



Establishing a Monitoring Approach for Marine Heatwaves in the Black and Mediterranean Seas

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Abstract. Increased frequency and intensity of marine heatwaves (MHWs) are contributing to cumulative thermal stress on
10 marine systems, as extreme temperature events interact with long-term ocean warming. These impacts are particularly
relevant in semi-enclosed basins such as the Mediterranean and Black Seas, where surface warming and rising ocean heat
content (OHC) have been especially pronounced over the past decade. While MHW-related effects have been documented in
the Mediterranean Sea, assessments remain limited for the Black Sea. Most studies to date have focused on sea surface
15 manifestations of MHWs, although it is well established that such extremes can also extend into near-surface layers below
the mixed layer. However, the vertical structure and persistence of MHWs beneath the surface remain less understood,
particularly in the Black Sea. In this context, this study aims to identify and characterize MHWs in both surface and
subsurface waters in the Mediterranean and Black Seas, and to provide a framework for monitoring MHWs within the upper
water column. To this end, MHWs were detected using both sea surface temperature (SST) and OHC anomalies down to 40
20 m depth, allowing for the assessment of their spatial structure and vertical consistency. SST- and OHC-derived metrics
generally show a strong agreement, particularly in event duration and frequency. Discrepancies between surface and
subsurface MHW metrics are particularly evident in the Black Sea, where circulation patterns associated with the Rim
Current appear to influence the vertical structure of heat extremes, leading to subsurface events that are not captured by
surface-based metrics. In contrast, in the Adriatic Sea, reduced winter mixing and persistent stratification contribute to
intensified MHW activity in both surface and subsurface layers. In 2024, both the Black Sea and Mediterranean Sea
25 experienced record-high MHW intensities and durations, with events lasting over 30 days and temperature anomalies
exceeding 4.6 °C in key regions such as the Anatolian coast, where summer upwelling commonly influences local ocean
conditions. To improve MHW monitoring, we recommend integrating both SST- and OHC-based methods to capture surface
and subsurface events in these regions. Nevertheless, due to regional variability, multiple MHW definitions such as threshold
based approaches, including the Hobday framework which also defines MHW categories, are necessary to accommodate
30 diverse monitoring objectives and management strategies.



1 Introduction

The rapid rise in ocean temperature due to global warming has led to a significant increase in the frequency and intensity of marine heatwaves (MHWs) in recent decades (Oliver et al., 2018; Fox-Kemper et al., 2021; Cooley et al., 2022). These extreme thermal events are typically characterized as periods lasting at least five days, during which sea surface temperatures (SSTs) exceed the 90th percentile relative to a historical baseline (Hobday et al., 2016; HD2016 hereafter). In recent years, favorable atmospheric conditions, such as weakened winds, increased shortwave radiation and reduced heat losses from the ocean, have contributed to the increased frequency and spatial extent of MHWs, resulting in severe disruptions to marine ecosystems and global biodiversity (Tan et al., 2022; Smith et al., 2023; Darmaraki et al., 2024; England et al., 2025). Large-scale climate modes, most notably the El Niño–Southern Oscillation (ENSO), also play a central role in driving prolonged MHW conditions, particularly when remote anomalies are reinforced by local atmospheric and oceanographic processes (Holbrook et al., 2019; Dutheil et al., 2024; Gregory et al., 2024). At the local scale, oceanographic mechanisms are also significant, as reduced upwelling limits the supply of cooler waters and enhanced eddy activity traps heat and prolongs events (Izquierdo et al., 2022; Su et al., 2025). The combined influence of large-scale climate modes and local ocean-atmosphere interactions has been recognized as a key driver of extreme events, as detailed by Sen Gupta et al. (2020) in their review of the most impactful MHWs globally. In the Mediterranean Sea, MHWs are associated with the onset of mass mortality events accounting for a unique threat to its ecosystem (Garrahou et al., 2022; Smith et al., 2023). A recent study also demonstrated that MHWs may disrupt essential ecosystem processes, such as by inhibiting the spring phytoplankton bloom in the northwestern Mediterranean (Li et al., 2024). The potential to cause significant changes in ecosystems and biota with vast socio-economic impacts makes the research on MHWs indispensable.

From HD2016's MHW definition, several variants have been developed to define extreme sea temperature events. These typically vary in the way temperature anomalies are identified. For instance, some definitions use fixed SST thresholds, while others rely on climatology-based percentiles, which may be calculated using either a fixed baseline or a moving average (Rosselló et al., 2023). Higher thresholds (e.g. 99th percentile) detect fewer but more extreme MHW events (Cheng et al., 2023). To separate long-term ocean warming from short-term extremes, detrending methods are often used (Martínez et al., 2023; Capotondi et al., 2024). In a similar way, moving-average climatologies – which consider years close to the target year – can reduce the imprint of the warming trend. There are also approaches that include spatial characteristics to better reflect the extent and ecological importance of these temperature events (Bonino et al., 2023). However, when considering ecological impacts specifically, it remains challenging to adopt a single MHW definition that applies across all regions, ecosystems, and species, as temperature thresholds and biological responses can vary widely (Amaya et al., 2023).

Recent studies have characterized MHWs in the Mediterranean Sea, highlighting their spatial features, temporal evolution, and representation in observational and reanalysis datasets (e.g. Dayan et al., 2022; Dayan et al., 2023; Marullo et al., 2023; Rosselló et al., 2023; Darmaraki et al., 2024; Pastor et al., 2024). For example, Dayan et al. (2022) have demonstrated the relevance of regional high-resolution reanalysis data for representing MHW statistics, showing high-skills of the regional



reanalysis as compared to the remote sensing data. In a subsequent study, Dayan et al. (2023) examined subsurface MHWs
65 by employing an ocean heat content (OHC) indicator that integrates temperature across different depths. The authors found
that subsurface MHWs occur less frequently but with longer duration than surface events, and this prolonged persistence at
depth may be linked to wind-driven processes that facilitate the downward propagation of thermal anomalies (Darmaraki et
al., 2024). Marullo et al. (2023) investigated the role of atmospheric forcing and linked the development of SST anomalies to
the prevalence of anticyclonic atmospheric conditions during the well-known MHW event of 2022-2023. Another study
70 revealed the co-occurrence of marine and atmospheric heatwaves, with their relationship exhibiting spatial variability across
the Mediterranean Sea (Pastor et al., 2024). Correlation of MHWs with large-scale climate modes such as the East Atlantic
and East Atlantic–West Russian patterns, combined with their concurrence with atmospheric heatwaves, may enhance MHW
intensity and spatial extent in the Mediterranean Sea (Hamdeno and Alvera-Azcaráte, 2023; Darmaraki et al., 2024).

While studies on MHWs are extensive in the Mediterranean Sea, comparable research in the Black Sea remains limited. To
75 our knowledge, Mohamed et al. (2022) is the only study to date that specifically investigates MHWs in this region using
satellite data. Their analysis examined trends in MHW frequency in relation to the rate of SST warming. The new
Copernicus Black Sea reanalysis (product ref. no. 3 in Table 1; Lima et al., 2025), configured at a horizontal resolution of
1/40° with 121 vertical levels, has served as the foundation for developing Ocean Monitoring Indicators (OMIs) for the
region. In particular, the OHC OMI indicates a warming trend of approximately 0.77 ± 0.07 W m⁻² (2005-2022) in the Black
80 Sea (EU Copernicus Marine Service Product, 2024f; <https://doi.org/10.48670/moi-00306>). This ocean warming signal,
which has also impacted the formation of its cold intermediate layer (CIL) in recent years (Stanev et al., 2019; Lima et al.
2021, 2025), emphasizes the importance of studying MHWs in Black Sea.

This study revises previous works on the Mediterranean Sea (e.g., Dayan et al., 2022, 2023) using an updated reference
climatology and includes an uncertainty assessment of key MHW metrics based on multiple datasets. Additionally, it
85 provides insights into historical MHW characteristics in the less-studied Black Sea. The primary objective is to develop a
comprehensive monitoring approach for MHWs in both regional seas. The manuscript is structured as follows: Section 2
describes the datasets and methodologies used to detect MHWs across both basins. Section 3 presents and discusses key
MHW metrics derived from the standard definition, applied to SST as well as OHC for subsurface detection. MHW metrics
are subsequently examined with respect to the water mass structures in the Mediterranean and Black Seas. Section 4
90 concludes the study and proposes an OMI for tracking MHWs in these regions. The comparison between standard MHW
metrics and those obtained using a detrending approach is presented exclusively in the Appendix as supplementary material.

Table 1: Product table.

Product ref. no.	Product ID & type	Data access	Documentation
1	SST_BS_SST_L4_REP_OBSE	EU Copernicus	Quality Information



	RVATIONS_010_022; satellite observations	Marine Service Product (2024a)	Document (QUID): Pisano et al. (2024a) Product User Manual (PUM): Pisano et al. (2024b)
2	SST_MED_SST_L4_REP_OBSERVATIONS_010_021; satellite observations	EU Copernicus Marine Service Product (2024b)	QUID: Pisano et al. (2024c) PUM: Pisano et al. (2024d)
3	BLKSEA_MULTIYEAR_PH Y_007_004 (BLKREA); numerical models	EU Copernicus Marine Service Product (2024c)	QUID: Lima et al. (2024) PUM: Lecci et al. (2024a)
4	MEDSEA_MULTIYEAR_PH Y_006_004 (MEDREA); numerical models	EU Copernicus Marine Service Product (2024d)	QUID: Escudier et al. (2024) PUM: Lecci et al. (2024b)
5	GLOBAL_MULTIYEAR_PH Y_001_030 (GLOREA); numerical models	EU Copernicus Marine Service Product (2024e)	QUID: Drévillon et al. (2024a) PUM: Drévillon et al. (2024b)

95 **2 Data and methods**

We follow the definition of MHWs from HD2016: a period in which the temperature exceeds a set threshold for at least five consecutive days. This threshold is the 90th percentile of the local daily mean temperature over the long-term reference period (1993–2022) thus considering the temperature increase in the last decades. If two MHW events are separated by a gap of two days or fewer during which temperatures remain below the threshold, they are merged and treated as a single continuous event. In addition to the standard approach, we perform a separate analysis to examine how removing long-term trends affects MHW detection, applying a detrending method to Mediterranean subregions and to the Black Sea as a whole (Appendix A). Specifically, we remove the linear SST or OHC trend individually at each grid point before applying the detection algorithm. Table 2 presents the MHW metrics analyzed and discussed in this study.

105 **Table 2: MHW metrics following Hobday et al. (2016) and Dayan et al. (2022).**

Frequency	Number of discrete events
Duration	Consecutive period of time during which the temperature exceeds the threshold



Maximum intensity	Highest temperature anomaly value relative to the 90th percentile
Trends	Least-squares regression of all metrics with 95% of confidence interval

We detect MHWs using both SST and upper OHC (0–40 m), based on regional reanalysis datasets. The Mediterranean Sea regional reanalysis (product ref. no. 4 in Table 1) is configured with a horizontal grid resolution of $1/24^\circ$ (approximately 4–5 km) and 141 unevenly spaced vertical levels (Escudier et al., 2021). In contrast, the Black Sea regional reanalysis (product ref. no. 3 in Table 1) employs a finer horizontal resolution of $1/40^\circ$ and 121 unevenly spaced vertical levels (Lima et al., 2025). Both regional reanalyses are forced with atmospheric data from the ERA5 reanalysis (Hersbach et al., 2020), assimilate in situ temperature and salinity profiles, along-track sea level anomaly observations, and apply SST relaxation to correct surface heat fluxes. They serve as the basis for MHW detection in this study. For broader comparison, MHWs are also identified using a global reanalysis product (product ref. no. 5 in Table 1), which has a coarser horizontal resolution of $1/12^\circ$ and includes 50 vertical levels (Lellouche et al., 2021). This global product is forced with ERA-Interim atmospheric reanalysis (Dee et al., 2011) until end of 2018 and ERA5 reanalysis thereafter and assimilates in situ observations, along-track SLA, and SST data. Additionally, for validation and complementarity, we compare reanalysis-derived MHW metrics based on SST with those obtained from an observational-based Level 4 SST product (product refs. no. 1 and 2 in Table 1; Pisano et al., 2016; Embury et al., 2024). All datasets can be accessed through the Copernicus Marine Service catalogue, which provides comprehensive documentation on their specifications and quality assessments.

For evaluating the OHC anomaly, we apply a formula similar to that used by Lima et al. (2020, 2021), which has also been adopted for calculating the OHC OMI for the Black and Mediterranean Seas within the Copernicus Marine Service framework (EU Copernicus Marine Service Product, 2024f, 2024g). The OHC anomaly is defined here as the deviation from the long-term reference period and is closely proportional to the average temperature change from $z_1 = 0$ m to $z_2 = 40$ m depth:

$$OHC = \int_{z_1}^{z_2} \rho_0 c_p (T_m - T_{clim}) dz \quad (1)$$

with a reference density $\rho_0 = 1020 \text{ kg m}^{-3}$ and a specific heat capacity $c_p = 3980 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$; T_m corresponds to the daily average temperature and T_{clim} denotes the climatological temperature for the corresponding day, calculated over a 30-year period (1993–2022), consistent with the baseline period used to define MHWs.

3 Results and discussion

3.1 SST-Derived Marine Heatwave Characterization

The surface MHW metrics in the regional reanalyses (product refs. no. 3 and 4 in Table 1) over the period 1993–2024 (Figure 1), confirm and update the basin-scale patterns of the Mediterranean Sea previously reported (e.g. Dayan et al., 2022; 2023). The average number of MHW events is slightly lower along certain coastal regions of North Africa, particularly



135 between 10°E and 35°E (Figure 1, row 1). Despite this lower frequency, the average duration of events in these areas is relatively high, exceeding 30 days, suggesting fewer but more persistent heatwaves. Mignot et al. (2022) define persistent MHWs as events lasting over 38 days with SST anomalies above 2.3°C at the global ocean scale. In contrast, regions such as the Adriatic Sea, Ionian Sea, Gulf of Lion, and the area extending from the Algerian current to Crete exhibit higher average numbers of events (e.g. >2.4 per year), but shorter durations (<18 days), indicating frequent but brief MHW occurrences.

140 A similar spatial pattern is observed in the northern Black Sea, particularly in the area near the Kerch Strait, where MHWs occur more frequently but are shorter in duration, with approximately 2.6 events per year lasting between 10 to 14 days (Figure 1, row 1). In contrast, the central and southern regions of the basin, highlighted by green shading in both the spatial maps of mean frequency and duration, exhibit a lower frequency of events, ranging from around 1.8 to 2.2 events per year, but with longer average durations of approximately 18 to 22 days. This spatial differentiation is generally consistent with the

145 findings of Mohamed et al. (2022), especially regarding the northern sector.

The mean intensity of MHWs is notably high in the Black Sea, exceeding 2.85°C relative to the daily climatology for 1993–2022 in specific areas such as the northwestern shelf, the Anatolian and Caucasian coasts (Figure 1, row 1). In the Mediterranean Sea, similarly elevated intensities are observed in the northern Adriatic Sea and the Gulf of Lion, extending offshore towards the regions surrounding Corsica. In these areas, the results suggest that MHWs tend to be short and

150 frequent but exhibit relatively high intensity.

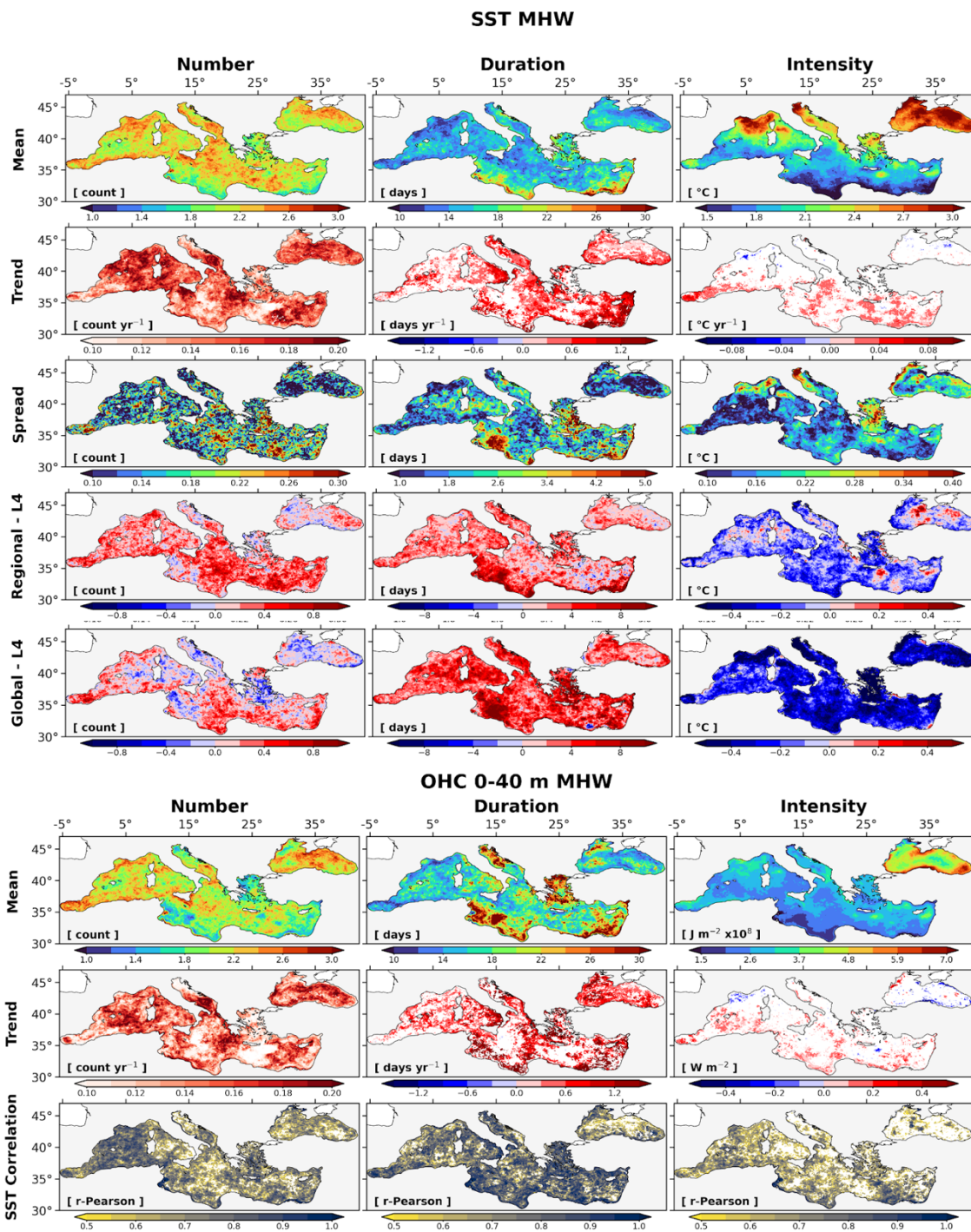


Figure 1: Spatial distribution of MHW metrics derived from SST and upper OHC (0–40 m) in the regional reanalyses (product refs. no. 3 and 4 in Table 1) for the period 1993–2024. Rows 1 and 2 show the spatial patterns of mean values and statistically significant trends ($p < 0.05$) based on the SST definition, respectively. Row 3 presents the spread of the selected MHW metrics



based on the SST definition across the regional reanalysis, global reanalysis (product ref. no. 5 in Table 1), and SST-L4 observational products (product refs. no. 1 and 2 in Table 1). Rows 4 and 5 show the differences in SST-derived MHW metrics between the regional and global reanalyses relative to the SST-L4 observational product. Rows 6 and 7 display the corresponding OHC-derived results from the regional reanalysis, including the spatial patterns of mean values and statistically significant trends ($p < 0.05$), respectively. Row 8 shows the significant spatial correlation ($p < 0.05$) between MHW metrics estimated from SST and OHC.

The number of MHW events has increased over time, showing positive trends of similar magnitude in both the Mediterranean and Black Seas (Figure 1, row 2). Notably, in the Mediterranean Sea the highest increases – exceeding 2 events per decade – are observed south of Sicily, in the southern Adriatic Sea, Cretan Passage (south of Greece and east of Ionian Sea), parts of the Balearic Sea, and east of Corsica and Sardinia. Regarding event duration, the most pronounced positive trends are observed in the eastern Mediterranean Sea, exceeding 12 days per decade. Meanwhile, intensity trends are strongest near the Alboran Sea, increasing around 0.5°C per decade, and extending across the central and eastern Mediterranean with generally positive values. However, this spatial extension is irregular and lacks a coherent pattern that would suggest a continuous or regionally connected increase. In the Black Sea, significant trends exceeding 0.15 events per day ($p < 0.05$) cover much of the basin, with the highest values observed south of the Crimean Peninsula (Figure 1, row 2). Duration trends reach maximum values between 0.6 and 1.2 days per decade, particularly in peripheral zones of the basin and over the northwestern shelf. In contrast, intensity trends are predominantly non-significant throughout the region.

We compute the spread of the main MHW metrics using the regional and global reanalyses (product refs. no. 3, 4 and 5 in Table 1) alongside the SST-L4 observational products (product refs. no. 1 and 2 in Table 1). For the number of events, relatively high spread values are observed throughout the domain (Figure 1, row 3); notably, the highest values, exceeding 0.3, are found in the Aegean Sea, the Alboran Sea, the eastern Mediterranean Sea. For event duration, the largest spread is observed in parts of the Aegean Sea and along the southern Mediterranean, particularly near the African coast south of Sicily, where values exceed 5 days. In comparison, the spread in duration values is generally lower across the Black Sea. The highest spread in MHW intensity, above 0.34°C , is observed in localized areas within the Gulf of Lion and continues along the coasts surrounding Corsica into the Tyrrhenian Sea, as well as in the northern part of the Adriatic Sea and in the Aegean Sea. In the Black Sea, intensity spread values of similar magnitude are found along the western coast and west of the Crimean Peninsula.

For validation, we computed the differences between metrics derived from both regional and global reanalysis data with respect to observed SST-L4 data (Figure 1, rows 4 and 5 and Table 3). For a more specific assessment, the Mediterranean Sea is divided into geographic subregions as proposed by Dayan et al. (2022). The MHW metrics derived from the regional reanalysis generally exhibit positive biases relative to the SST-L4 product in terms of number and duration, while MHW intensity from reanalysis is lower than the observed one. Overall, the regional reanalysis demonstrates superior performance compared to the global reanalysis, producing results that more closely match the SST-L4 reference data, as reported for the Mediterranean Sea in previous analyses by Dayan et al. (2022). An exception is observed in the number of detected events in the whole Mediterranean Sea and the West and East Mediterranean regions, where the global reanalysis typically outperforms the regional analysis. The overall mean values of MHWs number across the entire Mediterranean and Black



Seas are 0.21 and 0.01, respectively, for the regional reanalysis, and 0.06 and – 0.10 for the global reanalysis. While the regional reanalysis exhibits an average positive bias in the number of events in the Adriatic and Aegean Seas, the global reanalysis shows a negative and larger bias in these regions. In contrast, both reanalyses show a predominantly positive bias in event duration and a negative bias in intensity.

Table 3. Basin-averaged differences in MHW metrics between the regional and global reanalyses (product refs. no. 3, 4 and 5 in Table 1), computed relative to the SST-L4 observational product (product refs. no. 1 and 2 in Table 1) for the period 1993–2024. Reanalysis products that produce MHW metrics closest to the observational SST-L4 product are highlighted in green. The subdomain definition follows Dayan et al. (2022).

	Number		Duration (days)		Intensity (°C)	
	Regional REA	Global REA	Regional REA	Global REA	Regional REA	Global REA
MED	0.21	0.06	2.37	4.20	–0.16	–0.35
WMED	0.19	0.06	2.11	3.61	–0.15	–0.30
EMED	0.25	0.10	2.52	4.34	–0.17	–0.34
Adriatic Sea	0.05	–0.13	2.73	4.28	–0.16	–0.48
Aegean Sea	0.05	–0.16	2.29	5.87	–0.22	–0.54
Black Sea	0.01	–0.10	1.20	2.43	–0.08	–0.42

3.2 OHC-Derived Marine Heatwave Characterization

We also compute analogous MHW metrics based on upper OHC (0–40 m; rows 6 and 7 in Figure 1). In the Mediterranean Sea, the average number of MHW events decreases compared to those derived from SST, particularly along the African coast (from 10°E to 35°E), in the Adriatic Sea, around the Gulf of Lion, and throughout much of the central basin between 15°E and 30°E (Figure 1, row 6). These results are consistent with the conclusions of Dayan et al. (2023). In contrast, the number of subsurface MHW events increases in certain regions, such as parts of the Alboran Sea, though this increase is spatially limited, and across most of the Black Sea.

Unlike the number of events, the mean duration of subsurface MHWs is generally longer as compared to the events observed at the sea surface across many regions in both the Mediterranean and Black Seas (Figure 1, row 6). In the Mediterranean Sea, notable increases in event duration are observed in the Aegean Sea, the northern and central Adriatic Sea, and the central basin – particularly between 10°E and 20°E. This includes the Gulf of Gabès and the adjacent coasts of Tunisia and Libya, where average event durations can exceed 28 days. In the Black Sea, duration increases are observed particularly in the western part, between 25°E and 35°E, with values exceeding 24 days along the northwestern coast.

For intensity, the OHC-based results reveal patterns that are not captured by the SST-based definition (Figure 1, row 1 versus row 6). A shared feature of both SST- and OHC-derived MHW intensity is the elevated values consistently observed



in the Black Sea. Notably, the mean intensity from OHC shows distinct signals associated with the Rim Current and mesoscale eddies. For example, values exceed 7.0 J m^{-2} in the Batumi region, located in the southeastern part of the basin, and reach approximately 6.0 J m^{-2} west of Crimea, near the Sevastopol eddy region. Similar to the SST-derived metric, the OHC-derived intensity also shows relatively higher values in the northern Mediterranean, particularly over the Gulf of Lion, Strait of Otranto, the Crete gyre, southeast of Cyprus (Latakia eddies), Antalya Bay (Asia minor current) and the Alboran Sea. In these regions, the mean intensity can reach values between approximately 3.7 and 4.8 J m^{-2} .

Similar to the SST-derived metric, the OHC-based trends show positive values for both the number and duration of MHW events (Figure 1, row 7). In the Mediterranean Sea, high trends, exceeding 2 events per decade, are observed in the central and south Adriatic Sea, Cretan Passage (east of the Ionian Sea and south of Greece), parts of the Balearic Sea and Algerian basin. These regions coincide with areas where the SST-based trends in the number of events are also elevated. In contrast, the OHC-derived trends are relatively lower in regions such as the southern coast of Sicily and the eastern coasts of Corsica and Sardinia. In the Black Sea, the number of events exhibits stronger increasing trends along the Rim Current, a signal not captured by the SST-based metric. For event duration, the OHC-based trends display more spatial gaps (areas with no statistically significant trend), particularly in the eastern Mediterranean, where trend values are also slightly lower compared to those derived from SST. An interesting finding emerges for MHW intensity: OHC-based trends show localized negative values along the Rim Current pathway, especially near the Anatolian coast and in areas adjacent to the Kerch Strait. In the Mediterranean Sea, negative trends in intensity are observed in regions such as the Gulf of Lion and the Crete gyre. Among these, only the Gulf of Lion also exhibits similar negative trends in the SST-based definition.

Correlation maps for the period 1993–2024 show statistically significant agreement between annual-average MHW metrics derived from SST and OHC in the upper 0–40 m throughout large areas of the western and central Mediterranean Sea (Figure 1, row 8). Considering the number of events, significant correlations are observed in most of the Mediterranean, but this decreases toward the central and eastern basins and in the Black Sea, where non-significant correlations ($r < 0.5$, $p > 0.05$) become more frequent. Event duration exhibits generally stronger and more spatially consistent correlations, particularly in the Mediterranean Sea, with values often exceeding $r > 0.8$ ($p < 0.05$), while correlations in the Black Sea are weaker overall. Correlations for event intensity tend to be lower and more variable, with non-significant values covering nearly the entire Black Sea and the central and northern Adriatic Sea.

While strong correlations indicate agreement between surface and subsurface MHW metrics on an annual scale, they may mask differences in timing, depth structure, or seasonal behavior, especially given that our analysis does not resolve intra-annual variability. In contrast, weak correlations highlight the added value of combining both indicators for a more complete assessment of MHWs.

3.3 Sensitivity of SST- and OHC-Based MHW Metrics to Water Mass Structure

The objective of this section is to characterize MHW events using both definitions and to assess the sensitivity of each approach to the vertical structure of water masses. Although water mass dynamics are known to influence thermal variability



in these semi-enclosed basins, this section does not explore causal relationships or feedbacks between MHWs and water mass formation. Instead, it provides a descriptive evaluation of how different MHW definitions respond to varying water mass structures, without attempting to attribute the physical mechanisms responsible for MHW occurrence.

3.3.1 Black Sea CIL

In the Black Sea, a prominent feature is the CIL, a subsurface cold water mass that forms during winter through surface cooling and convective mixing. The CIL, typically characterized by temperatures below 8°C and found between depths of 30 and 80 meters (Ivanov et al., 2001), contributes significantly to subsurface ventilation (Özsoy and Ünlüata, 1997). Its seasonal formation is driven by dense surface waters sinking during cold winters, and it can modulate heat distribution in the upper ocean, thus affecting MHW development. The warming of the Black Sea has contributed to the gradual disappearance of the CIL, as evidenced by both observational and reanalysis datasets (Stanev et al., 2019; Lima et al., 2021, 2025).

In the Black Sea, the detection of MHWs differs significantly between surface- and subsurface-based metrics, particularly in recent years marked by the formation of the CIL (e.g. 2012) which alters the thermal structure of the water column. Figure 2 shows MHWs intensity and duration evaluated using both SST-based (left) and OHC-based (right) definitions for selected years: 2011 is included due to a pronounced positive surface temperature anomaly. The years 2012 and 2017 feature the presence of the CIL, with 2012 showing a well-developed CIL and 2017 a less pronounced presence (Stanev et al., 2019; Lima et al., 2025). The year 2024 is included as it exhibited record breaking MHW intensity. In 2011, reanalysis data revealed negative temperature anomalies confined to the near-surface layers, promoting the subduction of cold water and contributing to the development of a well-defined CIL in 2012 (Lima et al., 2021, 2025). These thermal structures influence MHWs detection differently depending on the metric applied. In 2011, SST-based metrics indicate limited MHW coverage due to cooler surface conditions. However, in 2012, OHC-based metrics, sensitive to subsurface heat content, show significantly reduced MHW spatial extent compared to SST-based estimates (see also Figure 4, discussed in a later section), highlighting the importance of vertical heat distribution in accurately characterizing MHWs. In 2017, another year marked by the presence of the CIL, cold temperatures were more uniformly distributed throughout the upper layers in the Black Sea. In this case, SST- and OHC-based definitions produced closely aligned metrics, both indicating diminished MHW coverage, particularly in the western Black Sea. These findings demonstrate how the presence and vertical structure of the CIL influence the detection and apparent intensity of MHWs, depending on whether surface or subsurface indicators are used.

In 2017 and 2024, the OHC-based metric detected a more pronounced signal, with intensified MHW events notably concentrated along the Rim Current and in eddy-dominated areas, such as the Sevastopol eddy located west of Crimea. This spatial distribution aligns with the long-term pattern observed in OHC-derived metrics over the period 1993–2024 (Figure 1, rows 6), reinforcing the consistency of subsurface-driven MHW signals in these dynamically active regions. In contrast, the SST-based approach does not capture these features, highlighting the added value of incorporating subsurface heat content to more accurately represent MHW intensity and spatial variability. In 2024, surface MHW intensity increased substantially, surpassing 4.6 °C along the Anatolian coast, a region influenced by summer upwelling (Gunduz et al., 2022), and reaching



up to $1 \times 10^9 \text{ J m}^{-2}$ in areas along both the southern and northern branches of the Rim Current. Furthermore, both SST- and OHC-based definitions identify events with durations exceeding 30 days, with consistent detections particularly evident west of Crimea and in the central and southwestern parts of the basin.

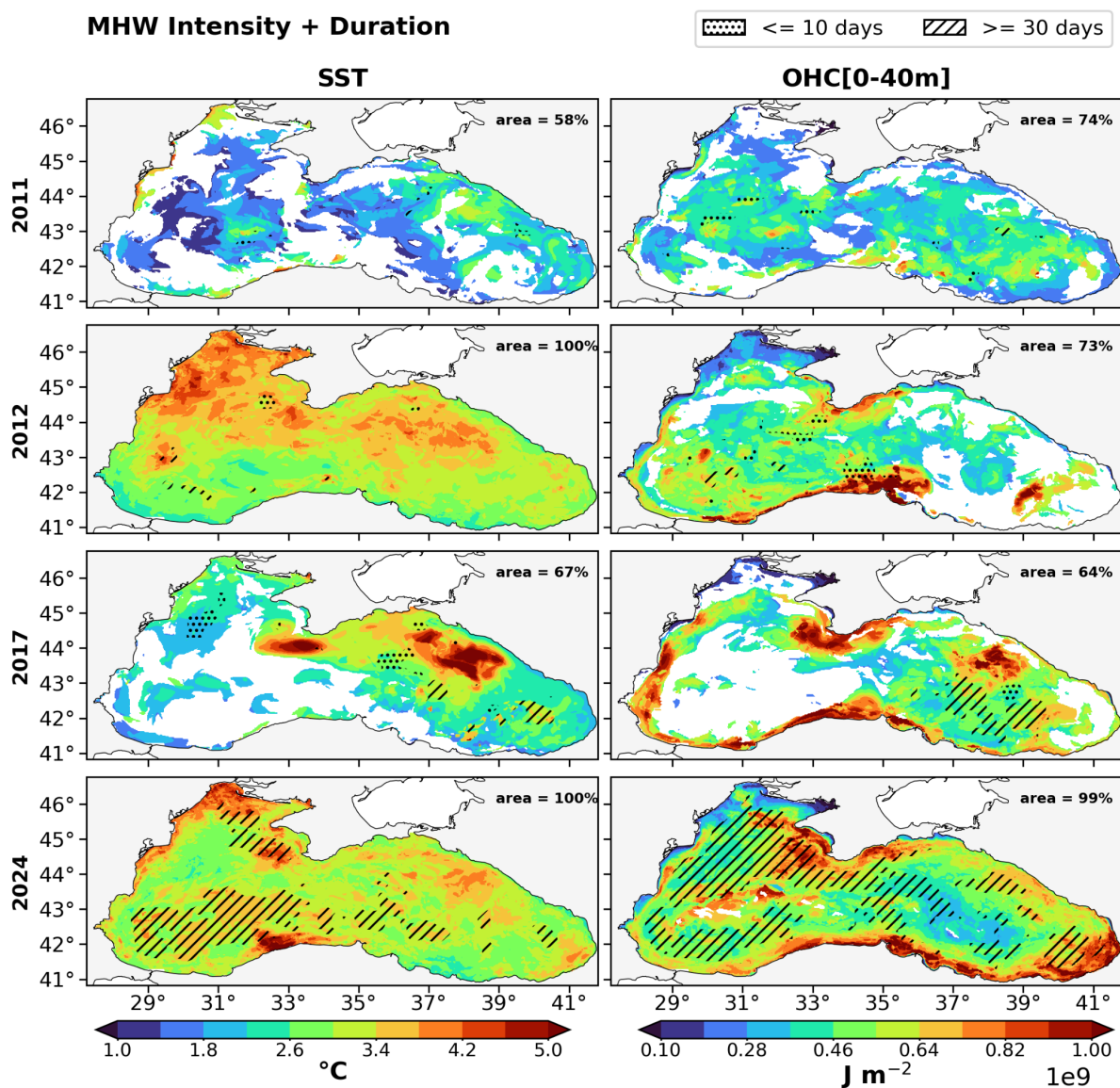


Figure 2: Spatial distribution of the mean intensity of MHW events for selected years in the Black Sea using SST-based (left) and OHC-based (right) definition. Hatched areas highlight regions where events lasted less than 10 days or more than 30 days. Results are derived from the Black Sea regional reanalysis (product ref. no. 3 in Table 1).



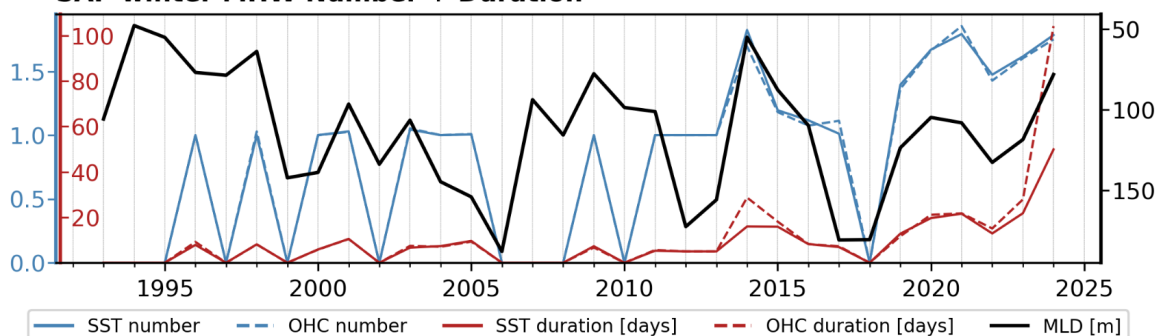
3.3.2 Southern Adriatic Sea Pit and the Eastern Mediterranean Deep Water

295 To better understand how MHW metrics respond to changes in water mass structure in the Mediterranean Sea, we focus on
the Southern Adriatic Sea Pit (SAP), a key area for the formation of Eastern Mediterranean Deep Water (EMDW), which
occurs during winter. Since this process affects how deep the surface layer mixes, it can influence how MHWs are detected.
The Adriatic Deep Water (ADW), along with the North Adriatic Dense Water (NAdDW), is identified as one of the main
sources of EDMW (Gačić et al., 2001; Paladini de Mendoza et al., 2022; Parras-Berrocal et al., 2023). The southward spread
300 of NAdDW along the western Adriatic coast, together with open-ocean convection in the center of the permanent cyclonic
gyre over the SAP, contributes to the formation of ADW (Denamiel et al., 2025). ADW plays a significant role in
maintaining the overturning circulation of the Mediterranean Sea.

Figure 3 presents a time series of wintertime mean values for the number, duration, and intensity of MHW events evaluated
using both SST-based and OHC-based approaches, together with the winter mean MLD, all averaged over the SAP basin. In
305 most years, lower MHW frequency and shorter event durations are associated with deeper MLDs, typically exceeding 100
m. An interesting observation occurs in 2014, when the winter MLD was relatively shallow, with a mean value of around 50
m; nevertheless, MHW metrics increased, reaching over two events with durations exceeding 15 days based on both SST-
and OHC-derived estimates. This anomaly is consistent with findings by Le Meur et al. (2025), who identified positive
anomalies of heat flux from atmospheric reanalysis (ERA-5) in 2014 winter in the South Adriatic.



SAP winter MHW Number + Duration



Winter MHW Intensity + Duration

≤ 10 days
 ≥ 30 days

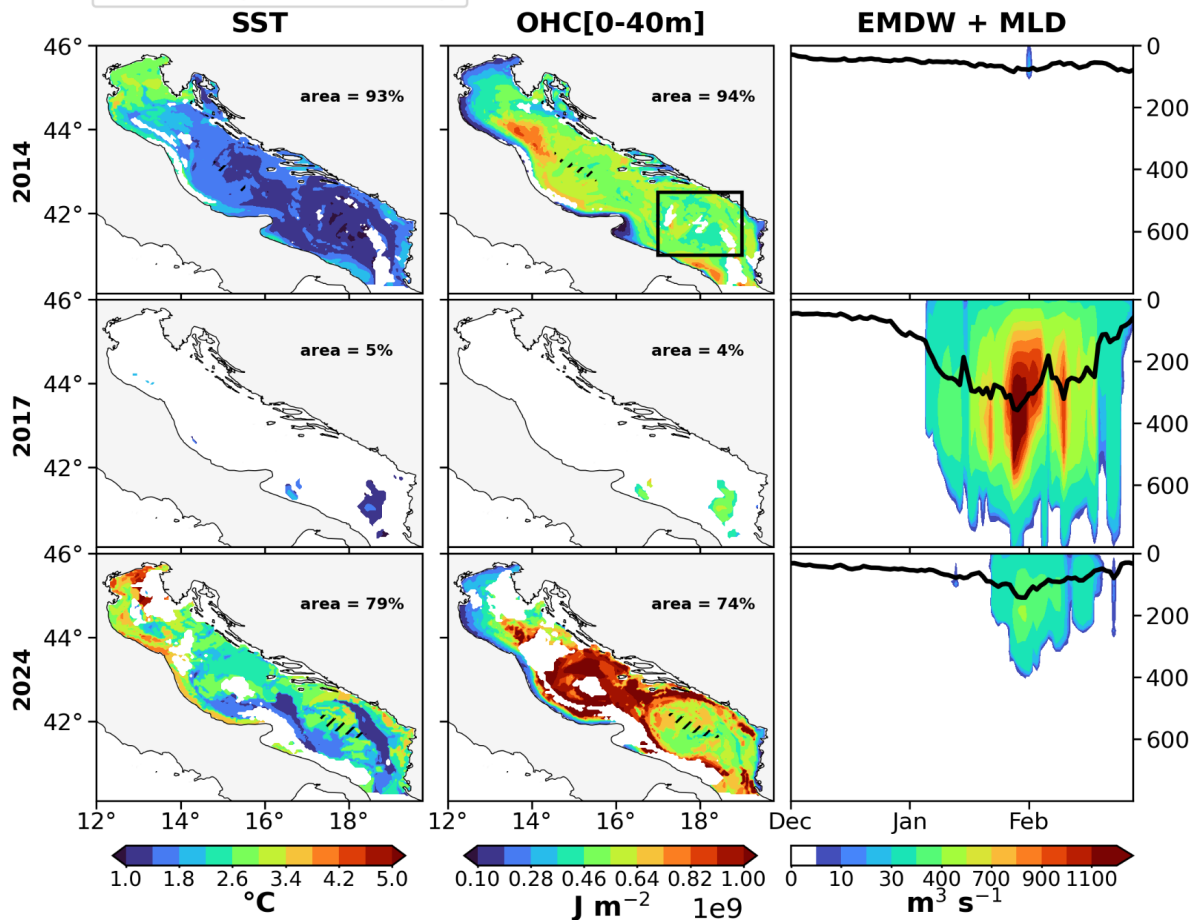


Figure 3: Upper plot: Time series show basin-averaged MHW number of events and duration (days) from two definitions based on SST and OHC, together with mean MLD during winter (1993-2024) in the SAP region. Lower plot: Spatial maps exhibit mean MHW intensity based on SST ($^{\circ}\text{C}$) on the left and OHC (0–40 m, J m^{-2}) in the middle for 2014, 2017, and 2024 in the Adriatic Sea. The black rectangle on the 2014 OHC map indicates the SAP region. Hatched areas highlight regions where events lasted less than 10 days or more than 30 days. Hovmöller diagrams on the right panels reveal water mass formation rates of the EMDW ($\text{m}^3 \text{s}^{-1}$)



overlapped by daily mean MLD values for the winter months in the SAP region. Results are derived from the Mediterranean Sea regional reanalysis (product ref. no. 4 in Table 1).

Similarly, data from the Copernicus OMI on Mediterranean Water Mass Formation Rates (EU Copernicus Marine Service Product, 2024h, <https://doi.org/10.48670/mds-00318>) indicate an abrupt decline in EMDW formation, with notably low transport (in Sverdrups), during the 2014–2016 period. Kokkini et al. (2020) reported that 2014 was characterized by less saline water dominating the upper layers across the entire pit, accompanied by a significant heat gain in the whole Adriatic Sea. These conditions likely suppressed winter convection, leading to weakened ADW formation, while the associated heat gain may have contributed to the observed increase in MHW activity. In 2017, EMDW formation was reestablished, consequently accompanied by an increase in winter MLD and a complete absence of MHW events.

The Hovmöller diagrams in Figure 3 presents the wintertime EMDW formation rates for key years, illustrating a significant increase in 2017 compared to 2014. The methodology for estimating EMDW formation follows Simoncelli and Pinardi (2018), consistent with the approach applied in the OMI analysis described in the paragraph above. These years were selected to illustrate contrasting MHW detection patterns under varying deep-water formation regimes (see spatial maps in Figure 3). In 2014, enhanced stratification indicated by a shallower MLD was associated with weaker EMDW formation and widespread MHW coverage across the Adriatic Sea, particularly in the SAP. Conversely, the stronger convective conditions in 2017, reflected in deeper MLDs and higher EMDW formation rates, were accompanied by reduced MHW activity.

We also present the results for 2024, when the MHW assumed a higher intensity in the Adriatic Sea and events lasted more than 30 days in the SAP region. In that year, the time series also indicates a considerable reduction in winter MLD, which is accompanied by elevated MHW metrics, indicating the sensitivity of MHW development to upper ocean stratification.

Unlike in 2014, when vertical convection ceased, the Hovmöller diagram for 2024 reveals signs of vertical convection that may be influenced by regional salinity.

Overall, time series of wintertime MHW estimates derived from both SST- and OHC-based definitions demonstrate strong spatial agreement in the Adriatic Sea, although intensity maps reveal differing spatial patterns, with distinct regions of higher intensity depending on the metric used (Figure 3). This suggests that, even under weak stratification, the OHC-based indicator captures complementary subsurface information not reflected by SST alone, strengthening the case for using both approaches in MHW detection.

3.4 Intensity-Based Analysis of MHW in the Black and Mediterranean Seas

Our findings indicate that the use of a single method for monitoring MHWs, whether based exclusively on SST or OHC, is insufficient to fully characterize and monitor MHWs across both the Black and Mediterranean Seas. Each index reflects different aspects of ocean warming and is influenced by distinct physical drivers, with SST closely linked to atmospheric conditions and OHC representing heat stored beneath the surface. When applied separately, these indices may offer an incomplete representation of thermal anomalies, limiting their effectiveness in capturing the full scope and variability of MHWs in both seas. Our results support previous findings (e.g., McAdam et al., 2023) that highlight the importance of



incorporating subsurface information into monitoring strategies. Therefore, we recommend a combined approach that
350 integrates SST- and OHC-based definitions, including event intensity levels based on the categorization framework such as
established by Hobday et al. (2018). Figures 4 and 5 show this combined approach applied to the Black Sea and
Mediterranean Sea respectively.

In the Black Sea, both the average spatial extent and basin-average number of days of moderate MHW events have increased
over time, with recent years showing coverage extending across nearly the entire basin (Figure 4). As discussed in the
355 previous section, years marked by the presence of the CIL can exhibit distinct behavior depending on the MHW definition
applied. In 2012, the SST-based definition indicates nearly complete basin-wide coverage of moderate MHWs on an annual
scale, whereas the OHC-based definition shows less than 80% coverage. In contrast, during 2017, when the cold signal
associated with the CIL was more uniformly distributed throughout the water column, both definitions produced similar
metrics for moderate events, with spatial coverage around 60% and a basin-average of approximately 25 days. A notable
360 result is found in 1995, when the SST-based definition indicates that moderate events cover almost the entire sea, with the
basin-average number of days exceeding 25. By comparison, the OHC-based definition for the same year shows spatial
coverage of about 60% and a slightly lower basin-average number of days, just below 25. The correlation between moderate
MHW metrics derived from SST and OHC definitions is 0.89 for spatial coverage and 0.88 for the basin-average number of
days.

365 The spatial coverage of strong MHW events shows a positive trend over time for both definitions. In contrast, no clear trend
is observed in the basin-averaged number of days, although elevated values are noted in recent years, particularly in 2023
and 2024. The year 2010 is particularly notable, with the SST-based definition indicating that strong events affect nearly the
entire basin and the basin-average number of days exceeded 10. This signal is not captured by the OHC-based definition.
Similarly, SST-based metrics indicate that more than 20% of the basin was affected by severe events in 2010, a pattern not
370 detected using the OHC approach. Mohamed et al. (2022) associated the exceptionally high MHW activity in 2010 with the
influence of El Niño, suggesting a potential link between large-scale climate variability and surface heatwave manifestations
in the Black Sea. The presence of the CIL is also reflected in the detection of strong events in 2012, when the SST-based
definition shows a wider spatial extent than the OHC-based definition, further highlighting the impact of subsurface thermal
structure on MHW detection in the Black Sea. To further illustrate this, we include the 0–100 m OHC anomaly from the
375 Black Sea regional reanalysis, together with observational estimates of CIL cold content from Capet et al. (2020). These
datasets respectively show a decline in OHC and an increase in CIL cold content in both 2012 and 2017, consistent with a
more pronounced CIL presence during those years, which may have affected the detection of MHWs using the OHC-based
definition. Correlation coefficients between SST- and OHC-based metrics for spatial coverage are 0.79, 0.81, and 0.80 for
the strong, severe, and extreme categories, respectively. For the basin-average number of days, the corresponding
380 correlations are 0.84, 0.43, and 0.67.

Considering all categories, the year 2024 exhibits record-high values in both spatial coverage and basin-average number of
days for MHW events, based on both SST- and OHC-based definitions. In this year, moderate events were detected on more



than 125 days according to both definitions, while the OHC-based definition indicates that strong events occurred with a basin-average duration of approximately 40 days. Detection based on either SST or OHC reveals spatial coverage exceeding 80% for strong events and approaching 50% for severe events. Although extreme events covered a smaller area in 2024, their occurrence remains relatively high compared to previous years in the time series. Additional MHW metrics for 2024 are summarized in the chart diagrams (Figure 4, right).

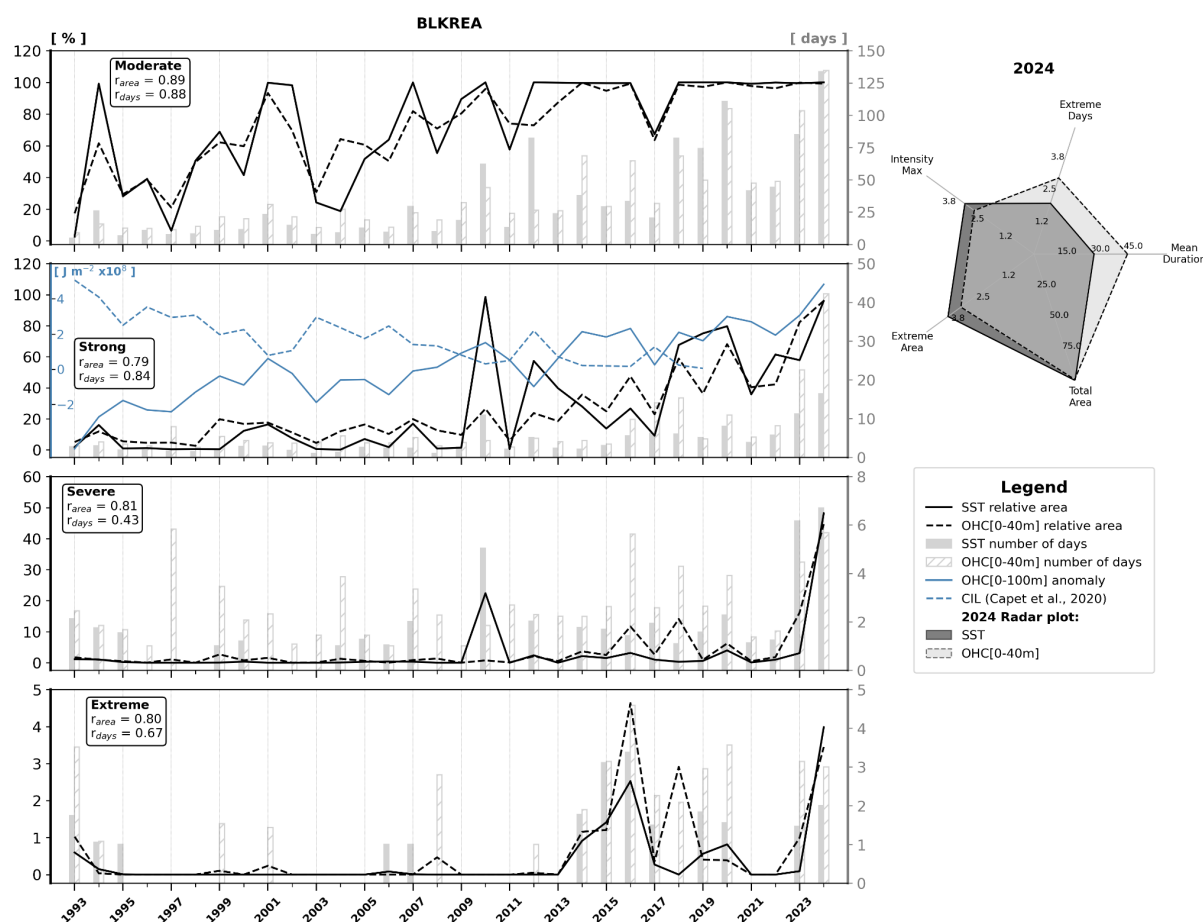


Figure 4: Time series of the temporal and basin-wide mean spatial coverage of MHW events in the Black Sea based on SST (solid line) and OHC (dashed line) definitions. Results are derived from the Black Sea regional reanalysis (product ref. no. 3 in Table 1). The bars show the mean number of days of events for each category over the years, with SST-based values in grey and OHC-based values shown with hatching. On the right, the radar chart summarizes selected MHW metrics using both definitions for the year 2024. Events are categorized as moderate, strong, severe, or extreme, following the classification by Hobday et al. (2018). The correlations between the spatial coverage (r_{area}) and number of days (r_{days}) are also presented for each category. For the “strong” category, blue curves show the time series of OHC (0–100 m; solid) and CIL cold content from observations (dashed; Capet et al., 2020).

In the Mediterranean Sea (Figure 5), both the basin-averaged number of days and spatial extent of moderate and strong MHW events have increased in recent years, with peaks occurring in 2023 or 2024 depending on the metric and definition used. In 2023 and 2024, moderate events nearly cover the entire basin, with the mean number of days exceeding 100.



400 Although strong events occur less frequently and affect smaller areas, their spatial extent and mean total days have increased significantly since 2021, peaking in 2024 with values exceeding 80% coverage and approximately 40 days. An exception to this overall increasing trend occurred in 2005, when a notable decline in the spatial extent of both moderate and strong MHWs was observed. This anomaly coincides with an abrupt disruption in the long-term warming trend reported in the Mediterranean Sea that year, which had consequences for the formation of Western Mediterranean Deep Water (López-Jurado et al., 2005; Beuvier et al., 2012).

405 When comparing definitions, OHC-based metrics generally indicate lower spatial coverage for both moderate and strong MHW events relative to SST-based estimates. Severe events cover less than 10% of the basin for most years in the study period, although recent years show an increase, with SST- and OHC-based values reaching approximately 40% and 20%, respectively, in 2024. Despite this expansion in spatial extent, the frequency of severe events remains low, with these events typically occurring on fewer than 7 days.

Overall, metrics derived from SST- and OHC-based definitions exhibit strong and statistically significant correlations ($r > 0.9$, $p < 0.05$ in most cases). However, the mean total days of severe and extreme events show lower correlations of 0.77 and 0.73, respectively. The year 2024 displays notably high values across multiple MHW metrics, as illustrated in the radar plot (Figure 5, right).

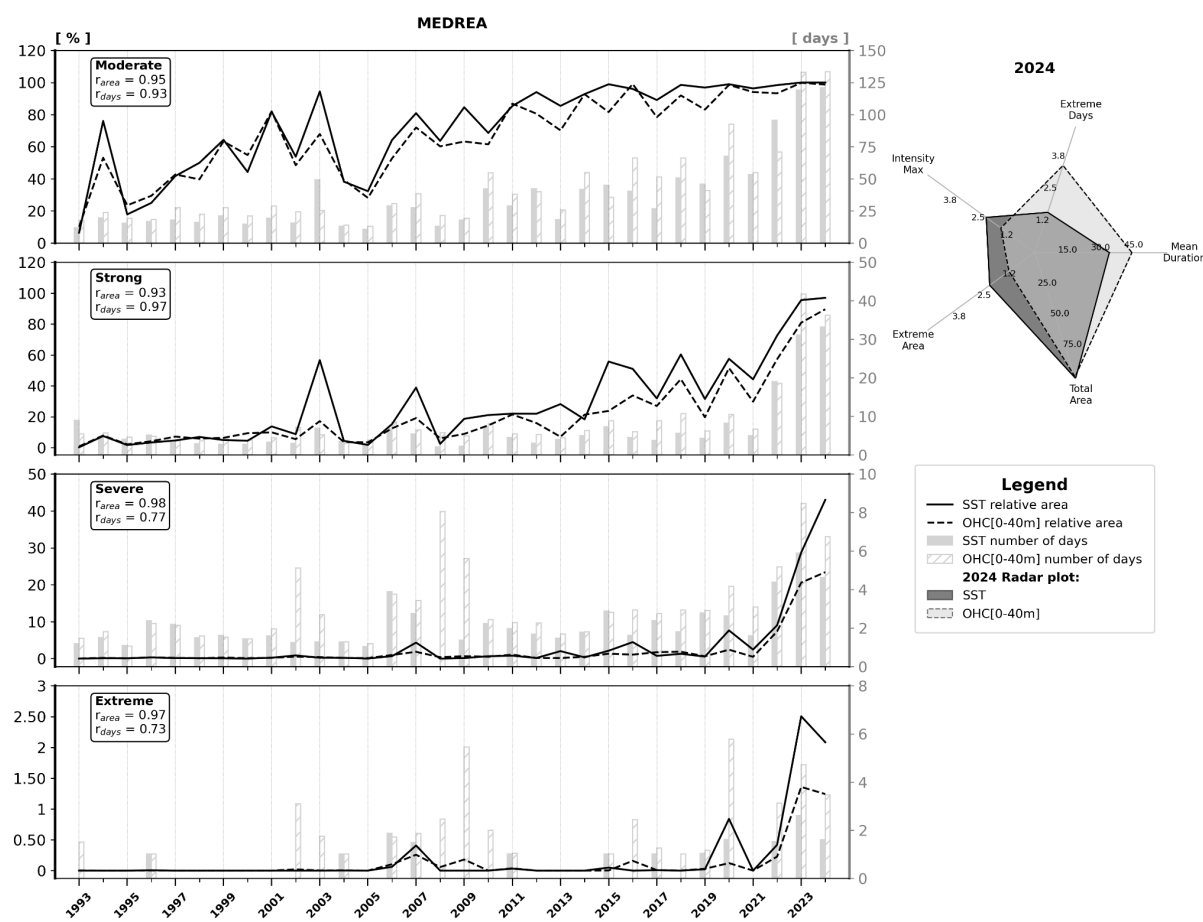


Figure 5: Time series of the temporal and basin-wide mean spatial coverage of MHW events in the Mediterranean Sea based on SST (solid line) and OHC (dashed line) definitions. Results are derived from the Mediterranean Sea regional reanalysis (product ref. no. 4 in Table 1). The bars show the mean number of days of events for each category over the years, with SST-based values in grey and OHC-based values shown with hatching. In the right, the radar chart summarizes selected MHW metrics using both definitions for the year 2024. Events are categorized as moderate, strong, severe, or extreme, following the classification by Hobday et al. (2018). The correlations between the spatial coverage (r_{area}) and number of days (r_{days}) are also presented for each category.

4 Conclusions

We update and expand the analysis of MHW metrics in the Mediterranean Sea and apply a similar assessment to the Black Sea, following HB2016. For both regions, we estimate the uncertainty of SST-based MHW metrics using three different products and extend the analysis to the sub-surface MHWs by means of an OHC-based formulation. This ensemble-based approach can be further strengthened by including additional reanalyses and observational datasets, thereby allowing for a more robust quantification of uncertainties. The regional reanalysis provides more reliable estimates than the global reanalysis, closely aligning MHW metrics with observational SST data. MHW metrics derived from SST and OHC are



generally consistent, with high spatial correlation in event duration ($r > 0.8$, $p < 0.05$) across the central and eastern Mediterranean. The number of MHW events also exhibits generally high correlations, though values decline toward the central and eastern Mediterranean and parts of the Black Sea, where correlation coefficients fall below 0.6 ($p < 0.05$) and become non-significant ($p > 0.05$) over a more extensive area (Figure 1, row 8). However, substantial differences also emerge, including variations in intensity patterns and cases where surface anomalies are not accompanied by subsurface warming, and vice versa. These contrasts highlight the importance of using SST- and OHC-based formulations as complementary sub-indicators to better characterize the full vertical structure and spatial complexity of MHWs, as further illustrated in the regional examples below.

In the Black Sea, OHC-derived MHW intensity highlights subsurface processes associated with the Rim Current, capturing localized maxima that are absent in SST-based estimates. For instance, in 2012, the presence of a well-developed CIL led to subsurface cooling, which masked the MHW signal in OHC, while surface temperature anomalies remained detectable using the SST-based definition. In the Adriatic Sea, surface and subsurface MHWs show generally consistent frequency and duration over time, particularly in the SAP region. However, the spatial distribution of maximum intensity often diverges between SST- and OHC-based definitions, with peak values located in different areas depending on the definition used. These variations highlight the limitations of using either SST- or OHC-based definitions alone. Radar plots that integrate intensity, duration, and spatial extent are useful for monitoring the temporal evolution of MHW characteristics. They serve as synthetic indicators for ocean monitoring and help synthesize interannual differences as well as those arising from the use of SST versus OHC definitions.

In 2024, both the Black Sea and Mediterranean Sea experienced record-high MHW intensities and durations, with events lasting over 30 days and temperature anomalies exceeding 4.6°C in key regions such as the Anatolian coast (Figure 2, bottom left), where summer upwelling commonly influences local ocean conditions. These extreme recent events underscore the urgency of refining monitoring strategies and understanding the mechanisms behind MHW development in these semi-enclosed basins.

Identifying the dominant MHW physical drivers associated with the detection criteria of each definition is beyond the scope of this study; nevertheless, our findings provide valuable insights to guide future research on the primary drivers of MHWs in both seas. We recommend a MHW OMI that integrates both SST and OHC definitions to capture surface and subsurface heatwave signals in the Mediterranean and Black Seas. While the HB2016 definition remains practical for current monitoring, future studies may benefit from refined methods such as higher percentiles, moving average climatologies, or detrending to better separate extremes from long-term warming (Appendix A). Since the 90th percentile may be less restrictive for some regions, categorizing MHWs according to their intensity remains essential, and the Hobday framework provides a robust basis by classifying events as moderate, strong, severe, or extreme.

While the need to provide information on both surface and subsurface characteristics of MHWs is made clear in this study for the Mediterranean and Black Sea, and in Sun et al. (2023) at global scale, the depth ranges of interest depend greatly on region and application. The range 0–40 m chosen here represents the upper part of the epipelagic zone, rich in biological and



socio-economic activity (Kubryakov et al., 2020; Konsta et al., 2025). Therefore, future work should explore region-specific
465 depth thresholds that reflect local oceanographic dynamics and ecological sensitivities.

Appendix A. Effect of SST and OHC Detrending on MHW Metrics

An additional analysis is performed to assess the impact of using a detrending approach for MHW detection by removing the
mean trend value over the full spatial domain of each product from the original SST and OHC time series before applying
the detection algorithm. Specifically, the linear trend is removed individually at each grid point to account for local
470 variations in long-term change.

According to the standard SST-based definition, basin-averaged values for both the number and duration of MHW events
exhibit marked interannual variability in both the Black and Mediterranean Seas, with particularly pronounced fluctuations
in the former. For example, the number of events in the Black Sea ranged from fewer than one to nearly five per year during
relatively short periods, such as between 2009 and 2013. Additional peaks approaching or exceeding five events were
475 observed in 2018, 2020, and 2024. In recent years, the number of events has increased in both basins, with 2024 marking a
record year for both. Elevated frequency in 2024 also extends to event duration, highlighting it as an exceptionally warm
year in both regions. In that year, the spatially averaged duration of extreme temperatures exceeds 30 days in the
Mediterranean Sea and approaches 30 days in the Black Sea. In the first part of the analyzed period, the detrended metrics
are larger until around 2007-2008, then they become lower than the "reference" metrics. Instead, the intensity of events is not
480 significantly influenced by detrending over the years. The intensity time series begins with elevated values exceeding 5°C in
1993 in the Black Sea and over time, intensity decreases and stabilizes around 3°C, whereas in the Mediterranean Sea, values
consistently remain close to 2°C.

The analysis is further extended beyond regional reanalysis products to assess the impact of detrending within a multi-
product framework (Figure A1 and Table A1). We first describe the results obtained using the formulation without
detrending the SST. Considering the number of events, regional reanalysis products always show higher trends with respect
485 to the global reanalysis and satellite observations. In contrast, the global reanalysis exhibits the highest trends in event
duration, surpassing both regional reanalysis and the observed SST except for the Adriatic and Black Seas, where the
duration trend is higher in the regional reanalysis. In these two regions, however, no product shows a statistically significant
intensity trend. After detrending SST, most trends in the number and duration of events become non-significant (Figure A1
490 and Table A1 exclude trends that are not statistically significant). Exceptions include the regional reanalysis in the western,
eastern, and entire Mediterranean Sea, where the duration of events shows small and negative trends. In the Aegean Sea, the
duration trend derived from the global reanalysis remains positive, although its magnitude is reduced to approximately half
of that observed under the standard (non-detrended) definition. Regarding MHW intensity, either the global or regional
reanalysis indicates increasing trends across most of the Mediterranean Sea. Again, in the Adriatic and Black Seas, no
495 product shows a statistically significant trend.



To distinguish the warming signal, Martinez et al. (2023) analyzed MHW metrics in the Mediterranean Sea by applying detections to the SST-L4 observational product and comparing results from the standard definition with those obtained after detrending. Similarly, their findings reveal positive trends using the standard method, whereas the detrended approach shows no statistically significant trends. Consistent with our findings, their results indicate that the occurrence of MHWs is predominantly driven by the underlying temperature trend.

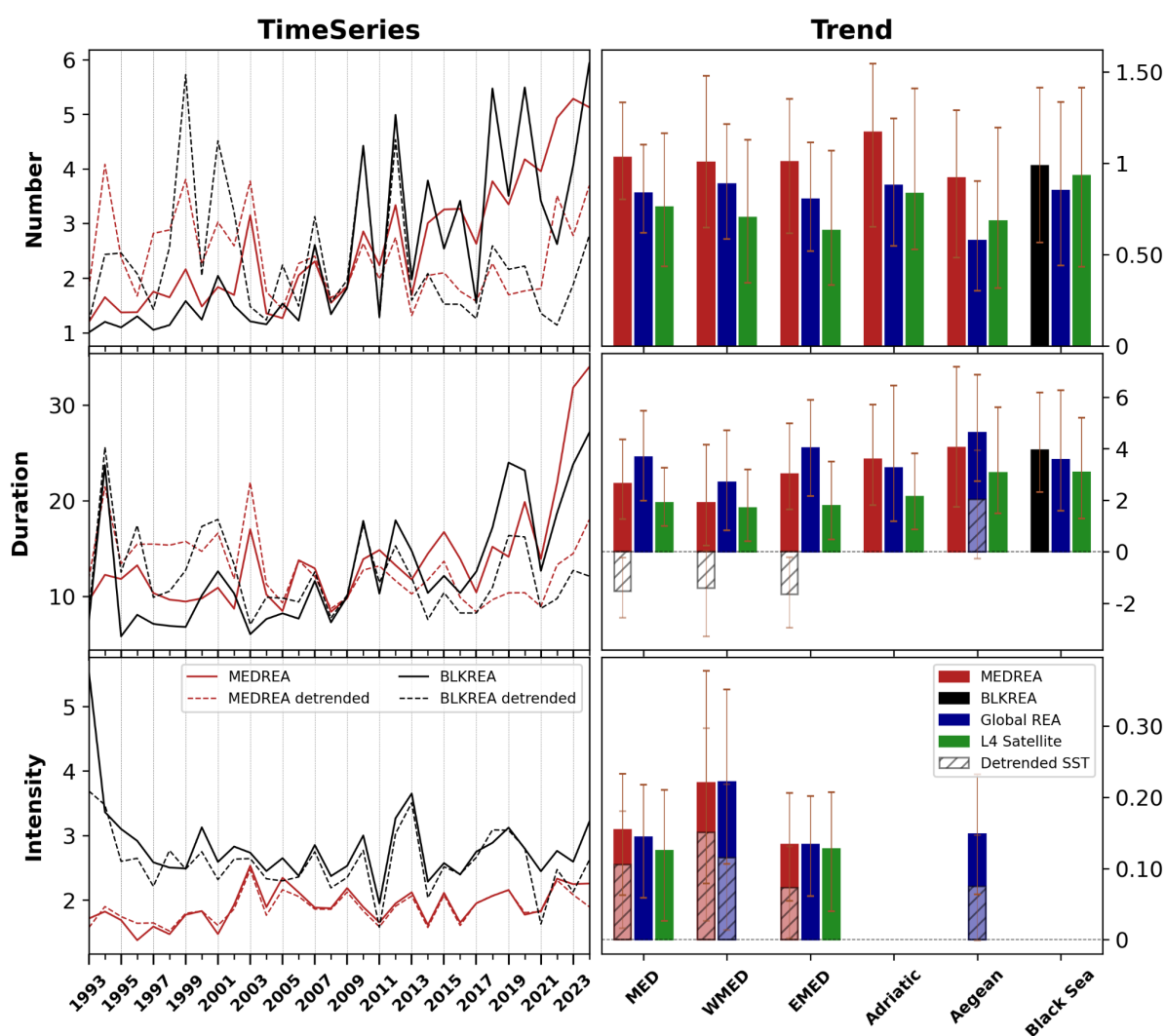


Figure A1: Left: Time series of annual MHWs metrics – number, duration (in days), and maximum intensity (in °C) – averaged over the entire Mediterranean (red lines) and Black Seas (black lines), comparing the SST definition (solid lines) with the detrended approach (dashed lines), based on the regional reanalysis (product refs. no. 3 and 4 in Table 1). Right: significant ($p < 0.05$) long-term trends (1993–2024) in MHWs number (events per decade), duration (days per decade), and maximum intensity (°C per decade), derived from regional and global reanalysis (product ref. no. 3, 4 and 5 in Table 1) as well as the SST-L4 observation product (product refs. no. 1 and 2 in Table 1), for selected (sub)regions following Dayan et al. (2022). Brown lines indicate the 95% confidence interval. Solid bars show standard metrics definition, striped bars show SST de-trended metrics.



510 **Table A1. Long-term trends (1993–2024) with 95% confidence interval indicated in brackets of MHW number, duration, and maximum intensity per year, derived from regional and global reanalysis (product refs. no. 3, 4 and 5 in Table 1) as well as the SST-L4 observation products (product refs. no. 1 and 2 in Table 1), for selected (sub)regions. The subdomain definition follows Dayan et al. (2022). Non-significant trends ($p \geq 0.05$) are indicated by hyphens. Both SST (top) and OHC (bottom) derived metrics are presented. Rows shaded in grey in the table represent trends calculated using the detrended approach.**

SST-derived metrics																				
	MED				WMED			EMED			Adriatic			Aegean			Black Sea			
	MEDREA	GLOREA	L4	Martinez et al. (2023)	MEDREA	GLOREA	L4	MEDREA	GLOREA	L4	MEDREA	GLOREA	L4	MEDREA	GLOREA	L4	BLKREA	GLOREA	L4	
Number events yr ⁻¹	0.103 (0.030)	0.084 (0.027)	0.076 (0.040)	0.074	0.101 (0.047)	0.089 (0.033)	0.070 (0.043)	0.101 (0.039)	0.080 (0.031)	0.063 (0.044)	0.117 (0.052)	0.088 (0.037)	0.083 (0.058)	0.092 (0.044)	0.058 (0.033)	0.068 (0.051)	0.098 (0.043)	0.085 (0.049)	0.093 (0.050)	
	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Duration days yr ⁻¹	0.263 (0.173)	0.367 (0.180)	0.190 (0.136)	0.154	0.189 (0.226)	0.269 (0.202)	0.169 (0.151)	0.300 (0.197)	0.401 (0.188)	0.177 (0.173)	0.359 (0.213)	0.325 (0.321)	0.213 (0.169)	0.404 (0.313)	0.461 (0.225)	0.306 (0.254)	0.394 (0.224)	0.356 (0.270)	0.308 (0.212)	
	-0.154 (0.130)	-	-	-	-0.142 (0.187)	-	-	-0.165 (0.143)	-	-	-	-	-	-	0.202 (0.228)	-	-	-	-	
Intensity °C yr ⁻¹	0.015 (0.009)	0.014 (0.008)	0.012 (0.010)	0.036	0.022 (0.016)	0.022 (0.013)	-	0.013 (0.008)	0.013 (0.007)	0.013 (0.009)	-	-	-	-	0.015 (0.008)	-	-	-	-	
	0.011 (0.009)	-	-	-	0.015 (0.015)	0.012 (0.010)	-	0.007 (0.007)	-	-	-	-	-	-	0.007 (0.008)	-	-	-	-	
OHC-derived metrics																				
	MEDREA		GLOREA		MEDREA		GLOREA		MEDREA		GLOREA		MEDREA		GLOREA		BLKREA		GLOREA	
Number events yr ⁻¹	0.849 (0.282)		0.654 (0.297)		0.948 (0.386)		0.687 (0.352)		0.763 (0.357)		0.574 (0.367)		0.997 (0.351)		0.584 (0.376)		0.741 (0.434)		0.390 (0.378)	
	-		-0.940 (0.604)		-		-0.954 (0.561)		-		-1.171 (0.570)		-		-0.674 (0.547)		-		-1.047 (0.683)	
Duration days yr ⁻¹	3.061 (1.679)		3.456 (2.726)		2.746 (2.598)		3.033 (2.430)		3.272 (2.006)		3.457 (3.099)		4.152 (2.507)		3.727 (4.654)		5.042 (3.362)		3.171 (3.966)	
	-		-2.976 (1.933)		-		-3.336 (2.232)		-1.126 (1.130)		-3.945 (2.860)		-		-2.919 (3.509)		-		-3.378 (2.544)	
Intensity W m ⁻²	-		-		-		-		-		0.011 (0.019)		-		-		-		-	
	0.218 (0.207)		-		0.481 (0.387)		-		-		-0.053 (0.043)		-		-		-		-0.034 (0.039)	

515

A similar pattern is observed using the OHC-based definition, with the number of MHWs exhibiting interannual variability (Figure A2 and Table A1). The annual count ranges from 1 event to a peak of over 5 events in 2020 in the Black Sea and in 2023 in both basins. When the time series is detrended, high MHW frequencies are also evident at the beginning of the period, with more than 4 events occurring in 1999 and 2001 in the Black Sea, compared to less than 3 events in the non-

520 detrended data. Regarding the duration, maximum values of approximately 40 days are observed in both seas in 2024, whereas the detrended data consistently show durations below 20 days. When considering MHWs intensity, consistently with SST-based metrics, The Black Sea constantly shows larger values with respect to the Mediterranean Sea.

After removing the warming trend, the number of MHW events shows negative trends in all regions, with statistically significant values observed in the global reanalysis (Figure A2 and Table A1). In contrast, trends from the regional

525 reanalysis become non-significant after detrending. The global reanalysis also shows lower event frequency trends compared



to the regional reanalysis across the study areas. Event duration exhibits the strongest trend of 5 days per decade in the Aegean Sea. In some areas, such as the entire Mediterranean, the WMED and EMED, and the Black Sea, duration trends from the global reanalysis are higher than those evaluated from the regional datasets. Furthermore, all duration trends become negative, or not significant, after detrending. Considering the MHWs intensity, most of the analyzed regions show not statistically significant values, with positive trends in the Mediterranean Sea and especially in the West Mediterranean basin when detrended OHC values are used. Notably, a negative trend in MHW intensity is observed in the Black Sea, which may be related to the reduction of intensity and negative intensity trend values along the Rim Current, such over the Anatolian and Caucasian coasts (see Figure 1, row 7).

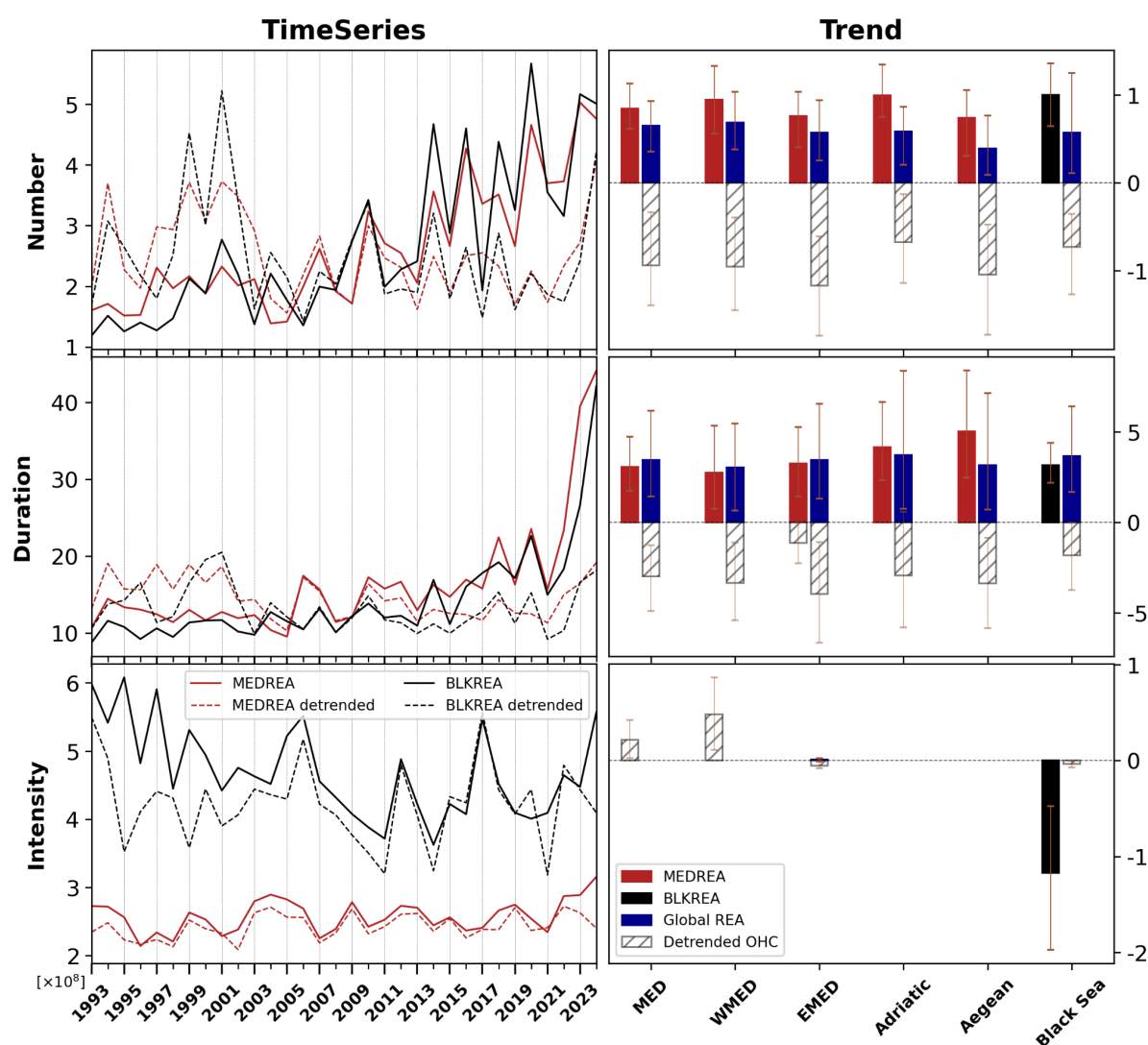


Figure A2: Left: time series of annual MHWs metrics number, duration (in days), and maximum intensity (in J m^{-2}) – averaged over the entire Mediterranean (red lines) and Black (black lines) Seas, comparing the OHC (0–40 m) definition without detrending



540 (solid lines) with the OHC-detrended approach (dashed lines), based on regional reanalysis data (product refs. no. 3 and 4 in Table 1). Right: long-term trends (1993–2024) in MHWs number (events per decade), duration (days per decade), and maximum intensity (W m^{-2}), derived from regional and global reanalyses (product ref. no. 3, 4 and 5 in Table 1), for selected (sub)regions following Dayan et al. (2022). Brown lines indicate the 95% confidence interval. Solid bars show standard metrics definition, striped bars show SST de-trended metrics.

Data availability

This study is based on public databases, and their references are listed in Table 1.

Author contribution

545 LL led the organization of the study, prepared the manuscript, defined plots and figure layout, participated in code implementation, and presented the results during meetings. RM contributed to key decisions and analysis discussions, which were essential to shaping the final form of the manuscript, worked on the code, especially for figure preparation, and reviewed the manuscript. ES provided useful input to the analyses throughout the study, contributed to the understanding of the code, and played a very important role in analyses related to the Mediterranean Sea, particularly the Adriatic Sea. He also
550 reviewed the manuscript. RMcA provided scientific guidance from the early stages, helped define objectives and conclusions, contributed with the initial analysis using the original code, and revised the manuscript, including scientific content and English writing. FC parallelized the processing code for MHW detection, which was crucial in accelerating the analyses, and actively contributed to scientific discussions. EC revised the manuscript in depth, improved analyses, results presentation, and conclusions, and contributed to leadership and planning. MI, EJ, and PM participated in technical
555 discussions, supported the interpretation of results, and reviewed the manuscript. AA contributed to specific analyses and helped improve the manuscript. FM participated in meetings where key aspects were discussed and followed the manuscript development.

Competing interests

The authors declare that they have no conflict of interest.

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