Global sea level trend during 1993–2012

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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 intrinsic 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 intrinsic trend function is established by Ezer and Corlett (2012), and applied to
identify the acceleration of the sea-level rise along the east coast of the 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 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 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...
the time series (Wu et al., 2007). $c_j(t)$ is the $j$th IMF of the original time series, which are extracted through a sifting process: (i) locate all maxima and minima and connect all maxima (minima) with a cubic spline as upper (lower) envelope of the time series; (ii) compute the difference between the time series and the mean of upper and lower envelopes to yield a new time series $h(t)$; (iii) repeat steps (i) and (ii) for the time series $h(t)$ until the upper and the lower envelopes are symmetric with respect to zero mean under the certain criteria, then an IMF, $c_j(t)$, is derived as the time series $h(t)$; (iv) subtract $c_j(t)$ from original time series to yield a residual $r(t)$ and treat $r(t)$ as the original time series and repeat steps (i)−(iii) until $r(t)$ becomes a monotonic function or a function with only one extremum.

One issue associated with EMD for determining the low frequency variability and the trend function is the data end effect, an unavoidable topic for any data analysis method. This is especially acute for the case of the GMSL with the rapid falling and rising during 2010–2012 at the end part of the time series. To assess the sensitivity of the derived IMFs, we repeat the EMD analysis of the time series with the ending dates changing from 1 to 24 months earlier relative to December 2012 (We also implemented the analysis of the time series with the starting date changing from 1 to 24 months later relative to January 1993. No significant differences are introduced.). This test will reveal the uncertainty introduced by the 2011 La Niña event to the estimated GMSL trend.

Several methods are developed to show the robustness of EMD by constructing the statistical confidence interval of each IMF and the final trend function (Wu et al., 2011; Ezer and Corlett, 2012). Taken into consideration the data length of the observations from the satellite altimeters, GRACE, and the temperature-salinity profiles, the bootstrap method suggested by Ezer and Corlett (2012) is applied in this paper.

3. Results

Fig. 1 shows the IMFs and the residual of the global area-weighted mean total sea level, the steric sea level, and the ocean mass, in descending order of the high-frequency noise, the annual cycle, the interannual variability, and the trend function. While EMD may decompose the interannual variability with different time scales into separated IMFs, we combine the IMFs with the time scales longer than the annual cycle and shorter than the last trend function together to yield the interannual variability IMF. The last two IMFs are the focus of this study.

3.1. Interannual variability

The interannual variability of the global-mean sea level, the steric sea level, and the ocean mass is shown in Fig. 1, respectively. It presents the impact of the El Niño on increasing the GMSL during 1994–1995, 1997–1998, 2006, and the mid-2008, and the opposite impact of the La Niña during 1995, 2007–2008, and 2010–2011. The significant correlation between the Niño 3.4 index (as shown in Fig. 1) and the interannual variability of the GMSL confirms the important role played by the ENSO cycle on the short-term sea level change.

Taking the time-derivative of the third IMF of the GMSL (Fig. 2), we could find that the instantaneous rate of the GMSL on the interannual time scale varied in the range from $-4$ mm/yr to $4$ mm/yr during 1993–2009, and exceeded $-5$ mm/yr during the recent strongest La Niña event in 2011 and almost reached 10 mm/yr during the rapid recovery period in 2012. However, the instantaneous rate of the global mean steric sea level variability on this time scale remained within $\pm 2$ mm/yr, this indicates that the change of the ocean mass plays the dominant role in modulating the interannual variability of the GMSL. The underlying mechanism of the interannual variability of the global mean ocean mass remains unclear for the short-period global-scale observations. The ocean mass variability in response to ENSO-related changes of the global water cycle is one of the possible causes as suggested by Boening et al. (2012).

The regression of the global sea level and the global steric sea level on their corresponding third IMFs (Fig. 3) shows very similar ENSO-like patterns. Notice that the sea level can adjust to changes in the ocean mass within a matter of days through barotropic waves traveling at speeds of order 200 m/s (Lorbacher et al., 2012), the spatial pattern of the ocean mass change on the interannual time scale is nearly homogeneous in the world ocean. This indicates that the spatial pattern of the interannual variability of the GMSL should be attributed to the steric sea level change, while the amplitude is dominated by the change of the ocean mass.

![Fig. 2](image_url). The instantaneous rate of interannual variability of (a) the GMSL, (b) the global mean steric sea level, and (c) the global mean ocean mass, i.e. the first-order time derivative of the third IMFs shown in Fig. 1.)
3.2. Intrinsic trend

The fourth IMFs shown in Fig. 1 give the trend functions of the GMSL, the global mean steric sea level during 1993–2012, and the global mean ocean mass during 2003–2012, respectively, whose intrinsic trends are shown in Fig. 4. As defined by Wu et al. (2007), the trend function depends on the length of the time series. The ending-point impacts must be estimated before interpreting the physics of the intrinsic trend. As shown in Figs. 1 and 4, the recent ENSO events in the GMSL introduces the large uncertainty into its intrinsic trend at the end part of the time series. But for the GMSL and the global mean steric sea level, this impact does not change the fundamental properties of the trend functions, especially how they varied during the last two decades. For the ocean mass, due to the short length of the time series, the data end effects are more obvious than in the other two time series, but the general accelerated rising pattern remains unchanged when the ending point is changed from 1 to 24 months earlier relative to December 2012.

The difference between the linear regression and the trend function of the GMSL derived by EMD is not easily captured by eye (Fig. 1), but the time-derivative of the trend function reveals the significant decelerated trend of the GMSL since 2004 (Fig. 4). It decreased to 1.8 ± 0.9 mm/year in 2012. Comparison with the intrinsic trend of the global mean steric sea level and the global mean mass-equivalent sea level indicates that the decelerated rising GMSL since 2004 is mainly due to the decreased steric sea level during the same period (Fig. 3), which reflects the stalled upper ocean heat content during the last decade (Meehl et al., 2011). Since the global ocean mass has accelerated increase during 2003–2012, even though the steric sea level may stop rising or start to fall, the GMSL is still rising but with a slower rate than that in the previous decade.

In order to investigate where and how the deceleration of the GMSL rising occurred, we compute the mean trend of the GMSL and the global mean steric sea level during the two periods, 1993–2003 and 2004–2012. As shown in Fig. 5, the GMSL and the global mean steric sea level experienced very similar spatial pattern of the intrinsic trend with each other during these two periods, including the significant rising in the western Pacific during the second period 2004–2012 with the mean trend larger than that during the first period 1993–2003 and the falling sea level in the eastern Pacific.

It should be noted that the intrinsic trend of the sea level rise in the Pacific shares a similar spatial pattern with that of its interannual variability (Fig. 2) but with much broader meridional extent. This result is consistent with the decadal sea level fingerprint derived by Zhang and Church (2012). Since the earlier 2000s, the rising trend of the GMSL and the global mean steric sea level started to decelerate. This is the period when the observed decadal variability of the sea surface temperature in the Pacific (Pacific Decadal Oscillation, PDO) switched from its warm polarity to cold polarity. During this transition, the eastern Pacific lost heat to the atmosphere, as indicated by the decrease of upper ocean heat content (Katsman and van Oldenborgh, 2011), while the western Pacific gained heat from the atmosphere as indicated by the increase of upper ocean heat content. Since there exists a high correlation between PDO and ENSO in the low frequency band (Newman et al., 2003), it is suggested that the dynamics of interannual variability and the variation of the intrinsic trend of the GMSL and the global mean steric sea level during 1993–2012 may be related to the frequency dependence of the atmosphere–ocean coupling in the Pacific (Zhang et al., 1997) under the global warming, for example, intensification of the easterly trade wind across the tropical Pacific (Merrifield, 2011). This hypothesis could be further tested when longer satellite altimeter observations are available in the future.

Fig. 3. a. Regression of total sea level (observed by altimeters) during 1993–2012 on the third IMF of the GMSL given in Fig. 1a. b. Same as panel a but for the steric sea level.
The pattern of the sea level rise in the Atlantic shows interesting changes in the Gulf Stream whereas the intrinsic trend became positive north of the Gulf Stream and negative south of the Gulf Stream since 2004 (Fig. 5, bottom panel). This pattern is associated with the recent dips in the Atlantic Meridional Overturning Circulation (AMOC) (McCarthy et al., 2012) and a weakening of the Gulf Stream after 2004 (Ezer et al., 2013), which might be responsible for the accelerated sea level rise along the US east coast (Sallenger et al., 2012), and the decelerated sea level rise in the tropical Atlantic.

Same as the interannual variability, although the intrinsic trend of the GMSL and the global mean steric sea level over the last 20-year period shares the similar spatial pattern, there exist quite large differences on the magnitude. This discrepancy can be explained by the accelerated rising of the ocean mass based on the sea level budget estimation (Leuliette and Willis, 2011; Stammer et al., 2013).

4. Discussions and conclusion

In this paper, we performed the analysis of the sea level change using the EMD method to derive the intrinsic trend of the GMSL, the global mean steric sea level, and the global mean ocean mass during the period from 1993 to 2012. Our result demonstrates the robustness of EMD to derive the physically sound intrinsic trend of the global sea level rise.

It is shown that the interannual variability of the GMSL has limited impact on the intrinsic trend over the 20-year period, even though a recent La Niña event in 2011 led to about 5 mm drop of the GMSL within one year and the recovery of more than 5 mm within several months. This illustrates the ability of the EMD method to isolate the short-term strong variability from the long-term trend, in spite of the large uncertainty due to the boundary effects.

The intrinsic trend of the GMSL derived by EMD exhibits an accelerated rising period during 1993–2003 with a mean rate of 3.2 ± 0.4 mm/yr and a decelerated rising period since 2004 with the rate of about 1.8 ± 0.9 mm/yr in 2012. This finding highlights the nonlinear and non-stationary rising process of the global sea level and implies that this intrinsic trend may also change again in the next decade, which makes the projection of the future sea level change a difficult challenge. Note that our analysis of the 20 yr altimeter data is relatively short compared with the long-term global tide record of nearly 130 yr (Church and White, 2011), and that some long-term patterns such as the 60 yr sea level cycle (Chambers et al., 2012) are not resolved, so they may be part of what is called here the intrinsic trend of the GMSL.

Comparison between the GMSL, the global mean steric sea level, and the global mean ocean mass indicates that the decreasing of the rising trend is mainly due to the stalled ocean heat content which started in the early 2000s, when the PDO switched from the warm polarity to cold polarity. The coherence between the GMSL and the global mean steric sea level, on both time scales and spatial patterns, suggested that the dynamics of interannual variability and the variation of the intrinsic trend of the GMSL and the global mean steric sea level during 1993–2012 may be related to the frequency dependence of the atmosphere-ocean coupling in the Pacific. This sheds light on the possibility to improve the predictability of the future sea level change by a deeper understanding of the ocean dynamics, which has received more attention recently (Clement et al., 2011; Sallenger et al., 2012; Ezer et al., 2013; Kopp, 2013).

Although the stalled upper ocean heat content during the last decade has reduced the rising trend of the GMSL, the global sea level kept rising because of the contribution of the accelerated melting of land ice in the warming climate. This means that if the land ice keeps melting at the same or faster pace due to anthropogenic warming, the world ocean will experience a significant accelerated total sea level rise when the steric sea level transitions to a stage similar to the period during 1993–2003.

Our analysis also underscores the importance of the global sea level observations, including the satellite altimeters, the global gravity fields, and the global ocean temperature–salinity profiles. There is only 20-year long global total sea level observation and 10-year long global ocean mass. Any estimation of the intrinsic trend of global sea level rising is likely contaminated by the potential decadal variability. This introduces a large uncertainty to the projection of future sea level change. Although there is another option to make the projection using tide gauge observation with long records, it is a challenge to establish the link between the sparsely distributed tide gauge observations and the large-scale global sea-level variability.

Fig. 4. a. The intrinsic trend of the GMSL, i.e. the first-order time-derivative of the trend function of the GMSL given in Fig. 1a. Thick solid black line denotes the mean intrinsic trend of all the sub-samples of the GMSL during 1993–2012. Thin solid black line gives the linear trend of the GMSL rise, and the thin dashed lines give its one standard deviation. b. Same as panel a but for the intrinsic trend of the global mean steric sea level. c. Same as panel a but for the intrinsic trend of the global mean ocean mass during 2003–2012.
Fig. 5. a. Mean trend of the total sea level rise during (top) period 1 (1993–2003) and (bottom) period 2 (2004–2012). b. Same as panel a but for the steric sea level.
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