# Evidence of increased deep ocean warming from a sea level budget approach

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**Abstract:** Assessments of the global mean sea level (GMSL) budget over the satellite altimetry era (since the early 1990s) have concluded that the GMSL budget is closed within data uncertainties until 2016. However, studies have shown that since then, the sea level budget based on Argo data down to 2000 for the thermosteric contribution is no longer closed. Using an ocean reanalysis with no altimetry data assimilation, we show that accounting for deep ocean thermosteric contribution (below 2000 m, not sampled by Argo) allows the GMSL budget to be almost closed since 2016. The deep ocean contribution over 2005-2022 is estimated to 0.4 +/- 0.15 mm/yr, i.e., about 10%. to the observed GMSL rise over that period. This finding reveals that deep ocean warming has started to be significant and that ocean heat uptake has now reached several oceanic regions below 2000m depth, notably the Northwestern Atlantic Ocean and areas around Antarctica.

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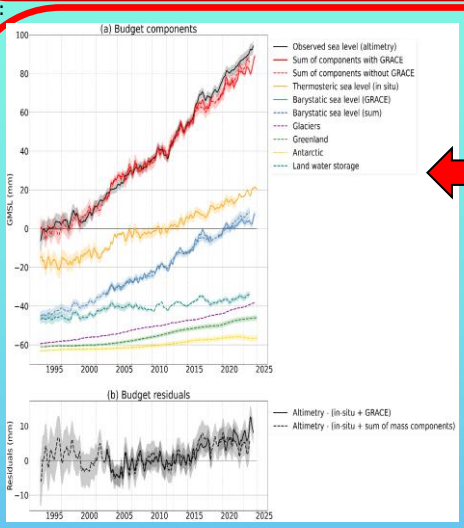
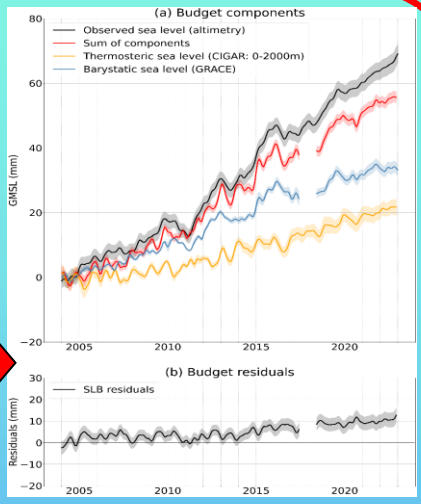



*Fig.2 GMSL budget over January 1993 to December 2022 with the Argo-based thermosteric component (data down to 2000m), individual mass contributions and GRACE-based ocean mass since 2004. The red curves are the sum components. The bottom panel shows the residuals (GMSL minus sum of components)*

*Fig.2: Sea level budget over January 2005-December 2022. Here the thermosteric component (0-2000m depth) is based on the CIGAR reanalysis (Storto & Yang, 2024). The ocean mass is based on GRACE*




In both cases the sea level budget is no more closed as of ~2016, as previously shown by Chen et al., 2020, Barnoud et al., 2021, 2023

**Question: Could the non closure of the sea level budget since about 2026 be due to non account of the deep ocean thermal expansion? To answer the question we considered the CIGAR-based thermosteric sea level over the full ocean depth**

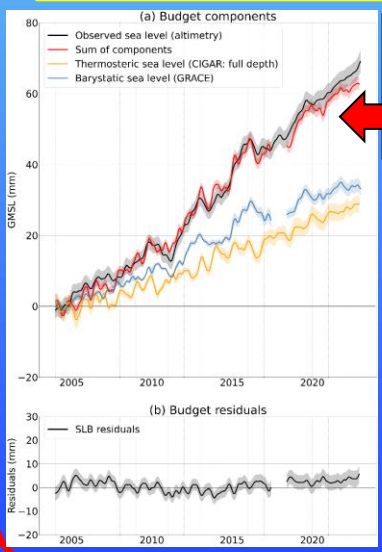



*Fig.3: Same as Fig.2 but with the CIGAR-based thermosteric full depth; In this case, the sea level budget is almost closed, even in the recent years*

**Validation of the CIGAR based thermosteric sea level**
**Left panel: 0-2000m; Right panel : Full depth**

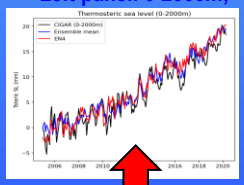



*Fig.4: Comparison with several Argo-baed Products (0-2000m)*

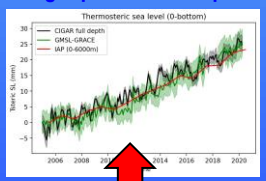



*Fig.5:Comparison with the IAP full depth thermosteric sea level and with « Altimetry minus GRACE »*

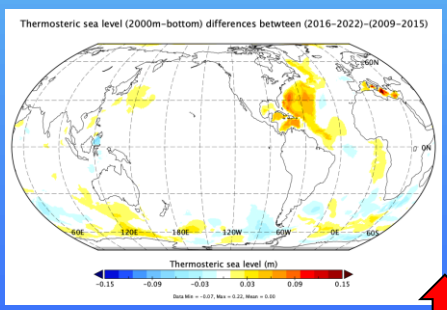



*Fig.6: Regional differences in CIGAR-based thermosteric sea level (2000m to bottom) between two seven-year-long time spans: 2016-2022 minus 2009-2015. Scale is in m.*

*According to CIGAR reanalysis, deep ocean warming starts to be visible in the Northwest Atlantic and around Antarctica.*

**Conclusion:** This study shows that the non-closure of the GMSL budget beyond 2016 is likely due to the emerging contribution of the deep ocean warming signal. The use of an ocean reanalysis to estimate the total (i.e., vertically integrated from surface to bottom) thermosteric component allows to close the sea level budget beyond 2016/17. A deep ocean contribution to the GMSL rise of 0.4 +/- 0.15 mm/yr is found for the 2005-2022 time span.

. **Reference:** Cazenave A., Yang C., Bouih M., Storto A., Chen J., Llovel W., von Schuckmann K., and Leclercq L., Evidence of increased deep ocean warming from a sea level budget approach, submitted, *Earth Future*, 2025.