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RESEARCH LETTER

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Key Points:

- The sea level budget approach allows quantifying instrumental drift of the TOPEX A altimeter operating in the early altimetry era
- Accounting for this drift leads to closure of the sea level budget and to revised rate of the global mean sea level
- The global mean sea level rate of the second half of the altimetry era has increased by 25% compared to the first half

Supporting Information:

- Supporting Information S1

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New estimate of the current rate of sea level rise from a sea level budget approach

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Abstract We revisit the global mean sea level (GMSL) budget during the whole altimetry era (January 1993 to December 2015) using a large number of data sets. The budget approach allows quantifying the TOPEX A altimeter drift (amounting 1.5 ± 0.5 mm/yr over 1993–1998). Accounting for this correction and using ensemble means for the GMSL and components lead to closure of the sea level budget (trend of the residual time series being 0.0 ± 0.22 mm/yr). The new GMSL rate over January 1993 to December 2015 is now close to 3.0 mm/yr. An important increase of the GMSL rate, of 0.8 mm/yr, is found during the second half of the altimetry era (2004–2015) compared to the 1993–2004 time span, mostly due to Greenland mass loss increase and also to slight increase of all other components of the budget.

1. Introduction

Present-day sea level changes integrate the response of several components of the Earth system (ocean, atmosphere, cryosphere, and hydrosphere) to anthropogenic and natural forcing, as well as to direct human intervention on the hydrological cycle. Studying the sea level budget helps to better understand processes at work and follow temporal changes (e.g., acceleration) of individual components. It also allows placing bounds on poorly known contributions (e.g., deep >2000 m ocean warming, not measured by current observing systems), constraining current Earth’s energy imbalance and validating climate models used for simulating future climate.

Since late 1992, the global mean sea level (GMSL) is monitored by high-precision satellite altimetry and shows a nearly linear rate of rise in the range 3.2–3.4 mm/yr [e.g., Ablain *et al.*, 2017]. GMSL change as a function of time t is usually expressed by the sea level budget equation:

$$\text{GMSL}(t) = \text{GMSL}_{\text{oceanmass}}(t) + \text{GMSL}_{\text{steric}}(t) \tag{1}$$

where $\text{GMSL}_{\text{oceanmass}}(t)$ refers to the change in mass of the oceans and $\text{GMSL}_{\text{steric}}(t)$ refers to the contributions of ocean thermal expansion and salinity to sea level change (in theory, salinity does not contribute to global mean sea level change because of salt conservation on long time scales, but as measurements are never fully global, in practice, salinity is accounted for when available).

Because of water conservation in the climate system, the ocean mass term (i.e., $\text{GMSL}_{\text{oceanmass}}(t)$, also noted $M_{\text{ocean}}(t)$) is such that

$$\begin{aligned} M_{\text{ocean}}(t) + M_{\text{Glaciers}}(t) + M_{\text{Greenland}}(t) + M_{\text{Antarct.}}(t) + M_{\text{LWS}}(t) + M_{\text{Atm}}(t) + M_{\text{Snow}}(t) \\ + \text{missing mass terms} \\ = 0 \end{aligned} \tag{2}$$

where $M_{\text{Glaciers}}(t)$, $M_{\text{Greenland}}(t)$, $M_{\text{Antarct.}}(t)$, $M_{\text{LWS}}(t)$, $M_{\text{Atm}}(t)$, and $M_{\text{Snow}}(t)$ represent temporal changes in mass of glaciers, Greenland and Antarctica ice sheets, liquid water storage on land (LWS), atmospheric water vapor, and snow mass changes. Missing terms could include, for example, permafrost melting. A large number of recent studies have investigated closure of the sea level budget; i.e., compare the observed rate of sea level rise with the sum of contributions estimated independently. Over the altimetry era, publications are numerous and regularly updated. Studies by *Leuliette and Willis* [2011], *Church et al.* [2013], and *Chambers et al.* [2017] count among the most recent. In these studies, the sea level budget was considered as closed within quoted uncertainties.

In this note, we revisit the sea level budget over the altimetry era (January 1993 to December 2015), using almost all available data sets for the sea level as well as steric and mass components. We show that considering ensemble means of different data sets improves closure of the sea level budget suggesting that the main

sources of error in data sets are random and average out in the ensemble mean (noted EM herein after) of the data sets. We also show that closure of the budget provides a robust method to estimate instrumental drifts of the altimetry system, in particular drift of the TOPEX A altimeter that operated during the first 6 years of the altimetry-based GMSL record. Correcting for this drift provides new insight on the GMSL rate evolution during the past 23 years.

2. Data

A total of 26 different data sets have been analyzed for estimating the sea level budget over the altimetry era. Six different altimetry-based GMSL data sets have been considered over the period January 1993 to December 2015 (see details on the GMSL products in the supporting information). These data sets include the Climate Change Initiative (CCI) sea level products (www.esa-sealevel-cci.org) from the European Space Agency (ESA). The CCI global mean sea level is based on the complete reprocessing of nine altimetry missions and improved geophysical corrections [Ablain *et al.*, 2015, 2017]. For the steric data, we used three data sets for January 1993 to December 2004 (updates from Ishii and Kimoto [2009] and from Levitus *et al.* [2012], plus the EN4 data set from Good *et al.* [2013]). Four Argo data sets were considered for January 2005 to December 2015 (see supporting information for details). The Purkey and Johnson's [2010] estimate for the deep and abyssal ocean contribution (of 0.1 mm/yr) was added over the whole record length. Three glaciers time series were used (data from Marzeion *et al.* [2015] and Leclercq *et al.* [2011] and the update from Cogley [2009]). For the ice sheets, the IMBIE (Ice sheet Mass Balance Intercomparison Exercise) [Shepherd *et al.*, 2012, <http://imbie.org/imbie-2012/>] data set was considered until December 2003 and the CCI_ice sheet products (www.esa-icesheets-cci.org) afterward. Both IMBIE and CCI products combine a large number of individual data sets. The land water data include two data sets: Wada *et al.* [2016] for the anthropogenic component and the Interaction Soil Biosphere Atmosphere (ISBA)/Total Runoff Integrating Pathways (TRIP) hydrological model [Decharme *et al.*, 2012, 2016; Vergnes *et al.*, 2014] for the natural climate variability component (for the latter, other hydrological models have been considered but not retained; see below). The atmospheric water vapor was accounted for using the ERA-Interim atmospheric reanalysis [Dee *et al.*, 2011]. Although small in terms of GMSL trend, water vapor significantly contributes to interannual GMSL variations. Snow was ignored because updated data are lacking, and as shown in Biancamaria *et al.* [2011], the snow contribution is negligible. Details about the 26 data sets considered in this study are given in the supporting information.

For those data sets that did not provide global mean estimates, we computed global means by spatially averaging the gridded data, applying cosine latitude area weighting. Most data time series are given at monthly interval, except for the glaciers given at annual or pentadal intervals. In the latter case, the time series were interpolated on a monthly basis. Except for glaciers, the annual signal was removed by a least squares fit of a periodic function to the data. For all terms of the sea level budget equation, we computed an ensemble mean, simply averaging (with no weighting) all available time series. Some data sets are provided with uncertainties, but some are not. We assumed that uncertainty associated with the time series (noted σ_i) gives an estimate of the random data errors while the spread of the time series around the ensemble mean (noted σ_{spread}) provides (at least partial) estimate of the systematic uncertainty. We further assume that both sources of uncertainties are Gaussian and independent and compute the total uncertainty through the quadratic sum: $\sqrt{\sum(\sigma_i^2 + \sigma_{\text{spread}}^2)}$. For those data sets that do not provide errors (e.g., the GMSL time series), the uncertainty is only derived from σ_{spread} . Uncertainty on trend estimates is deduced from a generalized (weighted) least squares adjustment [e.g., Bevington and Robinson, 1969; Kirkup, 1994], accounting for the total uncertainty of the ensemble of time series (as indicated above).

Figure 1 gathers individual time series over January 1993 to December 2015 for the steric, glaciers, ice sheets, and water vapor components.

3. Results

Individual altimetry-based GMSL products display significant discrepancies at interannual time scale (see Figure S1). These discrepancies are more pronounced during the first few years of the altimetry record.

On the other hand, trend differences between the different GMSL products over the whole altimetry period are small (0.17 mm/yr). Table S1 gathers residual trends and standard deviations (noted RMS hereafter) of the

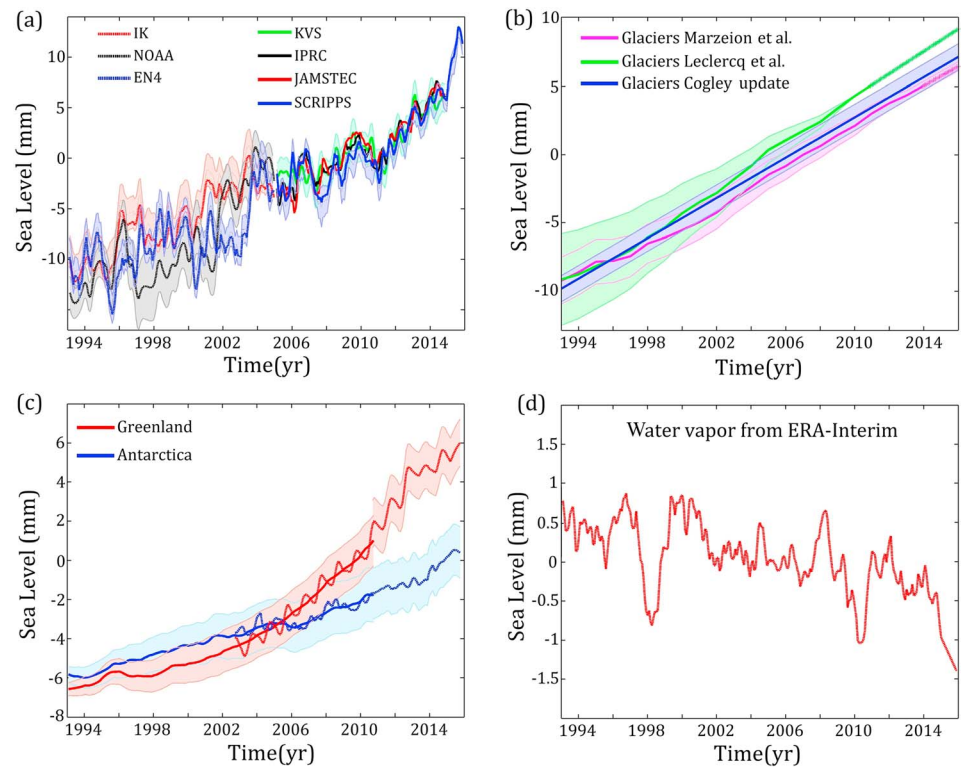


Figure 1. (a) Global mean steric sea level time series from IK, NOAA, and EN4 for January 1993 to December 2004 and Argo (data from update of von Schuckmann and Le Traon [2011], noted KVS, IPRC, JAMSTEC, and SCRIPPS) for January 2005 to December 2015. (b) Glacier component (data from Marzeion et al., Leclercq et al., and Cogley et al.—version R1501-). (c) Greenland and Antarctica components from IMBIE for 1993–2010 and CCI for May 2002 to December 2015. (d) Water vapor contribution expressed in equivalent sea level (data from ERA-Interim). For all curves, shaded areas represent 1 standard deviation uncertainty.

differences between each GMSL time series and the EM GMSL. We note that CCI GMSL leads to the smallest RMS compared to other products and is in much better agreement with the EM GMSL, compared to other GMSL products taken individually.

The steric sea level products show important differences between 1993 and 2004 (Figure 1a). This results from incomplete coverage of temperature and salinity measurements and differences in interpolation methods [Abraham et al., 2013]. The use of Argo data to estimate the steric component as of January 2005 significantly reduces the dispersion.

The three glaciers time series agree well in terms of trends (Figure 1b). We note very good agreement between the IMBIE and CCI ice sheet products over their overlapping period (May 2002 to December 2010) (Figure 1c). We thus considered IMBIE data until December 2002 then extended the ice sheet time series with the CCI data. The seasonal cycle visible in Figure 1c was removed as explained above. The atmospheric water vapor component (expressed in equivalent sea level) is shown in Figure 1d. Besides the interannual variability, we note a decreasing trend, suggesting increase in atmospheric water vapor content over the study period.

Another important source of GMSL interannual variability comes from terrestrial water storage in response to natural climate variability [e.g., Boening et al., 2012; Cazenave et al., 2014]. It can be quantified by using either GRACE space gravimetry over land [e.g., Fasullo et al., 2013] or global hydrological models. Here we use the latter approach. In addition to ISBA/TRIP, we also considered the Water Gap Hydrological Model [Döll et al., 2014a, 2014b], the Global Land Data Assimilation [Rodell et al., 2004], and the MERRA reanalysis [Mantas et al., 2015]. Comparison between detrended GRACE-based ocean mass (see Dieng et al. [2015a, 2015b] for information on the GRACE data) and detrended land water contribution (expressed in equivalent sea level) estimated with the four hydrological models over January 2003 to December 2015 led us to only consider ISBA/TRIP because of its higher correlation (of 0.95) with the ocean mass component. This is illustrated in

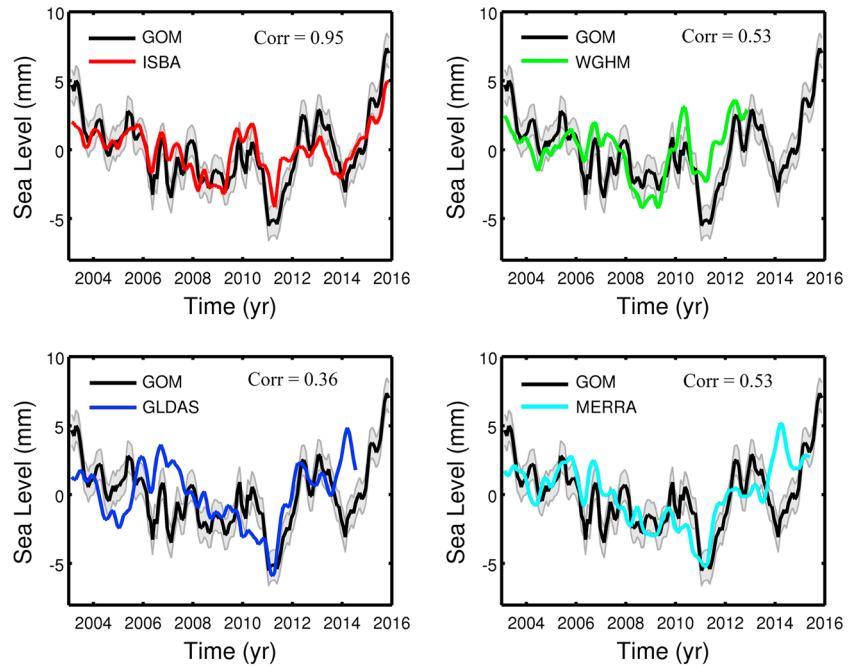


Figure 2. Detrended GRACE-based ocean mass (GOM; black curve) (data processed in *Dieng et al. [2015b]*) and detrended land water contribution from four hydrological models (colored curves) over 2003–2015. The correlation between detrended ocean mass and models is indicated.

Figure 2 that shows detrended GRACE-based ocean mass and detrended model-based land water storage (expressed in equivalent sea level) over 2003–2015.

Because ISBA/TRIP does not include direct anthropogenic forcing on land hydrology (dam building on rivers and groundwater depletion in aquifers), we used the most recent estimate from *Wada et al. [2016]* for the net effect of reservoirs and groundwater depletion (trend of 0.12 ± 0.04 mm/yr over the altimetry era). We also accounted for the small ISBA/TRIP trend to the total land water contribution. Figure 3a compares the EM GMSL (average of the six products) with the sum of all components over January 1993 to December 2015. Individual EM components are also shown. Uncertainties are estimated as explained above.

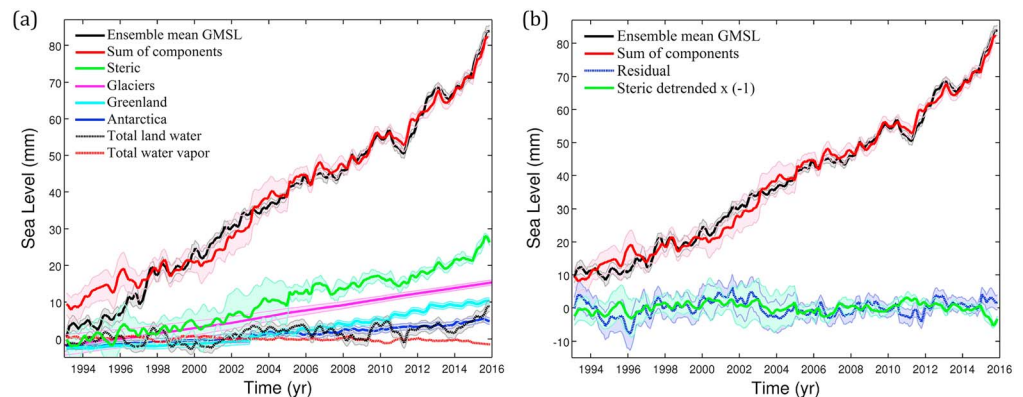


Figure 3. (a) EM GMSL without TOPEX A drift correction (black curve), sum of EM components (red curve), and individual EM components over January 1993 to December 2015. Shaded areas represent one standard error as described in text. (b) EM GMSL with TOPEX A drift correction (black curve), sum of EM components (red curve), and residuals (calculated as the difference between EM GMSL and sum of EM components) over January 1993 to December 2015. The detrended EM steric component (multiplied by -1) is superimposed to the residual curve. Shaded areas represent one standard error as described in text.

From Figure 3a, we note very good agreement between observed EM GMSL and sum of EM components, except at the beginning of the record (from January 1993 to December 1998) where a single altimeter (TOPEX A) of the TOPEX/POSEIDON mission was in operation. The TOPEX/POSEIDON project, led by CNES (Centre National d'Etudes Spatiales) and NASA (National Aeronautics and Space Administration), had for long detected instrumental aging of the TOPEX A altimeter, impacting significant wave height estimates [Hayne and Handcock, 1998]. For that reason, TOPEX A was switched off and replaced early 1999 by the redundant TOPEX B altimeter. At that time, it was assumed that the TOPEX A-derived GMSL was not impacted by these instrumental problems. However, based on comparison between TOPEX A sea level and tide gauges data, Valladeau *et al.* [2012] questioned the latter conclusion although they did not quantify this effect on the GMSL.

Recently, two studies have attempted to quantify the effect of the TOPEX A drift on the GMSL trend over the period January 1993 to December 1998. Watson *et al.* [2015] interpolated the altimetry-based sea level data at tide gauge sites and estimated the trend of differences between altimetry and vertical land motion-corrected tide gauge records. Their estimate of the TOPEX A drift over the 1993–1998 time span ranges from 0.9 ± 0.5 mm/yr to 1.5 ± 0.5 mm/yr, depending on the vertical land motion correction applied to the tide gauges. Recently, Zawadzki *et al.* [2016] estimated the TOPEX A drift by comparing with POSEIDON altimeter data. The POSEIDON altimeter developed by CNES was placed on board the TOPEX/POSEIDON platform as an experimental instrument. It shared the same antenna as the NASA TOPEX altimeter and worked only about 10% of the time, i.e., one cycle out of 10 (<http://www.aviso.altimetry.fr/>). Unlike TOPEX that emitted on two frequencies to correct for the ionospheric delay of the radar signal, POSEIDON used a single frequency (Ku band). Thus, the ionospheric correction was derived from the onboard DORIS (Doppler orbitography and radiopositioning integrated by satellite) system. The inferred Zawadzki *et al.*'s TOPEX A drift estimate amounts to 2.8 ± 0.6 mm/yr, i.e., about twice the Watson *et al.*'s value. Such a large correction does not reduce the GMSL minus the sum of components difference, possibly a result of the low temporal resolution of POSEIDON data, leading to more uncertain TOPEX A drift estimate.

In the present study, we take advantage of the good agreement between EM GMSL and the sum of EM contributions beyond 1998 and estimate the TOPEX A drift by least squares adjustment of a linear function to the differences between EM GMSL and the sum of EM components over the period January 1993 to December 1998 (note that TOPEX A drift may present more complex temporal behavior but information is lacking to justify more sophisticated calculation). We find a drift of 1.5 ± 0.5 mm/yr, in agreement with Watson *et al.*'s preferred value. To check whether this drift estimate is significant (i.e., higher during the early part of the altimetry record), we computed similar linear drifts over overlapping 6 year time spans shifted by 1 year (see Figure S2). The computed drifts are <0.5 mm/yr beyond ~ 2005 and in the range 0.1 mm/yr to 0.8 mm/yr (absolute value) over 2000–2004, thus most of the time within the 0.5 mm/yr uncertainty.

In the following, we apply the 1.5 mm/yr drift value to the 1993–1998 EM GMSL time series. Figure 3b shows the corrected EM GMSL together with the sum of EM components. The residual time series (i.e., the difference between corrected EM GMSL and the sum of EM components) is also shown.

The residual trend over 1993–2015 amounts to 0.03 ± 0.22 mm/yr, indicating closure of the sea level budget within ~ 0.2 mm/yr. Note that the residual uncertainty represents 1 sigma error and is based on the error calculation described above. It does not account for potential (but unknown) systematic errors affecting the terms of the sea level budget (note that based on independent assessment of all source of errors affecting the altimetry system, Ablain *et al.* [2017] estimated the GMSL rate uncertainty to ~ 0.5 mm/yr but this value represents 2 sigma uncertainty). RMS of residuals amounts 2.4 mm over the whole altimetry time span. If we divide the whole record into two 12 year time spans (January 1993 to December 2004 and January 2004 to December 2015), we find larger residual trend uncertainty and RMS during the first period compared to the second one (0.36 mm/yr and 2.9 mm versus 0.21 mm/yr and 1.8 mm). Higher values for the first period may have several causes. In addition to the imperfect TOPEX A drift correction, lesser precision of steric products before the Argo era can also be invoked. In Figure 3b, the detrended steric component (multiplied by -1) is superimposed to the residual curve. We note high correlation (0.7) between inverse steric time series and residuals during the first period while the correlation breaks down afterward. This is not surprising considering the high dispersion between the steric data sets before Argo (see Figure 1a).

Table 1. Trends of All Terms of the Sea Level Budget Equation Estimated Over Three Time Spans (in mm/yr); Bottom Numbers Refer to RMS of the Residuals and Correlation With Detrended Inverse Ensemble Mean Steric Component

	Trends (mm/yr)		
	Jan 1993 to Dec 2004	Jan 2004 to Dec 2015	Jan 1993 to Dec 2015
Ensemble mean GMSL rate without TOPEX A drift correction	3.40 ± 0.18	3.49 ± 0.14	3.28 ± 0.10
GMSL rates with TOPEX A drift correction as estimated in this study			
AVISO	2.50	3.48	2.96
CU	2.82	3.38	3.10
NOAA	2.48	3.34	2.93
NASA	2.85	3.48	3.11
CSIRO	2.77	3.69	3.05
CCI	2.57	3.57	3.05
Ensemble mean GMSL	2.67 ± 0.19	3.49 ± 0.14	3.03 ± 0.15
GRACE ocean mass	---	2.24 ± 0.10	---
Glaciers (mean of three data sets)			
Greenland	0.32 ± 0.04	0.82 ± 0.06	0.61 ± 0.05
Antarctica	0.29 ± 0.04	0.33 ± 0.06	0.30 ± 0.06
Total Land water	0.23 ± 0.10	0.25 ± 0.08	0.24 ± 0.09
Natural (ISBA/TRIP)			0.12
Anthropogenic [Wada et al., 2016]			0.12 ± 0.04
Water vapor	-0.03	-0.05	-0.04
Sum of mass components	1.52 ± 15	2.13 ± 14	1.87 ± 14
Ensemble mean steric	0.94 ± 0.27	1.14 ± 0.09	1.13 ± 0.12
Sum of components	2.46 ± 0.31	3.27 ± 0.16	3.00 ± 0.19
Residual trendRMS (mm)	0.21 ± 0.36	0.22 ± 0.21	0.03 ± 0.22
	2.88 (1993–2004)	1.85 (2005–2015)	2.44 (1993–2015)
Correlation with inverse steric	0.7	-0.1	0.3

Table 1 gathers trend and standard errors estimated for the different terms of the sea level budget and residual time series, for three time spans 1993–2015, 1993–2004, and 2004–2015.

Accounting for the TOPEX A drift correction has another implication. As previously noticed by *Watson et al.* [2015] for the period 1993 to mid-2014, the new EM GMSL rate amounts to 3.0 ± 0.15 mm/yr for the 1993–2015 time span, a value lower than the 3.3 mm/yr rate generally reported [e.g., *Ablain et al.*, 2017]. We have estimated new GMSL rates over the two periods 1993–2004 and 2004–2015. Figure 4 compares GMSL rates using sea level data from the six processing groups (TOPEX A drift correction of 1.5 mm/yr as

estimated here applied to all GMSL data sets over 1993–1998), as well as the EM GMSL.

The EM GMSL rate is significantly lower during the first period compared to the second one (2.7 ± 0.2 mm/yr versus 3.5 ± 0.15 mm/yr; see Table 1 for individual values). This 0.8 mm/yr EM GMSL increase dominantly results from increased land ice loss from Greenland (+0.5 mm/yr; see Table 1), while slight increases are also noticed for all other components (except for the water vapor component that shows slightly larger negative contribution).

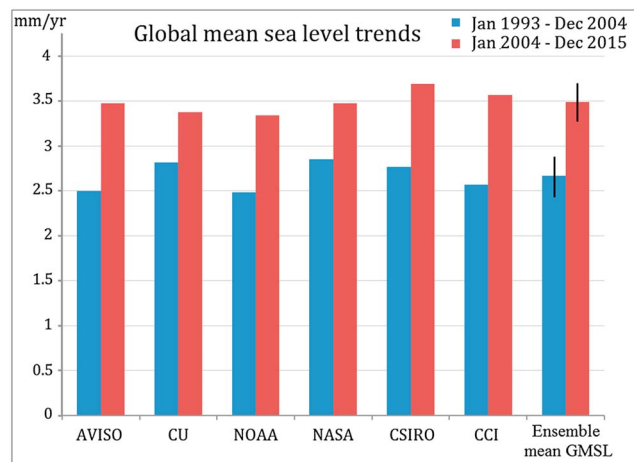


Figure 4. GMSL trends after TOPEX A drift correction computed over two time spans (January 1993 to December 2004 and January 2004 to December 2015) using satellite altimetry data from six processing groups (see details in the supporting information). The EM GMSL trend (average of the six GMSL data sets) is also shown.

4. Conclusion

In this study, we have investigated the sea level budget over the altimetry era (1993–2015) by comparing the

temporal evolution of GMSL and the sum of the components using a large number of data sets and computing ensemble means for all terms of the sea level budget equation. Our results confirm, as in previous studies, the importance of correcting for TOPEX A instrumental drift. The new approach based on the GMSL budget indicates a drift of 1.5 ± 0.5 mm/yr, in agreement with the preferred value of *Watson et al.* [2015] but lower than *Zawadzki et al.* [2016]. Applying this correction over the first 6 years of the altimetry record leads to lower GMSL rate (of 3.0 ± 0.15 mm/yr) over the altimetry era than previously assumed. More importantly, the GMSL rise since the mid-2000s shows significant increase compared to the 1993–2004 time span. This contradicts conclusion of previous studies [e.g., *Cazenave et al.*, 2014] that reported slowing down of about 30% of the GMSL rise during the years 2000s (without TOPEX A drift correction), attributed to La Niña events. Here we show that in spite of the several temporary sea level drops caused by La Niña events, the GMSL rise has increased during the last decade.

Slower rate during the first decade of the altimetry era may result from lower contributions, including the persistent cooling impact of the 1991 Mount Pinatubo eruption as proposed by *Fasullo et al.* [2016]. Finally, our analysis shows that the use of an ensemble mean for each component of the sea level budget equation leads to better budget closure than when using individual data sets. The nearly zero residual trend indicates that missing contributions (e.g., deep ocean warming) are still negligible (within 0.2 mm/yr).

Acknowledgments

All data sets are available at the websites indicated in the main text and supporting information. The corrected EM GMSL and the sum of EM components time series are available upon request to the authors of this paper. We are very grateful to G. Cogley, B. Decharme, P. Leclercq, and B. Marzeion for providing us with their data sets on glacier mass balance and land water storage. This study is partly supported by the ESA Climate Change Initiative sea level project.

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