SLBC_cci+

Sea Level Budget Closure - Climate Change Initiative +

Final Report and Scientific Roadmap (FR)

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Document reference:	SLBC_CCI-DT-089-MAG_FR_D4-2
Edition.Revision:	1.0
Release date:	01/09/2025
Customer:	ESA
Ref. Market, consultation:	ESA AO/1-11340/22/I-NB

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Document evolution sheet

Ed.	Rev.	Date	Purpose of evolution	Observations
1	0	01/05/2026	First version of the document	

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1. Introduction

1.1. Scope and objective

This document is the Final Report and the Scientific Roadmap for the ESA SLBC_cci+ project ([AD-1] and [AD-2]). It aims at defining the main actions and at describing the key challenges for future scientific activities.

1.2. Document structure

In addition to this introduction, the document is organised as follows:

- Section 2 details the final report with a summary of the activities performed as well as a summary of the project achievements compared to original objectives
- Section 3 details the scientific roadmap with a work plan proposed to achieve the scientific objectives

1.3. Related documents

1.3.1. Applicable documents

Table 1 *List of applicable documents.*

Id.	Name	Description
[AD1]	ESA AO/1-11340/22/I-NB	Call to tender "SEA LEVEL BUDGET CLOSURE_CCI+ (SLBC_CCI+)"
[AD2]	MAG-22-PTF-060_DetailedProposal_V2	Detailed proposal in response to ESA/ESRIN Request for Quotation "SEA LEVEL BUDGET CLOSURE_CCI+ (SLBC_CCI+)" ESA AO/1-11340/22/I-NB [AD-1]

[AD3]	SLBC_CCI-DT-076-MAG_UCR	SEA LEVEL BUDGET CLOSURE_CCI+ Uncertainty Characterisation Report
[AD4]	SLBC_CCI-DT-075-MAG_PVIR	SEA LEVEL BUDGET CLOSURE_CCI+ Product Validation and Intercomparison Report

1.3.2. Bibliography

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1.4. Acronyms

Table 2 *List of abbreviations and acronyms.*

Acronyms	Description
C3S	Copernicus Climate Change Service
CCI	The ESA Climate Change Initiative
CDS	Climate Data Store
ECV	Essential Climate Variable
ERA5	ECMWF Atmospheric Reanalysis v5
ESA	European Space Agency
ECMWF	European Centre for Medium-range Weather Forecasts
GIA	Glacial Isostatic Adjustment
HOAPS	Hambourg Ocean-Atmosphere Fluxes and Parameters from Satellite
ISBA-CTRIP	Interaction Soil-Biosphere-Atmosphere, Total Runoff Integrating Pathways from the Centre National de Recherches Météorologiques
LWS	Land Water Storage
SLBC	Sea level budget closure
SLBC_cci	Sea Level Budget Closure of the ESA Climate Change Initiative (first phase)
SLBC_cci+	Sea Level Budget Closure of the ESA Climate Change Initiative (second phase, this activity)
SL_cci	The Sea Level component of the ESA Climate Change Initiative
TCWV	Total Column Water Vapour
TWS	Terrestrial Water Storage
WaterGAP	Water Global Assessment and Prognosis
WGHM	WaterGAP Hydrological Model

w.r.t	With respect to
WTC	Wet Troposphere Correction
C3S	Copernicus Climate Change Service
CCI	The ESA Climate Change Initiative
CDS	Climate Data Store
ECV	Essential Climate Variable
ERA5	ECMWF Atmospheric Reanalysis v5
ESA	European Space Agency
ECMWF	European Centre for Medium-range Weather Forecasts
GIA	Glacial Isostatic Adjustment
HOAPS	Hambourg Ocean-Atmosphere Fluxes and Parameters from Satellite
ISBA-CTRIP	Interaction Soil-Biosphere-Atmosphere, Total Runoff Integrating Pathways from the Centre National de Recherches Météorologiques

2. Final report

2.1. Summary

The SLBC_cci+ project has significantly advanced our understanding of the sea level budget (SLB) by focusing on a rigorous estimation of the different SLB components (relative sea level, manometric sea level and steric sea level) as well as the characterization of measurement uncertainties. An estimation of the SLB over the period 1993-2022 at global scale and over period 2004-2022 at regional scale has been produced.

The estimation of each SLB component has been carried out by using the most mature datasets with particular attention to combine those in a coherent way to estimate the SLB (e.g. GIA correction, spatial and temporal resolution, etc…). A particular effort through a meticulous analysis of the impacts of data processing and algorithm application on observed values, has allowed to provide a more robust and reliable uncertainty assessment. The persistence of this detailed uncertainty characterization is crucial for future research and operational endeavors.

For satellite altimetry and gravimetry data, a comprehensive uncertainty budget was constructed. This budget identified and described each contribution to the total uncertainty, including linear time-correlated effects and various forms of correlated or uncorrelated effects. Moreover, each identified contribution was assigned a standard uncertainty value. This systematic approach facilitates the generation of precise variance-covariance matrices, which are essential for accurately assessing uncertainties across different temporal scales and periods. This uncertainty budget has been evaluated at global and regional scale. Even though the temporal information on the correlation of the errors has been estimated, the spatial correlations are to date not available.

In contrast, for the steric component and various mass components (e.g., land ice melt, terrestrial water storage), measurement uncertainties were primarily modeled by estimating a standard deviation. While this provides fundamental information for uncertainty assessment, it falls short in adequately describing the more complex correlated effects that can significantly influence overall uncertainties. Therefore, a key area for future development is to improve the understanding and modeling of these components to enable the estimation of correlated uncertainties, thereby enhancing the overall accuracy of the SLB. Also, the evaluation of spatial correlation remains a challenge in the future to evaluate uncertainties at basin scale for more regional investigations.

These characterized uncertainties were then integrated into the computation of the sea level budget and its residuals. Given the assumption of independence among the different observing systems, the uncertainties of individual components were summed to determine the total SLB uncertainty.

Those results have been compared to the first phase product of the SLBC_cci dataset (Horwath et al., 2021) on the common period (first phase product ended in 2016) in order to highlight the improvements performed on the estimation of the components and their uncertainties (Figure 1 and Figure 2). Those comparisons have shown that over the GRACE period, a misclosure of the SLB is still observed with comparable magnitude across the different datasets highlighting the need to continue investigating the causes of the latter. Moreover, the new dataset shows an increase of the misclosure over the GRACE-FollowOn period of 1.1 ± 0.54 mm/yr that is still under investigations since several causes could explain a part of this important misclosure. Recent studies (Cazenave et al., 2026) suggest that part of this misclosure may be explained by deep ocean warming below 2,000 m. This contribution has been estimated at about 0.4 ± 0.15 mm/yr over 2005–2022, representing roughly 10% of the observed GMSL rise over that period. It 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. Additional factors, such as salinity drift on Argo float after 2016, may also play a secondary role but require further assessment.

In addition to the gravimetry-based assessments, results using the sum-of-mass-components approach to estimate the barystatic component were compared with phase 1 results (Figure 2). Over the common period from 1993 to 2016, the estimates from the two project phases differ slightly, with a calculated trend of 1.75 mm/yr for Phase 1 (SBLC_cci dataset) compared to 1.67 mm/yr for phase 2 (SBLC_cci+ dataset). This decrease in the barystatic trend is analyzed further in this document and appears to stem primarily from the Land Water Storage (LWS) contribution estimate, which was updated in the new phase of the project. This update highlighted significant discrepancies between the two methodologies for estimating this specific component.

A visual inspection of the time series reveals a critical artifact: between 2015 and 2016, a jump of approximately 10 mm appears in the phase 2 barystatic curve (blue dashed line) but is notably absent in the phase 1 barystatic estimate (blue solid line). This discrepancy is directly reflected in the respective residual time series of the phase 2 budget (Figure 2 a) appears to be closely linked to the presence of this jump in the updated dataset.

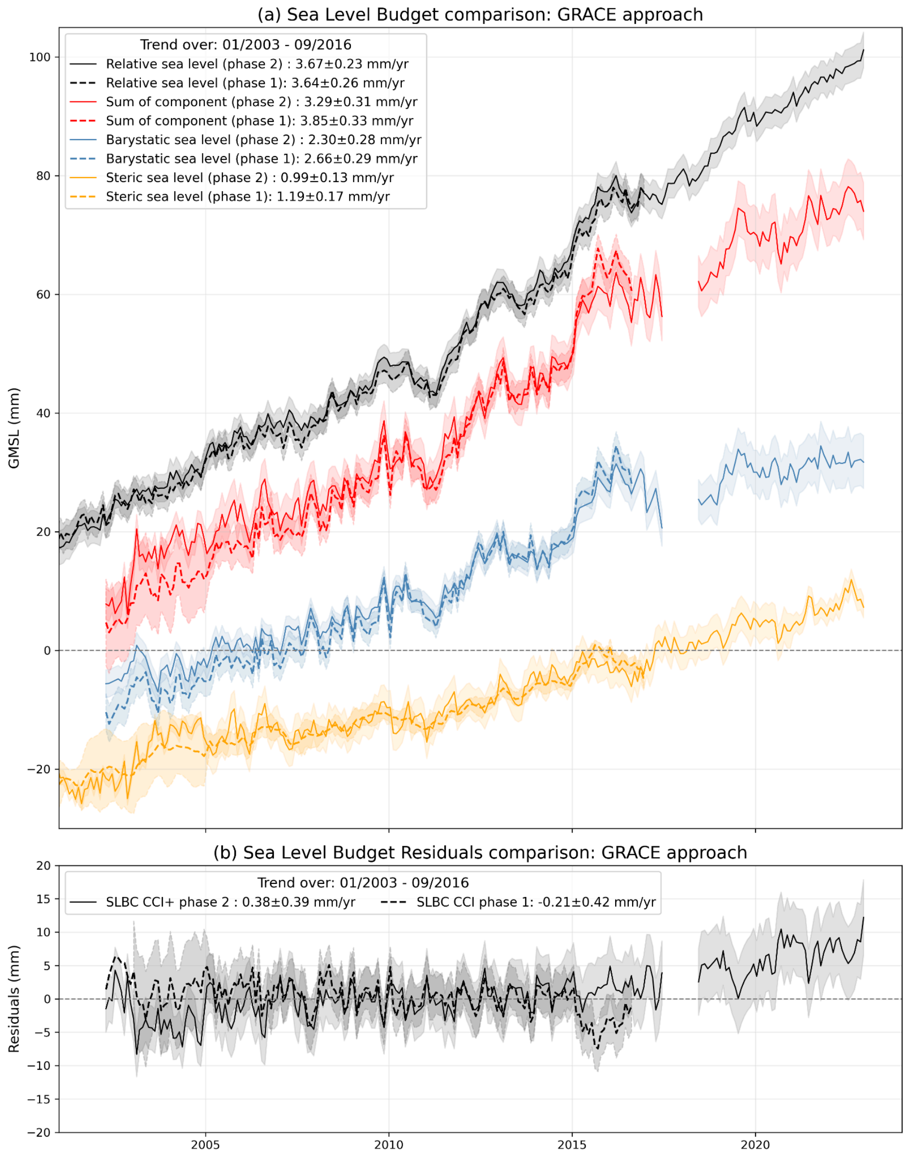

Figure 1 : (a) Global mean sea level budget components using the GRACE-derived barystatic estimate, for SLBC CCI (Phase 1, dashed lines) and SLBC CCI+ (Phase 2, solid lines). The black curves represent altimetry-based sea level; the blue curves show the barystatic component from GRACE; the orange curves show the thermosteric contribution; and the red curves show the sum of all components. (b) Residuals of the sea level budget, computed as the difference between the observed sea level (altimetry) and the sum of thermosteric and GRACE-based barystatic components. Trends are estimated over 01/2003-09/2016 period.

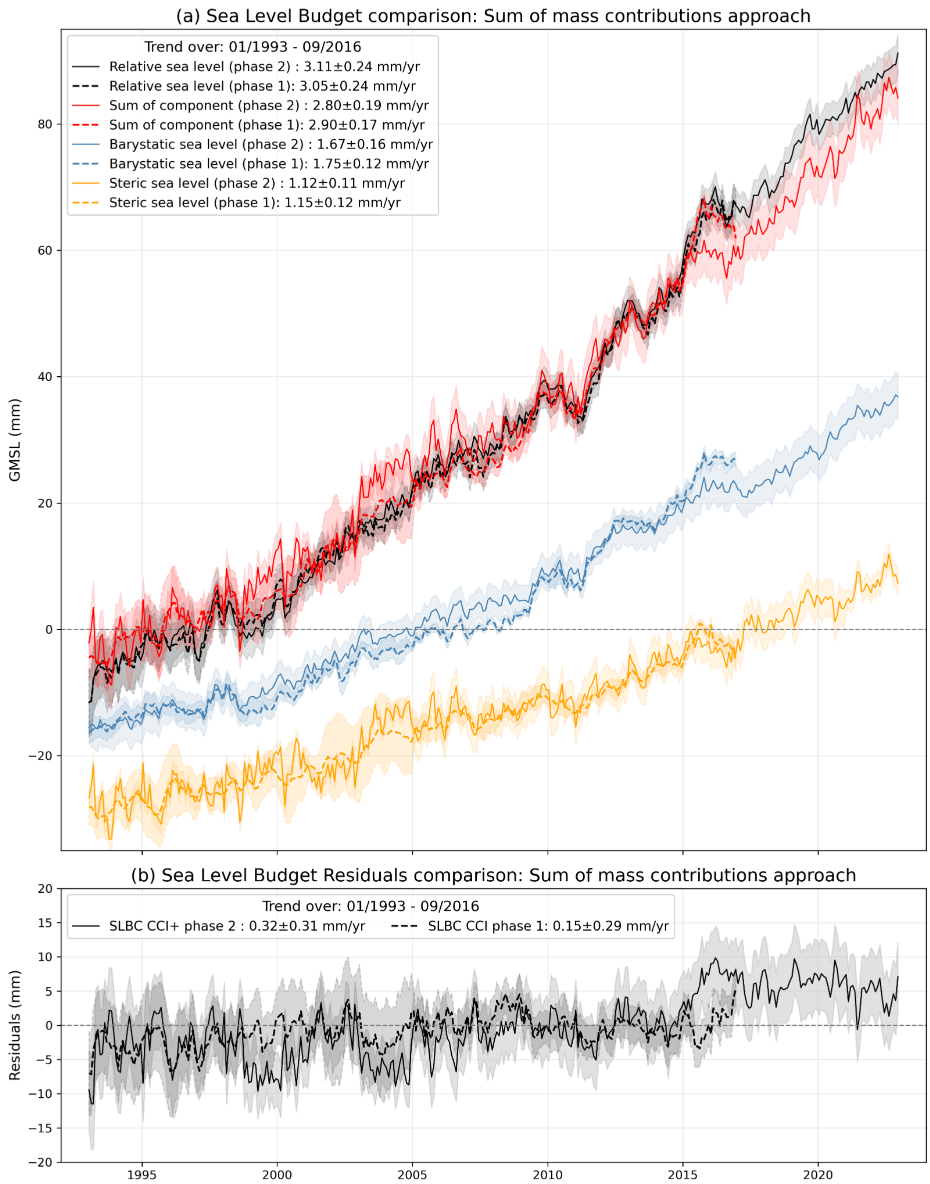

Figure 2 : (a) Global mean sea level budget components using the sum of individual mass components estimate, for SLBC CCI (Phase 1, dashed lines) and SLBC CCI+ (Phase 2, solid lines). The black curves represent altimetry-based sea level; the blue curves show the barystatic component; the orange curves show the thermosteric contribution; and the red curves show the sum of all components. (b) Residuals of the sea level budget, computed as the difference between the observed

sea level (altimetry) and the sum of thermosteric and barystatic components. Trends are estimated over the 01/1993-09/2016 period.

A significant step forward compared to the first phase that has been carried out is the estimation of the SLB at regional scale thanks to the estimation of the manometric component at this level with gravimetry missions, see Figure 8. This estimation at regional scale has allowed us to identify particular areas of interest with significant misclosure observed (e.g. North Atlantic Ocean). Some analysis and scientific publications regarding this topic have been published and have allowed us to identify possible causes without formally identifying the source (see (Bouih et al., 2025; Cazenave et al., 2026; Song et al., 2026).

For altimetry and gravimetry, this involved developing location-dependent uncertainty budgets, mirroring the detailed approach used for global analyses. These regional uncertainty estimates were subsequently applied to determine regional trend uncertainties for the various SLB components, as well as to estimate the regional SLB residuals.

Furthermore, a significant breakthrough was the decomposition of SLB uncertainty into two distinct sources: measurement uncertainties and structural uncertainty. Measurement uncertainties are intrinsic to each individual observing system, arising from errors and approximations within instruments or algorithms. These uncertainties represent areas where improvements in technology or methodologies can directly enhance the accuracy of observations. Conversely, structural uncertainty stems from the inherent differences in effective resolution among the various observing systems, such as Argo floats, GRACE satellites, and altimeters. This type of uncertainty reflects the limitations of inherent observability with the current suite of observing systems and is being estimated by using synthetic data.

The estimation of structural uncertainty, particularly using synthetic observations derived from the OCCIPUT ocean model, yielded a noteworthy finding: the potential existence of large-scale, time-correlated structural errors. These errors appear to affect certain observing systems, primarily altimetry and in-situ data. A crucial implication of this discovery is that these systematic errors could potentially explain the persistent non-closure of the SLB observed over the period of 2009-2015. Further in-depth analysis, especially over longer time periods, is imperative to consolidate the robustness of this significant result. Should this finding prove to be consistently robust, it would necessitate the development and proposal of a specific correction for these systematic errors in future SLB computations, thereby contributing to a more accurate and closed sea level budget.

To validate the uncertainty characterization that has been made on the SLB components, an objective inverse method has been developed. This solution aims for an optimal combination of sea level contributions that ensures the SLB closes (i.e., budget residuals are theoretically zero) by weighting contributions according to their instrumental uncertainty estimates. This approach is inspired by the methodologies used to close the energy and water cycles in publications such as those by (L'Ecuyer et al., 2015; Rodell et al., 2015).

If the inverse method yields an optimal solution that falls within the established uncertainties, it confirms the consistency of the current uncertainty description. Although this optimal solution may not be physically realistic, it successfully closes the SLB within the known limitations of the observation system. Conversely, a more critical conclusion must be drawn if the inverse method fails to find any optimal solution that falls within the pre-defined range of uncertainties. The results of this objective method have been obtained at global scale over the GRACE era (2002-2022), see Figure 3. The inversion successfully identified an optimal solution that perfectly closes the SLB (panel d), a solution consistent with the estimated uncertainties of each component.

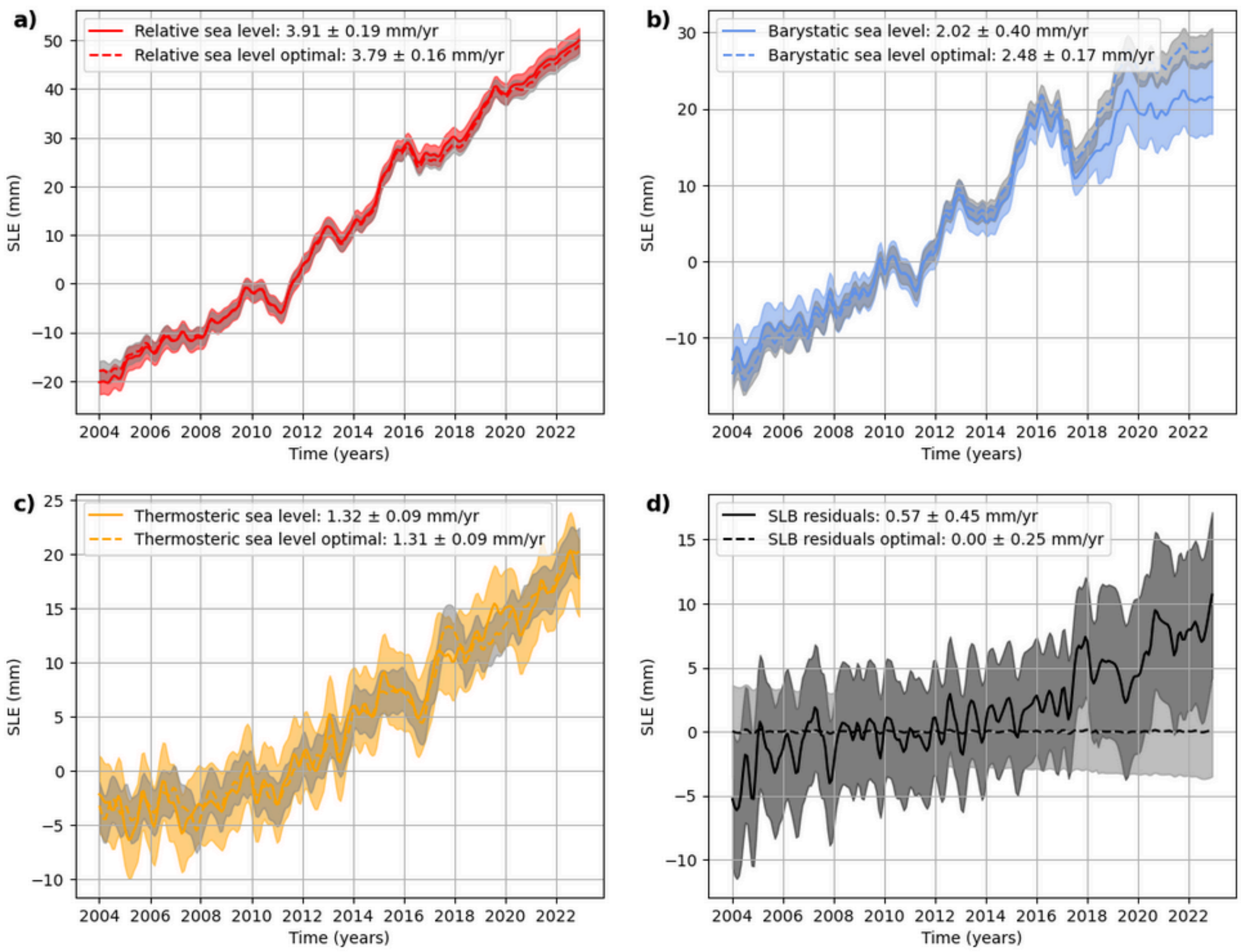

Figure 3 : Comparison of various sea level components. Solid lines represent components derived directly from observations, dashed lines show those obtained through an objectively constrained optimal approach. The panels display: (a) Relative sea level, (b) Barystatic sea level, (c) Thermosteric sea level, and (d) SLB residuals. Uncertainties envelope are presented at 1-sigma confidence level.

We can therefore conclude that the budget can be closed within the described uncertainties. However, the confidence level of this optimal solution cannot be assessed within the 1-sigma interval, suggesting less than a 32% probability of its existence. This indicates a continuing need for effort in evaluating SLB uncertainties to ensure more robust and realistic results from the inversion process.

2.2. Achievement of project objectives

As described above, the SLBC_cci+ project has reached many of its original objectives and led to improve our estimations of the SLB at both global and regional levels. A description of the results for each original objective is made in the following section.

2.2.1. Perform a sea-level budget assessment using the classical approach at both global and regional scales for the periods 1993–2022 and 2004–2022.

In order to evaluate the consistency of the global mean sea level (GMSL) budget by comparing the different components contributing to sea level change, the studies planned within the SLBC_cci+ proposal were framed to address two fundamental aspects:

- Mass budget – assessing the consistency between the barystatic sea level derived from satellite gravimetry and the sum of the individual mass components (ice sheets, glaciers, and land water storage).
- Sea level budget – assessing the consistency between the sum of the individual contributions (thermosteric and barystatic) and the relative global mean sea level from satellite altimetry, with particular emphasis on trend variability.

Studies on budget consistency focused on comparing the barystatic component computed as the sum of individual mass contributions against the barystatic component directly estimated from GRACE/GRACE-FO satellite gravimetry. While these estimates show good agreement over most of their common period, particularly between 2004 and 2015 (see Figure 4), a noticeable trend emerges in the differences between the two time series from 2016 to 2024. This divergence coincides with a period where the sea level budget fails to fully close, suggesting potential inconsistencies in either the individual mass components or the gravimetric measurements during this timeframe.

As previously noted (see Figure 2), this interval is characterized by a signal that crests and then recedes over a three-year period between 2015 and 2018. This high-amplitude signal, measured at approximately 10 mm in the GRACE/GRACE-FO data, is only partially captured by the land water storage (LWS) component, which presents a signal roughly half the magnitude of that observed by gravimetry. Other mass components show no significant response to this event. Analysis suggests this underestimation is linked to the updated forcing model used for LWS estimations (WGHM 22 d).

This discrepancy also coincides with a period of strong El Niño Southern Oscillation (ENSO) activity. The results indicate that the LWS model may struggle to accurately represent mass changes under such intense climatic conditions. Within the budget residuals derived from the sum-of-mass approach (see Figure 5 b), this event appears as a "step" that shifts the baseline for the remainder of the time series. In contrast, the residuals calculated using GRACE/GRACE-FO data are markedly lower during this period.

We conclude that gravimetric data provide a more faithful representation of the actual signal amplitude between 2015 and 2018 than the sum-of-mass approach, as the latter is hindered by a misestimation of the LWS signal during the ENSO event. Overall, while analysis over the 2002–2022 period shows a trend in residuals for both methods (Figure 5 b), the sea level budget demonstrates better closure when the GRACE-based barystatic component is employed. GRACE-based barystatic estimates generally agree with the sum of individual mass contributions (2004–2015), though low-frequency variations in the budget residuals remain unexplained.

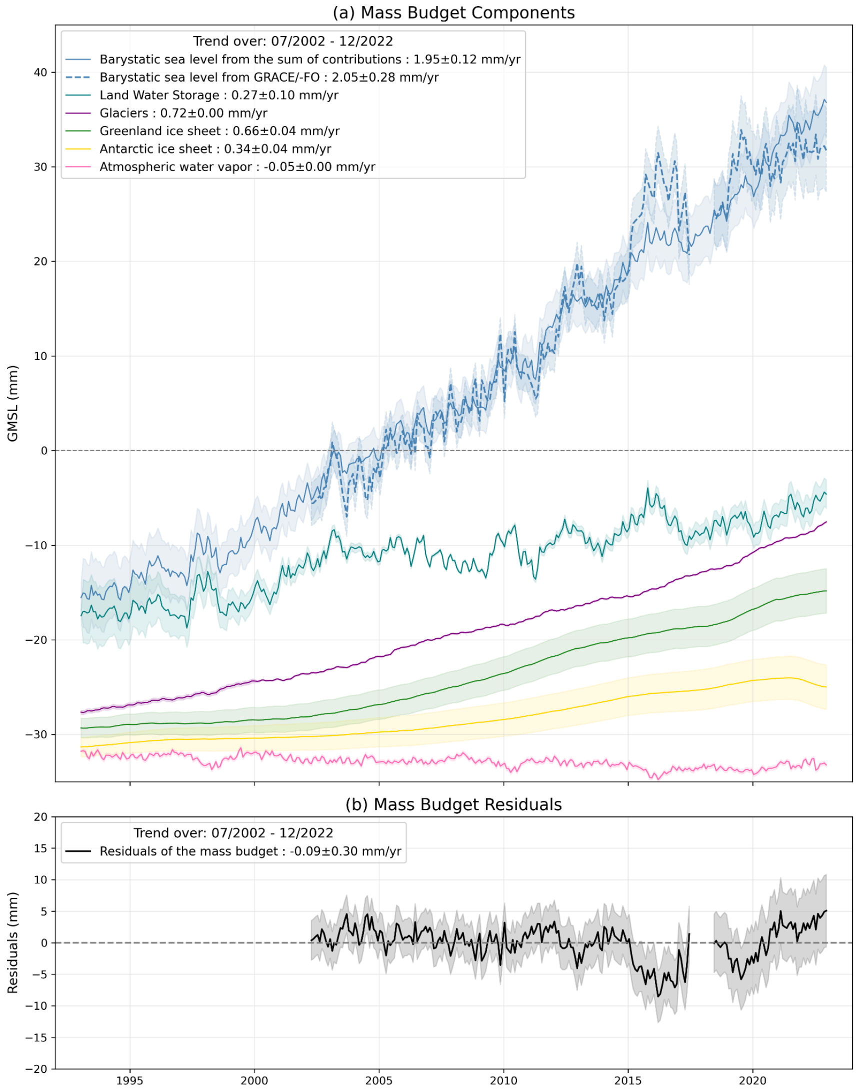

Figure 4 : a) Global mean barystatic sea level time series for SLBC CCI+. Blue lines show the total barystatic component: solid for barystatic from GRACE/GRACE-FO data, and dashed for barystatic from the sum of individual mass components. Teal lines show land water storage, purple lines show glacier melt, green lines Greenland Ice Sheet mass loss, and yellow lines Antarctic Ice Sheet mass loss. (b) Difference between barystatic sea level estimates from GRACE/GRACE-FO and sum of individual mass components. Trends estimated over the period 07/2002 - 12/2022

The phase 1 of SLBC_cci project concluded that, over 1993–2016, the sea level budget was closed within the estimated uncertainties. During the present project phase, GMSL budget closure assessment was extended beyond 2016 using the historical method (2005–present). Results indicate that the budget is no longer closed after 2016.

Regional-scale analyses were conducted to investigate spatially resolved patterns of sea level change and budget closure over selected regions, providing insight into potential local discrepancies and the spatial variability within the SLBC.

The GRACE-based manometric component shows strong spatial coherence with the residual trends (see Figure 8), suggesting it is the main driver of unexplained signals in the regional sea level budget. The anticorrelation between the residuals and the manometric component extending across entire ocean basins, highlighted the role of mass redistribution processes in shaping the residual budget.

Complementary analyses assessing the sensitivity of the regional budget to the choice of both the present-day ice melting (PDIM) and Glacial Isostatic Adjustment (GIA) corrections were conducted, noting that this choice significantly alters the spatial patterns of trends and residuals, thereby underlining the critical role of the applied correction models.

2.2.2. Estimate the uncertainties of the various components and break them down into measurement uncertainties and observability uncertainties.

In the original proposal of the SLBC CCI+ project, the objective was to break down the uncertainties of each SLB component into 2 parts:

- the structural/observability uncertainty of the SLB associated to the effective resolution of the current observing system,
- the measurement uncertainties of the SLB associated with the instrumental error and the algorithmic approximations of each observing system that measures an individual contribution to sea level.

Measurement uncertainties for various SLB components were estimated by analyzing the impact of data processing and algorithms. These efforts improved the characterization of measurement uncertainties and standardized approaches by providing an uncertainty budget for altimetry and gravimetry, offering insights into the temporal correlation of errors. For in-situ measurements, uncertainties were refined, leading to new estimates for different applied algorithms (e.g., optimal interpolation). However, the characterization of temporal error correlations has not yet been evaluated and remains a future objective, as does the estimation of spatial error correlations (see SO-2).

For the first time in this project, observability uncertainties were estimated using synthetic data from the OCCIPUT ocean model (Bessières et al., 2017). Initially, the IMHOTEP model was chosen for its longer data period (22 years vs. 7 years). However, a detected negative trend in IMHOTEP's Ocean Heat Content led the consortium to switch to OCCIPUT. These data were used to reconstruct synthetic components of the Sea Level Budget (relative, manometric, and steric sea level) and assess their respective observability uncertainties from 2009 to 2016. Preliminary results indicate that observability uncertainties are of the order of 0.1 mm/yr at the global scale (1-sigma , 10 years), however, these estimates need to be confirmed through the analysis of a larger ensemble of simulations. Additionally, the full characterization of observability uncertainties at regional scale has not yet been achieved and would necessitate incorporating more model members.

2.2.3. Perform a sea-level budget assessment using the objective approach at both global and regional scales for the periods 1993–2022 and 2002–2022.

In parallel to the historical unconstrained approach, an innovative objective (constrained) method has been developed to deliver a solution to the SLB that closes within uncertainties. The method applies an inverse approach, derived from techniques used to close the energy and water cycles (L'Ecuyer et al., 2015; Rodell et al., 2015), and is mathematically described in section 3.4.2 of the ATBD.

By minimizing the residuals under the SLB uncertainties, the method provides optimal estimates of each component and their associated objective uncertainties. This approach has been applied at both global mean and regional scales.

The budget closure with an objective approach has been implemented at global scale over the period 2009-2015. The original objectives of the project were to perform this new approach at global and regional scale and over a long period. However, the preliminary results obtained with this approach have shown that a robust uncertainties estimates assessment is mandatory to provide substantive analysis. Indeed, the objective approach will yield solutions that close the SLB, but information on the temporal correlations of the errors is crucial and, to date, has not been provided for steric sea level. Partly independent model-based simulations or reanalyses may help in the future to quantify such temporal correlations, enabling their use within the objective approach.

Nevertheless, this approach has demonstrated its feasibility and contribution compared to traditional methods of closing the SLB, which can provide crucial information on investigating the causes of non-closure at both global and regional levels. Therefore, this approach must be refined and extended over a longer period to enhance our understanding of the phenomena involved in estimating the SLB and all related activities. Comparisons with the reference solution from the phase 1 SLBC_cci project at both global and regional scales will allow us to assess the robustness of each solution and explain the reasons for misclosure at particular times and places.

2.2.4. Perform detection and attribution Analyses

Detection and attribution analyses have not yet been carried out within the SLBC_cci+ project. These analyses aim to identify the specific physical drivers responsible for observed changes in sea level and its components. However, performing robust detection and attribution analyses benefits from a well-constrained sea level budget at both global and regional scales. As long as significant residuals remain in the budget, attribution of observed changes to specific underlying processes should be interpreted with caution. Nevertheless, such analyses may still provide useful qualitative insights, even if the budget is not fully closed. Therefore, detection and attribution analyses are planned under SO-4 and will be conducted once the current efforts to identify and reduce the causes of the budget misclosure (SO-3) have progressed sufficiently.

2.3. Results in analysis and current conclusions

2.3.1. Analysis of the SLBC (historical approach) at global and regional scale

At the global scale

At the global scale, the SLBC_cci+ project first assessed the SLB using the classical, unconstrained approach. This consists in comparing the observed sea level from satellite altimetry to the sum of the thermosteric (ARGO-based) and barystatic (GRACE-based or based on the sum of individual mass components) contributions.

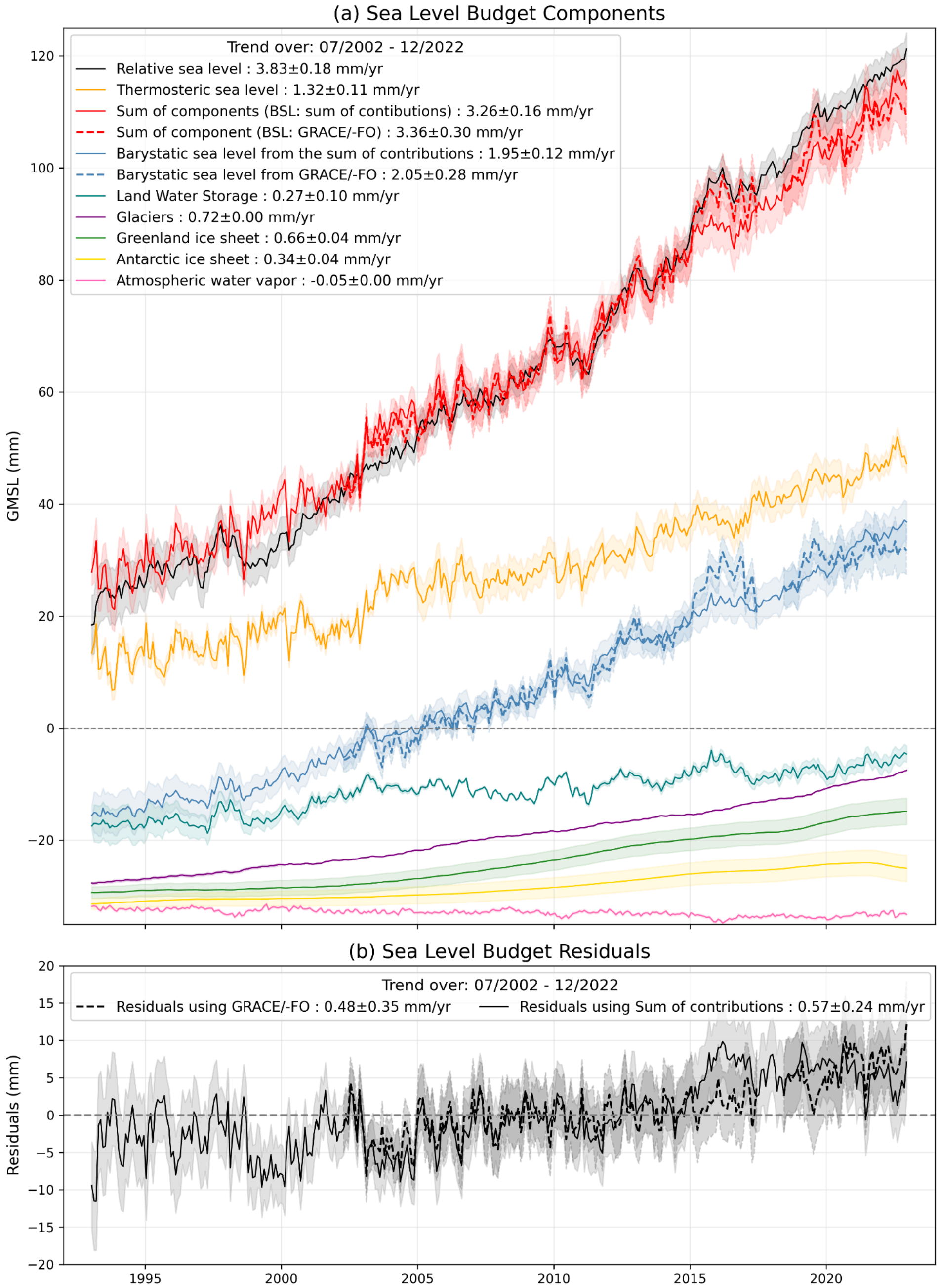

Figure 5 : Sea level budget comparison using two different barystatic components. (a) Global mean sea level budget components using SLBC CCI+ data. The black curves represent altimetry-based sea level; the blue curves show the manometric (barystatic) component from GRACE; the orange curve shows the thermosteric contribution, respectively; and the red curves show the sum of all

components. Dashed lines indicate values based on GRACE-derived barystatic sea level; solid lines indicate values based on the sum of individual mass contributions. (b) Residuals of the sea level budget, computed as the difference between the relative sea level (altimetry) and the sum of all components. Trends estimated over the period 07/2002 - 12/2022

Results show that, over the period 2002–2022, the global mean sea level rises at about 3.83 ± 0.18 mm/yr, driven mainly by ocean thermal expansion (~1.32 ± 0.11 mm/yr) and mass input from land water sources (~2.05 ± 0.28 mm/yr using satellite gravimetry). The closure of the global budget is generally achieved within the observational uncertainties, although moderate residuals persist, particularly after 2015. These residuals may reflect limitations in the datasets (e.g. salinity drift in Argo, or uncertainties in GRACE processing) or inconsistencies in reference frames. Over the GRACE period (2002-2022), the residual trend of the SLB was estimated to be 0.48 ± 0.35 mm/yr when utilizing gravimetric data. In scenarios where mass components were employed, the residual trend was found to be 0.57 ± 0.24 mm/yr. These values highlight the ongoing challenge of achieving complete closure of the SLB, even with refined uncertainty assessments.

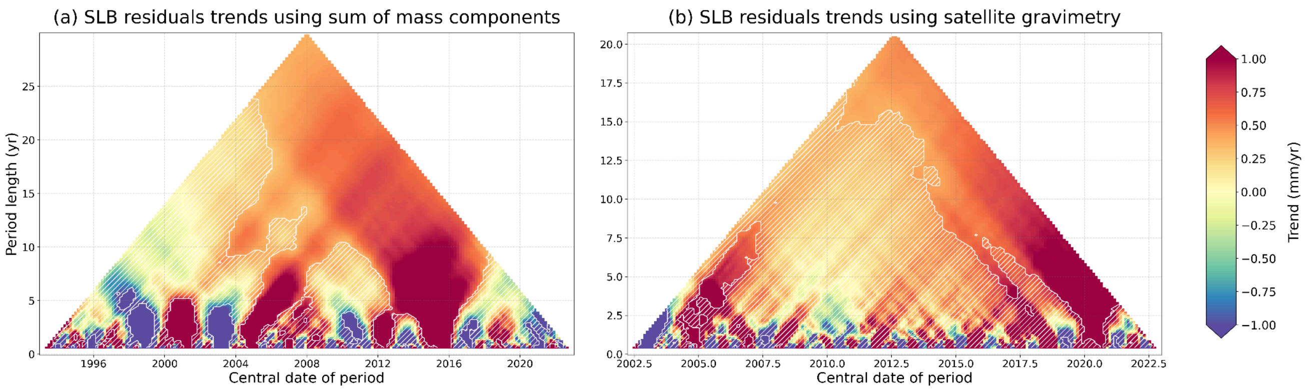

Figure 6 : Pyramid trend diagram of the SLB residual trend with manometric estimate from mass component (a) and GRACE (b) for any period and at any time. Dashed areas correspond where the trend is not significant compared to its uncertainty.

Pyramid trend diagrams shown in Figure 6, reveal that long-term trends in the residuals emerge from specific events occurring toward the end of the time series. The budget residuals consistently exhibit low-frequency variations, which remain an open question and may reflect inconsistencies or errors in one or more of the input components. Furthermore, Figure 5 and Figure 6 indicate that ENSO events exert a significant short-term influence on the closure of the sea level budget, particularly when using mass components. This highlights the challenges in capturing these signals, which are likely associated with the LWS component.

At the regional scale (between 60°S and 60°N)

At the regional scale, the SLBC_cci+ project implemented a similar unconstrained analysis to assess how well the budget closes locally. This approach combined altimetry-based sea level (corrected for GIA and PDIM), GRACE-based manometric signals (also corrected for GIA), and the thermosteric and halosteric components derived from Argo floats. Only the GRACE-based manometric component could be used regionally, as the barystatic sum of individual mass contributions is only available at the global scale.

Trend maps over 2004–2022 period (see Figure 7 for trend maps and Figure 8 for trend anomaly maps) reveal that relative sea level exhibits the highest spatial variability, followed by the thermosteric component. In contrast, halosteric and manometric signals appear significantly weaker. Large-amplitude residuals are particularly concentrated in the North Atlantic Ocean and around Australia. Additionally, signals from major earthquakes, such as the 2004 Sumatra (Mw 9.3) and 2011 Tohoku Oki (Mw 9.1) events, remain uncorrected in the manometric component and are clearly visible in the budget residuals.

Residual trends show amplitudes comparable to those of the individual components, with strong large-scale spatial coherence and a marked anticorrelation with the manometric signal across multiple ocean basins (Figure 8 b and e). Conversely, small-scale patterns in the residuals correlate highly with relative sea level patterns (Figure 8 a and e). This suggests that while unexplained large-scale signals are likely driven by mass redistribution processes, smaller-scale patterns may stem from resolution inconsistencies between high-resolution altimetry and coarser observational systems (GRACE/GRACE-FO and Argo floats).

Additional sensitivity tests demonstrated that the choice of GIA and PDIM corrections strongly influences the spatial patterns of trends and residuals, confirming that these corrections are a major source of uncertainty in regional closure.

A complementary analysis for 2004–2022 using Copernicus gridded altimetry, SCRIPPS steric data (corrected for Argo salinity drift), and an ensemble of three GRACE mascon solutions (JPL, CSR, GFZ) confirmed persistent residuals in the North Atlantic. This pattern proved robust to different GRACE products, geocenter models, and GIA corrections. An alternative approach using six ocean reanalyses to derive the manometric component produced qualitatively similar patterns (with slightly smaller residuals), again pointing to issues in the steric (especially halosteric) component.

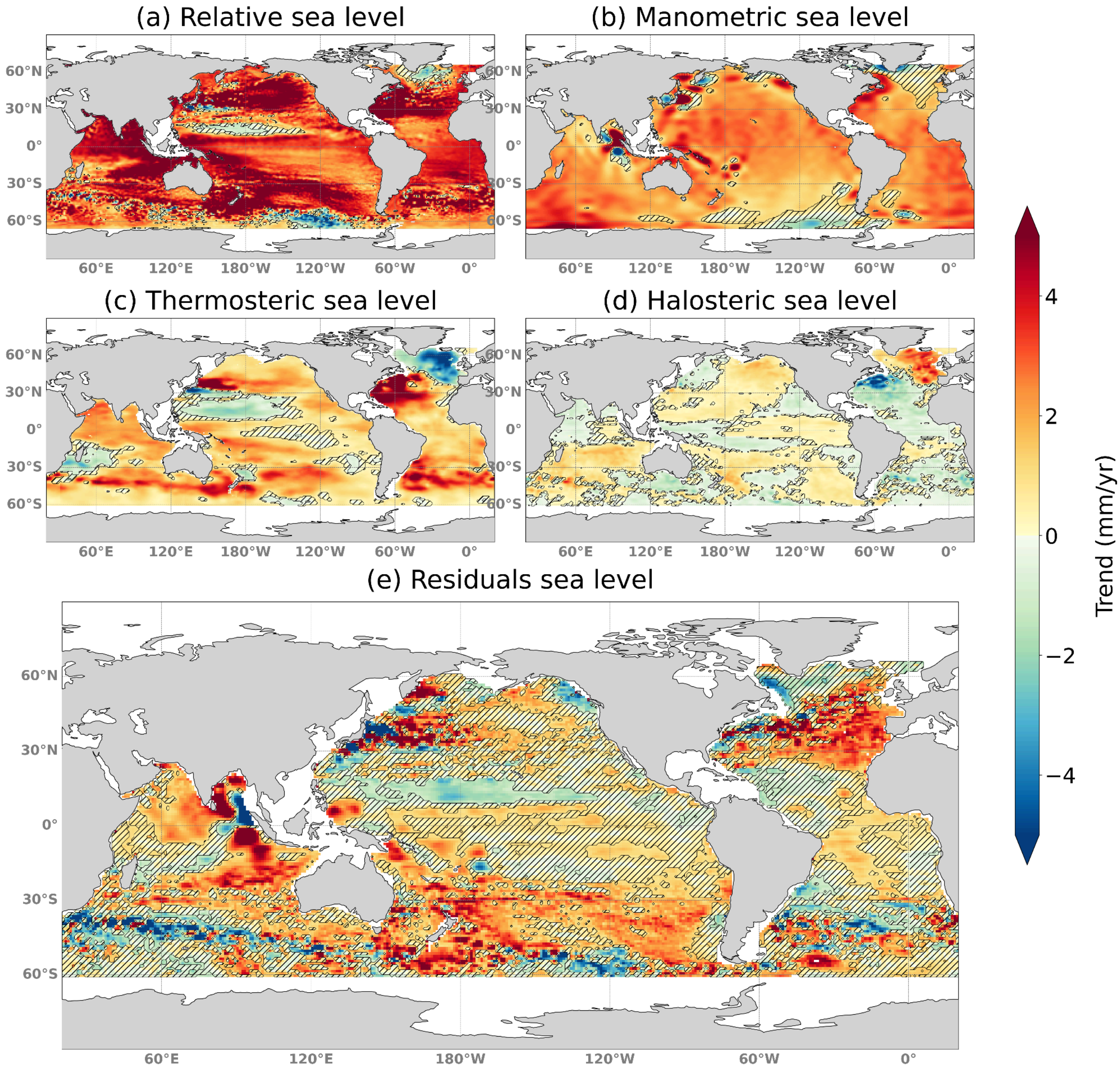

Figure 7 : Sea level trends over April 2002 to December 2019 in observed altimetry-based sea level (a), components (b, c, d: GRACE-based manometric, Argo-based thermosteric and Argo-based halosteric sea level) and budget residual trends (observed sea level minus sum of components) (e).

These results are detailed in Bouih et al. (2025) and demonstrate that regional SLB assessment is both more demanding and more informative than global analysis, as it avoids the compensation of spurious regional anomalies. It also highlights specific regions where the budget does not close, providing valuable guidance for improving the input datasets.

The hypothesis regarding missing steric or deep ocean components has been studied in recent publications. Cazenave et al. (2026) demonstrate that while the global mean sea level budget was closed until 2016, the budget based on Argo data down to 2,000 m has since failed to close. Their study shows that accounting for the deep ocean thermosteric contribution (below the 2,000 m depth sampled by Argo) allows the budget to be almost closed. This deep ocean contribution for the 2005–2022 period is estimated at 0.4±0.15 mm/yr, representing roughly 10% of the observed GMSL rise. This finding reveals that deep ocean warming is gaining importance, particularly in regions such as the Northwestern Atlantic and Southern Ocean.

Focusing specifically on the residuals in the North Atlantic, Song et al. (2026, under review) analyzed the impact of salinity measurement errors reported in Argo floats since approximately 2015/2016. By utilizing the CIGAR ocean reanalysis-based manometric component, they found a significant reduction in North Atlantic residuals compared to those derived from standard GRACE data. Their study indicates that accounting for deep ocean thermal expansion below 2,000 m reduces North Atlantic budget residuals by 30% when using GRACE, and by half when using the CIGAR manometric component, bringing the budget closure within 1 mm/yr. While a halosteric decrease observed in the region since the early 2010s may reflect real salinity changes, instrumental errors have likely impacted the component after 2016.

Despite these advancements, the exact causes of regional residuals remain a subject of active research and will be further addressed as part of SO-3.

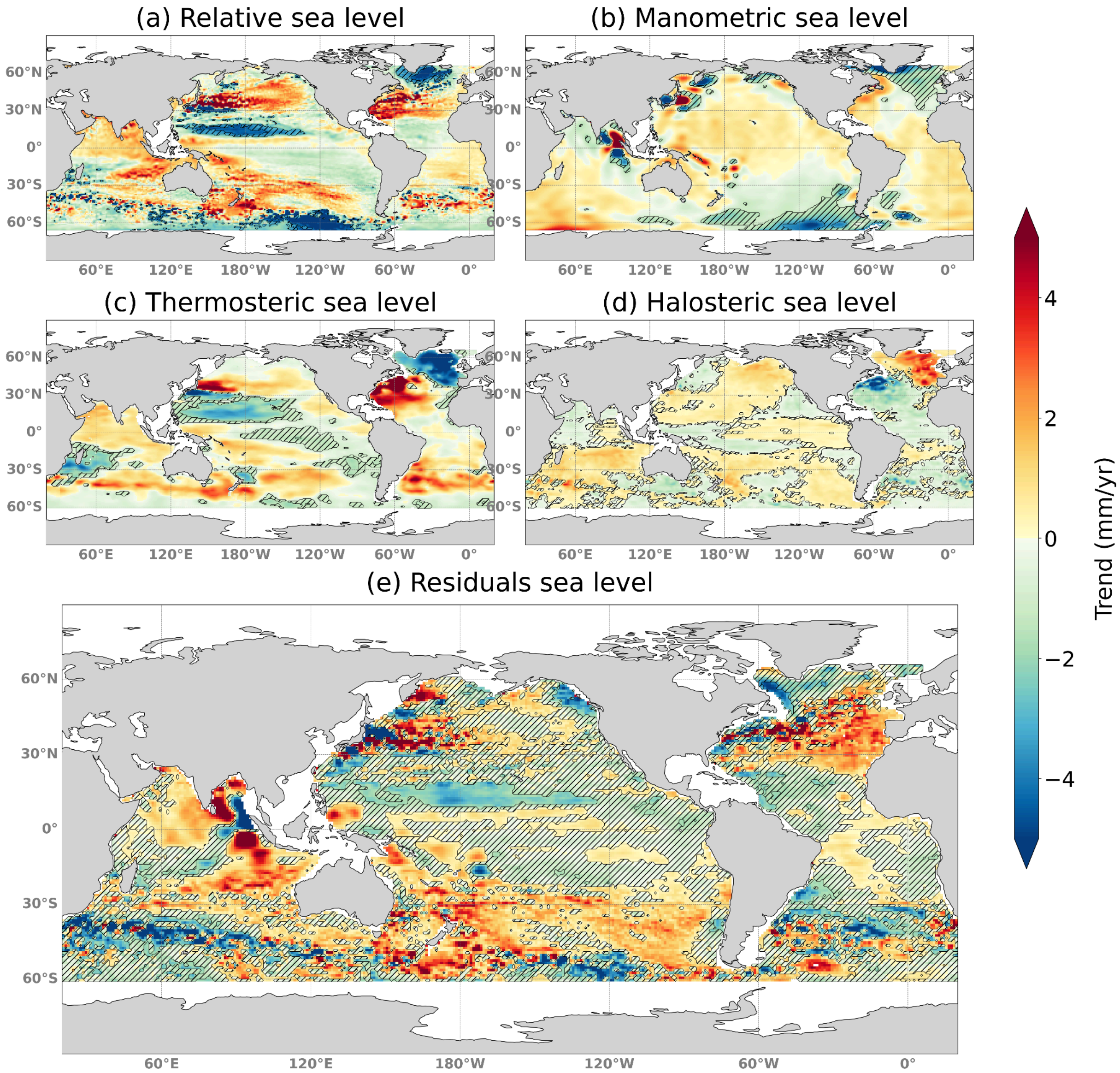

Figure 8 : *Sea level regional trends anomaly over January 2004 to December 2022 in observed Altimetry-based relative sea level (a), components (b, c, d: GRACE-based manometric, Argo-based thermosteric and Argo-based halosteric sea level) and budget residual trends (observed sea level minus sum of components) (e). Hatched areas correspond to trends that are not significant compared with 1σ interval trend uncertainties.*

At the regional scale (Arctic Ocean)

This section presents a sea-level trend budget for the Arctic Ocean for the period between January 2011 and December 2021 (11 years) by exploiting the synergy of remote sensing observations, analysis and reanalysis datasets. This aims to evaluate how well the current observing and modelling systems can reconstruct and help understand oceanographic variations in the Arctic (as done, for example, by Raj et al., 2020).

First, it shows results for the sea-level trend in the Arctic as provided by three different sea-level datasets, with a focus on the Beaufort Gyre and on the open ocean off the East Siberian Shelf, where sea-level trends are particularly pronounced. We then evaluate and discuss our ability to close the budget, using EN4 for the steric contribution, and four GRACE/GRACE-FO products for the mass contribution. The four GRACE/GRACE-FO products are produced, respectively, by the Goddard Space Flight Center (GSFC), the Jet Propulsion Laboratory (JPL), the Center for Space Research (CDS), and Magellium. Finally, we assess how well Topaz4 (Xie et al., 2017), an ocean reanalysis dataset, reproduces the observed oceanographic changes in the Arctic.

Arctic sea-level trend between January 2011 and December 2021

The sea-level trends over the Arctic Ocean between January 2011 and December 2021 were investigated by using three different sea-level datasets (Figure 9). Two of them are dedicated to the Arctic, while the other is global. The Arctic-dedicated datasets are the “Experimental Ssalto/Duacs gridded multimission altimeter products dedicated to the Arctic Ocean” (Veillard et al., 2024), available on the AVISO website, and a dataset developed within the Cryo-TEMPO project. The global dataset is the “Global Ocean Gridded L 4 Sea Surface Heights And Derived Variables Reprocessed Copernicus Climate Service”, available on the CMEMS website. While not specifically designed for the Arctic, it can be used to evaluate the ability of a global dataset to investigate Arctic processes. For convenience, the three datasets will be respectively referred to as “AVISO Experimental”, “Cryo-TEMPO”, and “CMEMS” hereafter.

Sea-level trends are estimated from sea-level time series at monthly temporal resolution. This implies that no additional processing is required for the Cryo-TEMPO and CMEMS datasets, as they are already provided at a monthly resolution. In contrast, monthly averaging is necessary for the AVISO Experimental dataset, which has a temporal resolution of 3 days. Furthermore, we note that the AVISO Experimental dataset does not provide data for 18th of June 2013. However, this gap is expected to have only a minor influence on average for the corresponding month and, thus, on the estimated trends.

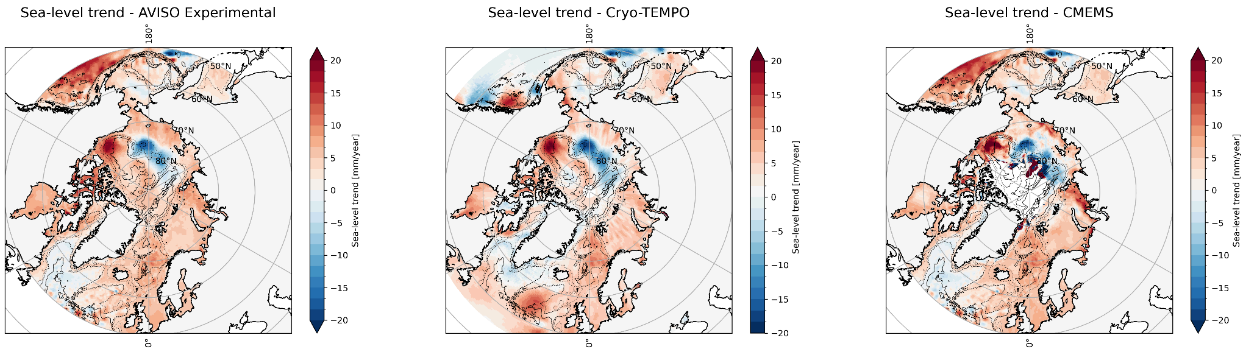

Figure 9 Sea-level trend over the Arctic between January 2011 and December 2021 computed from the AVISO Experimental (left), Cryo-TEMPO (middle), and CMEMS (right) datasets.

The three datasets agree that the Arctic sea-level trend, while mostly positive, ranges from about −17 mm/year, off the East Siberian Shelf, to +17 mm/year, in the Beaufort Gyre. To place these values in context, they correspond to a sea-level change of circa ±0.19 m over the 11-year period under study. These magnitudes are not negligible when compared with the magnitude of the mean dynamic topography (MDT-CNES-CLS2022), which provides the mean of the sea surface height above geoid over the period between 1993 and 2012 (Figure 10).

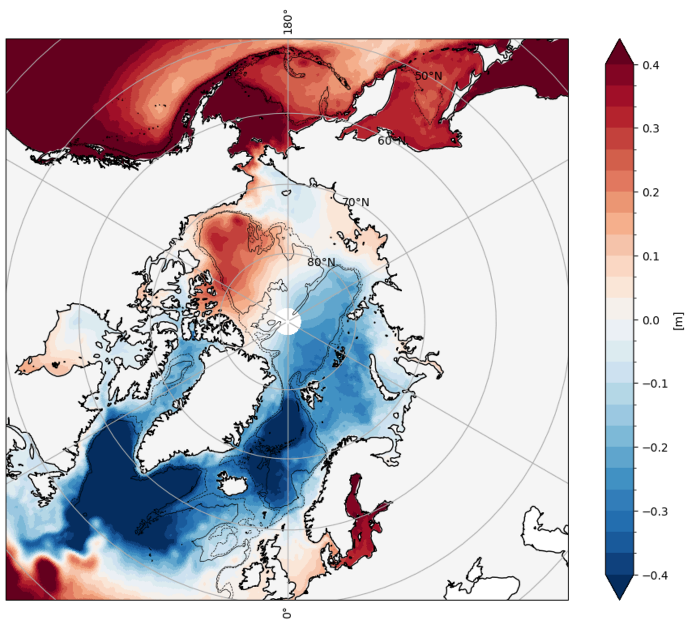

Figure 10 Mean dynamic topography over the Arctic Ocean.

Because of the pronounced sea-level trends in the Beaufort Gyre and off the East Siberian shelf, we show the timeseries at these two locations (Figure 11). The timeseries highlight that the sea-level change has mostly occurred over a few-year period. The inter-annual nature of the sea-level change explains why CMEMS also captures the sea-level trends, despite it only providing sea-level observations in summer (or, more generally, where the presence of sea ice is limited).

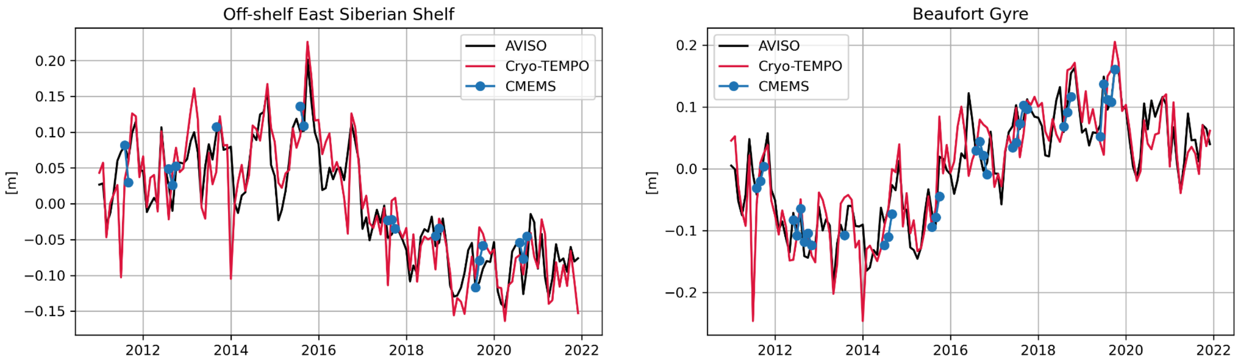

Figure 11 Sea-level anomaly timeseries between January 2011 and December 2021 computed from AVISO Experimental (black), Cryo-TEMPO (red), and CMEMS (blue) datasets at a grid point offshore the East Siberian Shelf (left) and in the Beaufort Gyre (right).

Arctic sea-level budget between January 2011 and December 2021

We compute the budget with respect to sea-level trends provided by the AVISO Experimental dataset (Figure 12). While not shown, the results are not expected to change when the Cryo-TEMPO dataset is considered, given the similarity of the sea-level trends provided by the two datasets (Figure 9). Instead, the CMEMS dataset has been discarded because of the lack of data over part of the Arctic Ocean.

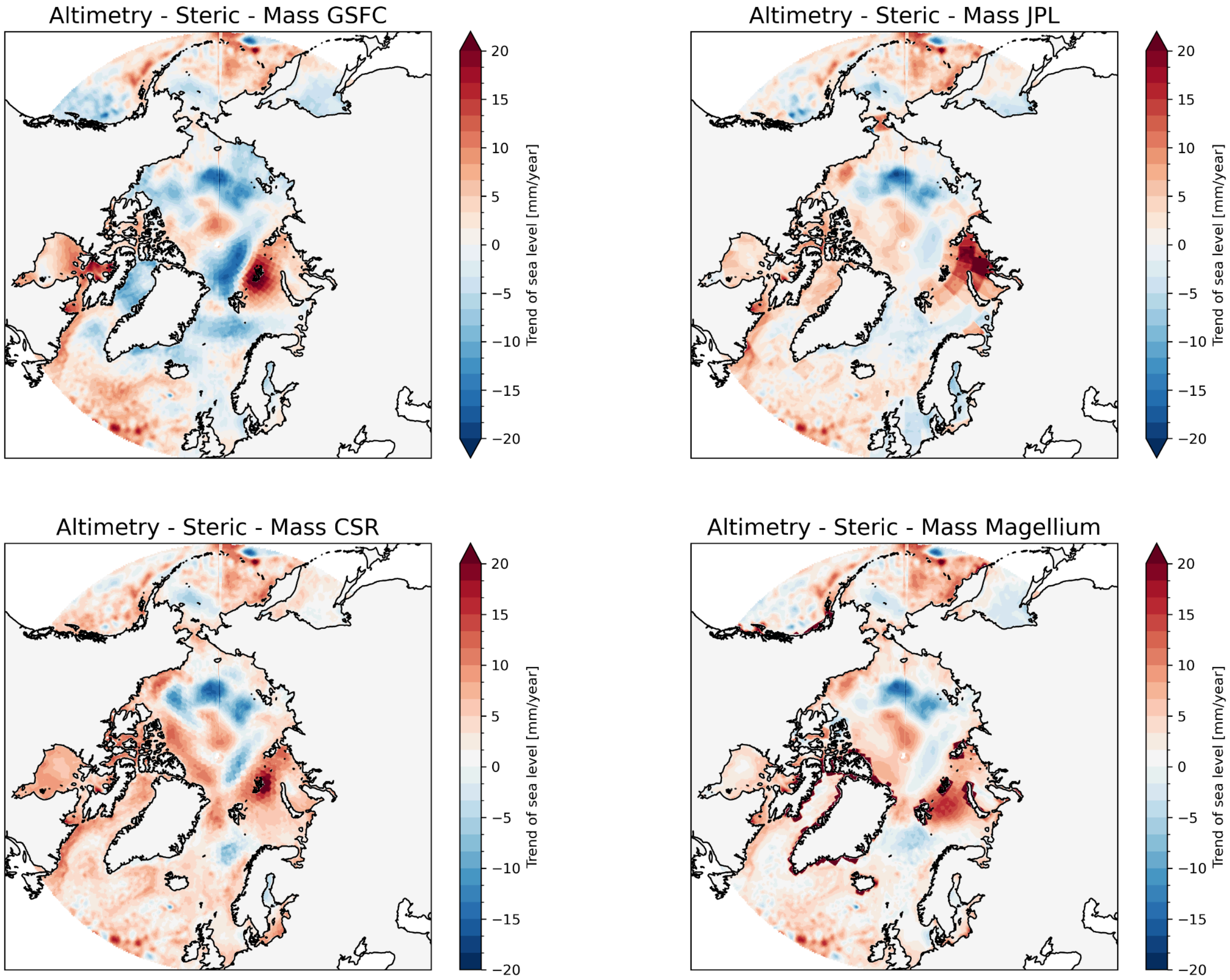

Figure 12 Trends of the difference between AVISO Experimental sea-level anomalies and the combined steric (EN4, upper 2000 m) and mass (GRACE/GRACE-FO) components. Results are shown for the GSFC (top left), JPL (top right), CSR (bottom left) mascon solutions, and the GRACE/GRACE-FO dataset provided by Magellium (bottom right).

Overall, the Arctic sea-level trend budget, computed as the linear trend of the residual between total sea level and the sum of steric and mass components, remains unclosed, with discrepancies exceeding ±10 mm/year over the Eurasian Basin, the Barents Sea, and offshore the East Siberian Shelf.

Despite their similarities, the maps in Figure 12 only show a partial agreement, with the choice of GRACE/GRACE-FO dataset influencing both the spatial pattern and the magnitude of the trend of the residuals. For example, residual trends exceeding 10 mm/year are found over the Barents Sea in the GSFC and CSR solutions, while the JPL solution shows residuals of similar magnitude shifted southeastward to the Kara Sea.

Regarding magnitudes, Figure 12 reveals negative trends in the Eurasian Basin across all solutions, although their amplitude depends strongly on the selected GRACE/GRACE-FO dataset. The trends exceed −10 mm/year when the GSFC solution is used, whereas they are only weakly negative when using the JPL and the Magelium datasets.

Contribution of mass

The linear trend of the sea-level mass component (Figure 13) shows anomalously high and low values in the Eurasian Basin and the Barents Sea, indicating that the corresponding residuals in the sea-level budget maps (Figure 12) originate from the GRACE/GRACE-FO datasets. We consider these features to be artefacts (e.g., due to gravimetry leakage in sea-ice covered areas close to islands and land), as they are difficult to justify from an oceanographic perspective and because of the limited agreement between the GRACE/GRACE-FO solutions.

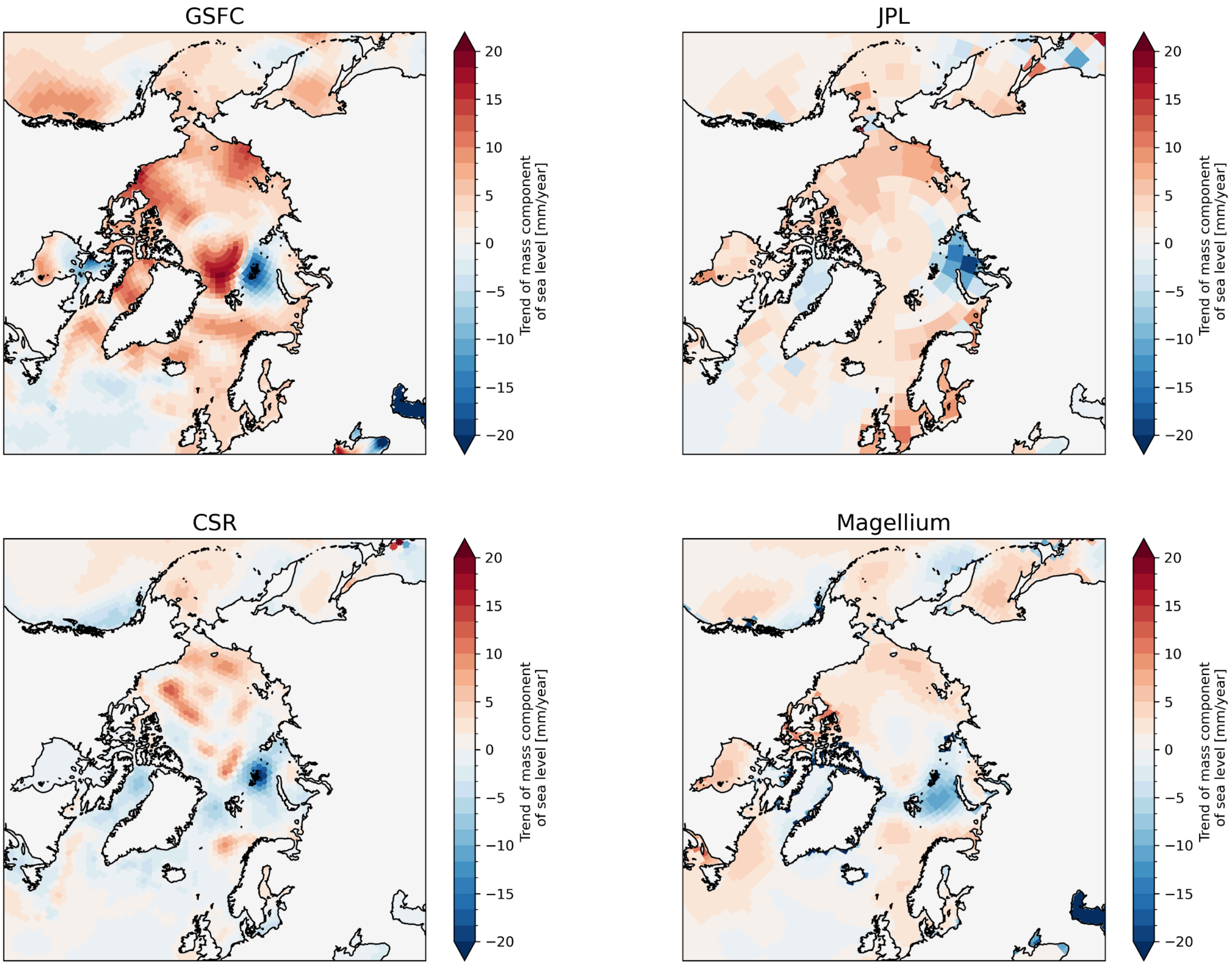

Figure 13 Linear trends of the mass component of sea level between January 2011 and December 2021 from GRACE/GRACE-FO. Results are shown for the GSFC (top left), JPL (top right), CSR (bottom left) mascon solutions, and the GRACE/GRACE-FO dataset provided by Magellium (bottom right).

Integrated contribution of temperature and salinity over the upper 2000m

Figure 14 highlights the role of salinity in affecting sea-level changes in the Arctic. Indeed, the halosteric component of the sea-level trend over the upper 2000m (Figure 14; right) shows the strongest resemblance to the observed Arctic sea-level trend. On the contrary, the thermosteric contribution over the upper 2000m (Figure 14; middle) is negligible. This difference is reflected in the map of the steric sea-level trend over the upper 2000m (Figure 14; left) which shows great similarity with the map of the halosteric component in the Arctic.

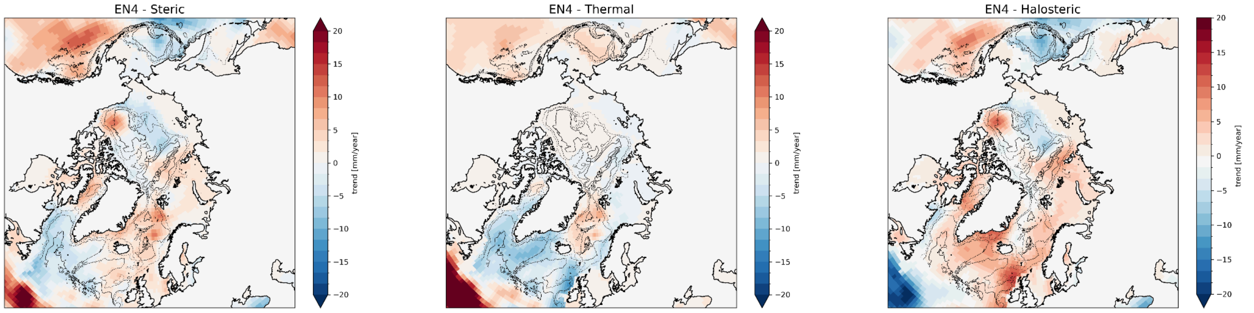

Figure 14 Linear trends of the steric (left), thermosteric (middle), and halosteric (right) sea-level over the upper 2000m between January 2011 and December 2021 computed using temperature and salinity values from EN4.

Despite the similarities, though, the halosteric sea-level trend from EN4 does not fully capture the observed sea-level trend, particularly off the East Siberian Shelf, possibly due to the scarcity of in-situ observations during the study period.

Depth-dependent contribution of temperature and salinity

Figure 14 highlights the role of salinity changes over the upper 2000m in driving the sea-level trend between January 2011 and December 2021. Here, we further investigate the depth range where the changes in halosteric contribution are most pronounced. The analysis appears relevant partly because it may suggest the oceanographic processes responsible for the observed sea-level trends, and partly because, if these changes were located at the surface, it would then be possible to infer the halosteric contribution to the sea-level trend from surface salinity variability and, thus, from space.

An analysis of the halosteric contribution from EN4 throughout the water column indicates that the salinity contribution mostly occurs due to a freshening between approximately 40 and 400m depth (Figure 15), while negative halosteric sea-level trend occur over the upper 40m circa.

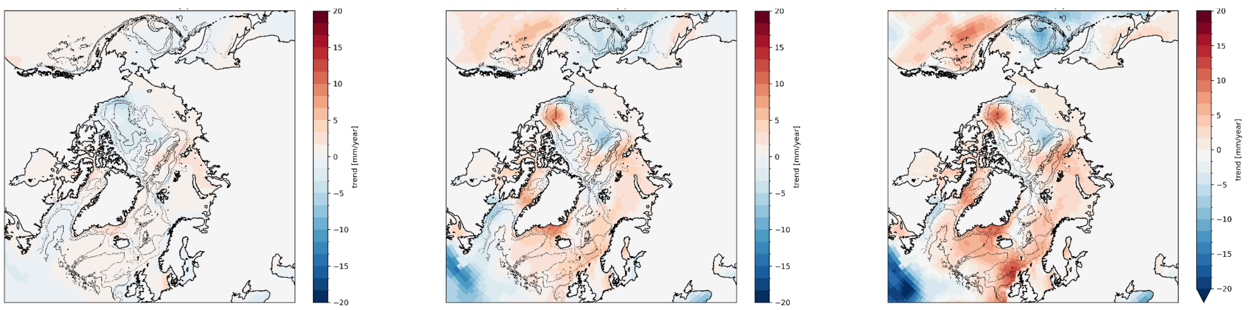

Figure 15 Linear trends of the halosteric sea-level from EN4 over the upper 40m (left), 400m (middle), and 2000m (right) between January 2011 and December 2021.

Comparison with Topaz4

A comparison with Topaz4 (Xie et al., 2017), an ocean reanalysis for the Arctic Ocean, shows partial agreement with the observations and the EN4 analysis dataset (Figure 16, Figure 17). The agreement is most pronounced in the Beaufort Gyre, where Topaz4 also returns a positive sea-level trend, of compatible magnitude with satellite altimetry, over the study period (Figure 16, top left). In line with observations, Topaz4 also attributes Arctic sea-level trends mostly to changes in salinity (Figure 16, bottom right), with the salinity changes occurring in the ocean interior, and not at the surface (Figure 17).

We should note that, despite the similarity in the Beaufort Gyre, Topaz4 disagrees with observations off the East-Siberian Shelf, where it returns a positive sea-level trend of exceeding 10 mm/year.

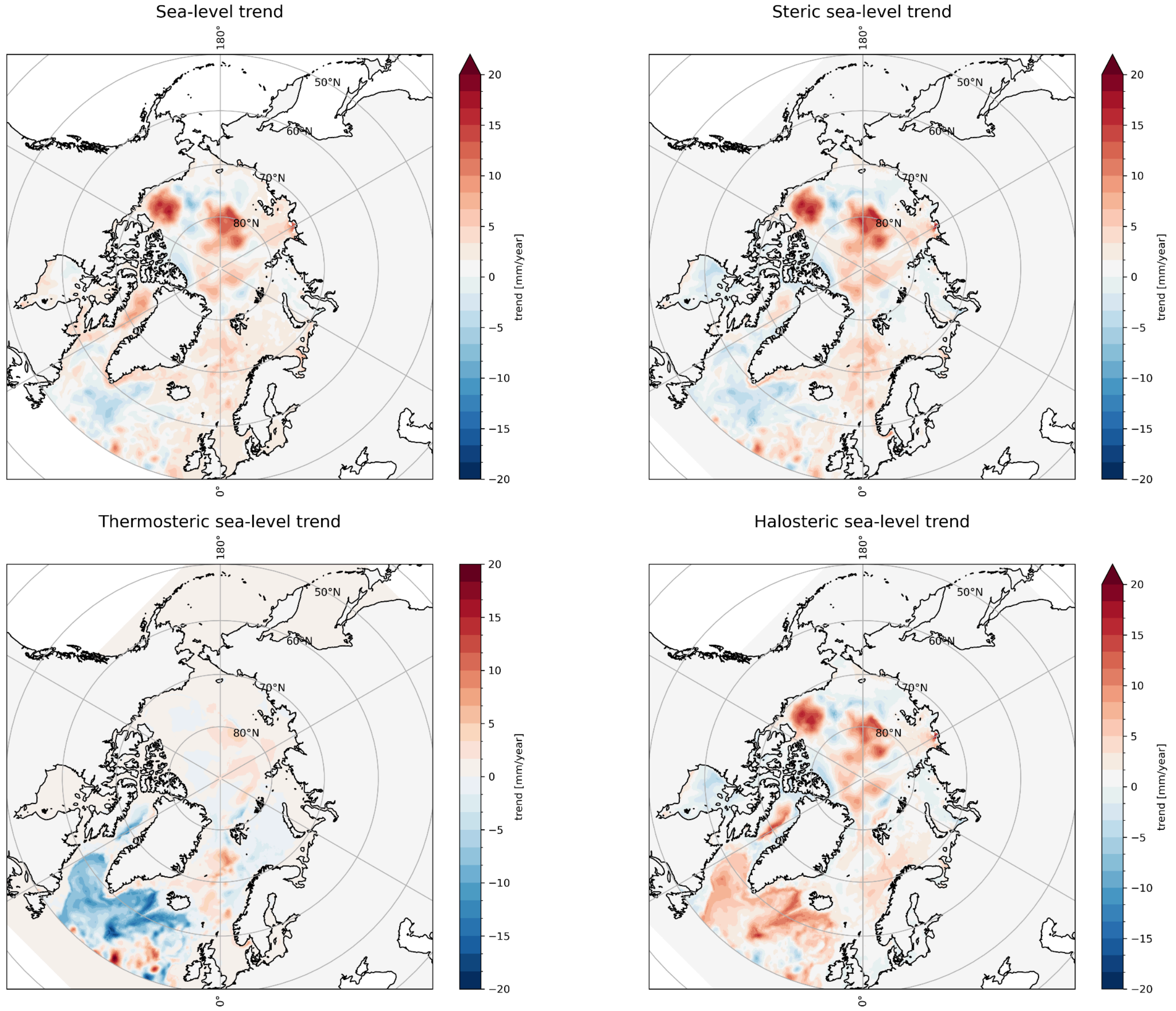

Figure 16 Linear trends of the sea level (upper left), steric sea level (upper right), thermosteric sea level (lower left) and halosteric sea level (lower right) estimated using Topaz4 between January 2011 and December 2021. The thermosteric, halosteric, and steric sea level are computed over the upper 2000m.

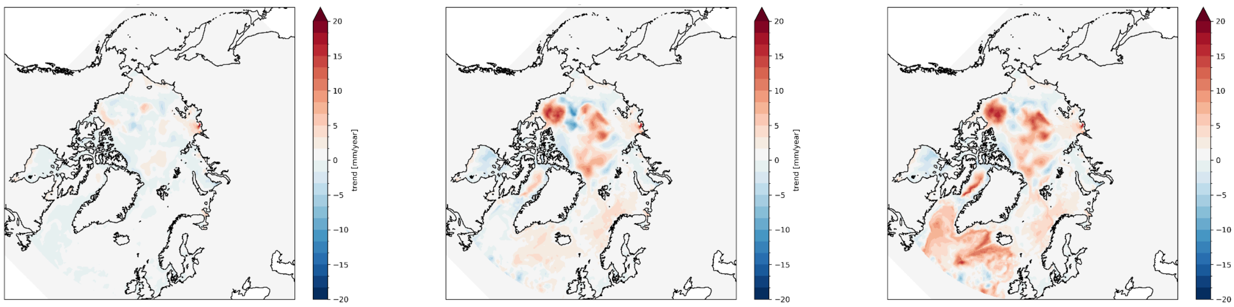

Figure 17 Linear trends of the halosteric sea-level from Topaz4 over the upper 40m (left), 400m (middle), and 2000m (right) between January 2011 and December 2021.

2.3.2. Analysis of the SLBC (innovative approach) at global and regional scale

An objective closure approach, based on an inversion method, was implemented to address the missing contribution in the global SLB residuals for the 2004–2023 period. This method successfully identified an optimal solution that perfectly closes the SLB, a result consistent with the estimated uncertainties of the standard components. Crucially, the optimization substantially reduced the uncertainties associated with each component in the optimal solution. The adjustments varied by component, with altimetry and gravimetry showing long-term modifications consistent with their error budgets for time-correlated effects, leading to changes in their trend estimates. In contrast, the thermosteric sea level was adjusted over the short-term, with no change to its trend. This outcome underscores the vital role of accurately characterizing component uncertainties, particularly time-correlated errors, for achieving robust budget closure in climate studies.

The inversion process validated the uncertainty models for the SLB components, confirming that the budget can be closed within the described uncertainties. However, the optimal solution's confidence level is low, suggesting a continuing need to refine SLB uncertainty evaluations for more robust results. Furthermore, the physical reliability of this optimal solution is questionable due to a significant change in the barystatic sea level after 2016, coinciding with the GRACE/GRACE-FO mission transition, which suggests a potential systematic effect influencing gravimetry measurements during that period.

To better understand the physical implications and global behavior, the objective closure approach is proposed for implementation at a regional scale. While this regional analysis would help identify affected areas and local patterns, a current limitation is the lack of estimated spatial correlations for each component, which restricts the inversion to being performed independently on each geographical cell.

2.4. Lessons learned

This section provides a comprehensive review of the lessons learned throughout the project's lifecycle. It synthesizes the technical challenges encountered and the scientific insights gained, offering a critical evaluation of the methodologies employed. These findings serve as a foundation for optimizing future workflows and mitigating risks in subsequent project phases.

2.4.1. Ensuring data consistency when calculating budgets

The primary challenge was ensuring the consistency of data across different components when calculating budgets. Due to the high level of expertise in certain components, dedicated meetings were crucial to verify the content of each dataset and avoid duplication.

Lessons learned:

- It is essential to schedule preliminary meetings systematically to establish a clear understanding of the data content and scope for each component before starting into the budget calculation.
- Questions that arose during project meetings, particularly those related to data scope and content, should have been addressed in a preliminary review phase. This suggests a need for a dedicated "Data Scoping and Review" phase at the start of the budget process.

2.4.2. Working with datasets of varying "maturity"

The challenge was to integrate datasets with different levels of maturity in their state of the art estimations, processing, time availability coverage and especially with regards to the estimation and knowledge of uncertainties. A significant portion of the project's effort and results relies on accurately handling the uncertainties of the various components.

Lessons learned:

- Dealing with components of varying maturity levels, or those using different approaches, makes it difficult to propose a uniform methodology for uncertainty budgeting across the project.

- This is a complex, long-term effort requiring sustained investment beyond the scope of a 3-year project. Future activities on this topic must ensure the continuation of this work on the uncertainty characterisation through a common methodological approach (uncertainty budgets). A key success was the ability to standardize this historical altimetry uncertainty budget approach, extending it to the manometric sea level estimates from gravimetry measurements and the LWS component.

2.4.3. Freezing developments/investigations on components

The challenge involved locking down developments and investigations on the scientific components to establish a final, stable version for the project product. As the subject matter is highly scientific, investigations and refinements of the sea level components are continuous.

Lessons learned:

- It is challenging to freeze a component estimation and state that ongoing investigations cannot be integrated into the final product of the project.
- A clear, early-defined "cut-off" or "freeze" date for component models/estimations is critical. This date should be agreed upon and communicated with scientific contributors in order to manage expectations regarding the integration of the latest research.

2.4.4. Timing of scientific analyses

The challenge was that starting scientific analyses only at the end of the project was constraining, as people often wanted to start subsequent activities as quickly as possible without having the final version of the input data/analyses.

Lessons learned:

- Early availability of robust scientific analyses (even if preliminary) is essential for efficient downstream activity planning. Delays to final analyses create bottlenecks and force subsequent teams to either wait or work with potentially obsolete data, resulting in additional work.
- Plan for phased releases of scientific results (e.g., preliminary, intermediate and final) to enable parallel activities to start earlier. This requires prioritising activities that can initially tolerate working with less mature data.

2.5. Steps put in place to actively pursue future opportunities for doing so within operational structures in Europe

The value and relevance of research into Earth system cycles (which lie at the heart of the CCI's X-ECV work plan) are now well established. Projects focusing on Sea Level Budget Closure have enabled the development and consolidation of an approach to assess and monitor whether the sea level budget is in balance, as well as to investigate specific scientific questions. Although there are still limitations and room for improvement in the methodology (see the lesson learned (§2.4) above), it now seems reasonable to consider the operational implementation of monitoring sea level budget closure.

The Copernicus C3S (Climate Change Service), which brings together all types of datasets (projections, seasonal forecasts, reanalyses, satellite and in situ observations) enabling us to monitor the state of the system, is probably the most suitable operational european entity to host this kind of activity. The Evaluation and Quality Control (EQC) framework is in particular well structured with its three complementary pillars:

1. Quality Assurance, checking for compliance with data requirements based on user needs, addressing the technical integrity, documentation, metadata, versioning, and accessibility of datasets
2. Quality Assessment, providing scientifically grounded evaluation of dataset behaviour in the context of specific use cases through reproducible analyses and diagnostics
3. Fitness-for-Purpose, translating quality information into clear, use-case-oriented statements that describe strengths, limitations, uncertainties, appropriate applications, and recommendations for correct usage

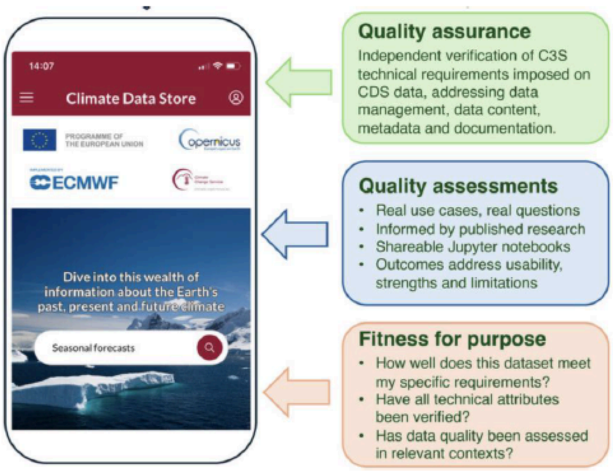

Figure 1: EQC Framework (adapted from Dee et al. 2024)

However, to date, it appears that the C3S service does not carry out any activities relating to the Earth cycle, but it focuses primarily on assessing the quality of a given dataset. Nevertheless, it would be worth exploring whether the assessment of budget closure (carbon, water, energy) could form part of the “quality assessments” activities (see figure above). Indeed, providing an annual assessment of the ECVs involved in the cycles would, on the one hand, inform ECV producers about the consistency of the uncertainties provided and suggest avenues for improvement, and, on the other hand, inform users about the ability of ECVs playing a role in the cycles to comply with conservation laws and determine their relevance for scientific studies.

The situation is the same with regard to the Copernicus Marine Service (CMEMS), for which no assessments appear to have been carried out. Only the Ocean Monitoring Indicators (OMI) are available (https://marine.copernicus.eu/access-data/ocean-monitoring-indicators). Nevertheless, the SLBC component could be taken over by the CMEMS for the same reasons as for the C3S.

Assessing Earth system cycles is a highly scientific activity that requires specific expertise (a thorough understanding of the processes involved in these cycles). This raises the question of whether this activity could be considered a recurring activity within ESA’s CCI programme, and more specifically within the X-ECV activity, as is currently the case. This point is all the more relevant given that ESA is directly involved in the NGGM/MAGIC missions and potentially the ECO mission which are directly related to these topics.

2.6. Communication and outreach activities

The project has been presented on numerous occasions at international conferences and workshops. Here is a non-exhaustive list:

- Döhne et al., Globally consistent land ice mass balance estimates from GRACE/GRACE-FO: Sensitivity to methodological choices, IUGG, 2023
- Ablain et al., Sea Level Budget Closure CCI+ project (ESA, 2023-2026): from validation of the Earth's observing system to scientific questions, OSTST, 2023
- Asselot et al., Reconstruction of the global ocean heat content and thermosteric sea-level rise with an improved configuration of the ISAS interpolation tool, EGU, 2024
- Bouih et al., Global mean and local sea level budget from updated observations and residual analysis (SLBC_cci+ project), International sea level workshop, 2024
- Döhne et al., Investigating effects of solution design choices on L2-based mascon estimates, GRACE-FO Science Team Meeting; 2024
- Bouih et al., How is the global and regional sea level budget closed from the latest observations?, Living Planet Symposium, 2025
- Ablain et al., Assessment of the TOPEX GMSL stability by analysing the global mean sea level closure using the AVISO L2P-2024 products, OSTST, 2025
- Ferrari et al., How is the global and regional sea level budget closed from the latest observations?, International sea level workshop, 2024

The project has also been presented at each ESA Colocation meeting and CMUG.

Furthermore, many scientific publications related to the project have been published (or nearly to be submitted), here is a non-exhaustive list:

- Meyssignac B. et al., How accurate is accurate enough in measuring sea-level rise and variability, Nature Climate Change, 2023, https://doi.org/10.1038/s41558-023-01735-z
- Llovel et al., Cause of substantial global mean sea level rise over 2014-2016, Geophysical Research Letters, 2023, https://doi.org/10.1029/2023GL104709
- Bouih et al., Regional sea level budget over 2004-2022, EGUsphere, 2025, https://doi.org/10.5194/egusphere-2024-3945
- Llovel, W., & Hochet, A. (2025). Salinity contribution to regional sea level trends in the Tropical Southwestern Pacific Ocean over 2014–2023. Geophysical Research Letters, 52, e2025GL116115. https://doi.org/10.1029/2025GL116115
- Cazenave et al., Evidence of Increased Deep Ocean Warming From a Sea Level Budget Approach, Earth's Future, 2026, https://doi.org/10.1029/2025EF007403

- Llovel et al., Salinity contribution to regional sea level trends in the Tropical Southwestern Pacific Ocean over 2014–2023, Geophysical Research Letters, 2025, https://doi.org/10.1029/2025GL116115
- Zilberman et al., Deep Ocean Steric Sea Level Change in the Subtropical Northwest Atlantic Ocean, Geophysical Research Letters, 2026, https://doi.org/10.1029/2024GL114158
- Donatelli et al., Effects of oceanic intrinsic processes on the mean seasonal cycle in sea level, JGR Oceans, 2025
- Song et al., North Atlantic sea level budget revisited, EGUsphere (preprint), 2026, https://doi.org/10.5194/egusphere-2026-802
- SLBC_cci+ paper., Update of global and regional sea-level budget assessment with new insights from alternative inverse method, in prep.

2.7. Point of contact for future enquiries

People that would need more details on the project should contact:

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- **Steric sea level:** Nicolas Kolodziejczyk, Nicolas.Kolodziejczyk(at)univ-brest.fr
- **Glaciers and Ice sheets:** Dr. Jonathan Bamber, j.bamber@bristol.ac.uk
- **Land water storage and atmosphere:** Dr. Ramiro Ferrari, ramiro.ferrari(at)magellium.fr
- **Glacial Isostatic Adjustment and fingerprints:** Dr. Giorgio Spada, giorgio.spada(at)unibo.it

3. Scientific roadmap

The SLBC_cci+ project was designed to advance the understanding of the sea-level budget through four main scientific objectives. First, it aimed to perform a comprehensive assessment of the sea-level budget using the classical approach at both global and regional scales over the periods 1993–2022 and 2002–2022, which was fully achieved. Second, the project sought to quantify uncertainties in the different components and to separate them into measurement and observability uncertainties; this objective was achieved and we have been able to show that the separating and evaluating the observability uncertainties is very important. Now in the future we need to consolidate these results and quantify the exact level of observability uncertainties. To do this we need a thorough and robust estimation of the observational uncertainties over a longer period based on an ensemble of ocean model simulations. Third, it aimed to implement an objective approach to assess the sea-level budget at global and regional scales over the same periods; while progress was made at the global scale, this objective was achieved but the uncertainty on regional scale is likely optimistic as it does not account for the spatial correlation. To get to the next step with a precise quantification we need a robust characterisation of the spatial correlation of errors. Finally, the project intended to carry out detection and attribution analyses to identify the drivers of sea-level change. This objective has been deferred and will be conducted once the current efforts to identify and reduce the causes of the budget misclosure have progressed sufficiently.

The new scientific objectives detailed in the following section have been refined to address key limitations and emerging questions identified during SLBC_cci+ project. While the original objectives focused on establishing and assessing the sea-level budget using classical and objective approaches, as well as estimating uncertainties and preparing for detection and attribution analyses, the results highlighted persistent budget misclosures and important gaps in the characterization of uncertainties. In particular, inconsistencies between observing systems (e.g., satellite altimetry, gravimetry, and in-situ measurements) and the limited consideration of deep ocean processes emerged as critical issues. These scientific objectives focused on a more process-oriented and diagnostic framework, with an emphasis on better quantifying observability and measurement uncertainties, understanding their spatial and temporal correlations, and investigating the physical sources of budget non-closure at both global and regional scales. This includes a stronger focus on deep ocean warming and large-scale circulation changes, such as those associated with the AMOC, which are not fully captured by existing observing systems. These efforts are essential to improve the consistency of the sea-level budget and to enable more robust detection and attribution analyses in the future, particularly in the context of distinguishing natural variability from anthropogenic forcing using climate model ensembles such as CMIP6.

3.1. Scientific Objectives (SO)

3.1.1. [SO-1] : Quantify systematic effects and uncertainties due to ocean observability discrepancies in the SLB components

The analysis performed on the estimation of the observability of the SLB system (combination of in-situ, satellite altimetry and gravimetry) have shown that a significant part of the non-closure observed in the SLB is likely coming from the time and space inconsistent resolution of the different observing systems to observe the same ocean (Figure 18), see [AD3].

These observability inconsistencies in the SLB systems could be explained by the altimetric and the in-situ observing systems (respectively 40% and 60% over the period 2009-2015). An extension of the work performed must be made on a longer time period with different ocean reanalyses to confirm and quantify these results and also to investigate the actual causes of the time and space variability observed in the residuals of the SLB. We suspect this time and space variability could be explained by the deep ocean warming (and in particular the part that is linked to the Atlantic meridional overturning circulation variability) that is not sampled consistently by Altimetry and Argo.

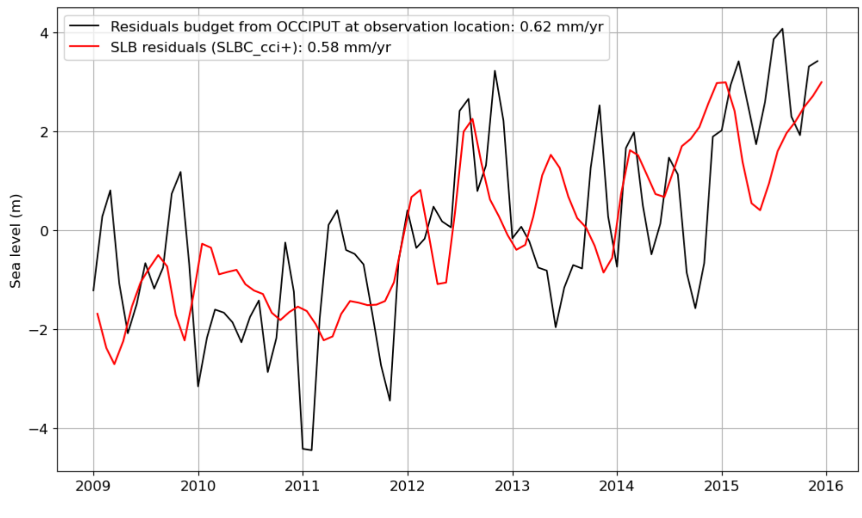

Figure 18 : SLB residuals from OCCIPUT at observation location (black curve) and SLB residuals from observed data (red curve) over the period 2009-2015. A 3-months temporal filter is applied

3.1.2. [SO-2]: Quantify measurement and model uncertainties in the SLB components

The estimation of the measurement and model uncertainties for each sea level budget component needs to be improved and homogenised. For instance only the uncertainties related to the observability of the in situ steric data had been provided, further investigations are needed in order to complete the uncertainty budget by taking into account the instrumental errors and processing errors (i.e. potential drifts). Moreover, estimating spatial correlations among the different SLB components would enable the assessment of uncertainties in the closure of the SLB at the basin scale, as well as the connection between global and regional uncertainty estimates.

The impact of the GIA model correction on the manometric component and the SLB residuals at regional scale has been found surprisingly significant. The use of different GIA models leads to opposite spatial patterns in the SLB residuals. Further analysis on the impact of this correction are needed in order to understand to which extent the correction can help to close the budget and to determine whether the GIA corrections are consistent between altimetry and gravimetry. The uncertainty related to the GIA correction might be taken into account in the budget uncertainty of the manometric component as it is already done in the altimetry error budget and used in the constrained sea level budget approach. That would help to identify objectively some potential deficiencies, bias or drift in the GIA correction.

3.1.3. [SO-3] : Investigate sources of non-closure observed on the SLB at global and regional scales

The first results have shown that an important trend and variability of the SLB residuals after 2016 is observed at global scale (Figure 19), see [AD4]. The source of this non-closure is under investigation. Longer time series of the SLB residuals derived from synthetic data taken from a longer model simulation should help in disentangling the causes for the time variability in the global SLB residuals. The temporal variability of the residuals is likely linked to deep ocean warming signals, potentially driven by AMOC changes for example. Longer time series will help us to compare the residual time series with deep ocean warming time variability and identify how this deep ocean warming variability is resolved in different ways by the different observing systems to shed light on the causes for the SLB residual. In addition the non-closure of the SLB is also observed at a regional scale where important regional patterns of non-closure are present in different locations (Bouih et al., 2025). Identifying these patterns with long time series will help in determining the process responsible for the SLB residuals.

A recent study developed in the framework of this SLBC CCI+ project (Cazenave et al., 2026) conducted with ocean reanalysis data on the non-closure of the global mean sea level budget since 2016 suggests that it results from non-accounting of the deep ocean thermosteric contribution. Using the CIGAR reanalysis developed by the CNR partners, the study shows that closure of the sea level budget is observed beyond 2016 when the deep ocean contribution is taken into account. Additional investigations using ocean reanalyses are required to clearly identify the deep ocean areas involved and the propagation of heat from the surface to depth as a function of time. Comparisons with coupled climate models (CMIP6/7) would also be worth performing. In parallel, comparisons of reanalyses-based deep ocean warming with available Deep Argo temperature data, which are getting more and more available, should be performed.

The approach based on the use of ocean reanalyses to study closure of the global mean sea level budget should be extended to the regional scale, in particular for explaining the large residuals in the North Atlantic found in (Bouih et al., 2025) with ocean reanalysis data.

An alternative approach for these investigations would be to use the objectively constrained product generated during the project. As this approach has allowed to produce optimal solutions that closes the SLB within the uncertainties, it could provide precious information. However, this objectively constrained product has only been provided at global scale to date. The development of the product at regional scale would be necessary to investigate more in depth about regional effects that could occur. However, moving to a regional scale implies considering oceanic transports in the optimization procedure, whose values and uncertainties need to be very carefully estimated, as they are not observed directly.

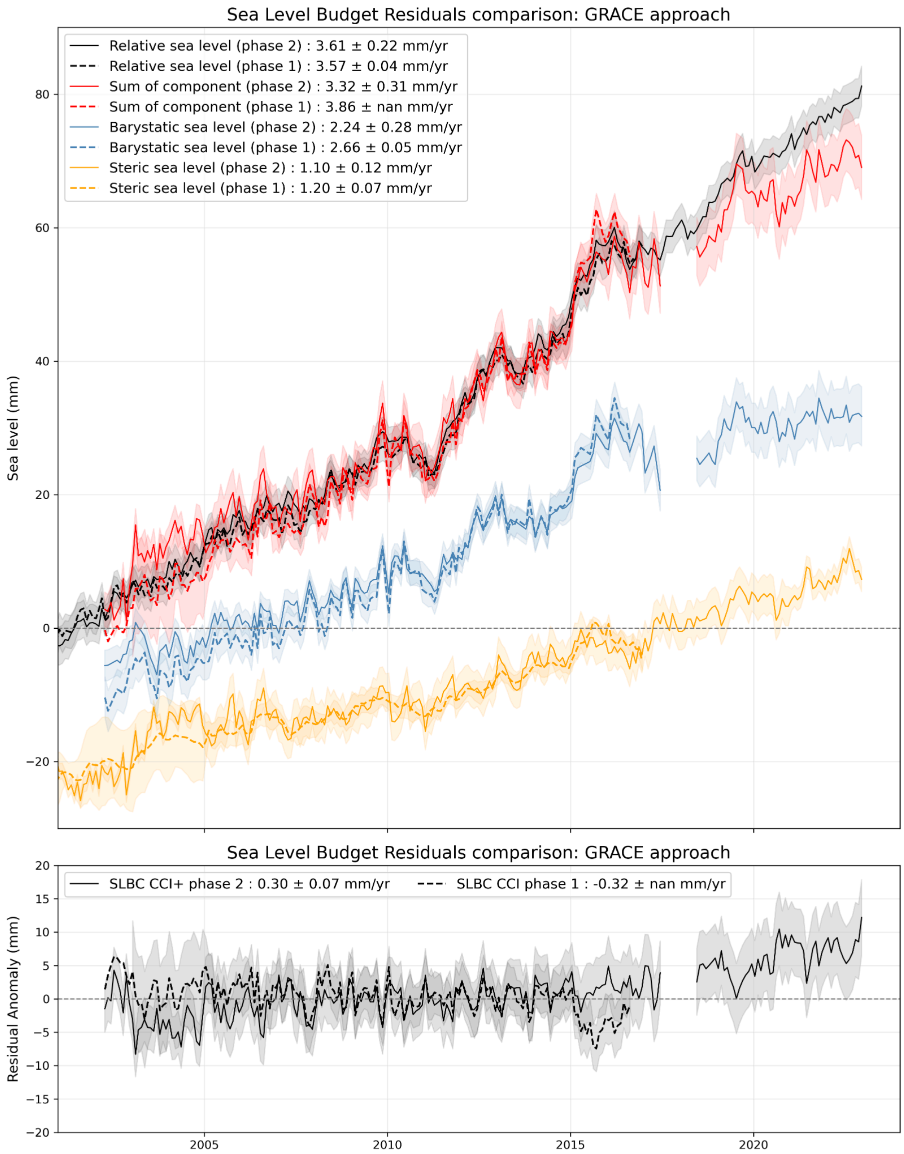

Figure 19 : (a) Global mean sea level budget components using the GRACE-derived barystatic estimate, for SLBC CCI (Phase 1, dashed lines) and SLBC CCI+ (Phase 2, solid lines) and their residuals (b).

3.1.4. [SO-4] : Detecting and attributing the signal in sea level that is forced by GHG emissions

Detection and attribution activities are key and respond to the question of whether the observed spatial trend patterns in sea level are due to the forced signal or they still reflect the natural climate variability. This question has been addressed in recent studies, but remains open and is a challenge to answer. Detection indicates a statistically significant change compared to a previous state, while attribution refers to the identification of the causes for the observed change.

Based on model comparisons (e.g., using the CMIP6/7 outputs), the objective is to distinguish effects from natural variability on the SLB components (i.e. ENSO, etc…) to force signals coming from anthropogenic emissions. At the global scale, studies have shown that the recent GMSL rise cannot be explained by internal climate variability only. However, at a regional scale, the role of anthropogenic forcing is still debated.

The observational evidence of the emergence of deep ocean warming mentioned above is another approach for the detection & attribution. As proposed, additional investigations based on ocean reanalyses and coupled climate models represent a promising new research direction.

3.1.5 [SO-5] Additional in-situ observations, dedicated reprocessing efforts, relationship between surface and interior properties of the ocean in the Arctic

The project's results were largely based on sea-level estimates derived from two different satellite altimetry products specifically developed for the Arctic. This choice behind the selection of Arctic-dedicated datasets was motivated by them allowing for an investigation of sea-level variations in regions that are covered by sea ice either permanently or on a seasonal basis.

The two products yielded interesting results. First, they demonstrated good consistency with each other and, where possible, with a global (not-Arctic-dedicated) sea-level dataset. Second, they suggested sea-level changes of up to ±20 cm over periods of a few-year only, which are indicative of changes in the ocean interior as well as the surface circulation of the Arctic Ocean.

The comparison with independent datasets further helped evaluate and understand the sea-level estimates. However, a thorough evaluation and understanding was hindered by the limited number of observations, both from in-situ and remote-sensing, as well as by their uncertainties. Within this context, future studies of the Arctic Ocean would benefit from the exploitation of in-situ observations to sample the ocean beneath sea-ice, enhancing and extending beyond ARGO floats observations. In this context, including acoustic data would also be beneficial as they would provide independent estimates of temperature and, thus, of its change in the region.

Future Arctic studies would also benefit from further dedicated reprocessing efforts for remote-sensing observations, similar to those undertaken for satellite altimetry. For example, the project's results have highlighted uncertainties in estimates of the sea-level mass component derived from GRACE and GRACE-FO, with different products yielding partially different trends across the Arctic. Further improvements in the reliability of remote-sensed sea-surface salinity estimates would also be highly valuable, as salinity appears to be a primary driver of sea-level variability in the Arctic.

Finally, future Arctic studies would also need a more thorough understanding and exploitation of the relationship between ocean variables at the surface and in the ocean interior. This effort would help maximize the use of the current observing system. For example, if a relationship between satellite and in-situ observations were established, the former could be exploited to infer sub-surface properties of the ocean where the latter are absent or few in number, as it can be the case in sea-ice covered regions.

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