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Geocentric sea-level trend estimates from GPS analyses at relevant tide gauges world-wide

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Abstract

The problem of correcting the tide gauge records for the vertical land motion upon which the gauges are settled has only been partially solved. At best, the analyses so far have included model corrections for one of the many processes that can affect the land stability, namely the Glacial-Isostatic Adjustment (GIA). An alternative approach is to measure (rather than to model) the rates of vertical land motion at the tide gauges by means of space geodesy. A dedicated GPS processing strategy is implemented to correct the tide gauges records, and thus to obtain a GPS-corrected set of 'absolute' or geocentric sea-level trends. The results show a reduced dispersion of the estimated sea-level trends after application of the GPS corrections. They reveal that the reference frame implementation is now achieved within the millimetre accuracy on a weekly basis. Regardless of the application, whether local or global, we have shown that GPS data analysis has reached the maturity to provide useful information to separate land motion from oceanic processes recorded by the tide gauges or to correct these latter. For comparison purposes, we computed the global average of sea-level change according to Douglas [Douglas, B.C., 2001. Sea level change in the era of the recording tide gauge. Int. Geophys. Ser., 75, pp. 37–64.] rules, whose estimate is 1.84±0.35 mm/yr after correction for the GIA effect [Peltier, W.R., 2001. Global glacial isostatic adjustment and modern instrumental records of relative sea level history. Int. Geophys. Ser., 75, pp. 65–95.]. We obtain a value of 1.31±0.30 mm/yr, a value which appears to resolve the 'sea level enigma' [Munk, W., 2002. Twentieth century sea level: an enigma. Proc. Natl. Acad. Sci. U.S.A., 99(10), pp. 6550–6555].

Introduction

Trends in global sea level over the last century have been estimated based upon tide gauge records with near global coverage (e.g. Gornitz et al., 1982, Barnett, 1984, Douglas, 1991, Douglas, 1997, Douglas, 2001, Church et al., 2004). Satellite altimetry records only inform on the last 15-years or so; a time span obviously too short to derive estimates for the rise in sea level on a century time scale. Several additional decades of measurements with T/P-like radar altimeter missions are required to allow definitive conclusions on the low-frequency global sea-level changes to measure the acceleration of global sea-level rise (Nerem and Mitchum, 2001, Cazenave and Nerem, 2004). However, two important problems arise when using tide gauges to estimate the rate of global sea-level rise. The first is the fact that tide gauges measure sea level relative to a point attached to the land which can move vertically at rates comparable to the long-term sea-level signal. The second problem is the spatial distribution of the tide gauges, in particular those with long records, which are restricted to the coastlines (see Fig. 1 in Woodworth and Player, 2003).

This paper focuses on the first point. The latter problem is only shortly reviewed here, for an extensive discussion and details on both issues, see Pirazzoli (1986), Pugh (1987), Douglas (1991), Emery and Aubrey (1991), for instance. The poor spatial distribution of historical gauges is problematic because of the evidence of regional variability of sea-level trends, this being confirmed by satellite altimetry results (e.g. Nerem and Mitchum, 2001, Cazenave and Nerem, 2004, Holgate and Woodworth, 2004). Some authors have attempted to overcome this problem by selecting tide gauge records of a minimum length, e.g. 60 years. Then, even a limited set of poorly distributed tide gauges could filter the decadal and multi-decadal sea-level fluctuations that correspond to the redistribution of ocean mass without any change in the total ocean volume. There is, however, some controversy on this major issue, whether global-average sea-level change estimates using tide gauges could be really representative of the 'true' global mean (e.g. Cabanes et al., 2001, Miller and Douglas, 2004, Miller and Douglas, 2006). Though some filtering is expected when the data from the different gauges are averaged, the uncertainty caused by these ocean signals could still be large. To provide definitive conclusions, future research will be useful to know the magnitude of the interannual, decadal, and interdecadal variability of mean sea level at the global scale.

The problem of correcting the tide gauge records for the vertical land motion upon which the gauges are settled has only been partially solved. At best, the analyses so far have included corrections for one of the many processes that can affect the land stability, namely the Glacial-Isostatic Adjustment (GIA) (e.g. Peltier and Tushingham, 1989, Trupin and Wahr, 1990, Douglas, 1991, Douglas, 1997, Douglas, 2001, Peltier, 2001, Church et al., 2004). However, Woodworth (2003) observes that different GIA models provide very different values in magnitude and sign. Moreover, GIA models do not account for the other sources of vertical land motion that can affect the tide gauges. A few examples of local land motions at individual tide gauge records are given for instance in Pugh (1987) or in Nerem and Mitchum (2001). The situation seems even worse for corrections of tectonic motions by using geological data than for GIA corrections (Gröger and Plag, 1993). An alternative approach is to measure (rather than to model) the rates of vertical land motion at the tide gauges by means of space geodesy (Carter et al., 1989, Carter, 1994, Neilan et al., 1998, Blewitt et al., 2006). However, this has proven not to be as straightforward as supposed 15–20 years ago.

Our study focuses on the geodetic issue of monitoring the vertical land motions at the tide gauges. It analyses the most recent results that we obtained from the implementation of a dedicated GPS processing strategy at the so-called ULR (Université de La Rochelle, Institut Géographique National) analysis centre consortium (Wöppelmann et al., 2004, Wöppelmann et al., 2005) to estimate vertical velocities at each tide gauge with the best possible accuracy to usefully correct relative sea-level records. Section 2 briefly describes this GPS processing strategy and its recent updates. The resulting GPS vertical trends are used to correct the tide gauge records, and thus to obtain a GPS-corrected set of 'absolute' or geocentric sea-level trends (Section 3). Since our study focuses on the geodetic tide gauge station stability monitoring issue, we simply adopted the tide gauge analysis approach of one of the most quoted studies, namely Douglas, 1991, Douglas, 1997, Douglas, 2001 to show up our contribution in this aspect. Section 4 discusses to what extent our approach improves the estimate of the global sea-level rise. In particular, we outline the recent performances we have achieved in the implementation of a more stable and accurate reference frame.

Section snippets

Tide gauge records

Tide gauge records of annual mean sea-level values were selected from the 'Revised Local Reference (RLR)' data set of the Permanent Service for Mean Sea Level (PSMSL). These records have been checked and corrected for local datum changes (Woodworth and Player, 2003). As stated in the Introduction, we adopted the Douglas, 1991, Douglas, 1997, Douglas, 2001 approach to perform the station selection and to compute the sea-level trends. Tide gauge records were rejected if they did not contain more…

Confronting tide gauge and GPS results

A careful inspection of both the individual tide gauge records and the corresponding co-located GPS time series was conducted prior to any trend computation. The GPS time series editing was based on a graphical tool developed by Xavier Collilieux (IGN) to analyse CATREF outputs from the position time series combination process (Section 2.3). It allowed an easy and practical way to identify and to reject outliers, as well as to handle the discontinuities in the time series using the break-wise…

Discussion

The tide gauge and GPS error estimates are each of comparable size (Table 1). These are formal standard deviations derived either from the least squares linear regression adjustment applied to the tide gauge records or from the time series combination process of the weekly GPS position solutions described in Section 2.3. The latter error computation is detailed in Altamimi et al. (2002), Appendix 1. These are, however, formal errors which usually appear to be optimistic. The estimation of a…

Conclusions

Munk (2002) stressed that the sum of climate-related contributions to sea-level change was low (0.7 mm/yr) compared to the observations over the last 50–100 years (1.8 mm/yr) by referring to this factor 2 difference as the 'enigma' of sea-level change. Since then, the more recent results now indicate a 1 mm/yr contribution from the melting of global land ice reservoirs (Mitrovica et al., 2006), as well as a 0.4 mm/yr contribution from the thermal expansion of the world ocean (Antonov et al.,…

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…Since last two decades, the sea level trend for the majority of the global ocean has been achieved through satellite altimeter missions (Milne et al., 2009) but the satellite measurements are unable to go beyond a decade or so (Cazenave et al., 2003) while the tide gauge records could extend further up to last 150 years (Revelle, 1990). However, localised vertical land movement can introduce additional signals to the tide gauge records, which can be addressed by isolating the land movement component from the sea level component using global positioning system (Wöppelmann et al., 2007; Milne et al., 2009). The most recent sea-level change during glacial-interglacial period has been underpinned during Last Glacial Maxima (LGM) that was decoded from direct dating of the shore markers and tropical reef deposits (Miller et al., 2005).…

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