North Atlantic sea level budget revisited

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Abstract

Based on satellite altimetry, GRACE space gravimetry and Argo-based steric data down to 2000m, recent studies have shown that the North Atlantic sea level budget (i.e., altimetry-based sea level minus sum of components) of the past two decades is not closed, with strong regional residuals in the North Atlantic. This was observed but not in this study, we revisit the North Atlantic sea level budget, using satellite altimetry, GRACE and GRACE-FO data, different Argo products and an ocean reanalysis (CIGAR) over the 2004-2022 time span. The ocean reanalysis is used to estimate the manometric contribution, an alternative to using GRACE data, as well as the deep ocean contribution to the sea level budget, not yet fully sampled by Argo. Analyzing different data sets allows us to assess their impact on the previously reported non-closure of the North Atlantic sea level budget. We first find that using the CIGAR ocean reanalysis-based manometric component significantly reduces the residuals of the North Atlantic sea level budget compared to GRACE. We also find that accounting for the deep ocean (below 2000m) thermal expansion (using the CIGAR reanalysis) allows for reducing 30% the North Atlantic budget residuals when using both GRACE and CIGAR for the manometric component. With manometric, the budget is closed within data uncertainties.

1 Introduction

While many studies have been devoted to assessing the global mean sea level budget over the satellite altimetry era (1993 to present) (e.g., Barnoud et al., 2021; Bouih et al., 2025; Chen et al., 2020; Dieng et al., 2017; Horwath et al., 2022; Llovel et al., 2023; Nerem et al., 2018; WCRP, 2018) , only a few have focused on the regional sea level budget, with mixed results (e.g., Bouih et al., 2025; Camargo et al., 2023; Frederikse et al., 2016; Hamlington et al., 2020; Mu et al., 2024; Royston et al., 2020). At the global scale, the two main contributors to the global mean sea level rise are ocean mass (known as barystatic sea level, Gregory et al., 2019) and thermosteric change. At regional scale, however, other factors play a non-negligible role, such as the halosteric (i.e., salinity-related) component, which makes the regional sea level budget more complex to assess. Considering all ocean basins, a recent study (Bouih et al., 2025) investigated the regional sea level trend budget closure over the 2004-2022 time span, using altimetry-based sea level data, GRACE space gravimetry for the regional ocean mass variations (also called manometric component, Gregory et al., 2019) and Argo data for the steric (sum of thermosteric and halosteric terms) component down to 2000m (global mean trends removed from all data sets). Bouih et al. (2025) also considered several ocean reanalyses to compute the manometric component (an alternative to using GRACE data), following the approach developed by Camargo et al. (2023), i.e., using the sterodynamic sea level (Gregory et al., 2019) computed by the reanalysis and correcting it for the local steric effect. The Bouih et al. (2025)'s study used the Argo-based product from SIO (SCRIPPS Institution of Oceanography) that corrected for the spurious salinity drift reported recently in some Argo-based salinity measurements (Liu et al., 2020; Ponte et al., 2021; Wong et al., 2023). They showed that in the Pacific, Indian and South Atlantic oceans, the sea level budget trend residuals (altimetry-based sea level minus sum of components) were non-significant, considering the data uncertainties.

On the other hand, strong positive residuals were found in the North Atlantic, whatever the manometric component considered (i.e., either from GRACE or from ocean reanalyses).
In the present study we revisit the question of the North Atlantic sea level budget over the 2004-2022 time span, using a variety of different data sets for the components of the sea level budget: different GRACE mascon solutions and different Argo-based gridded products down to 2000m, as well as an ocean reanalysis that provide an estimate of the steric signal from the deep ocean. Our objective is to evaluate the impact of each product on the currently reported non-closure of the North Atlantic sea level budget. An important addition, compared to the Bouih et al. (2025)'s study, consists of accounting for the deep ocean warming below 2000m (not sampled by Argo) using estimates from the ocean reanalysis. This paper is organized as follows. Section 2 presents the data and analysis method. Section 3 displays the results for the North Atlantic sea level budget, both in terms of trend maps and time series. A synthesis of the results is presented in the Discussion section (section 4) with some highlights on the few main messages arising from this study.

2 Data and methods

2.1 Data

2.1.1 Altimetry-based total sea level

Sea level variations have been continuously measured by satellite altimetry since 1993. In this study, we use the daily 0.25° ×0.25° gridded sea level anomaly data, version DT2021 available from the Copernicus Climate Change Service (C3S) (https://cds.climate.copernicus.eu/). The data set is further corrected for the TOPEX-A instrumental drift that affected the first 6 years of the time series, but the correction has no impact on our assessment that starts in 2004 (Ablain et al., 2017). The Jason-3 radiometer drift that impacts the wet troposphere correction (Brown et al., 2023) is corrected for. The altimetry data set is also corrected for the absolute Glacial Isostatic adjustment (GIA) effect, using the ICE6G-D model from Peltier et al. (2018).

2.1.2 GRACE-based ocean mass

The Gravity Recovery and Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) are joint missions by the National Aeronautics and Space Administration (NASA) and the German Aerospace Center (DLR) (Tapley et al., 2019). These satellites have been measuring temporal variations in Earth's gravity field since 2002. This data set is essential for estimating mass redistribution in the oceans, terrestrial water storage, ice sheets, and glaciers. GRACE/GRACE-FO data are generally available in two forms: Spherical Harmonic (SH) coefficients and Mass Concentration (mascon) solutions. In this study, we utilize the latest Release 6 (RL06) mascon solutions provided by three different institutions: the Center for Space Research (CSR, Save et al., 2016), the Jet Propulsion Laboratory (JPL, Watkins et al., 2015), and the Goddard Space Flight Center (GSFC, Loomis et al., 2019). These mascon solutions, at monthly temporal resolution, are corrected for the geocentric motion (degree-1) using the Sun et al. (2016) solution. The C_{20} and C_{30} coefficients are derived from Satellite Laser Ranging (SLR) data. The GIA correction for GRACE is based on the ICE6G-D model from (Peltier et al. (2018). Additionally, the GAD product derived from AOD1B models (Dobslaw et al., 2017; Flechtner et al., 2014), which represents non-tidal atmospheric and oceanic mass redistribution, is added back over the ocean areas to restore the ocean bottom pressure, which combines the effects of ocean mass and atmospheric loading. For alignment with altimetry-based sea level data which are corrected for the inverse barometer, we remove the global mean atmospheric pressure at every grid mesh in GRACE/GRACE-FO ocean mass data using the spatial mean of the GAD product at each month (Chen et al., 2019). In this study, we use the ensemble mean of the three mascon solutions.

2.1.3 Argo-based gridded data

The Argo program is an international observational network that deploys a global array of autonomous profiling floats to measure temperature and salinity in the upper 2000m of the ocean. Several institutions process the raw data from these floats and publish gridded temperature (T) and salinity (S) data sets. In this study, we utilize three distinct gridded products: the Scripps Institution of Oceanography (SIO, Roemmich and Gilson, 2009), the Japan Agency for Marine-Earth Science and Technology (JAMSTEC, Hosoda, 2007), and the Met Office Hadley Centre (EN4 product, version 2.2, Cheng et al., 2014). Note that the SIO product rejects salinity profiles exceeding a difference of 0.1 psu when comparing to historical estimate based on the WOCE Global Hydrographic Climatology (Roemmich and Gilson, 2009). This correction tends to withdraw the salinity drift reported in Argo floats since 2016 (Liu et al., 2020; Ponte et al., 2021; Wong et al., 2023). Note that the other two products do not apply such a correction. All three data products are available at https://argo.ucsd.edu/data/data-access/ (downloaded in October 2025). The thermosteric, halosteric and total steric sea level time series are computed from these gridded temperature and salinity data using the Gibbs SeaWater (GSW) Oceanographic Toolbox (McDougall et al., 2011) which implements the 2010 Thermodynamic Equation Of Seawater (TEOS-10) standard. The gridded Argo-based time series have a spatial resolution of 1°×1° at monthly interval over January 2004 to December 2022.

2.1.4 Ocean reanalyses

We also used the ocean reanalysis data sets: tCNR-ISMAR Global Historical Reanalysis (CIGAR, Storto and Yang, 2024). CIGAR is a reanalysis system developed by Storto and Yang (2024). Its resolution is 1°x1°. It is based on the NEMO ocean model version 4.0.7 (https://www.nemo-ocean.eu/) and is forced by the ERA5 atmospheric reanalysis from the European Center for Medium-range Weather Forecast (ECMWF) (https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5). The system uses a three-dimensional variational (3D-Var) scheme to assimilate in situ profiles from the EN4 data set. Notably, CIGAR does not assimilate satellite altimetry data, which allows for independent comparisons. The system consists of 32 ensemble members generated through varying configurations (e.g., perturbed initial conditions and atmospheric forcing). In this study, we use the ensemble mean of the 32 members to derive the thermosteric, halosteric and steric sea level. Bouih et al. (2025) considered the ensemble mean of five ocean reanalyses over 2004-2019, including CIGAR, to compute the manometric component and showed that this ensemble mean and CIGAR manometric components are highly similar. For that reason, here we only consider CIGAR, but extend it until 2022.

2.2 Methods

2.2.1 Computation of the manometric component

Manometric sea level change generally refers to the sea-level component associated with ocean mass variations. It is driven by water mass exchange with the continents, such as land ice melt and terrestrial water storage changes, as well as by mass redistribution within the ocean driven by ocean circulation. In this study, because the global mean ocean mass trend is removed, the manometric sea level refers to the regional redistribution of ocean mass around the global mean, with the GRD effect added as described below. In this study, we utilize two methods to obtain an estimate of the manometric component. One method is to use the ensemble mean of the GRACE mascon solutions from CSR, JPL, and GSFC to obtain the GRACE-based manometric estimate. The other method, an alternative to using GRACE solutions, relies on ocean reanalysis data and follows the approach developed by Camargo et al. (2023). Here, we use the sterodynamic sea level provided by the CIGAR ocean reanalysis, which combines steric and dynamic sea level changes. To isolate the manometric component, we subtract the local steric effect from the sterodynamic sea level and further add the contemporary Gravitational, Rotational, and Deformation (GRD) fingerprints (representing solid Earth deformations and gravitational effects due to present-day land ice melt and terrestrial water storage changes; Gregory et al., 2019), to obtain a manometric component comparable to GRACE. The sea level fingerprint data used in this study are based on monthly GRD fingerprint grids (0.5°×0.5° resolution) estimated by Adhikari et al. (2019). Since this original dataset ends in 2016, we extended the time series up to 2022 using linear extrapolation, assuming that the observed trend remains constant after 2016 (see Bouih et al., 2025 for details). This reanalysis-based estimate is hereafter referred to as CIGAR manometric sea level.

2.2.2 Post processing of the data

To ensure spatial consistency across all observing systems, all gridded data sets were spatially interpolated onto a 1°×1° grid and averaged at monthly interval. A three-month moving average filter was applied to the time series. For the spatial analysis, a common mask was applied to all gridded components to exclude regions with high uncertainty. This mask covers latitudes from 66°S to 66°N, excludes inland seas, and omits coastal regions where the distance from land is less than 300 km (see Bouih et al., 2025 for details). Seasonal signals (annual and semi-annual) are removed from the time series through a least-squares adjustment of 6 and 12-month sinusoids. For the spatial maps, this linear least-squares fit was used to calculate the trends at each grid point. Finally, the globally averaged trend of each data set computed over the study period was subtracted from each grid point before constructing the spatial trend maps to focus on regional spatial patterns. The study period spans from January 2004 to December 2022.

2.2.3 Data uncertainties

For the altimetry data, we use the uncertainties estimated by Prandi et al. (2021). For the GRACE-based manometric component, uncertainties can be derived from the dispersion of the data sets with respect to the ensemble mean. For the CIGAR-based manometric, thermosteric, halosteric and steric data, the dispersion of the 32 realizations around the ensemble mean was used to estimate the uncertainties. For the residual time series, the uncertainty was estimated by quadratically summing the error of each term of the budget equation. Regarding the trend uncertainty, it is expressed as the standard error of the least-squares fit. To obtain the uncertainty at the 95% confidence level, we scaled the standard error by a factor of 2 (representing the 2-sigma interval).

3 Results

3.1 Comparison of the different steric products over the North Atlantic

3.1.1 Upper ocean (0-2000m) thermosteric, halosteric and steric products

Figure 1a-d show the thermosteric sea level (TSL) trends over 2004-2022 over the North Atlantic for the three Argo products SIO, JAMSTEC and EN4, and CIGAR (0-2000m) reanalysis data. Similarly, Figure 1e-h shows the halosteric sea level (HSL) trends for the same data sets and period. As expected, due to thermohaline compensation particularly strong in the North Atlantic (e.g., Pardaens et al., 2011; Wang et al., 2010; Wunsch et al., 2007), the two components display opposite trends. Regarding the thermosteric component (Figure 1a-d), all four products display similar spatial patterns, especially indicating significant positive signals in the western North Atlantic. Regarding the halosteric component, the four products share similar spatial patterns; however, the magnitude of the SIO product is smaller than the other three, the others being very similar. This difference likely results from the SIO processing that corrects for the instrumental salinity drift reported in Argo floats since 2016, whereas the other products do not account for this. The steric sea level (SSL) trends are shown in Figure 1i-l. The magnitude of the total steric change is smaller than that of the thermosteric component alone. This implies that the halosteric contribution plays a significant compensatory role in the North

Atlantic (consistent with previous published studies; e.g., Bouih et al., 2025; Llovel and Hochet, 2025). Unlike in the case of the global mean, the influence of salinity changes on sea level cannot be ignored in this region.

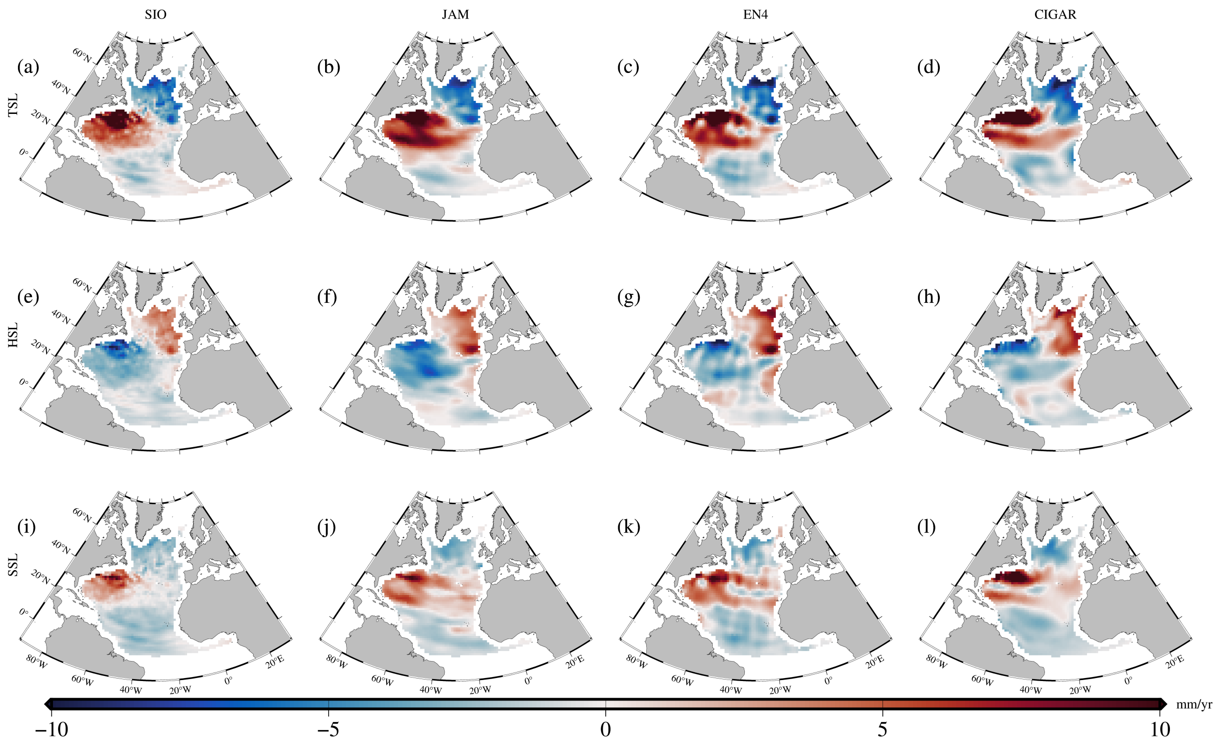

Figure 1. Trends of thermosteric (a–d), halosteric (e–h), and steric (i–l) sea level change in the North Atlantic (0-2000m depth) over 2004–2022 derived from the SIO (a, e, i), JAMSTEC (b, f, j), EN4 (c, g, k) Argo products and CIGAR (d, h ,l) ocean reanalysis.

3.1.2 Full depth thermosteric, halosteric and steric products

Here we use the CIGAR reanalysis data to compute thermosteric, halosteric, and steric sea level changes for the deep ocean (below 2000 m). We consider two cases: (1) SIO upper ocean (0-2000) combined with CIGAR deep ocean (below 2000 m). Hereafter it is called SIO hybrid.

(2) CIGAR full depth. Trends of thermosteric, halosteric, and steric full depth for SIO hybrid and CIGAR full depth over 2004–2022 are shown in Figure 2. Differences are seen between the two cases in around 20N° for the thermosteric and halosteric components. Both products display strong positive thermosteric and negative halosteric signals in the western North Atlantic.

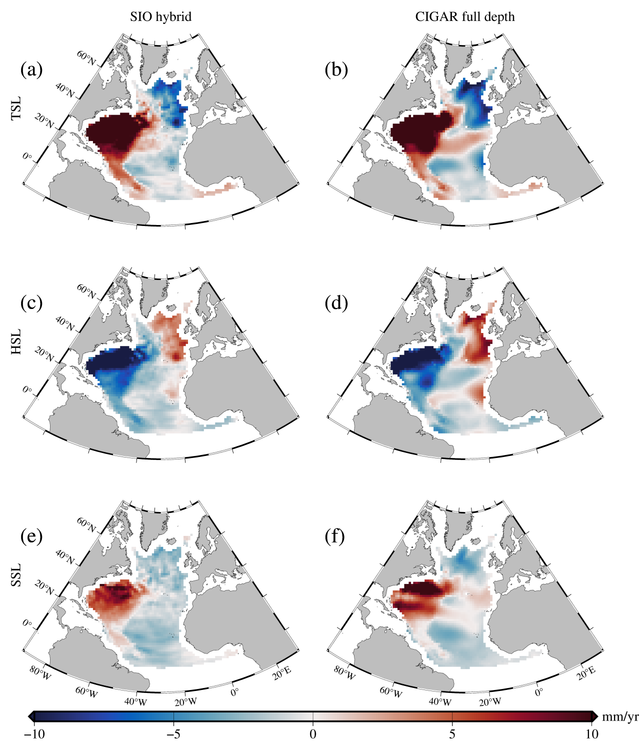

Figure 2. Trends of thermosteric (a, b), halosteric (c, d), and steric (e, f) for SIO hybrid (a, c, e) and CIGAR full depth (b, d, f) sea level change in the North Atlantic over 2004–2022.

3.2 Upper ocean Argo-based and CIGAR-based ocean reanalysis thermosteric, halosteric and steric time series over 2004-2022 (global mean trend removed)

Next, we examine the thermosteric, halosteric and steric time series (weighted averages of the gridded data in the North Atlantic) for the different Argo and ocean reanalysis product (Figure 3). Figure 3a indicates that the thermosteric component (0-2000m) displays a positive trend in all products as of about 2010. Regarding the halosteric component (0-2000m) (Figure 3b), we observe that the JAMSTEC curve exhibits spurious positive anomaly between 2008 and 2012, while the EN4 curve (and to a little extent also SIO and JAMSTEC) shows a strong decrease as of 2016, possibly linked to the salinity drift in EN4 and JAMSTEC data sets, to together with a potential physical salinity increase. The latter issue needs further investigation. In the following, we will only consider the SIO product (as mentioned before, corrected for salinity drift).

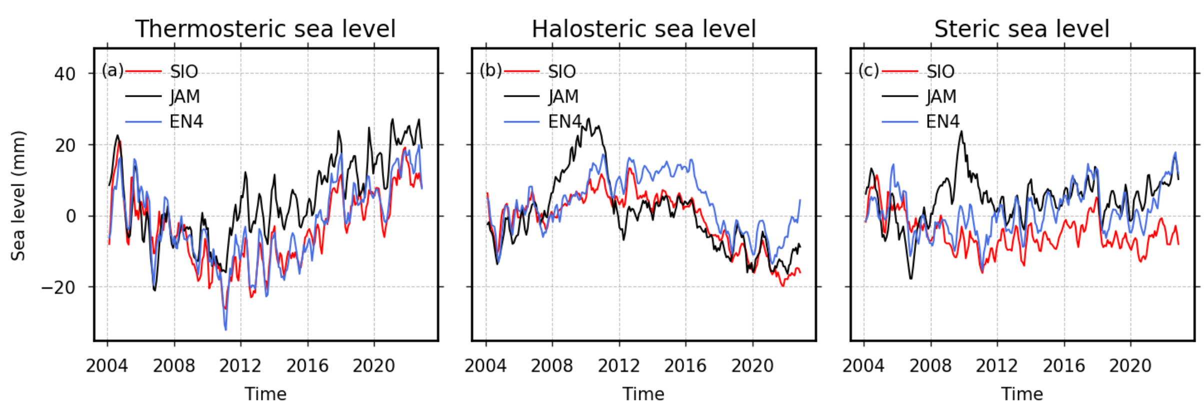

Figure 3. Upper ocean time series of thermosteric (a), halosteric (b), and steric (c) sea level time series in the North Atlantic derived from Argo products (SIO, JAMSTEC*, EN4). All time series have applied three-month moving average filtering.*

3.3 Comparison of the different manometric components over the North Atlantic

Figure 4a, b, shows the spatial manometric trends in the North Atlantic using the GRACE and CIGAR manometric data. Comparing Figure 4(a) and (b), we distinctly observe contrasting patterns between the GRACE and CIGAR manometric components. For the GRACE-based component, significant negative trends dominate most of the basin, with magnitudes gradually weakening from east to west. However, positive trends are observed in the western tropical Atlantic. In contrast, the CIGAR manometric component displays positive trends in the east and negative trends in the west, separated by a distinct dividing line, which likely corresponds to the position of the Mid Atlantic Ridge.

Figure 4c,d also shows the 'Altimetry minus steric full depth' trends for both the SIO hybrid case and CIGAR. These maps are supposed to represent the manometric component, plus the deep ocean contribution. Comparing Figure 4c,d with a,b, we note a better agreement between 'Altimetry minus steric full depth' and CIGAR manometric in the Eastern Atlantic, both maps showing positive trends, while the GRACE manometric trends are negative in this region. On the other hand, it is worth noting that the positive trend area seen in the GRACE manometric map in the western Atlantic around 30°N is also seen in the 'Altimetry minus steric full depth' trend map, although with smaller extension, but not in the CIGAR manometric map. Such comparisons seem point to problems in GRACE data in the eastern North Atlantic region.

A recent study by Hightower et al. (2026) revisited the GIA correction applied to GRACE data. They developed a 3D GIA model, considering 3D viscosity fields derived from tomography and two commonly used ice-loading histories. While traditional GIA models assume laterally homogeneous mantle viscosity, these authors show that because the Earth's rheology varies significantly from place to place, this strongly affects how the Earth's mantle rebounds after ice melts, with important impact on the GIA correction applied to GRACE-based ocean mass data in many regions, in particular in the whole Northeast Atlantic. Since here we use GRACE data corrected for the traditional GIA correction, the discrepancy between the GRACE and CIGAR manometric trend maps may result from an inadequate GIA correction.

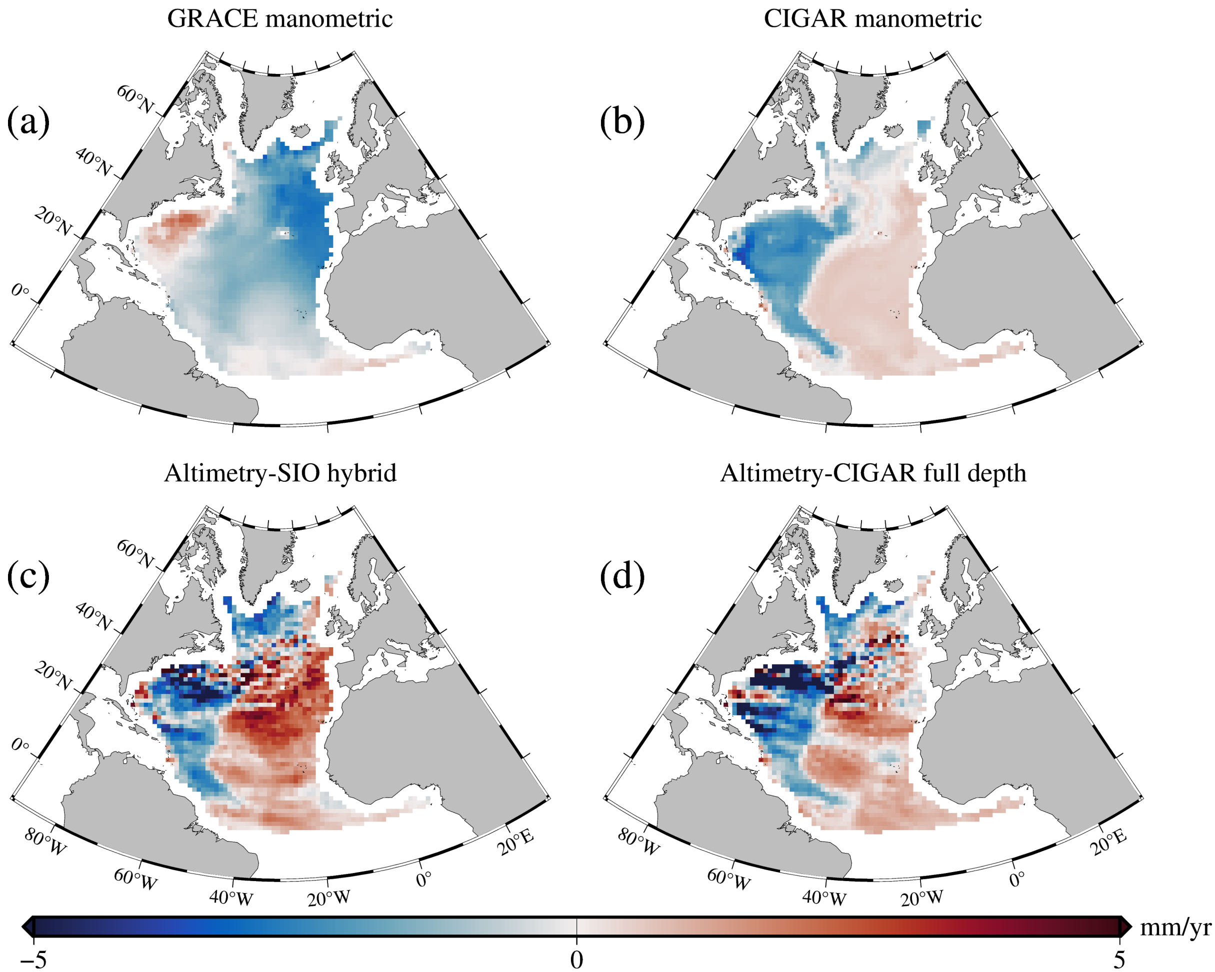

Figure 4. Manometric sea level trends in the North Atlantic over 2004.01-2022.12 derived from (a) the mean of three GRACE mascon solutions, (b) the CIGAR ocean reanalysis, (c) 'Altimetry minus SIO hybrid' and (d) 'Altimetry minus CIGAR full depth'.

3.4 Residual trend maps in the North Atlantic

In this section, we utilize data from the observing systems described above to compute spatial maps of the sea level budget residuals.

3.4.1 North Atlantic budget residuals for GRACE and CIGAR manometric and different steric (0-2000m and full depth) components

We computed the residuals by subtracting various combinations of manometric (GRACE, CIGAR) and steric (SIO and CIGAR, upper 2000 m and full depth) components from the altimetry data (Figure 5).

In Figure 5a,b,e,f (upper ocean), the residuals implicitly include the deep ocean steric contribution. As previously observed by Bouih et al. (2025), strong residuals are seen in the Northeast Atlantic with GRACE, and in the Northwest Atlantic with CIGAR. When the deep ocean accounted for (Figure 5c,d,g,h), strong residuals are still seen in the Northeast Atlantic with GRACE, while the residual signal is much attenuated with CIGAR.

Indeed, when using the CIGAR manometric component, the residuals decrease significantly in both spatial variability and magnitude.

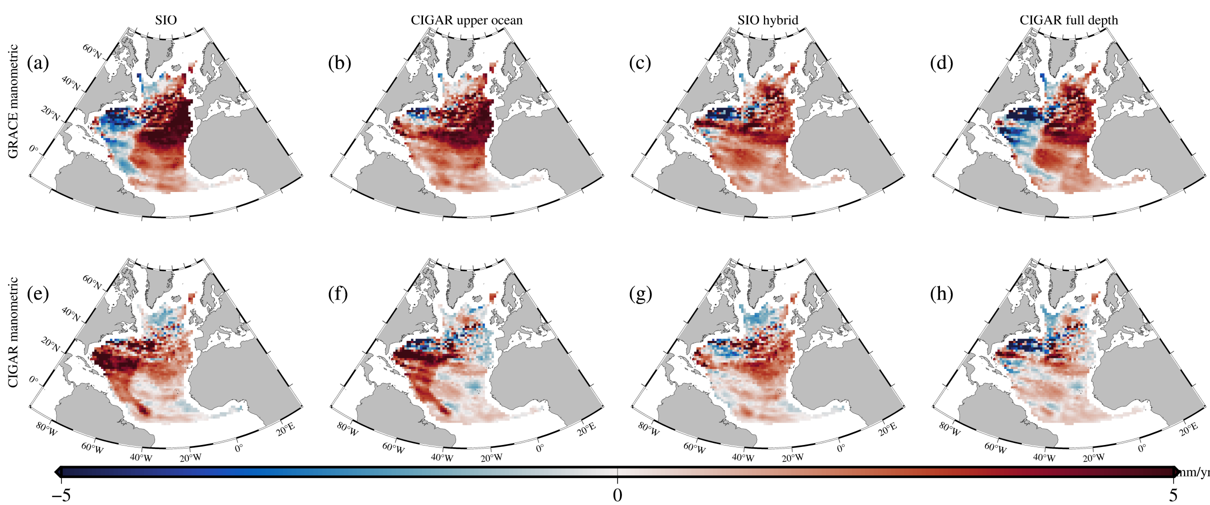

Figure 5. Maps of sea level residuals (mm/yr) in the North Atlantic. The residuals are calculated by subtracting manometric and steric components from satellite altimetry. The manometric component is derived from GRACE (a–d) and CIGAR (e–h). The steric component from SIO (a, e), SIO hybrid CIGAR DO (b, f), CIGAR UP (upper ocean, c, g) and CIGAR full depth (d, h).

To quantify the residual trends, we computed the latitude-weighted spatial mean trend of each map. Results are shown in Table 1. Regardless of the steric data used (whether from SIO or CIGAR), the residuals derived using the CIGAR manometric component are always smaller than those derived using GRACE, for both upper ocean and full depth.

Table 1. Trend values (mm/yr) of sea level residuals in the North Atlantic corresponding to SIO and CIGAR for upper ocean and deep ocean, and two manometric components. Uncertainties are 2-sigma errors of the least-squares fit.

Trend (mm/yr)	SIO	CIGAR	SIO hybrid	CIGAR full depth
GRACE manometric	2.15±0.19	1.52±0.21	1.53±0.21	0.90±0.23
CIGAR manometric	1.50±0.23	0.86±0.25	0.88±0.25	0.24±0.22

We note that the mean residual magnitude is reduced when the deep-ocean steric change is included: by about 30% when using the GRACE manometric component with SIO upper-2000 m steric sea level, and by about 70% when using the CIGAR manometric component together with the CIGAR full-depth steric component.

3.5 Time series of the North Atlantic mean sea level budget (global mean trends removed)

Figure 6 displays the North Atlantic budget time series using CIGAR for the manometric component and two steric full depth configurations. Figure 6 shows that the CIGAR manometric component display a changing trend as of 2016, which origin remains to be explained. Because of this behavior, the residual curves are not purely linear. However, Figure 6 clearly shows a larger positive trend with SIO hybrid than with CIGAR full depth. Corresponding residual linear trends amount to 0.88±0.20 mm/yr for the hybrid steric case and 0.24±0.22 mm/yr for the CIGAR full-depth case. In the latter case, we may conclude that the North Atlantic sea level budget is closed within data uncertainties.

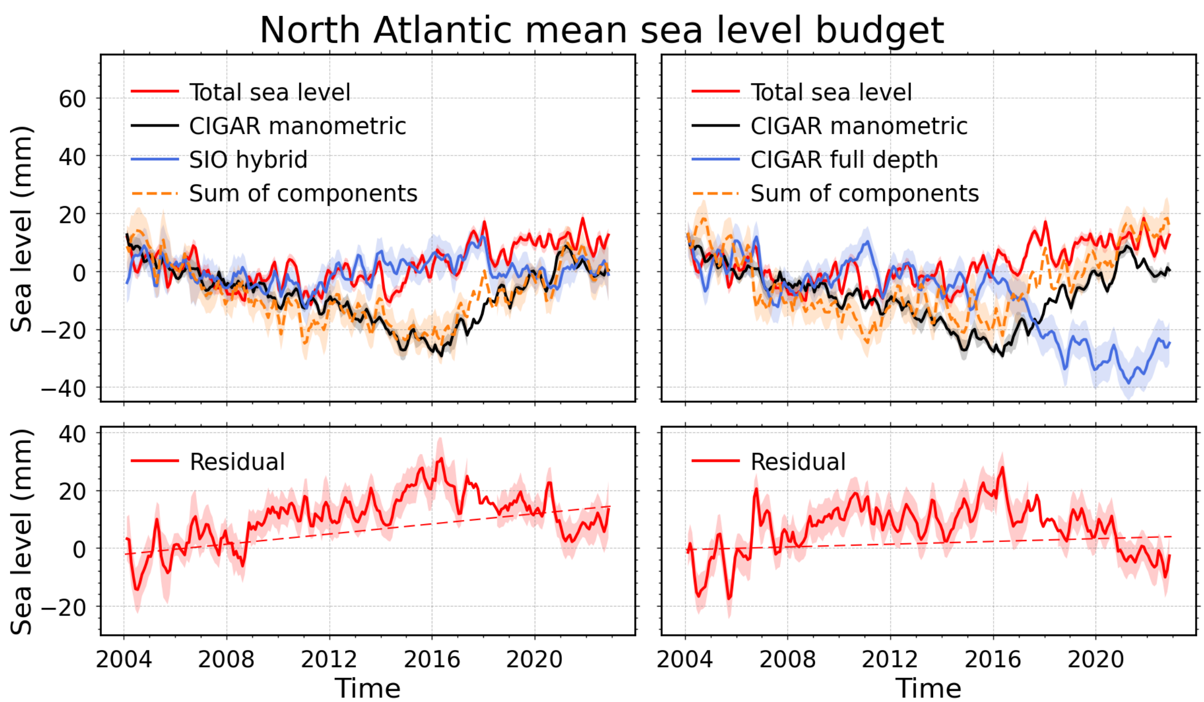

Figure 6. Time series of North Atlantic sea level change components (top) and budget residuals (bottom). The left panels use a hybrid steric estimate (SIO for 0–2000m combined with CIGAR for 2000–6000m), while the right panels use the full-depth CIGAR steric estimate (full-depth). In both left and right panels, CIGAR manometric components are considered. All time series have applied three-month moving average filtering. The global mean trend of each component is removed. Shaded areas represent data uncertainties.

4 Discussion

In this study, we have revisited the sea level budget of the North Atlantic over the 2004-2022 period, using a variety of different data sets. The objective was to further investigate the results from Bouih et al. (2025) who reported non-closure of the sea level budget in the North Atlantic over the same time span, and to identify which components of the budget (or which missing component) are responsible.

The main results of our study can be summarized as follows:

(1) By comparing the GRACE and CIGAR manometric trends with the ‘Altimetry minus steric full depth sea level’, we note a better agreement (same positive sign) between the latter and the CIGAR-based manometric component in the northeastern Atlantic, while the GRACE manometric trends have an opposite (negative) sign in this region. The cause is so far unknown but possibly related to the GIA correction applied to GRACE data, as shown in the recent study by Hightower et al. (2026).

(2) Our study shows that the deep ocean (>2000 m of depth) contribution to the North Atlantic sea level budget is not negligible and needs to be taken into account to obtain better closure of the sea level budget in this region. Based on CIGAR, the additional deep ocean steric contribution to the North Atlantic sea level budget allows to almost close regional sea level budget. Accounting for the deep ocean steric contribution reduces by a factor of 30% the residuals of the North Atlantic sea level budget when using the GRACE manometric component, and by a factor of 70% when using CIGAR for the manometric component (and CIGAR full depth for the steric component). In the latter case, the mean residual trend over the North Atlantic is <1mm/yr, i.e., of the same order of magnitude as the regional trend error for altimetry gridded data according to Prandi et al. (2021). We can thus conclude that the closure of the sea level budget holds within the data uncertainties in this case.

To conclude, these new findings represent a step further towards better understanding of the present-day sea level budget in the North Atlantic region. These investigations also support the need to better observe the deep ocean especially in the North Atlantic Ocean which is one of the objectives of the One Argo Project (Thierry et al., 2025). Nevertheless, some issues still merit deeper investigation. We can quote the followings, among others: Why GRACE manometric data give less good results in the Northeast Atlantic than the CIGAR-based manometric sea level? Which inaccurate correction applied to GRACE is involved? Is it related to the GIA correction applied to GRACE? Can we explain the physical process causing the reported CIGAR-based positive deep ocean steric sea level? What is the impact on the CIGAR steric component estimates of the use of EN4 (with no salinity drift correction applied) in the assimilation procedure? What is the source of the (small) remaining residual trend of the North Atlantic sea level budget (after accounting for the deep ocean)? Clearly, future studies should be devoted to try answering these puzzling questions.

Author contributions

AC, WL and ZS designed the study. All analyses have been performed by ZS. ZS and AC wrote a first version of the manuscript. All co-authors contributed to the discussion of the results, editing and final writing of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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