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Sea level budget over 2005–2013: missing contributions and data errors

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Abstract

Based on the sea level budget closure approach, this study investigates the residuals between observed global mean sea level (GMSL) and the sum of components (steric sea level and ocean mass) for the period January 2005 to December 2013. The objective is to identify the impact of errors in one or several components of the sea level budget on the residual time series. This is a key issue if we want to constrain missing contributions such as the contribution to sea level rise from the deep ocean (> 2000 m). For that purpose, we use several data sets as processed by different groups: six altimetry products for the GMSL, four Argo products plus the ORAS4 ocean reanalysis for the steric sea level and three GRACE-based ocean mass products. We find that over the study time span, the observed trend differences in the residuals of the sea level budget can be as large as $\sim 0.55\,\mathrm{mm\,yr^{-1}}$. These trend differences essentially result from the processing of the altimetry data (e.g., choice the geophysical corrections and method of averaging the along-track altimetry data). At short time scale (from sub-seasonal to multi-annual), residual anomalies are significantly correlated with ocean mass and steric sea level anomalies (depending on the time span), indicating that the residual anomalies are related to errors in both GRACE-based ocean mass and Argo-based steric data. Efforts are needed to reduce these various sources of errors before using the sea level budget approach to estimate missing contributions such as the deep ocean heat content.

1 Introduction

For the 1993–2010 time span of high-precision satellite altimetry era, the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) reported that the rate of global mean sea level (GMSL) rise could be explained by the combined effects of land ice melt (50 %), ocean thermal expansion (37 %) and anthropogenic land water storage decrease (13 %) (Church et al., 2013). Over this period, GMSL rise observed by altimeter satellites amounted $3.2 \pm 0.4\,mm\,yr^{-1}$, a value only slightly higher than the sum of the contributions (amounting to $2.8 \pm 0.5\,mm\,yr^{-1}$). Although of the same order of magnitude as associated uncertainties, the $0.4\,mm\,yr^{-1}$ difference may also reflect missing contributions, e.g., the deep ocean contribution below 700 m depth where the coverage of ocean temperature data before the Argo era is very poor. Estimating the deep ocean warming is an important issue in the context of the current pause reported since the early 2000s in global mean air and sea surface temperature evolution (also called the "hiatus", e.g., Held, 2013; Trenberth and Fasullo, 2013; Smith, 2013). Different explanations have been proposed to explain the hiatus, ranging from reduced radiative forcing due to prolonged solar minimum, increased aerosols emissions and small numerous volcanic eruptions, changes in stratospheric water vapor, and enhanced heat uptake in the deep ocean, either in the Pacific or Atlantic regions (e.g., Trenberth and Fasullo, 2010, 2013; Hansen et al., 2011; Solomon, 2010; Guemas et al., 2013; Kosaka and Xie, 2013; Balmaseda et al., 2013a; Watanabe et al., 2013; England et al., 2014; Chen and Tung, 2014). The deep ocean heat uptake is currently the favored explanation of the hiatus considering that greenhouse gases continue to accumulate at an increasing rate (Peters et al., 2012) and the Earth's energy imbalance at the top of the atmosphere is still in the range $0.5–1\,W\,m^{-2}$ (e.g., Hansen et al., 2011; Loeb et al., 2012; Trenberth et al., 2014; Allan et al., 2014). However, there are still too few studies dedicated to quantify deep ocean heat uptake. Accurate observations of sea level rise and its components (ocean thermal expansion and ocean mass change) can, in principle, help constraining the deep ocean contribution (e.g., von Schuckmann et al., 2014). In particular satellite altimetry-based GMSL rise corrected for ocean mass change (for example using GRACE space gravimetry data over the oceans) provides estimate of the total (full depth integrated) ocean thermal expansion (or equivalently ocean heat content). Since the year 2005, comparison with observed Argo-based ocean thermal expansion (down to ~ 2000 m depth) may help quantifying any deep ocean contribution (below 2000 m). In effect, the sea level budget equation is described as follows:

$$\text{GMSL} = \text{Ocean Mass} + \text{Steric sea level (0–2000 m)} + \text{Steric sea level (> 2000 m)} + \text{data errors} \quad (1)$$

The residual term defined as the difference between observed GMSL and observed estimates of ocean mass and steric sea level down to 2000 m depth (see Eq. 2 below) includes the deep ocean contribution (called "steric sea level (> 2000 m)"):

$$\text{Residual} = \text{GMSL} - \text{Ocean mass} - \text{Steric sea level (0–2000 m)} = \text{Steric sea level (> 2000 m)} + \text{data errors} \quad (2)$$

Attempts to estimate the deep ocean contribution from the sea level budget approach were performed in two recent studies (Llovel et al., 2014; Dieng et al., 2015). Dieng et al. (2015) considered two periods (2005–2012 and 2003–2012) which correspond to the availability of new observing systems for estimating thermal expansion and ocean mass (nearly full ocean temperature and salinity coverage down to 2000 m from Argo floats and direct ocean mass measurements from GRACE space gravimetry). Time series of satellite altimetry-based sea level (5 different data sets), thermal expansion (8 different products; integration down to 1500 m) and ocean mass (3 products) components were analyzed in order to estimate the residual term of Eq. (2). Llovel et al. (2014) performed a similar study over the 2005–2013 time span but with less data sets. Another attempt concerning this issue is by von Schuckmann et al. (2014). These studies came up to the same conclusion, i.e., the residual term is contaminated by too large data errors to provide any robust deep ocean contribution estimate. Here we build on these previous studies, in particular that from Dieng et al. (2015). We focus on the 2005–2013 time span corresponding to full Argo coverage and compute the steric sea level component integrating the data down to 2000 m. We also include in our analysis the new sea level product from ESA Climate Change Initiative (CCI)project (www.esa-sealevel-cci.org), available up to December 2013. We use the same approach as in Dieng et al. (2015), i.e., we compute the residual time series. The main

OSD
12, 701–734, 2015

objective of the present study is to quantify the contributions of errors coming from one or several terms of the sea level budget (GMSL, ocean mass, steric sea level) in the residual time series. This is an important issue to be addressed before trying to estimate any deep ocean contribution.

2 Data and method

2.1 Sea level data

We used six different products from five processing groups for the altimetry-based sea level data:

1. Validation and Interpretation of Satellite Oceanographic (AVISO; http://www.aviso.altimetry.fr/en/data/products/ocean-indicators-products/actualitesindicateurs-des-oceansniveau-moyen-des-mersindexhtml.html).
2. Colorado University (CU Release 5; http://sealevel.colorado.edu/).
3. National Oceanographic and Atmospheric Administration (NOAA; http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/LSA_SLR_timeseries_global.php).
4. Goddard Space Flight Center (GSFC version 2; http://podaac-ftp.jpl.nasa.gov/dataset/MERGED_TP_J1_OSTM_OST_GMSL_ASCII_V2).
5. Commonwealth Scientific and Industrial Research Organization (CSIRO; www.cmar.csiro.au/sealevel/sl_data_cmar.html).
6. The Climate Change Initiative (CCI) sea level data (ftp://ftp.esa-sealevel-cci.org/Products/SeaLevel-ECV/V1_11092012/).

The first five sea level data sets are based on Topex/Poseidon, Jason-1 and Jason-2 data averaged over the 66° S–66° N domain, except for the CSIRO data averaged

OSD
12, 701–734, 2015

over 65° S–65° N. For each product, a set of instrumental and geophysical corrections is applied (details are given on the websites of each data set). In addition, the effect of Glacial Isostatic Adjustment (GIA, i.e. a small correction of $-0.3\,\mathrm{mm\,yr^{-1}}$, Peltier, 2004) is accounted for in each sea level time series except in the NOAA data set. Thus we corrected the latter sea level data for the GIA effect, using the $-0.3\,\mathrm{mm\,yr^{-1}}$ value. The sea level time series used in this study cover the period January 1993–December 2013. The five sea level time series (AVISO, CU, GSFC, NOAA and CSIRO) are obtained either by directly averaging the along-track sea surface height data (e.g., CU) or by firstly gridding the unevenly distributed along track data and then performing grid averaging (e.g., AVISO and NOAA). In all cases, an area weighting is applied. In addition to the geographical averaging method, other differences exist between the GMSL data sets because of the applied geophysical and instrumental corrections and the number of satellites considered (discussion on these differences can be found in Masters et al., 2012 and Henry et al., 2014).

In the context of the European Space Agency/ESA Climate Change Initiative/CCI"SeaLevel"project, a new improved product has been computed. It combines data from the Topex/Poseidon, Jason-1/2 with the ERS-1/2 and Envisat missions and is based on a new processing system with dedicated algorithms and adapted data processing strategies (Ablain et al., 2015). The main improvements include: reduction of orbit errors and wet/dry atmospheric correction errors, reduction of instrumental drifts and bias, inter-calibration biases, inter-calibration between satellite altimetry missions and combination of the different sea level data sets, and an improvement of the reference mean sea surface. The CCI sea level products have been validated using different approaches, including a comparison with tide gauges records as well as to ocean reanalyses and climate model outputs (see Ablain et al., 2015 for more details). The CCI sea level data set is freely available over January 1993–December 2013.

Figure 1a shows the GMSL time series from January 2005 to December 2013 for the 6 products presented above. Trend values estimated over this time span are given in Table 1. We first note important trend differences between all GMSL time series, up to

0.55 mm yr^{-1} between GFSC and CSIRO data. The lowest trends (around 2.8 mm yr^{-1}) are obtained for the CU and GSFC data sets. Higher trends (from 3.11 to 3.35) are obtained for CCI, AVISO, NOAA and CSIRO GMSL. At shorter time scales (from sub-seasonal to multi-annual) significant discrepancies of several mm are observed between the data sets, especially between 2005 and 2008, and between mid-2010 and mid-2011. The latter period coincides with a strong La Nina event.

2.2 Ocean mass data

We use three different data sets for estimating the ocean mass component: the GRACE Release 05 products from the Center for Space Research of the University of Texas (CSR RL05), the Helmholtz-Zentrum Potsdam Deutsches (GFZ RL05, GeoForschungsZentrum), the Jet Propulsion Laboratory (JPL RL05). The GRACE release 05 ocean mass data have been specifically processed by D. Chambers to study the ocean mass temporal evolution (data available at http://grace.jpl.nasa.gov). In effect, gridded Release 05 data cannot be used to compute ocean mass changes because they have the global mean removed (as warned on the http://grace.jp.nasa.gov web site). The corresponding RL05 GRACE ocean data are publicly available from https://dl.dropboxusercontent.com/u/31563267/ocean_mass_orig.txt. They are provided as global mean (averaged over the 90° S–90° N domain) time series with associated uncertainty. The data processing is described in Chambers (2009) and Johnson and Chambers (2013) (see also Chambers and Schroeter, 2011, and Chambers and Bonin, 2012). The GIA component has been subtracted from each GRACE ocean mass time series using the GIA correction computed in Chambers et al. (2010). Figure 1b shows the global ocean mass (called GOM hereafter) time series and associated uncertainties over 2005–2013 for the CSR, GFZ and JPL products (see also Table 1 for associated trend values). All three GOM products are quite close to each other, both in terms of trend and short-term fluctuations.

OSD
12, 701–734, 2015

2.3 Steric data

We used 4 Argo temperature and salinity data sets.

Three gridded data sets are provided by the following groups:

- The International Pacific Research Center (IPRC; http://apdrc.soest.hawaii.edu/projects/Argo/data/gridded/On_standard_levels/index-1.html).
- The Japan Agency for Marine-Earth Science and Technology (JAMSTEC; ftp://ftp2.jamstec.go.jp/pub/argo/MOAA_GPV/Glb_PRS/OI/).
- The SCRIPPS Institution of Oceanography (SCRIPPS; http://sio-argo.ucsd.edu/RG_Climatology.html).

These data sets are available at monthly interval on a global 1° × 1° grid down to 2000 m, over the period January 2005 to December 2013.

Argo data sets do not cover the whole ocean before 2005 (von Schuckmann et al., 2014; Roemmich et al., 2015). Thus we computed the steric sea level time series (and associated uncertainty; but note that only Jamstec provides errors), over January 2005-December 2013, integrating the data over the 0–2000 m depth range. The global mean steric time series from IPRC, Jamstec and SCRIPPS are estimated over the 62.5° S–64.5° N, 60.5° S–66° N and 61.5° S–64.5° N domains, respectively.

We also used an updated version of the steric data set processed by von Schuckmann and Le Traon (2011). This data set provides steric sea level and associated uncertainty based on quality controlled Argo temperature and salinity data from IFREMER (http://wwz.ifremer.fr/lpo_eng/content/view/full/83074), with integration down to 2000 m depth and averaging on a 5° × 10° grid. Their method is described in detail in von Schuckmann and Le Traon (2011). In the following, we call this data set "KVS". The KVS data set covers the 60° S–60° N domain. Area weighting is applied to all data sets when averaging.

Figure 1c presents the 4 steric sea level time series and associated uncertainties (except for IPRC and SCRIPPS) over 2005–2013. Trend values over the study time span can be found in Table 1. Figure 1c shows significant discrepancies of several mm from one data set to another at sub-seasonal to multi-annual time scale, in particular in the early part of the time series (e.g., in 2005) and in late 2007-early 2008. Between 2005 and early 2008, the KVS time series is rather flat, unlike the other steric time series derived from gridded Argo fields. In terms of trends, we note differences of up to 0.2 $mm\,yr^{-1}$, the KVS data set giving lower steric trend than the other three (this is actually due to the rather flat start of the KVS curve in 2005).

Finally, we include the ORAS4 reanalysis from Balmaseda et al. (2013b) https://icdc.zmaw.de/easy_init_ocean.html?&L=1#c2231). It is based on the Nucleus for European Modelling of the Ocean (NEMO) circulation model (version 3.0) with data assimilation. Assimilated data include temperature and salinity profiles over 1958–2009 from the v2a version of the EN3 data base constructed by the Met Office Hadley Center (Good et al., 2013), along-track altimetry-based sea level anomalies and global sea level trend from AVISO, sea surface temperature and sea ice from the ERA-40 archive (prior to November 1981), from NCEP (National Centers for Environmental Prediction) OI version 2 (1981 until December 2009) and from OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis; January 2010 onwards). The ORAS4 temperature and salinity data are available at monthly intervals over 42 depth levels ranging from the ocean surface down to 5350 m depth, on a global $1^\circ \times 1^\circ$ grid from January 1958 to December 2014 (see Balmaseda, 2013b for more details). To estimate the ORAS4 global mean steric sea level, the data are averaged over the 66° S–66° N domain.

3 Residual time series (GMSL minus ocean mass minus steric sea level)

In this section, we present the residual time series (Eq. 2, called “residuals” hereinafter) over January 2005–December 2013. The main objective is to check whether the residual anomalies are correlated -or not- with one or several terms of the sea level budget (GMSL, ocean mass, steric sea level; see Eq. 1). A significant correlation of the residuals with one component of the budget equation (GMSL, ocean mass, steric sea level) would indicate that this particular component is in error. Inversely, a low correlation means that the signal associated with this component is well compensated by the other two components of the budget equation (Eq. 1).

3.1 Residuals with trends

Figure 2 shows residual time series computed for each GMSL estimate (i.e., AVISO, CU, NOAA, GSFC, CSIRO and CCI), using an average of the 3 GOM and 4 Argo-based steric sea level products. For the comparison, all curves start at the same (arbitrary) value in January 2005. In Table 1 are gathered the trend values over January 2005–December 2013 for each GMSL, GRACE-based ocean mass, Argo-based steric sea level and residual time series. Figure 2 indicates that over the January 2005–February 2007 time span, the residuals are in fairly good agreement. Late 2007 (a period coinciding with the 2007–2008 La Nina), all residuals are strongly negative. By mid-2008, we observe a step like increase for several GMSL residuals (AVISO, NOAA, CSIRO and CCI time series) while a decrease is noticed for the CU residuals until mid-to-late 2011. The residual trends seem to fall into two groups (see Table 1): (1) AVISO, NOAA, CSIRO and CCI, and (2) CU and GSFC, with large trend differences $> 0.5\,\mathrm{mm\,yr^{-1}}$. The positive residual trends correspond to group 1. The residual trends of group 2 are negative.

Because the same "mean" ocean mass and "mean" steric sea level are used when computing the residuals shown in Fig. 2, differences in residual trends necessarily result from trend differences in the GMSL time series. To investigate this further, we show below (Fig. 3) difference time series between GMSL products, using the CCI GMSL as reference.

The two groups of GMSL products mentioned above appear much more clearly in Fig. 3. We note that the AVISO, NOAA and CSIRO GMSL (corresponding to group 1) follow a different trajectory than the CU and GSFC GMSL (group 2), except during 2008–2010. This is particularly obvious during 2005–2008 and to a lesser extent beyond 2010. The sources of these differences have been investigated in two recent

OSD
12, 701–734, 2015

papers by Master et al. (2012) and Henry et al. (2014). These studies showed that the choice of the geophysical corrections applied to the data and the averaging method to calculate the GMSL from along track data are the two main causes of differences between the GMSL time series. For example, AVISO and CU apply different averaging methods that significantly impact the GMSL products (Henry et al., 2014). Moreover, during 2005 to mid-2008 corresponding to the use of Jason-1 satellite data, these groups use different orbit solutions and different corrections for ocean tides and sea surface bias, while beyond mid-2008, they use exactly the same orbit solution and same sea surface bias correction (see the respective web sites for more details). Thus differences between AVISO and CU GMSL are to be expected over 2005 to mid-2008. This is indeed what Fig. 3 shows over this time span. To check this somewhat further, we computed the residuals trends between January 2005 and June 2008 for all GMSL time series. We find highly negative residual trends for CU and GFSC (of −0.67 and −0.91 mm yr^{-1} respectively) while for all other GMSL time series the residual trends are in the range −0.05 to 0.08 mm yr^{-1}. Other differences noticed in Fig. 3 beyond 2010 are less clear but may be related to the averaging method with a stronger impact during the 2011 La Nina. More investigation and collaborative work between the different processing groups are needed to fully understand and reduce the reported differences in the GMSL time series.

In a next step, we examine the contribution of the ocean mass and steric components to the residual trend for each GMSL product. Figure 4a, b shows residual curves for the CCI GMSL computed with each ocean product and each steric sea level product. Results show that the different ocean mass products show almost similar residual trends (up to $\sim$ 0.1 mm yr^{-1} trend differences are noted; see Fig. 4a). For the Argo products, the effect on the trend differences is $<$ 0.2 mm yr^{-1} (see Fig. 4b). We do not show similar figures for other GMSL products because the differences in the residual trends computed between all Argo products (and all ocean mass products as well) are similar to those computed with CCI GMSL.

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

OSD

12, 701–734, 2015

Sea level budget over 2005–2013: missing contributions and data errors

H. B. Dieng et al.

From this section, we conclude that the largest trend differences observed in the residual time series (Fig. 2) come from differences in the altimetry-based GMSL products.

4 Detrended residuals

Figure 2 shows that the residual time series also display important high frequency (sub annual to multi annual) anomalies of up to 4 mm amplitude. These anomalies are highly correlated for all GMSL products, in particular for AVISO, NOAA, CSIRO and CCI data sets. In the following, we analyze the detrended residual time series. Only 3 GMSL data sets are considered: the AVISO, CU and CCI GMSL data (AVISO and CU being representative of group 1 and group 2, respectively). In order to understand whether a given variable (GMSL, ocean mass or steric sea level) is responsible for all -or part- of the observed short-term (from sub-seasonal to multi annual) residuals, we correlate this variable (trend removed) with its associated residual. What we would expect, if all data sets were error free, is to see no correlation between the detrended variable and its associated (detrended) residual. Therefore a low correlation indicates "good result", i.e., little contamination by errors of the associated variable.

4.1 GMSL short-term (from sub-seasonal to multi-annual) errors

To analyze the impact of the short-term GMSL errors on the residuals, we simply superimpose the detrended GMSL with its associated residual (also detrended). Figure 5a–c shows for AVISO, CU and CCI data, the detrended residual curves and associated detrended GMSL. In Table 2 are given the correlation computed the detrended residual curve and its associated detrended GMSL as well as the root-mean-squares (rms) of the residual time series. At seasonal to interannual time scales, most of the observed anomalies have been reduced after subtracting the ocean mass and steric sea level components from the GMSL. Nevertheless, some anomalies still remain (see Fig. 5a–

OSD
12, 701–734, 2015

c), indicating that part of the short-term fluctuations seen in the residuals result from short-term errors in the GMSL. This is particularly striking for the 2007–2008.5 time span. This period corresponds to a La Nina event. While the 2011 La Nina is well explained by the mass plus steric components (see Boening et al., 2012, and Cazenave et al., 2014), the question arises why the same data sets do not explain the negative GMSL anomaly related to the 2007/08 La Nina. During the period February 2007 to June 2008, the correlation computed between the CCI, AVISO and CU residual curves and associated detrended GMSL amounts to 0.79, 0.89 and 0.92 respectively. This high correlation and amplitude comparison suggests that the residual anomaly during this time span largely comes from the GMSL. We cannot exclude however that it could also be due to errors in either the steric or the ocean mass components. We will see below that the observed discrepancy at this particular date also partly arises from errors in the GRACE and Argo data.

Over the whole time span (2005–2013), the correlations are 0.02, 0.26 and 0.55 for the CCI, AVISO and CU GMSL, respectively (see Table 2). The lowest correlation is obtained for the CCI data, indicating that the CCI residuals show less GMSL short-term errors than the other two data sets.

4.2 Short-term (from sub-seasonal to multi-annual) errors in the global ocean mass

We perform a similar comparison with the GRACE-based ocean mass products. For that purpose we only consider a single GMSL data set (i.e., CCI) and superimpose the detrended CCI residual time series computed separately for each ocean mass product with the corresponding detrended GRACE data set. These are shown in Fig. 6a–c. In Table 2 are given the correlation computed between the detrended residual curve and its associated detrended ocean mass component. The rms of the residual time series are also given.

The correlation is relatively high in all three cases, of 0.46, 0.55 and 0.57 for the CSR, GFZ and JPL data respectively. The detrended global ocean mass and residual

OSD
12, 701–734, 2015

time series coincide almost perfectly between mid- 2006 and mid-2007 and between mid-2009 and early 2012 (Fig. 6). This indicates that the short-term residual errors are largely affected by errors in GRACE-based ocean mass products. During the 2007/08 La Nina, we also observe a significant correlation between the detrended ocean mass and associated residual, of 0.57, 0.69 and 0.69 respectively for the CSR, GFZ and JPL data.

4.3 Short-term (from sub-seasonal to multi-annual) Argo-based steric sea level errors

The rms of the residual time series based on the CCI, AVISO and CUGMSL, IPRC, Jamstec, SCRIPPS and KVS Argo data (linear trend removed from each time series) are in the range 1.3–1.6 mm (see Fig. 7 and Table 2). Lowest rms is obtained with SCRIPPS data when using the CCI and CU GMSL. For AVISO, the lowest rms is obtained with the KVS steric sea level. Overall, no best Argo product emerges, rms differences being small.

As mentioned previously, in the early part of the time series (2005–2006), we note larger dispersion between all Argo products compared to the subsequent years. These differences can be explained by a still incomplete global coverage of Argo data during this period (Lyman and Johnson, 2014; Roemmich et al., 2015). The 2007–2008 time span coincides with a La Nina event, giving rise to a temporary negative anomaly in the GMSL (Dieng et al., 2014). We note that this negative anomaly is still present in the residual curves, with almost the same amplitude as in the GMSL data, indicating that the GMSL, or the mass or the Argo-based steric components (or all of them) are in error at that particular period (but see Sect. 4.4 for more discussion).

We next examine the correlation between the residual time series and the detrended steric sea level, considering each Argo product successively. Figure 8a–d shows the detrended residual time series computed with the CCI GMSL superimposed to the detrended steric sea level time series. Each of the four steric products (SCRIPPS,

OSD
12, 701–734, 2015

IPRC, Jamstec and KVS) are considered. In each case the mean global ocean mass is used for computing the residual.

Examination of Fig. 8 shows that lowest residual rms is obtained with the SCRIPPS time series, but the rms difference with other Argo products is small. We also note that the short-term residual fluctuations are significantly correlated with the associated (detrended) Argo-based steric sea level time series at some periods, for example between mid-2010 and mid-2013, and especially when using the IPRC data. This indicates that the short-term fluctuations of the residuals partly reflect Argo-based steric sea level errors during this period.

4.4 Sea level budget using the ORAS4 ocean reanalysis

Errors in Argo-based steric sea level estimates arise from different sources (gaps in some regions, data editing, mapping techniques, etc., Abraham et al., 2013; Lyman and Johnson, 2014, von Schuckmann et al., 2014). To investigate further the effect of Argo sampling, as well as other Argo data processing errors on the residual time series, we recomputed the residuals using steric data from the ORAS4 ocean reanalysis (Balmaseda et al., 2013). The integration is performed over the whole ocean depth range (0–5350 m) and between 66° S and 66° N. Figure 9 shows the residual time series computed with the CCI GMSL, and mean of the 4 Argo products (black curve) and ORAS4 data (dotted curve). The detrended CCI GMSL is superimposed. In terms of residual rms, we see little difference between the considered steric sea level products, even if at some periods (e.g., between mid-2010 and mid-2011) the steric curves do not agree very well to each other. For most of the time span, there is good coherency between the mean of the 4 Argo time series and ORAS4. However, the correlation between the residuals and the detrended CCI GMSL is slightly lower when using the mean of the 4 Argo products than using the reanalysis.

4.5 Contribution of the Indonesian region and other areas not covered by Argo

Differences in the residuals shown in Fig. 9 directly results from differences in the steric time series (all other parameters being the same). The ORAS4 minus mean Argo time series is shown in Fig. 10. It displays significant short-term fluctuations, up to 4 mm and a trend of 0.28 $\mathrm{mm\,yr^{-1}}$ (the ORAS4 steric trend being larger than the mean Argo trend). The ORAS4 reanalysis provides gridded steric data with no gaps, unlike the Argo products. In effect, the coverage of Argo data is not fully global, some regions (e.g. the Indonesian region and Gulf of Mexico) being not covered. Another factor contributing to the difference curve is the integration depth of the temperature and salinity data (0–2000 m for Argo and 0–5350 m for ORAS4). In Fig. 10 the ORAS4 contribution for the 2000–5350 m depth layer is also shown. It only explains 0.06 $\mathrm{mm\,yr^{-1}}$ sea level trend, and (as expected) none of the short-term anomalies seen in the residual curves when using Argo. More likely, both trend difference and short term anomalies result from gaps in the Argo geographical coverage (von Schuckmann et al., 2014). This is illustrated also in Fig. 10 that shows the steric sea level contribution from the Indonesian region (0–2000 m layer) computed with ORAS4. Part of the short term anomalies of the difference curve is due to lack of Argo data in this region (e.g., in 2011, coinciding with the La Nina event). Moreover, in terms of trend, the Indonesian region explains about the whole trend difference between Argo-based and ORAS4-based steric sea level. This suggests that the steric sea level trend estimated when using Argo is underestimated by $\sim 0.25\,\mathrm{mm\,yr^{-1}}$. Hence the residual (GMSL minus steric sea level minus ocean mass) trend may be in error (i.e., overestimated) by about this amount. This has important implication on the missing contributions derived from the sea level budget approach.

OSD

12, 701–734, 2015

5 Conclusions

In this study, we estimated the sea level budget over the 2005–2013 time span using a large set of different observational products for the satellite altimetry-based sea level (6 products), GRACE-based ocean mass (3 products) and steric sea level (5 data sets). We analyzed the residual time series (i.e. observed GMSL minus sum of mass plus steric components) and attempted to attribute an error source to the residual trends and short-term residual anomalies. We found that errors in the GMSL products have large impact on the residual trends, with differences, up to 0.55 $\mathrm{mm\,yr^{-1}}$, that prevent from accurately constraining missing contributions. These errors largely arise from differences in processing the Jason-1 satellite data: differences in the choice of GMSL averaging method and geophysical corrections (orbit solutions, ocean tides and sea surface bias geophysical corrections) are likely the cause of the large trend differences reported between the GMSL products during the Jason-1 mission. While trying to identify the outliers and select the best corrections to be used is beyond the scope of the present study, we need to stress that this is definitely an important goal to pursue in the future. In terms of absolute residual trend, we identified the contribution of the Indonesian region, not covered by Argo, as contributing by about 0.25 $\mathrm{mm\,yr^{-1}}$ (the computed residual trends being overestimated about this amount). Estimates (using ORAS4 data) of other regional gaps in the Argo coverage (e.g., Gulf of Mexico) indicates that the latter negligibly contribute to the residual trends. Thus, if we account for the residual trend overestimate due to lack of Argo data in the Indonesian region, the residuals with CCI, AVISO and NOAA become close to zero (i.e., 0.00, 0.04 and 0.16 $\mathrm{mm\,yr^{-1}}$ respectively) while the CU and GSFC residual trends are now negative (−0.29 and −0.33 $\mathrm{mm\,yr^{-1}}$ respectively). This suggests that the sea level budget is closed when using the CCI, AVISO and NOAA data. Hence, in these cases, the deep ocean (below 2000 m) contribution is negligible. It is worth mentioning that the residual trend (with CCI GMSL) amounts about zero (exactly −0.01 $\mathrm{mm\,yr^{-1}}$) when using ORAS4 (0–2000 m; Indonesian region accounted for), in agreement with the above

OSD
12, 701–734, 2015

statements. Moreover, as mentioned above, the ORAS4 steric sea level trend for the 2000–5350 m depth range amounts to 0.06 mm yr^{-1}. However, further investigation is needed on that issue before drawing any definitive conclusion.

Another important result from our study is the attribution of the short-term (from sub-seasonal to multi-annual) anomalies of the residual time series to errors in both Argo-based steric sea level and GRACE-based ocean mass. Short-term errors in these two components sometimes act in concert (thus amplifying the residual errors; e.g., during the 2007/08 La Nina) or subsequently affect the residuals at different periods (e.g. over 2011–2014 for Argo, or in 2006 for GRACE).

To summarize the findings of this study, the main source of residual trend differences appears to be related to altimetry-based sea level data processing. The case of missing Argo data in the Indonesian region needs also further investigation but crude estimate using the ORAS4 reanalysis suggests that its contribution is important. Accounting for it leads to closure of the sea level budget, at least with the CCI, AVISO and NOAA GMSL. At sub-seasonal to multi-annual time scales, the main source of uncertainty comes from short-term errors in GRACE and Argo data. More work is required by the different communities involved in either satellite altimetry or GRACE and Argo data processing, to clearly identify the causes of these errors and reduce/eliminate them. This is a challenge of primary importance if we want to precisely address a number of key issues, like the deep ocean heat uptake and its role in the current “hiatus”.

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OSD
12, 701–734, 2015

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OSD
12, 701–734, 2015

Table 1. Trends estimated over January 2005–December 2013 for the GMSL, global ocean mass, Argo-based steric sea level, and residuals. Errors associated with "mean global ocean mass" and "mean Argo-based steric sea level" are estimated from the dispersion around the mean.

Global mean sea level (GMSL) product	GMSL trends ($mm\,yr^{-1}$)	Residual trends ($mm\,yr^{-1}$) (residual computed with mean global ocean mass and mean Argo-based steric sea level)
AVISO	3.17	0.3
CU	2.83	−0.03
NOAA	3.26	0.42
GSFC	2.80	−0.07
CSIRO	3.35	0.49
CCI	3.11	0.26
Global ocean mass	**Global ocean mass trends ($mm\,yr^{-1}$)**	**CCI residual trends ($mm\,yr^{-1}$)**
CSR	2.01	0.28
GFZ	2.11	0.18
JPL	2.00	0.29
Mean	2.04 ± 0.08	
Argo-based steric sea level	**Argo-based steric sea level trends ($mm\,yr^{-1}$)**	**CCI residual trends ($mm\,yr^{-1}$)**
KVS	0.74 ± 0.13	0.33
IPRC	0.76	0.31
JAMSTEC	0.94 ± 0.16	0.14
SCRIPPS	0.83	0.24
Mean	0.82 ± 0.08	

OSD
12, 701–734, 2015

Table 2. Correlations estimated between detrended residual time series and associated detrended component. Estimated rms of the corresponding detrended residual time series.

Global mean sea level (GMSL) product	RMS of the residual computed with mean global ocean mass and mean Argo-based steric sea level (mm)	Correlation (detrended GMSL and associated detrended residual)
CCI	1.38	0.02
AVISO	1.32	0.26
CU	1.36	0.55
GRACE-based global ocean mass product	RMS of the CCI residual computed with mean Argo-based steric sea level (mm)	Correlation (detrended global ocean mass and associated detrended residual)
CSR	1.37	0.46
GFZ	1.46	0.55
JPL	1.56	0.57
Argo-based steric sea level (0–2000 m)	RMS of the CCI residual computed with mean global ocean mass (mm)	Correlation (detrended steric sea level and associated detrended residual)
KVS	1.59	0.53
IPRC	1.56	0.51
JAMSTEC	1.56	0.51
SCRIPPS	1.45	0.50

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OSD
12, 701–734, 2015

Sea level budget over 2005–2013: missing contributions and data errors

H. B. Dieng et al.

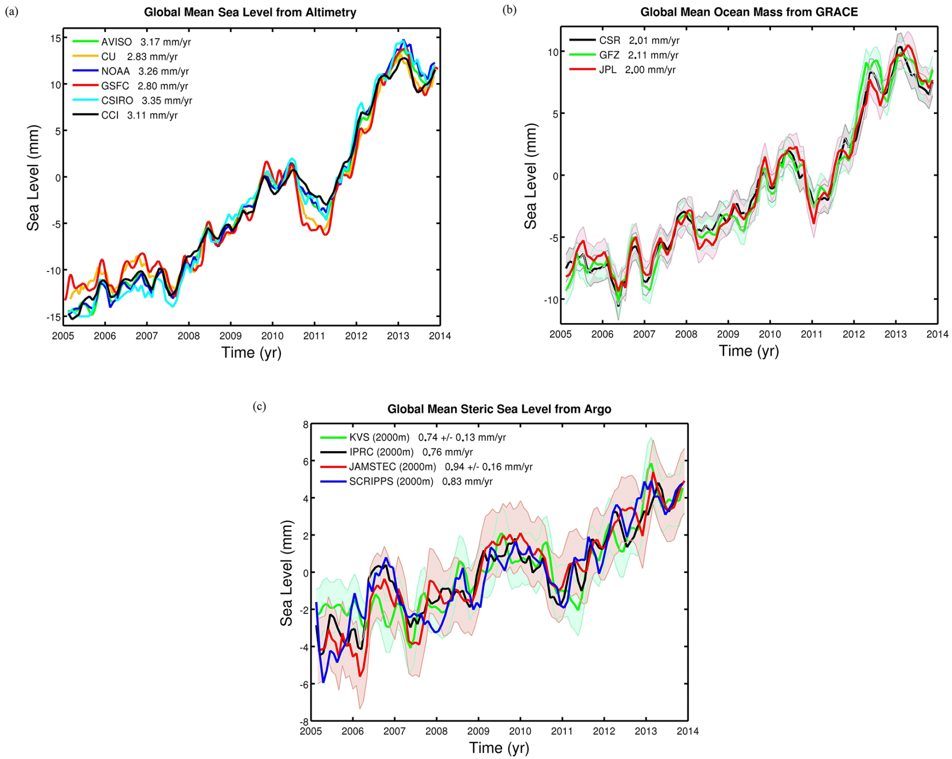

Figure 1. (a) Global mean sea level (GMSL) time series (January 2005–December 2013) from the five satellite altimetry processing groups (AVISO, CU, NOAA, GSFC and CSIRO) and CCI. **(b)** Global ocean mass (GOM) time series and associated uncertainty (shaded area) (January 2005–December 2013) from GRACE based on the data from CSR (black curve), GFZ (green curve) and JPL (red curve). **(c)** Argo-based monthly global mean steric sea level time series (January 2005–December 2013) (integration down to 2000 m) from four processing groups (KVS, IPRC, JAMSTEC and SCRIPPS). Shaded areas represent uncertainties of the JAMSTEC and KVS steric sea level data.

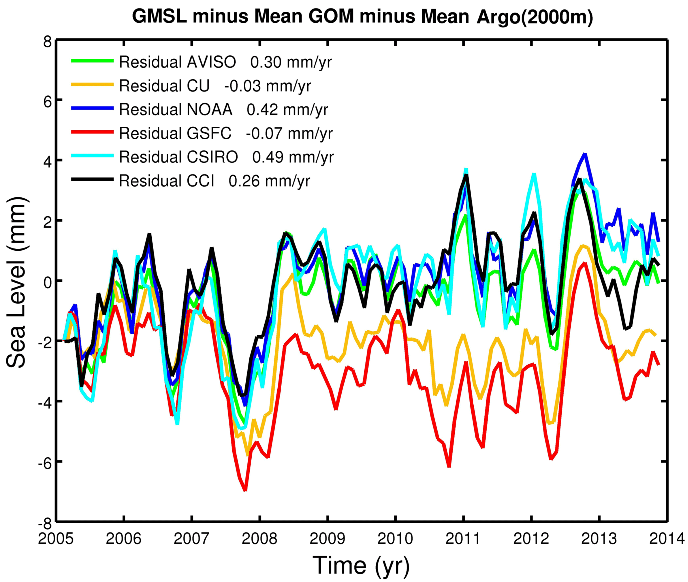

Figure 2. Residual curves (January 2005–December 2013) computed for each of the 6 GMSL products (AVISO, CU, NOAA, GSFC, CSIRO and CCI). Mean global ocean mass (GOM) and mean Argo-based steric sea level are used. (For example: “Residual AVISO” = “GMSL from AVISO minus Mean GOM minus Mean Argo”).

OSD
12, 701–734, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

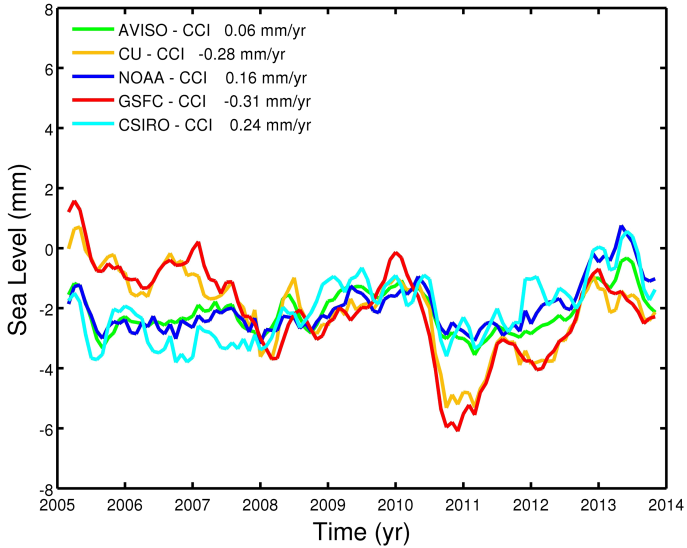

Figure 3. Time series of GMSL differences with respect to the CCI GMSL (January 2005–December 2013).

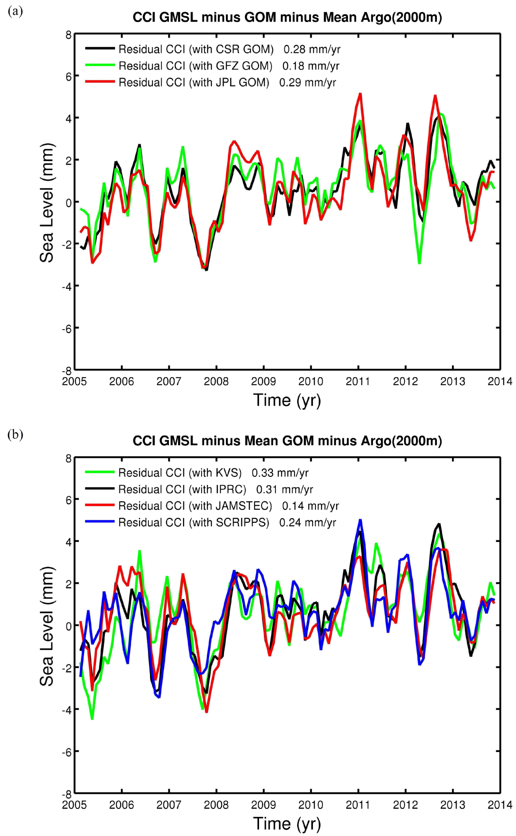

Figure 4. Residual sea level time series (January 2005–December 2013) computed with the CCI GMSL. **(a)** Mean of the 4 Argo and each GOM products; **(b)** Mean of the 3 global ocean mass (GOM) data sets and each Argo product.

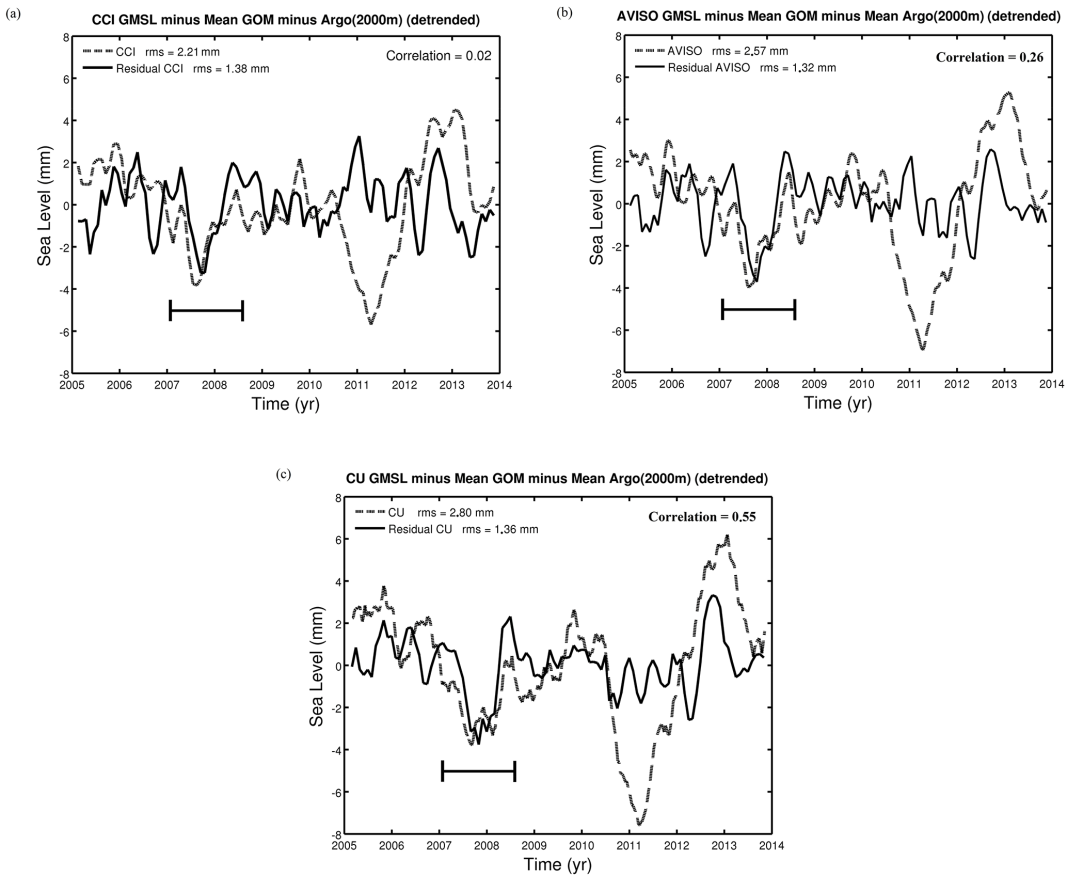

Figure 5. Detrended residual time series (January 2005–December 2013) (mean global ocean mass (GOM) and mean Argo-based steric sea level are used to compute the residual) for CCI **(a)**, AVISO **(b)**, and CU **(c)**. The detrended GMSL CCI, AVISO and CU, are superimposed on each residual respectively.

OSD
12, 701–734, 2015

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◄ | ►
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

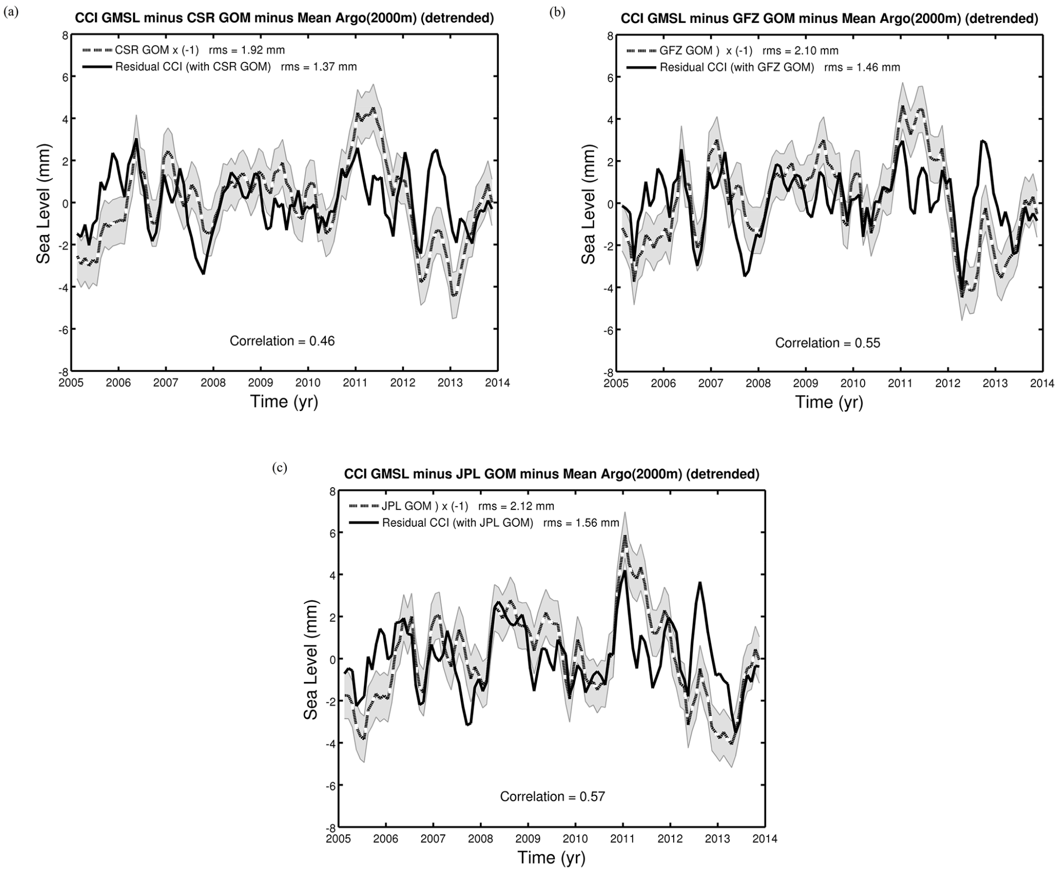

Figure 6. Detrended residual time series (January 2005–December 2013) computed with the CCI GMSL, mean Argo-based steric sea level and different ocean mass products. Associated detrended global ocean mass (GOM) time series superimposed. **(a)** CSR; **(b)** GFZ; **(c)** JPL.

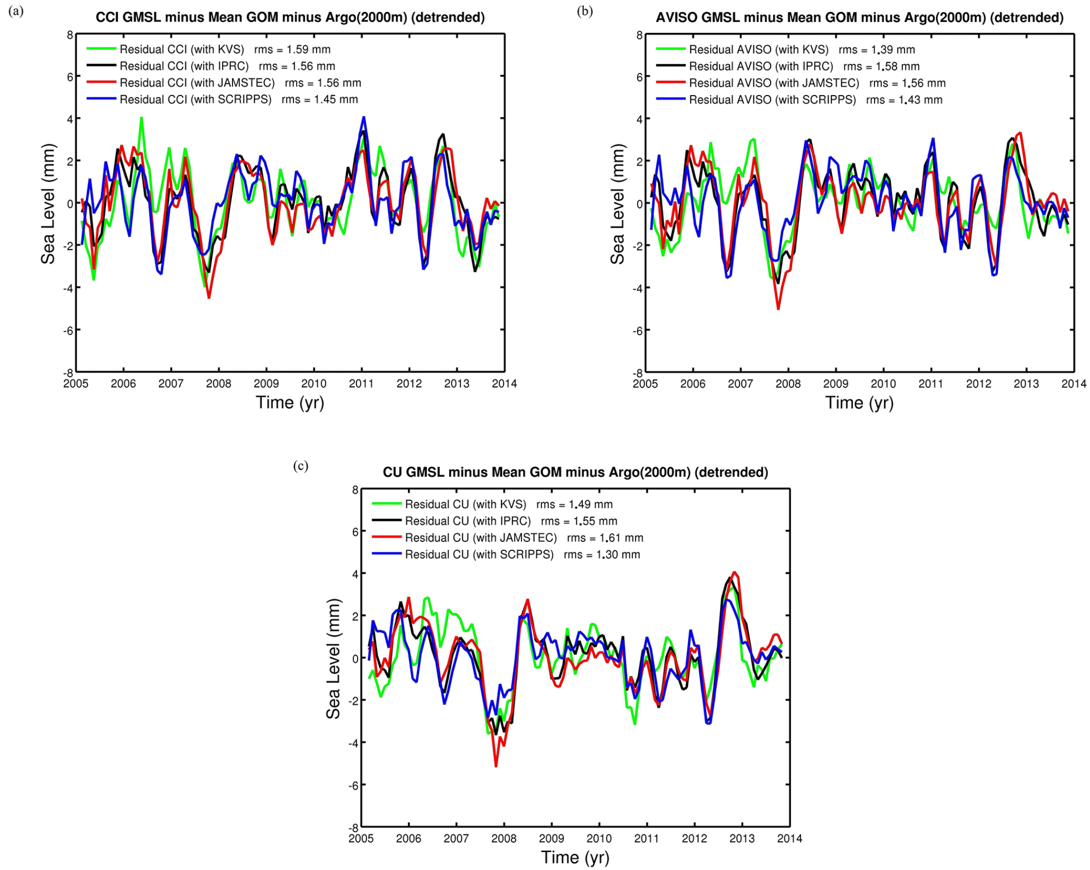

Figure 7. Residual time series (January 2005–December 2013) computed for each of the 3 GMSL: CCI **(a)**, AVISO **(b)**, and CU **(c)**. Mean global ocean mass (GOM) and each of the 3 steric sea level products (IPRC, JAMSTEC, SCRIPPS and KVS) are used for computing the residuals.

OSD
12, 701–734, 2015

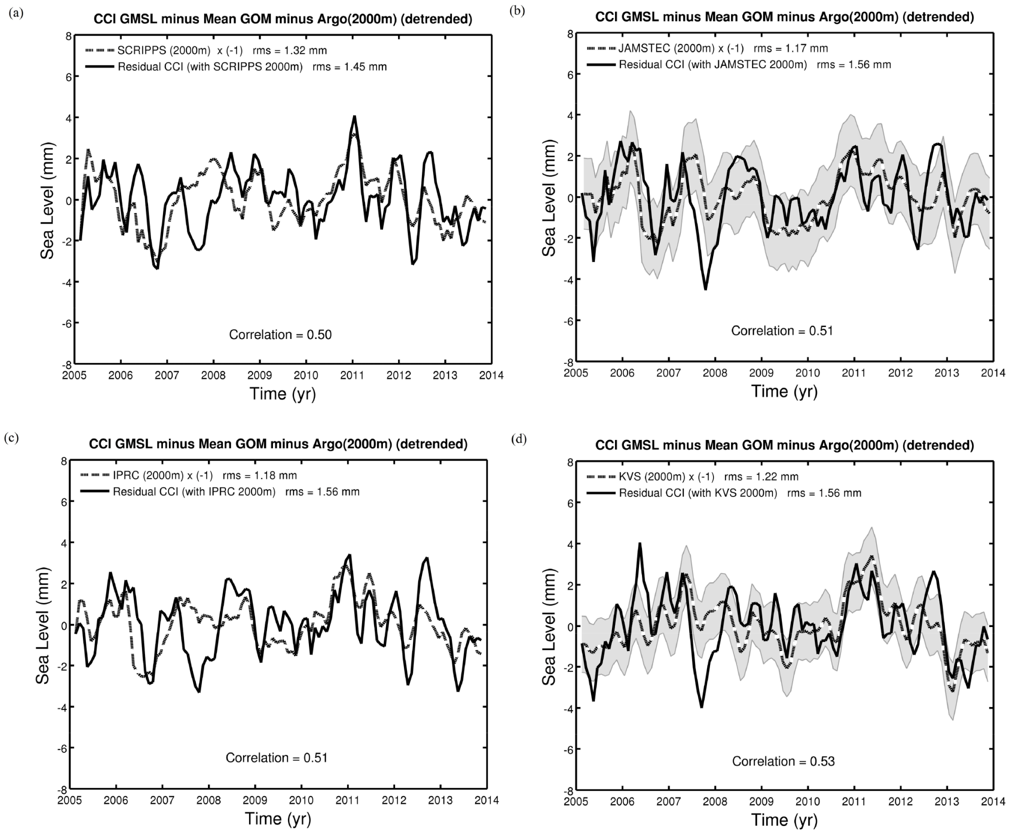

Figure 8. Detrended residual time series of CCI GMSL (January 2005–December 2013) computed with the mean global ocean mass (GOM) and each of the 4 steric sea level products: SCRIPPS **(a)**, JAMSTEC **(b)**, IPRC **(c)**, and KVS **(d)**; superimposed the corresponding detrended steric sea level time series.

OSD
12, 701–734, 2015

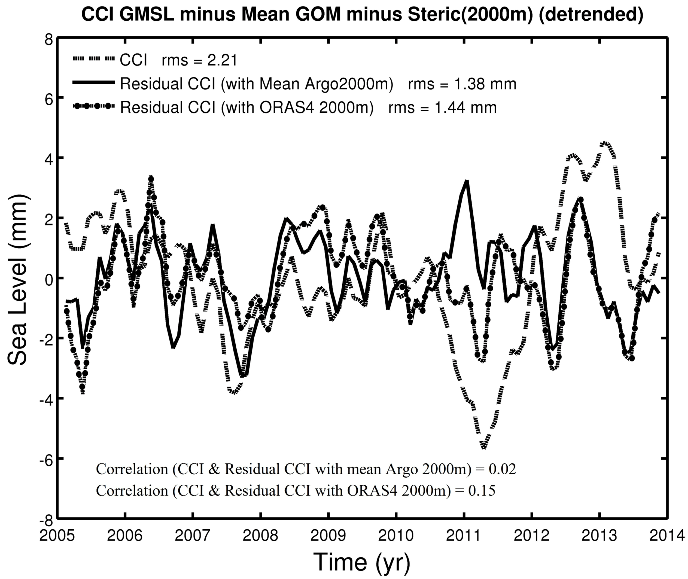

Figure 9. Residual time series (January 2005–December 2013) computed with the CCI GMSL, and the mean of the 4 Argo products (black curve) and ORAS4 data (dotted curve). The detrended CCI GMSL is superimposed.

OSD
12, 701–734, 2015

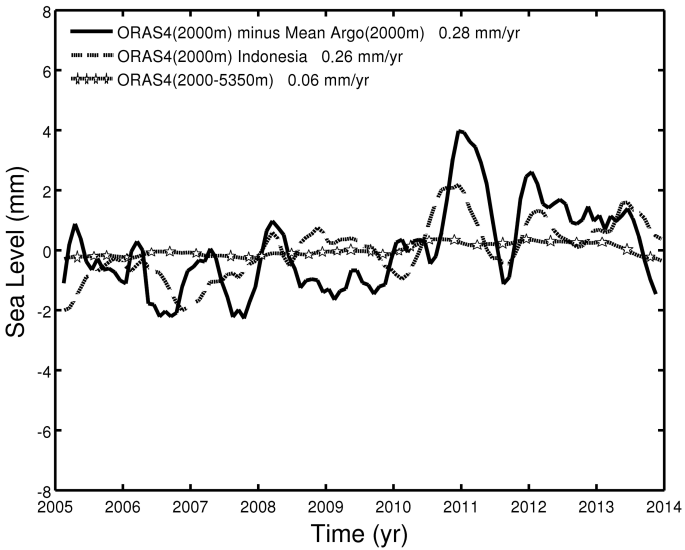

Figure 10. Steric sea level difference "ORAS4 minus mean Argo" time series (black curve) (January 2005–December 2013) up to 2000 m depth. The dashed curve is the Indonesian steric sea level time series estimated from ORAS4 up to 2000 m depth. The starry curve is steric sea level time series from ORAS4 below 2000 m depth.

OSD
12, 701–734, 2015

H. B. Dieng et al.