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# Geophysical Research Letters

## RESEARCH LETTER

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### Key Points:

- The global mean sea level budget is not closed after 2016 from altimetry, Argo and GRACE/GRACE Follow-On data
- We show that errors in Argo salinity data lead to non-physical halosteric sea level negative trends responsible for ~40% of the non-closure
- We also show that Jason-3 altimeter and radiometer are unlikely to play a major role in the remaining budget error

### Supporting Information:

Supporting Information may be found in the online version of this article.

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## Contributions of Altimetry and Argo to Non-Closure of the Global Mean Sea Level Budget Since 2016

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**Abstract** Over 1993–2016, studies have shown that the observed global mean sea level (GMSL) budget is closed within the current data uncertainties. However, non-closure of the budget was recently reported when using Jason-3, Argo and GRACE/GRACE Follow-On data after 2016. This non-closure may result from errors in the data sets used to estimate the GMSL and its components. Here, we investigate possible sources of errors affecting Jason-3 and Argo data. Comparisons of Jason-3 GMSL trends with other altimetry missions show good agreement within 0.4 mm/yr over 2016–present. Besides, the wet tropospheric correction uncertainty from the Jason-3 radiometer contributes to up to 0.2 mm/yr. Therefore, altimetry alone cannot explain the misfit in the GMSL budget observed after 2016. Argo-based salinity products display strong discrepancies since 2016, attributed to instrumental problems and data editing issues. Reassessment of the sea level budget with the thermosteric component provides about 40% improvement in the budget closure.

**Plain Language Summary** Sea level rise, due to the addition of meltwater from glaciers and ice-sheets in the oceans and to the thermal expansion of seawater, is commonly used as an indicator for climate change. The sea level budget provides information on temporal changes in one or more components of the budget, on process understanding, on missing contributions and allows cross validation of the observing systems involved in the sea level budget (satellite altimetry, Argo oceanic float and GRACE/GRACE Follow-On satellite gravimetry). The sea level budget was closed until 2015–2016, that is, the observed global mean sea level agrees well with the sum of components. However, since 2016, the budget is not closed anymore. In this study, we show that errors in Argo salinity measurements are responsible for about 40% of the budget error while the altimetry data cannot explain the remaining error. Other sources of errors should be further investigated to fully understand the error in the budget after 2016, in particular satellite GRACE/GRACE Follow-On gravity measurements or missing physical contributions.

## 1. Introduction

Sea level has been routinely measured by satellite altimetry for nearly three decades, while, for about 15 years, Argo floats and GRACE (Gravity Recovery and Climate Experiment; Tapley et al., 2019) and GRACE Follow-On (GRACE-FO; Landerer et al., 2020) allow quantifications of the steric effect and ocean mass change respectively, the two main components of the global mean sea level (GMSL) budget. In recent years, numerous studies have been devoted to assess the GMSL budget, that is, comparing the altimetry-based GMSL time series with the sum of components (e.g., Chambers et al., 2017; Chen et al., 2018; Dieng et al., 2017; WCRP Global Sea Level Budget Group, 2018). Assessing the GMSL budget closure is important for detecting temporal changes in the GMSL or in its components, and missing contributions (e.g., deep ocean warming, Llovel et al., 2014), for process understanding, validating climate models and detecting systematic bias or drifts in the observing systems involved in the sea level budget (i.e., altimetry, Argo, GRACE and GRACE-FO). Recently published studies have shown that until 2015/2016, the GMSL budget is closed within respective uncertainties of the sea level budget components (e.g., the Nerem et al., 2018; WCRP Global Sea Level Budget Group, 2018). However, beyond 2016 the GMSL budget appears no longer closed (Chen et al., 2020). Motivated by assessing the accuracy of GRACE-FO ocean mass data, Chen

et al. (2020) compared GRACE/GRACE-FO ocean mass time series with altimetry minus Argo time series over 2005–2020, and reported a systematic misfit as of mid-2016, between the two independent estimates of ocean mass changes, clearly indicating that the sea level budget is no longer closed in the recent years, with the altimetry-based GMSL rate being significantly larger than the rate of the sum of components. Chen et al. (2020) discussed some potential sources of uncertainties in recent GRACE/GRACE-FO data post-processing, and also addressed the impact of problems affecting the accelerometer instruments at the end of the GRACE life time and the GRACE-FO mission. Although not excluding that the single accelerometer mode of operation at the end of the GRACE mission and of GRACE-FO could play a role, Chen et al. (2020) suggested that the non-closure of the GMSL budget observed in the recent years could also result from errors in altimetry and Argo data.

In this study, we explore the latter possibility and examine the altimetry-based GMSL and Argo-based steric sea level over the 2005–2019 time span. Since 2016, GMSL is mostly based on the Jason-3 altimetry mission. Any instrumental drift of the onboard altimeter or/and radiometer (used to measure the atmospheric water content, hence the wet tropospheric correction applied to the altimeter range) may induce errors in the GMSL estimate since 2016. Similarly, instrumental problems were reported in salinity measurements of some of the autonomous Argo floats for the recent years, that may induce errors in the steric component (Wong et al., 2020). We first examine different Argo data sets available from different processing groups and highlight the error introduced by Argo salinity data beyond 2016 in the sea level budget closure. We next investigate whether Jason-3 data present any anomalous behavior that could lead to an overestimation of the GMSL trend compared to the sum of the components. This is done by comparing: (a) Jason-3-based GMSL with data of the SARAL/AltiKa and Sentinel-3A missions (launched respectively in 2013 and 2016), and (b) the Jason-3 radiometer-based wet tropospheric correction with data from the SARAL/AltiKa and Sentinel-3A radiometers on the one hand, and with ECMWF (European Center for Medium Range Weather Forecast) reanalysis for the atmospheric water vapor component on the other hand.

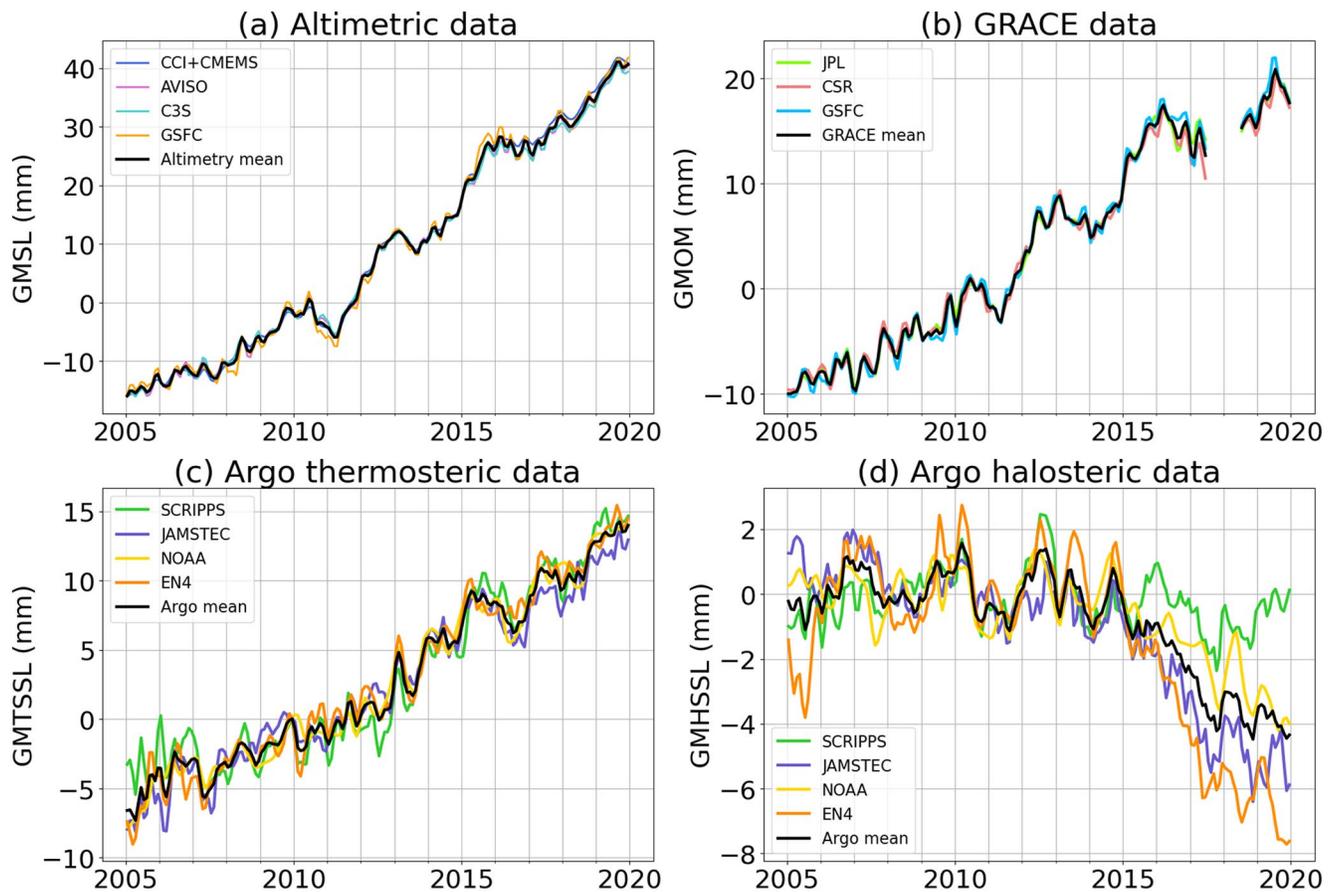
## 2. Data Sets

### 2.1. Altimetry Data

Four different estimates of the altimetry-based global mean sea level (GMSL) products are used in this study: (a) the ESA Climate Change Initiative (CCI) series up to December 2015 (Legeais et al., 2018), extended by the Copernicus Marine Environment Monitoring Service (CMEMS) (<https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/gridded-mean-sea-level-trends-over-global-ocean>) data as of January 2016; (b) AVISO (<https://www.aviso.altimetry.fr/>), (c) C3S (Copernicus Climate Change Service, Mertz & Legeais, 2020) and GSFC (Goddard Space Flight Center, Beckley et al., 2016). More details on these data sets are provided in the Supporting Information (SI, Text S1). All four GMSL data sets cover the 66°S to 66°N latitudes. They are corrected for GIA (Glacial Isostatic Adjustment) using a value of  $-0.3$  mm/yr (Pelletier, 2004). The January 2005–December 2019 time span is considered here for the four GMSL time series.

### 2.2. Steric Sea Level Data

Four different estimates of the global mean steric sea level (GMSSL) are used: (a) NOAA (National Oceanic and Atmospheric Administration) data (Garcia et al., 2019), (b) EN4 data set from the Met Office Hadley Center (Good et al., 2013), (c) SCRIPPS Institution of Oceanography climatology monthly gridded  $1^\circ \times 1^\circ$  data (Roemmich & Gilson, 2009), and (d) JAMSTEC (Japan Agency for Marine-Earth Science and Technology) MILA GPV (Mixed Layer data set of Argo, Grid Point Value) product data set (Hosoda et al., 2010). All four data sets are based on Argo data (Argo, 2000), except EN4 data that also includes MBT and XBT data (with the correction of Gouretski & Resghetti, 2010 applied). All data sets cover the period January 2005–December 2019, the 0–2000 m depth range for integration of temperature and salinity, and the 66°S and 66°N averaging domain. GMTSSL, GMHSSL and GMSSL stand for thermosteric, halosteric and total steric (sum of thermosteric and halosteric) sea level. A linear trend supposed to represent the contribution of the deep ocean to the GMTSSL and GMHSSL, of respectively  $0.12 \pm 0.03$  mm/yr (Chang et al., 2019) and  $0.007 \pm 0.010$  mm/yr (Llovel et al., 2019), are added to the two time series.



**Figure 1.** Individual contributions to the global mean sea level (GMSL) budget. (a) GMSL, (b) global mean ocean mass, (c) thermosteric and (d) halosteric time series. The ensemble mean of each component is displayed as a black line. Note that the y-axis scale is different for all panels for readability.

### 2.3. GRACE-Based Ocean Mass Data

The global mean ocean mass (GMOM) contribution to the GMSL budget is calculated using the latest GRACE and GRACE-FO Release 6 mascon solutions from the Center for Space Research (CSR; Save et al., 2016), Jet Propulsion Laboratory (JPL; Watkins et al., 2015), and GSFC (Loomis et al., 2019). Details on the post-processing of the GRACE mascon solutions are given in the SI (Text S2). From these three products, the GMOM time series are simply calculated as the global average of the gridded ocean mass estimates weighted by the relative contribution of ocean area within each grid cell. As for the GMSL and GMTSSL, the GMOM time series are computed between 66°S and 66°N. Because the leakage has already been processed through the Coastal Resolution Improvement correction (Wiese et al., 2016) for the JPL solution and through the regularization procedure for the GSFC (Loomis et al., 2019) and CSR (Save et al., 2016) solutions, we did not remove coastal areas from our analysis for any of the solutions. The GMOM time series are given from January 2005 to December 2019.

## 3. Sea-Level Budget Over 2005-2019

Figures 1a–1d presents individual time series of altimetry-based GMSL, GRACE and GRACE-FO ocean mass, Argo-based thermosteric and halosteric components from January 2005 to December 2019. The time series are expressed as anomalies with respect to the January 2005 to December 2015 time span. For each time series, the annual and semi-annual signals are removed and a 3-month Lanczos filter is applied. For each component of the sea level budget, we compute the ensemble mean of all time series (in black on Figures 1a–1d). Trends and associated uncertainties are gathered for each individual time series in SI (Table S1). The GMSL uncertainty is computed using the error budget approach of Ablain, Meyssignac et al. (2019).

Due to the lack of information about GMOM and GMSSL errors, their uncertainties are estimated as the maximum differences between the different datasets constituting the ensembles. This approach is likely to underestimate the uncertainty as it only considers the variability of a limited number of datasets.

Figure 1a shows that all four altimetry-based GMSL time series agree well, both in terms of interannual variability (e.g., during the 2010/2011 La Niña and 2015 El Niño) and trend (with an average trend of  $3.96 \pm 0.23$  mm/yr). Trend differences over January 2005–December 2019 do not exceed 0.2 mm/yr (Table S1), which is below the uncertainty estimated from the error budget approach (0.23 mm/yr), taking into account all sources of errors affecting the altimetry-based GMSL (Ablain, Meyssignac et al., 2019).

Over January 2005–December 2019, the GRACE-based GMOM rose on an average at a rate of  $2.14 \pm 0.02$  mm/yr (Figure 1b, Table S1). The CSR, JPL and GSFC GMOM estimates exhibit remarkable consistency throughout the period. The largest differences of  $\sim 3.7$  mm observed in 2016 between the three GMOM estimates might be due to instrumental issues (including battery power issues, leading to the loss of one of the two accelerometer data) that have impacted the spacecrafts toward the end of the GRACE mission (Bandikova et al., 2019).

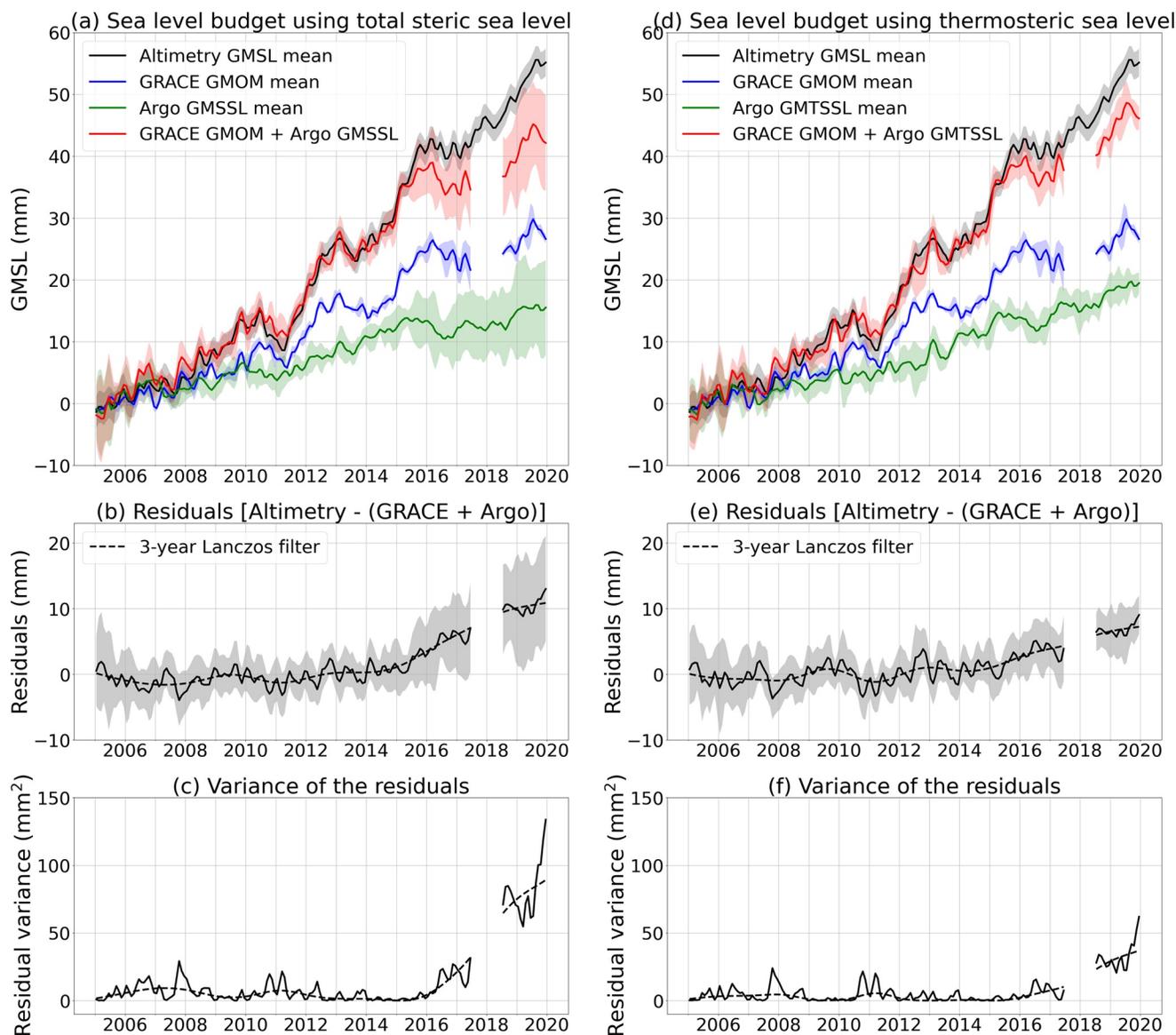
Since the focus of this paper is to study the sea level budget, we separate the Argo-based thermosteric (Figure 1c) and halosteric (Figure 1d) contributions. Large differences are observed between the different estimates of the thermosteric and halosteric components (up to  $\sim 6.3$  and  $\sim 7.7$  mm respectively). Over January 2005–December 2019, the GMTSSL rose on average by  $1.34 \pm 0.05$  mm/yr, while the GMHSSL dropped by  $-0.28 \pm 0.07$  mm/yr over the same period. This negative trend observed in the halosteric component is not physically possible: a decrease in the GMHSSL, caused by a global rise in salinity, is in contradiction with the observed global freshening of the oceans mainly due to land-based and floating sea ice melting (e.g., WCRP Global Sea Level Budget Group, 2018). The halosteric trend, which should be close to zero on global average (Gregory & Lowe, 2000; Llovel et al., 2019), therefore exhibits an unexpected behavior. Three products (JAMSTEC, NOAA, and EN4) show a strong decrease from late 2014–early 2015 onwards. This leads to negative trends ranging from  $-0.22$  mm/yr to  $-0.43$  mm/yr over the full study period. The SCRIPPS analysis differs radically from the others as it shows no clear negative trend.

The sea level budget is shown in Figure 2a using the ensemble mean of all datasets available for each component and the total steric component.

The residuals of the GMSL budget remain close to zero up to about 2015 (Figure 2b), then start increasing since around 2015/2016 (Table S2). The residual trend amounts to  $2.17 \pm 0.74$  mm/yr over January 2015–December 2019, that is,  $\sim 50\%$  of the GMSL rate over the same time span. To further investigate the residual behavior as of 2015, we also computed the variance of the residuals (Figure 2c). The variance is close to zero until early 2016, then abruptly increases. An increase of the variance of a time series may be an early indicator of an abrupt change or a transition in a system described by a data time series (e.g., Dakos et al., 2012; Scheffer et al., 2009). The variance curve clearly reveals a modification in the behavior of the residuals as of early 2016 (Figure 2c), hence in at least one of the three components of the sea level budget. In the following sections, we will investigate the steric component (Section 4) and the altimetry-based GMSL (Section 6).

#### 4. Instrumental Errors in Argo-Based Salinity Data

The unexpected decrease observed in the halosteric sea level as of 2015 in some of the Argo time series questions the reliability of these datasets (Figure 1d). Before being available in the Argo data centers as real time (RT) data, Argo profiles pass through an automatic quality control (within 24 h) that attributes a quality flag to the data (Wong et al., 2020). A second quality control is performed by a scientist who examines carefully the RT data to detect, and correct if necessary any sensor bias or drift. This second procedure takes 6–12 months after receiving the data by the Argo centers and produces the delayed mode (DM) data. Starting in 2015, a significant number of Conductivity-Temperature-Depth sensors (CTDs) in the serial number band 6,000–7,100 drifted toward higher salinity values within 2–3 years after deployment (Wong et al., 2020). The exact fraction of these floats is not known but the best estimate is that 25% of the float might be subject to salinity drift. The spatial coverage of affected floats is not known either and some floats



**Figure 2.** Sea level budget over the January 2005–December 2019 period. The shaded areas correspond to the estimated 1-sigma uncertainties. (a) Budget with altimetry, Gravity Recovery and Climate Experiment and steric Argo contributions. (b) Residuals of the budget. (c) Variance of the residuals. The right three panels (d, e and f) are similar to the left, but with only Argo thermosteric effect considered.

are still active at that time. This drift may cause a RT salinity data error that could be larger than 0.01 PSU-78 (Wong et al., 2020).

The last full processing done in 2017 by JAMSTEC and EN4 includes mostly DM data. After that year, the temperature and salinity gridded products have been computed using mostly RT data. The NOAA product also considers RT for the past 4 years (2017–2020). While the SCRIPPS solution also uses DM and RT data to construct their gridded fields, RT profiles are adjusted by an offset to match the WOCE Global Hydrographic Climatology when necessary (Roemmich & Gilson, 2009). This thorough procedure should correct the drifted salinity RT profiles. This could explain why the SCRIPPS halosteric time series remains close to zero (Figure 1d). Observed differences in GMHSSL are likely due to processing methods and inclusion of drifted RT data. A full reprocessing considering all available DT data would be needed from each group to reassess the closure of sea level budget since 2016.

## 5. Reassessment of the GMSL Budget With the Thermosteric Sea Level Only

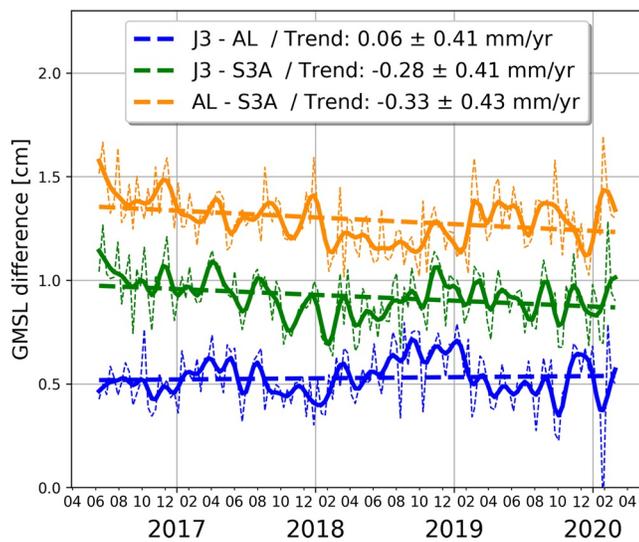
Considering that (a) the halosteric contribution to the GMSL budget should be close to zero and (b) the observed drifts in salinity measurements lead to non-physical negative trends in the halosteric time series, we reassess the GMSL budget using the sum of the GMTSSL (thermosteric only) and GMOM. The new sea level budget is shown in Figure 2d. Without the halosteric contribution, the thermosteric contribution to the GMSL trend rises to  $1.34 \pm 0.05$  mm/yr instead of  $1.07 \pm 0.08$  mm/yr with the total steric. The residuals of the GMSL budget (Figure 2e) are therefore reduced to  $0.47 \pm 0.24$  mm/yr over January 2005–December 2019 (trend reduced by 34%) and to  $1.20 \pm 0.72$  mm/yr over 2016–2019 (trend reduced by 39%). These results are summarized in Table S2 for Case 1 (total steric) and Case 2 (thermosteric only). At the end of the time series, in December 2019, the residuals amount to  $9.05 \pm 2.90$  mm with the GMTSSL instead of  $13.01 \pm 8.01$  mm with the GMSSL (residuals reduced by 30%). The variance of the residuals (Figure 2f) is reduced by about a factor three compared to Case 1 (with halosteric component accounted for). In SI, the sea level budget with each individual steric data set is shown (Figure S1–S4). The residuals using the SCRIPPS total steric sea level appear not affected by the salinity measurement errors.

Hence, we conclude that the halosteric component, except for SCRIPPS, is responsible for about 40% of the non-closure of the sea level budget beyond 2015. But, unlike over the previous years, the GMSL budget is still not closed within the error bars. We examine next the altimetry-based GMSL as another possible source of the discrepancy.

## 6. Assessment of the Jason-3 Altimetry Data

We investigate potential issues related to the Jason-3 altimetry mission, launched in January 2016, that might explain part of the non-closure of the sea level budget, since the two events coincide in time. We compare Jason-3 data to the altimetry missions SARAL/AltiKa and Sentinel-3A over June 2016–February 2020 to quantify the altimeter relative drifts and their uncertainties based on an error budget approach from Ablain, Meyssignac et al. (2019). We preferred to use such a multi-mission comparison approach instead of a comparison of the Jason-3 altimeter to independent tide-gauge data as the uncertainties associated to the latter method over a short period of 3.5 years only (availability of Jason-3 data) is of the same order of magnitude ( $\sim 2$  mm/yr; Ablain et al., 2018) as the residual trend of the sea level budget we try to explain. The multi-mission analysis allows to detect and quantify instrumental drifts with a greater level of confidence that depends on the data quality and time series length. To do this, we use along-track sea level anomalies (SLA) for Jason-3 and SARAL/AltiKa (AVISO Level 2 products), and the reprocessed PLRM (Pseudo Low Resolution Mode) Sentinel-3A (S3A) data (<https://www.eumetsat.int/s3-altimetry-reprocessing>). The S3A SAR (Synthetic Aperture Radar) mode data are not used in this study, because of a drift of about 1.3 mm/yr over 2016–2020 reported from a cross-comparison between S3A, Jason-2, Jason-3 and SARAL/AltiKa mission data (Ablain, Jugier et al., 2019; Dinardo et al., 2018). Note that the reprocessed PLRM S3A data still exhibit a small drift of about 0.2–0.3 mm/yr (Aublanc et al., 2020; Poisson et al., 2019). Two approaches are followed: (a) we inter-compare the different missions' GMSL in which we replace the radiometer-based Wet Tropospheric Correction (WTC) by the ECMWF WTC model data (available in the products for all altimeter-based SLA data), and (b) we inter-compare the radiometer-based WTCs for the different missions. Approach (a) allows us to focus on the altimeter instrument only while a potential radiometer drift is investigated in the second approach (detailed in SI, Text S3). Errors in other geophysical corrections have been extensively investigated in the literature (e.g., Taburet et al., 2019 for the AVISO products, <https://www.eumetsat.int/s3-altimetry-reprocessing> for S3A PLRM data) and no major issues were identified. Except for the WTC, it is thus very unlikely that errors in the geophysical corrections could explain the non-closure of the sea level budget as of 2016.

Figure 3 derived from approach 1 shows the differences in GMSL time series recovered from independent measurements of Jason-3, SARAL/AltiKa and Sentinel-3A altimeters over June-2016–February-2020. For all three missions, GMSL time series are computed using 10-days time steps, corresponding to Jason-3's cycles, and annual and semi-annual cycles are removed through a least squares fit. We limit the data coverage to 66°S–66°N to minimize systematic errors due to the natural ocean variability. We apply a 2-month low-pass filter and estimate the trend of the GMSL time series through a least squares approach that accounts



**Figure 3.** Global mean sea level (GMSL) differences (cm) over time between Jason-3 (J3), SARAL/AltiKa (AL) and Sentinel-3A (S3A). The drift correction  $-0.3$  mm/yr (see text) has not been applied directly on the S3A data, that is, the trends involving S3A presented here are underestimated by  $0.3$  mm/yr. The inter-mission biases have been set to arbitrary values as we look for drift estimations that are independent from the absolute GMSL level of each mission.

budget (Ablain, Meyssignac et al., 2019). This level of error, even though it might be slightly underestimated for the most recent missions, is a more likely estimate of the radiometer error. We conclude that WTC errors would not contribute by more than 10% ( $0.2$  mm/yr over 4 years) of the residual trend in the GMSL budget.

Finally, the 1-sigma uncertainty on the inter-mission bias between Jason-2 and Jason-3 is estimated to be  $\sim 0.5$  mm (Ablain, Meyssignac et al., 2019), hence would not create any significant drift in the residuals shown in Figures 2b and 2e.

## 7. Discussion

Instrumental drifts in Argo sensors measuring salinity appear to be responsible for about 40% of the non-closure of the sea level budget since early 2016. Potential sources of errors in the altimetry system, including both the altimeter measurements and the radiometer-based wet tropospheric correction, could only explain a small fraction of the remaining misfit in the GMSL budget. The order of magnitude of any potential drift in the Jason-3 system is comparable to the uncertainty on the GMSL trend (Ablain, Meyssignac et al., 2019). It seems thus unlikely that Jason-3 altimetry overestimates the GMSL rate, and plays a major role in the reported non-closure of the sea level budget. Errors in the other components, that is, the Argo-based thermosteric component and the GMOM component based on GRACE and GRACE-FO data, or a missing physical contribution, for example, from the deep ocean below 2000 m not sampled by Argo, should be further investigated.

The thermosteric component accuracy relies on the sampling of the in-situ data. Homogeneous float cover is necessary to capture the ocean variability, especially in the tropical Pacific where most of the GMSL interannual variability occurs (Piecuch & Quinn, 2016) in particular during strong El Niño/La Niña events. The core Argo float coverage has been close to global and complete since 2007 (Wong et al., 2020) and since then, no major change in the sampling of the various regions was observed with the noticeable exception of an increased sampling of the marginal seas after 2012 (Figure S7). During the 2011 La Niña event, the GMSL dropped by  $\sim 5$  mm but the budget remained closed without any complete sampling for marginal seas (e.g., Ablain et al., 2017; Boening et al. 2012; Llovel et al., 2014). During the 2015–2016 El Niño event, the

for an error budget to quantify data uncertainties (Ablain, Meyssignac et al., 2019). The content of the error budget is given in Table S3. In order to account for the detected instrumental drift reported in the reprocessed S3A PLRM data, a  $-0.3$  mm/yr correction is applied to the corresponding S3A-based GMSL time series.

From Figure 3, we conclude that no significant relative drift in the Jason-3 altimeter instrument over June 2016–February 2020 is detectable within an uncertainty of  $0.4$  mm/yr (1-sigma). It is worth noting that this  $0.4$  mm/yr altimeter drift uncertainty would contribute to increasing the uncertainty envelope of the GMSL budget estimated from Ablain, Meyssignac et al. (2019). However, it would not decrease the residual trend of the sea level budget observed in Figure 2e.

Approach (b) investigates the impact of a potential drift of the Jason-3 radiometer on the GMSL estimates. We compare the radiometer-based WTC of Jason-3, S3A and SARAL/AltiKa (detailed analysis in SI, Text S3). The relative drift of the radiometer-based WTC reaches  $0.5$  mm/yr when comparing Jason-3 to S3A, and  $0.8$  mm/yr when comparing Jason-3 to SARAL/AltiKa. Such drift estimates are only relative values and cannot be fully attributed to one or the other radiometer. We conclude that, over a 4-year period (January 2016–December 2019), any Jason-3 radiometer drift would overestimate the GMSL by  $\sim 3$  mm at most. In the worst case scenario, the Jason-3 radiometer drift may contribute by 30% of the remaining misfit in the GMSL budget. It is worth noting that differences in WTCs of that order of magnitude are common for radiometers onboard altimetry missions. They contribute up to  $0.2$  mm/yr in the GMSL error

Argo data sampling was at least as good as during previous years and in particular during the 2011 La Niña event (Figure S8). Besides, even though potential local undersampling might affect the accurate estimate of GMTSSL, a subsequent non-closure of the budget would only be temporary. Hence the spatial sampling is unlikely to explain an error in the GMSL budget beyond 2016. Another possible candidate to explain the non-closure of the budget would be an underestimated contribution of the deep ocean (below 2000 m) to the thermosteric component. We consider in this study the best estimate based on ship-based hydrographic measurements (updated from Purkey and Johnson, 2010, by Chang et al., 2019), but scarcity of the data, both in space and time, might have underestimated the deep ocean contribution to the GMTSSL. The estimation of this contribution is expected to be improved in the future with the deep Argo array (e.g., Jayne et al., 2017).

As discussed in detail by Chen et al. (2020), some uncertainties due to leakage, geocenter and GIA corrections persist in the estimation of the GMOM contribution to the GMSL, that are very likely underestimated by the mascon solutions. For example, geocenter and GIA corrections applied to GRACE/GRACE-FO data could be responsible for uncertainties of about 0.21 mm/yr and 0.12 mm/yr respectively (Blazquez et al., 2018). Such systematic errors not considered in the present study could increase the uncertainty of the GRACE contribution. In addition, instrumental issues affected the GRACE spacecrafts at the end of the mission resulting from battery power failures, and ultimately leading to the loss of one of the two accelerometers. GRACE-FO is also operating in single accelerometer mode upon launch due to similar hardware issues. An accelerometer data transplant method, allowing to generate the missing accelerometer data using data from the remaining operational accelerometer, has been designed to alleviate the issue (Bandikova et al., 2019), but led to significantly noisier gravity field solutions for low harmonic degrees, though no bias was detected when tested on the fully functional part of the mission (2003–2015). Other studies focusing on ice mass loss signals estimated independently by surface mass balance models (e.g., Velicogna et al., 2020) or large terrestrial water storage changes (e.g., Landerer et al., 2020) have not detected any discontinuity between GRACE and GRACE-FO measurements throughout the 11-month gap between the two missions. However, such studies focus on extremely large signals that could easily mask tenuous instrumental drifts or bias, that would generate millimetric errors in the GMOM over a few years. Therefore, while most on-going studies may not allow for tracking of unusual errors in GRACE/GRACE-FO measurements, several sources of errors (including background models, instrumental errors and geophysical corrections) should be investigated to better quantify GMOM using GRACE and GRACE-FO gravity measurements.

To conclude, the present study shows that accounting for the halosteric component leads to a major error in the sea level budget closure since 2016. We therefore recommend using only global mean thermosteric sea level as long as salinity measurements have not been corrected yet in the Argo datasets. Alternatively, the total Argo-based global mean steric sea level from SCRIPPS appears to be a robust option when studying the global mean sea level budget. Furthermore, no major drift has been identified in the Jason-3 altimetry system. Nevertheless, independent calibration of altimetry with tide gauges should be conducted in the future to confirm our findings but this will require a longer record than available at present to detect drifts of the Jason-3 altimeter system at the level of 2 mm/yr or better. More generally, investigations over a longer time span are still needed to robustly quantify the uncertainties associated with the three observing systems considered in order to estimate the global mean sea level budget since 2016.

### Data Availability Statement

The datasets for this research are publicly available from previously published sources. The ESA CCI altimetry data are available from <https://catalogue.ceda.ac.uk/uuid/1562578dd07844f19f01f0db9366106d>. The CMEMS altimetry data are available from <https://marine.copernicus.eu/access-data/ocean-monitoring-indicators/gridded-mean-sea-level-trends-over-global-ocean>. The AVISO altimetry data are available from <https://www.aviso.altimetry.fr/>. The C3S altimetry data are available from <https://cds.climate.copernicus.eu/cdsapp#!/dataset/satellite-sea-level-global?tab=overview>. The GSFC altimetry data are available from <https://doi.org/10.5067/GMSLM-TJ142>. Argo data were collected and made freely available by the international Argo Program and the national programs that contribute to it (<https://argo.ucsd.edu>, <https://www.ocean-ops.org>). The Argo Program is part of the Global Ocean Observing System. The NOAA Argo data are available from <https://www.ncei.noaa.gov/access/global-ocean-heat-content/>. The SCRIPPS Argo

climatology data are available from [http://sio-argo.ucsd.edu/RG\\_Climatology.html](http://sio-argo.ucsd.edu/RG_Climatology.html). The JAMSTEC MILA GPV data are available from <http://www.jamstec.go.jp/datadoi/doi/10.17596/0000105.html>. The EN4 Argo data are available from <http://hadobs.metoffice.com/en4/download.html>. The GRACE/GRACE Follow-On JPL and CSR Level 3 Release 6 data are available from <https://podaac.jpl.nasa.gov>. The GRACE/GRACE Follow-On GSFC data are available from <https://earth.gsfc.nasa.gov/geo/data/grace-mascons>.

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#### References

- Ablain, M., Jugier, R., Meyssignac, B., Guérou, A., Labroue, S., Raynal, M., & Poisson, J.-C. (2019). *Estimation and impact of Sentinel-3a GMSL drift on climate-driven studies*. OSTST. Presentation retrieved from [https://meetings.avisio.altimetry.fr/fileadmin/user\\_upload/2019/SC1\\_01\\_s3a\\_gmsl\\_drift\\_ablain.pdf](https://meetings.avisio.altimetry.fr/fileadmin/user_upload/2019/SC1_01_s3a_gmsl_drift_ablain.pdf)
- Ablain, M., Jugier, R., & Picot, N. (2018). *Estimating of any altimeter mean sea level (MSL) drifts between 1993 and 2017 by comparison with tide-gauges measurements*. Azores: 25 years of progress in radar altimetry symposium. Presentation retrieved from [www.altimetry2018.org](http://www.altimetry2018.org)
- Ablain, M., Legeais, J. F., Prandi, P., Fenoglio-Marc, L., Marcos, M., Benveniste, J., et al. (2017). Altimetry-based sea level at global and regional scales. *Surveys in Geophysics*, 38, 7–31. <https://doi.org/10.1007/s10712-016-9389-8>
- Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Rives, A., Spada, G., et al. (2019). Uncertainty in satellite estimates of global mean sea-level changes, trend and acceleration. *Earth System Science Data*, 11(3), 1189–1202. <https://doi.org/10.5194/essd-11-1189-2019>
- Argo. (2000). *Argo float data and metadata from Global Data Assembly Center (Argo GDAC)*. SEANO. <https://doi.org/10.17882/42182>
- Aublanc, J., Dinardo, S., Cadier, E., Raynal, M., Moreau, T., Boy, F., et al. (2020). *Impact of the range walk processing in the Sentinel-3A sea level trend*. OSTST. Oral presentation Retrieved from [https://meetings.avisio.altimetry.fr/fileadmin/user\\_upload/tx\\_ausylsseminar/files/S3A\\_range\\_drift OSTST\\_3.pdf](https://meetings.avisio.altimetry.fr/fileadmin/user_upload/tx_ausylsseminar/files/S3A_range_drift OSTST_3.pdf)
- Bandikova, T., McCullough, C., Kruijzinga, G. L., Save, H., & Christophe, B. (2019). GRACE accelerometer data transplant. *Advances in Space Research*, 64(3), 623–644. <https://doi.org/10.1016/j.asr.2019.05.021>
- Beckley, B., Zelensky, N. P., Holmes, S. A., Lemoine, F. G., Ray, R. D., Mitchum, G. T., et al. (2016). *Global Mean Sea Level Trend from Integrated Multi-Mission Ocean Altimeters TOPEX/Poseidon Jason-1 and OSTM/Jason-2 Version 4.2*. NASA Physical Oceanography DAAC. <https://doi.org/10.5067/GMSLM-TJ142>
- Blazquez, A., Meyssignac, B., Lemoine, J. M., Berthier, E., Ribes, A., & Cazenave, A. (2018). Exploring the uncertainty in GRACE estimates of the mass redistributions at the Earth surface: Implications for the global water and sea level budgets. *Geophysical Journal International*, 215(1), 415–430. <https://doi.org/10.1093/gji/ggy293>
- Boening, C., Willis, J. K., Landerer, F. W., Nerem, R. S., & Fasullo, J. (2012). La Niña: So string, the ocean fell. *Geophysical Research Letters*, 39, L19602. <https://doi.org/10.1029/2012GL053055>
- Chambers, D. P., Cazenave, A., Champollion, N., Dieng, H., Llovel, W., Forsberg, R., et al. (2017). Evaluation of the global mean sea level budget between 1993 and 2014. *Surveys in Geophysics*, 38(1), 309–327. <https://doi.org/10.1007/s10712-016-9381-3>
- Chang, L., Tang, H., Wang, Q., & Sun, W. (2019). Global thermosteric sea level change contributed by the deep ocean below 2000 m estimated by Argo and CTD data. *Earth and Planetary Science Letters*, 524, 115727. Elsevier BV. <https://doi.org/10.1016/j.epsl.2019.115727>
- Chen, J., Tapley, B. D., Save, H., Tamisiea, M. E., Bettadpur, S., & Ries, J. (2018). Quantification of ocean mass change using gravity recovery and climate experiment, satellite altimeter, and Argo floats observations. *Journal of Geophysical Research: Solid Earth*, 123(10), 10212–10225. <https://doi.org/10.1029/2018JB016095>
- Chen, J., Tapley, B., Wilson, C., Cazenave, A., Seo, K.-W., & Kim, J.-S. (2020). Global ocean mass change from GRACE and GRACE Follow-On and altimeter and Argo measurements. *Geophysical Research Letters*, 47, e2020GL090656. <https://doi.org/10.1029/2020GL090656>
- Dakos, V., Van Nes, E. H., d'Odorico, P., & Scheffer, M. (2012). Robustness of variance and autocorrelation as indicators of critical slowing down. *Ecology*, 93(2), 264–271. <https://doi.org/10.1073/pnas.0802430105>
- Dieng, H., Cazenave, A., Meyssignac, B., & Ablain, M. (2017). New estimate of the current rate of sea level rise from a sea level budget approach. *Geophysical Research Letters*, 44, 3744–3751. <https://doi.org/10.1002/2017GL073308>
- Dinardo, S., Scharroo, R., Lucas, B., Martin-Puig, C., & Nogueira-Loddo, C. (2018). *Impact of the Sentinel-3 SRAL PTR Width Drift on the L2 Marine Measurement*. OSTST. Poster retrieved from [https://meetings.avisio.altimetry.fr/fileadmin/user\\_upload/tx\\_ausylsseminar/files/Impact\\_of\\_the\\_Sentinel-3\\_SRAL\\_PTR\\_Width\\_Drift\\_on\\_the\\_L2\\_Marine\\_Measurement\\_v1.0.pdf](https://meetings.avisio.altimetry.fr/fileadmin/user_upload/tx_ausylsseminar/files/Impact_of_the_Sentinel-3_SRAL_PTR_Width_Drift_on_the_L2_Marine_Measurement_v1.0.pdf)
- García, H. E., Boyer, T. P., Baranova, O. K., Locarnini, R. A., Mishonov, A. V., Grodsky, A., et al. (2019). *World ocean atlas 2018: Product documentation*. NOAA. Technical Editor: A. Mishonov. Retrieved from <https://data.nodc.noaa.gov/woa/WOA18/DOC/woa18documentation.pdf>
- Good, S. A., Martin, M. J., & Rayner, N. A. (2013). EN4: Quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *Journal of Geophysical Research: Oceans*, 118, 6704–6716. <https://doi.org/10.1002/2013JC009067>
- Gouretski, V., & Reseghetti, F. (2010). On depth and temperature biases in bathythermograph data: Development of a new correction scheme based on analysis of a global ocean database. Deep Sea Research Part I: Oceanographic Research Papers, 57, 812–833. Elsevier BV. <https://doi.org/10.1016/j.dsr.2010.03.011>
- Gregory, J. M., & Lowe, J. A. (2000). Predictions of global and regional sea-level rise using AOGCMs with and without flux adjustment. *Geophysical Research Letters*, 27(19), 3069–3072. <https://doi.org/10.1029/1999GL011228>
- Hosoda, S., Ohira, T., Sato, K., & Suga, T. (2010). Improved description of global mixed-layer depth using Argo profiling floats. *Journal of Oceanography*, 66(6), 773–787. <https://doi.org/10.1007/s10872-010-0063-3>
- Jayne, S. R., Roemmich, D., Zilberman, N., Riser, S. C., Johnson, K. S., Johnson, G. C., et al. (2017). The Argo program: Present and future. *Oceanography*, 30, 18–28. <https://doi.org/10.5670/oceanog.2017.213>
- Landerer, F. W., Flechtner, F. M., Save, H., Webb, F. H., Bandikova, T., Bertiger, W. I., et al. (2020). Extending the global mass change data record: GRACE follow-on instrument and science data performance. *Geophysical Research Letters*, 47, e2020GL088306. <https://doi.org/10.1029/2020gl088306>
- Legeais, J.-F., Ablain, M., Zawadzki, L., Zuo, H., Johannessen, J. A., Scharffenberg, M. G., et al. (2018). An improved and homogeneous altimeter sea level record from the ESA Climate Change Initiative. *Earth System Science Data*, 10, 281–301. Copernicus GmbH. <https://doi.org/10.5194/essd-10-281-2018>

- Llovel, W., Purkey, S., Meyssignac, B., Blazquez, A., Kolodziejczyk, N., & Bamber, J. (2019). Global ocean freshening, ocean mass increase and global mean sea level rise over 2005–2015. *Scientific Reports*, 9(1), 17717. <https://doi.org/10.1038/s41598-019-54239-2>
- Llovel, W., Willis, J. K., Landerer, F. W., & Fukumori, I. (2014). Deep-ocean contribution to sea level and energy budget not detectable over the past decade. *Nature Climate Change*, 4, 1031–1035. <https://doi.org/10.1038/nclimate2387>
- Loomis, B. D., Luthcke, S. B., & Sabaka, T. J. (2019). Regularization and error characterization of GRACE mascons. *Journal of Geodesy*, 93(9), 1381–1398. <https://doi.org/10.1007/s00190-019-01252-y>
- Mertz, F., & Legeais, J.-F. (2020). *Product user guide and specification; Sea level v1.2 (ECMWF Copernicus Report)*. CLS.
- Nerem, R. S., Beckley, B. D., Fasullo, J. T., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate-change-driven accelerated sea-level rise detected in the altimeter era. *PNAS Proceedings of the National Academy of Sciences*, 115(9), 2022–2025. <https://doi.org/10.1073/pnas.1717312115>
- Peltier, W. R. (2004). Global glacial isostasy and the surface of the ice-age Earth: The ICE-5G (VM2) model and GRACE. *Annual Review of Earth and Planetary Sciences*, 32, 111–149. <https://doi.org/10.1146/annurev.earth.32.082503.144359>
- Pieuch, C. G., & Quinn, K. J. (2016). El Niño, La Niña, and the global sea level budget. *Ocean Science*, 12, 1165–1177. <https://doi.org/10.5194/os-12-1165-2016>
- Poisson, C., Piras, F., Raynal, M., Cadier, E., Thibaut, P., Boy, F., et al. (2019). *Sentinel-3A, Jason-3 and AltiKa instrumental drifts and their impacts on geophysical estimates*. OSTST. Presentation retrieved from [https://meetings.avisio.altimetry.fr/fileadmin/user\\_upload/2019/IPM\\_02\\_Poisson\\_OSTST2019\\_PTR\\_Drift.pdf](https://meetings.avisio.altimetry.fr/fileadmin/user_upload/2019/IPM_02_Poisson_OSTST2019_PTR_Drift.pdf)
- Purkey, S. G., & Johnson, G. C. (2010). Warming of global abyssal and deep southern ocean waters between the 1990s and 2000s: Contributions to global heat and sea level rise budgets. *Journal of Climate*, 23, 6336–6351. <https://doi.org/10.1175/2010jcli3682.1>
- Roemmich, D., & Gilson, J. (2009). The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo Program. *Progress in Oceanography*, 52, 81–100. Elsevier BV. <https://doi.org/10.1016/j.pocean.2009.03.004>
- Save, H., Bettadpur, S., & Tapley, B. D. (2016). High-resolution CSR GRACE RL05 mascons. *Journal of Geophysical Research: Solid Earth*, 121(10), 7547–7569. <https://doi.org/10.1002/2016JB013007>
- Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., et al. (2009). Early-warning signals for critical transitions. *Nature*, 461, 53–59. Springer Science and Business Media LLC. <https://doi.org/10.1038/nature08227>
- Taburet, G., Sanchez-Roman, A., Ballarotta, M., Pujol, M.-I., Legeais, J.-F., Fournier, F., et al. (2019). DUACS DT2018: 25 years of reprocessed sea level altimetry products. *Ocean Science*, 15, 1207–1224. Copernicus GmbH. <https://doi.org/10.5194/os-15-1207-2019>
- Tapley, B. D., Watkins, M. M., Flechtner, F., Reigber, C., Bettadpur, S., Rodell, M., et al. (2019). Contributions of GRACE to understanding climate change. *Nature Climate Change*, 9, 358–369. <https://doi.org/10.1038/s41558-019-0456-2>
- Velicogna, I., Mohajerani, Y., Geruo, A., Landerer, F., Mougnot, J., Noel, B., et al. (2020). Continuity of ice sheet mass loss in Greenland and Antarctica from the GRACE and GRACE follow-on missions. *Geophysical Research Letters*, 47, e2020GL087291. <https://doi.org/10.1029/2020gl087291>
- Watkins, M. M., Wiese, D. N., Yuan, D. N., Boening, C., & Landerer, F. W. (2015). Improved methods for observing Earth's time variable mass distribution with GRACE using spherical cap mascons. *Journal of Geophysical Research: Solid Earth*, 120(4), 2648–2671. <https://doi.org/10.1002/2014JB011547>
- WCRP Global Sea Level Budget Group (the). (2018). Global sea level budget, 1993–present. *Earth System Science Data*, 10, 1551–1590. <https://doi.org/10.5194/essd-10-1551-2018>
- Wiese, D. N., Landerer, F. W., & Watkins, M. M. (2016). Quantifying and reducing leakage errors in the JPL RL05M GRACE mascon solution. *Water Resources Research*, 52, 7490–7502. <https://doi.org/10.1002/2016WR019344>
- Wong, A. P. S., Wijffels, S. E., Riser, S. C., Pouliquen, S., Hosoda, S., Roemmich, D., et al. (2020). Argo data 1999–2019: Two million temperature–salinity profiles and subsurface velocity observations from a global array of profiling floats. *Frontiers in Marine Science*, 7. Frontiers Media SA. <https://doi.org/10.3389/fmars.2020.00700>