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Spectral analysis of sea level during the altimetry era, and evidence for GIA and glacial melting fingerprints

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ABSTRACT

We study the spatial patterns of the mass and steric components of sea-level change during the "altimetry era" (1992–today), and we characterize them at different scales by the orthonormal functions method. The spectrum of the altimetry-derived rate of sea-level rise is red and decays with increasing wavenumber nearly following a power law with exponent ≈2. By analyzing the degree correlation and the admittance function, we find that the altimetric rate of sea-level change is coherent with the total steric field in the whole range of wavelengths considered (down to ≈1000 km), but particularly for wavelengths exceeding ≈2000 km. Thermosteric and halosteric components are moderately anti-correlated within the range of wavelengths 1000–4000 km. Their power spectrum varies significantly with the wavelength and, for ≈2000 km, it is equally partitioned between the two components. The power of regional sea-level variations driven by Glacial Isostatic Adjustment and the melting of continental ice sheets is small compared to that held by the steric component, which explains most of the regional variability shown by the altimetry record. This causes the elusiveness of the "static" sea-level fingerprints, which at present are hidden in the pattern of the residual sea-level (i.e., the altimetry-derived sea-level minus the steric component). However, we find that at harmonic degree 2, mainly associated with rotational variations, the power of glacial melting is significant and it will progressively increase during next century in response to global warming. We also estimate that at the end of the Mid-Holocene the strength of the glacial isostatic readjustment fingerprints was ≈10 times larger than today, well above the long-wavelength component of residual sea-level.

1. Introduction

During the "altimetry era" (1992–today), absolute sea-level has been rising at the global average rate of about 3 mm yr^{-1} (Church et al., 2013), i.e., twice as fast as the average rate recorded by the tide gauges deployed along the world's coastlines during 1880–2010 (e.g. Spada and Galassi, 2012). However, the spatial pattern of sea-level trends obtained from the altimetric observations, visible at the page *http://www.aviso.altimetry.fr/* shows striking deviations from the mean value, with amplitudes exceeding 10 mm yr^{-1} in some regions. This marked spatial imprint visually suggests a rich spectrum of variability, which is the result of concurrent global, regional and even local ocean processes causing both density and mass variations of the oceans (Meyssignac and Cazenave, 2012), tightly linked to dynamic effects associated with currents and winds (Griffies and Greatbatch, 2012). A major challenge today is to determine to what extent anthropogenic factors are contributing, and will contribute, to the sea-level variability revealed by the altimetry record (Meyssignac et al., 2012; Becker et al., 2014; Dangendorf et al., 2015).

The origin of the multi-scale spatial variability revealed by the altimetric sea-level record, and its time variations, have been the subject of various analyses during the last decade. It is now recognized that during the altimetry era the spatial variability of the sea-level trend has been mainly due to the heat redistribution caused by the ocean circulation (Wunsch et al., 2007; Lombard et al., 2009; Fukumori and Wang, 2013). Globally, the effects of thermal expansion (i.e., the thermosteric component of sea-level rise) dominate those from salinity (the halosteric component), which nevertheless can be important in regional patterns of sea-level change (Köhl and Stammer, 2008). However, steric sea-level variations are not the only potential cause of regional sea-level change. It has been long known that the slow readjustment of the Earth in response to the late-Pleistocene de-glaciations (the Glacial Isostatic Adjustment, or GIA) still causes a significant regional sea-level variability (Farrell and Clark, 1976). GIA involves visco-elastic deformations of the Earth (Wu and Peltier, 1982) and also acts through gravitational and rotational effects. Similarly, ocean mass variations due to ongoing glacial melting (GM) and changes of continental water storage are an important source of global mean sea-level rise (Church et al., 2013),

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but they are also expected to induce significant regional variations. These result from the same physical mechanisms of GIA, but only involve elastic deformations because of their relatively short time-scales compared to the characteristic Maxwell time of the Earth's mantle (e.g. Spada et al., 2013).

According to Peltier (2009), presently GIA affects the absolute sea-level change at an average rate of $\approx$ -0.3 mm yr^{-1} (see also Tamisiea, 2011). This GIA contribution, which is caused by the isostatic readjustment of the sea surface and of the ocean floor and not by changes in the oceans mass, is smaller by one order of magnitude than the observed ocean-averaged rate obtained from altimetric measurements (see Fig. 3a below). Nevertheless, GIA is important for the understanding of regional sea-level change close to previously glaciated areas (Cazenave and Llovel, 2010; Cazenave and Remy, 2011), where deviations from the average values are significant. GM has been assessed to contribute approximately 1.5 $\pm$ 0.5 mm yr^{-1} to mean sea-level rise during 1993–2010 (Church et al., 2013), a sizable fraction of the rate of global mean sea-level rise observed by altimetry. Since the Earth's short-term response is elastic, the rate of absolute sea-level change associated with GM, averaged over the oceans, is proportional to the present melting rate of the ice sources. Thus, in the sea-level budget currently estimated by altimetry GM dominates GIA, which is caused by the melting of past ice sheets and is not involving mass variations of the oceans. The impact of GM on regional sea-level is considered small at present (Meyssignac et al., 2012), although it has been proposed that it may become substantial as the rate of melting of glaciers and ice sheets will further increase in response to global warming (see e.g., Cazenave et al., 2009a).

To date, the problem of the closure of the budget of global mean sea-level rise has been the subject of intense research, focused over different time scales (Cazenave et al., 2009a, 2009b; Leuliette and Miller, 2009; Peltier, 2009; Church et al., 2011, 2013; Hay et al., 2015). However, the relative importance of the components of contemporary sea-level change at regional scales has not been systematically investigated within a unified scheme. This is accomplished here, adopting a straightforward approach based on the so-called orthonormal (ON) functions method first introduced by Hwang (1991) and subsequently reassessed by Hwang (1993). This spectral technique extends the traditional spherical harmonic (SH) approach to the case in which the 2-D fields to be analyzed are not defined on the whole sphere, as in the case of the altimetric sea-level observations. Similar methods are used in practical astronomy, when a full sky coverage of the data is not available (see e.g., Gorski, 1994). Contrary to the SHs, the ONs do not possess an analytical expression. Therefore, our analysis relies upon purely numerical techniques exploiting the orthonormality of the ON functions over the ocean domain sampled by altimetry. From the perspective of spectral methods, our study will also provide some new answers to the long-standing question of the effective "detectability" of the GIA and GM "sea-level fingerprints" (Mitrovica et al., 2001; Clark et al., 2002; Bamber and Riva, 2010; Mitrovica et al., 2011), in the current altimetric record (Douglas, 2008; Cazenave and Llovel, 2010; Kopp et al., 2010).

The paper is organized as follows. In Section 3 the methods are illustrated and in Section 4 we present our results. These concern the harmonic analysis of the altimetry map of sea-level change (Section 3.1), of the patterns of thermosteric and halosteric sea-level changes (Section 3.2), and of the GIA and GM contributions to present sea-level rise (Section 3.3). We discuss the results in Section 5, and our conclusions are drawn in Section 5.

2. Methods

The choice of the representation basis most suitable for the description and the analysis of the pattern of sea-level change revealed from altimetric observations is somewhat subjective. A concise review has been given by Wunsch and Stammer (1995). Here we have adopted and numerically implemented the basis of the ON functions, whose conceptual and practical merits with respect to the traditional SHs have been illustrated by Hwang (1991, 1993), to which the reader is referred for details. With respect to the Empirical Orthogonal Functions (EOFs), commonly employed in climate data analysis (see e.g., Navarra and Simoncini, 2010), the ON functions have the advantage of being independent from a specific geophysical dataset. In fact, they are uniquely determined by the geometry of the oceans over which they are mutually orthogonal. A significant part of this work concerns the GIA and GM sea-level fingerprints, which are defined over the entire globe. Since they are obtained applying spectral techniques based on the SHs (see e.g., Spada and Stocchi, 2007), the extension to the ON functions constitutes a natural generalization. We note that despite the completeness and the non-independence problem posed by the SHs when they are restricted to a non-spherical domain (Hwang, 1993), these have often been preferred to the ON functions (e.g. Wunsch and Stammer, 1995) probably because of the availability of well tested numerical and statistical tools.

Hwang (1991, 1993) has shown that any square integrable function $f(\omega)$ defined on an arbitrary subset D of the sphere S, and undefined elsewhere, can be approximated by the expansion

$$f(\omega) = \sum_{l=0}^{l_{max}} \sum_{m=0}^{l} \left(\alpha_{f,lm} O_{lm}(\omega) + \beta_{f,lm} Q_{lm}(\omega)\right), \tag{1}$$

where $\omega = (\theta, \lambda)$, θ is co-latitude, λ is longitude, l and m are the harmonic degree and order, $l_{\max}$ is the truncation degree, $(\alpha_{f,lm}, \beta_{f,lm})$ are real coefficients, and the ON functions $(O_{lm}, Q_{lm})(\omega)$ are linearly obtained from the usual fully normalized SHs (see e.g., Heiskanen and Moritz, 1981) by the Gram-Schmidt orthonormalization process (Gorski, 1994). Since in the following the field $f(\omega)$ will always represent a rate of sea-level change, the expansion coefficients $(\alpha_{f,lm}, \beta_{f,lm})$ will be expressed in units of mm yr^{-1}. A few low-degree ON functions are displayed in Fig. 1. These have patterns similar to the usual harmonics, but show distortions due to the irregular geometry of the domain D on which they are defined, that is the portion of the world's oceans sampled by the altimetric missions considered in this study. The double index (lm) of the ON functions should not be considered as formally equivalent to that used for the SHs (Hwang, 1991, 1993). However, the symmetries of the ON functions according to the value of the harmonic order m (zonal, tesseral and sectorial patterns, see Heiskanen and Moritz, 1981) are broadly comparable to those of the SHs, since D is quasi-global (D covers $\approx$64% of the globe and $\approx$90% of the oceans). For globally defined functions ($D = S$), Eq. (1) reduces to the traditional SHs expansion

$$f(\omega) = \sum_{l=0}^{l_{max}} \sum_{m=0}^{l} \left(c_{f,lm} \overline{C}_{lm}(\omega) + s_{f,lm} \overline{S}_{lm}(\omega)\right), \tag{2}$$

where $(\overline{C}_{lm}, \overline{S}_{lm})(\omega) = \overline{P}_{lm}(\cos\theta)(\cos m\lambda, \sin m\lambda)$ are the fully normalized real SHs and $\overline{P}_{lm}(\cos\theta)$ denotes the fully normalized associated Legendre functions (e.g. Heiskanen and Moritz, 1981).

By orthonormality of the ON functions, the coefficients in Eq.(1) are obtained by integration

$$\begin{Bmatrix} \alpha_{f,lm} \\ \beta_{f,lm} \end{Bmatrix} = \frac{1}{A_D} \int_D f(\omega) \begin{Bmatrix} O_{lm} \\ Q_{lm} \end{Bmatrix} (\omega)\, d\omega, \tag{3}$$

where $A_D = \int_D d\omega$ and $d\omega = \sin\theta d\theta d\lambda$ is the area element over S. In Hwang (1991), least-squares adjustment and numerical quadrature have both been employed to evaluate Eq.(3). Here, an equal-area icosahedron-based geodesic grid is constructed on S, based on the method of Tegmark (1996). The grid defines $N_p = 40R(R-1) + 12$ pixels over the whole sphere, where R is the resolution parameter. Then, by program GRDTRACK included in the GMT software package of Wessel and Smith (1998), we interpolate $f(\omega)$ on the "wet" pixels falling within D,