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Marine Heatwaves in the Mediterranean Sea: A Literature Review

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Abstract

Marine heatwaves (MHWs) are prolonged periods of exceptionally warm temperatures in the ocean, which have forced profound transformations in marine biodiversity and socio-economic systems globally over the last decades. The Mediterranean basin, a highly vulnerable area to climate change, has been particularly affected as a marginal sea, experiencing multifaceted changes due to these events. This literature review brings together a comprehensive list of interdisciplinary research on MHW evolution in the Mediterranean basin, from the past to the future, covering the most common driving mechanisms of MHWs, known feedbacks and impacts on various marine organisms and local economies. Aiming to enhance our understanding of Mediterranean MHWs across various dimensions, we further discuss ongoing challenges in their detection and characterization, highlighting the need to improve monitoring systems and forecasting capabilities using novel approaches in the basin and beyond.

Keywords: Marine Heatwaves; Mediterranean Sea; climate change; extreme warming; climate extremes; sea surface temperature.

Introduction

The Mediterranean Sea (Med Sea) is a semi-enclosed basin situated in the confluence of the Southern European, North African and Middle Eastern continental regions, connected to the Atlantic Ocean through the Gibraltar Strait and to the Red Sea via the Suez Canal (Fig. 1). Despite its small size (~2.5 million km^2), it hosts high marine biodiversity (more than 17 000 marine species), featuring the highest rate of endemism in the world (United Nations Environment Programme, n.d.) and is home to 542 million people as of 2020 (IPCC report, Ali *et al.*, 2022) from 21 sovereign countries (Dayan *et al.*, 2023). Marine ecosystems in the Med Sea are of profound ecological significance and major socio-economic interest for coastal communities, being one of the most heavily exploited seas in the world (Cappelletto *et al.*, 2021). Its location and semi-enclosed nature make it particularly sensitive to climate influences from the surrounding continents and oceanic warming, thus it is described as a climate change "hotspot" (Giorgi *et al.*, 2006; Lionello *et al.*, 2006; Ali *et al.*, 2022). Due to its distinct thermohaline circulation, multiple deep water formation areas (Gulf of Lion, Adriatic, southern Aegean, northeastern Levantine Seas) and complex dynamics at various spatiotemporal scales, it is also considered as a "miniature ocean", attracting major oceanographic interest (Bethoux *et al.*, 1999).

Over the past decades, the Med Sea has experienced significant warming. In particular, Sea Surface Temperature (SST) in the basin exhibited an increasing trend from 0.034 to 0.041 °C/year (Mohamed *et al.*, 2019; Pisano *et al.*, 2020; Pastor *et al.*, 2020; EU Copernicus Marine Service Product, 2022a), which is more than twice the

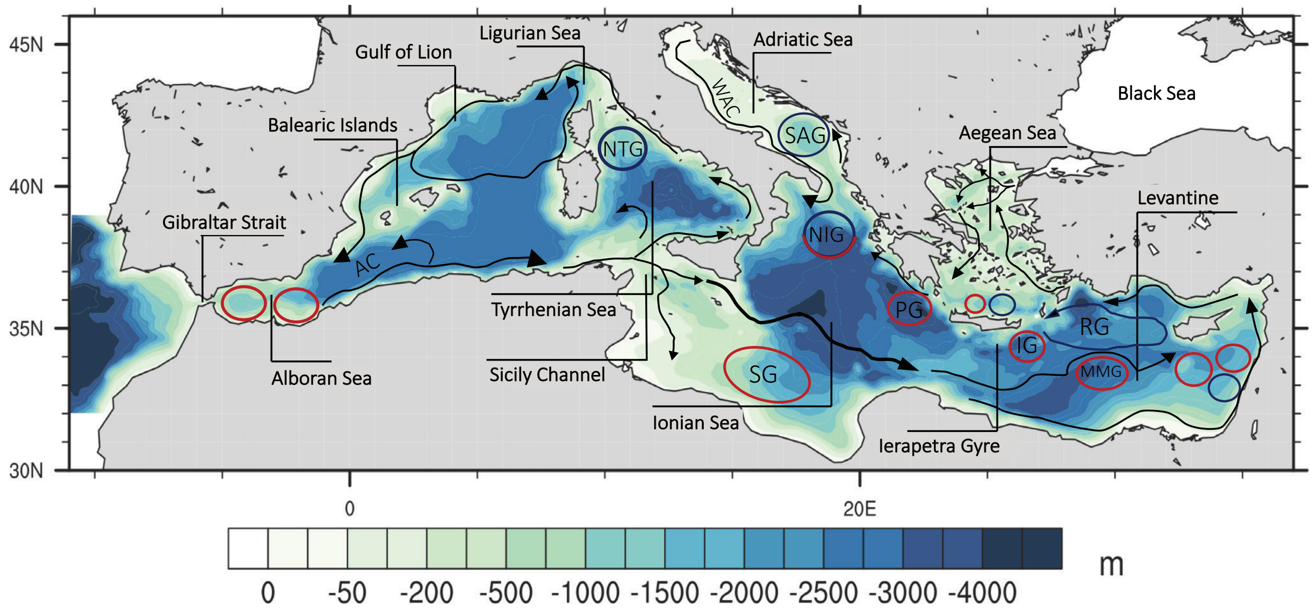

Fig. 1: Mediterranean Sea and its main sub-basins. Key features of the surface circulation in the basin are illustrated with black arrows, red (anticyclonic) and blue (cyclonic) circles. The figure is reprocessed based on Menna *et al.* (2022) and Velaoras *et al.* (2021); Acronyms: AC, Algerian Current; NTG, North Tyrrhenian Gyre; SG, Sidra Gyre; WAC, Western Adriatic Current; SAG, Southern Adriatic Gyre; NIG, Northern Ionian Gyre; PG, Pelops Gyre; IG, Ierapetra Gyre; RG, Rhodos Gyre; MMG, Mera-Matruh Gyre. Bathymetry (m) is given in colors based on the CNRM-RCSM6 model. (Florence Sevault, personal communication).

corresponding global SST trend of 0.015 ± 0.001 °C/year (EU Copernicus Marine Service Product, 2022b). However, this SST warming is not uniformly distributed in space. The eastern Med Sea and the northern half of the western Med Sea have been warming at a faster rate (0.048 ± 0.006°C/year) compared to the entire western basin (0.035 ± 0.006°C/year) between 1982-2018 (Pisano *et al.*, 2020; Pastor *et al.*, 2020). Within the eastern Med Sea, the largest warming trend for the period 1982-2021 is observed in the Aegean and Levantine seas (> 0.05°C /year), with local maximum values in the Rhodes Gyre region (> 0.06°C /year), and lower trends (< 0.03°C /year) over the Ionian basin (Aboelkhair *et al.*, 2023). In the western Med Sea, the largest warming trends between 1993-2022 were observed in the Balearic islands, the Tyrrhenian and the Adriatic seas, ranging approximately from 0.04 °C to 0.05 °C per year (EU Copernicus Marine Service Product, 2022c). Warming of the upper layers of the Med Sea is expected to continue throughout the 21st century, with climate models projecting an average temperature anomaly increase of 0.81 °C to 3.7 °C, relative to late 20th century conditions and under high emission scenarios (Adloff *et al.*, 2015; Darmaraki *et al.*, 2019b; Soto-Navarro *et al.*, 2020; Parras-Berrocal *et al.*, 2020).

Alongside long-term warming trends, there is a growing interest in extreme warm temperature events in the global ocean and the Med Sea, termed as Marine Heatwaves (MHWs). By definition, MHWs are statistically rare episodes of exceptionally high ocean temperatures that persist for long periods of time (Oliver *et al.*, 2021). They can occur in the coastal zone or the open ocean, at the surface and at depth, extending horizontally up to thousands of kilometers, while forcing abrupt and severe changes in marine biodiversity and ecosystem functioning (e.g., Wernberg *et al.*, 2016; Garrabou *et al.*, 2022; Smale *et al.*, 2019), on timescales from days to years. Their characteristics and impacts depend on the physical processes that cause and maintain them, as well as on the location and season of their occurrence (Holbrook *et al.*, 2020). However, climate change has dramatically changed their frequency, duration and intensity over the past decades across the global ocean (Oliver *et al.*, 2018), raising major concerns on their environmental and socio-economic implications (Smith *et al.*, 2021; 2023). Given the diversity of these impacts, successful forecasting of MHWs can provide effective tools for developing mitigation strategies and facilitating proactive management in the affected regions.

The goal of this literature review is to present a comprehensive overview of the current knowledge on Mediterranean surface and subsurface MHWs, using the latest, regional studies on the topic. We initiate the discussion by providing a historical, interdisciplinary perspective on MHWs in the basin, including long-term trends and descriptions of major events. Based on recent studies, we summarize the mechanisms behind MHW development, discussing the role of local-scale processes and large-scale climate modes, with a specific emphasis on the exceptional MHW of 2022/2023. Additionally, we explore feedback of MHWs to the atmosphere and the concept of concurrent extreme events in the Med Sea. In the context of climate change, we then review the projected trends and characteristics of Mediterranean MHWs in the 21st century. The various impacts of these events are addressed, alongside long-term warming effects on marine ecosystems, the fishing and aquaculture industries in the Med Sea, and their broader implications for the economy and well-being of Mediterranean coastal communities. Given these profound impacts, we review the current methodologies employed in observing MHWs in the Med Sea and the advancements in their forecasting and monitoring. Finally, we identify and discuss several limitations associated with MHW analyses, definitions, and methodological choices for identifying past and future events and their underlying modulating processes.

Overview of past MHWs in the Mediterranean Sea

Multiple studies have documented MHWs in the Med Sea, revealing a broad spectrum of sub-basin to basin scale phenomena, with variations in intensity, duration and spatial extent. While this information has been crucial in establishing a baseline understanding of MHW conditions in the Med Sea, challenges arise from the diverse methods and datasets employed, hindering effective inter-comparison of event properties. This section aims to provide a comprehensive summary of key findings on MHW properties observed in the basin over recent decades, highlighting commonalities and differences.

Characteristics of surface MHWs in the past

To date, the majority of studies dedicated to specific MHWs have focused on spring or summer events, which have displayed significant impacts on marine ecosystems and distinct warming signatures in the Med Sea. One of the most notable events occurred in late summer of 1999, when persisting temperature anomalies exceeded 2-4°C in the Ligurian Sea and 2-3°C in the Marseilles region (Romano *et al.*, 2000; Cerrano *et al.*, 2000). The well-known and extensively studied summer MHW of 2003 is recognized for its predominant impact on the western Med Sea. During this event SST anomalies were reported to reach 2° - 7°C locally, its duration was estimated as 48 to almost 100 days, with its spatial extent ranging from 46% - 70% of the entire basin (Grazzini & Viterbo, 2003; Marullo & Guarracino, 2003; Sparnocchia *et al.*, 2006; Darmaraki, 2019; Martínez *et al.*, 2023). A particularly intense MHW affected the Aegean Sea in June 2007, with SSTs about 3°C higher than normal (Mavrakis & Tsiros, 2019), and the eastern Med Sea during 2013, with mean intensities exceeding 1°C (Ibrahim *et al.*, 2021; Juza *et al.*, 2022). Between July - August 2015 severe MHW conditions were reported in the southeast of Spain, with SST anomalies of 2°C persisting for 6 weeks (Rubio-Portillo *et al.*, 2016) during an event that affected around 89% of the Med Sea for approximately 63 days (Darmaraki, 2019; Simon *et al.*, 2022). In the summer of 2017, the Med Sea experienced widespread warm temperatures again (Martínez *et al.*, 2023), marked by the highest number of MHW days since 1982. Particularly in the northwest Med Sea, MHWs lasted about 6 months and maximum SST anomalies reached 6°C (Bensoussan *et al.*, 2019). Another intense MHW affected the entire basin in the summer of 2018 and particularly the Gulf of Lions, the south Adriatic Sea and the region between Cyprus and Crete, with the Levantine basin exhibiting prolonged extreme temperatures (Simon *et al.*, 2022). Between June and December 2019, the western Med Sea experienced 6 MHWs with mean intensities from 1.8°C to 5.3°C and durations ranging from 5 to 20 days, while 2 events occurred in the eastern Med Sea with longer durations (21 and 159 days) and a mean intensity of about 2°C (Hamdeno & Alvera-Azcarate, 2023). The eastern Med Sea was affected yet again by a MHW in May 2020, where maximum event intensity exceeded 6°C (Ibrahim *et al.*, 2021; Denaxa *et al.*, 2022) and during the summer of 2021, where temperatures in the northern Aegean exceeded 31°C for more than 20 days (Androulidakis & Krestenitis, 2022). In winter, spring, and summer of 2020, multiple MHWs occurred in the western Med Sea, lasting up to 80 days with SST anomalies around 2 °C (Juza *et al.*, 2022). Most recently, an exceptionally long MHW impacted the entire basin, persisting from the summer of 2022 until the first months of 2023 (Marullo *et al.*, 2023). During this event the northwest Med Sea presented mean and maximum daily SST anomalies of 2.6°C and 4.3°C, respectively (Guinaldo *et al.*, 2023). For a more detailed catalog on past MHWs in the basin and their characteristics, readers are referred to Darmaraki *et al.* (2019a), Simon *et al.* (2022), Martínez *et al.* (2023), Pastor & Khodayar (2023) and Serva (2024).

Although summer events have been the primary focus, there exists a seasonal variation of MHW frequency, intensity and spatial coverage, with lowest values in the winter, followed by a rise during the summer and spring and a gradual decrease in autumn (Juza *et al.*, 2022; Simon *et al.*, 2022; Pastor & Khodayar, 2023; Martínez *et al.*, 2023). Furthermore, all studies consistently report a rising trend in MHW frequency, duration, intensity and spatial extent in the Med Sea since the 1980s (e.g., Darmaraki *et al.*, 2019a; Ibrahim *et al.*, 2021; Dayan *et al.*, 2022; Juza *et al.*, 2022; Androulidakis & Krestenitis, 2022; Pastor & Khodayar, 2023; Martínez *et al.*, 2023), despite variations in methodology, including the use of different datasets, MHW definitions and periods of examination (see Fig. 2 and Table S1). The highest frequency and duration are consistently observed towards the end of each examined period (Juza *et al.*, 2022; Androulidakis & Krestenitis, 2022; Pastor & Khodayar 2023; Martínez *et al.*, 2023) along with the most severe events, for example, in 2003, 2012 & 2015 (Darmaraki *et al.*, 2019a), 2020 (Ibrahim *et al.*, 2021) and 2022 (Guinaldo *et al.*, 2023).

The accelerating trend in MHW properties has become more pronounced over the last decades (Simon *et al.*, 2022; Hamdeno & Alvera-Azcarate, 2023), particularly after 2000 (Pastor & Khodayar, 2023). This can be explained by a shift in the basin-mean SST towards warmer values increasing the likelihood of extreme warm event occurrence (Martínez *et al.*, 2023). Specifically, the long-term SST warming trend has been indicated as the main driver behind basin-scale, summer MHWs between 1982-2022, with the increase in SST variability partly contributing to long-term trends of MHW activity (a metric indicating the strength of MHWs) in the western

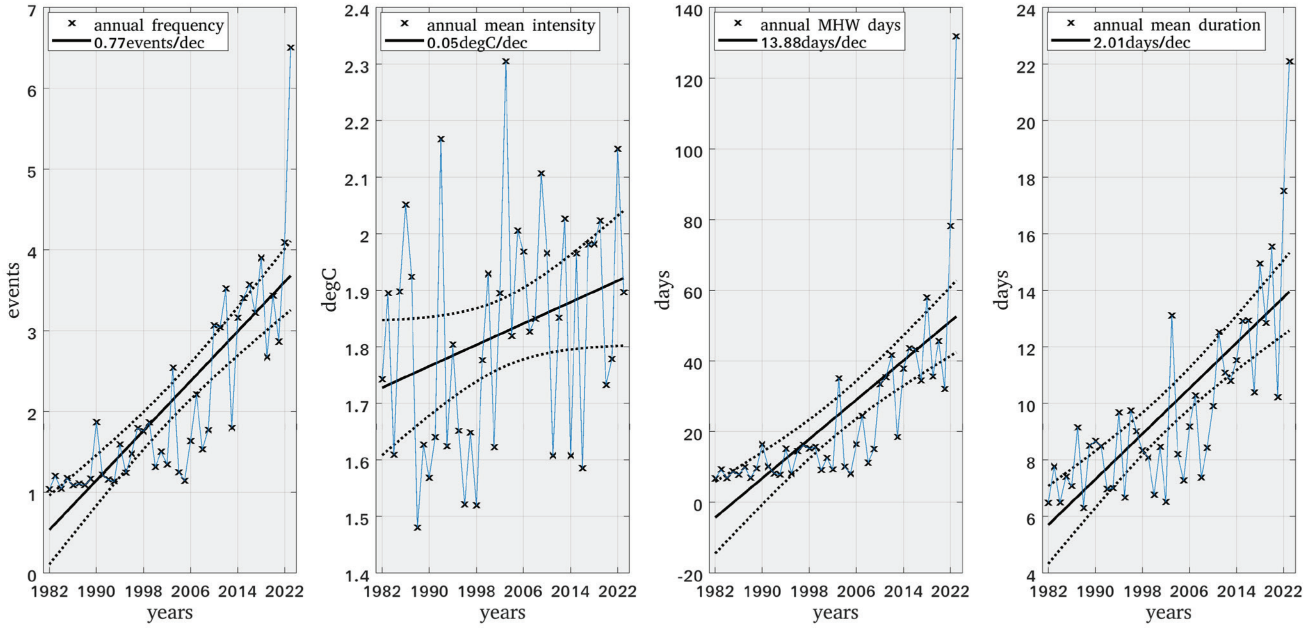

Fig. 2: Example of annual mean MHW metrics in the Mediterranean Sea for the period 1982-2023. Shown are (a) MHW frequency, (b) mean MHW intensity, (c) total number of MHW days and (d) MHW duration. Linear trend and confidence intervals (95th confidence level) are given in black solid and dashed lines, respectively. Events are detected based on the climatology period of 1982-2023, by applying the Hobday et al. (2016) methodology to the satellite SST dataset: Mediterranean Sea High Resolution L4 Sea Surface Temperature Reprocessed (https://doi.org/10.48670/moi-00173).

Med Sea and the Adriatic Sea (Simon *et al.*, 2023). In contrast, SST variability mainly acts to reduce the long-term trend of MHW activity in the remaining part of the basin. Similarly, an analysis of detrended SST data over the last 41 years (1982-2022) yielded statistically insignificant trends in MHW properties, as opposed to their increase when the warming trend was included (Martínez *et al.*, 2023). These results are analogous to the reduced or roughly constant values of mean MHW properties seen when employing a 20-year moving compared to a fixed (1982 - 2001) baseline climatology, for the detection of Med Sea events between 1982-2100 (Rosselló *et al.*, 2023).

Subsurface MHWs in the Mediterranean Sea

The intensification of surface MHWs throughout the 21st century has raised concerns about the survival and functionality of marine ecosystems and the services they provide to human societies around the basin (Smith *et al.*, 2021). This has motivated research on subsurface MHWs in the Med Sea, with a primary focus on ecosystem-relevant layers. For instance, an analysis of basin-scale MHWs at 23m, 41m, and 55m depths showed longer and more intense subsurface events between 1982-2017, albeit less frequent and spatially extended compared to surface MHWs. The longest MHW durations were seen at 55m depth, consistent with the long-term preservation of heat in deeper layers, as a result of the low frequency variability in the ocean interior (Darmaraki *et al.*, 2019a). Dayan *et al.* (2023) observed a similar increase in MHW frequency and duration over 1987-2019 across the Med Sea surface and subsurface. Compared to surface events, the study found longer but less frequent MHWs up to 100m depth, corresponding to the deep chlorophyll maximum layer. Both studies noted the possibility of subsurface events in the Med Sea with weak (e.g., MHW 2016) or no surface signature at all. In the case of the Eastern Med Sea, however, a 40-member forecast ensemble yielded greater subsurface (0-40m) than surface MHW activity between 1993-2016, based on the total number of MHW days and the proportion of the affected region (McAdam *et al.*, 2023). This may imply a dominant influence of the mean warming trend over that of natural variability in subsurface layers, impacting other MHW properties as well. Although differences in the characteristics between surface and subsurface MHWs most commonly include a decreasing MHW intensity with depth, Dayan *et al.* (2023) identified specific locations in the eastern Med Sea (e.g., Levantine basin) where maximum MHW intensities reach up to 300m depth, suggesting certain events may propagate into deeper layers without being dissipated through dynamical processes (e.g., downwelling, deep convection). This observation aligns with the subsurface intensification of MHWs suggested by Darmaraki *et al.* (2019a) and Juza *et al.* (2022).

Spatial variability of MHWs in the basin

In addition to research on temporal trends a substantial body of literature has explored trends in MHW characteristics on a basin- or sub-basin scale, highlighting a strong spatial variability of surface MHW properties. Overall, a declining north-south gradient has been observed for the mean (and maximum) MHW intensity (see Fig. 3) and frequency so far, with surface waters of northwest Med Sea, the Adriatic and Aegean seas as well as the subsurface Levantine waters, exhibiting increased susceptibility to higher values of these characteristics. Conversely, the long-duration events are more prevalent around the Balearic Islands, the surface Levantine basin and across the entire basin at depth, though away from the boundary currents (Darmaraki *et al.*, 2019; Ibrahim *et al.*, 2021; Juza *et al.*, 2022; Simon *et al.*, 2022; Dayan *et al.*, 2022;2023; Pastor & Khodayar, 2023). In comparison, areas with water mass inflow, such as the Alboran Sea and the northeastern Aegean, but also the Ierapetra gyre, seem to experience shorter surface MHWs (Pastor & Khodayar, 2023). Within the eastern Med Sea and over the last decades, prolonged and frequent MHWs have occurred in the broader north Aegean area and sporadically in the Ionian Sea. In contrast, fewer events were observed in the southeastern Aegean, Cyclades Archipelago and Cretan Seas (Ibrahim *et al.*, 2021; Aboelkhair *et al.*, 2023). Notably, the northwestern part of the Aegean Sea was identified as a hotspot for MHWs during 2008-2021, implying considerable risks for the surrounding coastal regions (Androulidakis & Krestenitis, 2022). Within the western Med Sea, the most pronounced MHW properties between 2012-2020 were observed in the Gulf of Lions, the Ligurian and the north Adriatic Sea, as well as in specific coastal areas as opposed to offshore locations (Juza *et al.*, 2022). These findings persist regardless of the varying methodologies that were employed for the detection of MHWs and the periods of examination upon which they were based (see Table S1).

Subsurface MHWs in the Med Sea are also characterized by a strong, northwest-southeast spatial variability. In particular, the highest number of subsurface events, spanning 0-100m, during the 1987-2019 period, were detected in western Med Sea areas, with no significant frequency trends seen in deep convection locations (Dayan *et al.*, 2023). Similar to surface events, the longest subsurface MHWs appeared around the Balearic Islands, in the Gulf of Gabes and the Levantine basin and in convection regions where the warming signal is propagated from surface to subsurface. However, the vertical extension of surface MHWs is not consistently distributed in space at all times. For instance, surface MHWs occurring between 2012-2020 exhibited a progressive, eastward subsurface extension, with positive temperature anomalies reaching between 50m-150m in the western Med Sea, around 200m in the middle and south Adriatic Sea and up to 400m - 700m in the eastern Med Sea (Juza *et al.*, 2022). While this sub-basin variability was evident in the MHWs of 2019, reaching depths of 20m in the western and 50m in the eastern Med Sea (Hamdeno & Alvera-Azcarate, 2023), the 2003 MHW was a relatively shallow event across most of the basin, except for the northwest Med Sea where it extended up to 100m depth (Dayan *et al.*, 2023; McAdam *et al.*, 2023).

Mechanisms driving Mediterranean MHWs

Although knowledge on MHW driving mechanisms in the Med Sea has yet to be enriched, valuable insights from the literature thus far are reviewed and discussed below.

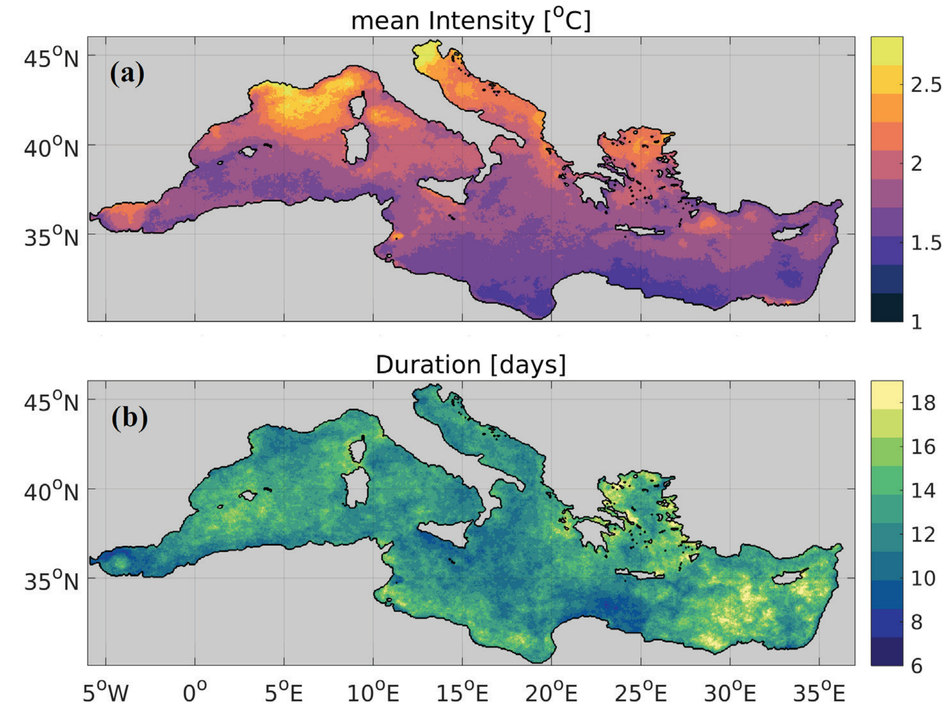

Fig. 3: Mean MHW intensity (a) and duration (b) in the Mediterranean Sea averaged over 1982-2023. MHWs are detected based on the climatology period 1982-2023 by applying the Hobday *et al.* (2016) methodology to the satellite SST dataset: Mediterranean Sea High Resolution L4 Sea Surface Temperature Reprocessed (https://doi.org/10.48670/moi-00173).

Local-scale mechanisms behind surface MHWs in the Mediterranean Sea

The formation of MHWs on a regional scale results from the interplay between air-sea heat fluxes and local-scale oceanographic processes. Typically, MHW development is associated with the physical process that contributes the highest amount of heat to the system. In the Med Sea, most summer MHWs have been attributed to a combination of increased radiation flux into the sea, persistent low wind speed conditions and the suppression of surface heat losses. The notable summer MHWs of 2003 (Olita *et al.*, 2007; Sparnocchia *et al.*, 2006), 2007 (Mavrakis & Tsiros, 2019) and the spring MHW of 2020 (Ibrahim *et al.*, 2021; Denaxa *et al.*, 2022) are examples of such major events, where strong anticyclonic conditions prevailed along with exceptionally high air-temperatures and reduced wind stress, leading to increased shortwave radiation and a reduction in latent and sensible heat fluxes from the ocean to the atmosphere. Atmospheric heatwave (AHW) conditions also played a significant role in driving strong MHWs in the northwest Med Sea during the summers of 2017 (Martínez *et al.*, 2023) and 2021 in the eastern Med Sea (Aboelkhair *et al.*, 2023).

However, the influence of atmosphere-related mechanisms may be modified by local-scale ocean circulation and weather features. For instance, the basin-scale, summer MHW of 2003 was primarily linked to increased atmospheric forcing, reduced wind speeds and vertical mixing, while advection-induced warming was found more important on regional scales, such as the Aegean and South Cretan sub-basins (Darmaraki, 2019). Likewise, water masses originating from the Black Sea were linked to increased temperatures in the North Aegean surface waters during the summer MHW of 2021 (Androulidakis & Krestenitis, 2022). These buoyant, shallow, and less saline waters occupy the upper 50 m of the water column, inducing strong stratification. This led to the shoaling of the Mixed Layer Depth (MLD), which further warmed the surface waters, facilitating the development of the MHW. Also, amid the large-scale MHW of August 2022, water masses inside the port of Genoa cooled abruptly, owing to a heavy rainfall event (Cutroneo & Capello, 2023). The weak summer dynamics constrained the water masses within the port, maintaining their stationarity and isolated state. Following the rainfall event, temperatures increased, remaining generally cooler than the external surroundings throughout August but rose during September again. A notable example highlighting the significance of regional influences, is the formation of strong and long-lived eddies around the Balearic Islands, which were primarily driven by salinity gradients in 2010 and by northwesterly winds in 2017, resulting in prolonged surface temperature anomalies, that displayed characteristics typical of local MHWs (Aguiar *et al.* 2022).

Recently, a few studies have explored the physical drivers behind multiple surface MHWs in the Med Sea, providing insights into how regional characteristics may systematically influence their formation in certain areas. For instance, an analysis of multiple MHWs throughout June - December 2019 revealed contrasting heat contributions to events in the western and the eastern sub-basin of the Med Sea (Hamdeno & Alvera-Azcarate, 2019). The strong MHWs in the western Med Sea were associated with increased air temperatures and total atmosphere heat input into the ocean, reduced latent heat loss and wind stress and shallower than normal MLD, coinciding also with an AHW in Europe and higher-than-normal mean sea level pressure (SLP). In contrast, despite an increase in air temperatures and shoaling of the MLD, the eastern Med Sea MHWs of June - July 2019 were associated with an anomalous net heat flux into the atmosphere and a reduction in mean SLP (Hamdeno & Alvera-Azcarate, 2023). Simon *et al.* (2023) associated the rise in summer MHWs from 1982 to 2022 in the west and central Med Sea and the Adriatic Sea with an increase in the downward shortwave radiation, as opposed to a reduction in the upward long-wave radiation associated with eastern Med Sea events. The interannual variability of MHW activity in the western and central regions was further linked to a reduction in the upward latent heat flux and an increase in downward sensible heat fluxes, likely through the advection of warm and humid air masses. Such warm air intrusions have been reported during the summer MHWs of 2003 (Sparnocchia *et al.*, 2006) and 2022 (Guinaldo *et al.*, 2023). However, the long-term increase of MHWs across the entire Med Sea was partly compensated by increased upward latent heat fluxes, representing a heat loss from the ocean to the atmosphere (Simon *et al.*, 2023). Abnormally high atmospheric heat fluxes also dominated the development of extremely warm marine summers in the northern Med Sea between 1950-2020, where longer, more frequent and intense MHWs have also occurred (Denaxa *et al.*, 2024). Specifically, during these summers the surplus heat at the sea surface was linked to reduced latent heat loss and increased net longwave radiation, in the Aegean and part of the Levantine Sea and to increased shortwave radiation in the central, western areas and the Adriatic Sea. Conversely, these summers were associated with a weaker role of air-sea heat exchanges in the southernmost Med Sea regions, attributed to enhanced latent heat losses and drier air masses in the region.

Influence from large-scale climate modes on Mediterranean MHWs

While the regional influences on Mediterranean MHWs have received a lot of attention, little is known about the linkages between the development of these extreme events and the large-scale climate modes (Darmaraki, 2019; Simon *et al.*, 2023). For the period 1982-2020, Hamdeno and Alvera-Azcarate (2023) showed that MHW frequency throughout the basin is well correlated (cc=0.74) with the East Atlantic Pattern (EA), while features a negative correlation with the East Atlantic/Western Russian teleconnection pattern. Simon *et al.* (2023) further associated the EA with the development of atmosphere-driven MHWs in the Med Sea. In particular, a joint Principal Component Analysis of summer events between

1982-2022 revealed that the long-term trend in MHW activity as well as the three notable summer MHWs of 2003, 2018, and 2022 co-varied with a positive 500hPa geopotential height anomaly over the North Atlantic/ European Sector. This large-scale atmospheric set up resembling the positive EA phase, induces an anticyclonic circulation that diminishes winds and heat losses from the ocean, facilitating the formation of MHWs. These findings align with the correlation between the basin SST and EA, proposed by Skliris *et al.* (2012) and Josey *et al.* (2011). The positive phase of summer North Atlantic Oscillation was also found to co-vary with the contribution from the interannual SST variability to the summers of 2003 and 2022. This large-scale atmospheric pattern features a negative 500hPa geopotential height anomaly over the Mediterranean and a positive one over Northern Europe, contributing to the formation of MHWs in the western basin, likely by driving the advection of warm air masses (Simon *et al.*, 2023). Major MHWs have additionally coincided with the positive phase of the Atlantic Multidecadal Oscillation (Marullo *et al.*, 2011), though no causal link has been suggested so far.

Drivers of subsurface MHWs in the Mediterranean Sea

The subsurface extent of surface MHWs depends on the location, drivers, season and characteristics of the event. For example, during the summer MHW of 2003, strong vertical stratification limited vertical penetration (~15m) of the heat gained from the atmosphere in the Ligurian Sea (Sparnocchia *et al.*, 2006). Conversely, wind-induced vertical mixing allowed the warming signal to reach depths of up to 50m in the eastern Med Sea during the spring event of 2020 (Denaxa *et al.*, 2022) and approximately 20m at the Lampedusa station during the 2022/2023 MHW (Marullo *et al.*, 2023). Local-scale influences (e.g., topography, mixed layer depth) may result in different vertical propagation depth even during the same MHW; *In situ* seawater temperature time series during the summer MHW of 2017 revealed a downward propagation of surface MHWs to approximately 40m in the Scandola Marine Protected Area (Bensoussan *et al.*, 2019) but only about 15m - 20m depth at the Columbretes island site (Martínez *et al.*, 2023).

The critical role of wind conditions in the formation of subsurface Med Sea MHWs has been further underlined by a number of recent studies examining multiple events. Between 1982-2017, Darmaraki *et al.* (2019a) reported that MHWs at surface, 23m, 41m, and 55m depth corresponded to seasonal changes of MLD, highlighting a connection between intensified wind speeds and events at deeper layers. Mixing due to moderate winds was proposed as a mechanism facilitating vertical propagation of surface temperature anomalies within a weakly stratified water column, reducing MHW intensity at surface. This aligns with the findings from Juza *et al.* (2022) and Hamdeno and Alvera-Azcarate (2023) that observed seasonal variations in the vertical extension of MHWs; MHWs tended to penetrate deeper during autumn compared to shallower and more intense events during the summer, most likely linked to atmosphere heat flux-induced stratification. In particular, observations of sub-regional events between 2012-2020, revealed that the most pronounced summer temperature anomalies occurred in the upper 30m depth, while in autumn significant anomalies were observed at surface and between 50m-100m. During winter, pronounced temperature anomalies extended to depths of up to 700m, though they were less intense at surface (Juza *et al.*, 2022). The vertical penetration of MHWs during winter and autumn, may be facilitated by wind-induced mixing in convection areas, (e.g., the Gulf of Lions, Ligurian Sea, Cretan Sea) or by downwelling processes along the African side of the Alboran Sea. Downwelling processes may facilitate MHW vertical extension during the summer as well, in areas like the western part of the Aegean Sea and the NE Crete (Juza *et al.*, 2022). The vertically-propagated anomalies may be stored beneath the mixed layer and re-emerge later (Marullo *et al.*, 2023).

The exceptional MHW of 2022

More recently, the record-breaking summer MHW of 2022 strongly affected the NW Med Sea, a region which is consistently warmer than average even during non-heatwave periods and thereby more susceptible to atmospheric forcing (Guinaldo *et al.*, 2023). Hence, a concurrent AHW over that area during summer 2022 led to more pronounced SST responses (Martínez *et al.*, 2023; Guinaldo *et al.*, 2023). In particular, this MHW was attributed to above-average shortwave radiation, lower than normal cloud coverage and wind speed (conditions related to atmosphere blocking), that diminished the efficiency of turbulent heat fluxes as a mechanism for oceanic heat dissipation. The event was further enhanced by the southward advection of hot and humid air masses, (as a result of cut-off lows off the Iberian Peninsula), which appeared to play a more significant role in the SST responses compared to the increased surface air temperatures (Guinaldo *et al.*, 2023). The study notes that the absence of tides in the Med Sea further accentuates the significance of wind-induced turbulent mixing as a heat dissipating mechanism, since it has the potential to augment the vertical exchange of surface waters with deeper and cooler layers.

The MHW 2022 displayed comparable characteristics to the pronounced 2003 event, yet differences also exist (Marullo *et al.*, 2023). The persistence of a high-pressure system along with suppressed northerly winds over the NW basin were linked to atmosphere blocking conditions over NW-central Europe, playing a key role in the formation of both MHWs during the summer. However, there was an exceptional persistence of the anticyclonic conditions until fall/winter season of 2022/2023 as opposed to 2003, where cyclonic conditions prevailed during fall/ winter of 2003/2004. This led to the 2022 MHW becoming the longest event in the basin over the last 4 decades, contrasting with the atmospherically-driven dissipation of the 2003 MHW during fall (Marullo *et al.*, 2023). The MHW 2003 is characterized as the most intense event over the last few decades, its intensity being comparable with that of the 2022 event on local scales (Fig. 4).

However, both events featured a stronger response in the northwest than the eastern part of the basin (Marullo *et al.*, 2023; Darmaraki, S. 2019). The MHW 2003 displayed a more pronounced subsurface signal in the northwest Med Sea compared to the rest of the basin, where it primarily affected surface layers, due to strong stratification and lower than normal wind-driven mixing (Olita *et al.*, 2007, McAdam *et al.*, 2023). An analysis of *in situ* observations from the Lampedusa Island (Central Mediterranean) showed that warm surface temperature anomalies during MHW 2022 penetrated in deeper layers (~ 20m) as a result of sudden, strong and short-lived, wind-induced mixing episodes throughout the event duration (Marullo *et al.*, 2023). These subsurface anomalies have likely persisted for longer time periods, especially in the central part of the basin, reducing the intensity of temperature anomalies at surface.

MHW feedback and concurrent extreme events in the Mediterranean Sea

AHWs were observed to occur together with MHWs during the summers of 2003 (Sparnocchia *et al.*, 2006), 2007 (Mavrakis & Tsiros, 2018), 2017 (Martínez *et al.*, 2023), 2021 (Aboelkhair *et al.*, 2023) and 2022/2023 (Marullo *et al.*, 2023). In light of the frequent concurrence of these events, we introduce here the concept of concurrent events within the Med Sea. This concept refers to the simultaneous or sequential occurrence of multiple extreme events (Gruber *et al.,* 2021) and is gaining increasing interest from the scientific community (e.g., Le Grix *et al.,* 2021). In our context, concurrent events specifically address concurrent MHWs with AHW or droughts, fires, acidification and other extremes in the Mediterranean basin.

Notably, over the last 4 decades (1982-2021) half (53%) of MHWs in the eastern Med Sea coincided with atmospheric events (Aboelkhair *et al.*, 2023). The frequency of AHWs and MHWs were strongly correlated (R>0.8), particularly over the Aegean and Levantine basins and during years with heightened MHW activity (2012, 2018 and 2021). In contrast, a reduced frequency of concurrent AHWs and MHWs manifested in the Ionian Basin, southeast Sicily and the offshore waters along the Libyan coast, most likely due to the presence of local oceanic circulation features. Concurrent AHWs and MHWs have been further related to drought conditions (e.g., Marullo *et al.*, 2023), which, in turn, can contribute to the occurrence of wildfires around the Mediterranean region. Such conditions were particularly pronounced during 2015, 2017 and 2022 over burned areas in the northwest Mediterranean (Santos *et al.*, 2024).

Therefore, the concept of concurrent events implicitly involves the feedback between the extreme events that co-occur or succeed one another. However, due to the high spatiotemporal variability of atmospheric dynamics over Europe, it is difficult to differentiate between the components of the regional climate system (Tomassini & Elizalde, 2012) and therefore between the cause and effects of concurrent events. This became more apparent when analyzing the summer MHW 2003 feedback to the atmosphere. Although it was originated from atmosphere-driven processes, this MHW has been shown

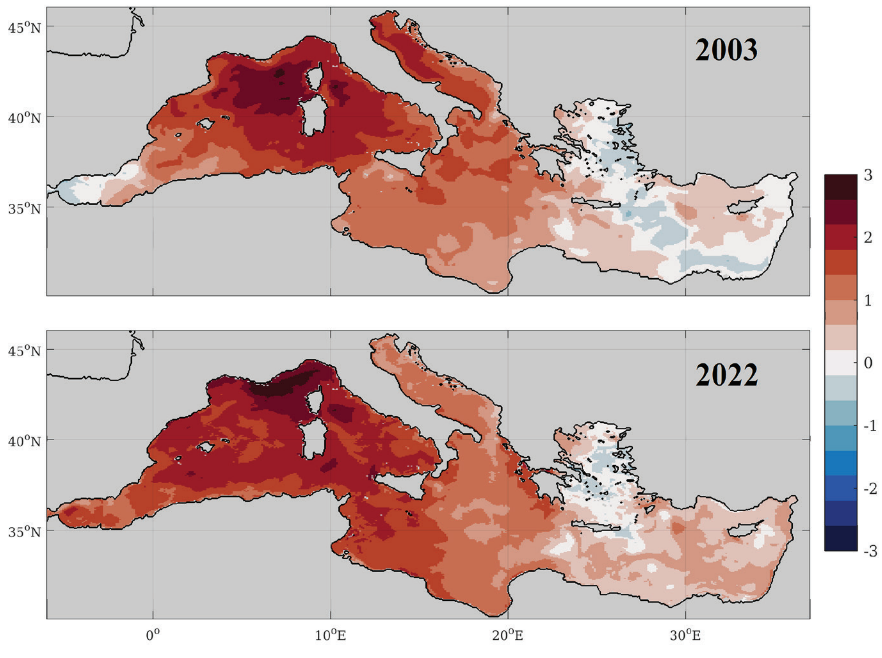

Fig. 4: Comparison of summer SST anomalies during June - August of 2003 (top) and 2022 (bottom) MHWs in the Mediterranean Sea, relative to the corresponding 1993-2022 period. Data are based on the satellite SST observations from the Copernicus Marine product: Mediterranean Sea High Resolution L4 Sea Surface Temperature Reprocessed (https://doi.org/10.48670/moi-00173).

to also reinforce the concurrent AHW over the Mediterranean basin (Black & Sutton, 2007; Feudale & Shukla, 2011; García-Herrera *et al.*, 2010) and its surroundings, through an increase of sensible heat fluxes into the atmosphere and by contributing more than half to the amplitude of the atmosphere blocking circulation (Feudale & Shukla, 2007). Conversely, Jung *et al.* (2006) argued for a minor role of the MHW on the mid-tropospheric circulation in Europe, emphasizing a more robust connection with rainfall in Sahel. In particular, the study proposed an increase of the humidity content in the lower troposphere as a result of the MHW, which was then advected by the mean flow over Sahel, enhancing the deep convection there. Tomassini and Elizalde (2012) corroborated this enhanced evaporation and moisture transport in the atmosphere due to warmer Mediterranean SST and concluded on a more passive role of the Med Sea in the European summer climate of 2003, in agreement with Xoplaki *et al.* (2003) and Black *et al.* (2004).

In addition to concurrent AHWs and MHWs, anomalously warm Med Sea temperatures have been associated with intense storms in the basin. Specifically, an abnormally long MHW in the eastern Med Sea between July - December 2019 coincided with Medicane Scott that affected parts of the southeast Mediterranean on October 25-26, 2019. According to Hamdeno and Alvera-Azcarate (2023) the unusual occurrence of a Medicane in the far east of the basin was primarily attributed to exceptionally warm waters that induced high heat losses to the atmosphere. Similarly, Miglietta *et al.* (2017) showed anomalously warm SST may have exerted a dramatic impact on the intensity of a tornadic supercell formed over the Ionian Sea in November 2012. During August 2022, a MHW was also shown to amplify a severe convective windstorm over the western Mediterranean (González-Alemán *et al.*, 2023) and to enhance a hailstorm in Spain by providing unprecedented amounts of energy and moisture to the atmosphere (Martín *et al.*, 2024).

Finally, in the less-explored realm of MHW impacts on ocean circulation, Olita *et al.*, (2007) observed a reduction in the intensity of the Atlantic Ionian Stream during the MHW of 2003, which exhibited fewer meanders as a result of reduced density gradients and low winds, while the Atlantic Tunisian Current became stronger. In general, the strengthening of the upper-ocean density stratification (strong surface density decrease) linked to MHWs over the last decades (Juza *et al.*, 2022) has the potential to amplify ocean circulation changes, affect deep convection (Margirier *et al.*, 2020, Josey & Schroeder, 2023) and water masses as well as modify ocean ventilation in the basin, with cascading effects on marine ecosystems of the Med Sea.

Future Projections on MHWs in the Mediterranean Sea

Surface MHW trends in the 21st century

By the end of the 21st century, the mean Mediterranean SST is anticipated to increase from + 1.5°C to + 4 °C, relative to the climate of the period 1961-2000 (Somot *et al.*, 2006; Adloff *et al.*, 2015; Darmaraki *et al.*, 2019b). In response to the heat stress induced by increasing Greenhouse Gas (GHG) emissions, this significant rise in SST is expected to amplify characteristics of MHWs in the basin. However, only a few regional studies have addressed the evolution of extreme warm temperatures in the Med Sea, as opposed to a considerable body of research on the future evolution of the basin-mean SST. Table 1 presents a compilation of these Med Sea-specific studies that have investigated future characteristics of extreme warm temperature events, some of which do not explicitly name them as MHWs. The events have been identified at surface or at depth, based on either percentiles of SST distribution (e.g., Jordà *et al.*, 2012; Darmaraki *et al.*, 2019b), fixed temperature thresholds associated with specific ecosystem thermotolerance limits (e.g., Bensoussan *et al.*, 2013; Galli *et al.* 2017) or shifting baseline periods (Konsta *et al.*, 2023; Rosselló *et al.*, 2023).

Despite variations in the climate change scenarios, the type and number of climate models employed, the examination periods and the different identification frameworks applied, all studies converge towards an increase in the frequency, duration, spatial coverage and intensity of future surface MHWs in the Med Sea (Table 1). Until the mid-21st century, there is a consistent increase in MHW characteristics across different climate change scenarios, but a distinct divergence occurs towards the end of the century, reflecting heightened heat stress linked to increased GHG emissions (Darmaraki *et al.*, 2019b; Rosselló *et al.*, 2023). By 2100, stronger and more intense surface MHWs are expected to take place between June - October under higher GHG emission scenarios, affecting at peak the entire Med Sea (Bensoussan *et al.*, 2013; Darmaraki *et al.*, 2019b). The signal of MHW amplification is estimated to be particularly strong in shallow areas, increasing the risk for low motility organisms living in such waters (Galli *et al.*, 2017). Specifically for the period 2036-2066 and under RCP8.5 Konsta *et al.* (2023) projects increased duration and intensity of shallow MHWs (0-40m) along coastal regions, with shorter durations but pronounced intensities (~2.5 °C), based on a shifted 30-year baseline period (starting from 2006-2035).

In addition to regional studies, rising trends in MHW properties in the Med Sea have been also documented in various global studies. This involves an increase in duration, frequency, maximum intensity, number of MHW days and cumulative intensity, according to the growing heat stress induced by increasing GHG emission scenarios. These consistent trends hold across studies which have adopted different frameworks, including ensembles of CMIP5 models under climate change scenarios RCP4.5 and RCP8.5, (Oliver *et al.*, 2019; Hayashida *et al.*, 2020; Guo *et al.*, 2022), of CMIP6 models under the new SSP1-2.6, SSP2-4.5, SSP3-7.0 scenarios (Plecha & Soares, 2020; Qiu *et al.*, 2021; Cheng *et al.*, 2023) and different MHW definitions (Guo *et al.*, 2022; Li & Donner, 2023). Specifically, between 2031-2060 and under RCP8.5 Oliver *et al.* (2019) showed a 2°C - 4°C increase in surface MHW intensity relative to the historical period of 1961-1990, while Cheng *et al.* (2023) indicated a permanent MHW state in the Med Sea from 2080 and onwards under the SSP5-8.5, in close agreement with the regional-scale projections under RCP8.5 by Darmaraki *et al.* (2019b). Alexander *et al.* (2018), using an ensemble of CMIP5 models under the RCP8.5 scenario, additionally suggested that between 2070-2099 annual SST anomalies in the Med Sea will exceed the maximum SST of the historical period (1976-2005) every year.

Subsurface MHW characteristics in the 21st century

Similar to the SST, by the end of the 21st century the upper layers (0 - 150m) of the Med Sea are projected to warm by 0.81°C - 3.71 °C (Soto-Navarro *et al.*, 2020). Therefore, recent studies reveal frequent, longer and more intense MHWs in deeper layers of the basin, featuring a distinct spatial distribution compared to surface events. For example, model projections between 2041-2050 and under RCP8.5 indicate a progressive, eastward increase in the average frequency and duration as well as deepening of MHWs (Galli *et al.*, 2017). In this scenario, the northwest sub-basins (except the Adriatic Sea) experience MHWs > 25 °C in the upper part of the water column (~ 12m), up to ~30 m depth in the central sub-basins and the most severe MHWs (> 30 °C) are expected in parts of the Ionian and eastern coast of Levantine basin, reaching depths of about 40m (see Table 1 and Supplementary Material in Galli *et al.*, 2017). Between 2036-2066, Konsta *et al.* (2023) projected subsurface MHWs characterized by a declining mean frequency and intensity but an increasing duration with depth, spanning from 40m to depths below 1000m (Table 1). However, the mean MHW intensity seems to increase from the mid- to the end of the century (2070-2100), by 0.1 °C in the epipelagic, 0.22 °C in the mesopelagic and 0.3 °C in the bathypelagic zone. While the highest mean MHW intensities (1.5 °C - 3 °C) at depths between 40-200m emerged in the eastern Med Sea, Adriatic basin and coasts of Tunisia, during 2036-2066, the Aegean sub-basin was projected to encounter the highest mean MHW intensity (1 °C - 1.5 °C) at depths between 200-2000m. Towards the end of the century, the southeast Med Sea demonstrated the longest (>100 days) events, on average, below 1000m depth, along with the Tyrrhenian Sea. While both Galli *et al.* (2017) and Konsta *et al.* (2023) agree on a decrease in MHW frequency with depth, the latter shows an increase in MHW duration with depth, as opposed to the former. This discrepancy may be due to the different baseline periods and temperature thresholds (fixed versus percentile) used in the two studies. In general, Konsta *et al.* (2023) identified longer but less intense subsurface compared to surface MHWs in the 21st century, in agreement with Fragkopoulou *et al.* (2023), implying that different physical drivers may operate at different depths. The long-term preservation of downward-mixed, surface temperature anomalies in deeper layers (Elzahaby *et al.*, 2022), suggests a long-term oceanic memory of MHWs and the potential for significant ecological impacts on the subsurface areas affected (Jackson *et al.*, 2018).

Marine Ecosystem Impacts of Mediterranean MHWs

Temperature plays a pivotal role in metabolic processes of organisms, ultimately determining their ecological performance (Gillooly *et al.*, 2001). Specifically for aquatic organisms, fluctuations in ocean temperatures, whether reflecting abrupt or long-term warming, can directly affect various physiological processes, such as growth, fertility and phenology, drive community shifts, and even lead to mass mortality events (MMEs). Warm temperatures can further amplify these impacts indirectly, via alteration of physical processes and nutrient supply (Marbà *et al.*, *2015*). Yet, there is a relative scarcity of studies providing evidence specifically on the impact of MHWs on marine life in the Mediterranean. Adding complexity, marine populations and communities typically respond gradually to both abrupt and continuous warming stress. In contrast, long-term fisheries landings data are usually available on annual timescales, making it challenging to capture the transient nature of MHWs. In light of these limitations, this section provides a thorough overview of the documented impacts on various Mediterranean marine biota from the long-term Med Sea warming exacerbated by the intensification of Mediterranean MHWs in recent decades.

Plankton

The mean warming trend of the ocean coupled with MHWs exerts profound impacts on the metabolic rates of planktonic organisms, altering the composition, dynamics, and energy transfer pathways of the marine microbial food webs, with implications for marine productivity (Courboulès *et al.*, 2022; Fouilland *et al.*, 2013; Šolić *et al.*, 2017; 2018;2019; Trombetta *et al.*, 2020). Experiments simulating MHW conditions (> +3°C above *in situ* temperatures) produce contradictory outcomes. In certain cases, warming pushes the system towards net heterotrophy (CO_2 source) (Garcia-Corral *et al.*, 2015; Soulié *et al.*, 2022, 2023; Vaquer-Sunyer & Duarte, 2013) while in others, a net autotrophic system (CO_2 sink) has been also reported, due to warming-induced trophic cascades (Vidussi *et al.*, 2011). Experimental (Agawin *et al.*, 2000; Pulina *et al.*, 2016, 2020; Soulié *et al.*, 2022, 2023; Stefanidou *et al.*, 2018), earth-observation (El Hourany *et al.*, 2021) and *in situ* data (Trombetta *et al.*, 2019) agree on a shift in phytoplankton size structure towards smaller groups. Species-specific thermal acclimation (Vrana *et al.*, 2023) as well as alterations in the phytoplankton species composition (Soulié *et al.*, 2022b; Domaizon *et al.*, 2012) have been also reported, in response to experimental warming. Basin-scale ocean color data indicate a negative relationship between MHW duration and chlorophyll-a concentration (a proxy for phytoplankton biomass) (Cabrerizo *et al.*, 2022). Moreover, during 2019,

Table 1. Compilation of regional-scale studies investigating MHW characteristics in the Med Sea over the 21st century. For each study shown are: The name of the climate model and GHG emission scenario employed, the region and depth of examination, the temperature (Extreme event threshold) and reference period against which the MHWs were identified, the period during which MHWs were detected as well as the mean MHW frequency, duration and intensity. Whenever average MHW characteristics were not reported for the period examined, the equivalent trends were provided and vice versa. Note that degree days unit represents the amount of heat accumulated over a specified period of time.

Climate Model	GHG Emission Scenario	Region	Extreme Event Threshold	Reference period	Examined period	Mean Frequency (Trend)	Mean Duration (Trend)	Mean Intensity (Trend)	Reference
AOGCM ensemble	SRES - A1B	Balearic Archipelago	SST≥ 99.5th percentile	1985-2009	2025-2050	0.78 ± 0.27 event/year	longer	513.4 ± 324.20 (degree-days °C)	Jorda *et al.* (2012)
					2075-2100	1.00 ± 0.01 event/year		3425.36 ± 1202.89 (degree-days °C)	
NEMO MED8	IPCC A2	NW Med.Sea	SST ≥ 23 - 28 (°C)	2000-2010	2090-2099	-	100 days	3 (°C)	Bensoussan *et al.* (2013)
MFS_ V2.2 NEMO	RCP8.5	North - Northwest Med Sea	Temp ≥ 25 (°C)	2001-2010	2041-2050	≤ 30 events /decade up to ~ 20m	≤ 40-50 days up to ~ 20m	-	Galli *et al.* (2017)
		Central Med Sea				≤ 20 events /decade up to ~ 29m	≤ 120 days up to ~ 20m	-	
		South - Southeast Med Sea				≤ 45+ events /decade up to ~ 20m	≤ 160 days up to ~ 29m	-	
MFS_ V2.2 NEMO	RCP8.5	North - Northwest Med Sea	Temp ≥ 28 (°C)	2001-2010	2041-2050	≤ 10 events /decade up to ~ 8m	-	-	Galli *et al.* (2017)
		Central Med Sea				≤ 12 events /decade up to ~ 12m	-		
		South - Southeast Med Sea				-	-		
MFS_ V2.2 NEMO	RCP8.5	North - Northwest Med Sea	Temp ≥ 30 (°C)	2001-2010	2041-2050	≤ 2 events /decade up to ~ 12m	-	-	Galli *et al.* (2017)
		Central Med Sea				≤ 4 events /decade up to ~ 5m	-		
		South - Southeast Med Sea				≤ 10 events /decade up to ~ 12m	-		
Med-Cordex ensemble	RCP8.5	Entire basin surface	SST≥99th percentile for 5 days, 20% min. spatial threshold	1976-2005	2071-2100	0.3 ± 0.2 events/year	94.1 ± 9.9 (days/ year)	1.4 ± 0.4 (°C)	Darmaraki *et al.* (2019b)
	RCP4.5					0.3 ± 0.2 events/year	59 ± 10 (days/ year)	0.5 ± 0.2 (°C)	
CNRM-RCSM4	RCP2.6	Entire basin surface	SST≥99th percentile for 5 days, 20% min. spatial threshold	1976-2005	2071-2100	0.7 events/year	17 (days/ year)	0.1 (°C)	

Continued

Table 1 continued

Climate Model	GHG Emission Scenario	Region	Extreme Event Threshold	Reference period	Examined period	Mean Frequency (Trend)	Mean Duration (Trend)	Mean Intensity (Trend)	Reference
POLCOMS ERSEM	RCP8.5	Entire basin 0 - 40m	Temp>95th percentile for 5 days	shifted baseline	2036-2066	2.9 events/year	19 (days/year)	1.5 (°C)	Konsta *et al.* (2023)
		Entire basin 40-200m Epipelagic				3.15 events/year	119 (days/year)	0.94 (°C)	
		Entire basin 200-1000m Mesopelagic				2.18 events/year	265 (days/year)	0.5 (°C)	
		Entire basin >1000m Bathypelagic				0.9 events/year	333 (days/year)	0.41 (°C)	
Earth System Models	SSP5-8.5	Entire basin surface	SST≥90th percentile for 5 days	1982 - 2001	2002-2100	>300 days/year	-	5.03 °C	Rosselló *et al.,* 2023
				shifted baseline		~100 days/year	-	1.59 °C	
	SSP1-2.6			1982 - 2001		<300 days/year	-	2.23 °C	
				shifted baseline		<50 days/year	-	1.53 °C	

only the most intense MHWs had a negative impact on surface chlorophyll-a concentration in both the eastern and western basin (Hamdeno and Alvera-Azcaráte, 2023). In comparison, coastal mucilage outbreaks, triggered from uncontrolled (benthic or pelagic) algal blooms, have been associated with increasing warming trends (Deserti *et al.*, 2005) and manifested during anomalously warm conditions (Danovaro *et al.*, 2009; Russo *et al.*, 2005), such as the MHWs of 2003 (Schiaparelli *et al.*, 2007) and 2017 (Bensoussan *et al.*, 2019).

MHWs have prompted variable responses from metazoan zooplankton as well. In particular, anomalously warm winter-spring periods have been shown to negatively affect total zooplankton abundances (Fernández De Puelles & Molinero, 2008; Fullgrabe *et al.*, 2020). On the other hand, warmer than average summer/autumn conditions have been associated with elevated cladoceran abundance, extending their growth season into autumn (Mazzocchi *et al.*, 2023; Yebra *et al.*, 2022). Concerning copepods, long-term warming induces delays in their peak appearance and alterations of their community composition, due to disappearance of cold-water species and shifts towards small-sized ones (Conversi *et al.*, 2009; Kamburska & Fonda-UmaniI, 2006; Villarino *et al.*, 2020), while anomalously warm temperatures have triggered a decline in their populations, in addition to jellyfish outbreaks (Molinero *et al.*, 2008).However, a summer *in situ* mesocosm simulation suggests a post-MHW increase in copepod abundances. This is mainly attributed to a community shift favoring harpacticoid copepods over calanoids, which experienced higher mortality during the heatwave (Zervoudaki *et al.*, 2024). Moreover, during the summer MHW 2003, copepod abundance remained unaffected, but the typical summer cladoceran *Penilia avirostris* declined by 50% in the Gulf of Trieste (Piontkovski *et al.*, 2010). Based on 26 years of bi-weekly measurements, Kalloniati *et al.* (2023) reported a similar decrease in the summer mesozooplankton biomass and cladoceran abundance in the Saronikos Gulf, partially in response to the long-term SST warming. Finally, meroplanktonic decapod larvae have been shown to be vulnerable to MHWs on a global scale, including the Med Sea (Monteiro *et al.*, 2023). This raises concerns about potential impacts on plankton and benthic communities, as well as fisheries for commercially important species.

Fish

Assessing the potential of anomalous ocean warming in shaping fish populations and thereby impacting fishing effort is challenging. Nonetheless, current research points towards a general influence of climate change-induced warming on Mediterranean fish distributions (Sanz-Martín *et al.*, 2024). Both the underlying Med Sea warming trend and an abrupt shift to warmer SSTs in the late 1990s (Raitsos *et al.*, 2010) have led to a notable decrease in Mediterranean fisheries landings, as well as a nonlinear tropicalization (Tzanatos *et al.*, 2014; Vasilakopoulos *et al.*, 2017). Small pelagic fisheries in the Med Sea have been particularly impacted through biomass changes (Coll *et al.*, 2019; Palomera *et al.*, 2007), shifts in key species distribution (e.g., European sardine and anchovy) and reduced egg production (Maynou *et al.*, 2014). For example, rising SSTs have indirectly benefited round sardinella and gelatinous zooplankton, influencing, in turn, sardine and anchovy abundance through species competition (Maynou *et al.*, 2014; Sabatés *et al.*, 2006, 2009; Tilves *et al.*, 2016). Conditions resembling MHWs can induce substantial changes in fish growth, average length, and spawning phenology (Moltó *et al.*, 2021). Indeed, experimental trials revealed that Gilthead seabream (*Sparus aurata*) is susceptible to prolonged MHWs at different life stages, including larvae, juveniles, and adults, based on mortality, tissue pathology, and cellular stress response capacity indices (Madeira *et al.*, 2020; Feidantsis *et al.*, 2020). Similar experimental results indicating diminished aerobic capacity, elevated stress levels and suppressed antioxidant and immunological responses under acute warming have also been reported for other important commercial species such as the European seabass (*Dicentrarchus labrax*) (Islam *et al.*, 2020a,b; Stavrakidis-Zachou *et al.*, 2022) and the meagre (*Argyrosomus regius*) (Kir *et al.*, 2017; Stavrakidis-Zachou *et al.*, 2021b).

Yet, long-term ocean warming has emerged as the primary driver of population size changes in the Med Sea, according to an analysis of twenty years long fish trawl surveys (Givan *et al.*, 2017) and as a major factor behind the increase in the frequency and abundance of thermophilic fish species from 1965 in the north-western Med Sea (Francour *et al.*, 1994). Over the last 40 years in particular, there have been notable changes in fish community composition of landings, marked by an increasing presence of thermophilic species in the Central (Fortibuoni *et al.*, 2015; Valente *et al.*, 2023) and Eastern Med Sea (Tsikliras *et al.*, 2015; Tsikliras & Stergiou, 2014; Chust *et al.*, 2024), combined with a simultaneous decrease in cold-affiliated species (Chust *et al.*, 2024). These shifts suggest a significant rise in the mean temperature of the catch, a proxy for the signature of ocean warming on fisheries catches (Cheung *et al.*, 2013). The warming of the Med Sea has also facilitated the expansion of warm-adapted invasive species of Indo-Pacific origin (Vergés *et al.*, 2014), leading to considerable shifts in native biota and alterations in ecosystem services (Tsirintanis *et al.*, 2022). The influx of warm-water non-indigenous species in the Eastern Med Sea has been significantly accelerated by the abrupt temperature rise post-1998, leading to a 150% increase in the annual mean arrival rate of new tropical species in the basin (Raitsos *et al.*, 2010).

Megafauna

The combined effect of intensified MHWs and mean warming trend in the Med Sea (Gambaiani *et al.*, 2009; La Manna *et al.*, 2023) have generally forced population relocations in the basin (Evans & Waggitt, 2020; Osland *et al.*, 2021). For instance, migration of bottlenose dolphins toward the open sea (Gambaiani *et al.*, 2009) and wider dolphin species movement have been documented as a consequence of altered distribution of key prey species (Bearzi *et al.*, 2003; Fuller *et al.*, 2016), in response to abnormally warm coastal waters. Loggerhead marine turtles utilize a wide range of depths, so changes in temperature across the water column can significantly affect their geographical distribution, reducing the thermally suitable habitats for their adult populations (Chatzimentor *et al.*, 2024). Loggerhead turtles have responded to warming by nesting earlier to synchronize with optimal thermal conditions, leading to increased hatching success but reduced egg production (Mazaris *et al.*, 2008). However, extreme temperatures have negatively impacted egg survival in green sea turtles' nests in the Eastern Med Sea, with negative implications for their future population persistence (Turkozan *et al.*, 2021). The loss of suitable nesting sites and alterations to the offspring sex ratios of hatchings associated with increased risk of feminization and potentially detrimental consequences for the population, have been highlighted as the major threats for marine turtles derived from climate change (Mazaris *et al.*, 2023). The survival of the endangered Mediterranean monk seal (*Monachus monachus*) is also threatened by warmer temperatures (Van De Bildt *et al.*, 1999), due to the spread of viruses and pathogens, that can lead to epizootic events like morbillivirus infections (Agardy, 1996).

Phytobenthos

Thermal stress can severely affect macrophytes, impairing leaf and rhizome growth (Marín-Guirao *et al.*, 2018; Mayot *et al.*, 2005; Stipcich *et al.*, 2022b), disrupting metabolic (Mannino *et al.*, 2016) and photosynthetic efficiency (Fabbrizzi *et al.*, 2023; Ontoria *et al.*, 2019), reducing nutritional value (Beca-Carretero *et al.*, 2018; Stipcich *et al.*, 2023), inducing leaf necrosis and prompting biomass loss (Hernán *et al.*, 2017; Stipcich *et al.*, 2022a), while in severe cases can lead to mortality (Díaz-Almela *et al.*, 2009; Hernán *et al.*, 2017; Marbà & Duarte, 2010; Mayot *et al.*, 2005; Pazzaglia *et al.*, 2020). Notably, increased shoot mortalities have been linked to intense MHWs reported in 1999, 2001 and 2003 (Díaz-Almela *et al.*, 2009; Marbà & Duarte, 2010; Mayot *et al.*, 2005). Although it has been observed that *Posidonia oceanica* responded to 2003 and 2022 major MHWs with intense flowering (Diaz-Almela *et al.*, 2007; Marbà & Duarte, 2010; Marín-Guirao *et al.*, 2019; Boudouresque *et al.*, 2024; Stipcich *et al.*, 2024), such a response was proven insufficient to offset the increased mortality rates observed after 2003 MHW event (Díaz-Almela *et al.*, 2009). Recent results from Tomas *et al.* (2024) suggest that, in addition to mass flowering, pseudovivipary can also occur as a response to thermal stress. The success of these reproductive mechanisms is equivocal, since seeds and seedlings produced through sexual recruitment can be particularly susceptible to warming (Hernán *et al.*, 2017; Rinaldi *et al.*, 2023), whereas clonal reproduction can reduce *Posidonia's* genetic diversity and thus adaptation ability (Reusch *et al.*, 2005). Even though macrophytes can develop physiological acclimation strategies to cope with warming conditions (Fabbrizzi *et al.*, 2023), these mechanisms are subject to complex natural interactions. It has been shown that populations from distinct bioregions exhibit clear differences in their thermal performance. For example, both cold- and warm- adapted seagrass and macroalgae ecotypes can be resilient to increased heat as long as they do not live close to their thermal limits (Beca-Carretero *et al.*, 2018; Marbà *et al.*, 2022; Saada *et al.*, 2016; Marín-Guirao *et al.*, 2017; 2018; Pazzaglia *et al.*, 2020; Stipcich *et al.*, 2022b). Additionally, the impact of extreme temperatures is highly dependent on the intensity of the event, as well as the duration and timing of thermal stress (Rinaldi *et al.*, 2023; Stipcich *et al.*, 2024). However, when multiple environmental stressors are combined with warming, they can synergistically intensify the overall stress levels (Guerrero-Meseguer *et al.*, 2020; Ontoria *et al.*, 2019; Pazzaglia *et al.*, 2020), or in some cases yield unexpected positive outcomes (Egea *et al.*, 2018). The overall structure of Mediterranean seagrass communities is expected to change as a result of both long-term warming and MHWs (Boudouresque *et al.*, 2024). Species thermal tolerance can be a crucial factor in determining their proliferation or regression, with literature projecting a decline of *P. oceanica*, and its potential replacement by *Cymodocea nodosa* and the invasive *Halophila stipulacea* (Chefaoui *et al.*, 2018; Beca-Carretero *et al.*, 2024).

Zoobenthos

Benthic invertebrates in the Med Sea, predominantly stationary (sessile) or slow-moving like Cnidaria, Porifera, Bryozoa, Bivalvia, Chordata (Ascidiacea), Annelida, and Echinodermata, have been documented to respond to MHWs or abnormally warm summer conditions via increased feeding (Gunderson & Leal, 2016), and reduced reproductive investment (Barbeaux *et al.*, 2020; Caputi *et al.*, 2016) or growth (Bay & Palumbi, 2017) due to energetic limitations (Smith *et al.*, 2023). Other biological systems may also be impacted, ranging from neuromuscular interference, affecting urchin camouflage behaviour (Brothers & McClintock, 2015) to the loss of symbiotic photosynthetic zooxanthellae in Anthozoans, leading to bleaching and increased vulnerability to disease (Crabbe, 2008). Furthermore, heat-stressed invertebrate colonies may be intensively consumed by specific predators (Bosch-Belmar *et al.*, 2024), or become more susceptible to opportunistic, and pathogenic microorganisms (Bally & Garrabou, 2007; Cerrano *et al.*, 2000; Coma *et al.*, 2009; Martin *et al.*, 2002), which may be even more detrimental than potential symbionts' decline (Prioux *et al.*, 2023).

Notably, Mediterranean invertebrate colonies have faced successive MMEs during or shortly after summer months due to MHWs (Bensoussan *et al.*, 2019;Turicchia *et al.*, 2018) in multiple years over the last decades (e.g.,, 1999, 2003, 2006, 2007, 2008, 2009, 2018, 2021, 2022) (Antoniadou *et al.*, 2023; Estaque *et al.*, 2023; Garrabou *et al.*, 2009, 2019, 2021; Marbà *et al.*, 2015; Marie *et al.*, 2023; Orenes-Salazar *et al.*, 2023; Parravicini *et al.*, 2010; Rivetti *et al.*, 2014; Smith *et al.*, 2021). Specifically, the MHW-induced MMEs of 2003 (Gómez-Gras *et al.*, 2021) and 2022 were particularly detrimental (Estaque *et al.*, 2023; Marie *et al.*, 2023). The latter impacted deeper ranges and resembled expectations of the sixth mass extinction (Cowie *et al.*, 2022; Thomas *et al.*, 2004). More than 2,300 MMEs, involving over 90 species, were recorded between 1979 and 2020. Cnidaria (corals and gorgonians) accounted for nearly half, followed by Porifera (sponges), with decreasing mortality in Bryozoa, Bivalvia, and Ascidacea (Garrabou *et al.*, 2019, 2022; Smith *et al.*, 2023) (Fig. 5). Over 50% of recorded MMEs occurred in the western Med Sea, although the sampling effort differs substantially between ecoregions (Garrabou *et al.*, 2019, 2022). The cumulative hotspots of these MMEs from 1979 to 2019 are shown in Figure 5, alongside MHW hotspots identified by the average cumulative intensity (°Cdays) for a similar period (1982–2017). Interestingly, the sub-basins with the highest cumulative MHW intensity (>35 °Cdays) in the North-central and North-western Mediterranean also correspond to regions with the greatest number of recorded MMEs (>140 events). Although establishing a direct correlation between MHW cumulative intensity and the frequency of MMEs is challenging—due in part to variations in sampling effort across ecoregions and differences in the periods analyzed—MMEs appear to be linked to both the high intensity and extended duration of MHWs. This suggests that cumulative intensity is a valuable metric for understanding MHW impacts on MMEs, a concept that warrants further investigation. Notably, there is evidence of limited species-specific coral resistance to MHW impacts (e.g, *Paramuricea clavata*, Capdevila *et al.*, 2023; *Cladocora caespitosa* & *Astroides calycularis*, Carbonne *et al.*, 2024), especially when deeper waters (>40m) can be utilized as thermal refuge, (Bramanti *et al.*, 2023). Rarely, summer MHWs have prompted the establishment of nonnative reef-forming fauna, enhancing species richness and abundance (Herbert *et al.*, 2016; Lejart & Hily, 2011; Ruesink *et al.*, 2005).

The existing climate-change pressure on marine life will likely be amplified as a result of the projected warming in the basin, inducing further ecosystem changes in the Med Sea. Specifically, models project community alterations (Benedetti *et al.*, 2018; Clark *et al.*, 2020), northward extension of species (Lloret *et al.*, 2015; Sabatés *et al.*, 2006), particularly pronounced in south and central Med Sea populations (Panzeri *et al.*, 2024), extinction or extirpation of native seagrass (Jordà *et al.*, 2012) and fish species (Albouy *et al.*, 2013; Ben Rais Lasram *et al.*, 2010), as well as increased introduction of exotic species (Boero *et al.*, 2008). However, projections diverge regarding primary production (Chust *et al.*, 2014; Herrmann *et al.*, 2014; Lazzari *et al.*, 2014; Macias *et al.*, 2015; Richon *et al.*, 2019) and commercial fish stocks (Albouy *et al.*, 2015; Gkanasos *et al.*, 2021; Issifu *et al.*, 2022; Moullec *et al.*, 2019), reflecting different effects (neutral, positive, or negative) in the sub-basins.

Socio-economic impacts of Mediterranean MHWs

Beyond disruptions to marine ecosystems, a cascading effect of MHWs extends to socio-economic ramifications on fisheries, aquaculture and communities that rely on them, due to distribution shifts and the migration or mortality of commercially important fish and invertebrates (e.g., Cheung *et al.*, 2021, Smith *et al.*, 2021). Con-

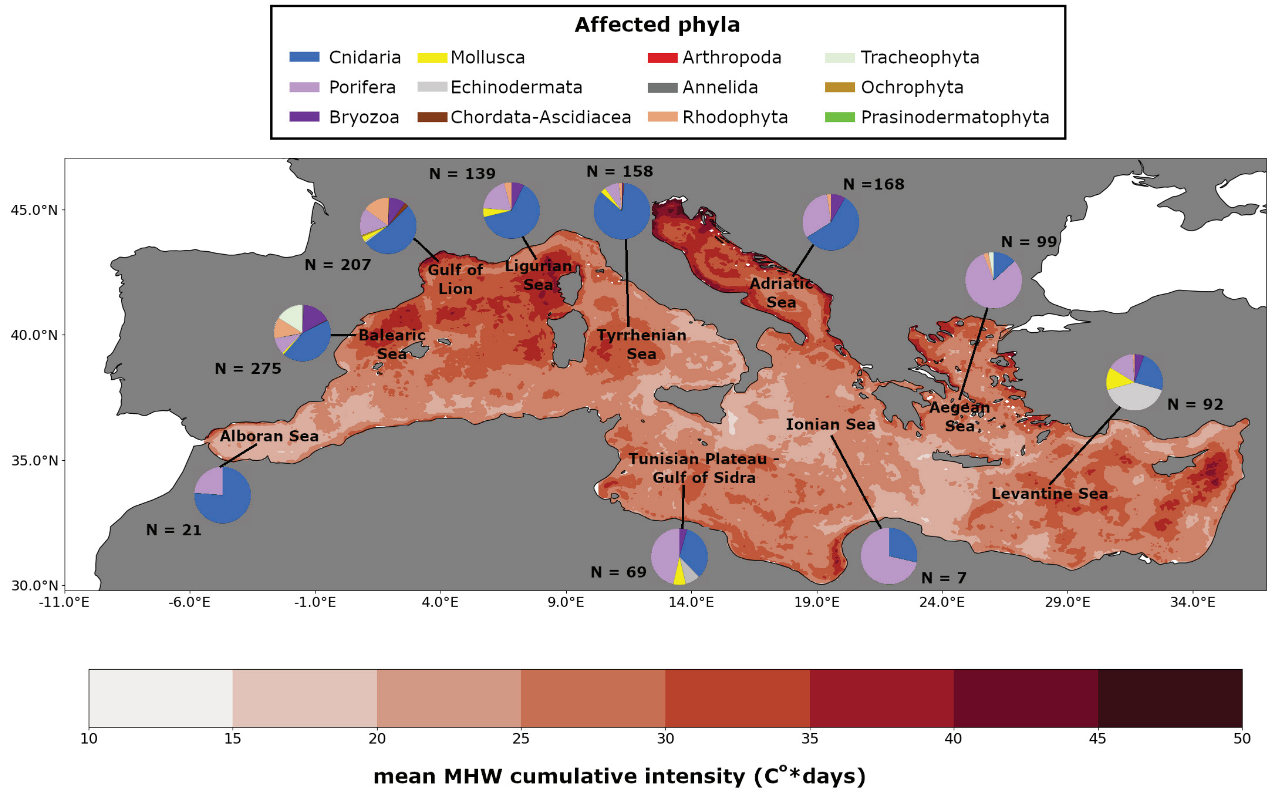

Fig. 5: Mass mortality events (MMEs) reported in the Mediterranean Sea between 1979 - 2019, combined with the MHW cumulative intensity (°C*days) averaged over 1982-2017. The number of MMEs (N), their geographic distribution, and the affected phyla, were obtained from Garrabou *et al.* (2019, 2022) (as MMEs) and Marbà *et al.* (2015) (as survival). The gridded average MHW cumulative intensity is derived from the HINDCAST Simulation of CNRM - RCSM6, using the MHW algorithm described by Hobday *et al.* (2016). MMEs and MHWs are not directly comparable due to differing time periods. Instead, this figure highlights the spatial hotspots of biological impacts (MMEs) and MHWs across the Mediterranean Sea. Figure is updated from Garrabou *et al.* (2019).

sidering the approximately 600,000 individuals engaged in fisheries and aquaculture industries in the Med Sea (Lacoue-Labarthe *et al.*, 2016) substantial consequences on the livelihoods of coastal communities in the basin are anticipated, as a result of MHWs. Yet, the available research and observational data regarding this dimension in the Med Sea are limited to date.

Impacts on Fisheries

MHWs have been reported to facilitate the reproduction of blue crab, an invasive species known for damaging fishing nets and prevailing over native species, threatening the income of fishermen and livelihoods of millions around the coasts of Tunisia (Reuters, 2022). Notably, the climate-change induced and MHW-driven regression of *Posidonia oceanica* over the last decades (Jorda *et al.*, 2012) has caused significant changes in the biodiversity of Mediterranean coasts, directly impacting the catch composition and income of coastal commercial fisheries in the Med Sea. Specifically, the economic loss of coastal fisheries correlated to the decline of seagrass meadows has been evaluated at about €60 million in 2014 and more than €750 million between 1990-2014 (El Zrelli *et al.*, 2020). MHWs also reduce the recreational and aesthetic value of coralligenous areas, resulting in a welfare loss of approximately €60 per dive, due to the total disappearance of gorgonians (Rodrigues *et al.*, 2016).

In addition to ocean warming, extreme weather events and changes in vertical mixing/stratification are the most important factors affecting the small pelagic and demersal Mediterranean fisheries, followed by the increase in frequency of MHWs and changes in precipitation-runoff, according to a semi-quantitative climate risk assessment by Hidalgo *et al.* (2022). This increase in MHW frequency seemed to be more relevant in the southeastern Mediterranean and Adriatic Sea. The highest risks were associated with impacts on fisheries resources, including catch composition, distribution changes, and abundance/biomass trends. Communities and livelihoods in the southeastern Med Sea were the most impacted for both the pelagic and demersal fisheries, with landing value being the most impacted parameter. Lower risk levels were highlighted for fishing operations, including fishing trips/days at sea and fishers' working conditions, as well as for the wider societal and economic implications, such as tourism activities, national income, and recreational fisheries. According to a social vulnerability assessment conducted in the western and eastern Med Sea by Gomez Murciano *et al.* 2021, storms and temperature are the main climate stressors affecting the fishing sector, increasing the sensitivity of fishing revenues, with fishers perceiving them as the main threat based on their experience, knowledge, and perception of the expected risks associated with extreme weather events.

MHWs may also result in fish diseases, posing a higher likelihood for adverse impacts on human health. Those risks may further be heightened whenever atmospheric and marine heatwaves co-occur in the Med Sea, leading to an increased likelihood for droughts, water scarcity and increased fire activity (Santos *et al*., 2024).). In particular, concurrent events are an emerging, albeit less recognized concern that can amplify damages on the ecosystems and economy of the climate-changed affected communities (Aboelkhair *et al.*, 2023). For example, the 2003 atmospheric and marine heatwaves incurred losses of nearly €15 billion, ranking it among the top five most expensive climate extreme events in EU Member States (Gagliardi *et al.*, 2022).

Impacts on Aquaculture

Mediterranean aquaculture, with an annual product worth of € 4.8 billion, involving predominantly marine finfish and to a lesser extent bivalves (FAO, 2020), is particularly vulnerable to MHWs. Unlike wild organisms, which can modify their behavior to escape unfavorable environmental conditions, farmed species are constrained by their rearing environment (Beever *et al.*, 2017) and must therefore rely solely on physiological adaptations to withstand the abrupt temperature changes during MHW. Laboratory trials investigating the effects of acute warming on the main farmed fish in the Med Sea have demonstrated diminishing performance and aerobic capacity at temperature exceeding 26°C, a progressive increase of stress biomarkers and deterioration of welfare as we approach 30 – 32°C, with physiological collapse eventually leading to death above that threshold (Kır, 2020; Islam *et al.*, 2020a, 2020c; Cascarano *et al.*, 2021; Stavrakidis-Zachou *et al.*, 2022; Sánchez-Cueto *et al.*, 2023). Under farming conditions, such effects are exacerbated by the high stocking densities maintained at the farming sites, be it either finfish or bivalve aquaculture, which ultimately transform temperature considerations to oxygenation considerations. Due to temperature and oxygen solubility being inversely related, during MHWs, the reared animals face both increased respiratory demands and reduced availability of oxygen (Burke *et al.*, 2022). The combination of these factors, coupled with the large production volumes can lead to hypoxic conditions, which, in turn, often result in mass mortalities (Roman *et al.*, 2019). In fact, hypoxia has been identified as the leading cause of environmentally-induced mass aquaculture mortalities in the Med Sea and shows seasonality, while being particularly pronounced on coastal regions where the bulk of aquaculture activity takes place (Eissa, 2024) and MHW intensity is the strongest (Dayan *et al.*, 2023).

Over the last 40 years, MHWs in the Western Mediterranean have increased in intensity and duration around aquaculture sites, with temperatures exceeding the welfare thresholds for the species, raising concerns (Atalah *et al.*, 2024). Depending on the scenario severity, simulations suggest that MHW - induced mortalities in the future may be detrimental for the sector causing as much as 80% (or € 10.8 million) losses in profitability for Mediterranean fish farms (Stavrakidis-Zachou *et al.*, 2021a). In addition to fish mortality, MHWs can also lead to unmarketable fish, by facilitating the proliferation of pathogens and subsequent disease outbreaks, posing significant financial challenges to aquaculture in the Mediterranean basin (Cascarano *et al.*, 2021). Substantial losses have also been registered for bivalve farming. Extended closures, seed mortalities, and abruption of the supply chain stemming from extended and more frequent warming periods, have been associated with the decline of mussel aquaculture in the European Union (Avdelas *et al.*, 2021). Recently, a 20% drop in the production of Spanish mussel has been attributed to the 2020 MHW (Sánchez-Jerez *et al.*, 2022). In the summer of 2021, a prolonged MHW over Thermaikos Gulf resulted in a 50% mortality rate for that year's mussel production in several aquaculture units in the area. In addition, infant mussels for export suffered mortality rates, ranging from 90% to 100% the following year, compromising the financial viability of the local industry and the well-being of more than 300 families relying on it (Androulakis & Krestenitis, 2022; Zgouridou *et al.*, 2022). Similarly, a MHW during 2013 resulted in the loss of 900 tonnes of Mediterranean mussels in the production area around the Ebro Delta river, amounting to a cost of approximately €9 million. The economic impact included revenue losses linked to the mortality of farmed species and additional adaptation costs required to restart the production (Rodrigues et al,. 2015).

MHW monitoring and forecasting

Observational approaches of MHWs impacts on Mediterranean Sea ecosystems

The understanding of MHW impacts on marine organisms and ecosystems is fundamentally hindered by a lack of observations across appropriate spatial and temporal scales. Marine organisms and ecosystems are sensitive to the diverse characteristics of MHWs—such as magnitude, recurrence, abruptness, and intensity—and their responses span a wide range of temporal scales, from hours to years (Gruber *et al.*, 2021). MHW impacts can be thus site-specific but may also affect broader spatial scales, with responses across different levels (from physiology to ecosystems) being difficult to disaggregate. This interplay across various biological levels necessitates observational and monitoring approaches tailored to specific organisms (e.g., sessile or motile) and habitats (e.g., benthic or pelagic). Addressing this complexity presents a significant challenge.

In the Med Sea, field surveys have extensively documented MHW-induced MMEs of several benthic taxa across different coastal habitats (Cerrano *et al.*, 2000; Garrabou *et al.*, 2009; Garrabou *et al.*, 2022), but observations were not homogeneously acquired across the entire basin and study periods (Garrabou *et al.*, 2022). Li *et al.* (2024) developed a multi-platform, multi-sensor and multi-frequency approach to address the impact of MHWs between 2012 and 2022, on offshore phytoplankton communities and productivity across the entire northwestern Med Sea, spanning from the surface to depth. The authors combined *in situ* observations of hydrological, bio-optical and biogeochemical variables acquired by autonomous BioGeoChemical-Argo profilers, with space-based observations of Ocean Colour and optically-derived proxies of phytoplankton community structure and carbon biomass (see Brewin *et al.*, 2023 for an overview). The use of population ecosystem models provided additional insights into trophic cascade events starting from zooplankton. This approach demonstrated that complementing observations from multiple systems is necessary to achieve the spatiotemporal continuity required to assess the physiology-to-ecosystems interplay in response to MHWs.

Forecasting of Mediterranean MHWs

Compared to other regions which have experienced distinctly long-lasting or intense periods of extreme heat associated with ecological impacts (e.g., Tasman Sea: de Burgh-Day *et al.*, 2022; Stevens *et al.*, 2022), there are fewer specific studies on the predictability of MHWs in the Mediterranean, or on quantification of forecast system skill. Nonetheless, there are indications of the skill of state-of-the-art forecasting, from short-term to seasonal. The Med Sea is home to high-resolution regional monitoring (near-time analysis and multi-decadal reanalysis) and short-term forecasting products, as well as a wealth of *in situ* observations used for validation of those products (Le Traon *et al.*, 2019). Short-term forecasts (up to 10 days) from the Copernicus Mediterranean Forecasting System successfully captured the various phases and intensity of the MHW of summer 2022 (McAdam, 2023). There is therefore great potential for short-term forecasts to be exploited by stakeholders and build the basis for alert systems. Sub-seasonal forecasts (up to 3 weeks) of MHWs in the Mediterranean have yet to be exploited, despite promising demonstrations in other areas (e.g., the Great Barrier Reef: Benthuysen *et al.*, 2021). Seasonal forecasts of MHWs, particularly desirable given the possibility to provide early-warning to marine industries and activities, display mixed capabilities in the Med Sea. Predictions of surface indicators are unreliable (de Boisséson & Balmaseda, 2024), have underestimate drastically the summer of 2003 (McAdam *et al.*, 2023), more so in the western Mediterranean. Subsurface extremes, due to their long-lasting nature, are easier to predict on seasonal timescales (McAdam *et al.*, 2023). Long-term trends contribute to interannual variability more so in the Eastern Mediterranean (Simon *et al.*, 2023), partly explaining the relatively higher seasonal forecast skill.

Machine Learning applications on MHWs in the Mediterranean Sea

Although forecasting system models have attained a significant level of reliability in MHW prediction at both global (e.g., Jacox *et al.* 2022) and regional scale (e.g., McAdam *et al.*, 2023), they do so at a high computational cost (Alvarez Fanjul *et al.*, 2022). The use of machine learning (ML) techniques to predict marine extreme events, therefore, emerges as a new promising approach, due to its lower computational requirements. As a data-driven method, ML offers several advantages, including transferability, flexibility, and ease of use (Boukabara *et al.*, 2019; Li *et al.*, 2020; Wei & Guan, 2022; Taylor & Feng, 2022). ML techniques are also less susceptible to model bias errors (Jacox *et al.*, 2020) and excel at approximating nonlinear functions (Hornik, 1991). Currently, physics-informed neural networks (e.g. Zhu *et al.*, 2022, de Wolff *et al.*, 2021) are designed to address the inherent limitations of machine learning methods in detecting violations of fundamental physical laws (Buizza *et al.*, 2022).

In the Med Sea, ML approaches for predicting SST and, in turn, MHWs are still in their early stages. One of the early works in the basin used Artificial Neural Networks to predict the seasonal and interannual variability of western Mediterranean SST, as well as the summer MHW impact of 2003 (Garcia-Gorriz & Garcia-Sanchez, 2007). This study trained several meteorological variables between 1960-2005 (e.g., 2m air temperature, wind, sea level pressure) and predicted reliable SST on a monthly scale. More recently, Bonino *et al.* (2024) compared several ML algorithms, including Long short-term memory (LSTM), Convolutional Neural Network (CNN) and Random Forest, to forecast daily SST at weekly lead times across 16 sub-basins in the Med Sea. The successful predictions of SST exceeding predefined thresholds were subsequently assessed as potential MHW indicators alongside various atmospheric variables. The results from all the ML methods were compared with the outputs of the Copernicus Mediterranean Sea Analysis and Forecasting System (MedFS), a model providing ocean state estimates and daily forecasts (Coppini *et al.*, 2023, Clementi *et al.*, 2021). The validation process showed that ML techniques outperformed the well-established MedFS on the SST prediction and MHW forecasting, especially in the early forecast days.

Current limitations on MHW analysis

Can there be an objective MHW detection method?

The study of MHWs on a global or Mediterranean scale requires the establishment of a standardized framework to detect and characterize extreme events. Numerous studies so far have employed a versatile statistical method by Hobday *et al.* (2016), whereby a MHW occurs when daily temperatures exceed a local, seasonally varying, 30-year climatological threshold (90th percentile) for at least 5 consecutive days, with allowed gaps of 2 days or less. Variations of this definition in the detection of Mediterranean MHWs include adjustments to fixed or percentile SST thresholds (e.g., Galli *et al.*, 2017; Darmaraki *et al.*, 2019a,b; Konsta *et al.*, 2023), the application of additional spatial criteria (Darmaraki *et al.* 2019a,b; Pastor & Khodayar, 2023) or the consideration of different baseline periods (Rosselló *et al.*, 2023; Martínez *et al.*, 2023). These adaptations aim to meet specific requirements, such as targeting the most intense and long-lasting events, in different seasons, or the most impactful ones in terms of biological impacts (see Table S1 & Table 1). Regarding spatial criteria, a few studies have attempted to define macroevents in the Med Sea, i.e. MHWs that affect multiple interconnected grid points in time and space. This has been achieved by either delineating the spatiotemporal extent of MHWs (e.g., Darmaraki *et al.* 2019a; Pastor & Khodayar, 2023) or by employing connected component analysis to aggregate spatiotemporally connected MHWs, producing a high-resolution, macroevent-based dataset (e.g., Bonino *et al.*, 2023). More recently, Simon *et al.* (2022; 2023) proposed a generalized approach for the identification of Mediterranean events, combining structural MHW characteristics, such as the number of events, duration, mean intensity and spatial extent within a predefined domain and a particular period of the year, into a *MHW activity* index. For the subsurface identification of MHWs in the basin, ocean temperatures at various depths, depth-integrated temperatures, vertical sections and ocean heat content-based (OHC) indicators have been used to replace or complement SST-based definitions (e.g., Darmaraki *et al.*, 2019a; Juza *et al.*, 2022; McAdam *et al.*, 2023, Dayan *et al.*, 2023).

Despite the diverse research objectives addressed through the different MHW definitions, certain challenges emerge when attempting quantitative comparisons across studies. In their early work, Hobday *et al.* (2016) underscored the potential for substantially different MHW information due to varying spatiotemporal resolution or quality issues across different datasets. The more representative example is when validating model-detected against satellite-detected events, where discrepancies in the presence or absence of MHWs and their characteristics may emerge. For instance, in lower-resolution, global-scale ocean simulations (Pilo *et al.*, 2019) and reanalyses datasets in the Med Sea (Dayan *et al.*, 2022) fewer, longer and less intense events are detected compared to observations. Weaker MHWs are also identified in coarser compared to eddy-permitting models of higher spatial resolution (Pilo *et al.*, 2019). In the case of the Med Sea, recent studies demonstrate a sensitivity of past MHW properties to changes in the baseline climatology and the temperature threshold (see Table S1), albeit their qualitative consistency. The temperature threshold in particular, is a metric dependent on the specific scientific problem (Qiu *et al.*, 2021), given that absolute temperature thresholds are more relevant for the assessment of ecological, physical or societal impacts (Dayan *et al.*, 2023), whereas (statistical) percentile-based ones represent MHWs in a more local context (Oliver *et al.*, 2021). This parameter can lead to quantitatively more intense MHWs with time (e.g., Rosselló *et al.*, 2023), without affecting the qualitative intensification of future events (Hayashida *et al.*, 2020).

Those results are consistent with Darmaraki, (2019) that performed sensitivity tests on the properties of the MHWs during the summer 2003, revealing a more significant influence of the baseline climatology, temperature threshold, and minimum event duration on the events' characteristics in the Med Sea, as opposed to changes in the gap days and the application of a spatial threshold. In line with Pastor and Khodayar, (2023), the latter more intrinsic settings of the statistical definition seem to mostly affect the frequency of detected events, which very often is a misleading metric, i.e. presents low values in areas with longer events and vice versa (Ibrahim *et al.*, 2021). Considering that certain (Mediterranean) marine ecosystems may be adversely affected by frequent MHWs while others by prolonged events, the severity of impacts does not necessarily correlate with high or low values of MHW frequency. In addition, an abundance of MHWs on a given period can no longer be deemed extreme, while an insufficient number of them requires longer temperature records for a statistically robust threshold estimation (Oliver *et al.*, 2021). Therefore, detecting a balanced number of MHWs using a statistical identification framework necessitates careful tuning of the spatiotemporal parameters.

Overall, each approach to detecting MHWs presents its own challenges. For instance, the MHW activity index proposed by Simon *et al.* (2022), offers more aggregated event characteristics but it is sensitive to the spatial extent of the domain considered, does not account for individual discrete events and requires a well-defined spatiotemporal framework. The assessment of MHW properties at depth using OHC indicators is particularly useful for marine ecosystem studies on species traversing various depths. However, this approach compromises detailed information on the variation of temperature anomalies at specific depths, which might be of greater relevance to marine stakeholders (Dayan *et al.*, 2023). It is therefore evident that no universal definition exists for extreme climate events and any specific variable (Stephenson *et al.*, 2008). While the integration of standardized indices or event categorization schemes (e.g., Hobday *et al.*, 2018) proves beneficial for comparing studies conducted under diverse MHW settings, the selection of the MHW detection method and the spatiotemporal points of reference should be also guided by the specific goals and context of each study.

Fixed versus shifted baseline climatology effect on MHWs

The accelerating ocean warming over the last decades has induced a positive trend in global ocean temperatures, leading, in turn, to intensified MHW properties with time (Jacox *et al.*, 2019; Oliver *et al.* 2018; Xu *et al.*, 2022). This becomes more apparent in climate-sensitive regions, like the Med Sea. To differentiate the influence of mean warming from abrupt variations, Martínez *et al.* (2023) identified Mediterranean MHWs based on detrended SST data between 1982-2022, revealing statistically insignificant trends in their properties but consistent mean annual metrics with the non-detrended dataset of the same period. MHWs in the basin were more uniformly distributed throughout the entire period of examination in contrast to the detection of events in the non-detrended data, which commenced only in the latter half of the period. As a consequence, there was a change in the order of event severity between the two datasets, while the detrended dataset did not capture the 2017 event at depth. Detrending shorter SST timeseries, however, showed an increase of MHW days at the beginning of the period, as opposed to Juza *et al.* (2022) and Simon *et al.* (2023) that reported underestimated or less significant trends in Mediterranean MHW properties in that case.

In the context of eliminating the long-term warming effect, detrending of temperatures is analogous to the shifting baseline approach, which results in varying event-detection thresholds during the examined period. The latter approach has sparked substantial controversy in the broader MHW research community, especially concerning the projections of future MHW characteristics (Oliver *et al.*, 2021; Amaya *et al.*, 2023). For the most part of the Med Sea, Darmaraki *et al.* (2019b) showed a predominant role of the mean warming trend on the evolution of surface MHWs in the 21st century (RCP8.5), with SST variability playing a critical role in specific regions only, in agreement with Oliver *et al.* (2019). The effect of the baseline period on the detection of Mediterranean MHWs becomes more evident through the comparison of the projected MHW characteristics in Galli *et al.* (2017) and Konsta *et al.* (2023). Despite employing fixed (2001-2010) and moving baseline climatologies, respectively, both studies reveal more frequent, intense and persistent events throughout the 21st century and under the same RCP8.5 scenario. This increase is observed both in comparison to historical conditions (Galli *et al.* 2017) and in projections for the end relative to the mid-21st century (Konsta *et al.*, 2023). In other words, the removal of the warming trend in the case of the Med Sea still returned a great increase in the intensity and persistence of 21st century MHWs in the water column (Konsta *et al.*, 2023).

Evaluation of climate extremes in variables subject to long-term trends, such as the ocean temperature, is often a topic of debate. Given that extreme events are statistically defined relative to a threshold that is exceeded on a somewhat constant but "rare" frequency, the choice of the reference period against which MHWs (or other extremes) are detected is critical. The use of a reference period fixed in the past increases the likelihood of future MHW occurrence (Amaya *et al.*, 2023), emphasizing changes in future properties and challenging the very definition of an extreme event. While this leads to a MHW saturation of the ocean by the end of the 21st century, it communicates effectively the message of the climate-induced, extreme warming of the ocean relative to periods when anthropogenic activities were minimal (Rosselló *et al.*, 2023). On the other hand, the use of a shifted baseline period identifies MHWs that are pertinent to a more recent climatological period, adhering to the default statistical definition of extreme events, masking, however, the impacts of a changing climate (Amaya *et al.*, 2023). Wang *et al.* (2022) further notes that employing a moving baseline in a conventional manner does not necessarily eliminate the impact of the mean warming signal. Instead, it frequently introduces artificial negative trends in MHW statistics and consistently underestimates the influence of temperature variability on MHW changes, suggesting an alternative methodology to address these challenges. In comparison, longer baseline periods may also lead to an increased number of MHWs, due to "cooler" years shifting the temperature threshold downwards (Rosselló *et al.*, 2023).

It is therefore clear that there are advantages and limitations in using a fixed versus a shifted baseline period as a reference for a statistical definition of MHWs. Hence, the decision to isolate the background warming signal in studies of (future) MHW characteristics or not is dictated by the specific research question. In particular, a fixed baseline climatology might be more appropriate for the study of marine ecosystems incapable to adapt to MHWs, whereas the use of a shifted baseline is more suitable for ecosystems with a faster ability to adapt (Oliver *et al.*, 2021). Although employing different definitions to describe extreme warm events in the ocean has its merits for public (and scientific) communication purposes and for clarifying the diverse quantitative estimates of MHW properties (Amaya *et al.*, 2023), the qualitative message of global warming remains timely. This debate is of particular relevance to the Med Sea, given that it displays a greater warming trend than the global average.

Challenges in analyzing physical drivers behind MHWs

Limitations also exist in the assessment of physical drivers behind MHWs and are not solely related to comparability challenges within literature. More recently, Bian *et al.* (2024) demonstrated that the governing mechanisms behind global MHWs shift from local oceanographic processes to atmospheric ones as the spatial scale of the event becomes larger. These mechanisms operate in various spatiotemporal scales in the Med Sea, with large-scale MHWs mainly controlled by atmospheric heat fluxes and oceanic advection with entrainment processes playing a more prominent role in local scales. For instance, differences in the heat contributions can be observed during a large-scale surface MHW detected in two areas of the eastern Med Sea, between July-November 2015; A smaller area near the coast and a slightly larger area extended meridionally (see Fig. 6, top). The event is primarily driven by high atmosphere heat fluxes in both cases, however, the contribution from total advection is positive and more significant in the smaller area near the coast (Fig. 6, left panel) compared to the larger, expanded region where it appears to play a slightly reduced and

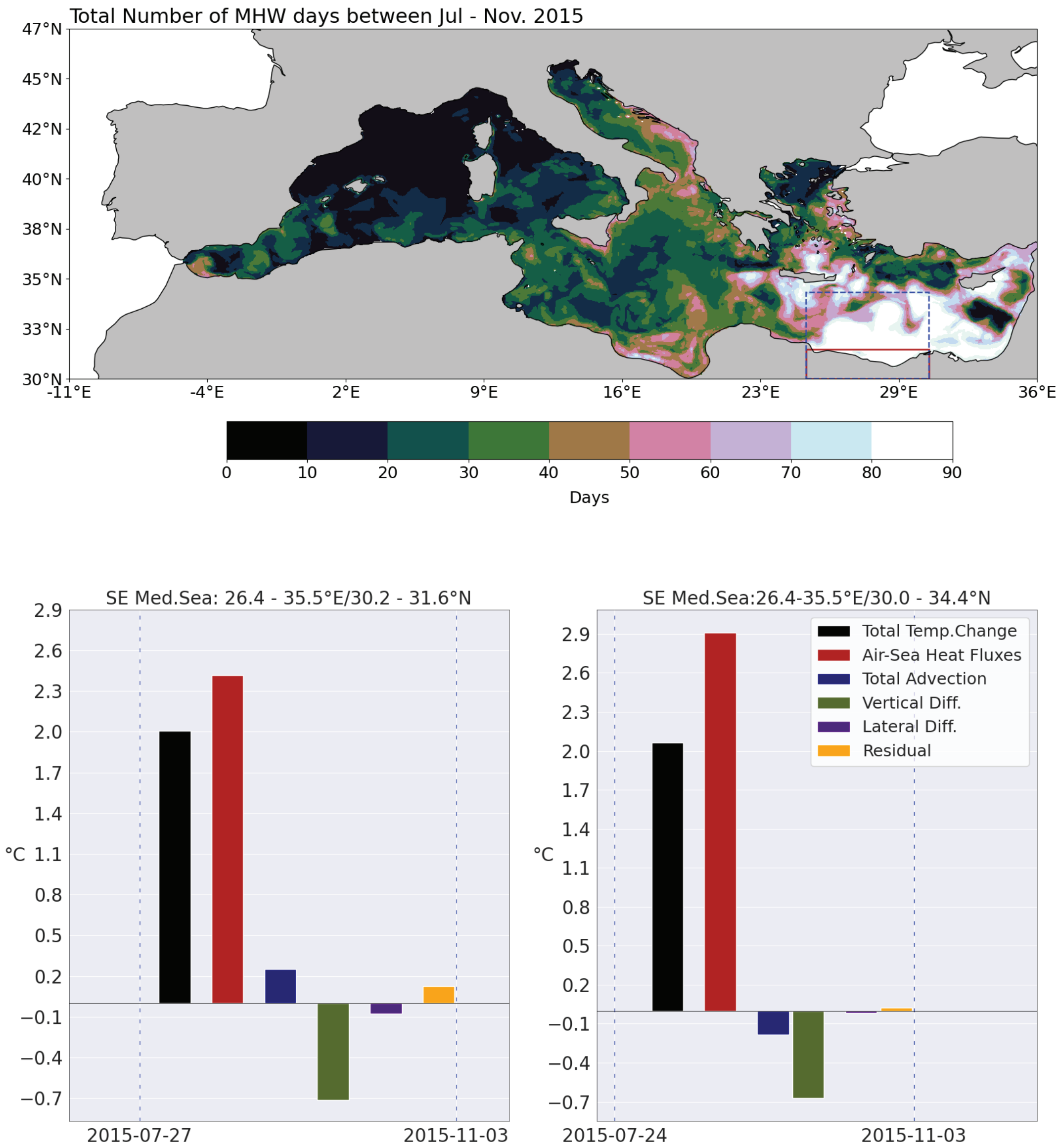

Fig. 6: (Top) Total number of MHW days between 20/7/2015 - 10/11/2015. The selected regions for computing heat contributions during the MHW days are illustrated as follows: a small coastal area (26.4°E - 35.5°E / 30.2°N - 31.6°N), marked by a solid red box, and a larger area extended meridionally (26.4°E - 35.5°E / 30.0°N - 34.4°N) from the coast, indicated by a dashed blue box. (Bottom) Cumulative sum of the heat contributions from the physical processes acting on the MLD throughout the onset period of the MHW 2015, in a coastal (left panel) and a slightly extended area (right panel) of the southeast Mediterranean Sea. The total heat contribution from the overall temperature changes (black), air-sea heat fluxes (red), horizontal advection (blue), vertical diffusion (green) and lateral diffusion (purple) and residual (orange) are presented. Note that the starting and peak day of the MHW in the two regions (blue dashed lines) is slightly different. The heat contributions are outputs from a Hindcast simulation of a mixed layer heat budget conducted with the CNRM-RCSM6 model.

cooling role (Fig. 6, right panel). Likewise, determining the drivers of subsurface MHWs, is contingent upon the selected integration depth or the extent of the mixed layer depth considered. It has been shown that when employing a mixed layer heat budget analysis, a fixed MLD generally results in more advection-driven MHWs when it is deep, whereas the atmosphere heat flux signal is more prominent in shallower MLD conditions (Elzahaby *et al.*, 2022). Therefore, the use of a daily or spatially variable MLD is recommended.

In addition to the effect of spatial scales, studies commonly define distinct temporal periods corresponding to different MHW phases, to examine the role of the different mechanisms driving MHWs. The most widely adopted approach is the distinction between the onset phase of a MHW; spanning from the start to the peak-intensity day and the decline period; extending from the peak to the final day. The duration of MHW onset and decline affects the dominant driver diagnosed in each phase, especially in prolonged events, where sequential warming and cooling sub-periods can naturally occur. In such cases, a separate examination of each sub-period enhances our understanding of the mechanisms at play during each phase, although such an analysis bears a great complexity when studying multiple events in a climatological context. The current definition of onset phase excludes the precedent period, where warming has been gradually evolving, leading to above-threshold temperatures in the first MHW day. Analogously, the decline phase does not consider the dissipation of heat that is still ongoing following the end of the MHW (where temperature drops below the threshold). This approach is thus expected to capture processes strictly relevant to these two periods. In this regard, Marin *et al.* (2022) defined the onset and decline phases of a MHW based on the temperature anomaly exceeding 10% of the maximum event intensity. This dynamic criterion includes a larger percentage of the temperature change during both the build-up and the dissipation period of events. An alternative approach includes dividing each event into 3 phases: a pre-event period, the interval between the start and end of the event, and a subsequent period following the MHW's end (e.g., Darmaraki, 2019).

Future perspectives on Mediterranean Sea MHWs

Perspectives on MHW monitoring

Despite the warming SST in the basin resulting in more MHWs over time (Pisano *et al.*, 2020), there appears to be a mismatch between the spatial patterns of MHW trends and those of the SST that suggests a more complex interplay between air-sea heat fluxes and local-scale oceanographic processes behind these events (Dayan *et al.*, 2022; Ibrahim *et al.*, 2021). In particular, different types of MHWs affect the western and eastern Med Sea, with the coastal ocean response to climate warming varying from that of the open ocean and subsurface MHWs sometimes lacking a surface signature and vice versa. In this context, several studies emphasize the need to strengthen subsurface monitoring systems, using *in situ* observation, BioGeoChemical-Argo autonomous profilers, gliders or fixed moorings over extended periods of time. Such observational platforms can complement existing remote-sensing observing systems, which currently track the development of surface MHWs (e.g., https://www.marineheatwaves.org/, https://t-mednet.org/visualize-data/marine-heatwaves), alongside high resolution, forecast, reanalysis and climate models that may offer more accurate information on poorly sampled dynamical regions of the basin (Juza *et al.*, 2022; Dayan *et al.*, 2023). This near-real time information can improve our understanding of the conditions facilitating MHW propagation from surface to the subsurface (e.g., Jacquemont *et al.*, 2024) and inform us about various physical (e.g., diurnal fluctuations of temperatures, thermal signals along the coasts) and biological indicators (Bensoussan *et al.*, 2019). Overall, they are valuable tools for diverse ocean stakeholders that seek targeted information i.e. policymakers, general public, aquaculture (Juza *et al.*, 2022, Dayan *et al.*, 2023).

The high spatial variability of ocean response to MHWs in the Med Sea may also necessitate location-specific monitoring approaches (Dayan *et al.*, 2022; Juza *et al.*, 2022). A recent study by Dayan *et al.* (2023) developed depth-integrated MHW indicators, partitioning the Med Sea in Exclusive Economic Zones (EEZs), with a view to deliver stakeholder-relevant information at a national level. Such a classification aims to bridge the gap between scientific research of extreme ocean events in national waters and the response to diverse stakeholder needs, although further sub-division is required for local-scale risk-assessments of higher accuracy. The study further notes that local-scale, subsurface information is more relevant than basin-scale data for national policymakers planning adaptation measures to MHWs. Since the marine ecosystems and resource-based economy are shared among many countries around the Med Sea, extreme events may be at the forefront of geopolitical and economic stakes (Dayan *et al.*, 2023)

Considerations on machine learning approaches

Future research on ML-based prediction of MHWs in the Med Sea could benefit from the increasing model complexity or the improvement of model architectures, to transition from (1D) time series forecasts to spatially comprehensive (2D) maps of predicted SST and MHW presence and absence. For instance, Sun *et al.* (2023a) trained a CNN combined with LSTM temporal layers to predict the existence and spatial development of MHWs. Their study suggests the use of a CNN-LSTM in combination with a U-net CNN regression model to forecast SST anomalies, which, when surpassing a specific threshold, can indicate the presence of MHWs. This hybrid ML technique, which predicts the spatial distribution of MHWs instead of single time series, shows high potential for predicting MHWs well in advance, which could aid stakeholders in high-risk regions of the Med Sea and elsewhere to timely implement mitigation strategies.

Despite their improved capacity to process large amounts of different data sources, ML techniques have their own set of challenges and limitations that need to be addressed to fully leverage their potential in this field. For example, CNNs that handle image-arrays as inputs and retain spatial information is a technique which requires a substantial amount of image data and computational resources in order to produce trustworthy results (Taylor & Feng, 2022). This, however, can lead to information loss on the spatial variability of SST, affecting, in turn, the detailed information on horizontal propagation of MHWs within the sub-domains. In other words, there is a tradeoff between the accuracy and computational costs of training large amounts of data, which is important to consider when applying ML techniques. Moreover, ML techniques lack inherent knowledge of physical laws, which can lead to violations of fundamental physical constraints. This limitation likely affects the accuracy of the ML prediction window (Boukabara *et al.*, 2019; Dueben & Bauer, 2018). Future research could explore integrating physical laws into ML frameworks governing ocean dynamics. For example, Zanetta *et al.* (2023) suggest including physical constraints, through analytic equations, in deep-learning-based post-processing models. Including these constraints could enhance the reliability of NN predictions and reduce the risk of deviating from physical realities. Considering the strengths of ML shorter-term predictions (3-5 days, Bonino *et al.*, 2024) and their potential limitations, it may be beneficial to use ML models alongside ocean forecasting systems for longer prediction intervals.

Avenues of future work on Mediterranean Sea MHWs

Despite recent advancements of MHW research in the Med Sea, there are still open questions for investigation. While the majority of studies so far have concentrated on describing the past and future trends, characteristics, spatial variability and regional drivers of MHWs, there is a need to broaden research focus beyond the summer, to include MHWs in other seasons and explore the feedback of these Mediterranean events to the atmosphere. This would require considering interactions with the Atlantic Ocean (Simon *et al.*, 2023) and further examine linkages with large-scale climate modes, which are currently poorly studied. To this end, methodologies like clustering can aid in the identification of meaningful links between atmospheric and oceanic parameters (e.g., Stefanon *et al.*, 2012, Bonino *et al.*, 2023), complementing studies using high resolution products that can more accurately represent events in different regions (Pilo *et al.*, 2019). Given the challenges with the existing statistical definition of MHWs, exploring alternative MHW indicators or employing different spatiotemporal frameworks, like Lagrangian MHW tracking (Sun *et al.*, 2023b), could also be a valuable avenue for further research in the Med Sea and elsewhere. Finally, the contrasting potential for enhanced stratification versus vertical propagation of MHWs under the 21st-century climate change regime in the Med Sea remains uncertain. This raises questions about changes in the local- and large-scale drivers of surface and subsurface MHWs under different climate change scenarios and their anticipated properties associated with their dominant drivers.

These climate change-induced changes in MHW properties will likely exert additional pressure on Mediterranean marine ecosystems. Thus far, the impacts of MHWs in the region have primarily revolved around MHW-induced mass mortalities and the effects of long-term warming. However, the increasing occurrence of MHWs rather than gradual warming can amplify marine species' susceptibility, reducing their ability for acclimation (Marbà & Duarte, 2010). Hence, there is a notable gap in research addressing the broader impacts of MHWs on the highly diverse Mediterranean marine biota. Considering the increasing need for the development of climate-based conservation strategies to protect vulnerable marine life, particularly within Mediterranean Marine Protected Areas (MPAs), which host several high-risk taxa, including sea turtles and marine mammals (Chatzimentor *et al.*, 2023), sustained efforts are crucial to enhance our understanding of Mediterranean marine ecosystems' response to (future) warming. This involves detailed spatiotemporal monitoring, along with experimental and modelling studies that better reflect MHW conditions, incorporating the complexity of natural systems driven by multiple environmental factors (Rindi *et al.*, 2022). Such insights can optimize management practices, including the identification of spatial refugia and the establishment of new MPAs (Ramírez *et al.*, 2021; Zentner *et al.*, 2023; Bates *et al.*, 2019). Protection can limit additional anthropogenic pressures and mitigate adverse effects of MHWs (Benedetti-Cecchi *et al.*, 2024), essential for enhancing the resilience of Mediterranean biota to current and projected climate change effects.

Increased research efforts are also needed to study the socio-economic implications of MHWs in collaboration with relevant stakeholders to determine appropriate indicators for subsurface MHW analysis (Dayan *et al.*, 2023) and enhance the adaptive capacity and resilience of fisheries against the impacts of MHWs and broader climate change effects. Drawing on past MHW experiences, effective climate-based strategies include incorporating climate-related indicators in stock assessments (Free *et al.*, 2023), implementing permissible harvest limits before the onset of MHWs and proactively harvesting aquaculture production ahead of MHWs to anticipate and mitigate potential consequences (Carey, 2022). Finally, further research is needed towards the concurrent MHWs and biogeochemistry extreme events in the basin, which remain poorly understood. To date, the only study by Major *et al.* (2021) reports enhanced subsurface deoxygenation signals in regions affected by intense MHWs throughout the 21st century, based on a physical-biogeochemical model and under the RCP4.5 climate change scenario. These signals are predominantly driven by stratification in addition to organic matter export.

Conclusions

The Med Sea, a semi-enclosed, biogeophysical crossroad stands out as a climate change "hotspot", with its extensive warming over the past decades surpassing global ocean trends. Due to its high marine biodiversity, it presents profound ecological significance and socio-economic interest for the surrounding coastal communities. However, over the past decades, several studies report an increased occurrence and intensification of surface and subsurface MHWs in the basin. Notably, the summers of 2003 and 2022 are marked by exceptionally long, intense and widespread MHWs compared to records dating back to the 1980s. In addition to the observed temporal trends, collective findings from Med Sea-specific studies reveal that both surface and subsurface events demonstrate a pronounced northwest - southeast gradient in their properties, with the most intense and frequent events observed in the western Med Sea and the longest ones in the eastern basin. At a local scale, the formation of MHWs in the Med Sea has predominantly been associated with increased radiation fluxes into the sea, weakened winds and reduced surface heat losses from the ocean. While the effect of atmosphere-induced warming may be modified by regional influences that enhance the warming role of oceanic processes, the wind emerges as a critical mechanism for the propagation of MHWs in deeper layers, where they persist for longer periods of time. Nonetheless, subsurface events in the Med Sea have also been reported to occur without a surface signature and vice versa. On broader spatiotemporal scales, MHWs are correlated with large-scale climate modes, such as the East Atlantic pattern and have frequently co-occurred with atmospheric heatwaves or contributed to the development of extreme weather events in the basin, forming concurrent events. As a response to increased GHG emissions, the properties of Med Sea MHWs are expected to amplify throughout the 21st century both at surface and at depth, particularly in coastal areas.

This trend in mean and MHW-induced warming, has already had far-reaching consequences on various marine species and ecosystems, with a substantial body of research documenting a wide range of changes in Mediterranean marine biota and recurrent MMEs. However, observations of biological impacts are biased towards the northern and western basin (Marbà *et al.*, 2015), potentially underestimating effects in the faster-warming eastern basin (Pisano *et al.*, 2020). Three main conditions are commonly linked to the most severe sessile biota responses: temperature extremes at the end of summer (Bensoussan *et al.*, 2010; Crisci *et al.*, 2011; Díaz-Almela *et al.*, 2009; Estaque *et al.*, 2023), cumulative effects of successive warm summers (Garrabou *et al.*, 2021;2022; Kersting *et al.*, 2013; Orenes-Salazar *et al.*, 2023; Stipcich *et al.*, 2022a) and local-scale characteristics affecting the vertical distribution of heat (Bensoussan *et al.*, 2010; Crisci *et al.*, 2011; Garrabou *et al.*, 2009; Genevier *et al.*, submitted 2023). Excess temperatures during these conditions can alter molecular and physiological processes, behavior and growth parameters, within individual organisms and scale up to changes in population abundance and composition, genetic traits and modifications in ecosystem productivity and structure (Gruber *et al.*, 2021). These changes extend, in turn, to considerable economic implications for the fisheries, aquaculture and livelihoods of coastal communities in the Med Sea. The increased frequency and intensity of MHWs affect fisheries resources, through distribution shifts, changes in catch composition and trends in abundance and biomass, with landing value recognised as the most impacted economic metric. In addition, the heightened temperatures during MHWs can exceed the thermotolerance threshold of farmed fish, leading to hypoxic conditions and often to MMEs, posing as a result significant challenges to aquaculture operations in the basin. The diverse responses of marine organisms in the pelagic and benthic marine ecosystems to MHWs highlight the need for comprehensive, multi-system observational approaches to studying these events. This is particularly crucial in the Med Sea, where current observations have predominantly documented recurrent MHW-induced MMEs and specific event-related impacts. In addition to ongoing monitoring efforts, MHW forecasting systems in the basin have yet to be expanded, with greater potential identified in short-term and seasonal predictions. Given that MHW forecasting is currently at the core of extreme event research, a few studies have also applied various machine learning methods to predict past MHWs in the basin, although there is need for further advancements in the area to fully exploit the predictive potential of data-driven techniques.

Despite significant advances in the analysis of Med Sea MHWs so far, we emphasize here the ongoing challenges in achieving a standardized framework for MHW detection in the basin and elsewhere. The very definition of MHWs, statistical in its root, comes with both advantages and limitations and requires careful consideration of its spatiotemporal settings (e.g., temperature thresholds, reference periods, duration of events etc.) together with the incorporation of appropriate (surface or subsurface) indices. Considering the challenges of selecting an objective MHW definition, we advise tailoring detection methods and spatiotemporal references to the specific goals and contexts of individual studies. Clear statements of these objectives are crucial for accurate interpretation and meaningful comparisons across studies. Although a contextual approach may not facilitate quantitative comparisons between studies, we note the significance of accounting for different temperature thresholds, given the varied responses of marine ecosystems to MHWs and argue that the application of fixed or shifted baseline climatology as a reference, addresses different scientific questions.

This review aggregated information on the evolving landscape of anomalously warm temperature events in the Med Sea, offering insights into their historical context, characteristics, impacts, drivers, feedback and future projections. Yet, the documented upward trend in their frequency, duration and intensity over the past decades highlights the need for enhanced monitoring and advanced forecasting of these events. We therefore discussed approaches that contribute towards this direction, drawing on the reviewed literature, the promising progress of novel techniques and the existing knowledge gaps that warrant attention from the scientific community. Such advancements are essential for the development of effective tools, aiming to mitigate MHW consequences.

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Supplementary Data

The following supplementary information is available online for the article:

Table S1. Compilation of regional-scale studies investigating past MHW characteristics in the MS. For each study shown are: The type of dataset employed, the region and depth of examination, the temperature (Extreme event threshold) and reference period against which the MHWs were identified, the period during which MHWs were detected as well as the mean MHW frequency, duration and intensity. Whenever average MHW characteristics were not reported for the period examined, the equivalent trends were provided and vice versa.