Projected intensification of subsurface marine heatwaves under climate change

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Abstract

Marine heatwaves (MHWs) are periods of abnormally warm ocean temperatures that severely impact marine ecosystems. Although they can propagate beneath the ocean's surface, MHWs are typically assessed using sea surface temperatures. Here, we investigated the future evolution and depth penetration of MHWs across the Mediterranean basin. Our analysis revealed that MHWs will become more intense and persistent by the end of the century, both on the surface and, especially, in deeper waters. Near the surface, we projected on average 51 annual MHW days and a mean intensity of 1.5°C, whereas at depths below 1000 m, MHWs may occur up to 340 days annually, with an intensity of 0.4°C. These findings highlight that MHWs penetrate deep into the ocean, posing a severe threat to marine life and ecosystems that are often overlooked, particularly in marine subsurface environments.

Main

Marine heatwaves (MHWs) are extreme ocean warming events that can cause abrupt ecological changes, compromising the functionality, goods, and services of living systems [1, 2]. There is mounting evidence that MHWs can lead to substantial ecological impacts, including mass mortality events [3, 4], and trigger socioeconomic consequences [5, 6]. Anthropogenic climate change has already led to an increase in the frequency and intensity of such oceanic extreme events [1, 7], and this alarming trend is projected to continue over the following decades [8, 9]. Given the devastating impacts of MHWs [10], sophisticated predictions of their future evolution are required to develop potential mitigation strategies.

Research on MHWs conducted to date has primarily focused on their severity based on sea surface temperature (SST) [11–13], indicating an increase in their occurrence, duration, and intensity over the past century [6, 14]. However, MHWs can exhibit considerable vertical expansion [15, 16] or even exist at a given depth with no surface expression [17, 18]. Moreover, the duration of such extreme events at depth has been observed to be longer than at the surface [19]. The focus on surface MHWs reflects the scarcity of subsurface ocean data [20], making systematic studies of MHWs difficult to undertake across depths. The extent to which MHWs extend across depths, how frequently a MHW may penetrate the open ocean, and the characteristics of deep events relative to surface MHWs remain largely unidentified [19].

The frequency, duration, and intensity of MHWs are generally higher at mid-latitudes [21, 22], in regions typically associated with high-temperature variability linked to significant variations in heat advection [23]. The Mediterranean is a well-known hotspot for climate change, with high SST variability and complex oceanographic processes that vary greatly in time and space [24, 25]. Notable examples of devastating impacts of MHWs have been reported in the region, associated with mass mortality outbreaks and changes in biotic community composition, affecting a wide variety of marine ecosystems [26]. While several global and regional studies predict a significant increase in surface MHWs in the Mediterranean basin [19, 27], a quantitative assessment of the future evolution of subsurface MHWs characteristics is currently missing.

The growing body of evidence on the impacts of MHWs upon the integrity and functionality of marine ecosystems highlights the need to better understand their spatiotemporal evolution in the coming decades. Previous studies have examined the properties of extreme oceanic thermal events and have consistently found that MHWs are becoming more frequent and intense, with projections suggesting a near-permanent state of MHWs by the end of the century [9]. However, these studies have defined thermal extremes relative to ocean temperatures over a fixed historical period, which captures a warming trend in the ocean rather than a change in the frequency and intensity of MHWs [28].

In this study, we addressed the shortcomings of previous research on MHWs and developed a methodology to identify MHWs and explore the depth penetration and future evolution of their properties across the Mediterranean basin. We applied a moving threshold to isolate the effect of the background warming trend and identify MHWs based on periods of abnormally higher temperatures relative to a shifting baseline period. Using daily projected subsurface temperature data from 2006 to 2100, based on an ultra-high-resolution ocean circulation model, we projected future MHW events across the Mediterranean basin over the period 2036–2100. The threshold for each year was calculated based on the climatology of the 30-year period preceding that year. The first 30 years of the model projections (2006–2035) were thus used as the first baseline period. We then compared mid-century (2036–2066) to end-of-century (2070–2100) MHW properties to detect changes in MHWs. We further explored the projected properties of MHWs over 36 depth layers expanding from the surface to 2000 m deep. We consider annual mean MHW intensity (Imean) and annual MHW duration, as proxies of acute and chronic heat stress for marine ecosystems, and identified two distinct bathymetric zones based on the statistical properties of the two metrics. The first zone expands down to 40m depth while the second deeper zone reached 2000m which experiences statistically different MHWs compared to the surface. We used these two generic depth zones to summarize MHWs properties through time and space and presented our results regarding shallow and deeper events based on the ocean bathymetric zones [29, 30]. Understanding the spatiotemporal patterns of MHWs over the three-dimensional marine environment is crucial to preserve the integrity and functionality of marine ecosystems. Our approach provides a more accurate and comprehensive assessment of future MHW characteristics.

Results

Surface and shallow MHWs characteristics

Our findings revealed that MHW properties were qualitatively similar within the first 11 depth layers from the surface, specifically those above 40 m. Both annual MHW duration and mean intensity showed no statistically significant difference between the surface and each of the individual depth layers up to 40 m (Supplementary Table 1). The strong correlation between surface and upper-depth temperature anomalies is likely to reflect a surface origin for shallow MHWs. From 2036 to 2100, the Mediterranean Sea was projected to experience shallow MHWs with an overall average duration of 52 days per year (Figure 1a), and with a mean intensity (Imean) of 1.5°C (Figure 1b). We also projected a 15-day increase in the annual duration of shallow MHW events from the mid-century period (2036-2066) to the end-of-century period (2070-2100) (Fig 2b). These findings contradict previous studies that relied on fixed thresholds, generated under either historical or future baseline periods, projecting two opposite end-of-century scenarios of either a permanent MHW state (a full year of MHW days) [9] or only minor increases in annual MHW duration and intensity [31]. Yet, both of these opposite scenarios include substantial biases. In the first case, projections based on historical thresholds might simply reflect the likelihood of future temperatures exceeding present fixed thresholds, rather than accurately indicating the existence of extreme fluctuations in ocean temperatures [28]. In the second, applying a fixed threshold calculated based on future baseline periods underestimates the potential impact of the ocean's dynamic warming trend on temperature variability and consequently on the intensification of extreme thermal events [32].

Our projections for the Mediterranean basin, based on temporally moving thresholds, indicated an average of 2.9 events per year, with a mean duration of 19 days, and a mean intensity of 1.5°C (Fig. 1b). Coastal regions displayed the most pronounced projected Imean of around 2.5 °C (Fig. 3a). The mean projected annual MHW duration ranged between 40 and 60 days in most areas, except for coastal regions where a reduced MHW period was detected (Fig. 2a). Previous studies suggested that surface MHWs tend to have a predominantly coastal distribution and significantly more ecological impacts near the coasts [23, 33]. Our findings indicate that climate change will indeed lead to an intensification of shallow MHW events and suggest that coastal areas in particular will probably experience acute heat stress in the future due to increased MHW intensity but for shorter periods compared to the rest of the Mediterranean basin.

Contrasting deep subsurface MHW properties

Typically, MHW properties were previously investigated along the coast, usually only up to 50 m or rarely up to 160 m deep, and were believed to be confined to shallow or relatively shallow waters [19,34]. However, our findings underscore the occurrence of MHWs in deeper waters, which is consistent with the depth profiles of temperature anomalies observed during past MHW events in other regions around the globe [15,16].

As MHWs propagate deeper into the water column, we encounter fewer extreme events of decreased intensity but increased duration. In the lower epipelagic zone (40-200m), the estimated average annual MHW duration was 119 days (Fig 2c), with an average of 3.15 events per year and a mean duration of 39.4 days per event. In the mesopelagic zone (200-1000m), the mean annual duration reached 265 days (Fig 2e), with 2.18 events per year and a mean duration of 131.3 days per event. Finally in the bathypelagic zone (below 1000 m), a maximum of 333 MHW days per year was reached (Fig. 2g), with projections predicting 0.9 events per year and an average duration exceeding a calendar year. Contrarily, the mean projected MHW intensity demonstrated a decreasing pattern from 0.94°C in the lower epipelagic (Fig 3c) to 0.5°C in the mesopelagic and 0.41°C in the bathypelagic zone (Fig 3e, g).

The observed decreased intensity over depth might be reversed in the future, setting deep-sea ecosystems in increasing danger. Indeed, we projected an increase in MHWs annual duration and intensity over depth and over time, from mid-century to the end-of-century periods (Fig 2b, d, f, h). Our projections revealed an increase of +27.5 days and +0.1°C (annual duration and mean intensity respectively) for the lower epipelagic zone (Fig 2d & 3d), to +41.5 days and +0.22°C for the mesopelagic (Fig 2f & 3f) and finally up to +45 days and +0.3°C for the bathypelagic zone (Fig 2h & 3h). These temperature anomalies in deeper waters are typically associated with a deepening of thermoclines and vertical flows in the presence of thermal stratification related to upwelling and downwelling processes [20].

The deep oceanic layers are disconnected from air-sea exchanges, due to the low-frequency variability and weak mixing [19], allowing for the long-term preservation of heat content [35]. Even when warmer surface temperature anomalies gradually mix downward, reaching significant depths, they can persist long after the surface MHW disappears, suggesting that the ocean can retain memory of long-lived MHWs [36]. The persistence of subsurface MHWs has potential implications for long-lasting ecological impacts. These include potential shifts in the distribution of fish species and marine megafauna [5,37,38]. Altered distribution and behaviour of marine life have also been documented, due to fluctuations of prey abundance following MHWs, and heat damage to benthic species such as corals and seagrasses [18, 26, 39].

The eastern part of the Mediterranean (Fig. 3c) was projected to exhibit a local intensification of MHWs of approximately 1.5–2 °C in the lower epipelagic zone, which was consistent with higher ocean temperatures compared to the western Mediterranean [40,41]. The highest projected Imean at this depth was 2.5–3 °C and emerged in the Adriatic Basin and the coasts of Tunisia. The trend of higher MHW intensity in the eastern Mediterranean was also evident in deeper waters, with the highest Imean (∼1–1.2 °C) observed in the mesopelagic zone of the Aegean Sea (Fig. 3e). Bathypelagic MHW events were projected to experience the lowest MHW intensity, with a smaller variation in Imean among different areas of the Mediterranean basin, except for some parts of the Aegean, where Imean reached ∼1 °C, compared to a variation of 0.3°C to 0.6°C for the rest of the basin (Fig. 3g). Especially in some areas around the Tyrrhenian Sea and the east Mediterranean, the annual MHW duration is expected to increase by approximately 100 days from the mid-century to the end-of-century period, subjecting the ecosystems of those areas to chronic heat stress (Fig. 2f, h). Despite our findings underscoring possible impacts for the eastern Mediterranean, considerable focus should also be given to the western Mediterranean Sea which exhibits the longest MHW events in the mesopelagic and bathypelagic zones (Fig. 2e, g), which could lead to adverse ecological changes since the region is currently subjected to low and moderate extreme events [13, 42].

Overall, although MHW properties significantly varied with depth in the Mediterranean basin, these extreme events were projected to become more intense and persistent in the future, occurring consistently throughout the year. Particularly, ecosystems below 1000m are expected to experience almost year-round MHW events. Our findings indicate that the effects of climate change on MHW attributes are certainly not limited only to coastal and/or near surface areas and that the existence, duration and intensity of deep subsurface MHWs may represent a significant disruptive factor for marine ecosystems across the bathymetric zones.

Discussion

While the accumulation of the underlying ocean warming is forcing temperature extremes to become more frequent and more intense [43], the severity of such events has largely been assessed on the ocean surface, neglecting heating across ocean depths. To address this gap, we used three-dimensional temperature data to project the depth structure of future MHWs in the Mediterranean basin. Our findings challenge previous understanding regarding the depth at which MHWs can occur in the region and suggest that MHWs may extend up to 2000m in the Mediterranean Sea. We found that subsurface MHWs are expected to last longer than surface MHWs and have temperature anomalies, that although smaller than those projected for the surface, are expected to become critically increased by the end of the century given the low temporal variability of these deep-sea habitats [44]. The disparity between surface and subsurface MHW properties suggests that different drivers could act on different depths causing these extreme events.

Surface MHWs in the Mediterranean Sea have been associated with atmospheric anomalies that passively elevate SST well above their normal range [19]. Atmospheric high-pressure systems cause warm air temperature anomalies, and reduced wind speeds, which coupled with increased thermal stratification, often result in rapid warming of the upper ocean [20]. On the contrary, deep MHWs are not related to surface conditions [17]. They have been associated with water-mass anomalies, shifts in warm ocean currents, mesoscale eddy activity, and vertical temperature advection, resulting from vertical flows, often related to upwelling and downwelling processes [11, 17, 45]. This study highlights that the projected characteristics of MHWs based on SST are only limited to interpreting shallow MHWs, being insufficient as a prognostic tool for anomalous warming deeper in the water column.

The increase in frequency and intensity of MHWs is driving major ecological changes in marine ecosystems worldwide [1, 2]. Our results clearly indicate that the Mediterranean Sea will experience an acceleration of extreme MHW events in both vertical and horizontal extents. Under future climate scenarios, it has been implied that most MHWs will emerge due to anthropogenic warming [32]. Natural variability in the climate system will still contribute as one of the major causes of MHW events, but global warming will substantially increase the odds of an MHW occurring [8]. Although most studies that describe how MHWs will be affected by climate have defined these events relative to historical ocean temperatures, significantly reflecting the warming trend of the ocean in their results [28], our findings highlight a great increase in the intensity and persistence of MHWs in the entire water column, even when isolating the mean ocean warming trend.

We anticipate that MHWs will emerge as major disruptors of marine ecosystems in the future. A deeper understanding of subsurface MHWs is critical to the advancement of marine science and the resolution of socioeconomic challenges. In future studies, it is necessary to quantitatively investigate the physical processes and climate drivers of subsurface MHWs and their links to the surface and develop reliable forecasting techniques. Anticipating regions that might be affected by longer-term MHWs intensification can guide management actions necessary to prevent irreversible impacts on oceanic ecosystems.

Declarations

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Author contributions

A.D.M. and K.K. conceived the ideas and designed the methodology. K.K. led the analysis and coding. A.D. and S.K contributed to statistical analyses and the assessment of produced outputs. All authors contributed critically to the drafts and gave final approval for publication.

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Methods

Temperature data

Consistently identifying and characterizing MHWs requires daily temperature data [11] over a sufficiently long period to estimate climatology, ideally a minimum of 30 years [46]. However, until recently, suitable oceanic projections for detailed three-dimensional future MHW assessments in the Mediterranean Sea were lacking, with most previous ensemble initiatives providing only monthly seawater temperatures.

For the present analysis, daily three-dimensional seawater temperature projections were obtained from simulations of the coupled POLCOMS-ERSEM system, retrieved from the Copernicus Climate Change Service. The regional ocean circulation model POLCOMS (the Proudman Oceanographic Laboratory Coastal Ocean Modelling System) tracks water movement and the transfer of energy and momentum in three dimensions, enabling accurate modeling of water temperature [47, 48]. The obtained data cover 94 years, from 2006 to 2100, and represent the future changes in the Mediterranean Sea under the RCP8.5 IPCC scenario. The model has a horizontal resolution of 0.1° (approximately 11 km) and a vertical extent of 43 depth levels, ranging from 0 to 5500 m below sea level. For the current analysis, 36 of the 43 depth layers were used, reaching 2000 m below sea level, to examine extreme events affecting the majority of marine ecosystems which are confined above that depth. Although using a single model-based dataset ignores model-selection uncertainty [49], our findings provide valuable insights for accurately predicting surface and subsurface MHWs. However, multimodel ensemble approaches are further needed to allow us to identify the envelope of potential changes in future MHWs over depth.

Defining MHWs and their properties

A marine heatwave (MHW) is a “prolonged, anomalously warm water event at a particular location” [50]. It is identified by exceeding a local daily upper-percentile climatology threshold, typically calculated over a 30-year baseline [46]. The threshold for defining MHWs may vary, from strict thresholds, such as the 99th percentile, which only captures the most intense MHWs [9], to more relaxed thresholds, such as the commonly used 90th-percentile, which is relatively easy to exceed and results in the identification of weaker and short-lived events [51]. In this study, we employed a 95th percentile threshold to accurately project heatwaves in the future while excluding small and short-lived events.

In contrast to previous studies, we used a moving 30-year baseline period to calculate temperature climatology and anomaly time series. For every grid point and depth level, we computed the 95th quantile of daily ocean temperature based on the climatology of the 30-year period preceding each day, constructing a 3D threshold map. The first 30 years (2006-2035) of the simulations of the ocean circulation model were solely used as the first baseline period for calculating the climatology for 2036; MHW metrics were not calculated for that period.

To define MHW events at each grid cell, we identified days where the local 95th percentile threshold was exceeded. An event was considered to occur when daily temperatures exceeded the seasonally varying threshold for at least five consecutive days. Consecutive events with a break of fewer than 3 days were considered a single event [50]. To calculate the climatological mean and threshold, we used daily ocean temperatures within an 11-day window centered on the calendar day of interest across all years within the climatology period [50]. The resulting climatology and threshold were smoothed by applying a 31-day moving average [50].

MHW metrics were used to characterize the identified events, focusing on two globally projected response metrics: annual MHW duration and annual mean MHW intensity. Annual MHW duration refers to the annual count of MHW days exceeding the temporal threshold for more than five consecutive days. The annual mean MHW intensity (Imean) represents the annual spatiotemporal mean temperature anomaly reached, calculated relative to the threshold over the event duration experienced yearly. Maximum MHW intensity (Imax), representing the annual spatiotemporal maximum temperature anomaly was also calculated and gave similar to Imean results (for Imax results see Supplementary material) These metrics represent the time spent in a MHW state and the magnitude of the temperature anomaly, respectively [50]. The temporal changes of these metrics were analysed over the mid-century (2036-2066) and end-of-century (2070-2100) time period. Temporal changes over the entire period (2036-2100) were also calculated (for results see Supplementary material).

Identifying distinct zones

Based on the aforementioned metrics, we identified two distinct zones that exhibited similar patterns and examined their properties through time and space. The first zone extended from the surface down to a depth of 40 m and represented shallow MHW events, while the second zone extended down to a depth of 2000m and represented deeper subsurface extreme events. For each individual depth layer, we computed the non-parametric Mann-Whitney U test to investigate whether depth-specific MHWs are independent of the surface events based on the two metrics, annual MHW duration and mean intensity. A p-value greater than 0.05 MHWs indicates no statistical difference to the surface events and therefore events at those depths were categorized as shallow events of likely surface origin. Depths with uncorrelated events to the surface (p-value< 0.05) were classified as deep subsurface MHW events. Subsurface MHW events were presented based on the ocean's biogeographical zones: Epipelagic- down to 200 m depth, Mesopelagic- 200 to 1000 m, and Bathypelagic- deeper than 1000 m [29,30].

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Figures

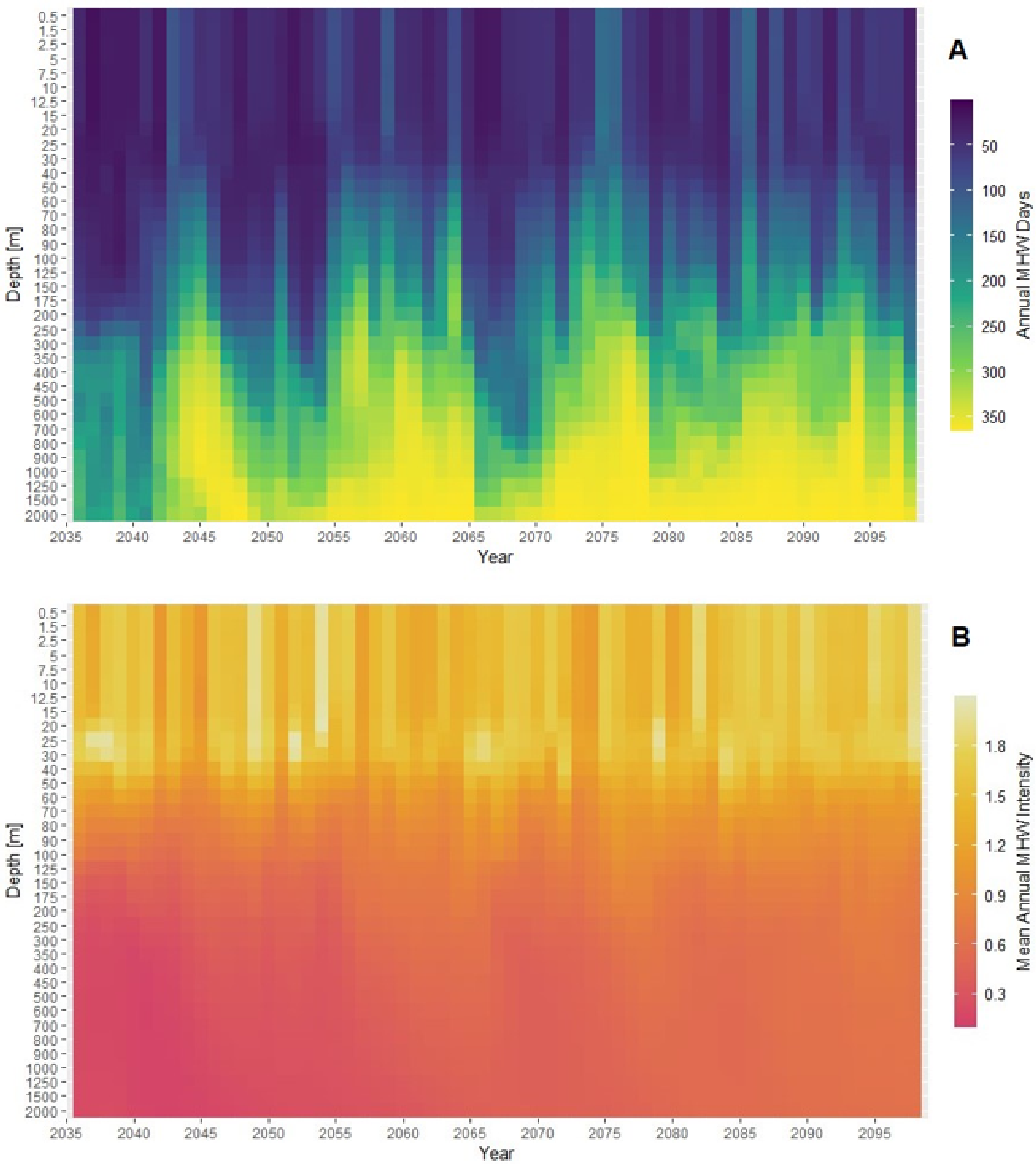

Figure 1

Simulated future MHW properties. Heatmaps indicating the temporal and vertical evolution of the projected response metrics: (**A**) annual MHW days, (**B**) mean annual MHW intensity (Imean),

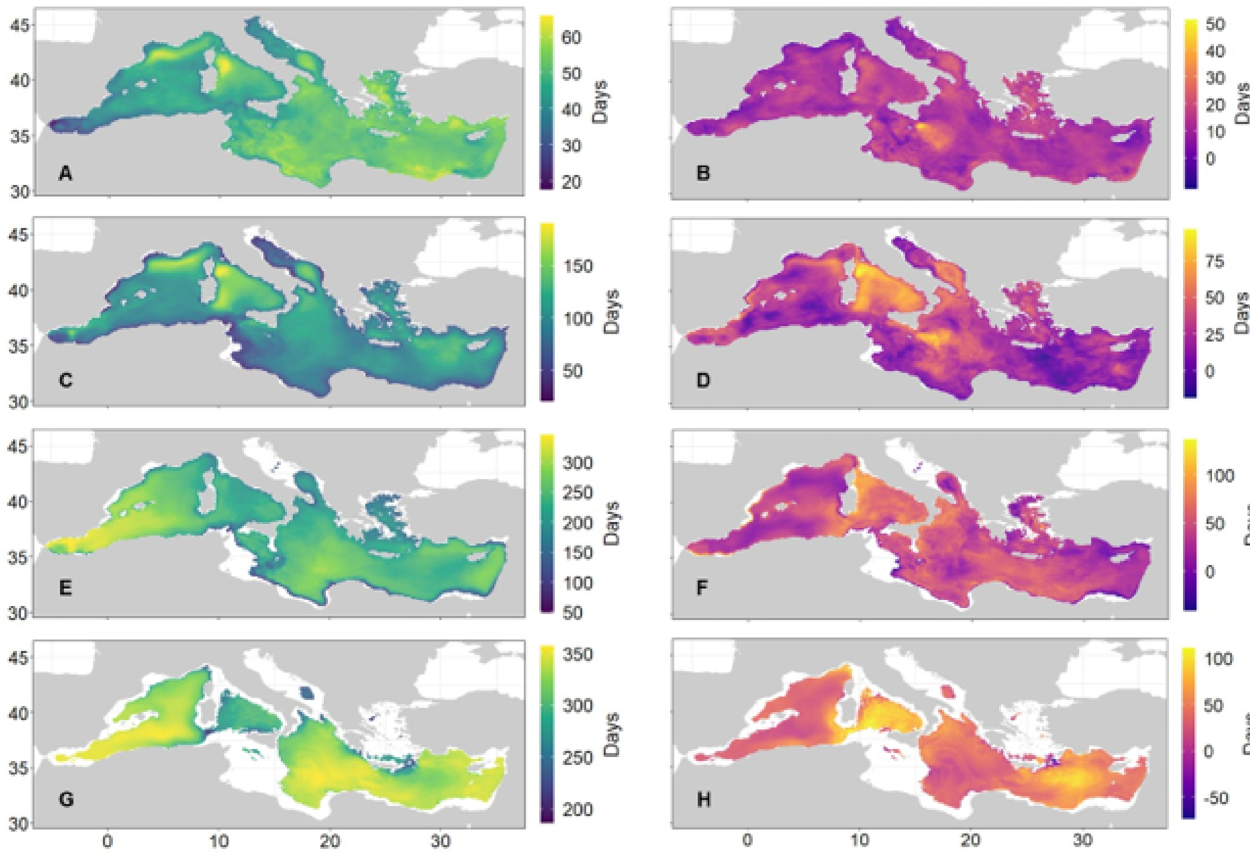

Figure 2

Patterns of annual projected MHW days across different depths in the Mediterranean Sea. Maps indicating means (left panels:A, C, E, G, in days) and difference of the means (right panels: B, D, F, H, in days) of the periods mid-century (2036-2066) and end-of-century (2070-2100) of annual MHW days at different depth zones: Shallow MHWs 0-40m (A, B), Lower Epipelagic MHWs 40-200 m (C, D), Mesopelagic MHWs 200-1000 m (E, F), and Bathypelagic MHWs 1000-2000m (G, H).

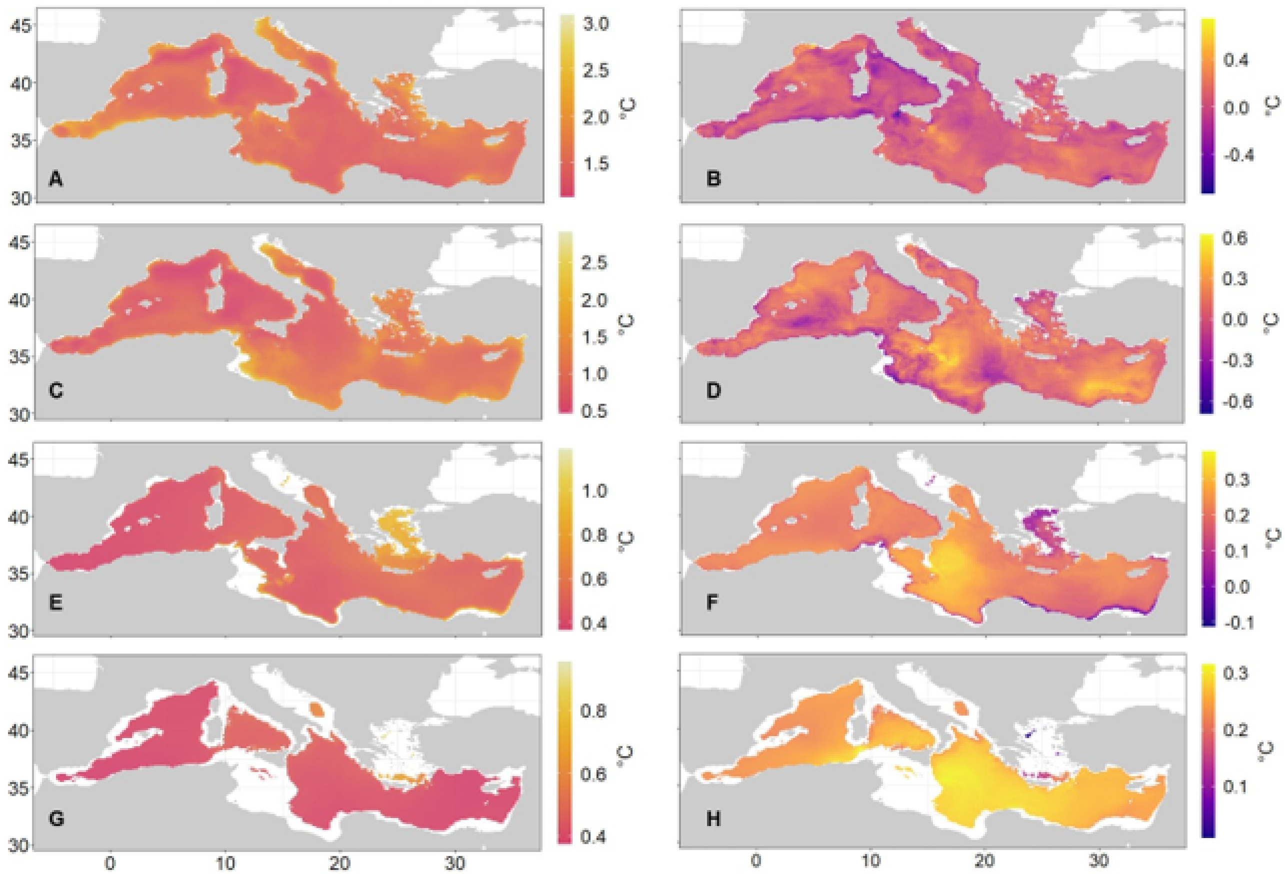

Figure 3

Patterns of annual projected mean MHW intensity (Imean) across different depths in the Mediterranean Sea. Maps indicating means (left panels: A, C, E, G, in °C) and difference of the means (right panels: B, D, F, H, in °C) of the periods mid-century (2036-2066) and end-of-century (2070-2100) of annual MHW intensity (Imean) at different depth zones: Shallow MHWs 0-40m (A, B), Lower Epipelagic MHWs 40-200 m (C, D), Mesopelagic MHWs 200-1000 m (E, F), and Bathypelagic MHWs 1000-2000m (G, H).

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Supplementarymaterial210623.pdf
- Supplementaryvideo1.mp4