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Global sea level trend during 1993–2012

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ABSTRACT

Projection of future sea level change relies on the understanding of present sea-level trend and how it has varied in the past. Here we investigate the global-mean sea level (GMSL) change during 1993–2012 using Empirical Mode Decomposition, in an attempt to distinguish the trend over this period from the interannual variability. It is found that the GMSL rises with the rate of 3.2 ± 0.4 mm/yr during 1993–2003 and started decelerating since 2004 to a rate of 1.8 ± 0.9 mm/yr in 2012. This deceleration is mainly due to the slowdown of ocean thermal expansion in the Pacific during the last decade, as a part of the Pacific decadal-scale variability, while the land-ice melting is accelerating the rise of the global ocean mass-equivalent sea level. Recent rapid recovery of the rising GMSL from its dramatic drop during the 2011 La Niña introduced a large uncertainty in the estimation of the sea level trend, but the decelerated rise of the GMSL appears to be intact.

1. Introduction

Current observations reveal that the rate of the global-mean sea level (GMSL) rise has increased from a few centimeters per century over recent millennia to a few tens of centimeters per century in recent decades (Milne et al., 2009), owing to the melting of the land ice and the thermal expansion of the ocean water as a result of global warming. Whether the sea level continues to rise at the current or even faster pace has received extensive attentions (Becker et al, 2012) but the answers to this question are still limited by the availability of observations (Cazenave and Llovel, 2010), and data analysis methods (Ezer and Corlett, 2012; Zhang and Church, 2012; Breaker and Ruzmaikin, 2013).

Since the launch of TOPEX/Poseidon altimeter in 1992, the Gravity Recovery and Climate Experiment (GRACE) twin satellites in 2002, and the initiation of the Argo project in 2000, global scale sea-level maps are available for estimating patterns of the sea level change with unprecedented accuracy (Nerem et al., 2010; Church and White, 2011; Church et al., 2011). However, the nonlinearity and nonstationarity of global sea-level change often elude the attempt to capture the longer-term accelerations from the interannual and decadal variability within the limited data span. For example, recently GMSL experienced a dramatic roller-coaster-like falling and rising within a period of about two years due to the fluctuations in the ocean mass in response to ENSO-related changes of the global water cycle (Boening et al., 2012). To what extent these ENSO events are responsible for the change in the longer-term trend cannot be estimated using the linear regression analyses, since the speed of the sea level rise is not necessarily piecewise constant during the studied period. Fitting a second order polynomial to the sea level records, which is used to estimate the quadratic coefficient of acceleration (Douglas, 1992), captures the accelerated sea level rise in the western Pacific. However the potential interannual and decadal sea level variability, which are absorbed by the only one acceleration parameter, introduce a large uncertainty since the residual of the regression does not have a white noise spectrum (Jevrejeva et al., 2006). Furthermore, these estimations are quite sensitive to the arbitrarily selected start and end dates (Baart et al., 2012).

Wu et al. (2007) proposed a trend function defined as *an intrinsically fitted monotonic function or a function in which there can be at most one extremum within a given data span*. The Empirical Mode Decomposition (EMD) method adopted is able to retain this fundamental property of the nonlinear and nonstationary time series, that the corresponding physical interpretation of the trend function within the given data span should not change with the addition of new data (Wu et al., 2011). Since the EMD method is non-parametric, the trend function may represent the low-frequency variability of the sea level whose periods are longer than the data span, which will be useful to investigate how the sea level trend of the GMSL varies during the period 1993–2012.

To this end, the EMD method (Huang et al., 1998) is applied to decompose the GMSL time series into a definite number of intrinsic mode functions (IMFs) with different time scales and the trend function with at most one extremum. The application of EMD to derive the spatial–temporal distributions of the rising rate of the global sea level is explored by Feng et al. (2011) and the confidence level of the derived trend function is established by Ezer and Corlett (2012), and applied to

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identify the acceleration of the sea-level rise along the east coast of United States, as well as connect this recent sea level acceleration with weakening of the Gulf Stream (Ezer et al., 2013).

Before further discussion, it is necessary to clarify the meaning of the terms *trend function* and *intrinsic trend* in this paper. The *trend function* refers to the last component derived by the EMD method in unit of mm. The *intrinsic trend* refers to the instantaneous rate of the sea level

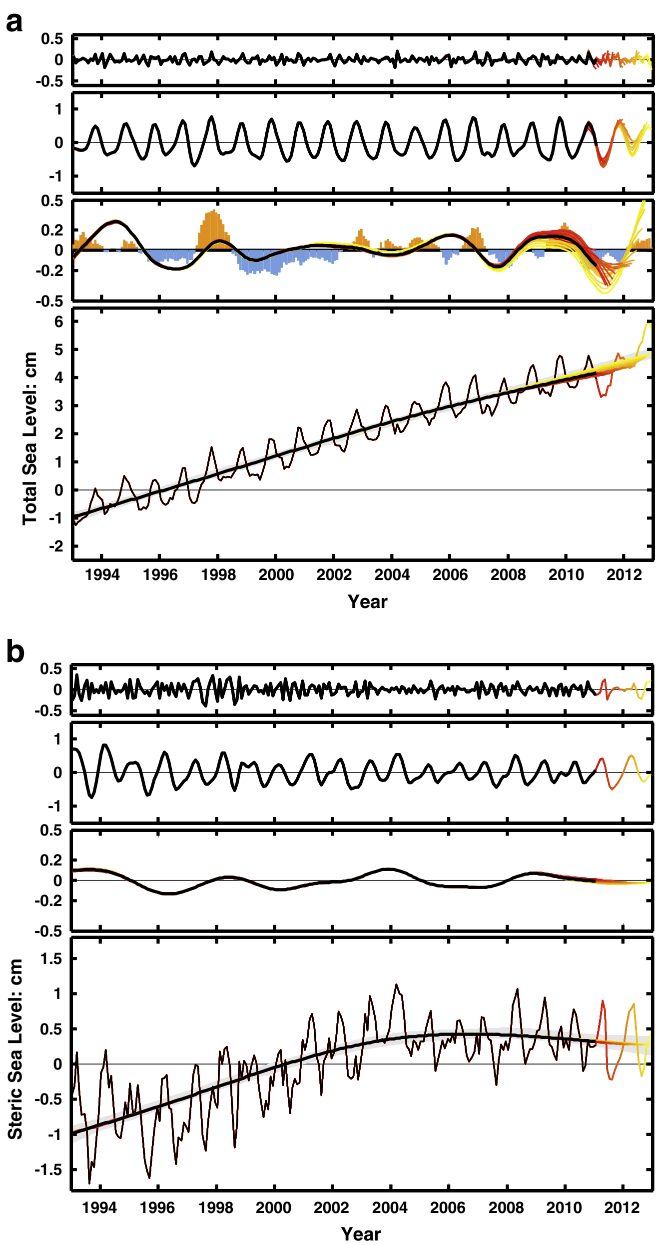

Fig. 1. a. The global mean sea level (GMSL) with the ending date changing from 1 to 24 months earlier relative to December 2012 (bottom panel, thin lines end with the color from red to yellow). The IMFs of each time series, corresponding to the high-frequency noise, the annual cycle, the interannual variability, and the trend function (see text), are given as the colored lines in the panels from top to bottom, respectively. The ensemble mean of the IMFs on the different time scales during 1993–2010 is given as the thick black solid line in each panel. The colored bar in the third panel is the normalized Niño 3.4 index with arbitrary amplitude. The statistical confidence interval of the trend function is given by gray shadow in the bottom panel. The data is in units of cm. b. Same as panel a but for the global mean steric sea level. c. Same as panel a but for the global mean ocean mass during the period from January 2003 to December 2012.

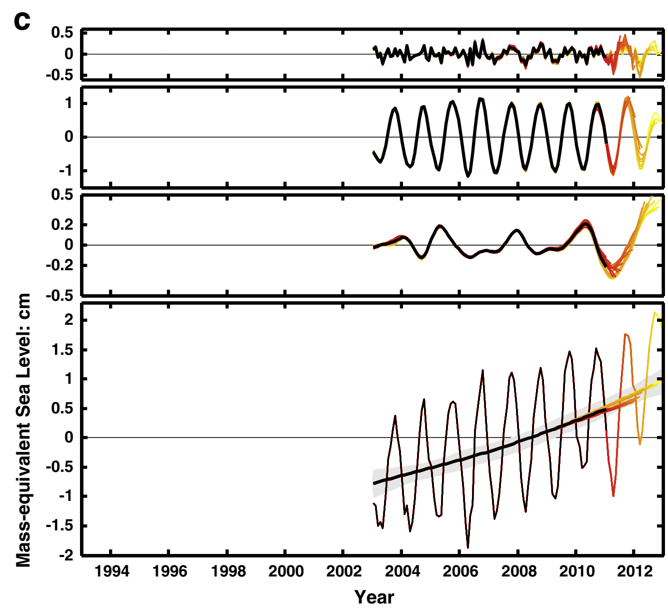

Fig. 1 (*continued*).

change in unit of mm/yr, i.e. the first-order time-derivative of the *trend function*.

2. Data and methods

2.1. Data

The GMSL during 1993–2012 is computed as the area-weighted monthly-mean sea-surface height, which is observed by altimetry satellites with 1/3 degree spatial resolution, available from the archive at the Archiving, Validation and Interpretation of Satellite Oceanographic Data (AVISO). In order to compare it with the steric sea level and the ocean mass data, the GMSL data are interpolated to 1 degree longitude by 1 degree latitude grid.

The contributions to sea-level variability from changes in ocean mass are estimated using the observations from the Gravity Recovery and Climate Experiment (GRACE) mission which began in 2002 (Chambers, 2006). The global-mean mass-equivalent sea level derived from the non-filtered JPL RL05 time series is used (available at http://xena.marine.usf.edu/~chambers/SatLab/Home.html).

The steric sea-level changes due to the variability of the ocean-water density from the surface to the ocean bottom (maximum ~5350 m) are derived from the monthly objective analyzed subsurface temperature–salinity dataset compiled by Ingleby and Huddleston (2007) (henceforth, EN3). While the EN3 provides the full-depth (5500 m depth) profiles, the contribution of the deep ocean warming on the steric sea level change is taken into account (Purkey and Johnson, 2010).

2.2. Empirical Mode Decomposition (EMD)

The general introduction of EMD is given in Huang et al. (1998) and Wu and Huang (2009) and some applications of EMD can be found in Wu et al. (2011) for the study of the time-varying trend in global surface temperature and in Ezer and Corlett (2012) for the coastal sea level rise from the tide-gauge-station observations. A brief introduction of EMD is given below for completeness.

EMD decomposes a time series into a set of intrinsic mode functions (IMFs) in the form of $x(t) = \sum_{j=1}^{N} c_j(t) + r(t)$, where $r(t)$ is the residual, which has at most one extremum representing the trend function of