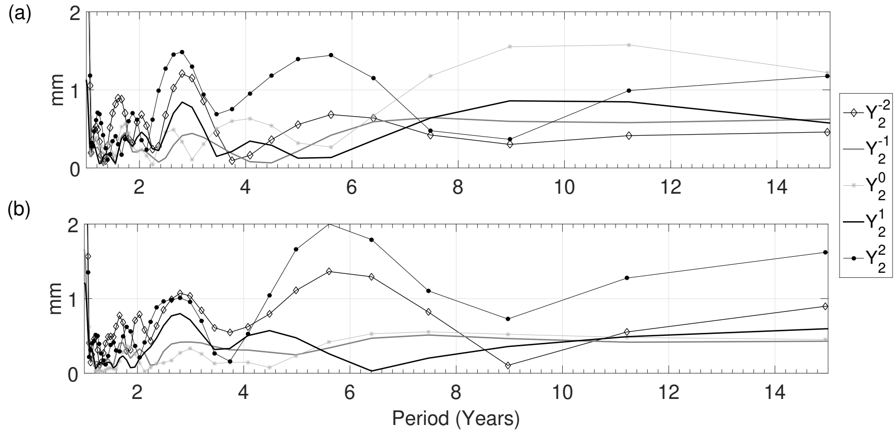

Figure 4: OSE on ∼20 years of hydrological loading predictions for (a) MERRA2 and (b) GLDAS model at stations of Network 2. The Y_n^m denote the degree-n order-m components retrieved from the OSE.

plitude larger than (for GLDAS) or equal to (for MERRA2) the GPS-derived vertical displacement. When comparing the OSE method on two station networks (Figure 3), the retrieved degree-2 spherical harmonic components are however clearly different. A bias due to the network geometry is inherent to any spherical harmonic method and was noticed for example in the application of OSE with noisy data by Majstorović et al. (2018). As known in signal processing, spectral aliasing of higher spherical degrees on the retrieved degree-2 components is another difficulty, particularly when the distribution of stations is sparse. Indeed, Network 2 (Figure 1) exhibits a non-uniform geometrical pattern for which spherical harmonic functions cannot be orthogonal.

Previous estimates using zonal pressure flows (Dumberry & Bloxham, 2004) show that the expected radial deformation at the Earth's surface will hardly reach the millimeter level on sub-decadal periods. If accounting for non-axisymmetric motions may help reach larger surface deformation, we may still miss one order of magnitude. Alternatively, hydrological decadal fluctuations are large and have already proven to be responsible for polar motion (Adhikari & Lvins, 2016). Hydrological models exhibit a strong degree-2 and order-2 component at ∼6 years (Figure 4) that may partially explain the interannual observed signal in GPS observations. Note that alternative mechanisms, like crystallization and dissolution processes at the CMB (Mandea et al., 2015), might also result in interannual deformation signals of similar pattern.

As a conclusion, if a signal from the outer core cannot be entirely discarded, our preliminary analysis render more probable a hydrological source to interannual surface deformation of degree-2. Further analyses using longer GNSS time-series corrected from hydrological loading will be required. However, sources of errors in vertical GPS solutions are numerous (Teferle et al., 2008) and separating the several geophysical contributions still remains a challenge.

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