



Decadal variability in the Eastern and Western Mediterranean sea level trends

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Abstract

15 The Mediterranean Sea is a semi-enclosed basin particularly sensitive to climate change, being recognized as a climate change hotspot associated with interconnected environmental and societal risks. Due to its nature as a concentration basin, where evaporation exceeds freshwater inputs, the combined effects of rising salinity and increasing heat content are expected to play a key role in shaping the basin's dynamic. This study investigates the decadal variability of sea level rise in the Mediterranean Sea, analyzing both basin-wide and coastal-scale patterns. Using satellite altimetry and ocean reanalyses, we assess sea level decadal trends from 1993 to 2024, distinguishing thermosteric and halosteric components. Our results reveal distinct trends in
20 the Western (WMED) and Eastern (EMED) Mediterranean sub-basins. In the WMED, sea level rise has recently accelerated, partly due to thermal expansion that is not compensated by halosteric contraction, with the remaining contribution linked to changes in the sea level mass component. In the EMED, sea level transitioned from a regime dominated by halosteric-induced steric drop to a recent state where steric contributions offset each other, leaving mass variability as the primary driver. Local analyses using tide gauge records generally confirm satellite-derived trends, with larger differences reported in the EMED
25 compared to the WMED. Recent trend reversals in the Adriatic and Aegean Sea further underscore the role of local processes like vertical land movement. These results demonstrate that sea level change in the Mediterranean Sea is non-linear and shaped by significant decadal variability, which overlays a clear long-term positive trend. Accurately capturing this variability is essential to avoid misinterpretation of the sea level trend and to support informed, location-specific adaptation strategies.



30 1 Introduction

Sea level rise is a major global concern due to its direct impact on densely populated coastal zones, posing growing challenges for adaptation and risk management (Parmesan et al., 2022). While global trends provide a broad picture, regional sea level rise can significantly diverge from the global average, especially in semi-enclosed basins, where local processes drive distinct patterns of variability (Calafat et al., 2022; Gräwe et al., 2019; Alothman et al., 2014). Accurately monitoring these regional trends is therefore essential to inform effective coastal planning at local scales.

The Mediterranean Sea represents a particularly relevant case in this context, as it is considered a climate change hotspot where environmental and societal risks are closely linked (Tuel and Eltahir, 2020; Cramer et al., 2018; Giorgi, 2006). The Mediterranean is described as a concentration basin, where evaporation exceeds precipitation and river runoff, generating a zonal salinity gradient (Pinardi and Masetti, 2000). The interplay between temperature and salinity is thus expected to have an influence on total sea level trends in the region, unlike the global ocean, where thermal expansion is the main driver of sea level rise (IPCC, 2023; Milne et al., 2009). Such a process has been analysed at the basin scale, with haline contraction counteracting the effect of ocean warming on sea level (Meli et al., 2023). Nevertheless, spatial and temporal variations in the offset between halosteric and thermosteric components highlight the value of analysing them separately to understand the physical drivers of sea level change. Understanding this interplay is therefore crucial for the interpretation of past variability and improvement of future sea level projections in the Mediterranean. Further complexity at the sub-basin scale arises from decadal variability in ocean dynamics and forcing mechanisms (Pinardi et al., 2015; Calafat et al., 2012) that drive sea level water budget changes, revealing significant differences in sea level evolution between the Western and Eastern Mediterranean sub-basins (hereafter WMED and EMED), which often respond differently to large-scale drivers (Borile et al., 2025).

Basin-scale sea level variations also affect coastal areas, where regional ocean processes, human activities, and local vertical land movements (Buzzanga et al., 2023) shape the impact on coastal communities (Cramer et al., 2018; MedECC, 2024). This study aims to investigate the Mediterranean decadal variability of sea level rise at both regional and local scales.



Product ref. no.	product ID and type	Data access	Documentation
1	SEALEVEL_GLO_PHY_CLIMATE_L4_MY_008_057, (satC3S) (1993-2024) satellite observations	EU Copernicus Marine Service Product (2024a)	QUID: Ballarotta et al. (2024) PUM: Pujol (2024)
2	SEALEVEL_EUR_PHY_L4_MY_008_068, (satCMEMS) (1993-2024) satellite observations	EU Copernicus Marine Service Product (2024b)	QUID: Ballarotta et al. (2025) PUM: Pujol (2025)
3	MEDSEA_MULTIYEAR_PHY_006_004, (MEDREA24) (1987-2025) numerical models	EU Copernicus Marine Service Product (2024c)	QUID: Escudier et al. (2024) PUM: Lecci et al. (2024)
4	GLOBAL_MULTIYEAR_PHY_001_030, (GLORYS12) (1993-2025) numerical models	EU Copernicus Marine Service Product (2023)	QUID: Dréville et al. (2023) PUM: Dréville et al. (2024)
5	INSITU_GLO_PHY_SSH_DISCRETE_MY_013_053, (tgCMEMS) (1821-2024) in-situ observations	EU Copernicus Marine Service Product (2024d)	QUID: Pérez Gómez et al. (2024a) PUM: Pérez Gómez et al. (2024b)
6	Tide gauges data, Permanent Service of Mean Sea Level (tgPSMSL) In-situ observations	https://psmsl.org/data/ , last access: 5 July 2025	Holgate et al. (2013)
7	Vertical land motion at tide gauges, ULR/SONEL group, GLOSS Data Assembly Centre for GNSS at Tide Gauges In Situ observations (GNSS)	URL/SONEL group: https://www.sonel.org/-GPS-.html?lang=en , last access: 27 June 2025	Gravelle et al. (2023)

Table 1: Product table

55 **2 Datasets and methods**

Daily sea level anomaly (SLA) data from two satellite altimetry products are used spanning the 1993–2024 period. The first dataset is satC3S (product ref. no. 1, in Tab. 1), a global gridded product with 1/4° spatial resolution, specifically designed to ensure the long-term stability of mean sea level estimates. The stability is achieved by relying exclusively on two satellite missions throughout the entire time series, thereby ensuring consistency for climate-related applications (Dibarboure et al., 2011; Pascual et al., 2006) and making this dataset recommended for trend analysis. The second dataset is satCMEMS (product ref. no. 2, in Tab. 1), which includes all available satellite missions and offers a spatial resolution of 1/16° over European seas. It is important to note that while both products provide data from January 1993 to November 2024, a non-corrected instrumental drift of TOPEX-A mission affects the SLA data until February 1999. This is a disclaimer to caution against using

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data from the 1993-1999 period for climatic analysis. However, the restriction will be lifted once the correction becomes
65 available in the current versions of both datasets.

The SLA data are spatially averaged over the WMED and EMED sub-basins, bounded at the Sicily Strait along a zonal transect
at 37°N. The obtained time series are then analysed following the methodology described by Borile et al. (2025). The seasonal
cycle over the 2000-2023 period is subtracted to obtain de-seasoned SLA, and then a low-pass filter is applied to the time
series to isolate long-term fluctuations. De-seasoned SLA trends are then computed using 10-year-long sliding windows shifted
70 by a monthly step: the fit is estimated using the Theil–Sen estimator (Theil, 1992; Sen, 1968), a non-parametric method that
is more robust to outliers compared to traditional linear regression, but does not allow the acceleration estimate. Finally, a
bootstrap procedure is applied with 1000 resamples (Patton et al., 2009; Politis and Romano, 1994) to assess the trend statistical
error. As expected, the uncertainties obtained in our analysis are higher than those reported by Prandi et al. (2021), likely due
to the finer spatial resolution adopted here, in contrast to their use of spatial filtering.

75 The same method is used to evaluate the decadal trend associated with thermosteric (η_T) and halosteric (η_H) sea level
components, defined as:

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

where T_f and S_f are reference temperature and salinity values, α and β are constant linear coefficients (values reported in
Borile et al., 2025), and H is the ocean depth. Temperature and salinity daily data are obtained from the regional MEDREA24
80 and the global GLORYS12 ocean reanalyses (products ref. no. 3 and 4, in Tab. 1), with a horizontal resolution of 1/24° and
1/12° respectively (Escudier et al., 2021; Lellouche et al., 2021).

To assess the reliability of satellite-derived sea level trends at the local scale, we analyse mean sea level records from tide
gauges of the tgCMEMS and tgPSMSL datasets (products ref. no. 5 and 6, in Tab. 1). The tgPSMSL serves as the Global Sea
Level Observing System (GLOSS) Data Assembly Center for monthly mean sea level records from tide gauges, collected
85 worldwide since 1933 (Holgate et al., 2013). Relying mostly on national providers for quality control, this dataset has been
central to IPCC assessments of sea level rise based on in situ observations (Oppenheimer et al., 2019). Since November 2022,
CMEMS has provided a reprocessed sea level product based on near-real-time data from the In Situ TAC (Lin-Ye et al., 2023).
This centrally validated dataset, updated biannually, is aimed to support validation of global and regional ocean models. The
hourly dataset is used in this study. Both the tgPSMSL and tgCMEMS datasets were explored, as they may contain different
90 sets of stations. In both cases, stations selection was based on time series length and completeness. Where data gaps exist, both
datasets are linearly interpolated, and hourly tgCMEMS records are daily averaged to match the temporal resolution of SLA
data. Where the information is 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, produced by the University of La Rochelle (ULR) for the
95 IGS's third reprocessing campaign, provides daily position time series (2000-2021) in the ITRF2014 (International Terrestrial
Reference System) frame for 601 GNSS stations worldwide, from which vertical land movement rates and uncertainties were



estimated with at least three years of continuous data (Gravelle et al., 2023b). Finally, we extract from the satC3S dataset the gridded sea point closest to each tide gauge location. The absolute sea level trend at each tide gauge site is then computed by adding the VLM rate to the relative sea level trend derived from tide gauge records, allowing for a direct comparison with the altimetric product (Santamaría-Gómez et al., 2012).

3 Results

3.1 Decadal trend at the basin scale

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, experiencing 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).

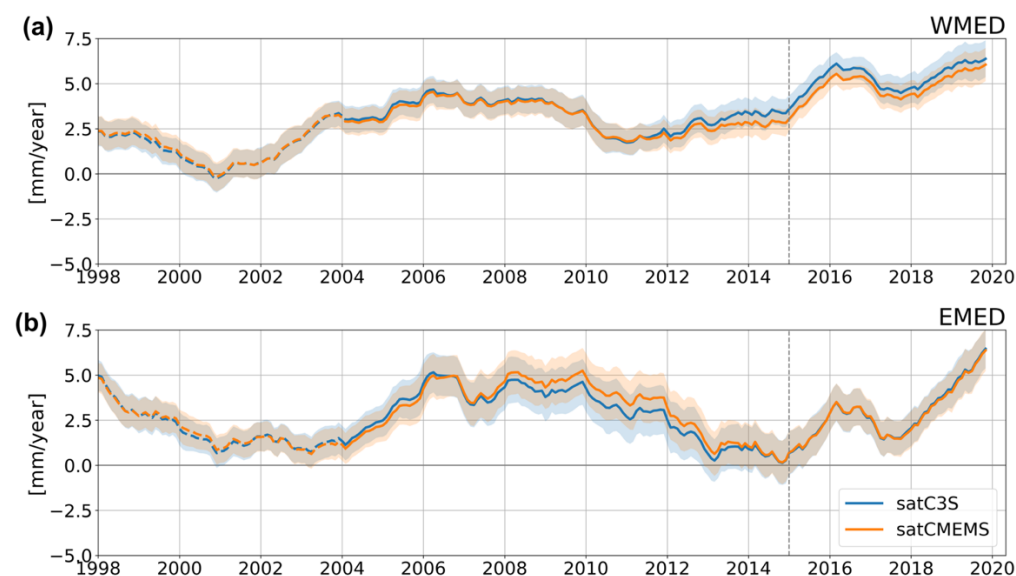


Figure 1: Time series of de-seasoned SLA decadal trend values computed over sliding windows shifted by one month across the period Jan1993–Oct2024 in the WMED (a) and EMED (b). Dashed lines indicate decadal trends computed over windows that partially include the period affected by the uncorrected TOPEX-A drift, when data should be interpreted with caution. Shaded areas represent the associated uncertainty, defined as the standard deviation of the residuals from the bootstrap procedure. The vertical dashed line at Jan2015 marks the starting point of tide gauges analysis shown in Fig. 4.



Focusing on the steric contribution to sea level change, Fig. 2 shows the thermosteric and halosteric components of the mean sea level trend. The concept of steric compensation results from the opposing behaviour of these two components: the thermosteric component is positive, driven by the thermal expansion of seawater (Pisano et al., 2020; Diffenbaugh et al., 2007), while the halosteric component is negative, associated with the observed salinity increase in the Mediterranean Sea (Aydogdu et al., 2023; Borghini et al., 2014). The temporal evolution emphasizes the need to account for the decadal variability of these sea level contributors, in combination with surface fluxes and boundary transports (Pinardi et al., 2014), to better understand the processes governing sea level change (Borile et al., 2025; Cazenave et al., 2014).

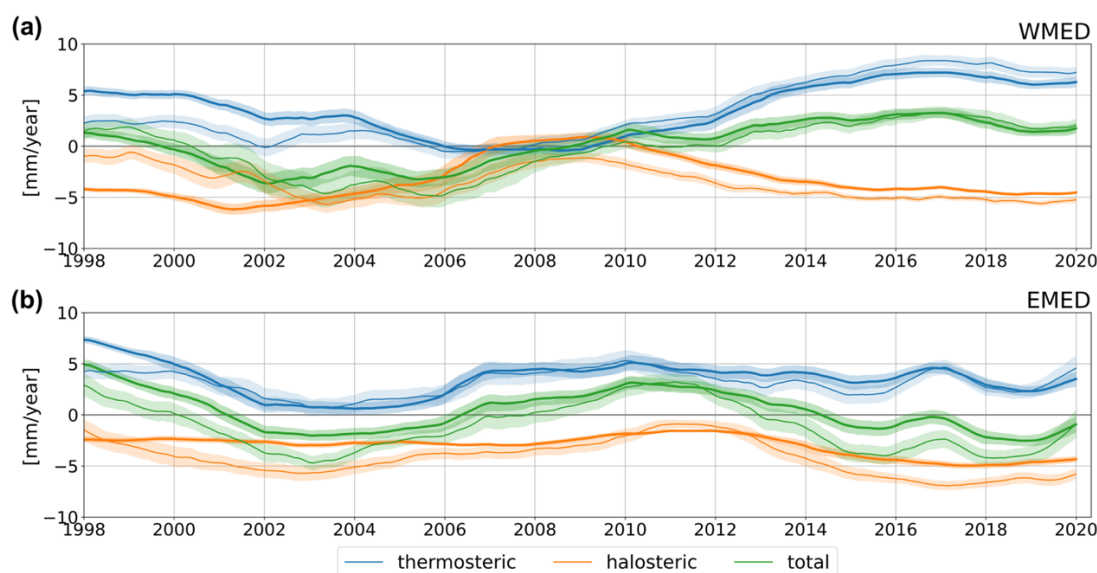


Figure 2: Time series of decadal trend associated to the de-seasoned thermosteric (η_T) and halosteric (η_H) sea level components, computed over sliding windows shifted by one month across the period Jan1993–Dec2024 in the WMED (a) and EMED (b). Different datasets are shown: MEDREA24 (thick lines) and GLORYS12 (thin lines). Shaded areas represent the associated uncertainty, defined as the standard deviation of the residuals from the bootstrap procedure.

In the WMED (Fig. 1a), neglecting the 1993–1999 period due to the uncorrected TOPEX-A drift, the decadal trend increased from 3.0 ± 0.7 mm/year to 6.4 ± 1.0 mm/year. A temporary slowdown is observed in the decades centered around 2011, coinciding with a phase during which the combined effect of thermosteric and halosteric components shifts from significantly contributing to sea level rise to becoming nearly neutral (Fig. 2a). Indeed, in both MEDREA24 and GLORYS12, this period marks a transition between two different regimes: before the decade centered in 2009, the steric contribution dampens the total sea level rise, afterward it contributes positively. Accordingly, the increasing decadal trend reported by satC3S is supported by thermal expansion that exceeds haline contraction.



On the other side of the Sicily Strait, the EMED trend (Fig. 1b) exhibits greater temporal variability compared to the WMED, without a clear increasing value over the entire analysed period. Two periods of negligible trends are observed around the decades centered in 2002 and 2014, separated by a rapid increase of trend followed by a smoother slowdown. After the decade centered in 2015, the trend value increases again, showing an almost constant acceleration after 2018 and reaching a peak of 6.5 ± 1.1 mm/year in the latest decade. Notably, while WMED and EMED currently experience similar rates of sea level rise, the EMED exhibits a much sharper acceleration.

The steric components in the EMED (Fig. 2b) help partially explain this behaviour. Halosteric contraction persisted throughout the period, with a strengthening negative trend observed from the decade centered in 2014 onward. In contrast, thermal expansion has remained relatively stable since 2007, after a period of minimal contribution centered around 2004. The combined effect of these two components caused the total steric contribution to alternate between negative and positive trend values. In the most recent decadal windows (centered from 2015 onward), the observed EMED sea level trend increases as the steric component's negative contribution weakens approaching negligible values, as shown in both MEDREA24 and GLORYS12.

3.2 Decadal trend on coastal areas

To identify the regions where sea level rise has the greatest impact on human activities, we analyse sea level data close to the coast. The accuracy of altimetry data in coastal zones is a known challenge due to land contamination on satellite measurements and small-scale dynamical processes that affect the sea level variability (Vignudelli et al., 2019; Cipollini et al., 2017).

Therefore, in-situ data are crucial to validate the altimetry performance.

Figure 3 presents the coastal decadal trend from satC3S, computed over the period Jul2014-Jun2024 to enable direct comparison with the most recent tide gauge observations from tgCMEMS and tgPSMSL. A general lack of in-situ measurements characterizes the EMED compared to the WMED, with most tide gauges located along the Spanish and French coasts (Pérez Gómez et al., 2022). Nevertheless, despite the coarse resolution of satC3S (grid cell area is ~ 600 km²), a good agreement is observed between altimetry and tide gauges trends within the estimated uncertainties (Tab. 2). Larger discrepancies are mainly observed in the Adriatic Sea, particularly at Trieste, where the in-situ trend from tgPSMSL is nearly four times higher than the altimetry-based estimate, highlighting the influence of local processes in driving sea level variability that may not be captured by satellite observations.

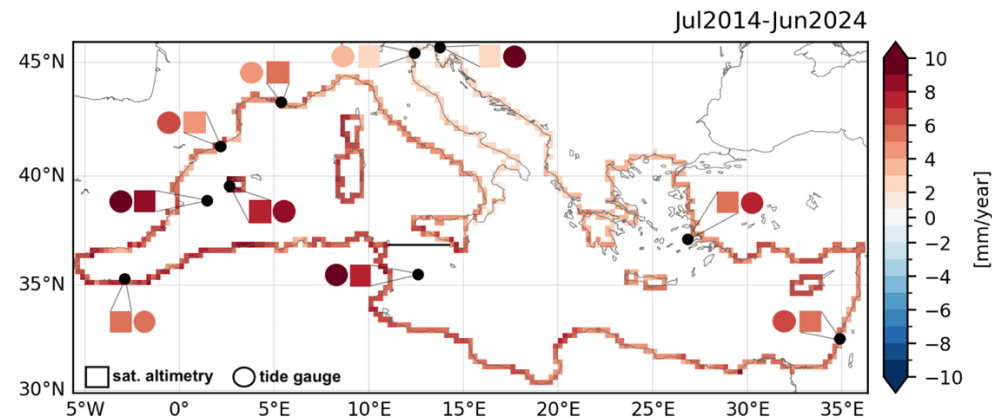


Figure 3: Map of sea level decadal trend computed at coastal points from the satC3S dataset. The analysed decade spans from July 2014 to June 2024, the latest available period for comparing decadal trends between satC3S altimetry and in-situ observations from tgCMEMS and tgPSMSL, corrected from VLM. Each black dot indicates the location of a tide gauge described in the text. Satellite and tide gauge-derived trends at the same location are shown as squares and circles, respectively, and are coloured according to the colorbar (values reported in Tab. 2). The thin black line corresponds to the zonal transect used to define the boundary between WMED and EMED at 37°N.

	Tide gauge coordinates	Relative sea level trend [tgCMEMS]	Relative sea level trend [tgPSMSL]	Absolute sea level trend [satC3S]	VLM trend [ULR/SONEL]
Marseille	43.28°N / 5.35°E	4.6 ± 2.1	4.7 ± 2.1	5.2 ± 1.0	-0.49 ± 0.27 (5m)
Barcelona	41.34°N / 2.16°E	6.0 ± 1.7	6.2 ± 1.2	4.2 ± 1.2	-0.86 ± 0.23 (0m)
Melilla	35.29°N / 2.92°W	5.8 ± 0.9	5.6 ± 0.9	5.8 ± 1.2	-
Mallorca	39.56°N / 2.64°E	8.2 ± 1.8	8.3 ± 1.8	7.8 ± 2.1	1.68 ± 0.83 (0m)
Ibiza	38.91°N / 1.45°E	9.3 ± 1.8	9.4 ± 1.7	8.3 ± 1.7	-1.28 ± 0.26 (78m)
Lampedusa	35.50°N / 12.60°E	9.8 ± 2.0	-	7.6 ± 1.2	-0.36 ± 0.37 (130m)
Venezia	45.42°N / 12.43°E	3.1 ± 3.2	-	2.4 ± 1.7	-1.51 ± 1.56 (741m)
Trieste	45.65°N / 13.76°E	9.6 ± 4.0	-	2.2 ± 1.5	0.01 ± 0.14 (6707m)
Hadera	32.47°N / 34.88°E	-	6.7 ± 2.3	5.0 ± 1.4	0.46 ± 0.21 (3145m)
Leros	37.13°N / 26.85°E	-	7.2 ± 1.8	5.1 ± 1.4	-

Table 2: Sea level trends near selected coastal cities for the most recent available decade (July 2014–June 2024) derived from different datasets: satC3S, tgCMEMS and tgPSMSL. The VLM trend shown in the last column (with the distance to the associated GNSS



station indicated in brackets) should be added to the relative sea level trend to compare it with absolute sea level trends. All trend values are reported in mm/year.

At the basin scale, the spatial distribution of trends from satC3S is quite homogeneous, with positive values across most of the Mediterranean coastal areas. Trends exceeding 8 mm/year are reported in the WMED, particularly along the Algerian coast, the Balearic Islands, and the western coasts of Sardinia and Corsica. Weaker trends are observed in the Adriatic and Aegean Seas, with the Adriatic showing values below 3 mm/year. Notably, marginal seas display a rapid shift of regime compared to the trend computed for the period Jan2013-Dec2022 (Borile et al., 2025), when negative values were previously reported. This behaviour aligns with the sharp trend increase recently observed at the EMED basin scale.

Figure 4 compares decadal trend time series of absolute sea level from altimetry and tide gauges, focusing on the period from 2010 onward to reduce data gaps and ensure overlap with GNSS-based VLM correction.

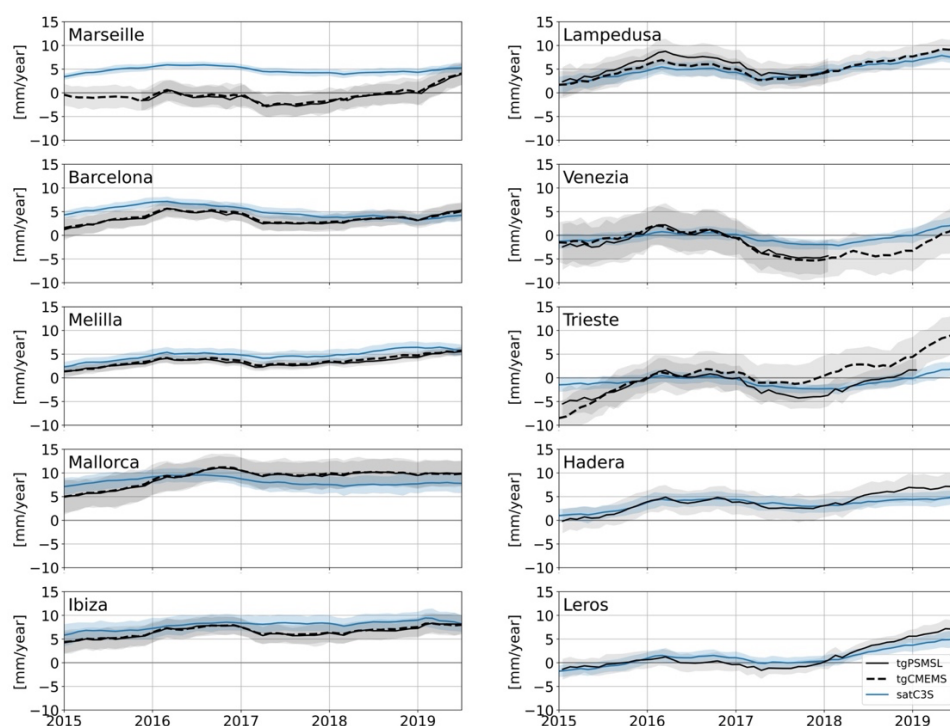


Figure 4: Time series of absolute sea level decadal trend computed nearby coastal cities, using tide gauges data from tgCMEMS, tgPSMSL, and satellite data from satC3S. For a direct comparison between satellite and in-situ data, the VLM trend is added to the relative sea level trend derived from tide gauge records. Decadal trends are computed over sliding windows shifted by one month across the period Jan2010–June2024 to match the period of tgCMEMS availability; where tgCMEMS data are not available (Hadera and Leros), only tgPSMSL data are analysed during the same period. Shaded areas represent the associated uncertainty, defined as the standard deviation of the residuals from the bootstrap procedure. *The decadal trend analysis will be extended to the July-Dec months of 2024 during the review phase, as soon as the tgCMEMS dataset is updated.*



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In the WMED, data from Melilla, Barcelona, Ibiza, Palma de Mallorca and Marseille all show a gradually increasing decadal trend consistent with the basin-scale evolution. Notably, the time series derived from tgCMEMS and tgPSMSL largely overlap, with only minor differences likely attributed to the distinct preprocessing filters applied in each dataset.

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In Barcelona and Melilla, the trend increased steadily from ~ 1 mm/year to over 5 mm/year. In contrast, Marseille experienced a slightly negative trend until the decade centered in 2019, after which it became positive and aligned with the altimetry trend. Ibiza and Palma de Mallorca show persistently high trends above 5 mm/year, though with less pronounced increase over time. Particularly in Palma de Mallorca, a shift of only two years in the decadal analysis window leads to a doubling of the estimated trend and remained nearly stable afterward. In this case, it is worth noting that the perceived sea level rise is partially dampened by local positive VLM.

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All WMED stations show a relative maximum trend around the decades centered between 2016 and 2017, consistent with the basin-scale signal. This feature is even more pronounced at tide gauges stations located in the EMED, such as Lampedusa, Leros, Hadera, Venezia and Trieste, where a marked slowdown follows the observed peak. However, the limited availability of data in this region often limits the possibility of a comparison between tgCMEMS and tgPSMSL.

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Trieste is the only station where tgPSMSL and tgCMEMS provide decadal trend estimates that differ beyond the uncertainty bounds, likely due to local effects not captured by altimetry. Nevertheless, both datasets capture a transition from negative to positive trends in the most recent period. The case of Venezia is similar, though more complex due to the city's geographical setting and the socio-economic implications of sea level changes (Zanchettin et al., 2021). Here, a minimum trend of -5.3 ± 3.7 mm/year is reported for the decade centered around 2018, which has recently turned weakly positive according to tgCMEMS. A similar pattern is also observed in Leros, in the Aegean Sea, where the trend remains negligible until the decade centered in 2018, followed by a sharp acceleration in the most recent period.

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By contrast, tide gauges outside the marginal seas show consistently positive trends exceeding the uncertainty bounds. At Lampedusa, in the Sicily Strait, the local trend increased sharply after the slowdown, rising from 2.6 ± 2.3 mm/year to nearly 10 mm/year. In Hadera, along the Israeli coast, the trend shows a more gradual acceleration persisting throughout the entire analysed period.

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4 Summary and conclusions

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This study provides an assessment of decadal sea level trends in the Mediterranean Sea, emphasizing both regional-scale and coastal-scale variability. The results confirm that sea level rise in the Mediterranean is not a linear process but exhibits significant decadal fluctuations due to a complex interplay between mass and steric sea level components (Pinardi et al., 2015; García-García et al., 2022; Meli et al., 2023). While the analysis focuses on the steric contribution, the mass component related to surface water budget and transport through the Straits is also essential to fully understand sea level decadal variability (Borile



et al., 2025). This emphasizes the importance of integrating all components to build a comprehensive picture of sea level evolution in the Mediterranean.

230 In the Western Mediterranean (WMED), a sea level acceleration has been observed since the early 2000s, partially sustained by thermal expansion that exceeds haline contraction (Pisano et al., 2020). In contrast, the Eastern Mediterranean (EMED) displays stronger temporal variability, with halosteric contraction playing a major counterbalancing role (Meli et al., 2023; Borghini et al., 2014). Only in recent years the EMED reached a comparable rate of sea level rise to the WMED, largely due to a weakening of the overall steric contribution.

235 At the coastal level, altimetry trends are generally consistent with tide gauge observations in the WMED, while larger uncertainties persist in the EMED, underscoring the need for improved in-situ monitoring networks and data sharing, including vertical land movement estimations as a relevant contribution to local effects (Buzzanga et al., 2023; Cramer et al., 2018). The observed reversal of trends in marginal seas such as the Adriatic and Aegean suggests that localized processes, including vertical land motion and regional circulation anomalies, can rapidly alter coastal sea level evolution. These findings highlight the importance of considering the sea level decadal trend variability within the definition of coastal adaptation strategies, because relying solely on long-term multi-decadal trends may lead to underestimations or overestimations of near-term risks.
240 We should therefore be aware of such variability and avoid assuming that local sea level rise will proceed with a constant trend or acceleration. Integrating long-term trajectories and decadal modulations can significantly improve the strength of adaptation plans.

Code and data availability:

245 The publicly available datasets analyzed in this study are referenced in Tab. 1. Other data and codes used to perform the analysis will be available on the Zenodo Repository upon manuscript acceptance.

Author contribution:

250 FB, EC, and PO contributed to the conceptualization, methodology, and analysis. FB, VL, BGP, and JLY were responsible for data curation and organization, with AM contributing to data resources. FB and VL performed software development, formal analysis, investigation, and visualization, while AM, BGP, JLY, and AA contributed to data investigation. EC was responsible for funding acquisition, and PO supervised the study. FB prepared the original draft of the manuscript, with contributions from all co-authors in the editing and reviewing.

Competing interests:

255 The authors declare that they have no conflict of interest.



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