AGU ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

RESEARCH ARTICLE
10.1029/2025EF007403

Key Points:
- Non closure of the global mean sea level budget since 2016 may be explained by the additional contribution of the deep ocean
- Decadal variations of the Pacific and Atlantic sea levels decorrelate from the Pacific Decadal Oscillation beyond 2016
- Using an ocean reanalysis, evidence of deep ocean warming (below 2,000 m) is found in the Northwest Atlantic and in the Southern Ocean

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

Correspondence to:
A. Cazenave,
anny.cazenave@univ-tlse3.fr,
anny.cazenave@gmail.com

Citation:
Cazenave, A., Yang, C., Bouih, M., Storto, A., Chen, J., Llovel, W., et al. (2026). Evidence of increased deep ocean warming from a sea level budget approach. *Earth's Future*, *14*, e2025EF007403. https://doi.org/10.1029/2025EF007403

Received 22 SEP 2025
Accepted 26 FEB 2026
Corrected 10 APR 2026

This article was corrected on 10 APR 2026. See the end of the full text for details.

Author Contributions:
Conceptualization: Anny Cazenave, Chunxue Yang, Andrea Storto
Formal analysis: Chunxue Yang, Marie Bouih, Andrea Storto, Karina von Schuckmann, Lancelot Leclercq
Methodology: Anny Cazenave, Chunxue Yang, Marie Bouih, Andrea Storto
Software: Chunxue Yang, Marie Bouih, Lancelot Leclercq

Evidence of Increased Deep Ocean Warming From a Sea Level Budget Approach

Anny Cazenave[1], Chunxue Yang[2], Marie Bouih[3], Andrea Storto[2], Jianli Chen[4,5,6], William Llovel[7], Karina von Schuckmann[8], and Lancelot Leclercq[1]

[1]Université de Toulouse, LEGOS (CNES/CNRS/IRD/UT3), Toulouse, France, [2]Institute of Marine Science, National Research Council of Italy, Rome, Italy, [3]Magellium, Ramonville St Agne, France, [4]Department of Land Surveying and Geo-Informatics and Research Institute for Land and Space, The Hong Kong Polytechnic University, Hong Kong, China, [5]State Key Laboratory of Climate Resilience for Coastal Cities, The Hong Kong Polytechnic University, Hong Kong, China, [6]The Hong Kong Polytechnic University Shenzhen Research Institute, Shenzhen, China, [7]Laboratoire D'Océanographie Physique et Spatiale (LOPS), Université de Brest, CNRS, Ifremer, IRD, IUEM, Plouzané, France, [8]Mercator Ocean International, Toulouse, France

Abstract Assessments of the global mean sea level (GMSL) budget over the satellite altimetry era (since the early 1990s) have concluded that the GMSL budget is closed within data uncertainties until 2016. However, studies have shown that since then, the sea level budget based on Argo data down to 2,000 m for the thermosteric contribution is no longer closed. Using an ocean reanalysis with no altimetry data assimilation, we show that accounting for deep ocean thermosteric contribution (below 2,000 m, not sampled by Argo) allows the GMSL budget to be almost closed since 2016. The deep ocean contribution over 2005–2022 is estimated to be 0.4 ± 0.15 mm/yr, that is, about 10% of the observed GMSL rise over that period. This represents a substantial increase of the deep ocean contribution to sea level rise, previously estimated on the order of 0.1 mm/yr only over 1980–2010. This finding reveals that deep ocean warming is gaining importance and that ocean heat uptake has now reached several regions below 2,000 m depth, notably the Northwestern Atlantic Ocean and Southern Ocean.

Plain Language Summary Until about 2016, the observed global mean sea level rise was well explained by upper ocean (0–2,000 m) warming, land ice melt and terrestrial water storage change. However, since that date, the budget is no more closed, even after accounting for errors in the observing systems. In this study, we use an ocean model to estimate the deep ocean (below 2,000 m) contribution not yet fully sampled by Argo floats. We find that account of deep ocean warming, in addition to upper ocean warming and ocean mass increase, well explains the global mean sea level rise of the recent years.

1. Introduction

While the global mean surface temperature has been often used in the past to characterize current global warming, in 2018, the World Meteorological Organization (WMO) identified seven global climate indicators to inform on the status of the global climate and its evolution. These include the global mean surface temperature, ocean heat content, Arctic and Antarctic sea ice extent, mass balance of land ice (Greenland and Antarctic ice sheets, world glaciers), ocean acidification (mean ocean pH), atmospheric carbon dioxide concentration and global mean sea level (GMSL). Because the GMSL integrates changes in all compartments of the climate system, that is, the ocean, cryosphere, land hydrosphere and atmosphere, through sea water thermal expansion and land-ocean and atmosphere-ocean water mass exchange, it is one of the best indicators of global climate change. During most of the 20th century, sea level changes at the coast were measured by tide gauges but since the early 1990s, sea level variations are routinely monitored by high-precision altimeter satellites with quasi-global coverage of the oceanic domain, allowing to accurately follow for more than three decades, the GMSL temporal evolution. Over 1993–2025, the GMSL has risen by about 12 cm on a global average (WMO, 2025), but the rate of sea level rise abruptly increased in the early 2010s, from 2.9 ± 0.22 mm/yr over 1993–2011 to 4.1 ± 0.25 mm/yr over 2012–2024 (Leclercq et al., 2026). Abrupt increase in sea level has also been observed at regional scale, in particular along the Southeast United States and Gulf coasts (e.g., Dangendorf et al., 2023; Leclercq et al., 2024; Yin, 2023).

The development of independent observing systems, for example, Argo for measuring ocean temperature and salinity changes down to 2,000 m since the mid-2000s (Riser et al., 2016), and since 2002, the Gravity Recovery

Supervision: Anny Cazenave
Validation: Anny Cazenave, Chunxue Yang, Jianli Chen, William Llovel, Karina von Schuckmann, Lancelot Leclercq
Writing – original draft: Anny Cazenave
Writing – review & editing: Chunxue Yang, Marie Bouih, Andrea Storto, Jianli Chen, William Llovel, Karina von Schuckmann, Lancelot Leclercq

and Climate Experiment (GRACE) space gravimetry missions for measuring mass variations in the cryosphere and hydrosphere (Tapley et al., 2019), has allowed the sea level community to disentangle and quantify the two main contributions to present-day GMSL rise: ocean thermal expansion and ocean mass increase, the latter resulting from ice mass loss from glaciers, Greenland and Antarctica and declining global water storage on land. The availability of these independent observations has led to the production of a large number of scientific publications dedicated to assessing the closure of sea level budget by comparing observed GMSL evolution to the sum of individual thermal and mass contributions (e.g., Chambers et al., 2017; Dieng et al., 2017; Horwath et al., 2022; Nerem et al., 2018; WCRP, 2018).

Assessing closure of the GMSL budget is of utmost importance (e.g., Cazenave & Moreira, 2022). It allows attributing the cause of the observed GMSL acceleration and eventually detecting runaway changes of some components (e.g., Greenland and/or West Antarctica melting), identifying missing contributions not yet quantifiable by the current observing systems (e.g., from the deep ocean below 2,000 m not yet sampled by Argo globally). Another important application of budget closure assessment is cross-calibration of the observing systems and detection of potential instrumental drifts or bias. Validation of climate models developed to project future sea level rise is another important outcome of this approach, since climate models do not directly compute the GMSL but rather the individual contributions and their sum.

Studies considering observations prior to 2016/17 for sea level and components concluded that the GMSL budget was closed within data uncertainties (e.g., Horwath et al., 2022). However recent investigations have shown that beyond that date, the GMSL budget closure is no more observed (Barnoud et al., 2021, 2023a; Chen et al., 2020; Cheng, Pan, et al., 2024, Cheng, Tan, et al., 2024). For example, comparing GRACE-based ocean mass change with altimetry-based sea level corrected for Argo-based thermosteric sea level (with temperature data down to 2,000 m), Chen et al. (2020) found good agreement over 2005–2015 but significant discrepancy between the two time-series since around 2016. These authors attributed this to errors in the data sets (either altimetry, Argo or GRACE). Assessing the sea level budget closure between 2005 and 2020, Barnoud et al. (2021) also found discrepancy between the altimetry-based GMSL and the sum of GRACE-based ocean mass and Argo (2,000 m)-based thermosteric contribution as of early 2016. Part of it was attributed to the erroneous wet tropospheric correction applied to the Jason-3 altimetry mission due to a drift of the onboard radiometer (Barnoud, Picard, et al., 2023; Brown et al., 2023) because the Jason-3 data are used at the end of the GMSL record. But even after correcting for this instrumental error, the GMSL budget remained unclosed beyond 2016 (Barnoud, Pfeffer, et al., 2023). In the latter study, the authors examined also the ocean mass budget over 2005–2020 using different data sets, in order to check whether GRACE and GRACE-Follow On (FO) data used to compute the ocean mass, could be responsible for the non-closure of the GMSL budget (both missions encountered some instrumental problems, from 2016 to the end of the mission in 2017 for GRACE and since its launch in 2018 for GRACE-FO). They concluded that uncertainties of the GRACE/GRACE-FO data set could not explain the budget mis-closure. Cheng, Pan, et al. (2024) and Cheng, Tan, et al. (2024) also report that after ∼2015, the sum of the steric and barystatic (i.e., ocean mass) components is smaller than the observed sea level rise for all ocean temperature products considered in their study (essentially limited to 2,000 m depth). However, using their latest IAPv4 data set that include a number of in situ temperature data from the deep ocean, these authors find reduced discrepancy between the GMSL and sum of components, and suggest stronger ocean warming in the recent years.

In the present study, we re-examine the GMSL budget and show that the apparent non-closure of the GMSL budget since 2016/17 can be explained by the non-accounted deep ocean component. This is done by using the thermosteric component over the full ocean depth estimated by the CIGAR ocean reanalysis (an ensemble mean of 32 members based on different configurations) developed by Storto and Yang (2024).

The study period ranges from January 2005 to December 2022 to cover the Argo and GRACE era.

2. Data

2.1. Altimetry-Based Sea Level

We use the daily 1/4° × 1/4° gridded sea level anomaly data version DT2021 from the Copernicus Climate Change Service (C3S) (https://climate.copernicus.eu). The latitudinal domain covered by the altimetry grids is 66°S–66°N. The data set is further averaged on a monthly basis and corrected for the TOPEX A instrumental drift using the Ablain et al. (2017) correction, and for the Brown et al. (2023) correction for the Jason-3 radiometer drift that impacts the wet troposphere correction. The GMSL data are also corrected for the Glacial Isostatic adjustment (GIA) effect using the ICE6G-D model (Peltier et al., 2018). The GIA effect on the GMSL amounts ∼−0.3 mm/yr. The mean uncertainty in the rate of the global mean sea level is estimated to be ∼0.3 mm/yr (Ablain et al., 2019; Guerou et al., 2023). For the GMSL time series uncertainty, we use the values provided by Prandi et al. (2021), based on realistic estimates of errors affecting the altimetry system.

2.2. In Situ Ocean Temperature Data

The thermosteric data used here are based on an ensemble mean (EM) of five Argo-temperature data sets (0–2,000 m ocean depth): (a) the Scripps Institution of Oceanography (SIO, Wong et al., 2020), (b) the International Pacific Research Center (IPRC), (c) The Japan Agency for Marine Earth Science and Technology (JAMSTEC, Hosoda et al., 2008), (d) EN4 version 2.2 (Good et al., 2013), and (e) In Situ Analysis system (ISAS, Kolodziejczyk et al., 2023).

The global mean thermosteric sea level time series are computed from the gridded temperature data using the Lenapy library (https://github.com/CNES/lenapy) from the Center National d'Études Spatiales (CNES), based on the Gibbs seawater oceanography toolbox of the 2010 Thermodynamic Equation Of Seawater (TEOS-10). The thermosteric data sets are provided at monthly interval on a 1° × 1° grid covering the 0–2,000 m depth range, the period from January 1993 to December 2022, and the latitudes between 66°S and 66°N. To estimate the uncertainty of the ensemble mean of the five Argo products, we consider the dispersion about the mean.

Finally, we also use the IAPv4 global ocean temperature product (Cheng, Pan, et al., 2024) to compute a thermosteric time series at monthly interval over 0–6,000 m depth.

2.3. GRACE-Based Ocean Mass

To estimate the global mean ocean mass change, we use an ensemble mean of the so-called mass concentration (mascon) solutions. For that purpose, 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 Goddard Space Flight Center (GSFC, Loomis et al., 2019) have been considered. These mascon solutions are corrected for the GIA effect using the ICE6G-D model (Peltier et al., 2018), as well as for the geocenter motion using the correction from GRACE Technique Note 13 (Landerer et al., 2019; Sun et al., 2016). The effects of the ocean dynamics and atmospheric loading are restored using the GAD product derived from the Atmosphere-Ocean Dealiasing (AOD1B) models (Dobslaw et al., 2017; Flechtner et al., 2015). To retrieve the ocean mass contribution comparable to the difference between altimetry and Argo, the effect of the mean atmospheric pressure over the ocean is removed using the spatial mean of the GAD product at each month (Chen et al., 2019). The ocean mass component is estimated as the mean of these three gridded ocean mass products, which are given in equivalent water height. As for altimetry and Argo data, only the domain 66°S–66°N is considered. The uncertainty of the GRACE-based global mean ocean mass time series is estimated from the dispersion of the three GRACE products around their mean.

2.4. Global Glacier Mass Balance

For the global glacier mass balance, we considered the gridded glacier mass change data set distributed by the Copernicus Climate Service from 1976 to present (https://doi.org/10.24381/CDS.BA597449). It is based on Dussaillant et al. (2025). The data set consists of global annual glacier mass changes (in Gt) distributed on a global regular grid at 0.5° resolution based on the Fluctuations of Glaciers (FoG) database of the World Glacier Monitoring Service (WGMS). Gridded data from the hydrological year (a period of 12-month from October to September) 1992–1993 to hydrological year 2021–2022 are averaged globally to obtain a global mean glacier time series.

2.5. Greenland and Antarctica Ice Sheet Mass Balance

We use the latest version of the ice sheet cumulative mass balance data from the IMBIE project (Otosaka et al., 2023). This data set provides monthly cumulative mass change and associated uncertainty for the Antarctic and the Greenland ice sheets and their sum. The data are reconciled estimates of mass balance from three independent satellite-based techniques: altimetry, gravimetry and input-output method. As the IMBIE data set ends in 2020, we extend the Greenland and Antarctica ice sheet mass balance time series until end 2022 using GRACE data.

2.6. Land Water Storage

For the land water storage time series, version v2.2e of the WaterGap Hydrological Model (WGHM) developed by Döll et al. (2017) and updated by Mueller-Schmied et al. (2024a) was used. The meteorological forcing of this version is the ERA5 reanalysis of the European Center for Medium-Range Weather Forecast (ECMWF) (Hersbach et al., 2020). The v2.2e version accounts for anthropogenic factors. Uncertainties of the land water storage are derived from the dispersion of different versions of the WGHM model.

2.7. CIGAR Ocean Reanalysis

The Cnr ISMAR Global historicAI Reanalysis (CIGAR) (http://cigar.ismar.cnr.it/) is the ensemble ocean reanalysis system developed by Storto and Yang (2024). It is based on the NEMO ocean model version 4.0.7 (Madec et al., 2017) which includes sea-ice dynamic and thermodynamic model, and an oceanic three-dimensional variational data assimilation covering the period from 1962 to 2022. The ocean model has 1° horizontal resolution, with increase meridional resolution to 1/3° in the Tropics and 75 vertical depth levels with partial steps. CIGAR is forced by the ECMWF ERA5 reanalysis (Hersbach et al., 2020) and assimilates in situ profiles based on UKMO EN4 data sets (Good et al., 2013). Satellite altimetry data are not assimilated in the system. CIGAR is a 32-member reanalysis based on different configurations, for example, initial conditions, air-sea flux formation, atmospheric forcing, sea surface temperature relaxation, observation bias correction, that allows us to estimate the uncertainty of the reanalysis system. In this study, we have used the ensemble mean of the 32 members to provide the thermosteric sea level. The CIGAR thermosteric grids are further averaged over $3° \times 3°$ grids. To compute the CIGAR-based mean thermosteric sea level time series a mask is applied (it is shown in Figure S1 of Supporting Information S1), and only data between 66°S and 66°N latitudes are considered (for consistency with the altimetry and GRACE data). The 1-sigma uncertainty of the global mean CIGAR-based thermosteric sea level is derived from the dispersion of the 32 members around their mean. Storto and Yang (2024) have extensively validated the uncertainty coming from the ensemble against independent estimates (from the Global Climate Observing System/GCOS comparison, von Schuckmann et al., 2023), resulting in close values and temporal variations of the uncertainty, proving that the ensemble generation method is well posed.

3. Results

Figure 1 shows the altimetry-based GMSL from January 1993 to December 2022 together with the mass and thermal components and their sum. The residual time series (satellite altimetry-based GMSL minus sum of components) is also shown. In Figure 1, individual mass contributions to the global mean ocean mass and their sum are shown, as well as the GRACE-based global mean ocean mass as of 2004. In both cases, the global mean thermosteric sea level is based on in situ ocean temperature data down to 2,000 m.

As previously reported by Barnoud et al. (2021) for the period 2005–2020, the budget non-closure, that starts around 2016, extends here to the end of 2022. The residual curves in Figure 1 clearly show significant departure from zero beyond 2016, either when computing individual mass components (i.e., glaciers, ice sheets, and terrestrial water storage) or using GRACE data to estimate the global mean ocean mass. The large residuals at the beginning of the record are due to the uncertainty of the Topex A drift correction applied to the altimetry-based sea level data between 1993 and 1998, and are not of concern here.

The residual trends over 2004–2022 amount to 0.5 ± 0.2 mm/yr and 0.55 ± 0.23 mm/yr for the GRACE-based ocean mass and individual mass components cases, respectively. Thus, the two approaches for estimating the global mean ocean mass contribution to the GMSL provide consistent results.

The fact that considering either GRACE-based global mean ocean mass or individual mass component estimated with different observing systems leads to similar results allows us to exclude GRACE data uncertainties as the cause of the budget non-closure. Moreover, the radiometer drift affecting the altimetry data of the Jason-3 mission as of 2016 has been estimated with independent data sets and further corrected (Barnoud, Picard, et al., 2023; Brown et al., 2023). Hence, this also eliminates the latter factor as the cause of the non-closure of GMSL budget. While we cannot totally exclude still unknown errors in the different observing systems considered to assess the

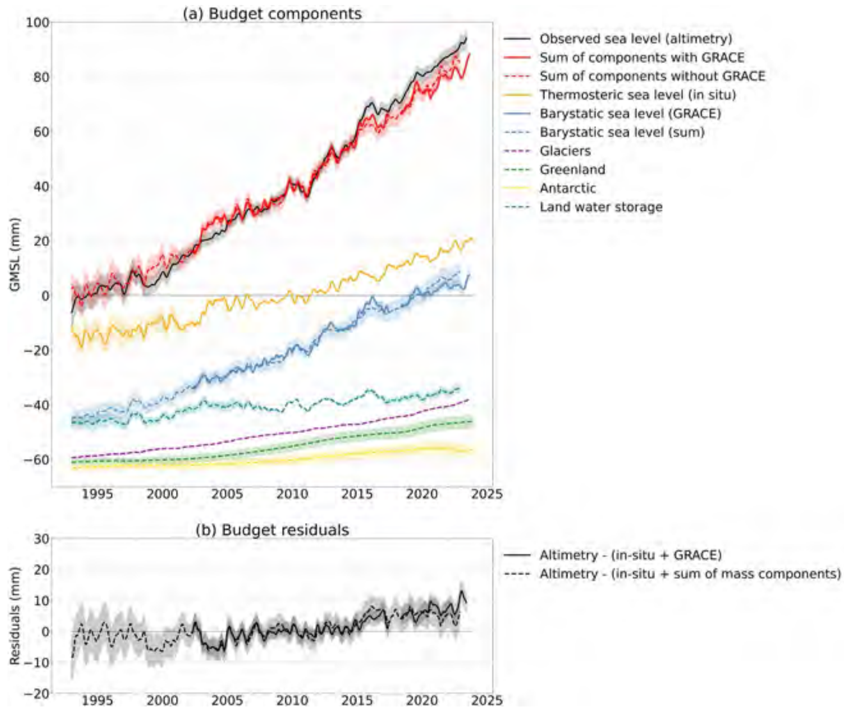

Figure 1. GMSL budget over January 1993 to December 2022 with the thermosteric component (data down to 2,000 m; yellow curve), the individual mass contributions (glaciers, Greenland ice sheet, Antarctica ice sheet, and terrestrial water storage; colored dashed curves)), and GRACE-based ocean mass (called barystatic sea level) since 2004 (blue solid curve). The red curves represent the sum of the thermosteric sea level and mass components (with GRACE: solid curve; sum of mass components: dashed curve). The bottom curves show the residuals (GMSL minus sum of components for the two cases: individual mass components (black dashed curve) and GRACE (black solid black)). Shaded areas correspond to 1-sigma uncertainties. A 3-month smoothing is applied to all time series.

GMSL budget, quasi closure of the budget until 2015 leads us to explore another credible possibility: the emergence of a so far unaccounted contribution to the budget. Permafrost melting and deep ocean warming are two possible candidates. Lack of information on permafrost melting leads us to focus here on the thermosteric contribution of the deep ocean below 2,000 m not sampled by Argo (note that in terms of global mean, the halosteric contribution to the GMSL is negligible, Gregory et al., 2019; note also that the Arctic Ocean is excluded from our budget analysis since all gridded data sets are averaged between 66°S and 66°N latitudes).

To estimate the deep ocean thermosteric contribution to the GMSL, we use an ocean reanalysis. We consider here an ensemble mean of 32 member realizations of the CIGAR reanalysis developed by Storto and Yang (2024). The CIGAR reanalysis does not assimilate altimetry data thus any influence of the altimetry-based GMSL on the deep ocean contribution may be excluded.

In the following we examine the GMSL budget closure using the CIGAR thermosteric component in two configurations: (a) model-based temperature data integrated over the 0–2,000 m ocean depth, and (b) model-based temperature data integrated over the full ocean depth. In both cases, we use the same altimetry-based GMSL and GRACE-based ocean mass (as for Figure 1).

Figures 2 and 3 show the altimetry-based GMSL over 2005–2022 together with the mass and thermal components and their sum. The residual time series (observed GMSL minus sum of components) are also shown. In Figure 2, the CIGAR thermosteric component is computed over the 0–2,000 m ocean depth layer, while in Figure 3, it corresponds to the full ocean depth (0–6,000 m), that is, including the deep ocean contribution.

From Figure 2, we note that when using the CIGAR-based thermosteric component for the upper 0–2,000 m depth layer, the budget is not closed since about 2016, like when using Argo data down to 2,000 m. The mean trend of the residual curve amounts to 0.46 ± 0.22 mm/yr over 2005–2022, a value comparable to the residual trend based

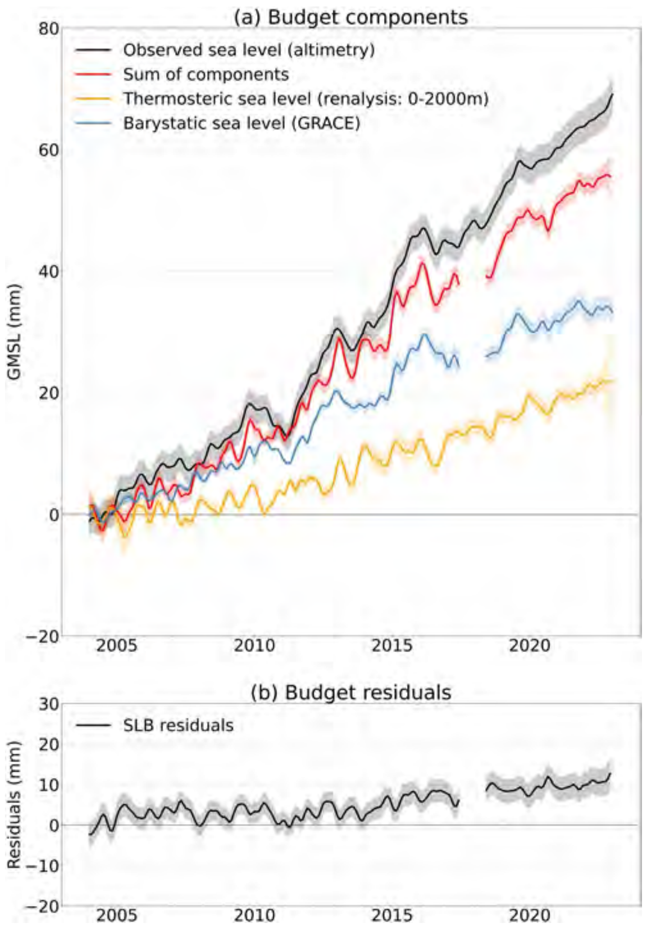

Figure 2. Sea level budget over January 2005–December 2022. The upper panel shows the altimetry-based GMSL (black curve), GRACE-based ocean mass component (called barystatic sea level, blue curve), CIGAR thermosteric component (0–2,000 m depth, yellow curve) and the sum of mass and thermal component (red curve). The bottom panel shows the residuals. Shaded areas represent the data uncertainties. A 3-month smoothing is applied to all time series.

on the use of Argo data down to 2000 m. However, the residual curve shown in Figure 2 does not show any steep change of the residuals beyond 2016 (unlike Figure 1) but rather a smooth positive trend since about 2014/2015.

In Figure 3 where the CIGAR thermosteric full depth is used, quasi-closure of the sea level budget is observed. On average, residuals are not departing from zero over 2002–2017. Slightly larger averaged residuals are noted over 2018–2022. But the mean residual trend over 2005–2022 (of 0.01 ± 0.22 mm/yr) is not significant.

A similar result was obtained by Barnoud, Pfeffer, et al. (2023) using the thermosteric full depth over 2005–2020 from the ORAS5 reanalysis (Copernicus Climate Change Service, 2021; Zuo et al., 2019). These authors assessed the ocean mass budget by comparing the GRACE-based ocean mass to the GMSL corrected for the ORAS5 thermosteric sea level full depth (0–6,000 m). They showed that the ocean mass budget is closed within data uncertainties, unlike when using Argo products over the 0–2,000 m depth range. The GMSL budget using the same data as in Barnoud, Pfeffer, et al. (2023) over January 2005–December 2020 is shown in Figure S2 of Supporting Information S1. Although the ORAS5 assimilates altimetry data unlike the CIGAR reanalysis, quasi closure of the sea level budget is also observed when the ORAS5 thermosteric full depth is accounted for. This agrees well with our result based on the CIGAR thermosteric full depth (Figure 3).

4. Validation of the CIGAR Thermosteric Sea Level

In order to further check the robustness of the CIGAR-based thermosteric sea level, we compared it with observed (mostly Argo-based) thermosteric sea level for the 0–2,000 m ocean depth. This is shown in Figure 4 where the CIGAR-based thermosteric (0–2,000 m) time series is superimposed to the Argo-based (ensemble mean of five Argo products, 0–2,000 m) and the IAPv4 (0–2,000 m) thermosteric time series over 2005–2022. The difference curves (residuals) are also shown. The linear trends of each time series (given in Table 1) are all close to 1.3 mm/yr. While the difference curves display high frequency signal, no significant residual trend (~0.1 mm/yr) is detected. Thus, the CIGAR-based thermosteric sea level (0–2,000 m) compares well with Argo data over the 0–2,000 m depth range.

We further compared the CIGAR full depth (0–6,000 m) thermosteric sea level to the altimetry-based GMSL corrected for the GRACE-based ocean mass contribution (Figure 5; the data sets described in Section 2 are used). Indeed, as discussed in Marti et al. (2022), the global mean sea level corrected for the ocean mass is supposed to represent the total (full depth) thermosteric sea level contribution. These authors applied this approach to estimate the ocean heat content from which the Earth energy imbalance was deduced.

The estimated linear trends computed over 2005–2022 are similar, both amounting 1.7 mm/yr (Table 1). We note that the two curves agree well beyond 2016. Figure 5 also superimposes the IAPv4 thermosteric (0–6,000 m) time series. Its trend over 2005–2022 amounts to 1.6 mm/yr, thus agree well with the CIGAR full depth and ocean mass corrected GMSL trends within their respective uncertainties (see Table 1).

From Table 1 and Figure 4, we conclude that the CIGAR reanalysis properly captures the upper ocean warming as observed by Argo. Besides, the good agreement noted between the trends of the CIGAR thermosteric full depth with the GMSL corrected for the ocean mass term and IAPv4 (0–6,000 m) thermosteric time series (Figure 5) also suggests that CIGAR correctly reproduces the deep ocean warming, at least in terms of global mean.

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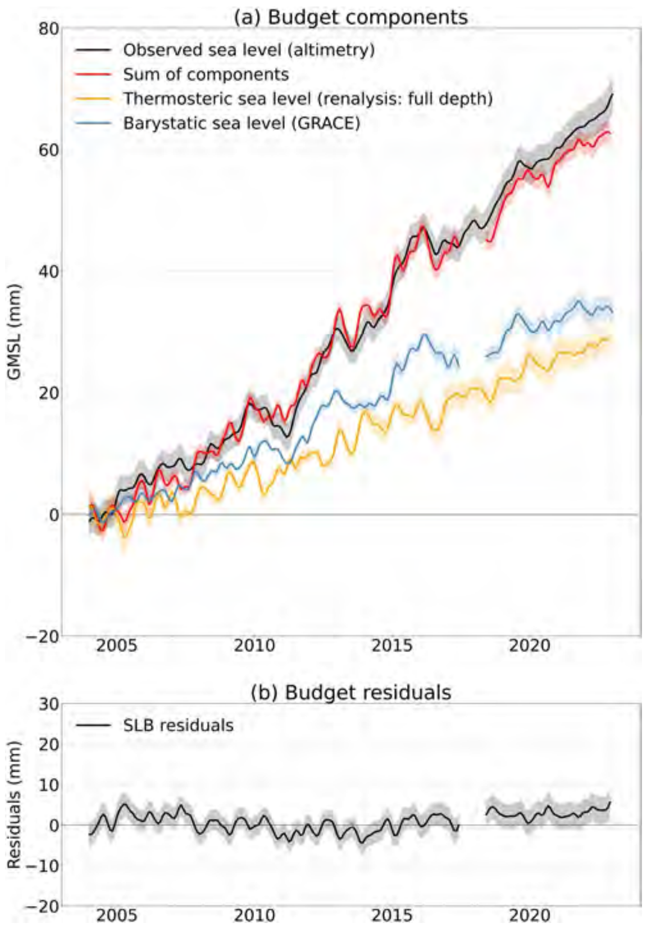

Figure 3. Sea level budget over January 2005–December 2022. The upper panel shows the altimetry-based GMSL (black curve), GRACE-based ocean mass component (called barystatic sea level, blue curve), CIGAR thermosteric component (full depth, 0–6,000 m, yellow curve) and the sum of mass and thermal component (red curve). The bottom panel shows the residuals. Shaded areas represent the data uncertainties. A 3-month smoothing is applied to all time series.

5. Deep and Upper Ocean Warming

According to Table 1, the deep ocean contribution to the GMSL rise of the 2005–2022 time span, based on the difference between CIGAR thermosteric full depth (0–6,000 m) and CIGAR (0–2,000 m) is estimated to 0.4 ± 0.15 mm/yr. Such a value compares well the residual trend of the observations-based GMSL budget when using either CIGAR or Argo-based thermosteric sea level over 0–2,000 m (estimated to 0.46 ± 0.2 mm/yr over 2005–2022, Figure 2).

Analyzing repeated in situ hydrographic sections from the 1980s to 2010, Purkey and Johnson (2010) found significant warming of the deep ocean (below 1,000 m) over that period in most ocean basins, especially in the Southern Ocean. Their estimated deep ocean contribution to the GMSL rise is of the order of 0.1 mm/yr. Our approach based on the sea level budget and use of the CIGAR reanalysis suggests a deep ocean contribution of 0.4 ± 0.15 mm/yr to the GMSL rise since 2005, hence a significant increase compared to the 1980–2010 time span.

Increased ocean warming may explain another intriguing phenomenon (Leclercq et al., 2026). In effect, if we consider the mean Pacific sea level time series over the whole altimetry era (since 1993) and remove a long-term linear trend supposedly accounting for part of the mean ocean mass and thermal expansion increase (note that removing a linear trend does not mean that the long-term sea level trend is purely linear since decadal changes due to various sources likely superimpose to this linear trend), the detrended Pacific sea level presents decadal fluctuations that appear well correlated with the Pacific Decadal Oscillation (PDO) until 2016/17 (correlation of 0.7). A similar observation is the made for the Atlantic Ocean sea level, even though the correlation (estimated to 0.45) with the PDO is lower than for the Pacific sea level. The linearly detrended Pacific and Atlantic mean sea levels over 1993–2023, with the PDO superimposed are shown in Figure 6 (the domains considered for averaging the sea level data over the Pacific and Atlantic oceans are shown in Figure S3 of Supporting Information S1). Figure 6 shows that until 2016/17, the decadal variations of the Pacific sea level were mostly driven by PDO. However, since then, the close consistency between the two curves breaks down: The Pacific sea level goes up and continues to increase beyond 2016/17 while the PDO goes down. A similar observation holds for the Atlantic Ocean.

The departure of the linearly detrended Pacific and Atlantic mean sea level from the PDO decadal variability as of 2016/17 suggests an accelerated sea level rise beyond that date. An increased thermosteric contribution due to increased upper and deep ocean warming could well explain this observation.

To explore this further, we consider regional deep ocean (2,000 m to bottom) thermal expansion from CIGAR. Figure 7 shows the CIGAR-based deep ocean thermosteric differences between two successive 7-year long periods: 2016–2022 minus 2009–2015.

Positive signal is observed in the Northwest Atlantic, Caribbean seas, Mediterranean Sea and in the Southern Ocean around Antarctica. In some places, deep ocean warming increase, observed over 2016–2022 versus the previous seven years, coincides with regions of deep water formation (Labrador Sea south of Greenland; Gulf of Lion, south Adriatic Sea and Levantine Basin in the Mediterranean Sea; Weddell and Ross seas around Antarctica). Moreover, the positive signal found in the Northwest Atlantic Ocean coincides with the location of the lower branch of the Atlantic Meridional Overturning Circulation (AMOC) (Rahmstorf, 2024) which brings deep ocean waters equatorward. Enhanced local subduction of intermediate warm and salty waters in the Northwestern Atlantic Ocean could contribute to the deep ocean warming therein.

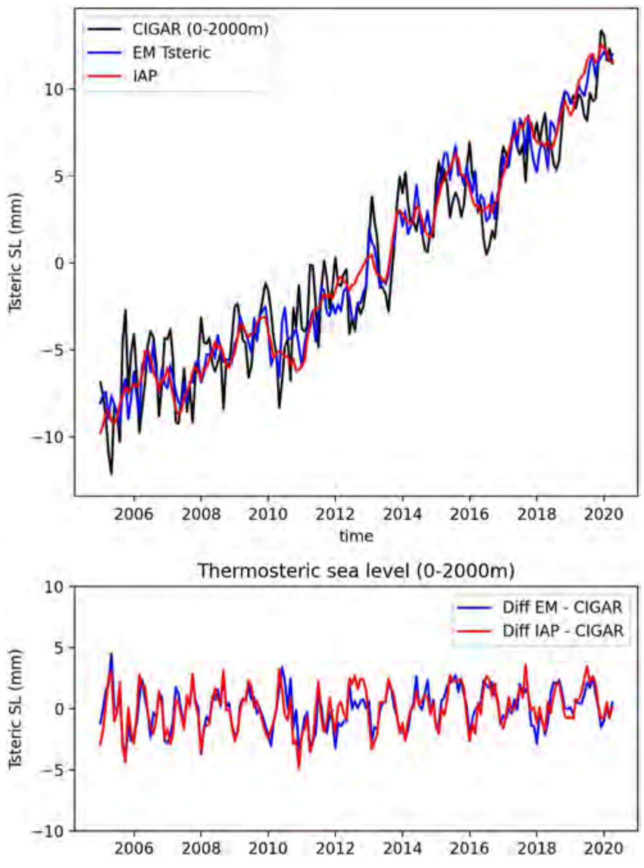

Figure 4. Upper panel: thermosteric (0–2,000 m) time series over 2005–2022 from CIGAR (black), ensemble mean (EM) of five Argo products (blue) and IAPv4 (red). The data and model uncertainties are not shown for clarity. Lower panel: Thermosteric differences EM 0–2,000 m minus CIGAR (blue) and IAPv4 0–2,000 m minus CIGAR (red).

However, according to Figure 7, the Pacific Ocean does not show any deep warming below 2,000 m, except in a limited region east of Japan. This would suggest that the departure of the decadal Pacific sea level from the PDO as of 2016/17 does not result from deep ocean warming, but more likely from an increased warming of the upper ocean. To check on this, we computed the CIGAR-based thermosteric differences between the two 7-year long periods: 2016–2022 minus 2009–2015 for the 0–2,000 m depth layer (Figure 8).

According to the CIGAR reanalysis (Figure 8), increased warming affected the upper Pacific Ocean during the 2016–2022 time span compared to the previous seven years (2009–2015). This may explain the observed accelerated rise of the Pacific sea level with respect to the mean linear trend of the 1993–2024 time span. If we except the strong signal associated with the western boundary currents (Gulf Stream and Kuroshio), significant warming of the upper Atlantic Ocean is also observed, in particular in the mid latitudes of the northwestern Atlantic and in almost the whole south Atlantic.

To check the robustness of the CIGAR-based regional upper (0–2,000 m) and deep (2,000 m-bottom) ocean warming signal, we reproduced Figures 7 and 8 using the IPAv4 data set. The corresponding maps (regional thermosteric sea level differences between two periods: 2016–2022 minus 2009–2015) are shown in Figure 9.

Comparing Figure 9 upper map (IAPv4 data, 0–2,000 m) with Figure 8 (CIGAR reanalysis, 0–2,000 m) shows very good agreement, with similar thermosteric patterns in all three main oceans. Figure 9 lower map (IAPv4, 2,000 m-bottom) displays similar characteristics as Figure 7 (CIGAR reanalysis, 2,000 m-bottom), i.e., some positive signal in the North Atlantic and in the southern Ocean south of 30°S, and almost no signal over the whole Pacific Ocean. For the 0–2,000 m upper ocean, IAPv4 and CIGAR agree also in terms of amplitudes. On the other hand, in the deep ocean, the IAPv4 signal is much smaller. As explained in Cheng, Pan, et al. (2024) and Cheng, Tan, et al. (2024), deep ocean temperature data are indeed very sparse both in time and space. They are mostly based on a few hydrographic lines (e.g., Katsumata et al., 2022), completed since only very recently by localized Deep Argo data (since 2014 in the western Pacific and since 2017 at some locations of the western Atlantic; see current Deep Argo coverage: https://www.ocean-ops.org/share/Argo/Maps/deep-models_.png, and recent published articles: Deybruyeres et al., 2025; Lele & Purkey, 2024; Zilberman et al., 2025). Spatial averaging of the limited in situ measurements will obviously provide lower signal than in the CIGAR reanalysis, where the numerical ocean model dynamically redistributes water masses even in absence of observations.

Table 1
Linear Trends and Associated Uncertainties (1-Sigma) Computed Over 2005–2022 for Different Thermosteric Sea Level Time Series

Thermosteric sea level time series	Linear trends (mm/yr) 2005–2022
CIGAR thermosteric (0–2,000 m)	1.3 ± 0.1
Ensemble mean (five Argo products) (0–2,000 m)	1.3 ± 0.15
IAPv4 (0–2,000 m)	1.5 ± 0.1
CIGAR thermosteric Full depth (0–6,000 m)	1.7 ± 0.10
GMSL corrected for the GRACE-based ocean mass	1.7 ± 0.25
IAPv4 thermosteric (0–6,000 m)	1.6 ± 0.1

Note. Except for the ocean mass corrected GMSL, the trend uncertainties are based on the least squares fit.

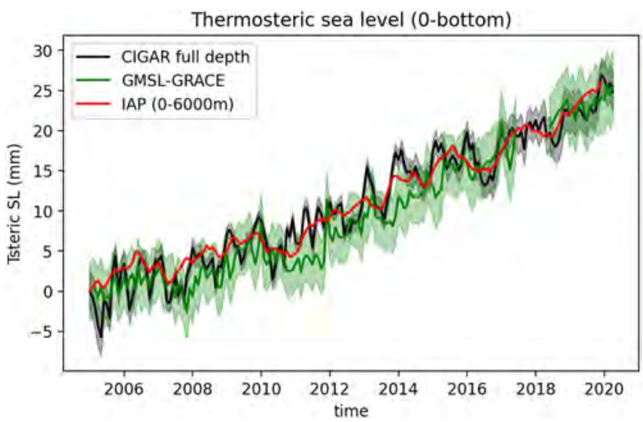

Figure 5. CIGAR thermosteric full depth (black) and altimetry-based GMSL corrected for the GRACE-based ocean mass (green). Shaded areas represent the data uncertainties. The IAPv4 thermosteric (0–6,000 m) time series is superimposed (red).

The lack of correlation between the detrended Pacific and Atlantic sea levels and PDO as of 2016/17 (Figure 6) may be understood as the result of increased upper ocean warming for the Pacific (Figure 8) and full depth warming for the Atlantic (Figures 7 and 8). To investigate this further, Figure 10 superimposes the non-detrended mean Pacific and mean Atlantic sea levels over 2005–2020 with the non-detrended CIGAR thermosteric time series for 0–6,000 m and 2,000–6,000 m. For the Pacific, a steep increase is noted in 2016 in the ocean thermosteric component, likely due to the upper ocean since no similar signal is seen in the deep ocean. This supports what is shown in Figure 8, that is, an increased warming contribution from the upper ocean as of 2016/17. It is worth noting that Cluett et al. (2025) reported that around 2015, the North Pacific sea surface temperature departed from its classical PDO expression, suggesting additional warming in this basin. Besides, Klavans et al. (2025) suggested that the recent decadal PDO index variations are largely driven by anthropogenic forcing rather than internal climate variability. Thus the observed correlation/decorrelation between Pacific sea level and PDO reported in our study does not lead to simple interpretation and a detailed attribution study remains to be conducted. For the Atlantic Ocean, Figure 10 shows a steep increase around the end 2016 in both the altimetry-based sea level and full depth thermosteric sea level, due to a combination of upper and deep ocean warming. We note a much larger contribution of deep ocean warming in the Atlantic Ocean compared to the Pacific Ocean (in agreement with Figure 7).

6. Discussion

The ocean is currently storing more than 90% of the heat excess accumulating in the climate system in response to greenhouse gas emissions (von Schuckmann et al., 2020, 2023). This heat is transported by ocean currents from the surface to depth and across the different oceans. Both large-scale currents and mesoscale eddies play a role in this transport (Wang et al., 2024). In spite of the still incomplete coverage of in situ data from hydrographic profiles and Deep Argo floats, a number of recent studies have quantified the amount of heat having reached the deep ocean (below 2,000 m) and how it is distributed regionally (Cheng, Pan, et al., 2024; Cheng, Tan, et al., 2024; Johnson and Purkey, 2024; Zhang et al., 2025). Using in situ temperature data from various sources, Cheng, Pan, et al. (2024) and Cheng, Tan, et al. (2024) report significant regionally averaged deep (2,000–6,000 m) ocean warming over the past three decades, with some acceleration in the recent years. Using Deep Argo temperature data and ship-based CTD (Conductivity-Temperature-Depth) instrumental data from the mid-1980s to the mid-2010s, Johnson and Purkey (2024) found widespread warming of the deep Southern Ocean south of 50°S, especially in regions of Antarctic Bottom Water formation. Significant warming was also reported south of Greenland and in the western subpolar Atlantic. Zhang et al. (2025) also reported increased ocean heat uptake in the deep ocean, especially in the Southern Ocean and Atlantic, using in situ hydrographic sections over January 1992 to December 2015 time span. However, when they compared in situ data with model-based estimates derived from the ECCO ocean state model (ECCO Consortium et al., 2021), they found some discrepancies between data and model that they attributed to the model.

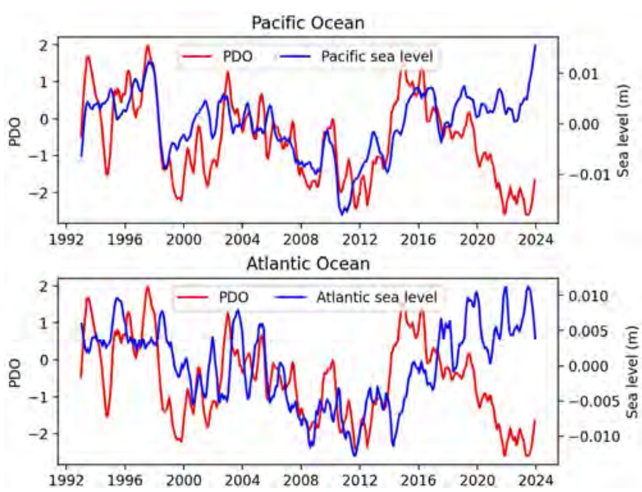

Figure 6. Time series of linearly detrended altimetry-based sea level averaged over the Pacific and Atlantic oceans (blue curves) and PDO (red curve) over 1993–2023. A 5-month running averaging is applied to all time series.

Enhanced deep ocean warming (>2,000 m) observed since mid-2010s in the western North Atlantic has been recently linked to shifts in ocean circulation and reduced deep-water formation, both increasing heat content at depth. In particular, a recent shift in the Atlantic overturning/gyre circulation has enhanced the advection of warm, salty subtropical waters into the deep subpolar North Atlantic (Desbruyères et al., 2017), while a weakening of deep convection/ventilation (e.g., in the Labrador Sea after 2016) has allowed existing deep waters to warm and expand (e.g., Clement et al., 2023;

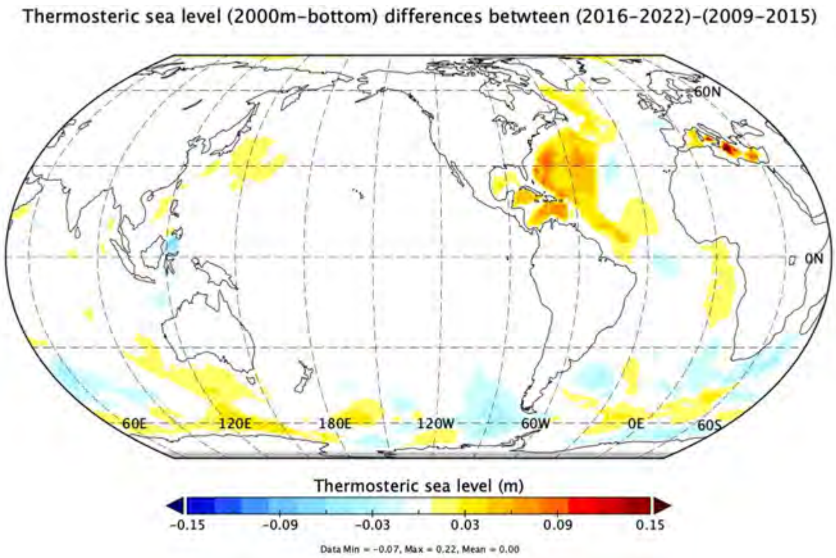

Figure 7. Regional differences in CIGAR-based thermosteric sea level (2,000 m to bottom) between two seven-year-long time spans: 2016–2022 minus 2009–2015. The scale is in m.

Yashayaev, 2024), all superimposed on a long-term anthropogenic warming trend in abyssal waters (Purkey & Johnson, 2010) and the strong increase in the North Atlantic Oscillation since the early 2010s (Chafik et al., 2023).

Concerning the Southern Ocean, several recent studies have argued that the abyssal Antarctic warming first described by Purkey and Johnson (2010) is a fingerprint of a slowdown in the Southern Ocean overturning cell (e.g., Gunn et al., 2023; Li et al., 2023). A slowdown in the lower cell overturning rate leaves the deepest waters off Antarctica both warmer and less oxygenated, with a deflation of the Antarctic Bottom Water layer (see also Rintoul et al., 2025). The above studies based on in situ measurements are highly promising. However, considering that current sampling of the deep ocean is still very limited in space and time, other approaches are worth to be considered. Previous studies based on the GMSL budget closure approach concluded that deep ocean warming was undetectable considering the data uncertainties (Dieng et al., 2015; Frederikse et al., 2020; Llovel

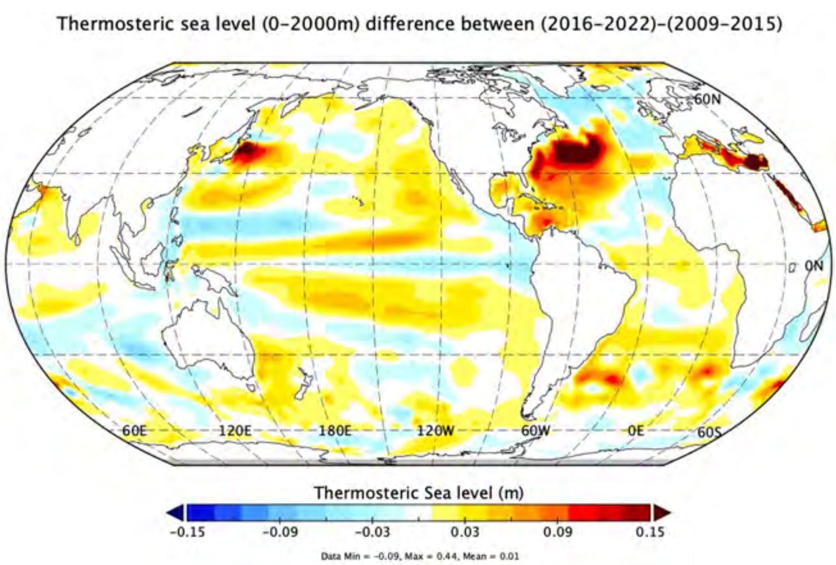

Figure 8. Regional differences in CIGAR-based thermosteric sea level (0–2,000 m) between two seven-year-long time spans: 2016–2022 minus 2009–2015. The scale is in m.

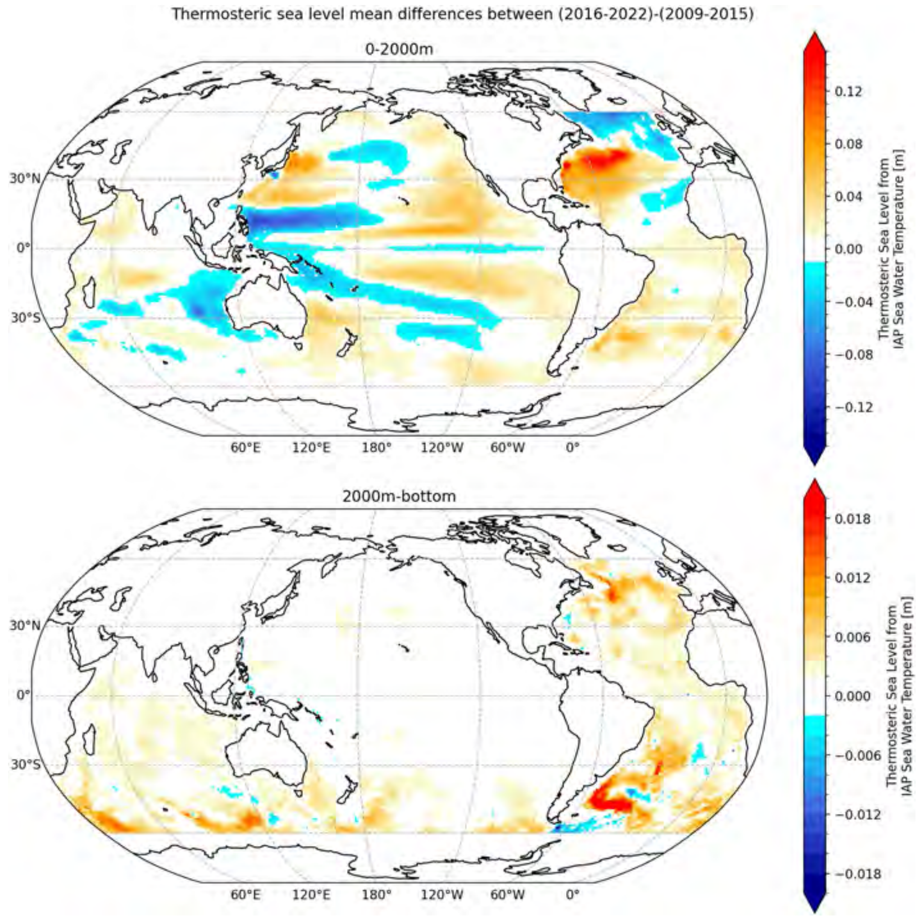

Figure 9. Regional differences in IAPv4-based thermosteric sea level (0–2,000 m, upper map and 2,000 m-bottom, lower map) between two seven-year-long time spans: 2016–2022 minus 2009–2015. The scale is in m.

et al., 2014). In effect, observed closure of the sea level budget until 2015/16 using Argo data down to 2,000 m confirmed the negligible contribution of deep ocean warming to the GMSL until that date.

Yang et al. (2021) indirectly investigated deep ocean warming over the 2005–2015 period, and its regional distribution, by analyzing gridded altimetry-based sea level data corrected for Argo-based steric sea level down to 2,000 m and GRACE-based ocean mass redistribution. They reported significant warming of the deep ocean in middle-east Indian Ocean, north and southeast Pacific and northeast Atlantic, and cooling in the northwest Atlantic and southern oceans over this time span. However, this study does not inform on deep ocean warming beyond 2015. Assessing the regional sea level budget closure over 2004–2022, using altimetry, Argo down to 2,000 m and GRACE data for the GMSL and its components, Bouih et al. (2025) found significant residuals in the North Atlantic region, attributed by the authors to the anomalous regional halosteric component affected by Argo-based salinity measurement errors since 2015 (Barnoud et al., 2021). However, we cannot exclude that part of the North Atlantic residuals comes from non-account of the deep ocean thermosteric sea level.

In the present study, we have shown that the non-closure of the GMSL budget beyond 2016 is possibly due to the emerging contribution of the deep ocean warming signal. The use of ocean reanalyzes to estimate the total (i.e., vertically integrated from surface to bottom) thermosteric component has allowed us to close the sea level budget beyond 2016/17. A deep ocean contribution of 0.4 ± 0.15 mm/yr to the GMSL rise was found for the 2005–2022 time span.

Departure as of 2016/17 of the decadal variations of the mean Pacific and Atlantic sea level from the PDO implies the influence of another climate-related contribution, either due to internal climate variability or driven by external forcing. Results based on the CIGAR thermosteric sea level suggest that the recent (since 2016) mean

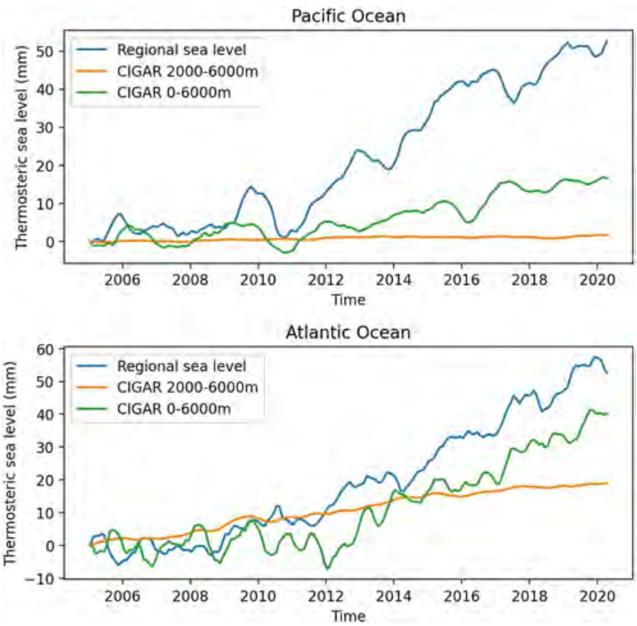

Figure 10. Basin-averaged altimetry-based sea level (in mm) over 2004–2020 (blue curve) with the CIGAR-based 0–6,000 m thermosteric sea level (green curve) and CIGAR-based deep ocean thermosteric sea level (orange curve). Upper panel: Pacific Ocean. Lower Panel: Atlantic Ocean.

Pacific sea level increase does not come from the deep ocean but rather from the upper 0–2,000 m ocean, while for the Atlantic, it is likely that warming of the whole ocean column has caused sea level rise to accelerate in the recent years. This definitely needs further investigation in order to discriminate between internal climate variability and external forcing.

Using CMIP5 simulations, Silvy et al. (2020) showed that the anthropogenic warming signal in deep waters of the subpolar North Atlantic first rose consistently above natural variability in the early 2010s, indicating the start of detectable deep ocean climate change in that basin. Recent studies of the Earth energy imbalance (EEI) based on top of the atmosphere radiative flux measurements (e.g., by the Clouds and the Earth's Radiant Energy System—CERES-, Loeb et al., 2018) report significant discrepancy with the EEI based on the upper ocean (0–2,000 m) ocean heat content, especially since the mid-2010s, calling for a new contribution from the deep ocean (Storto et al., 2022). This aligns well with our finding based on the sea level budget.

As a final note, it is worth noting that our conclusions depend on the CIGAR ocean reanalysis. Previous literature (e.g., Cheng et al., 2025; Hakuba et al., 2024; Pan et al., 2026; Prigent et al., 2025; Storto & Yang, 2024) has shown that CIGAR well reproduces the global and Atlantic, upper ocean or full-column, warming compared to independent data sets. Storto and Yang (2024) extensively validated the warming signal against independent data sets (geodetic approach or Top of the Atmosphere/TOA-derived ocean heat content) and assessed the robustness of the reanalyzed signal with respect to partial withholding of observations or reanalysis configuration. Additionally, the recent literature based on satellite data (e.g., Chafik et al., 2023; Meyssignac et al., 2024) confirms that the western North Atlantic is a recent hotspot of warming, due to concurrent factors like weakening of deep convection, shift of North Atlantic gyre circulation, and other factors.

Moreover, in the present study, we have provided independent validation of the global mean CIGAR-based thermosteric sea level, both for the 0–2,000 m upper ocean and 0–6,000 m depth layer, comparing with four independent data sets, leading to very good agreement in terms of trend. In addition, the regional thermosteric differences between the two periods 2016–2022 minus 2009–2015 using CIGAR on one hand and the in situ data-based IAPv4 product on the other hand compare well, at least in terms of patterns. Our study should be considered as a first attempt to demonstrate the significant role of deep ocean warming for closing the recent years GMSL budget. As more Deep Argo temperature measurements become available, it will be possible to provide direct observational evidence of the deep ocean heat uptake and of its spatio-temporal evolution. Conducting the three independent approaches (sea level budget approach, analysis of the EEI and direct Deep Argo-based in situ measurements) should robustly inform on the recent emergence of deep ocean warming. The next step will be to determine whether the recent deep ocean change is due to internal climate variability, forced anthropogenic response or a combination of both. Such a mechanistic analysis (beyond the scope of the present study) could be conducted using CMIP-type coupled climate models. In addition, the specific physical processes behind deep ocean warming found in this study with the CIGAR reanalysis should be addressed in future investigations, especially the respective contribution of ocean circulation, ventilation processes (deep water formation) and surface atmospheric forcing.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

All data to support the analysis are publicly available and can be accessed from the following sources.

The DT2021 gridded altimetry data set is available at Copernicus Climate Change Service, Climate Data Store (2018).

The Argo-based temperature data used to compute the thermosteric time series come from different sources: (a) SIO, data available from https://argo.ucsd.edu/data/argo-data-products, (b) IPRC, data available from https://apdrc.soest.hawaii.edu/projects/Argo/, (c) JAMSTEC, data available from http://www.jamstec.go.jp/ARGO/J_ARGOe.html., (d) EN4, data available from https://www.metoffice.gov.uk/hadobs/en4/, (e) ISAS, data available at Kolodziejczyk et al. (2023), (6) IAPv4, data available at Cheng, Tan, et al. (2024). The corresponding thermosteric time series are available from https://github.com/CNES/lenapy.

The GRACE, GRACE FO mascon data are available from Save et al. (2016) for CSR (http://www2.csr.utexas.edu/grace), Watkins et al. (2015) for JPL (http://grace.jpl.nasa.gov/) and Loomis et al. (2019) for GSFC (https://earth.gsfc.nasa.gov/geo/data/grace-mascons).

The glacier mass balance data are available at Dussaillant et al. (2024).

The IMBIE ice sheet mass balance data are available at Shepherd et al. (2021).

The land water storage data are available at Mueller-Schmied et al. (2024b).

The PDO time series are available from the NOAA web site (https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat).

Description of the CIGAR data set, instructions, and data sets are available through the website https://cigar.ismar.cnr.it.

Acknowledgments
We thank three anonymous reviewers whose comments helped us to improve our manuscript. This research was carried out under a programme of and funded by the European Space Agency (ESA) Climate Change Initiative (CCI), within the project entitled "Sea level budget closure CCI+ (SLBC_CCI+)" (contract number 4000140620/23/IBN). This study is also partly funded by the ESA Climate Change Initiative Coastal Sea Level project (https://climate.esa.int/en/projects/sea-level). LL is supported by the latter project (Grant 765 4000126561/19/I-NB). Part of this work was also performed in the context of the ERC Synergy GRACEFUL project (ERC Synergy Grant 855677). JC was supported by the NSFC Major Programme (42394132), Hong Kong RGC Collaborative Research Fund (C5013-23G) and the State Key Laboratory of Climate Resilience for Coastal Cities at the Hong Kong Polytechnic University. WL is supported by the OST/ST "Global and Regional/coastal sEa level chAnge over the enTire altimetric period" project (GREAT).

References

Ablain, M., Jugier, R., Zawadki, L., & Taburet, N. (2017). The TOPEXA drift and impacts on GMSL time series. *AVISO Website, user_upload/tx_ausyclsseminar/files/Poster_OSTST17_GMSL_Drift_TOPEX-A.pdf*. https://meetings.aviso.altimetry.fr/fileadmin/

Ablain, M., Meyssignac, B., Zawadzki, L., Jugier, R., Ribes, 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

Barnoud, A., Pfeffer, J., Cazenave, A., Fraudeau, R., Rousseau, V., & Ablain, M. (2023). Revisiting the global mean ocean mass budget over 2005–2020. *Ocean Science*, *19*(2), 321–334. https://doi.org/10.5194/os-19-321-2023

Barnoud, A., Pfeffer, J., Guérou, A., Frery, M., Siméon, M., Cazenave, A., et al. (2021). Contributions of altimetry and Argo to non-closure of the global mean sea level budget since 2016. *Geophysical Research Letters*, *48*(14), e2021GL092824. https://doi.org/10.1029/2021GL092824

Barnoud, A., Picard, B., Meyssignac, B., Marti, F., Ablain, M., & Roca, R. (2023). Reducing the uncertainty in the satellite altimetry estimates of global mean sea level trends using highly stable water vapor climate data records. *Journal of Geophysical Research: Oceans*, *128*(3), e2022JC019378. https://doi.org/10.1029/2022JC019378

Bouih, M., Barnoud, A., Yang, C., Storto, A., Blazquez, A., Llovel, W., et al. (2025). Regional sea level budget over 2004–2022. *Ocean Science*, *21*(4), 1425–1440. https://doi.org/10.5194/os-21-1425-2025

Brown, S., Willis, J., & Fournier, S. (2023). *Jason-3 wet path delay correction*. Ver. F. PO.DAAC, CA. https://doi.org/10.5067/J3L2G-PDCOR

Cazenave, A., & Moreira, L. (2022). Contemporary sea level changes from global to local scales: A review. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *478*(2261), 20220049. https://doi.org/10.1098/rspa.2022.0049

Chafik, L., Penny Holliday, N., Bacon, S., Baker, J. A., Desbruyères, D., Frajka-Williams, E., & Jackson, L. C. (2023). Observed mechanisms activating the recent subpolar North Atlantic Warming since 2016. *Philosophical Transactions of the Royal Society A*, *381*(2262), 20220183. https://doi.org/10.1098/rsta.2022.0183

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

Chen, J. L., Tapley, B. D., Seo, K.-W., Wilson, C., & Ries, J. (2019). Improved quantification of global Mean Ocean mass change using GRACE satellite gravimetry measurements. *Geophysical Research Letters*, *46*(23), 13984–13991. https://doi.org/10.1029/2019GL085519

Chen, J. L., Tapley, B. D., 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*(22), e2020GL090656. https://doi.org/10.1029/2020GL090656

Cheng, L., Abraham, J., Trenberth, K. E., Reagan, J., Zhang, H. M., Storto, A., et al. (2025). Record High Temperatures in the Ocean in 2024. *Advances in Atmospheric Sciences*, *42*(6), 1092–1109. https://doi.org/10.1007/s00376-025-4541-3

Cheng, L., Pan, Y., Tan, Z., Zheng, H., Zhu, Y., Wei, W., et al. (2024). IAPv4 ocean temperature and ocean heat content gridded dataset. *Earth System Science Data*, *16*(8), 3517–3546. https://doi.org/10.5194/essd-16-3517-2024

Cheng, L., Tan, Z., Pan, Y., Zheng, H., Zhu, Y., Wei, W., et al. (2024). IAP temperature 1° gridded analysis product (IAPv4) [Dataset]. *CODC*. https://doi.org/10.12157/IOCAS.20240117.002

Clément, L., Frajka-Williams, E., von Oppeln-Bronikowski, N., Goszczko, I., & de Young, B. (2023). Cessation of Labrador Sea convection triggered by distinct fresh and warm (Sub)Mesoscale flows. *Journal of Physical Oceanography*, *53*, 1959–1977. https://doi.org/10.1175/JPO-D-22-0178.1

Cluett, A. A., Bograd, S. J., Jacox, M. G., Buil, M. P., & Hazen, E. L. (2025). Pan-basin warming now overshadows robust Pacific Decadal Oscillation. *Nature Climate Change*, *15*(12), 1340–1347. https://doi.org/10.1038/s41558-025-02482-z

Copernicus Climate Change Service. (2021). ORAS5 global ocean reanalysis monthly data from 1958 to present. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. https://doi.org/10.24381/cds.67e8eeb7

Copernicus Climate Change Service, Climate Data Store. (2018). Sea level gridded data from satellite observations for the global ocean from 1993 to present [Dataset]. *Copernicus Climate Change Service (C3S) Climate Data Store (CDS)*. https://doi.org/10.24381/cds.4c328c78

Dangendorf, S., Hendricks, N., Sun, Q., Klinck, J., Ezer, T., Frederikse, T., et al. (2023). Acceleration of U.S. Southeast and gulf coast sea-level rise amplified by internal climate variability. *Nature Communications*, *14*(1), 1935. https://doi.org/10.1038/s41467-023-37649-9

Desbruyères, D., McDonagh, E. L., King, B. A., & Thierry, V. (2017). Global and full-depth ocean temperature trends during the early twenty-first century from Argo and repeat hydrography. *Journal of Climate*, *30*(6), 1985–1997. https://doi.org/10.1175/JCLI-D-16-0396.1

Desbruyères, D., Mercier, H., Johnson, G. C., Thierry, V., & Mork, K. A. (2025). Deep Argo observations of buoyancy redistribution in the Atlantic overturning. *Geophysical Research Letters*, *52*(17), e2025GL117970. https://doi.org/10.1029/2025GL117970

Dieng, H., Cazenave, A., von Shuckmann, K., Ablain, M., & Meyssignac, B. (2015). Sea level budget over 2005–2013: Missing contributions and data errors. *Ocean Science*, *11*, 1–14. https://doi.org/10.5194/osd-11-1-2015

Dieng, H. B., 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*(8), 3744–3751. https://doi.org/10.1002/2017GL073308

Dobslaw, H., Bergmann-Wolf, I., Dill, R., Poropat, L., Thomas, M., Dahle, C., et al. (2017). A new high-resolution model of non-tidal atmosphere and ocean mass variability for de-aliasing of satellite gravity observations: AOD1B RL06. *Geophysical Journal International*, *211*(1), 263–269. https://doi.org/10.1093/gji/ggx302

Döll, P., Douville, H., Güntner, A., Müller Schmied, H., & Wada, Y. (2017). Modelling freshwater resources at the global scale: Challenges and prospects. *Surveys in Geophysics*, *37*(2), 195–221. https://doi.org/10.1007/s10712-015-9343-1

Dussaillant, I., Hugonnet, R., Huss, M., Berthier, E., Bannwart, J., Paul, F., & Zemp, M. (2025). Annual mass change of the world's glaciers from 1976 to 2024 by temporal downscaling of satellite data with in situ observations. *Earth System Science Data*, *17*(5), 1977–2006. https://doi.org/10.5194/essd-17-1977-2025

Dussaillant, I., Bannwart, J., Paul, F., & Zemp, M. (2024). Glacier mass change global gridded data from 1976 to present derived from the fluctuations of Glaciers database [Dataset]. *World Glacier Monitoring Service*. https://doi.org/10.24381/cds.ba597449

ECCO Consortium, Fukumori, I., Wang, O., Fenty, I., Forget, G., Heimbach, P., & Ponte, M. (2021). Synopsis of the ECCO central Production Global Ocean and sea-ice State Estimate, Version 4 Release 4. *Zenodo*. https://doi.org/10.5281/ZENODO.4533349

Flechtner, F., Dobslaw, H., & Fagiolini, E. (2015). *AOD1B product description document for product release 05 Rev4.4 GRACE* (pp. 327–750). Geo Forschungszentrum Potsdam.

Frederikse, T., Landerer, F., Caron, L., Adhikari, S., Parkes, D., Humphrey, V. W., et al. (2020). The causes of sea-level rise since 1900. *Nature*, *584*(7821), 393–397. https://doi.org/10.1038/s41586-020-2591-3

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*(12), 6704–6716. https://doi.org/10.1002/2013JC009067

Gregory, J. M., Griffies, S. M., Hughes, C. W., Lowe, J., Church, J. A., Fukimori, I., et al. (2019). Concepts and terminology for Sea level: Mean, variability and change, both local and global. *Surveys in Geophysics*, *40*(6), 1251–1289. https://doi.org/10.1007/s10712-019-09525-z

Guérou, A., Meyssignac, B., Prandi, P., Ablain, M., Ribes, A., & Bignalet-Cazalet, F. (2023). Current observed global mean sea level rise and acceleration estimated from satellite altimetry and the associated measurement uncertainty. *Ocean Science*, *19*(2), 431–451. https://doi.org/10.5194/os-19-431-2023

Gunn, K. L., Rintoul, S. R., England, M. H., & Bowen, M. M. (2023). Recent reduced abyssal overturning and ventilation in the Australian Antarctic Basin. *Nature Climate Change*, *13*(6), 537–544. https://doi.org/10.1038/s41558-023-01667-8

Hakuba, M. Z., Fourest, S., Boyer, T., Meyssignac, B., Carton, J. A., Forget, G., et al. (2024). Trends and variability in Earth’s energy imbalance and Ocean heat uptake since 2005. *Surveys in Geophysics*, *45*(6), 1721–1756. https://doi.org/10.1007/s10712-024-09849-5

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. (2020). The ERA5 global reanalysis. *Quarterly Journal of the Royal Meteorological Society*, *146*(730), 1999–2049. https://doi.org/10.1002/qj.3803

Horwath, M., Gutknecht, B. D., Cazenave, A., Palanisamy, H. K., Marti, F., Marzeion, B., et al. (2022). Global sea level budget and ocean mass budget, with focus on advanced data products and uncertainty characterization. *Earth System Science Data*, *14*(2), 411–447. https://doi.org/10.5194/essd-14-411-2022

Hosoda, S., Ohira, T., & Nakamura, T. (2008). A monthly mean dataset of global oceanic temperature and salinity derived from Argo float observations. *JAMSTEC report of research and development*, *8*, 47–59. https://doi.org/10.5918/jamstecr.8.47

Johnson, G. C., & Purkey, S. G. (2024). Refined estimates of global ocean deep and abyssal decadal warming trends. *Geophysical Research Letters*, *51*(18), e2024GL111229. https://doi.org/10.1029/2024GL111229

Katsumata, K., Purkey, S. G., Cowley, R., Sloyan, B. M., Diggs, S. C., Moore, T. S., II, et al. (2022). GO-SHIP Easy Ocean: Gridded ship-based hydrographic section of temperature, salinity, and dissolved oxygen. *Scientific Data*, *9*(1), 103. https://doi.org/10.1038/s41597-022-01212-w

Klavans, J. M., DiNezio, P. N., Clement, A. C., Deser, C., Shanahan, T. M., & Cane, M. A. (2025). Human emissions drive recent trends in North Pacific climate variations. *Nature*, *644*(8077), 684–692. https://doi.org/10.1038/s41586-025-09368-2

Kolodziejczyk, N., Prigent-Mazella, A., & Gaillard, F. (2023). ISAS temperature, salinity, dissolved oxygen gridded fields [Dataset]. *SEANOE*. https://doi.org/10.17882/52367

Landerer, F. W. (2019). *Monthly estimates of degree-1 (geocenter) gravity coefficients, generated from GRACE (04-2002–06/2017) and GRACE-FO (06/2018 onward) RL06 solutions, GRACE Technical Note 13, the GRACE Project*. NASA Jet Propulsion Laboratory. Retrieved from https://podaac-tools.jpl.nasa.gov/drive/files/allData/grace/docs/TN-13_GEOC_CSR_RL06.txt

Leclercq, L., Cazenave, A., Leger, F., Birol, F., Nino, F., Tolu, L., & Legeais, J. F. (2024). Coastal sea level rise at altimetry-based virtual stations in the Gulf of Mexico. *Advances in Space Research*, *75*(2), 1636–1652. https://doi.org/10.1016/j.asr.2024.11.069

Leclercq, L., Oelsmann, J., Cazenave, A., Passaro, M., Jevrejeva, S., Connors, S., et al. (2026). Regime shift in the global mean sea level and components in the early 2010s. *Communications Earth and Environment*, *7*(1), 130. https://doi.org/10.1038/s43247-025-03149-5

Lele, R., & Purkey, S. G. (2024). Understanding full-depth steric sea level change in the Southwest Pacific Basin using Deep Argo. *Geophysical Research Letters*, *51*(12), e2023GL107844. https://doi.org/10.1029/2023GL107844

Li, Q., England, M. H., Hogg, A. M. C., Rintoul, S. R., & Morrison, A. K. (2023). Abyssal ocean overturning slowdown and warming driven by Antarctic meltwater. *Nature*, *615*(7954), 841–847. https://doi.org/10.1038/s41586-023-05762-w

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*(11), 1031–1035. https://doi.org/10.1038/nclimate2387

Loeb, N., Doelling, D. R., Wang, H., Su, W., Nguyen, C., Corbett, J. G., et al. (2018). Clouds and the Earth’s Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) top-of-atmosphere (TOA) Edition-4.0 data product. *Journal of Climate*, *31*(2), 895–918. https://doi.org/10.1175/JCLI-D-17-0208.1

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

Madec, G., et al. (2017). NEMO ocean engine (Version v3.6), Notes Du Pôle De Modélisation De L'institut Pierre-Simon Laplace (IPSL). https://doi.org/10.5281/zenodo.1472492

Marti, F., Blazquez, A., Meyssignac, B., Ablain, M., Barnoud, A., Fraudeau, R., et al. (2022). Monitoring the ocean heat content change and the Earth energy imbalance from space altimetry and space gravimetry. *Earth System Science Data*, *14*(1), 229–249. https://doi.org/10.5194/essd-14-229-2022

Meyssignac, B., Fourest, S., Mayer, M., Johnson, G. C., Calafat, F. M., Ablain, M., et al. (2024). North Atlantic heat transport convergence derived from a regional energy budget using different Ocean heat content estimates. *Surveys in Geophysics*, *45*(6), 1855–1874. https://doi.org/10.1007/s10712-024-09865-5

Mueller-Schmied, H., et al. (2024a). The global water resources and use model WaterGAP v2.2e: Description and evaluation of modifications and new features. *Geoscientific Model Development*, *17*, 8817–8852. https://doi.org/10.5194/gmd-17-8817-2024

Mueller-Schmied, H., et al. (2024b). The global water resources and use model WaterGAP v2.2e - Daily water storage model output driven by GSWP3-ERA5 and historical setup of direct human impacts [Dataset]. *Goethe University Data Repository (GUDe)*. https://doi.org/10.25716/GUDE.17VN-ZP9G

Nerem, R. S., Beckley, B. D., Fasullo, J., Hamlington, B. D., Masters, D., & Mitchum, G. T. (2018). Climate change driven accelerated Sea level rise detected in the altimeter era. *Proceedings of the National Academy of Sciences*, *15*(9), 2022–2202. https://doi.org/10.1073/pnas.1717312115

Otosaka, I., Shepherd, A., Ivins, E. R., Schlegel, N. J., Amory, C., van den Broeke, M. R., et al. (2023). Mass balance of the Greenland and Antarctic ice sheets from 1992 to 2020. *Earth System Science Data*, *15*(4), 1597–1616. https://doi.org/10.5194/essd-15-1597-2023

Pan, Y., Cheng, L., Abraham, J., Trenberth, K. E., Reagan, J., Du, J., et al. (2026). Ocean heat content sets another record in 2025. *Advances in Atmospheric Sciences*. https://doi.org/10.1007/s00376-026-5876-0

Peltier, R. W., Argus, D. F., & Drummond, R. (2018). Comment on "An assessment of the ICE-6G_C (VM5a) glacial isostatic adjustment model" by Purcell et al. *Journal of Geophysical Research: Solid Earth*, *123*(2), 2019–2028. https://doi.org/10.1002/2015JB012742

Prandi, P., Meyssignac, B., Ablain, M., Spada, G., Ribes, A., & Benveniste, J. (2021). Local sea level trends, accelerations and uncertainties over 1993–2019. *Scientific Data*, *626*, 8-1. https://doi.org/10.1038/s41597-020-00786-7

Prigent, A., Richter, I., Storto, A., Farneti, R., Imbol Koungue, R. A., Okumura, Y. M., & Chang, P. (2025). Interannual variability of upper ocean temperature in the tropical Atlantic: An ocean reanalysis intercomparison. *Climate Dynamics*, *63*(9), 339. https://doi.org/10.1007/s00382-025-07820-7

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*(23), 6336–6351. https://doi.org/10.1175/2010JCLI3682.1

Rahmstorf, S. (2024). Is the Atlantic overturning circulation approaching a tipping point? *Oceanography*, *37*. https://doi.org/10.5670/oceanog.2024.501

Rintoul, S. R., Stewart, A. L., Johnson, G. C., Zhou, S., Foppert, A., Li, Q., et al. (2025). Antarctic Bottom Water in a changing climate. *Nature Reviews Earth & Environment*, *7*(2), 17–102. https://doi.org/10.1038/s43017-025-00750-2

Riser, S. C., Freeland, H. J., Roemmich, D., Wijffels, S., Troisi, A., Belbéoch, M., et al. (2016). Fifteen years of ocean observations with the global Argo array. *Nature Climate Change*, *6*(2), 145–153. https://doi.org/10.1038/nclimate2872

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

Shepherd, A., Ivins, E., Rignot, E., Smith, B., van den Broeke, M., Velicogna, I., et al. (2021). Antarctic and Greenland Ice Sheet mass balance 1992–2020 for IPCC AR6 (version 1.0) [Dataset]. *UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation*. https://doi.org/10.5285/77b64c55-7166-4a06-9def-2e400398e452

Silvy, Y., Guilyardi, E., Sallée, J. B., & Durack, P. J. (2020). Human-induced changes to the global ocean water masses and their time of emergence. *Nature Climate Change*, *10*(11), 1030–1036. https://doi.org/10.1038/s41558-020-0878-x

Storto, A., Cheng, L., & Yang, C. (2022). Revisiting the 2003–18 deep ocean warming through multiplatform analysis of the global energy budget. *Journal of Climate*, *35*(14), 4701–4717. https://doi.org/10.1175/jcli-d-21-0726.1

Storto, A., & Yang, C. (2024). Acceleration of the ocean warming from 1961 to 2022 unveiled by large-ensemble reanalyses. *Nature Communications*, *15*(1), 54. https://doi.org/10.1038/s41467-024-44749-7

Sun, Y., Riva, R., & Ditmar, P. (2016). Optimizing estimates of annual variations and trends in geocenter motion and J2 from a combination of GRACE data and geophysical models. *Journal of Geophysical Research*, *121*(11), 8352–8370. https://doi.org/10.1002/2016JB013073

Tapley, B., 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*(5), 358–369. https://doi.org/10.1038/s41558-019-0456-2

von Schuckmann, K., Cheng, L., Palmer, M. D., Hansen, J., Tassone, C., Aich, V., et al. (2020). Heat stored in the Earth system: Where does the energy go. *Earth System Science Data*, *12*(3), 2013–2041. https://doi.org/10.5194/essd-12-2013-2020

von Schuckmann, K., Minière, A., Gues, F., Cuesta-Valero, F. J., Kirchengast, G., Adusumilli, S., et al. (2023). Heat stored in the Earth system 1960–2020: Where does the energy go? *Earth System Science Data*, *15*(4), 1675–1709. https://doi.org/10.5194/essd-15-1675-2023

Wang, S., Jing, Z., Wu, L., Sun, S., Chen, Z., Ma, X., & Gan, B. (2024). A more quiescent deep ocean under global warming. *Nature Climate Change*, *14*(9), 961–967. https://doi.org/10.1038/s41558-024-02075-2

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. (2018). Global sea level budget, 1993-present. *Earth System Science Data*, *10*(3), 1551–1590. https://doi.org/10.5194/essd-10-1551-2018

WMO. (2025). World Meteorological Organization, Statement on the state of the global Climate in 2024, WMO report n° 1368.

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*(700), 700. https://doi.org/10.3389/fmars.2020.00700

Yang, Y., Zhong, M., Feng, W., & Mu, D. (2021). Detecting regional Deep Ocean warming below 2000m based on altimetry, GRACE, Argo and CTD data. *Advances in Atmospheric Sciences*, *38*(10), 1778–1790. https://doi.org/10.1007/s00376-021-1049-3

Yashayaev, I. (2024). Intensification and shutdown of deep convection in the Labrador Sea were caused by changes in atmospheric and freshwater dynamics. *Communications Earth & Environment*, *5*(1), 156. https://doi.org/10.1038/s43247-024-01296-9

Yin, J. (2023). Rapid decadal acceleration of sea level rise along the U.S. East and Gulf coasts during 2010–22 and its impact on hurricane-induced storm surge. *Journal of Climate*, *36*(13), 4511–4529. https://doi.org/10.1175/JCLI-D-22-0670.1

Zhang, Y., Liang, X., Chambers, D. P., & Huang, M. (2025). Assessing deep and abyssal ocean heat content changes with a dynamically consistent ocean state estimate. *Journal of Geophysical Research: Oceans*, *130*(3), e2024JC020925. https://doi.org/10.1029/2024JC020925

Zilberman, N. V., Llovel, W., Steinberg, J., Meyssignac, B., Ablain, M., & Fraudeau, R. (2025). Deep ocean steric sea level change in the subtropical Northwest Atlantic Ocean. *Geophysical Research Letters*, *52*(16), e2024GL114158. https://doi.org/10.1029/2024GL114158

Zuo, H., Balmaseda, M. A., Tietsche, S., Mogensen, K., & Mayer, M. (2019). The ECMWF operational ensemble reanalysis–analysis system for ocean and sea ice: A description of the system and assessment. *Ocean Science*, *15*(3), 779–808. https://doi.org/10.5194/os-15-779-2019

Erratum

The originally published version of this article contained a typographical error. Coauthor William Llovel's name was misspelled as William Lovell. The error has been corrected, and this may be considered the authoritative version of record.