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Regional sea level budget

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over 2004-2022

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27 **ABSTRACT**

28

29 Closure of the regional sea level budget is investigated over the 2004-2022 time span by
30 comparing trend patterns from the satellite altimetry-based sea level with the sum of
31 contributions, i.e. the thermosteric, halosteric, manometric and GRD (Gravitational, Rotational,
32 and Deformational fingerprints due to past and ongoing land ice melt) components. The
33 thermosteric and halosteric components are based on Argo data. For the manometric
34 component, two approaches are considered: one using GRACE/GRACE-Follow On satellite
35 gravimetry data, and the other using ocean reanalyses-based steric sea level data
36 corrected for local steric effects. For the latter, six different ocean reanalyses are considered,
37 including two reanalyses that do not assimilate satellite altimetry data. The results show
38 significantly high residuals in the North Atlantic for both approaches. In other regions, small-
39 scale residuals of smaller amplitude are observed and attributed to the finer resolution of
40 altimetry data compared to the coarser resolution of data sets used for the components. Focus
41 on the strong residual signal seen in the North Atlantic suggests Argo-based salinity errors in
42 this region. However, it is not excluded that other factors also contribute to the non-closure of
43 the budget in this region.

44



45 1. Introduction

46

47 On interannual to decadal time scales, sea level changes in a specific oceanic region arise
48 from several factors. The global mean geocentric sea level rise is primarily driven by ocean
49 warming, land ice melting, and water exchange with continents. Additionally, local and regional
50 effects contribute, including changes in seawater density caused by variations in temperature
51 and salinity (steric effects), as well as the redistribution of ocean water mass through
52 circulation changes (manometric component, Gregory et al., 2019) and variations in
53 atmospheric loading. Furthermore, changes in the solid Earth's gravity, rotation, and
54 deformation (GRD) occur in response to mass redistributions from past and present-day land
55 ice melt and land water storage changes. These GRD factors include two components : the
56 Glacial Isostatic Adjustment (GIA) effect, which stems from the last deglaciation, and GRD
57 fingerprints, which are associated with contemporary land ice melting and, to a lesser extent,
58 changes in land water storage (Gregory et al., 2019).

59 In terms of global average, the rate of sea level rise is dominated by ocean warming via
60 thermal expansion of seawater, and land ice melting (from glaciers, Greenland and Antarctica
61 ice sheets), in response to global warming (e.g., Cazenave et al., 2018, Nerem et al., 2018,
62 Cazenave and Moreira, 2022, IPCC, 2019, 2021; Llovel et al., 2023). The spatial variations of
63 the rate of sea level rise mainly result from steric effects, with the thermosteric contribution
64 being generally dominant (e.g., Stammer et al., 2013, Hamlington et al., 2020), except in the
65 Arctic where the halosteric effect is important (e.g., Carret et al., 2017; Tajouri et al., 2024).

66 Many studies have computed the global mean sea level budget over the altimetry era (i.e.,
67 since the early 1990s) by comparing the global mean sea level rise with the sum of the thermal
68 and mass components from independent observing systems (e.g., Dieng et al., 2017, Nerem
69 et al., 2018, WCRP, 2018, Horwath et al., 2022, Chen et al., 2018, 2020, Barnoud et al., 2021,
70 2023, to focus only on the most recent publications). These studies have shown that at least
71 until 2016, the global mean sea level budget is closed within the data uncertainties. In recent
72 years, some discrepancy has been observed between the altimetry-based global mean sea
73 level and the sum of the Argo-based steric and gravimetry-based mass components (e.g.,
74 Chen et al., 2020, Barnoud et al., 2023, Mu et al., 2024), especially when using the Gravity
75 Recovery And Climate Experiment (GRACE) and GRACE Follow-On (GRACE-FO) satellite
76 data to estimate the manometric sea level change, instead of individual mass contributions
77 (i.e., glaciers, Greenland and Antarctica ice sheets, land waters and atmosphere water
78 vapour). At regional scale, the closure of the sea level budget has been less studied so far. A



79 few recent studies have assessed the closure of the sea level budget at the basin-scale, over
80 the altimetry era (e.g., Rietbrock et al., 2016, Frederiske et al., 2016, 2018, 2020; Hamlington
81 et al., 2020, Royston et al., 2020, Camargo et al., 2023, Mu et al., 2024). The regional ocean
82 mass budget has also been investigated (Ludwigsen et al., 2024). Closure of the regional
83 budget is only observed in some regions but not everywhere. For example, using altimetry,
84 gravimetry and Argo data over 2005-2015, Royston et al. (2020) concluded that the regional
85 budget cannot be closed in the Indian-South Pacific region. Similarly, Camargo et al. (2023)
86 also found non-closure of the regional sea level budget in a number of oceanic areas. Using
87 machine learning techniques, these authors were able to identify processes not well captured
88 by the observations that are considered to assess closure of the regional sea level budget.

89 In the above studies, closure of the regional budget was assessed by averaging the data either
90 at basin-scales or sub-basin scales. In the present study, we revisit the regional sea level
91 budget over the GRACE/Argo era (starting in 2004) at the local scale, without averaging the
92 data at the basin-scale. After removing the global mean trend of each component, we focus
93 on the spatial trend patterns, with a resolution of about 300 km, as allowed by the gridded data
94 sets considered, an approach not applied in the previous studies. This approach avoids
95 compensation of spurious positive/negative sub-basin trend patterns and allows for more
96 precise identification of the areas where the sea level budget is not closed.

97 For this investigation, we used gridded satellite altimetry data for the observed sea level
98 changes and Argo data to estimate the thermosteric and halosteric sea level changes. For the
99 manometric component, two types of data are considered: satellite gravimetry data from the
100 GRACE and GRACE FO missions as well as ocean reanalyses to estimate the redistribution
101 of water mass already in the ocean (following the same approach as in Camargo et al., 2023,
102 i.e., estimating steric sea level changes corrected for local steric effects; see section
103 3). The study period covers the period from January 2004 to December 2022 (although some
104 data sets end in December 2019; section 3).

105



106 **2. Brief overview of the sea level components at**
107 **regional scale**

108 **2.1. Steric component**

109 The steric component includes the effects of ocean temperature and salinity changes. Remote
110 surface wind forcing, heat and freshwater fluxes associated with variations in the overlying
111 atmospheric state are the two main forcing mechanisms causing steric changes (Stammer et
112 al., 2013, Roberts et al., 2016). Wind forcing modifies the ocean circulation which further
113 redistributes heat and water masses. It is the dominant mechanism of interannual to decadal
114 steric changes in many regions, particularly in the tropics (e.g., Timmermann et al., 2010;
115 Merrifield and Maltrud, 2011; Piecuch and Ponte, 2014; England et al., 2014). Wind forcing
116 can also play a role in the extra tropics and at high latitudes (Roberts et al., 2016). Buoyancy
117 forcing, i.e. surface air-sea fluxes of heat and freshwater (due to surface warming and cooling
118 of the ocean, and exchange of freshwater with the atmosphere and land through evaporation,
119 precipitation, and runoff) is important in mid to high latitudes, e.g., in the North Atlantic Ocean
120 (Gulf Stream and North Atlantic subpolar gyre) (Roberts et al., 2016).

121 Over the altimetry era, regional sea level patterns are dominated by steric changes. In most
122 regions, the thermosteric component by far dominates the halosteric one, except in the North
123 Atlantic Ocean (Llovel and Lee, 2015) and in high latitude areas, e.g., in the northeast Pacific,
124 and particularly in the Arctic (e.g., Carret et al., 2016; Ludwigsen et al., 2022, Tajouri et al.,
125 2024). On interannual to multidecadal time scales, the spatial trend patterns in (thermo) steric
126 sea level are still largely influenced by basin-scale internal climate modes of variability, e.g.,
127 El Niño-Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), Atlantic Multidecadal
128 Oscillation (AMO), North Atlantic Oscillation (NAO) and Indian Ocean Dipole (IOD). Wind
129 stress changes on such time scales are indeed directly related to climate modes (Han et al.,
130 2017). For example, sea level in the tropical Pacific oscillates from west to east with ENSO
131 (with high/low sea level in the eastern/western part during El Niño/La Niña events), in response
132 to wind-forced propagating waves. In the North Atlantic, surface wind and heat flux partly drive
133 interannual to decadal sea level fluctuations and are associated with the NAO (but changes
134 in the Atlantic Meridional Ocean Circulation also contribute) (Han et al., 2017). In the tropical
135 Indian Ocean, interannual to decadal variability in sea level is strongly influenced by ENSO
136 and the IOD (Han et al., 2017, 2019).



137 2.2. Manometric component

138 The regional manometric sea level change essentially results from spatial redistribution of
139 water mass already in the ocean by the ocean circulation, plus the total water mass added to
140 the ocean (the latter being called barystatic component; Gregory et al., 2019), due to land ice
141 melt and to the exchange of water with the continents. The barystatic contribution nearly
142 uniformly covers the oceanic domain rapidly (within a few weeks) via a barotropic global
143 adjustment occurring on short time scales (Lorbacher et al., 2012). Because the global mean
144 trend of each component of the regional sea level budget is removed in this study, the
145 barystatic component disappears. Compared to steric changes, the manometric sea level
146 change due to water mass redistribution (barystatic contribution removed), plays a smaller
147 role on interannual to decadal time scales, but can be sizeable (e.g., Dangendorf et al., 2021,
148 Wang et al., 2022), in particular at high latitudes and over shallow continental shelves (e.g.,
149 Forget and Ponte, 2015; Carret et al., 2021).

150 2.3. Atmospheric loading

151 On seasonal and longer time scales, sea level responds as an inverted barometer to
152 atmospheric loading (Wunsch and Stammer, 1997) i.e. the sea surface height increases
153 (decreases) by 1 cm if the local surface pressure decreases (increases) by approximately 1
154 mbar. The atmospheric loading component is quite small compared to the thermosteric one,
155 but it is non-negligible at high latitudes (e.g., in the Arctic Ocean where it can reach 0.3 mm/yr
156 on interannual to decadal time scales, Proshutinski, 2004). Atmospheric loading can be
157 estimated using e.g. surface pressure data from atmospheric reanalyses. Note that it does not
158 affect the global mean sea level because of mass conservation.

159 2.4. Gravity, Earth Rotation, and solid Earth Deformations (GRD)

160 The response of the solid Earth to past and present-day water mass exchange between
161 continents and oceans causes global and regional sea level changes. The GIA results from
162 the ice and water mass redistribution of the last deglaciation. Its effect depends on the Earth's
163 mantle viscosity and deglaciation history. The response of the solid Earth to ongoing land ice
164 melt essentially depends on the elasticity of the lithosphere and mantle, as well as on the
165 amount and location of ice mass loss. These mass redistributions induce changes in the
166 gravity, rotation, and visco-elastic deformations of the solid Earth (Mitrovica et al., 2001; Milne
167 et al., 2009; Stammer et al., 2013). These are the so-called GRD (Gravity, Earth Rotation, and
168 solid Earth Deformations) fingerprints (Gregory et al., 2019). In the literature, the GRDs are



169 often separated into the ones resulting from the GIA (last deglaciation) and the contemporary
170 GRDs, the latter referring to mass redistributions due to present-day land ice melt and land
171 water storage variations. In terms of global average, the GIA effect on sea level change is
172 around -0.3 mm/yr (Peltier, 2004; Tamisiea, 2011; Caron et al., 2018). Its regional signature
173 is mostly uniform, except in formerly glaciated high-latitude regions. The contemporary GRD
174 fingerprints produce complex regional patterns in sea level change : sea level drops near the
175 melting bodies but sea level rises in the far field (e.g., along the northeast coast of America).
176 Several studies have theoretically computed the impact of contemporary GRD changes on
177 relative and absolute sea levels, by solving the sea level equation, either assuming a priori
178 current ice sheet mass loss (e.g., Mitrovica et al., 2001, Tamisiea, 2011, Spada, 2017), or
179 using realistic ice mass loss based observations from the GRACE satellite gravimetry mission
180 (Adhikari et al., 2019). Note that the sea level fingerprints associated with the GIA and the
181 contemporary GRDs are mostly expressed in terms of linear trends and have a small
182 amplitude compared to the observed regional sea level and steric sea level trends. However,
183 with the expected increase of land ice melt in the coming decades, the contribution of the
184 contemporary GRD fingerprints to regional sea level trends may become increasingly
185 significant.
186

187 3. Data and methods

188 3.1. Data

189 3.1.1 Total sea level

190 The total sea level is routinely observed by satellite altimetry. In this study, we use the daily
191 $1/4^\circ \times 1/4^\circ$ gridded sea level anomaly data from the Copernicus Climate Change Service (C3S)
192 Climate Data Store (CDS) (Copernicus Climate Change Service, 2018). To ensure the long-
193 term stability of this altimetry-based data, C3S sea level anomalies rely on two simultaneous
194 satellite missions at any given time : the successive reference missions (TOPEX/Poseidon,
195 Jason-1, Jason-2, Jason-3, and Sentinel-6 Michael Freilich) plus an auxiliary mission from the
196 global constellation. The dataset is corrected for TOPEX-A altimeter drift (Ablain et al., 2017),
197 as well as for the Jason-3 radiometer drift that impacts the wet troposphere correction (Brown
198 et al. 2023). The dataset covers the period from January 1993 to December 2023. The C3S
199 dataset is corrected for GIA using the ICE6G-D model (Peltier et al., 2018). Total sea level
200 uncertainties are derived following Ablain et al. (2019) and updated by Guérou et al. (2023).



201 3.1.2 Steric sea level

202 We use the Argo-based steric sea level data from the Scripps Institution of Oceanography
203 (SIO), which provides monthly gridded data at a $1^\circ \times 1^\circ$ resolution (Roemmich and Gilson,
204 2009). The choice for the SIO product is motivated by the fact that its post-processing corrects
205 for the salinity drift reported in Argo floats since 2015, which misleads to a spurious increase
206 reported in the global mean salinity (Wong et al., 2023; Liu et al., 2020, 2024; Ponte et al.,
207 2021). This salinity drift has a significant impact on the sea level budget closure (Chen et al.,
208 2020; Barnoud et al., 2021). The SIO processing methodology considers the most up-to-date
209 delayed-mode Argo profiles which have been meticulously quality-controlled by a scientist
210 (typically within 1-2 years after the float transmits the data). In addition, the SIO processing
211 adjusts the real-time Argo profiles (which have passed through automatic quality-control
212 typically within 24 h) to fit the WOCE (World Ocean Circulation Experiment) global
213 hydrographic climatology. This specific processing has the benefit of removing the salinity drift
214 in the SIO steric sea level data (Liu et al., 2024). The dataset covers the period from January
215 2004 to December 2022, within the 0–2000 m depth range, and the latitudes between 66°S
216 and 66°N .

217 In this study, the deep ocean's contribution to steric sea level is not considered due to its small
218 magnitude and possibly high uncertainty (e.g., Purkey and Johnson, 2010). The thermosteric
219 steric sea level, halosteric sea level and total steric sea level changes are computed from the
220 temperature and salinity gridded data using the lenapy library
221 (<https://github.com/CNES/lenapy>) from the Centre National d'Études Spatiales (CNES), based
222 on the Gibbs seawater oceanography toolbox of the 2010 Thermodynamic Equation Of
223 Seawater (TEOS-10).

224 3.1.3 Manometric sea level

225 The manometric sea level change is estimated using two independent methods.

226 The first approach relies on satellite gravimetry data from the GRACE mission (2002-2017,
227 Tapley et al., 2019) and GRACE-FO mission (launched in 2018, Landerer et al., 2020), which
228 enables to estimate changes in the Earth's gravitational field linked to mass redistribution,
229 including the regional sea level variations due to GRD effects. Two sources of GRACE
230 solutions are considered:

- 231 - (1) An ensemble mean of so-called mass concentration (mascon) solutions. We use
232 the latest GRACE and GRACE-FO Release 6 mascon solutions from the Center for
233 Space Research (CSR; Save et al., 2016), Jet Propulsion Laboratory (JPL; Watkins et
234 al., 2015), and Goddard Space Flight Center (GSFC; Loomis et al., 2019). These
235 mascon solutions are corrected for the GIA effect using the ICE6G-D model (Peltier et



236 al., 2018), as well as for the geocenter motion using the correction from Sun et al.
237 (2016). The manometric component is estimated as the mean of these three gridded
238 ocean mass products, which are given in equivalent water height.

239 - (2) An ensemble of 60 spherical harmonic solutions. This ensemble is derived from the
240 manometric GRACE-based products (DOI: 10.24400/527896/a01-2023.011 version
241 4.0) and distributed at AVISO+ (<https://aviso.altimetry.fr>). This product allows for
242 uncertainty estimates linked to various stages of GRACE and GRACE-FO data
243 processing (Blazquez et al, 2018). This ensemble of 60 solutions results from the
244 combination of five processing centres, three C20/C30 (spherical harmonics of degree
245 2 and 3 of the gravity field potential) estimates, two GIA models (ICE6G-D from Peltier
246 et al., 2018 and the model from Caron et al., 2018), and two filtering levels. The
247 geocenter motion is corrected with a model based on the approach developed by Sun
248 et al. (2016) and Swenson et al. (2008). Each ensemble member is also corrected for
249 the water vapor mass in the atmosphere using the C0 from GAA (Chen et al, 2019).
250 For each ensemble member, atmospheric loading over the ocean is restored using the
251 GAD products (Flechtner et al., 2015) to correct for the inverse barometer effect,
252 aligning the ocean mass variations with satellite altimetry data in which atmospheric
253 loading is already accounted for.

254 The two sets of GRACE data used here cover the period from January 2004 to December
255 2022.

256 The second approach follows Camargo et al. (2023) method which derives the manometric
257 sea level change from ocean reanalyses. Ocean models provide the steric sea level
258 change, i.e., the sea level change due to changes in ocean density and circulation, with the
259 inverse barometer correction applied (Gregory et al., 2019; Storto et al., 2024). The
260 corresponding manometric component is derived by correcting the reanalysis-based
261 steric sea level by the local steric effect and adding the contemporary GRD
262 fingerprints. It is the approach followed here. Due to the temporal availability of some
263 reanalyses, part of the analyses only cover the period from January 2004 to December 2019,
264 while others are extended to December 2022.

265 We consider six different ocean reanalyses with different characteristics as listed in Table 1.
266 GLORYS, C-GLORS, ORAS5, and FOAM use the NEMO (Nucleus for European Modelling of
267 the Ocean) ocean model and assimilate satellite altimetry-based sea level data. The SODA
268 reanalysis is based on the MOM (Modular Ocean Model) developed by NOAA (National
269 Oceanographic and Atmospheric Administration, USA) and does not include altimetry data.
270 All these reanalyses have a spatial resolution of 0.25° . In order to assess the regional sea
271 level budget with another manometric component independent of satellite altimetry data, we
272 also consider an ensemble reanalysis at lower resolution and without altimetry data



273 assimilation (called CIGAR; see Table 1). This variety of reanalyses offers the opportunity to
 274 evaluate the degree of consistency of the manometric signal from reanalysis-based products.

275

276 *Table 1 : Characteristics of the six ocean reanalyses used in this study to estimate the*
 277 *manometric sea level change patterns independently from GRACE and GRACE-FO data.*

<i>Reanalysis</i>	Ocean model, Spatial Resolution, End date	Data assimilation of altimetry-based sea level data	References
GLORYS (MOI)	NEMO, 0.25°, 2022	Yes	Garric and Parrent (2017)
C-GLORS (CMCC)	NEMO, 0.25°, 2022	Yes	Storto and Masina (2016)
ORAS5 (ECMWF)	NEMO, 0.25°, 2022	Yes	Zuo et al. (2019)
FOAM (UK Metoffice)	NEMO, 0.25°, 2022	Yes	Blockley et al. (2014)
SODA (Version 3.4.2, U.Maryland)	MOM4, 0.25°, 2019	No	Carton et al. (2018)
CIGAR (CNR- ISMAR)	NEMO, 1°, 2022	No	Storto and Yang (2024)

278

279 To compare the manometric component derived from ocean reanalyses with the one based
 280 on GRACE and GRACE-FO, we added the contemporary GRD contribution to the reanalysis-
 281 based manometric sea level change. We used the sea level fingerprint data from Adhikari et
 282 al. (2019), which provides monthly contemporary GRD fingerprints at a 0.5° x 0.5° resolution.
 283 Because the Adhikari et al. (2019) data set ends in 2016, we linearly extrapolated the GRD
 284 fingerprints up to 2022 and added the corresponding trends to the ocean reanalyses-based
 285 manometric trends.

286 3.2. Method

287 Systematic corrections for both atmospheric loading and GIA effects are applied to altimetry-
288 based and satellite gravimetry datasets, even though different models are used in each
289 dataset. The MOG2D (Carrere and Lyard, 2003) and inverse barometer model is used for
290 altimetry data (www.aviso.altimetry.fr), while the GAD product, which represents monthly
291 mean ocean bottom pressure due to non-tidal dynamic oceanic and atmospheric mass
292 variations, is used for GRACE and GRACE-FO data. It is based on the AOD1B model
293 (Flechtner et al., 2015). Likewise, the GIA corrections rely on the ICE6-G model for altimetry
294 (Peltier et al. 2018), while GRACE datasets use either ICE6-G (Peltier et al. 2018) or Caron
295 et al. (2018) models.

296 All datasets were spatially interpolated onto a $1^\circ \times 1^\circ$ grid and were averaged on a monthly
297 basis. For spatial consistency, a common masking technique was applied to all gridded
298 components. This mask covers latitudes from 66°S to 66°N , excludes inland seas, and omits
299 coastal regions where the distance from land is less than 300 km. A spatial $3^\circ \times 3^\circ$ Lanczos
300 filter was then applied to each grid to smooth out the highest resolution features not observed
301 by all observing systems.

302 Finally, seasonal signals (annual and semi-annual) were removed at each grid mesh of each
303 data set through a simple least-squares adjustment of 6-month and 12-month sinusoids, and
304 a 3-month Lanczos filter was applied locally to each dataset to remove high frequency signals.
305 The global mean trend of each dataset computed over the study period was also removed.

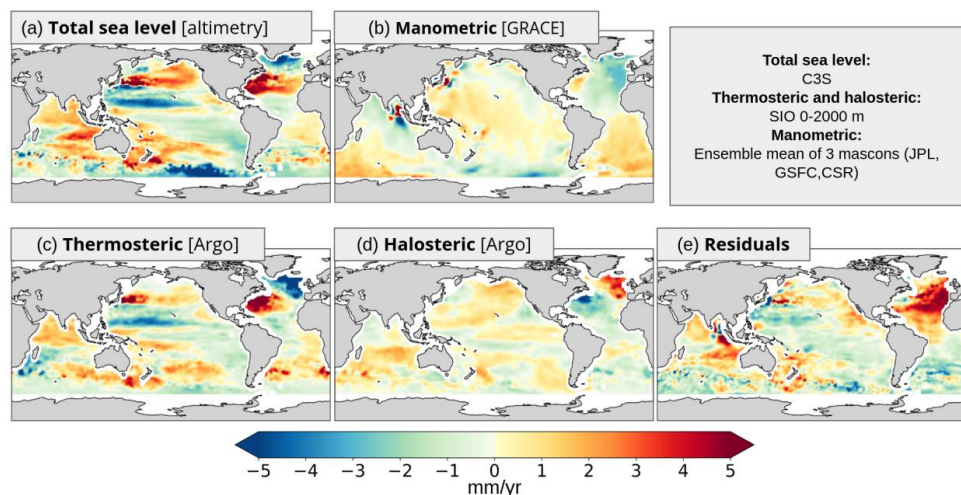
306 All datasets span from January 2004 to December 2022, except for the oceanic reanalyses-
307 based manometric components for which two study periods were considered, depending on
308 the dataset availability: January 2004-December 2019 and January 2004-December 2022.

309 4. Results : Regional sea level budget with GRACE 310 and Argo

311 4.1. Trend patterns in observed sea level, components and 312 residuals

313 Figure 1 shows the maps of altimetry-based sea level trends, of the GRACE- and Argo-based
314 component trends, and of the residual trends (i.e., trend differences between altimetry-based
315 sea level and sum of components).

316



317

318 *Figure 1: Sea level trends over January 2004 to December 2022 in observed altimetry-based*
319 *sea level (a), components (b, c, d: GRACE-based manometric, Argo-based thermosteric and*
320 *Argo-based halosteric sea level) and budget residual trends (observed sea level minus sum*
321 *of components) (e).*

322

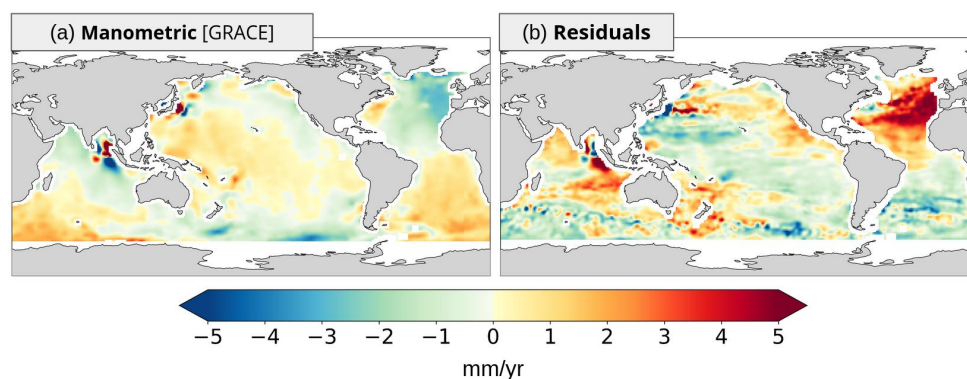
323 Visual inspection of Figure 1 confirms earlier findings, i.e., the observed regional trend patterns
324 are dominated by the thermosteric trend patterns (e.g., Stammer et al., 2013; Hamlington et
325 al., 2020; Cazenave and Moreira, 2022). The manometric and halosteric components have in
326 general lower amplitude than the thermosteric one, except in the North Atlantic where
327 thermosteric and halosteric trends have opposite signs (e.g., Stammer et al., 2013).

328 The residual map shows that in many regions, the sum of components does not cancel out
329 the observed trends. This is the case in the North Atlantic where a strong positive residual is
330 observed. In this region, altimetry-based sea level displays positive trends in the western part
331 and negative trends south of Greenland. The opposite patterns in the thermosteric and
332 halosteric components of the North Atlantic agree well in terms of regional extent but a larger
333 amplitude is noted in the thermosteric component. It is worth noting that the North Atlantic
334 manometric sea level has similar patterns as the thermosteric ones but they are more diffuse
335 (possibly due to the lower resolution of GRACE data) and of lower amplitude.

336 In the northeast Atlantic, the observed strong residuals result from an absence of signal in this
337 region in the thermosteric and halosteric component combined with a slightly negative signal
338 in the manometric component, possibly a result of errors in both GRACE and Argo datasets.
339 The strong residual signal in the North Atlantic is discussed in detail in section 6.



340 Another striking observation from Figure 1 is that large-scale residuals over the Pacific, Indian,
341 North and South Atlantic Oceans are anti-correlated to those of the manometric sea level. This
342 is highlighted in Figure 2. A priori, such an anti-correlation would suggest that the large-scale
343 residual patterns are caused by spurious GRACE signal since its removal in the altimetry-
344 based sea level trends corrected for the Argo-based steric component does not lead to
345 cancellation.



346

347 *Figure 2: Large-scale trend patterns in the GRACE-based manometric sea level (a) and*
348 *residuals (b).*

349

350 4.2. GRACE data assessment

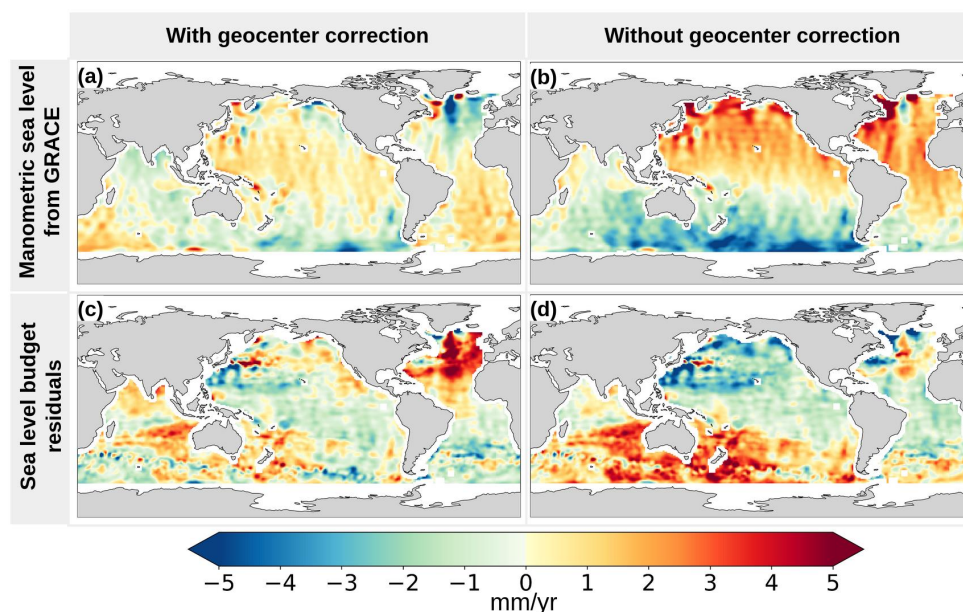
351 To explore the origin of the observed large-scale anti-correlation between GRACE-based
352 manometric and residual trends, we analysed the effects of the geocenter and GIA corrections
353 applied to GRACE data. To assess the contribution of low degrees to the sea level budget
354 residuals, we decomposed the sea level budget components into spherical harmonics and
355 computed the residuals for various configurations of low degree harmonics (see
356 supplementary information, SI). Figure S1 and Table S1 show that degree 1,0 (related to the
357 geocenter motion) and degree 2,1 (related to polar motion and GIA correction) harmonics
358 contribute to the high residuals in the North Atlantic Ocean.

359 GRACE data are classically corrected for the geocenter motion when compared with altimetry
360 data, which leads to moving GRACE observations from the centre of mass to the centre of
361 figure of the reference system. However, the theoretical basis for correcting GRACE data for
362 the geocenter motion when comparing with altimetry remains unclear. Indeed, altimetry data



363 are supposed to be also provided in a centre of mass reference system, the satellite orbits
364 being expressed in such a reference system (Alexandre Couhert, personal communication).

365 Using the ensemble of 60 spherical harmonic solutions described in Section 3.1, we
366 constructed an alternative ensemble of 60 solutions without applying the correction for the
367 geocenter motion, i.e. keeping the GRACE observations in the centre of mass reference
368 system. Comparing these two ensembles of solutions allows us to assess the influence of the
369 geocenter correction on the manometric component and, consequently, on the residuals of
370 the sea level budget. Figure 3 shows the impact of the geocenter correction on the manometric
371 trends as well as on the associated residual trends. Not correcting for the geocenter motion
372 reduces the residuals observed in the North Atlantic Ocean but increases the residual trends
373 elsewhere, with larger residuals in almost all other ocean basins. Thus, even if the Sun et al.
374 (2016)'s geocenter correction may not be optimal, it minimizes the residual trends everywhere,
375 except in the northeast Atlantic Ocean. This questions the actual referential of altimetry data
376 and the consistency of the processing between satellite altimetry and satellite gravimetry data.
377 Besides, if no geocenter correction should be applied, this means that GRACE observes large
378 scale signals not observed by altimetry data, so that one may wonder whether some altimetry
379 data corrections and post-processing could alter large-scale signals.



380

381 *Figure 3: Sea level trends of manometric and corresponding budget residuals with and without*
382 *geocenter correction. (a) Manometric sea level trend map with the geocenter correction, (b)*
383 *Manometric sea level trend map without the geocenter correction, (c) Sea level budget*



384 *residual trend map computed with the manometric component corrected for the geocenter, (d)*
385 *Sea level budget residual trend map computed with the manometric component not corrected*
386 *for the geocenter.*

387

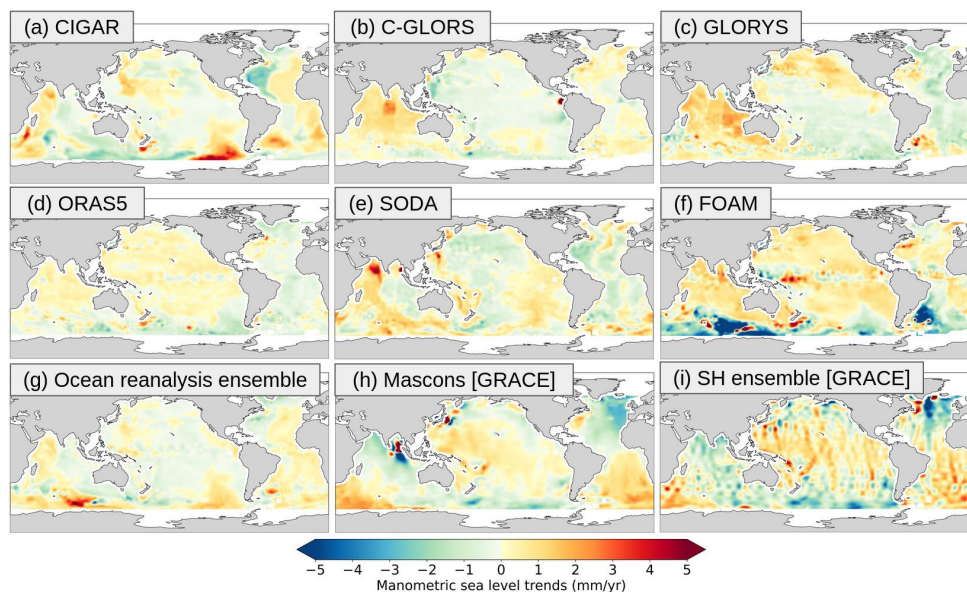
388 To estimate the impact of the GIA corrections on the manometric component and budget
389 residuals, we further formed two separate subsets of 30 solutions each for each GIA model
390 (Peltier et al, 2018 and Caron et al., 2018), applying the Sun et al. (2016)'s geocenter
391 correction to each subset. Unlike for the geocenter case, no significant difference was
392 observed.

393

394 5. Regional sea level budget using ocean 395 reanalyses for the manometric component

396 As explained in section 2, according to Gregory et al. (2019) and Camargo et al. (2023), the
397 dynamic ocean mass redistribution due to ocean circulation changes can be estimated from
398 the steric sea level corrected for local steric changes. Thus, in this study, we apply
399 here the Camargo et al. (2023)'s approach and use ocean reanalyses to estimate the
400 manometric component, in order to further assess closure of the regional sea level budget.

401 As detailed above (section 3), six different ocean reanalyses have been considered over their
402 common period from January 2004 to December 2019. Figure 4 shows the reanalysis-based
403 manometric trend maps over 2004-2019, for each of the six data sets, as well as their mean.
404 The manometric components based on the two sets of GRACE solutions, restricted to this
405 study period, are also shown.



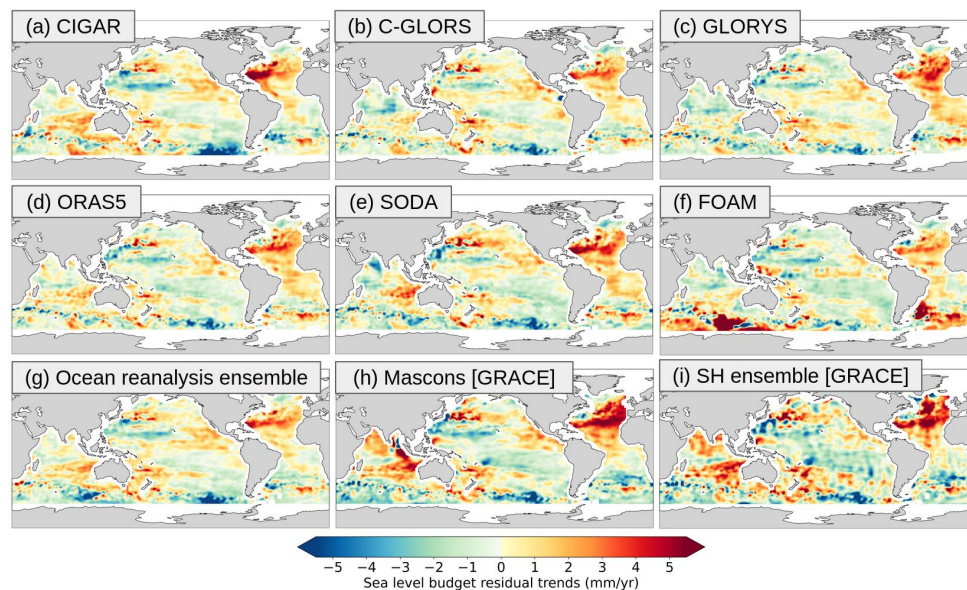
406

407 *Figure 4: Reanalysis-based manometric trend maps over January 2004-December 2019 for*
 408 *each of the six ocean reanalyses: CIGAR, C-GLORS, GLORYS, ORAS5, SODA and FOAM*
 409 *(panels a to f). Panel (g) shows the ensemble mean of the six reanalyses. Panels h and i refer*
 410 *to the manometric component from the GRACE mascon and GRACE spherical harmonic (SH)*
 411 *ensembles.*
 412

413 The six reanalyses provide quite different manometric trend patterns. The FOAM and ORAS5
 414 patterns are quite similar in the Pacific and Indian Oceans. In these regions, C-GLORS,
 415 CIGAR and GLORYS show rough agreement. SODA's patterns differ from the other
 416 reanalyses everywhere, although they look similar to CIGAR in the Indian Ocean.

417 Two statements can be made by comparing reanalyses-based averaged map with the
 418 GRACE-based manometric map : (1) the spatial patterns of the reanalysis-based manometric
 419 trend map have generally lower amplitude than the GRACE ones, and (2) except in the North
 420 Atlantic, the spatial trends of the ensemble mean reanalyses and GRACE have opposite signs.

421 The regional budget has been computed with each of the six reanalyses as well as their mean,
 422 all other data being kept unchanged. The corresponding residual trend patterns are shown in
 423 Figure 5.



424

425

426 *Figure 5: Residual trends of the regional sea level budget computed with each of the six*
 427 *reanalyses-based manometric data sets, as well as with their mean (panels a to g) (with*
 428 *altimetry-based and steric components unchanged). GRACE-based residual trends for both*
 429 *mascons and spherical harmonic solutions are also shown (panels h and i). The period of*
 430 *analysis here is from January 2004 to December 2019.*
 431

431

432 The CIGAR, C-GLORS, SODA, ORAS5, and GLORYS reanalyses give very similar residual
 433 trend patterns, even though SODA uses completely different ocean models, data assimilation
 434 schemes, and no altimetry-based sea level anomaly data assimilated. Note that CIGAR does
 435 not either assimilate altimetry-based sea level anomaly data, but it is forced by the latest
 436 atmospheric reanalysis from ECMWF (unlike the other reanalyses) and embeds a daily
 437 varying runoff dataset for freshwater discharge into the oceans. One outlier is FOAM which
 438 shows strong positive residual trends in the southern Atlantic and Indian Oceans. The
 439 ensemble mean residual trend map displays a lower signal than the GRACE cases (panels h
 440 and i of Figure 5). What is striking is that the two approaches (reanalyses and GRACE) show
 441 positive residual trends in the North Atlantic. However, the residuals are significantly stronger
 442 using GRACE, especially in the northeastern part of the Atlantic Ocean. This will be discussed
 443 in section 6.

444 Table 2 shows the root mean square (RMS) of the gridded residuals trends over 2004-2019,
 445 averaged over the Pacific, Indian, North and South Atlantic Oceans for the reanalyses and
 446 GRACE cases.



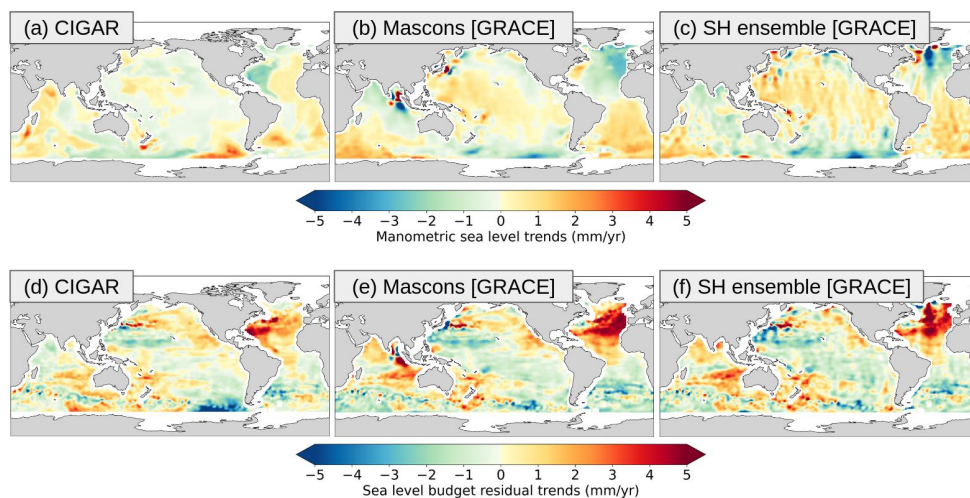
447 If we except FOAM which displays higher RMS in the Indian and South Atlantic Oceans than
448 other reanalyses, Table 2 clearly shows systematically higher RMS (in the range 2-3 mm/yr)
449 in the North Atlantic Ocean for the C-GLORS, SODA, GLORYS and ORAS5 reanalyses as
450 well as for GRACE mascons.

451 *Table 2: RMS of gridded residuals trends over 2004-2019, averaged over the Pacific, Indian,*
452 *North and South Atlantic Oceans for the GRACE and reanalyses cases.*

RMS (mm/yr)	Pacific	Indian	North Atlantic	South Atlantic
C-GLORS	1.48	1.46	2.02	1.35
FOAM	1.66	2.81	1.99	2.54
SODA	1.58	1.79	2.68	1.56
GLORYS	1.34	1.61	2.49	1.72
ORAS5	1.39	1.38	2.15	1.37
GRACE mascons	1.51	1.78	2.92	1.43

453

454 Because four of the reanalyses used above assimilate altimetry data (i.e., C-GLORS,
455 GLORYS, ORAS5 and FOAM), our approach may introduce some circularity to the regional
456 sea level budget assessment. This is the reason for also using reanalyses without altimetry
457 data assimilation (SODA and CIGAR). Here we focus on CIGAR and extend the study period
458 to December 2022. Results are shown in Figure 6. Comparing the manometric components
459 of two versions with and without altimetry data assimilation (e.g., C-GLORS and CIGAR,
460 noting however that they differ in terms of resolution, configuration and forcing) shows some
461 differences locally, in particular in the northwestern Atlantic and North Indian Oceans.
462 However, the residual trend maps are very similar. The case without altimetry data assimilation
463 (CIGAR) still shows significant residual signal in the North Atlantic Ocean. This observation
464 points to the steric component (and possibly the halosteric component) as the main suspect
465 for the non-closure of the budget in the North Atlantic Ocean.



466

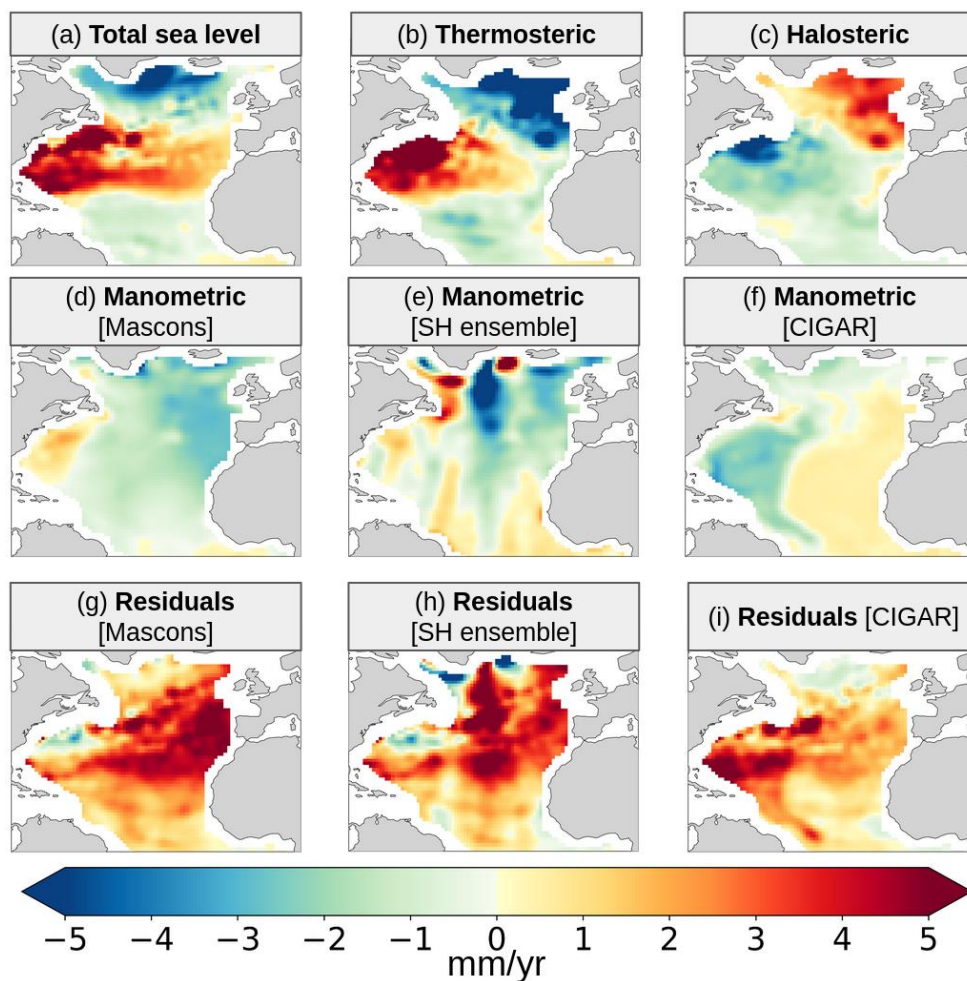
467 *Figure 6: Manometric component based on the CIGAR reanalysis (reanalysis without altimetry*
468 *data assimilation) (panel a), and the two GRACE solutions (panels b and c). Sea level budget*
469 *residuals using the CIGAR-based manometric component (panel d) and the two GRACE*
470 *manometric components (panels e and f). The period of analysis here is from January 2004*
471 *to December 2022.*

472

473 6. Residual trends in the North Atlantic Ocean

474 In this section, we focus on the North Atlantic Ocean where positive residuals are observed
475 when using either GRACE or the CIGAR reanalysis for estimating the manometric component.

476 Figure 7 shows each component of the budget over the North Atlantic Ocean over January
477 2004-December 2022, computed using three manometric component estimates: GRACE
478 mascons, ensemble mean GRACE SH and CIGAR reanalysis. Associated residual maps (all
479 components unchanged except the manometric one) are also shown.
480



481

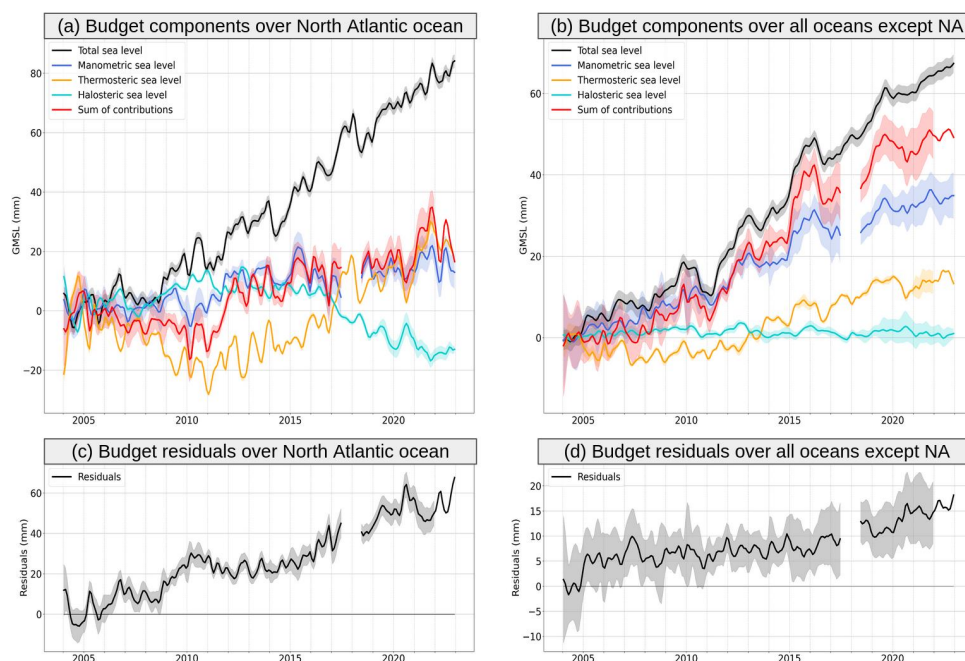
482 *Figure 7: North Atlantic Ocean sea level trends (mm/yr) over January 2004 to December 2022:*
483 *Observed altimetry-based sea level (a), Argo-based thermosteric and halosteric components*
484 *(b,c), manometric components from GRACE mascon (d), ensemble mean GRACE spherical*
485 *harmonics (e) and derived from CIGAR reanalysis (f). Sea level budget residuals (observed*
486 *sea level trends minus sum of component trends) using GRACE mascon (g), ensemble mean*
487 *GRACE spherical harmonics (h) and CIGAR (i).*

488 The North Atlantic Ocean residuals of all three manometric component cases (GRACE
489 mascons, ensemble mean GRACE spherical harmonics and CIGAR) show a positive signal.
490 However, the patterns are significantly different between the reanalysis and GRACE cases.
491 They are localized in the western part of the tropical North Atlantic Ocean with the CIGAR
492 reanalysis and in the eastern part (between the Gibraltar Strait and the Gascogne Gulf) with
493 GRACE mascons. The residuals based on the ensemble mean GRACE spherical harmonics
494 display a strong north-south signal in the mid North Atlantic, likely due to north-south strip



495 noise affecting spherical harmonic solutions (Blazquez et al., 2018). CIGAR differentiates the
 496 sign of the patterns from the mid-Atlantic ridge, likely due to its effect on the basin-scale
 497 barotropic circulation. This effect is not seen in the gravimetry-based trends. To further
 498 investigate the North Atlantic sea level misclosure, we computed the North Atlantic sea level
 499 budget after geographically averaging each component over the region, using GRACE
 500 mascons for the manometric component. This is shown in Figure 8, along with the sea level
 501 budget, averaging the data globally but excluding the North Atlantic Ocean.

502

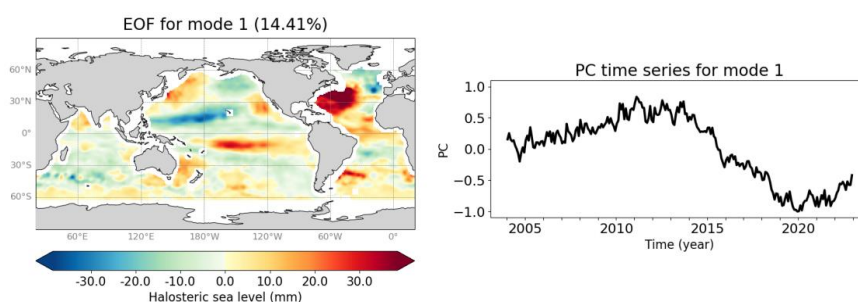


503

504 *Figure 8: Regionally averaged sea level budget for January 2004 to December 2022, over the*
 505 *North Atlantic Ocean (a) and over all oceans except the North Atlantic (NA) one (b). On each*
 506 *panel are shown the altimetry-based sea level (black curve), the thermosteric and halosteric*
 507 *components (orange and turquoise curves), the manometric component (GRACE mascons,*
 508 *blue curve) and the sum of all components (red curve). The panels c and d show the*
 509 *corresponding residuals (observed sea level minus sum of components). Shaded areas*
 510 *represent the standard one-sigma uncertainties.*

511 Figure 8 well confirms the non-closure of the budget over the North Atlantic Ocean, with a
 512 significant positive residual trend, whereas in the remaining oceanic domain, no significant
 513 residual trend is noticed. Figure 8 (panel a) suggests that the North Atlantic residual trend is
 514 related to the observed decrease of the halosteric component as of 2013-2014. A similar
 515 finding is provided in Mu et al. (2024).

516 We performed an Empirical Orthogonal Decomposition (EOF) of the gridded halosteric time
517 series over 2004-2022 (global mean trend removed). The dominant mode (mode 1) is shown
518 in Figure 9. The mode 1 principal component (PC) has a strange temporal behavior, with a
519 significant slope as of 2013 (right panel), likely associated with the strong signal seen in the
520 North Atlantic Ocean on the spatial map (left panel).



521

522 *Figure 9: Mode 1 of the EOF decomposition of the gridded halosteric component over 2004-*
523 *2022. Spatial map (left panel). Principal component (right panel). This first mode accounts for*
524 *14.4 % of the total halosteric signal.*
525

526 7. Conclusion

527 In this study, we have revisited the regional sea level budget over the GRACE and Argo era.
528 Using different data sets for the manometric component (GRACE and ocean reanalyses), we
529 found significant non-closure of the budget in the North Atlantic Ocean in all studied cases.
530 However, the residual patterns are not localized over the same areas in the GRACE and ocean
531 reanalyses cases. They are stronger in the northeast Atlantic Ocean when considering the
532 GRACE manometric component (mascon solution) while they are more localized in the
533 western tropical part with the reanalysis-based manometric component. The sea level budget
534 averaged over the whole North Atlantic Ocean leads us to suspect the steric contribution,
535 especially the halosteric component, as the main contributor to the budget non-closure in this
536 region, as the global budget without the North Atlantic region is closed within the error bars.
537 Although we chose the SIO data set to estimate the steric component, considering that the
538 salinity data had been corrected for the Argo floats instrumental drift that led to spurious salinity
539 measurements, our study points to remaining errors affecting the halosteric component. Mu
540 et al. (2024) also suggest a potential salinity bias in the Argo data set of the North Atlantic.
541 Our results suggest that the salinity adjustment to the WOCE salinity climatology proposed by
542 the SIO methodology may not fully correct for the rapid salinity drift experienced by some Argo
543 floats. However, the different locations of the North Atlantic residual patterns when considering

544 the reanalyses or GRACE for the manometric component, as well as larger residuals in the
545 northeast Atlantic Ocean in the GRACE case, suggest that uncertainty in GRACE data also
546 plays a role. In other oceanic regions, some small-scale residual structures are observed,
547 especially over western boundary currents and along the Antarctic circumpolar current. This
548 may eventually result from differences in resolution of the gridded data sets used in this study,
549 even though a low pass filter was applied to all data sets. .

550 The problem of the North Atlantic halosteric component highlighted in our regional budget
551 study needs to be fixed up at the processing level of the Argo-based measurements. Our
552 findings are helpful to the scientific groups involved in the Argo network as we can identify
553 regions where the salinity contribution to regional sea level change appears to be spurious.
554 This may help them in refining their investigations on the quality control checks to be applied
555 to the Argo profiles. In addition, detailed investigation of the GRACE contribution to the
556 residuals of this region should also be carried out in parallel. Our study highlights the necessity
557 of applying consistent data processing and using similar reference systems for satellite
558 altimetry and gravimetry data. Improved data should indeed be made available to the
559 community, not only for sea level budget assessments but also for other applications in
560 oceanography or climate-related research (i.e., for Earth's energy imbalance studies based
561 on sea level budget approaches).

562 **Acknowledgements**

563 We thank the Magellium/LEGOS climate change team for providing us with the ensemble
564 mean of the GRACE-based spherical harmonics solutions.

565 This research was carried out under a programme of, and funded by, the European Space
566 Agency (ESA) Climate Change Initiative, within the project entitled "Sea level budget closure
567 CCI+ (SLBC_CCI+)" (contract number 4000140620/23/I-BN).

568 Part of this work was performed in the context of the ERC Synergy GRACEFUL project (ERC
569 Synergy grant n° 855677).
570

571 **Authors contribution**

572 Conceptualization : MB, AB, AC. Data analysis : MB, AB. Reanalysis computation: CY,
573 AS. Writing original draft : AC. Writing, review and editing: all co-authors.

574 **Conflict of interest**



575 The authors declare no conflict of interest relevant to this study.

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