

Decadal variability in the Eastern and Western Mediterranean sea level trends

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Below is the reviewer comment written in *blue italics*, while our response is in **black** and the inserted text in the revised manuscript is in **red**.

Comment by reviewer #2

The manuscript presents diagnostics related to sea level rise (and its partitions) and could be a valuable contribution to understanding sea level variability in the Mediterranean Sea; however, it requires a more targeted discussion to be ready for publication, in my opinion.

General comment: while there is quite good material in the manuscript, the main conclusions seem quite weak (non-linearity of sea level in the Med Sea appears to be the main point) and do not exploit the full set of information presented. I recommend reframing the conclusions to better exploit what was offered in the paper, including, for instance, trends, partition of sea level components, asymmetric behavior of thermo-halo variations between the western and eastern Med, etc.

R: We thank the reviewer for pointing out the necessity of an improved discussion, which will be addressed by strengthening the interpretation of the results, integrating additional details on the data analysis, and providing a more comprehensive comparison with the existing literature, as detailed in our responses to the comments below. We agree that the conclusions need to be revised to improve clarity and consistency with the paper outcomes, and to better explain the full set of information presented, while balancing the summarized information with the manuscript length, which is subject to specific limitations imposed by the Ocean State Report framework.

L23, L223: the manometric sea level variability is mentioned in several places as the main basin-wide driver of sea level rise, but never discussed in detail. It should be recalled, at the very least, how much it contributes to the two basins (WMED and EMED) based on recent literature and quantitatively, and how and why it shapes the basin-averaged sea level rather than local variations.

R: The basin-scale manometric sea level variability has been documented in recent studies including Garcia-Garcia et al. (2022) and Borile et al. (2025), the latter specifically focusing on the EMED. At the scale of the entire Mediterranean basin, Borile et al. (2025) quantify the contribution of surface freshwater fluxes (evaporation, precipitation, river runoff) as -595 mm/yr, while the net transport across the lateral open boundaries (Gibraltar and Dardanelles Straits) amounts to 603 mm/yr. The resulting residual contribution to basin-mean sea level is $+8$ mm/yr over the period 1993–2022.

Estimating the same water mass sea level contribution at the sub-basin scale is more complex, as it strongly depends on the definition of the boundary separating the two regions and on the considered time window. Moreover, the involved variables are not meaningful when interpreted locally: freshwater fluxes and lateral transports must instead be regarded as quantities integrated over the domain of interest, since their contributions can be highly localized in time or space, while their impact on sea level emerges only through the large-scale balance. For this reason, water mass variability primarily shapes the basin-averaged sea level signal rather than local sea level variations.

In the present study, however, we focus on the steric component only, which is generally considered to play a minor role in the long-term mean sea level budget of the Mediterranean Sea compared to the global ocean (Pinardi et al., 2014, Criado-Aldeanueva et al., 2008). The objective is to demonstrate that

the steric contribution can play a significant influence on sea level trends at decadal timescales, reaching the same order of magnitude as the trends observed from satellite altimetry. This highlights the importance of steric processes in modulating Mediterranean sea level variability, even in this basin where mass-driven contributions dominate the mean budget.

This information is now included in *Section 3.1* of the revised manuscript:

"The evolution of the sea level decadal trend over the WMED and EMED basins is presented in Fig. 1, based on satC3S and satCMEMS. Each point represents the trend over the decade centered on that date (e.g., the value reported for Jan2005 corresponds to the period Jan2000–Dec2009). Both sub-basins exhibit a decadal variability, with positive sea level trends ranging from negligible values up to 6.4 ± 1.0 mm/year, and two periods of relative slowdown (around 2001 and 2011 in WMED, and 2002 and 2014 in EMED). It is worth noting that satCMEMS generally agrees with satC3S within the associated uncertainty, though the latter is preferred for long-term consistency (Dibarboure et al., 2011). **At basin scale, variability is strongly influenced by the sea level mass component, which reflects the large-scale balance between surface freshwater fluxes and boundary volume transports. Recent studies quantify this contribution over the Mediterranean basin as the residual of large but compensating terms, resulting in a basin-mean sea level contribution of about +8 mm/year over 1993–2022, similar to the observed sea level trend from altimetry data (Borile et al., 2025; García-García et al., 2022).** Because mass contribution may be highly localized in time and space, its effect on sea level emerges primarily through integration over large domains, shaping the basin-averaged signal rather than local sea level variations. Focusing on the steric contribution to sea level change, Fig. 2 shows the thermosteric and halosteric components of the mean sea level **decadal** trend. The concept of steric compensation **in the Mediterranean Sea arises** from the opposing behaviour of these two components: the thermosteric **trend** component is positive **and** driven by seawater thermal expansion, while **the** halosteric contribution is negative **and** associated with the observed salinity increase (Aydogdu et al., 2023; Borghini et al., 2014). **Although the steric components play a relatively minor role in the long-term mean sea level budget of the Mediterranean compared to mass-driven contributions (Pinardi et al., 2014), their decadal variability can reach amplitudes comparable to the observed sea level trends. This highlights the importance of accounting for steric processes, together with surface fluxes and boundary transports, to better understand the mechanisms governing the mean sea level change (Borile et al., 2025; Cazenave et al., 2014).**"

L26: It seems like VLM is the main factor of possible disagreement between satellite altimetry and tide gauges. Further to the fact that processing might be different and needs to be discussed in more detail (e.g., how consistent are the atmospheric corrections in SLA with tide gauge data processing? How can the spatial and temporal filtering applied to SLA impact the difference between the two networks?), There may be processes at a scale that altimetry cannot resolve, and all these points need to be better discussed and addressed, with reference to the relevant literature. Sometimes it appears like altimetry is being validated against tide gauges (e.g., L155, but also elsewhere). Still, the two networks inherently bear different information due to different spatio-temporal scales spanned, and the data processing.

R: Satellite altimetry measures absolute sea level variability and therefore does not require VLM corrections, but it includes the dynamic atmospheric correction (DAC). Conversely, tide-gauge Revised Local Reference (RLR) data are referenced to the ground and do not include DAC or VLM corrections. To improve comparability between the two datasets, we have already applied VLM corrections to the in situ data using SONEL/ULR products, and in the reviewed manuscript we reintroduce the DAC correction into the satellite data using AVISO+ product (following the comment made by reviewer #1). This processing strategy is consistent with standard approaches adopted in sea level intercomparison and budget studies (e.g., Bonaduce et al., 2016; Wöppelmann and Marcos, 2016).

Nevertheless, despite these corrections, the two datasets remain intrinsically different: satellite altimetry provides spatially distributed observations with limited resolution near the coast, while tide gauges measure local sea level and can capture small-scale processes unresolved by altimetry (Vignudelli et al., 2019). To enhance consistency, we harmonized the temporal scales of the datasets by averaging hourly tgCMEMS observations to daily values to match the satC3S sampling, and by applying the same low-pass filter to both datasets to remove variability at frequencies higher than 5 cycles/year. This ensures that sea level trends are estimated from time series characterized by comparable temporal variability.

These aspects are more clearly described in *Section 2* of the revised manuscript:

"[...] Both the tgPSMSL and tgCMEMS datasets were considered, as they may include different sets of stations. In both cases, **stations are selected based on record length and data completeness; short data gaps are linearly interpolated, and hourly records are averaged to daily values** to match the temporal resolution of SLA data.

Where available, preference is given to stations located nearby GNSS (Global Navigation Satellite System) sensors to allow vertical land movement (VLM) correction, using trend values provided by URL/SONEL data server, ULR7 solution (product ref. n.7, in Tab. 1). The ULR7 solution **provides vertical velocity estimates in the ITRF2014 (International Terrestrial Reference System) frame** (Gravelle et al., 2023). Accordingly, absolute sea level trends at tide gauge locations are computed by adding the VLM rate to the relative sea level trend derived from tide gauge records (Santamaría-Gómez et al., 2012).

Finally, for direct comparison between satellite and in-situ observations, satC3S SLA values are extracted at the grid point closest to each tide gauge. Differences in reference frame and high-frequency signal treatment are minimized by reintroducing the dynamic atmospheric correction (DAC) into altimetry data and applying VLM corrections to tide gauge records. The DAC is taken from the CLS product based on the Mog2D model and distributed by Aviso+, with support from CNES (product ref. no. 8, in Tab. 1; Pascual et al., 2008). Overall, these processing choices aim to reduce methodological inconsistencies while acknowledging that satellite altimetry and tide gauges sample sea level variability at different spatial and temporal scales, and therefore provide complementary, rather than strictly equivalent, information."

Equation (1): The approximation implied in using constant T_f , S_f versus spatially varying T_f , S_f seems quite crude and needs to be justified.

R: In Eq. (1) we chose to prescribe the reference temperature and salinity, T_f and S_f , as spatially constant values, consistently with previous analyses available in the literature (Pinardi et al., 2014; Borile et al., 2025), in continuity with which the present work is developed. Specifically, our focus here is on the basin-mean value of the steric component, while neglecting its spatial variability and, consequently, the spatial variability of the reference fields within the considered domain. To further support this choice, we report below the corresponding formulation. Let us define the spatially averaged reference fields as

$$\bar{T}_f = \langle T_f(x, y) \rangle, \bar{S}_f = \langle S_f(x, y) \rangle,$$

where $\langle \cdot \rangle$ denotes the horizontal spatial averaging operator. The spatially averaged steric sea level contribution can then be written as

$$\langle \eta_s \rangle = \int_{\{-H\}}^0 \alpha(z) [\langle T \rangle - \langle T_f \rangle] dz - \int_{\{-H\}}^0 \beta(z) [\langle S \rangle - \langle S_f \rangle] dz = \int_{\{-H\}}^0 \alpha(\langle T \rangle - \bar{T}_f) dz - \int_{\{-H\}}^0 \beta(\langle S \rangle - \bar{S}_f) dz$$

which is equivalent to the spatial average of eq (1).

A possible refinement would be to prescribe distinct reference values for the WMED and EMED, however, given that these two regions are strongly interconnected, we chose to adopt a single basin-averaged reference value representative of the entire Mediterranean Sea.

This information is now clarified as follow in *Section 2*:

"The same approach is used to evaluate the decadal trend associated with thermosteric (η_T) and halosteric (η_H) sea level components, **whose sum defines the total steric sea level (η_S)**:

$$\eta_S = \eta_T + \eta_H = \int_{-H}^0 \alpha (T - T_f) dz - \int_{-H}^0 \beta (S - S_f) dz \quad (1)$$

where T_f and S_f are reference temperature and salinity values, α and β are constant linear coefficients **of thermal expansion and haline contraction**, and H is the **spatially varying** ocean depth. **Both reference values and steric coefficients are taken as spatially constant basin-mean values, consistent with previous studies and suitable for a basin-averaged steric sea level analysis (Borile et al., 2025; Pinardi et al., 2014).**"

Section 3.1: The section will benefit from having a Table summarizing, for the WMED and EMED basins, the 1993-2024 trend (e.g., as average of the "moving trend" in the figures) and the acceleration (e.g., as slope of the "moving trend"); this would be very useful for further studies and comparisons, and can be done for the different components and data.

R: We agree with the reviewer that a Table would be useful to summarize the information provided in Figures 1 and 2. Although the main focus of this study is the analysis of decadal timescales, we will include a summary of the mean trends of SLA (from satCMEMS and satC3S) and its steric contributions (from MEDREA24 and GLORYS12) for the WMED and EMED basins, excluding the period affected by the uncorrected TOPEX-A drift.

Regarding the mean acceleration values, these were intentionally not provided, as the method used to estimate the trend does not allow for a robust estimation of its first derivative. Consequently, we chose not to report acceleration values derived from a simple linear fit, which we consider less accurate than the Theil–Sen estimator adopted in this study.

In the reviewed manuscript we include the new *Table 2*:

	SLA trend		Total steric sea level trend		Thermosteric sea level trend		Halosteric sea level trend	
	satCMEMS	satC3S	MEDREA24	GLORYS12	MEDREA24	GLORYS12	MEDREA24	GLORYS12
WMED	3.69 ± 0.77	3.95 ± 0.79	0.78 ± 0.68	0.10 ± 0.83	3.36 ± 0.55	3.95 ± 0.64	-2.52 ± 0.45	-3.91 ± 0.48
EMED	3.12 ± 1.17	2.95 ± 1.16	0.23 ± 0.67	-1.07 ± 0.92	3.53 ± 0.66	3.30 ± 0.91	-3.15 ± 0.26	-4.15 ± 0.59

Table 2: Summary of the mean decadal sea level trend values derived from Figs. 1 and 2 and computed for decades centered between 2004 and 2020, thus excluding the period affected by the uncorrected TOPEX-A drift. All values are reported in mm/year.

Also, section 3.1 appears somewhat inconclusive. I recommend the authors speculate on the reasons why WMED exhibits strong thermo/halo compensation, while EMED does not, i.e., why adiabatic processes dominate in the western MED compared to the EMED. This is an important point to discuss.

R: This section is now improved by adding a more detailed discussion on the physical interpretation of the presented results. In particular, as suggested by reviewer #3, we discuss the steric compensation observed in the EMED in connection with the Adriatic-Ionian Bimodal Oscillation System (see reply to RC3).

To improve the link between the total sea level and steric sea level trends, we also note that in the Mediterranean the combined contribution of sea level mass components and the steric components are of the same order of magnitude. Within this framework, we argue that the decadal variability of the halosteric and thermosteric components plays a crucial role in shaping the overall sub-basin sea level evolution.

Table 2. I suggest adding a column either with the adjusted values (Absolute – VLM) or the residuals (Absolute – VLM - Relative), so that one can more easily understand when there is statistically significant consistency of the datasets or not. Detailed comments about this last point can be added as well.

R: We include an additional column reporting the trend residuals, defined as the difference between satellite-derived and tide gauge estimates, to facilitate the assessment of the statistical consistency among the datasets. Additional comments discussing these residuals will also be included. The Table is now updated to fit the Ocean State Report requirements, reporting the latest decadal trend values, computed up to December 2024 (at the time of submission, tide gauges data were available only until July 2024). In addition, we reintroduce the DAC correction in the satellite data, as explained in a previous response.

The reviewed *Table 3* is here reported:

	Tide gauge coordinates	Relative sea level trend [tgCMEMS]	Relative sea level trend [tgPSMSL]	Absolute sea level trend [satC3S]	VLM trend [ULR/SONEL]	Sea level trend DIFF [satC3S – tg]
Marseille	43.28°N / 5.35°E	-	7.4 ± 1.7	7.5 ± 1.0	-0.49 ± 0.27 (5m)	0.5 ± 2.2
Barcelona	41.34°N / 2.16°E	7.9 ± 1.3	8.1 ± 1.2	6.6 ± 1.7	-0.86 ± 0.23 (0m)	-0.4 ± 2.3
Melilla	35.29°N / 2.92°W	6.3 ± 0.9	6.1 ± 1.1	6.6 ± 1.2	-	0.3 ± 1.5
Mallorca	39.56°N / 2.64°E	6.9 ± 1.9	7.0 ± 1.6	8.8 ± 2.1	1.68 ± 0.83 (0m)	0.2 ± 3.4
Ibiza	38.91°N / 1.45°E	7.9 ± 1.8	7.9 ± 1.7	8.1 ± 1.7	-1.28 ± 0.26 (78m)	1.5 ± 2.7
Lampedusa	35.50°N / 12.60°E	11.8 ± 1.4	-	10.0 ± 1.5	-0.36 ± 0.37 (130m)	-1.5 ± 2.4
Venezia	45.42°N / 12.43°E	6.9 ± 3.1	-	5.8 ± 2.0	-1.51 ± 1.56 (741m)	0.4 ± 5.1
Trieste	45.65°N / 13.76°E	13.2 ± 3.5	-	5.6 ± 2.1	0.01 ± 0.14 (6707m)	-7.6 ± 4.2
Hadera	32.47°N / 34.88°E	-	7.7 ± 2.3	7.2 ± 1.7	0.46 ± 0.21 (3145m)	-0.9 ± 3.0
Leros	37.13°N / 26.85°E	-	8.6 ± 1.6	7.7 ± 1.6	-	-0.9 ± 2.2

Table 3: Sea level trends near selected coastal cities for the most recent available decade (2015-2024) derived from different datasets: satC3S (with DAC reintroduced), tgCMEMS and tgPSMSL. The VLM trend, with the distance between each tide gauge and its associated GNSS station indicated in brackets, should be added to the in-situ relative sea level trend to allow comparison with the satC3S absolute sea level trends (see Fig. 3). The resulting trend difference is reported in the last column. When both tide gauge datasets are available, tgCMEMS data are used. All trend values are reported in mm/year.

Typos

R: We fixed the highlighted typos.