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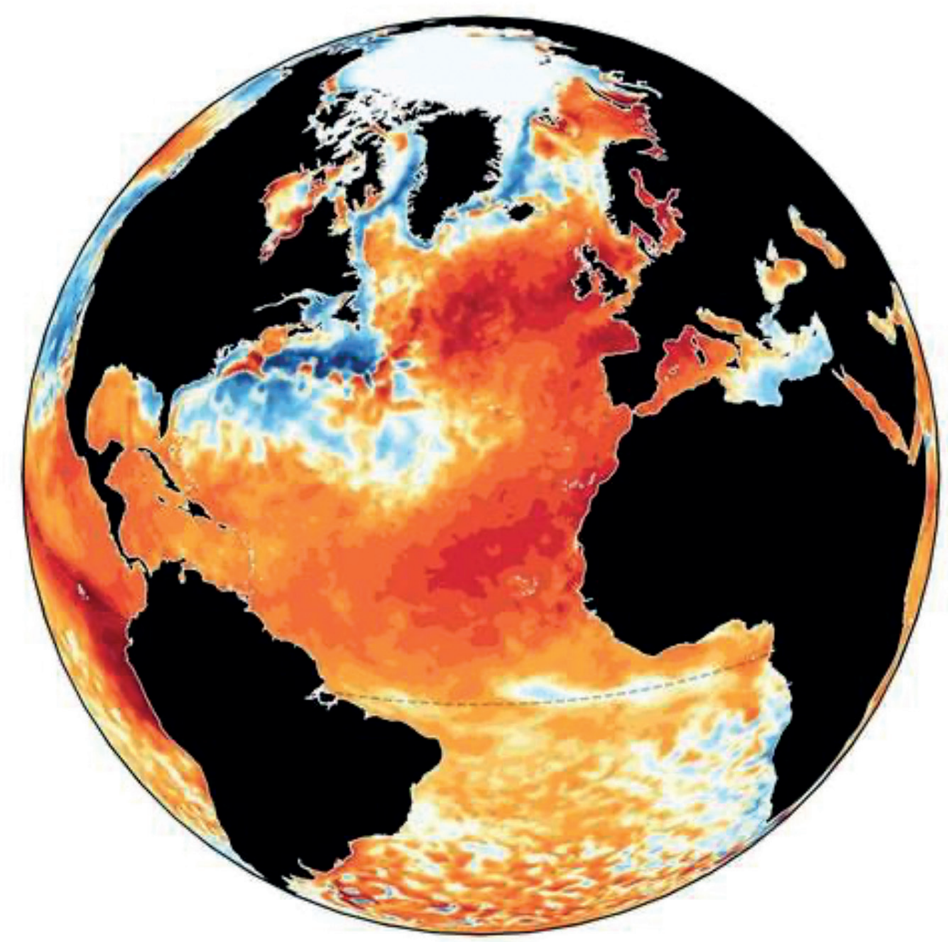
Marine heatwaves in the Mediterranean Sea and beyond

Paris (France)
27 - 30 November 2023



The Mediterranean Science Commission

Cover illustration: Mean Sea Surface Temperature anomalies for June 2023 relative to the June baseline averaged over 30 years (1991-2020).

[Copernicus ERAS data. Credit: C35/ECMWF]

C I E S M W o r k s h o p M o n o g r a p h s

Marine heatwaves in the Mediterranean sea and beyond

Paris, France, 27 – 30 November 2023

CIESM Workshop Monographs ◊ 51.

This collection offers a broad range of titles in the marine sciences, with a particular focus on emerging issues. CIESM Monographs do not aim to present state-of-the-art reviews; they reflect the latest thinking of researchers gathered at CIESM invitation to assess existing knowledge, confront their hypotheses and perspectives, and to identify the most interesting paths for future action.

A collection founded and edited by Frédéric Briand.

CONTENTS

Biological responses

MARINE HEATWAVES IN THE MEDITERRANEAN SEA AND BEYOND – AN OVERVIEW [(1)]

[(1)] To be cited as: Schroeder K., Azzurro E., Briand F., Rilov G., Simon A., Garrabou J., Juza M., Androulidakis Y., Ličer M., Schlegel R., Chartosia N., Besiktepe S., B. Mohamed., Liguori G. and Ghanem R. 2024. Marine heatwaves in the Mediterranean Sea and beyond – An overview. pp 5 – 24 *In* CIESM Monograph 51 [F. Briand, ed.] CIESM Publisher, Paris, Monaco, 174 p.

This synthetic overview, first outlined during the course of an immersive CIESM Workshop (Paris, Oceanographic Institute, 27-30 November 2023), was developed in the months thereafter on the basis of written contributions provided by the participants under the coordination of Katrin Schroeder and Ernesto Azzurro, chairs respectively of CIESM committees on Physics & Climate of the Ocean, and Living Resources & Marine Ecosystems. Frédéric Briand, editor of the CIESM Monographs Series, reviewed the entire manuscript, with particular attention to this introductory chapter. The authors are grateful to Annelyse Gastaldi who was responsible for the physical, timely production of the volume at CIESM headquarters.

1. BACKGROUND

Marine heatwaves (MHWs) are prolonged periods of anomalously warm water temperatures in oceanic environments. They are typically defined as events where temperatures exceed the local 90th percentile for at least five consecutive days (Hobday *et al*. 2016). They form a rapidly developing area of research, reflecting the fact that in the past two decades many ocean areas – and notably the Mediterranean Sea – have experienced peaks of temperatures, along with more frequent, more intense, more prolonged MHWs than ever met on record. The years 2022 and 2023 were exceptional in that regard (see *Juza *et al.* 2024), quite possibly an indication of things to come in a not-distant future.

In the Mediterranean basin, MHWs have garnered growing attention due to the increase in their frequency, intensity, duration, and wide-ranging impacts. Concerned by the emergence of this phenomenon, the Mediterranean Science Commission invited to Paris in November 2023 a number of experts, with backgrounds anchored in physical oceanography and biology, to review the latest data and trends, and discuss over the course of a CIESM exploratory workshop the drivers, nature, extent, trends, geographic location, and various impacts of such extreme episodes on a semi-enclosed sea already much impacted by the assaults of humans.

* *the asterisk refers to a distinct chapter in this Monograph*

Ocean temperature levels are controlled by several environmental factors, such as atmospheric conditions (e.g. heat fluxes, precipitation/evaporation rates and winds), lateral fluxes (e.g. river discharges and exchanges with marginal seas through straits), circulation conditions (e.g. currents, vertical advection processes, mesoscale eddies and gyres), and topographic characteristics. By nature, as it is relatively isolated and constricted in its water mass exchanges through the Strait of Gibraltar (with the Atlantic Ocean) and the Dardanelles (with the Black Sea), the Mediterranean Sea will tend to amplify the effects of MHWs, making them more pronounced compared to the global ocean (Garrabou *et al*. 2022).

Extreme climatic events like MHWs are likely to cause greater impacts on natural ecosystems than the progressive temperature increase induced by global warming. MHWs will adversely affect many key components of marine life (see review by Smith *et al*. 2023), from benthic producers to pelagic fish that are key components of marine biodiversity, together with other economic sectors such as tourism that will be significantly impacted as well. Certain individual events have caused massive financial losses to regional industries. On a global scale, it is estimated that the yearly economic losses due to MHWs are already over US$800 million, but may well exceed US$3.1 billion in indirect losses of ecosystem services (Smith *et al*. 2021).

Additionally, through compound events, MHWs can negatively impact freshwater water availability by affecting evaporation rates and altering rainfall patterns (Wang *et al*. 2023). This is an issue of much importance in the Mediterranean due to the Basin's negative freshwater balance where evaporation losses strongly exceed rainfall and runoff freshwater influx - an imbalance which is mostly compensated by the surface inflow of Atlantic water masses through the Strait of Gibraltar. Furthermore, MHWs contribute to increased ocean stratification when warmer surface temperatures create a deepening and sharpening of the pycnocline, limiting vertical nutrient fluxes from deeper layers to the surface, impacting primary productivity and overall ecosystem health. Increased stratification can simultaneously lead to inhibited oxygen flux from the surface into the deep ocean, leading to hypoxic conditions (low oxygen levels) in deeper waters, increasing the stress on marine organisms. These hypoxic zones can have cascading effects on marine biodiversity and fisheries, impacting the entire marine food web.

2. DEFINITIONS OF MHWs AND METHODOLOGICAL IMPLICATIONS

In the last few years MHWs have gained fast public recognition and media coverage, spurred on by the mounting occurrence, duration, and severity of these episodes. While the impacts of MHWs are becoming increasingly known, the challenges these events represent to the present and future inhabitants of coastal regions are daunting. But what actually defines a MHW?

The general consensus in the scientific community is that a MHW is an event that occurs over a discrete space and time, with a clear start and end, during which temperatures are dramatically elevated above the normal values for that area. The main difficulties with this broad definition emerge when one must quantify what the normal temperature state is, and what the discrete spatial extent of the event may or must be.

It is perhaps for such reasons, although there were notable extreme temperature events previously (e.g. in 1999 and 2003 in the Mediterranean), that the research into MHWs had to wait until the mid 2010s to start to develop. A turning point was arguably the publication of the MHW detection algorithm by Hobday and his collaborators (2016), who followed soon with a qualitative definition (Hobday *et al*. 2018).

The algorithm aimed to codify a single numeric definition of MHWs that could be used with temperature data acquired anywhere in the world so as to produce results that could be compared across the different studies. This was accomplished by using percentile values for temperatures which would define the seasonally-varying climatology and the threshold above which one could say an event was occurring. This threshold was set as the 90^{th} percentile of the temperatures for a given day-of-year (after two moving average smoothing passes), and the minimum duration was set at five days. Gaps between events of two days or less are treated as a continuous event. To facilitate the implementation of this relatively simple numerical approach, modules for python and later R were quickly developed and made freely available by the same team at Dalhousie University (see Oliver 2016).

The advantages were many: to gain entrance into this methodology, no longer was it required to possess an in-depth knowledge of physical oceanography or air-sea interactions plus the ability to code in one of the more foundational computational languages (e.g., C or Fortran). Yet the ensuing deluge of research precipitated by these toolboxes has not been without creating difficulties: nowadays much research is being published in extremely incremental steps, with many studies replicating global analyses for small scale local regions, without utilising higher resolution data or pursuing novel interpretations of the results.

From a higher-level perspective, the choice of using a statistical definition of MHWs has opened new challenges. Since it is necessary to define a baseline climatological period in order to create the threshold value for detecting events, the rapid, accelerated rate of global warming (and hence higher SST) now renders the choice of the baseline particularly sensitive, with significant impacts on MHWs detection. Clearly an older baseline (e.g. 1970-2000) will generally be much cooler than a more recent one (e.g. 1990-2020). Therefore, present-day MHWs detected with an older baseline will generally appear to be longer and more intense (i.e. greater temperature anomaly) than those detected with a modern baseline. One solution to this issue is to remove the climate warming trend from a time series before defining the baseline, but this is problematic because these detrended temperatures no longer represent the thermal environment that is affecting the local flora and fauna.

Another problem created by the numerical approach of Hobday *et al*. (2016) is that it does not naturally lend itself to a spatial definition of MHWs. Although the discrete spatial extent is part of the written definition of these events, numerically it is not accounted for. The reader interested in the limitations and implications of MHW methodologies and their definitions will find useful discussions in various chapters of this volume.

For instance, while there have been some approaches to define events spatially (see *Simon, 2024), it is not clear whether extreme temperature events in the ocean have limits on their spatial extent (*Liguori 2024), if their frequencies should be determined along a fixed or moving baseline (*Ličer 2024) so as to avoid reaching a point where they will be never ending (*Schlegel 2024).

Related issues are attracting an increasing number of specialised articles (see for instance Frölicher *et al*. 2018; Oliver 2019; Schlegel *et al*. 2019), covering a broader range of variables (Sen Gupta *et al*. 2020), with recent attention paid to the occurrence of bottom marine heatwaves and their correlation or not with surface heatwaves (Amaya *et al*. 2023).

3. GENESIS OF MHWs IN THE MEDITERRANEAN SEA

3.1. Atmospheric drivers of MHWs

The genesis of MHWs is mainly influenced by a combination of oceanic and atmospheric factors, with air-sea heat flux and oceanic drivers playing crucial roles (Sen Gupta *et al*. 2020; Schlegel *et al*. 2021). Most studies emphasise the role of atmospheric circulation patterns in triggering MHW development, particularly high-pressure systems that will reduce cloud cover and increase solar radiation absorption by the sea surface. Further, as high-pressure systems are often associated with reduced wind speed, this will lead to reduced cooling of the ocean through heat flux and ocean vertical mixing (Oliver *et al*. 2021). Large-scale modes of atmospheric variability such as ENSO events can also influence SST and favour the initiation of MHWs (Holbrook *et al.* 2020). Therefore, local air–sea interactions and large-scale atmospheric circulation, in isolation or collectively, can enhance MHW development. Indeed such atmospheric-driven MHWs have been reported repeatedly in the Mediterranean Sea (Marin *et al.* 2022), including persistent high-pressure systems in summer 2003, 2019 and 2022 (Sparnocchia *et al*. 2006, Olita *et al*. 2007; Hamdeno and Alvera-Azcara 2023; Simon *et al*. 2023; Martinez *et al*. 2023).

Human-induced climate change is bound to play a growing role in the genesis of MHWs. As climate warming progresses, the frequency, intensity and duration of MHWs are expected to increase in the Mediterranean. While the oceans naturally undergo fluctuations in temperature due to such factors as ocean-atmosphere interactions, upwelling and downwelling processes, internal climate variability, which will contribute to the occurrence of MHWs on shorter time scales, one may expect complex interactions in the future between natural and human-induced factors leading to the formation and persistence of MHWs in the Mediterranean.

3.2. Oceanographic drivers of MHWs

Favourable ocean dynamic conditions and processes also contribute to the formation of MHWs. The strong stratification of the water column, controlling upper-ocean stability, is a decisive factor for near-surface MHW occurrence (Lee *et al.* 2023). Hence shallower mixed layer depths during summer periods significantly impact SST anomalies and contribute to the frequency and magnitude of MHWs (Alexander *et al*. 2000). In conditions dominated by weak winds, reduced evaporative cooling and low wind-driven upper-ocean mixing can occur, particularly with shallow mixed layers.

This, in combination with strong downward surface heat fluxes, traps heat in the thinner surface layer, triggering intensified surface warming (Benthuysen *et al*. 2018; Huang *et al*. 2024). In the Mediterranean Sea, the most intense near-surface MHWs predominantly occur in summer and autumn when the water column is most stratified, again implying a major role of air-sea fluxes (Juza *et al*. 2022). Furthermore, shallow mixed layers associated with low haline levels (e.g., riverine brackish plumes and lateral fluxes from marginal seas) can form surface barrier layers, more exposed to MHW formation under favourable atmospheric conditions (Androulidakis and Krestenitis 2022). Warm core eddies over continental shelves, combined with trapping processes, are additional contributors to MHWs (Gawarkiewicz *et al*. 2019). The variability of deeper MHWs (e.g., near-bottom) in coastal areas is controlled by the formation of coastally trapped waves that may depress the thermocline along the shelf, moving warmer waters from the surface towards the near-shore ocean floor (Amaya *et al.* 2023). Near-bottom and near-surface MHWs are therefore more synchronous in shallow coastal regions, where the mixed layer is more likely to extend to the ocean floor.

Oceanic drivers will also form conditions that facilitate abrupt sea temperature increases and favour the formation of MHWs episodes. Thus the Mediterranean Sea is influenced by various ocean currents, including the Atlantic Jet, which transports warm and relatively less salty water from the Atlantic Ocean into the Mediterranean. When this warm water encounters regions of reduced vertical mixing, such as in the summer months, it can lead to the formation of positive temperature anomalies and the initiation of MHWs.

4. REGIONAL PATTERNS IN THE MEDITERRANEAN

4.1. Geographic patterns

The expression of MHWs main features differs among Mediterranean regions as well as seasons, except for event frequency which remains between 1.5 - 2 per season in most sectors of the Mediterranean (Figure 1). The most intense events occur in the summer and autumn in the northern Mediterranean, while the longest events happen in these seasons in the eastern Mediterranean. The longest events in the winter are observed mostly in the western and central Mediterranean.

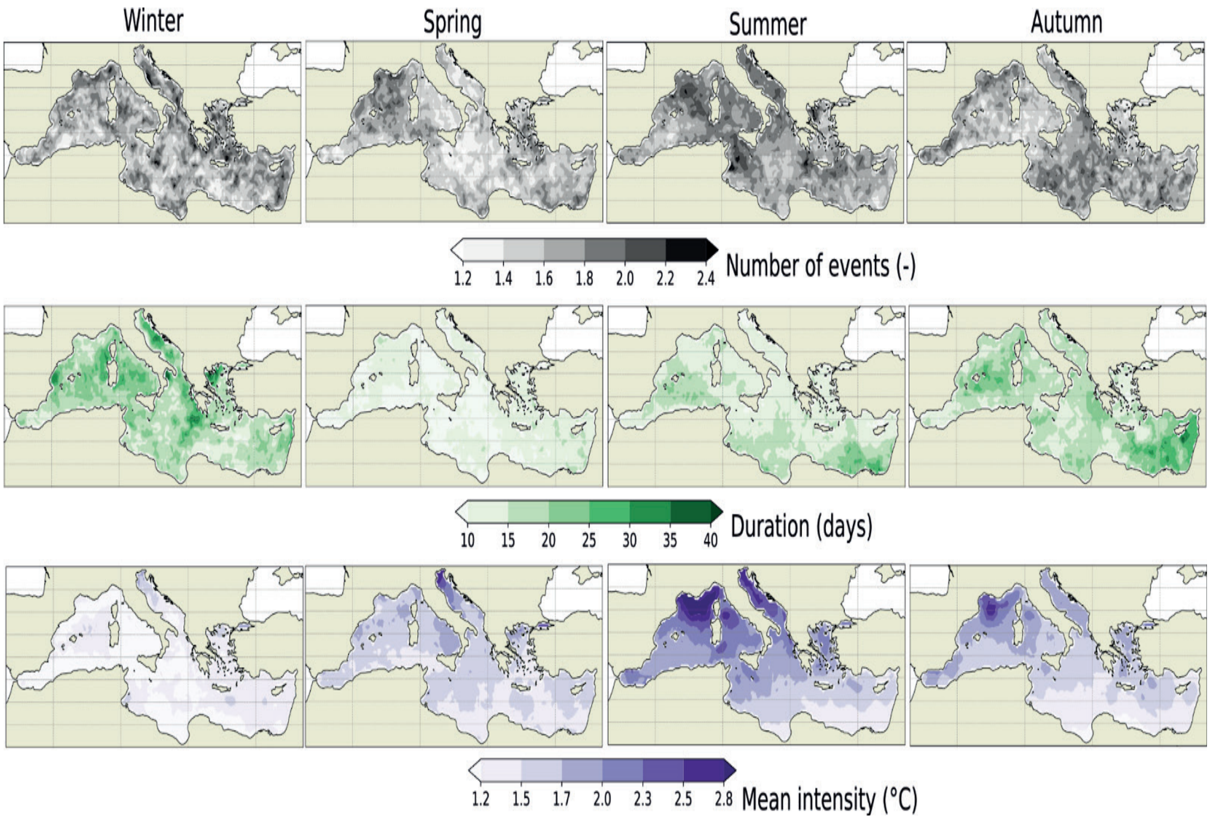


Figure 1. Number of events (top row), average duration (middle row; in days) and average mean intensity (bottom row; °C) for all detected MHWs in the four seasons within the period 1982-2023 in the Mediterranean. The MHW detection follows the definition of Hobday *et al.* (2016) and uses the period 1982-2014 as the climatological baseline. The SST satellite product is derived from NOAA OISST v2.1 (Reynolds *et al.* 2007; Huang *et al.* 2020).

4.2. Trends in temporal MHW variability

The increase in Mediterranean MHWs can be due to a shift of the distribution of the mean SST toward warmer states (positive trend of the mean SST; Fig. 2a) or a widening of the probability density function of the SST (a positive trend in the SST variance or other higher order moments, like skewness and kurtosis; Fig. 2a, b). In the Mediterranean, analysis suggests that long-term warming is the main driver for the increase of MHW occurrences (Oliver *et al*. 2021; Xu *et al.* 2022; Martinez *et al*. 2023), albeit change in SST variability also contributes in some regions. Figure 2a illustrates the influences of long-term warming and the interannual variability of SST on the trend of MHW activity. While long-term warming (or mean SST) contributes to the increase of MHW across the whole basin in a quasi-similar way, temperature variability contributes in the western basin and the Adriatic Sea (Simon *et al*. 2023).

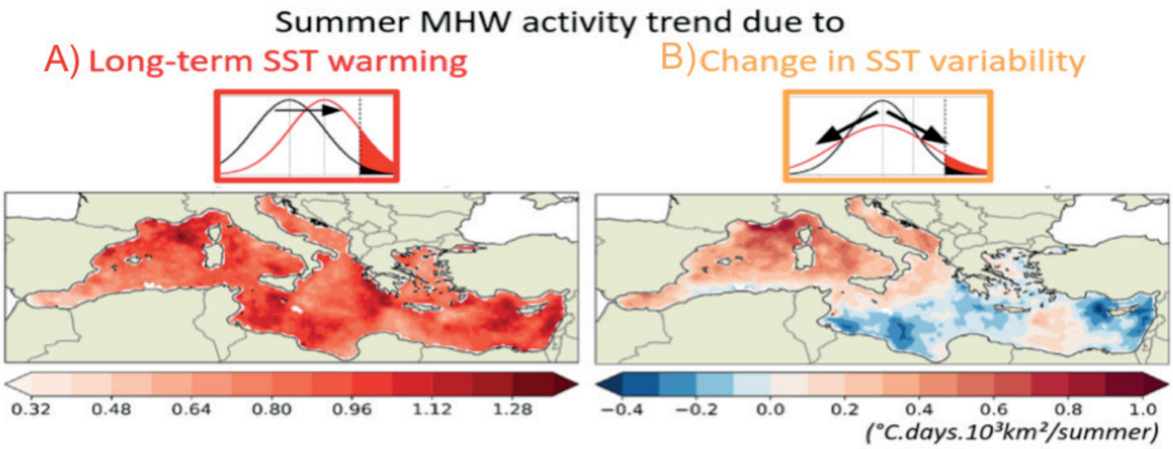


Figure 2. Summer MHW activity trend (°C.days.10^3km²/summer) due to long-term SST warming (left) and change in SST variability (right) using daily SST from NOAA OISSTV2 satellite data at 0.25°x0.25° resolution. The MHW activity temporal index combines the number of events, duration, intensity and spatial extent of MHWs occurring in each extended summer (JJAS). [Adapted from Simon *et al.* 2023].

4.3. Physical feedbacks of MHWs

Warming seas and MHWs may have profound impacts on dense water formation, particularly in key Mediterranean regions like the northern Adriatic, northern Aegean Sea, and the Gulf of Lion. These areas are known as crucial sites for the formation of dense water (Zervakis *et al*. 2004; Roether *et al*. 2007; CIESM 2009; Janeković *et al*. 2014; Houpert *et al*. 2016; Testor *et al*. 2018), a process primarily driven by winter cooling and evaporation which increases the salinity and density of surface water, leading to its sinking and driving deep water circulation. However, as ocean temperatures are on the rise, the intensity and frequency of such events is disrupted (e.g. Josey and Schroeder 2023). In the northern Adriatic and the Gulf of Lion warmer surface temperatures inhibit the cooling of water masses in winter, reducing the density required for their sinking. In the northern Adriatic, where deep water formation is induced by fierce winter Bora winds (Pirazzoli and Tomasin 2002), long term prospects remain uncertain as the reduction of Bora might be offset by the reduction of relative humidity (Denamiel *et al*. 2020).

The northern Aegean was long considered less important for deep water formation than the Adriatic (Pollak 1951), but in the 1990s mounting evidence accumulated, indicating that the northern Aegean is in fact a major supplier of dense waters for the Eastern Mediterranean (see CIESM 2000; Zervakis *et al*. 2004). As northern Aegean sites for these processes like the Thermaikos Gulf (Estournel *et al*. 2005) are now experiencing intense summer and winter MHWs (see Androulidakis and Krestenitis 2022), such disruptions may trigger cascading effects on marine ecosystems, nutrient cycling and the overall deepwater renewal of the Mediterranean Sea.

High sea surface temperature anomalies and formation of MHWs will furthermore strongly enhance heat fluxes and subsequently intensify atmospheric low-pressure systems, as illustrated by the tropical-like cyclones in the Mediterranean, called 'Medicanes' (Koseki *et al*. 2021). It has been shown recently (Varlas *et al*. 2023), that SST anomalies up to 2°C may increase by approximately 50% the enthalpy fluxes - i.e. the sum of sensible and latent heat fluxes - in a Medicane, enhancing wind speed (by 15%) and precipitation level (by 44%). If intense and persistent MHWs significantly impact the characteristics of atmospheric cyclones (e.g. intensity, track, and landfall position), this may have profound socio-economic implications, especially in the context of a changing climate.

Ocean mixing is essential for the cycling of carbon, nitrogen, phosphorus, etc, and for the oxygenation of deeper waters. Increased stratification induced by MHWs will interfere with these processes and limit both the downward transfer of oxygen and carbon as well as the vertical upwelling that transports nutrients from deeper waters to the top layer and fuel phytoplankton productivity at the basis of marine foodwebs (see section 4.4. below).

4.4. Biological impacts of Mediterranean MHWs

The Mediterranean Sea is a major marine biodiversity hotspot with marked differences between its western and eastern regions (see Coll *et al*. 2010). Yet, in spite of serious mass mortality events (Rivetti *et al*. 2014) having affected the Mediterranean benthic fauna and flora in recent decades, the scientific attention given to MHWs impacts on Mediterranean biodiversity is still lagging far behind the attention paid to these episodes elsewhere in the world ocean ([*]Chartosia 2024; [*]Garrabou *et al*. 2024). As MHWs tend to be much stronger (and shorter) in the west but much longer and weaker in the east (see section 4.1 above), one may speculate that their impacts will also be stronger and quicker on thermally sensitive marine organisms in the west (see discussion in [*]Rilov *et al*. 2024) but the eastern sub-basin suffers from an historic lack of attention as observations and reports essentially concern the western Mediterranean (Marbà *et al*. 2015; Garrabou *et al*. 2019, 2022). There is nonetheless strong, but circumstantial, evidence of the collapse of native benthic populations in the southeast Mediterranean which seems related to ocean warming (Rilov 2016). Mass Mortality Events (MMEs) in the Mediterranean were first documented for red coral in the early 1980s (Harmelin 1984). The number as well as the diversity of species affected by MMEs related to MHWs have been on a steady increase ever since (see Boero *et al*. 2008), especially in the past two decades, following two devastating MMEs recorded in 1999 and 2003 that affected over 30 benthic species. To date Mediterranean MMEs have affected 96 species in total, spread among ten different phyla dominated by Cnidaria - in particular octocorals (see Fig. 3) - Porifera, and Bryozoa (see [*]Garrabou *et al.* 2024). This number is likely an underestimate.

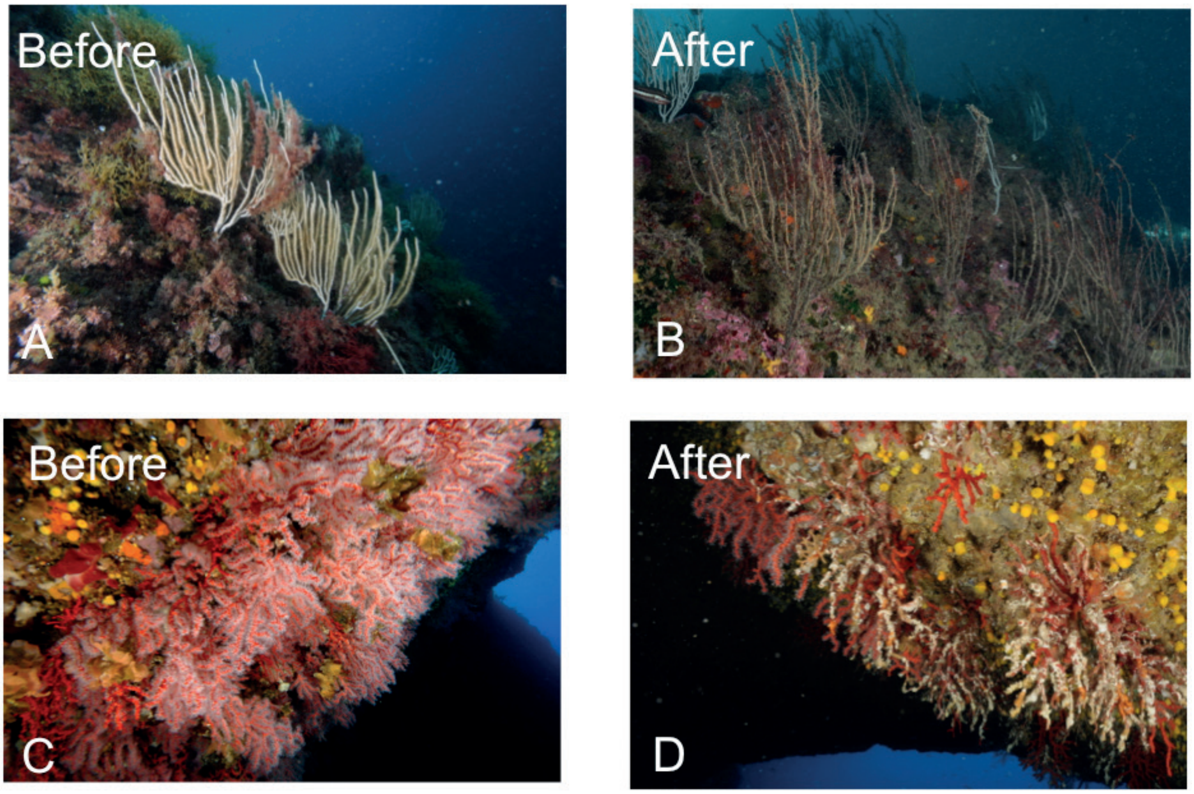


Figure 3. State of coralligenous assemblages dominated by the white gorgonian *Eunicella singularis* in the Catalan Coast and the red coral *Corallium rubrum* in Corsica, before (A,C) and after (B, D) the impact of marine heatwaves. (Photos : MedRecover research group ©).

In general, MMEs concern species dwelling in a range from 0 to 40 m depth, and mainly impact those settled at intermediate depths (15-25 m). Most of the affected species are long-lived, with low growth rates and massive-arborescent growth forms, like gorgonians and sponges. Such species are considered 'foundation' or habitat-forming species and play a key structural and ecological role in the habitats in which they thrive. The consequences of MMEs are of great concern, both at population and community level. In the affected populations, the percentage of impacted individuals may reach up to 90% in the worst cases. The severity of impacts will vary depending on the species and within populations across the affected areas. Bearing in mind the life-history traits of affected species and the increased intensity and frequency of MHWs, the capacity of affected populations to recover will likely be null or quite limited. As a result we are witnessing local extinctions which may soon become regional, with devastating consequences for community and ecosystem functioning.

By reducing nutrient availability to surface waters through enhanced stratification, MHWs may also deeply affect the structure and production of phytoplankton communities (Hayashida *et al*. 2020; Zhan *et al*. 2023), leading to cascading impacts on upper trophic levels all the way to commercial fisheries. Increased stratification can further lead to reduced oxygenation in deeper waters and to the multiplication of vast hypoxic "dead zones" (Kirchman 2021), where marine life struggles to survive.

5. MONITORING MHWs AND THEIR IMPACTS

5.1. Oceanographic monitoring

The monitoring of MHWs is enabled through the observation of ocean temperature. In the Mediterranean Sea, multi-platform observing systems (e.g. MOOSE, SOCIB, PORTUS, COAST-HF and IEOOS in the western Mediterranean; MAOS and RITMARE in the central Mediterranean; POSEIDON, DEKOSIM and SELIPS-ISPRAMAR in the eastern Mediterranean) collect in-situ oceanographic data from bottom tripods, coastal and deep moorings, monitoring cruises and ferrybox, glider lines, drifters, profiling floats, tagged sea turtles (Tintoré *et al.* 2019). As shown in Table 1, multi-platform ocean temperature observing systems offer a highly diversified toolbox to study ocean processes at various spatial and temporal scales from the coastal to open ocean waters and from surface to subsurface.

Table 1: Observational platforms in the Mediterranean Sea equipped with temperature sensors. Associated spatial and temporal scales for process study (inspired by Dickey and Bidigare 2005) and sampling coverage from surface to subsurface and from coastal to open ocean waters are indicated.

Observational platform	Spatial scale	Temporal scale	Surface	Sub-surface	Coastal ocean	Open ocean
Bottom tripod	~ 1cm	1h-1decade	-	-	yes	-
Coastal mooring	~ 1cm	1h-1decade	yes	Partially yes	yes	-
Deep mooring	~ 1cm	1h-1decade	yes	yes	-	yes
Research vessel	1m - 100km	1h-1season	yes	yes	yes	yes
Gliders	10m - 100km	1h-1season	-	yes	yes	yes
Saildrones	10m - 100km	1h-1season	yes	-	yes	yes
Drifters	10m - 100km	1h-1year	yes	-	-	yes
Profiling floats	10m - 100km	1h-1year	-	yes	-	yes
Sea turtles	10m-100km	1h-1year	yes	yes	yes	yes
Satellite	1km-10.000km	1day-1decade	yes	-	-	yes

In recent years MHWs have been monitored and analysed in the Mediterranean Sea using mainly the following observational platforms (for details see *Juza *et al*. 2024) :

(1) satellite products that provide continuously daily sea surface temperature since 1982, allowing a/ to build a robust climatology over a long-term period, b/ to detect and characterise MHWs at the surface from local to sub-regional scales (in real-time and as a reanalysis), and c/ to define and monitor long-term variations of annual MHW indicators (intensity, duration, frequency);
(2) fixed moorings (bottom tripod, coastal and deep moorings) which collect locally (usually hourly) temperature, in particular in the coastal and near-shore ocean waters;
(3) profiling floats which provide hydrographic profiles allowing to study the propagation of MHWs in subsurface and estimate changes in vertical ocean structure. More recent multi-sensor mobile platforms such as gliders, BGC-Argo, saildrones and research vessels that collect both physical and biogeochemical data enable us to extend our understanding of impacts (e.g. carbon, chlorophyll-a concentration, irradiance, turbidity, oxygen and pH). The multi-platform and multi-scale observations are also essential for data assimilation in modelling systems that will improve prediction of ocean extremes such as MHWs.

5.2. Biological and ecological monitoring

Temperature and ecological time series are and will be precious to detect and follow the impacts of MHWs on given species or ecological communities. That would help in distinguishing between natural variability within a given biological population from changes driven by strong external events like MHWs, as shown in studies of the Israeli rocky intertidal shores (Zamir *et al*. 2018; Rilov *et al.* 2020a). Unfortunately long, reliable Mediterranean biological time series are not many (see CIESM 2003 for detailed references).

For marine coastal ecosystems, the T-MEDNet collaborative initiative (www.t-mednet.org) aims to facilitate the acquisition and sharing, over the long term, of high resolution in situ data on climate change indicators now collected at over 120 sites, through the development of a pan-Mediterranean observation network involving marine scientists and managers of Marine Protected Areas. The network, mainly concentrated on the western sub-basin, has been most effective to date in supporting the implementation of cost-effective protocols to track changing seawater temperature conditions, shifts in the distribution of climate-sensitive indicator species, and to reconstruct through harmonized approaches past mass mortality events (Garrabou *et al.* 2022a).

In T-MEDNet, seawater temperature is being measured continuously at high frequency (every hour) using data loggers deployed by divers at standard depth levels, every 5 m from the surface down to 40 m depth or more.

These data have been key for the characterisation of thermal regimes in the highly dynamic coastal zone and for detecting MHWs subsurface layers that are rarely analyzed (Garrabou *et al*. 2022b). Further T-MEDNet keeps up-to-date a comprehensive inventory of MMWs in the Mediterranean with records today encompassing more than 90 species (see details in *Garrabou *et al*. 2024)

6. EXPERIMENTAL APPROACHES – TESTING SPECIES VULNERABILITY

In their easiest application, studies aim to identify temperature tolerance thresholds by exposing organisms to various temperature regimes, determining upper and lower thermal limits crucial for predicting species responses to MHW events. So far limited studies have been conducted on Mediterranean species in this regard; they concern gorgonians, macrophytes and fish (Vinagre *et al*. 2013, Savva *et al*. 2018; Gómez-Gras *et al*. 2022), among others.

Other more complex experimental studies investigate metabolic rates and energy budgets, providing finer insights into the overall capacity of a given species to cope with thermal stress, which is useful for assessing the possible suitability of other habitats under climate change scenarios (Marras *et al.* 2015). Other researchers will follow a different tack, focusing on the response of host/pathogens interactions to MHWs (Lattos *et al.* 2022). A key element to keep in mind, accounting for large potential differences in temperature responses and sensitivity, is intra-specific variability within different populations of the same species across its range. For example, it is known that resilience to MHWs will vary from one intertidal population to another (Leung *et al*. 2019). Variability may arise from acclimation processes, involving physiological, anatomical or morphological adjustments, or from local adaptation through genetic traits acquired over generations as for the Manila clam *Ruditapes philippinarum* that can trigger compensatory mechanisms to mitigate MHW-induced thermal stress (Yang *et al*. 2023).

Vulnerability to heat stress may further vary across seasons, influenced by factors such as food availability, ontogenetic state, or body size (e.g. Coma *et al*. 2009; Kipson *et al.* 2012; Peralta-Maraver 2021). A better understanding of this variability will provide insights into species' resilience and evolutionary potential, so as to guide conservation and management strategies in the face of climate change.

To assess the vulnerability/resilience of species and communities to MHWs, experimental manipulations are essential, for example to determine a species thermal performance curve (TPC) under a wide temperature range (Amsalem and Rilov 2021; Mulas *et al.* 2022). TPC experiments involve an acclimation period, followed by a gradual change of temperatures until the target temperature is reached.

The performance of the organism studied is tested, ideally under increasing durations of exposure to the target temperature (see *Rilov *et al*. 2024), keeping in mind that different traits or functions may have very different optimum performance and maximum threshold levels (Ørsted *et al*. 2022).

BOX 1. Choosing species for experimental studies (criteria for selection and ranking)

Given the extensive number of vulnerable species and the resource-intensive nature of such studies, we propose a set of criteria to prioritize species for examination. These criteria include:

Previous evidence of temperature sensitivity: Species that have shown sensitivity to temperature changes in previous studies, particularly those impacted by mass mortalities, deserve special attention.

Easy Identification: Prioritise species that are easily identifiable, facilitating efficient and accurate data collection in the field.

Distribution: Consider species with a wide distribution, as understanding their response across diverse habitats will provide more insights. Species with a narrow distribution may be on the edge of extinction and so their high vulnerability deserves special attention as well.

Ecological Role: Focus on species with significant ecological roles, as their vulnerability can have cascading effects on marine ecosystems.

Feasibility: many (key) species cannot be maintained in the lab and thus cannot be considered for laboratory experiments.

MHW impact experiments, designed differently from TPC experiments, simulate abrupt changes above a set temperature, often including a recovery period. Their experimental design must account for the diverse shapes, patterns, and durations of MHWs, varying by region.

7.WARNINGS FOR CONSERVATION AND ECOLOGICAL RESTORATION

The likelihood of more intense MHWs affecting the global ocean and the Mediterranean Sea in coming decades, combined with shifts in other climate regimes, poses challenges for ecological conservation and restoration efforts. These changes necessitate a thorough consideration of their implications for ecological conservation and restoration efforts. Clearly, climate change presents a huge challenge for marine conservation and restoration which will require adaptive thinking and strong reliance on latest scientific evidence in order to catch up with the rapid pace of biodiversity change (Rilov *et al.* 2019, 2020b) Marine protected areas cannot protect from MHWs but they may provide some conservation insurance in the face of climate change (Roberts *et al.* 2017).

Ecological restoration is a crucial aspect of humanity's conservation toolbox (Harris *et al.* 2006) and its outcomes will be highly dependent on the impacts of climate change. Latest research findings provide new insights on MHWs but they also underscore an important warning for marine restoration. Under climate change scenarios, restoration actions will only be effective and sustainable if they succeed in incorporating the probability and the dynamics of climatic drivers and of their impacts, still improperly known. As highlighted by [*]Garrabou *et al*. (2024), MHW-induced mass mortalities do impact long-lived organisms, such as gorgonians that have a lifespan of up to 100 years. Restoring these populations to their original status would necessitate an extensive period of time, which is clearly unrealistic given the current climatic trajectories.

The three-dimensional structure of marine habitats - with depth as a key variable affecting the extent of, and biological response to MHWs - further complicates the task of identifying the most suitable areas for conservation and restoration (Aoki *et al*. 2020). Charting potential refuge areas in deeper waters, as proposed by Bramanti *et al*. (2023) for the red gorgonian *Paramuricea clavata* that was much impacted by recent MHWs in shallow waters but tolerates conditions in deeper waters, may offer a suitable mitigation strategy in specific cases.

Marine ecosystem restoration is particularly challenging in a changing ocean (Danovaro *et al*. 2021), especially in the Mediterranean Sea where global warming trends favour the arrival and settling at unprecedented rates of exotic species of mostly tropical origin (see CIESM Atlases of marine exotic species 2001-2021). How to identify and set realistic conservation goals if we are dealing with such a fast-moving target? As a start, knowledge of the climatic vulnerability of many species threatened by MHWs is urgently needed, but scientific information is often missing, and baselines or historical data seldom available.

8. SOME RECOMMENDATIONS FOR FUTURE RESEARCH

More research is urgently needed to understand the drivers, the distribution, duration and impacts of MHWs and to develop mitigating strategies. Various promising paths for research have been already outlined, in more or less detail, in the previous pages. To sum up, we suggest as priority areas:

• The physical processes driving MHWs are not fully understood. More research is needed to better identify the mechanisms and drivers of these events, including the role of ocean currents, atmospheric circulation, and greenhouse gas emissions.

• The role of MHWs in inhibiting the formation of dense waters (and thus deep ventilation) should be a matter of more in-depth research.

• Prediction and early warning systems: while some progress has been made in predicting MHWs, there is a need for more accurate models and more timely warnings to help mitigate their impacts in the face of a fast-changing climate.

• Identify vulnerable species and ecosystems: the effects of MHWs on marine populations and ecosystems are wide and varied, and there is a need for coordinated research to detect and follow the early signals of mass mortality events and study their potential recovery at distinct sites.

• Systematically compare the thermal resilience and upper thermal edge of native benthic species *vs* non indigenous, closely related species of tropical origin: this will help predict the look of things to come.

• Deep sea: while deep MHWs have been recorded in various sectors of the world ocean, their impact on the survival and distribution of deep-sea organisms - generally considered to have a much lower thermal tolerance- requires coordinated, large-scale investigations.

• Socioeconomic impacts: MHWs will directly hurt important sectors of the economy, like fisheries and tourism, and in turn many coastal populations. These costs are not well understood and need to be properly assessed.

9. REFERENCES

Alexander M.A., Scott J.D. and C. Deser. 2000. Processes that influence sea surface temperature and ocean mixed layer depth variability in a coupled model. *J.Geophy.Res Oceans*, 105: 16823-16842.

Amaya D.J., Jacox M.G., Alexander M.A., Scott J.D., Deser C., Capotondi, A. and A.S. Phillips. 2023. Bottom marine heatwaves along the continental shelves of North America. *Nature Comm*, 14(1), p.1038.

Amsalem E. and G. Rilov. 2021. High thermal plasticity, and vulnerability, in extreme environments at the warm distributional edge: The case of a tidepool shrimp. *J. Experim. Mar. Biol. Ecol*, 545, 151641.

Androulidakis Y.S. and Y.N. Krestenitis. 2022. Sea surface temperature variability and marine heat waves over the Aegean, Ionian, and Cretan Seas from 2008–2021. *J. Mar. Sci. Engineering*, 10(1), p.42.

Aoki L.R., McGlathery K.J., Wiberg, P.L. and A. Al-Haj. 2020. Depth affects seagrass restoration success and resilience to marine heat wave disturbance. *Estuaries & Coasts*, 43: 316–328.

Benthuysen J.A., Oliver E.C., Chen K. and T. Wernberg. 2020. Advances in understanding marine heatwaves and their impacts. *Front. Mar. Sci*, 7, p.147.

Boero F., Briand F., Féral J.P., Azzurro E., Cardin V., Riedel B. et al. 2008. Climate warming and related changes in Mediterranean marine biota. pp. 5–21 In CIESM Monograph n° 35 (F. Briand, editor). CIESM Publisher, Paris, Monaco. 152 p.

Bramanti L., Manea E., Giordano B., Estaque T., Bianchimani O. *et al.* 2023. The deep vault: a temporary refuge for temperate gorgonian forests facing marine heat waves. *Mediterranean Marine Science*, 24(3): 601-609.

CIESM. 2000. The Eastern Mediterranean climatic transient; its origin, evolution and impact on the ecosystem. CIESM Monograph n° 10 (F. Briand and A. Lascaratos, eds). CIESM Publisher. 86 p.

CIESM Exotic Atlas series. 2001-2021. (F. Briand, ed.). CIESM Publisher, Paris, Monaco.

CIESM. 2003. Mediterranean biological time series. CIESM Monograph n° 22 (F. Briand and K. Stergiou, eds). CIESM Publisher. 140 p.

CIESM. 2009. Dynamics of Mediterranean deep waters. CIESM Monograph n° 38 (F. Briand, ed.). CIESM Publisher. 132 p.

Coll M., Piroddi C., Steenbeek J., Kaschner K., Ben Rais Lasram F., Aguzzi J., *et al.*, 2010. The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats, *PLoS One*, 5, e11842, doi:10.1371/journal.pone.0011842

Coma R., Ribes M., Serrano E., Jimenez E., Salat J. and J. Pascual. 2009. Global warming-enhanced stratification and mass mortality events in the Mediterranean. *PNAS,* 106 (15): 6176-6181

Danovaro R., Aronson J., Cimino R., Gambi C., Snelgrove P.V. and C. Van Dover. 2021. Marine ecosystem restoration in a changing ocean. *Restoration Ecology*, 29, p.e13432.

Denamiel C., Tojčić I. and I. Vilibić. 2020. Far future climate (2060–2100) of the northern Adriatic air–sea heat transfers associated with extreme bora events. *Clim. Dyn*., 55: 3043–3066.

Dickey T. D. and R.R. Bidigare. 2005. Interdisciplinary oceanographic observations: the wave of the future. *Scientia Marina*, 69(S1) : 23-42.

Estournel C., Zervakis V., Marsaleix P., Papadopoulos A., Auclair F., Perivoliotis L. and E. Tragou. 2005. Dense water formation and cascading in the Gulf of Thermaikos (North Aegean), from observations and modelling. *Continental Shelf Research*, 25(19-20): 2366-2386.

Frölicher T.L., Fischer E. M. and N. Gruber. 2018. Marine heatwaves under global warming. *Nature*, 560: 360–364.

Garrabou J., Gómez-Gras D., Ledoux J.B. Linares C., *et al*. 2019. Collaborative Database to Track Mass Mortality Events in the Mediterranean Sea. *Front. Mar. Sci.* 6: 707. https://doi.org/10.3389/fmars.2019.00707

Garrabou J., Bensoussan N., Di Franco A., Boada J., Cebrian E., Santamaria J., Guala I., Grech D., Cerrano C., Pulido T., Jou M., Marambio M. and E. Azzurro. 2022a. Monitoring Climate-related responses in Mediterranean Marine Protected Areas and beyond: Eleven Standard Protocols. 74 p. Edited by ICM-CSIC, Barcelona, Spain.

Garrabou J., Gómez-Gras D., Medrano A., Cerrano, C., Ponti M., Schlegel R., Bensoussan N. et al. 2022b. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biol*. 28 (19): 5708-5725.

Gawarkiewicz G., Chen K., Forsyth J., Bahr F., Mercer A.M., Ellertson A., Fratantoni P., Seim H., Haines S. and L. Han. 2019. Characteristics of an advective marine heatwave in the Middle Atlantic Bight in early 2017. *Front. Mar. Sci*, 6, p.712.

Gómez-Gras D., Bensoussan N., Ledoux J.B. *et al.* 2022. Exploring the response of a key Mediterranean gorgonian to heat stress across biological and spatial scales. *Sci. Rep*., 12, 21064.

Hamdeno M. and A. Alvera-Azcará. 2023. Marine heatwaves characteristics in the Mediterranean Sea: case study the 2019 heatwave events. *Front. Mar. Sci*. 10, 1093760,

Harmelin J.G. 1984. Biologie du Corail Rouge. Paramètres de populations, croissance et mortalité. État des connaissances en France. pp. 99–103 In FAO Report 306 on Fisheries (Charbonnier & Garcia, ed). FAO, Roma.

Harris J.A., Hobbs R.J., Higgs E. and J. Aronson. 2006. Ecological restoration and global climate change. *Restoration Ecology.*, 14(2): 170-176.

Hayashida H., Matear R.J. and P.G. Strutton. 2020. Background nutrient concentration determines phytoplankton bloom response to marine heatwaves. *Global Change Biol*., 26: 4800–4811.

Hobday A.J., Alexander L.V., Perkins S.E., Smale D.A., Straub S.C., Oliver E.C. ... and T. Wernberg. 2016. A hierarchical approach to defining marine heatwaves. *Progress Oceanogr*., 141: 227-238.

Hobday A.J., Oliver E.C., Gupta, A.S., Benthuysen, J.A., Burrows, M.T., Donat, M.G. ...and D.A. Smale. 2018. Categorizing and naming marine heatwaves. *Oceanography.*, 31(2): 162-173.

Holbrook N.J., Scannell H.A., Sen Gupta A., Benthuysen J.A., Feng M., Oliver E.C., Alexander L., Burrows M.T., Donat M.G., Hobday A.J., Moore P.J., Perkins-Kirkpatrick S.E., Smale D.A., Straub S.C. and T. Wernberg. 2020. A global assessment of marine heatwaves and their drivers. *Nature Comm*. 10 (1)

Houpert L., Durrieu de Madron X., Testor P., Bosse A., d'Ortenzio F., Bouin M.N.... and P. Raimbault. 2016. Observations of open-ocean deep convection in the northwestern Mediterranean Sea: Seasonal and interannual variability of mixing and deepwater masses for the 2007-2013 period. *J. Geophy. Res. Oceans.*, 121(11): 8139-8171.

Huang B., Liu C., Banzon V.F., Freeman E., Graham G., Hankins W., Smith T.M. and H.-M Zhang. 2020. NOAA 0.25-degree Daily Optimum Interpolation Sea Surface Temperature (OISST), Version 2.1 dataset for 1982-2021. NOAA National Centers for Environmental Information. Accessed on 11-05-2022. https://doi.org/10.25921/RE9P-PT57.

Huang Z., Feng M., Dalton S.J. and A.G. Carroll. 2024. Marine heatwaves in the Great Barrier Reef and Coral Sea: their mechanisms and impacts on shallow and mesophotic coral ecosystems. *Science Total Environment.*, 908, p.168063.

Janeković I., Mihanović H., Vilibić I. and M. Tudor. 2014. Extreme cooling and dense water formation estimates in open and coastal regions of the Adriatic Sea during the winter of 2012, *J. Geophys. Res. Oceans.*, 119 : 3200–3218.

Josey S.A. and K. Schroeder. 2023. Declining winter heat loss threatens continuing ocean convection at a Mediterranean dense water formation site**.** *Environ. Res. Lett*., 18 024005

Juza M., Fernández-Mora À. and J. Tintoré. 2022. Sub-regional marine heat waves in the Mediterranean Sea from observations: Long-term surface changes, Sub-surface and coastal responses. *Front. Mar. Sci.,* 9, p.785771.

Kipson S., Linares C., Teixidó N., Bakran-Petricioli T. and J. Garrabou. 2012. Effects of thermal stress on early developmental stages of a gorgonian coral. *Mar. Ecol. Prog. Ser*., 470: 69-78.

Kirchman D.L. 2021. Dead zones discovered in coastal waters. pp. 21-35 In Dead Zones (D.L. Kirchman, editor). Oxford University Press.

Koseki S., Mooney P. A., Cabos W., Gaertner M.Á., de la Vara A. and J.J. Gonzáles Alemán. 2020. Modelling a tropical-like cyclone in the Mediterranean Sea under present and warmer climate. *Natural Hazards and Earth System Sciences Discussions*. 1-35.

Lattos A., Papadopoulos D.K., Feidantsis K., Karagiannis D., Giantsis I.A. and B. Michaelidis. 2022. Are marine heatwaves responsible for mortalities of farmed Mytilus galloprovincialis? *Animals*. 12, 2805.

Lee E.Y., Lee D.E., Park Y.G., Kang H. and H. Baek. 2023. The local stratification preconditions the marine heatwaves in the Yellow Sea. *Front. Mar. Sci*., 10, p.1118969.

Leung J.Y., Russell B.D., and Connell S.D. 2019. Adaptive responses of marine gastropods to heatwaves. *One Earth*, 1(3): 374-381.

Marbà N., Jordà G., Agustí S.L, Girard C. and C.M. Duarte. 2015. Footprints of climate change on Mediterranean Sea biota. *Front. Mar. Sci*. 2:56.

Marin M., Feng M., Bindoff N.L. and H.E. Phillips. 2022. Local drivers of extreme upper ocean marine heatwaves assessed using a global ocean circulation model. *Front. Clim*., 4:788390.

Marras S., Cucco A., Antognarelli F., Azzurro E., Milazzo M., Bariche M., Butenschön M., Kay S., Di Bitetto M., Quattrocchi G. and M. Sinerchia. 2015. Predicting future thermal habitat suitability of competing native and invasive fish species: from metabolic scope to oceanographic modelling. *Conservation Physiology*, 3(1), cou059, https://doi.org/10.1093/conphys/cou059

Martinez J., Leonelli F.E., Garcia-Ladona E., Garrabou .J, Kersting D.K., Bensoussan N. and A. Pisano. 2023. Evolution of marine heatwaves in warming seas: the Mediterranean Sea case study. *Front. Mar. Sci*., 10, 1193164.

Mulas M., Silverman J., Guy-Haim T., Noé S. and G. Rilov. 2022. High climate vulnerably of the Levantine endemic and endangered habitat-forming macroalga, Gongolaria rayssiae: implications for reef carbon budget. *Front. Mar. Sci.*, 9, 1447.

Olita A., Sorgente R., Natale S., Gaberšek S., Ribotti A., Bonanno A. and B. Patti. 2007. Effects of the 2003 European heatwave on the Central Mediterranean Sea: surface fluxes and the dynamical response. *Ocean Sci*., 3 : 273–289.

Oliver E.C. 2016. MarineHeatWaves v0.16. https://github.com/ecjoliver/marineHeatWaves/releases/tag/v0.16

Oliver E.C. 2019. Mean warming not variability drives marine heatwave trends. *Clim. Dyn.,* 53: 1653–1659.

Oliver E. C., Benthuysen J.A., Darmaraki S., Donat M.G., Hobday A.J., Holbrook N.J., Schlegel R.W. and A. Sen Gupta. 2021. Marine heatwaves. *Annual Rev. Mar. Sci.*, 13: 313-342.

Ørsted M., Jørgensen L.B. and J. Overgaard. 2022. Finding the right thermal limit: a framework to reconcile ecological, physiological and methodological aspects of CTmax in ectotherms. *J. Experim. Biol.*, 225, jeb244514.

Peralta-Maraver I. and E.L. Rezende. 2021. Heat tolerance in ectotherms scales predictably with body size. *Nat. Clim. Change*., 11: 58–63.

Pirazzoli P. A. and A. Tomasin. 2002. Recent evolution of surge-related events in the NA Area. *Journal of Coastal Research*, 18(3): 537–554.

Pollak, M.J. 1951. The sources of the deep water in the Eastern Mediterranean Sea. *J. Mar. Res*., 10 (1): 128–152.

Reynolds R.W., Smith T. M., Liu C., Chelton D. B., Casey K. S. and M.G. Schlax. 2007. Daily high-resolution-blended analyses for sea surface temperature. *J. Clim.* 20 5473–96.

Rilov G. 2016. Multi-species collapses at the warm edge of a warming sea. *Sci. Reports* 6, 36897.

Rilov G., Mazaris A.D., Stelzenmüller V., Helmuth B., Wahl M., Guy-Haim T., Mieszkowska N., Ledoux J.B. and S. Katsanevakis. 2019. Adaptive marine conservation planning in the face of climate change: What can we learn from physiological, ecological and genetic studies? *Global Ecol. Cons*., 17, e00566

Rilov G., Peleg O., Guy-Haim T. and E. Yeruham. 2020a. Community dynamics and ecological shifts on Mediterranean vermetid reefs. *Mar. Env. Res*., 160

Rilov G., Fraschetti S., Gissi E., Pipitone C., Badalamenti F. *et al.* 2020b. A fast-moving target: achieving marine conservation goals under shifting climate and policies. *Ecological Applications*. 30(1), e02009.

Rivetti I., Fraschetti S., Lionello P., Zambianchi E. and F. Boero. 2014. Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. PLoS ONE, 9(12): e115655.

Roberts C.M., O'Leary B.C., McCauley D.J., Cury P.M., Duarte C.M., Lubchenco J., Pauly D., Sáenz-Arroyo A., Sumaila U.R. and R. W. Wilson. 2017. Marine reserves can mitigate and promote adaptation to climate change. *PNAS*, 114: 6167-6175.

Roether W., Klein B., Manca B.B., Theocharis A. and S. Kioroglou. 2007. Transient Eastern Mediterranean deep waters in response to the massive dense-water output of the Aegean Sea in the 1990s. *Prog. Oceanog.*, 74(4): 540-571.

Savva I., Bennett S., Roca G., Jordà G.and N. Marbà. 2018. Thermal tolerance of Mediterranean marine macrophytes: Vulnerability to global warming. *Ecology & evolution*, 8(23): 12032-12043.

Schlegel R.W., Oliver E.C., Hobday A.J. and A.J. Smit. 2019. Detecting marine heatwaves with sub-optimal data. *Front. Mar. Sci.,* 6, 737.

Schlegel R.W. and E.C. Oliver. 2021. Drivers of marine heatwaves in the Northwest Atlantic: The role of air–sea interaction during onset and decline. *Front. Mar. Sci.*, 8, p.627970.

Sen Gupta A., Thomsen M., Benthuysen J.A., Hobday A.J., Oliver E.C. *et al*. 2020. Drivers and impacts of the most extreme marine heatwaves events. *Sci. Rep*., 10, 19359.

Simon A., Pires C., Frölicher T. L. and A. Russo. 2023. Causes of future changes in marine heatwaves in the North Atlantic. *Environm. Research Lett*, 18(1), 014028.

Smith K.E., Burrows M.T., Hobday A.J., Sen Gupta A., Moore P.J., Thomsen M., Wernberg T. and D.A. Smale. 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, 374(6566), p.eabj3593.

Smith K.E., Burrows M.T., Hobday A.J., King N., Moore P.J., Sen Gupta A., Thomsen M.S., Wernberg T. and D.A. Smale. 2023. Biological impacts of marine heatwaves. *Annual Rev. Mar. Sc.*, 15 (1): 119-145.

Sparnocchia S., Schiano M.E., Picco P., Bozzano R., Cappelletti A., 2006. The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean). *Ann. Geophys.,* 24 (2): 443–452.

Testor P., Bosse A., Houpert L., Margirier F., Mortier L., Legoff H. et al. 2018. Multiscale observations of deep convection in the northwestern Mediterranean Sea during winter 2012–2013 using multiple platforms. *J. Geophys. Res. Oceans*, 123: 1745–1776.

Tintoré J., Pinardi N., Álvarez-Fanjul E., Aguiar E., Álvarez-Berastegui D., Bajo M. and G. Zodiatis. 2019. Challenges for sustained observing and forecasting systems in the Mediterranean Sea. *Front. Mar. Sci.*, 568.

Varlas G., Pytharoulis I., Steeneveld G.J., Katsafados P. and A. Papadopoulos. 2023. Investigating the impact of sea surface temperature on the development of the Mediterranean tropical-like cyclone "Ianos" in 2020. *Atmospheric Research*, 291, 106827.

Vinagre C., Dias M., Roma J., Silva A., Madeira D. and M.S. Diniz. 2013. Critical thermal maxima of common rocky intertidal fish and shrimps - A preliminary assessment. *J. Sea Res*., 81: 10-12.

Wang S., Jing Z., Wu L., Sun S., Peng Q., Wang H., Zhang Y. and J. Shi. 2023. Southern hemisphere eastern boundary upwelling systems emerging as future marine heatwave hotspots under greenhouse warming. *Nature Comm.*, 14(1), p.28.

Xu T., Newman M., Capotondi A., Stevenson S., Di Lorenzo E. and M.A. Alexander. 2022. An increase in marine heatwaves without significant changes in surface ocean temperature variability. *Nature Comm.*, 13(1), 7396.

Yang K., Xu Y., He G., Liu X., Liu,Y. and L. Zhao. 2023. Physiological and biochemical responses of clams to recurrent marine heatwaves. *Marine Environmental Research*, 190, p.106105.

Zamir R., Alpert P., and G. Rilov. 2018. Increase in weather patterns generating extreme desiccation events: implications for Mediterranean rocky shore ecosystems. *Estuaries & Coasts* 41:1868–1884.

Zervakis V., Georgopoulos D., Karageorgis A.P. and A. Theocharis. 2004. On the response of the Aegean Sea to climatic variability: a review. *Internat. J. Climatol.*, 24(14): 1845-1858.

Zhan W., Zhang Y., He Q. and H. Zhan. 2023. Shifting responses of phytoplankton to atmospheric and oceanic forcing in a prolonged marine heatwave. *Limnol. Oceanogr*., 68: 1821-1834.

WORKSHOP COMMUNICATIONS

A) THE PHYSICAL NATURE OF MARINE HEATWAVES

Seasonality, return periods and intensity of surface marine heatwaves in the Mediterranean Basin

Matjaž Ličer [1 2]

[1] *Slovenian Environment Agency, Ljubljana, Slovenia*
[2] *National Institute of Biology, Marine Biology Station, Piran, Slovenia*

Abstract

We use level-4 satellite and in-situ ocean temperature observations from several locations in the Mediterranean basin to estimate seasonality and frequency of occurrence of marine heatwaves and marine cold spells in the past 30 years. We use established methodologies and libraries to detect and categorize marine heatwaves with respect to a 30-year climatology. We independently compute return periods of specific temperature anomalies at a number of Mediterranean ports for three consecutive decades (1990s, 2000s, 2010s) using generalized extreme value distributions. These indicate (independently from the distribution bulk) that, at all locations, return periods associated with a specific temperature anomaly grow shorter as we progress in time from the 1990s to 2010s. Cumulative intensities of these events are calculated at several Mediterranean ports as time integrals of SST anomalies over the 90th climatological percentile. We identify the Gulf of Lion, the Adriatic and the Aegean as marine heatwave hotspots and compute the cumulative intensity differences between the periods 2015-2019 and 1989-1993. In the period 2015-2019 most of the Mediterranean (with the exception of the Levantine basin) witnessed a higher MHW induced cumulative intensity than during the period 1989-1993. The methodology used however poses the question of how to interpret increasing MHW frequencies, arising from a time series with a temperature trend. We argue that while MHW frequencies are increasing in part due to the presence of a trend in the data, this increase nevertheless appropriately reflects a de facto rise of thermal stress on marine organisms.

1 Introduction

The world oceans are in a state of constant change, driven by complex climatic and environmental factors. One increasingly frequent phenomenon (Simon *et al*. 2022) in recent years is the occurrence of marine heatwaves (MHWs), causing much concern. These events, characterized by prolonged periods of unusually warm sea surface temperatures, have far-reaching consequences for marine ecosystems and coastal communities (Barbeaux *et al*. 2020; Brown *et al*. 2021; Garrabou in this volume 2024). As emphasized repeatedly during this workshop, among the regions most susceptible to these heatwaves, the Mediterranean stands out as a prominent hotspot, due in particular to the combination of shallow waters, limited exchange with the Atlantic ocean, and a rapidly warming climate.

The threats posed by MHWs in the Mediterranean are multifaceted (Hamdeno and Alvera-Azcarate 2023 ; Darmaraki *et al*. 2019). Elevated sea temperatures can lead to coral bleaching, harmful algal blooms, mass mortality events (Garrabou *et al*. 2022 ; Verdura *et al*. 2019) and shifts in the distribution and behavior of marine species (Gómez-Gras *et al.* 2021a, 2021b). These disruptions have ripple effects throughout the food webs, impacting fisheries and the livelihoods of coastal communities (Harris *et al*. 2018 ; Brown *et al*. 2021). They can disrupt tourism, damage coastal property, and even compromise the availability of fresh water as seawater intrudes into aquifers. Moreover, MHWs can exacerbate extreme weather events, such as heatwaves and heavy rainfall, leading to increased risks of flooding and wildfires in coastal regions. Such was, for example, the case of unprecedented catastrophic floods in Slovenia in August 2023, which were boosted by the presence of a MHW in the Western Mediterranean. There are several methodologies proposed to detect and categorize MHWs and we will focus on one of the most established approaches (Hobday *et al*. 2016, 2018). A very recent categorization leveraging MHWs spatial extent also merits further attention (Pastor and Khodayar, 2023). According to the definition of Hobday *et al*. (2016), a MHW is defined as a period lasting over 5 days during which the temperature never drops below the 90th percentile of the climatological temperature for the respective day of year on the location of observation. The threshold of five days seems a somewhat arbitrary value, which nevertheless balances ecological relevance, statistical robustness, and practical considerations of marine environmental monitoring. It is futhermore related to the decay timescale of the ocean temperature auto-correlation function (Robert Schlegel, personal communication) and therefore a sensible lower limit for the duration of a single MHW. We will correspondingly define a marine cold spell (MCS) as a period, lasting over 5 days, during which the temperature never rises above the 10th percentile of the climatological temperature for the respective day of year on the location of observation. Climatological means and 10th and 90th percentiles are defined for each day of year as respective statistical values over a 30-year baseline time period, which were additionally low-pass filtered using a 11-day running window as recommended (Hobday *et al*. 2016).

2 Climatological baseline, temperature anomalies and cumulative intensities

This work will focus on sea surface temperatures (SST) from in situ or remote sensors. Daily satellite SSTs were obtained from CMEMS 30-year L4 SST dataset for the Mediterranean Basin; the ocean temperature climatology was ob tained from Copernicus CMEMS Climatology GLOBAL REANALYSIS 001 030 product and remapped to our model grid using bilinear interpolation at each grid point. An example of these time series is presented in Figure 1, depicting a yearly cycle of SST offshore Livorno (Italy) during the MHW-intensive year 2003, along with respective filtered climatological time series.

Figure 1 also indicates a categorization of MHWs, following Hobday *et al*. (2018), which categorizes the 2003 MHW in the Mediterranean as strong (in the scale of moderate/strong/severe/extreme).

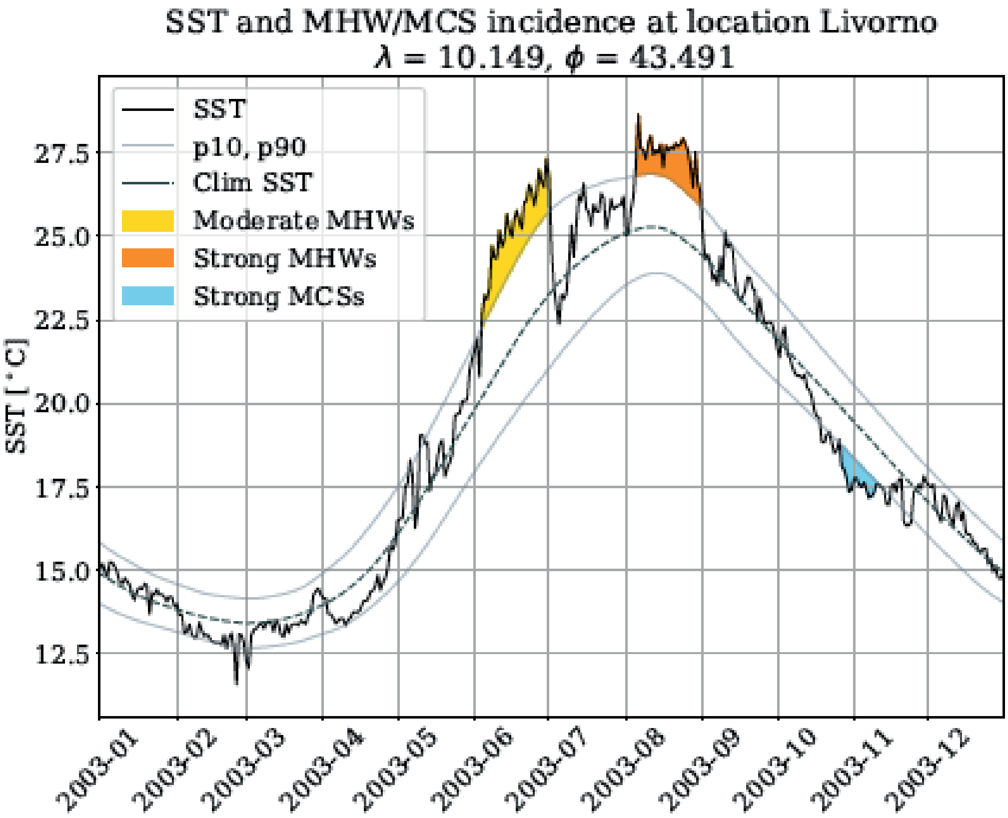


Figure 1. Seasonal cycle of SST (full black line) offshore of Livorno (Italy) during the year 2003, along with respective 11-day low-pass filtered climatological time series for the climatological mean (dashed gray line) and 10th and 90th percen tiles (lower and upper smooth gray lines, respectively). Colored regions mark the area that corresponds to the cumulative intensity of the particular MHW, while colors themselves correspond to MHW categories, introduced in (Hobday *et al.* 2018).

The category C of a MHW at location (λ, ϕ) at time $\boldsymbol{t}$ is computed as a ratio between in situ anomaly from the 30-year climatological baseline to that of the 90th percentile anomaly from the 30-year climatological baseline (see also Sen Gupta *et al*. 2020):

$$C(\lambda, \phi, t) = \frac{SST(\lambda, \phi, t) - SST_{\mathrm{clim}}(\lambda, \phi, t)}{SST_{\mathrm{p90}}(\lambda, \phi, t) - SST_{\mathrm{clim}}(\lambda, \phi, t)} \, .$$

To automatically detect and categorize MHWs along the stated lines, we use the MarineHeatWaves library, developed by Hobday *et al*. (2016) which is available on Github (Oliver 2016).
Satellite L4 temperature anomalies were computed as differences of the SST from the 11-day low-pass filtered climatology. For each location in the Basin, we can plot these anomalies by day of year, every year. Such a plot for the location of coastal buoy Vida in the Gulf of Trieste is depicted in Figure 2. There is a clear decline of MCS events as we traverse through the years from left to right and a visible rise in the number and intensity of MHWs within the same period.

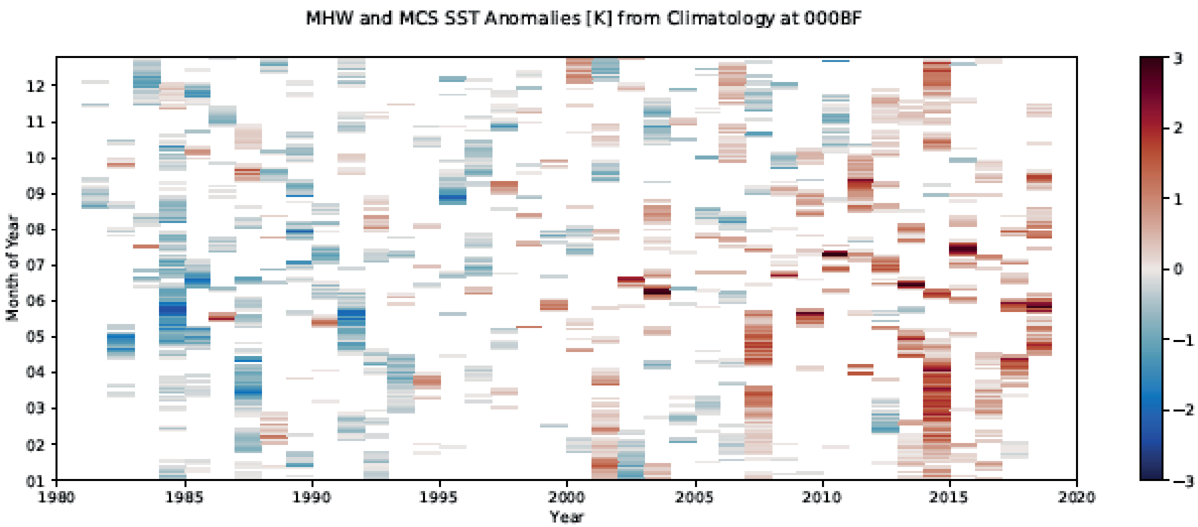


Figure 2. Daily SST anomaly from the 11-day low-pass filtere climatological time series at the location of coastal buoy Vida in Piran (Slovenia, Gulf of Trieste, Northern Adriatic). Only anomalies above 90th percentile and values below the 10th percentile are plotted. Anomalies closer to climatology are masked out for clarity.

Averaging anomalies on Figure 2 over all years reveals a clear seasonal cycle, albeit with substantial variances, of these anomalies. For coastal buoy Vida location this seasonal cycle is depicted on Figure 3, which indicates that in the Gulf of Trieste largest cold or hot anomalies occur predominantly in summer months. In the Gulf of Trieste this can be attributed to the shallow water column and predominant presence of summer stratification. Such stable conditions coupled to increased seasonal convective activity in the atmosphere likely pave the way for higher anomalies, when they happen. Integrated in time, these anomalies, depicted on Figures 1 and 2, give the cumulative intensity *CI* [$\circ$ K- days] at location (λ, ϕ) over selected period:

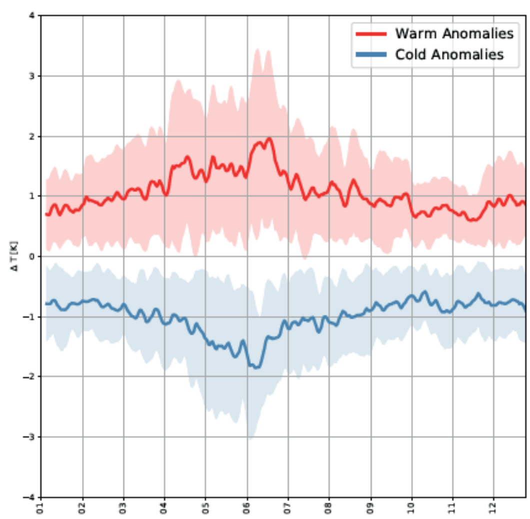


Figure 3. Time averaged SST anomaly (y-axis) versus the month of year (x-axis) over the period 1989-2019 at the location of coastal buoy Vida in Piran (Slovenia, Gulf of Trieste, Northern Adriatic).

$$CI(\lambda, \phi) = \int_{t_{\text{start}}}^{t_{\text{end}}} \left[SST(\lambda, \phi, t) - SST_{\text{p90}}(\lambda, \phi, t) \right] \mathrm{d}t,$$

where the accumulation is computed as an integral of SST anomaly over the 90th climatological temperature percentile over the entire time interval of interest, and including all MHW events during this interval. Cumulative intensity has been suggested (Sen Gupta *et al*. 2020) as a more suitable metric to quantify the impacts of MHWs on marine organisms that are sensitive to accumulated thermal stress. For example, the yearly 2003 cumulative intensity offshore Livorno (Figure 1) is computed as the sum of both detected MHWs, i.e. the sum of orange and yellow areas. Cumulative MCS intensities were computed in a similar fashion, as the integral difference between the in situ SST and the 10th climatological percentile.We have integrated these values for a number of Mediterranean ports over each consecutive year between 1989 and 2019 and the results are presented in Figure 4. A clear rise in MHW cumulative intensity in the surface layers is clearly visible at all locations around the Mediterranean basin: 1980s were marked by frequent occurrences of MCSs, which have practically disappeared by the 2010s. An inverse pattern is present when talking about the MHWs: these events were rare in the 1980s but are responsible for substantial heat accumulation in 2010s.

Immediately the question arises whether this shift is real or a mere reflection of the fact that we have a 30-year baseline and a global ocean warming trend (or even a more non-linear gradual low-frequency variability), which taken together guarantee more MCSs in the beginning of the observation period and more MHWs towards its end? Recent studies have shown that a fixed baseline can lead to saturation of MHW numbers by mid-century and therefore a moving baseline (Rosselló *et al*. 2023) or a detrending procedure (Martínez *et al.* 2023) should be used in order to asses MHW frequencies. Indeed, once we remove the linear trend from the temperature timeseries data, there seems to be no clear indication that the frequency of thus detected MHWs is on the rise - this is clearly seen on Figure 5.

However, an ecological aspect of the shifting baseline maintains that the shift is an environmental fact for any ocean species that can only adapt to a changing climate on timescales longer than a decade, since in this case these rising frequencies of MHWs correspond to actual increases in environmental stresses experienced by these respective populations (Laufkötter *et al.* 2020, Gómez-Gras *et al.* 2021a). A shifting baseline and an overlay of extreme temperature events may, for example, push certain populations from survivable extremes into regions of extinction extremes (Harris *et al*. 2018), see e.g. (Yeruham *et al.* 2015) or (Rilov 2024, in this volume) for the collapse of the echinoid *Paracentrotus lividus* (European purple sea urchin) populations in the Eastern Mediterranean. Marine organisms can adapt to thermal stress in different ways and on different timescales.

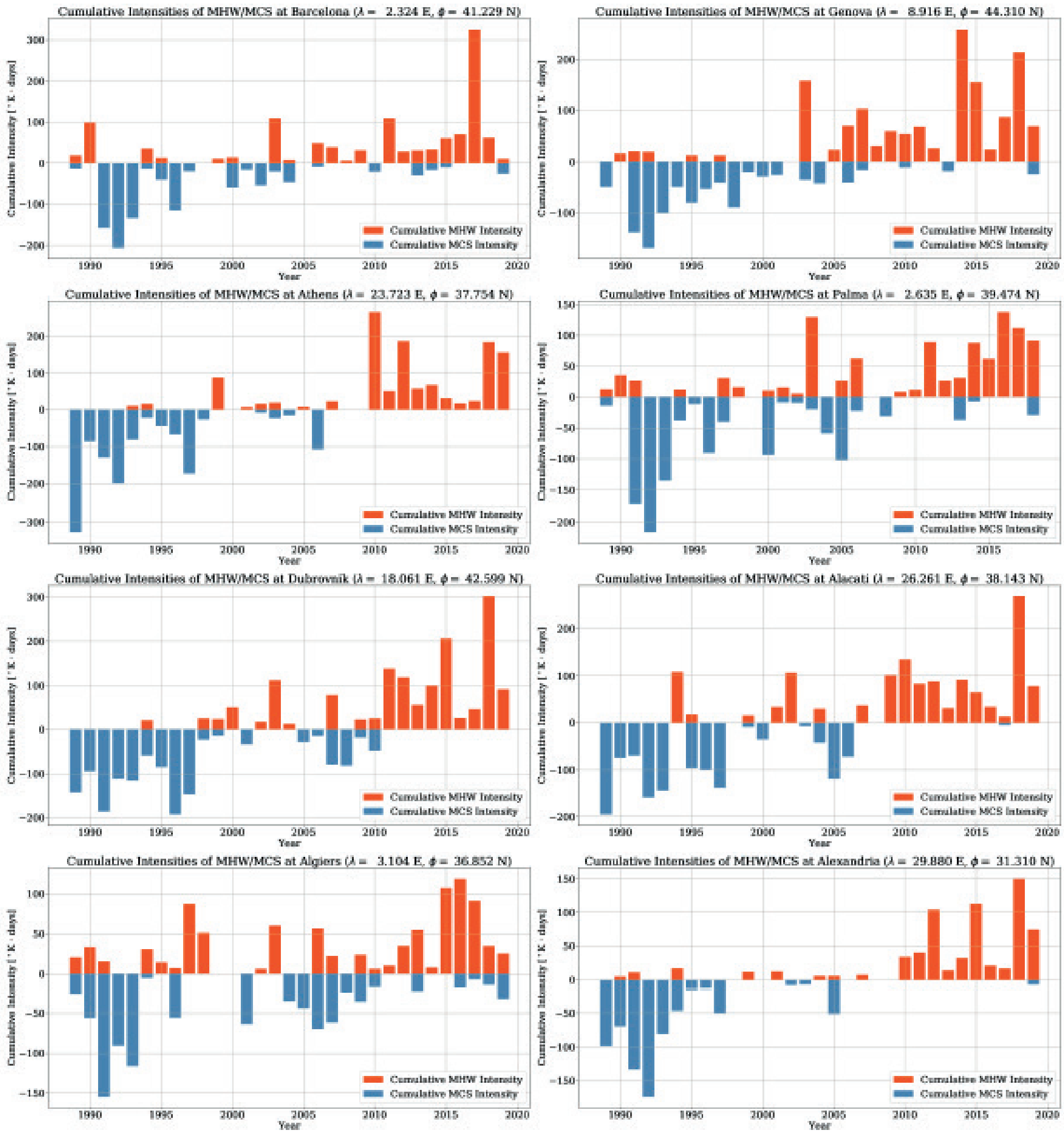


Figure 4. Surface cumulative intensity [K - days] of MHWs (red bars) and MCS (blue bars) offshore eight distinct Mediterranean ports for each consecutive year between 1989 - 2019.

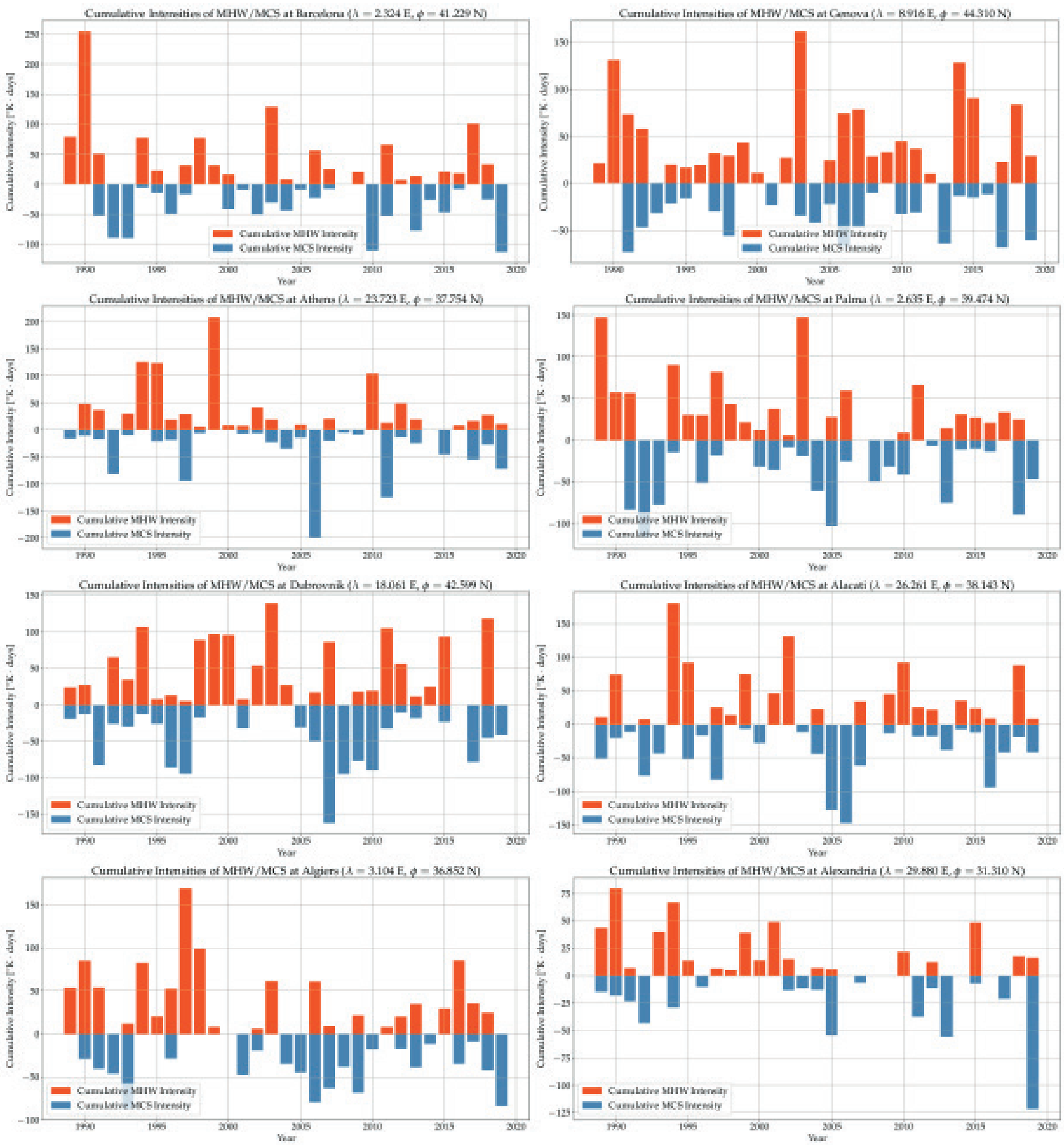


Figure 5. Same as Figure 4 but with surface cumulative intensity based on a detrended temperature time series. Surface cumulative intensity [K - days] of MHWs (red bars) and MCS (blue bars) offshore eight distinct Mediterranean ports for each consecutive year between 1989 - 2019. Linear trend has been removed from the time series prior to computation of MHW and MCS cumulative intensity.

Among fast adaptations, typically achieved on the timescale of days to a year, are for example:

– Behavioral changes: organisms might adapt by altering their feeding, breeding, or migratory behaviors to cooler times of the day or season.

– Shifts in distribution: species may move to cooler areas, either deeper waters or higher latitudes, to escape rising temperatures.

– Phenotypic plasticity: some species might exhibit rapid changes in their physiology or morphology that allow them to better cope with higher temperatures.

On the other hand, slow adaptations (several years to several decades) include, among others:

– Genetic adaptation: over longer periods, natural selection may favor individuals with traits that confer higher tolerance to elevated temperatures, leading to evolutionary changes.
– Altered life histories: changes in growth rates, size at maturity, or reproductive strategies might occur as organisms adapt to the new thermal regime.
– Community and ecosystem-level changes: over time, the composition of communities may shift, with heat-tolerant species becoming more dominant. This could lead to changes in predator-prey dynamics, species interactions, and overall ecosystem functioning.

For organisms which have limited adaptability on shorter timescales, the trend in the temperature data represents a de facto growing thermal stress. This means that keeping the trend (or other types of low-frequency variability) is imperative for analyses with the ambition to:

– Reflect real-world conditions: the long-term warming trend is a reality of our changing climate. Excluding this trend from analysis could lead to underestimating the actual stress experienced by marine ecosystems, as these trends represent ongoing environmental changes.
– Accurately assess risk: keeping the warming trend in the analysis helps inunderstanding the full scope of risks and stresses faced by marine ecosystems. It provides a more realistic picture of future conditions, crucial for effectiveconservation and management strategies.
– Understand ecosystem vulnerabilities: the trend itself may be a stressor, potentially causing gradual shifts in species distribution, phenology, and ecosystem structure. Analyzing MHWs with the trend provides insights into how ecosystems are adapting to not just episodic extremes but also chronic changes.
– Define policy implications: for policy makers and environmental managers, understanding the full extent of climate change impacts, including long-term trends, is vital for crafting effective mitigation and adaptation strategies.

An alternative approach to assessing the frequencies of MHWs is possible through fitting the dataset of SST time series extremes to Generalized Extreme Value (GEV) distribution (Rypkema and Tuljapurkar, 2021). We have split our 30-year SST time series at each location into three decades: the 1990s (years 1990-1999), the 2000s (years 2000-2009) and the 2010s (years 2010-2019). We used the pyextremes Python library using the Block-Maximum method with 1-year block size to construct extremes dataset for each decade, which we then fit to the GEV distribution to obtain the return values of specific SST anomaly. In this way, we make no assumptions about the fixed baseline, relative to which extremes are computed, but rather only focus on the extremes of the distribution, obtained from the SST timeseries at each location. Results are presented on Figure 6.

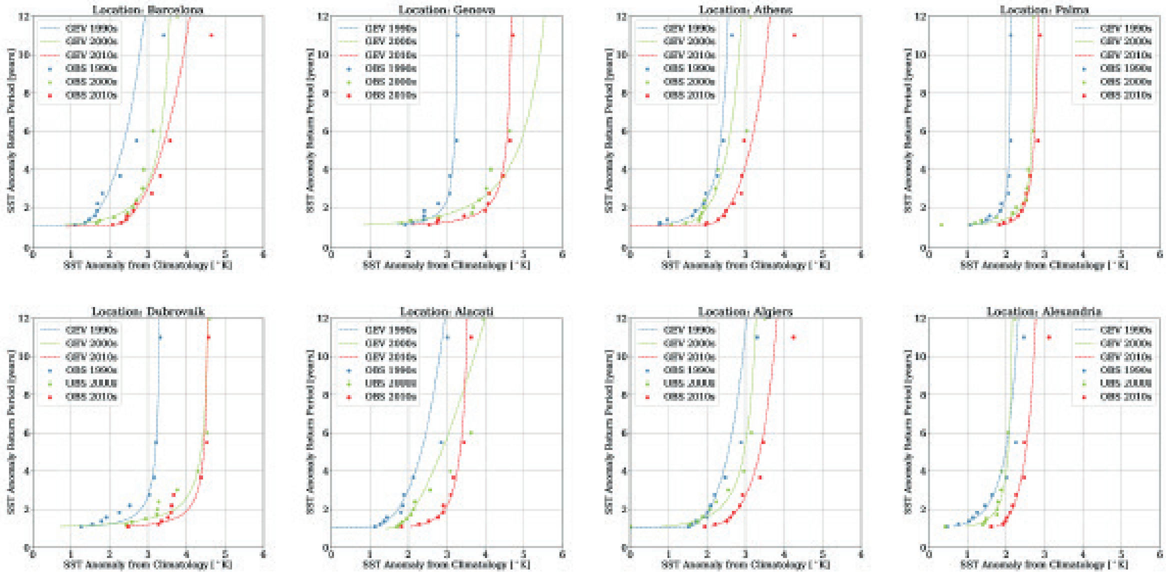


Figure 6. Return periods of SST anomalies computed for three subsequent decades, the 1990s (blues), 2000s (greens) and 2010s (reds). Plots are shown for various locations (indicated in the title of each plot) around the Mediterranean basin. Dots correspond to detected extremes, while the lines of the same color correspond to the GEV fit of these extremes.

There is a general observation to be made regarding the return periods of a specific temperature anomaly at any analyzed location: a particular SST anomaly from the 1990s (blue dots) has a longer return period than the same SST anomaly in the 2010s (red dots). Or, inversely, a specific return period from the 1990s dataset corresponds to a lower SST anomaly than the same return period in the 2010s. Inasmuch as temperature extremes occur during a MHW event, this supports (independently of the approach to MHW detection and classification in Hobday *et al*. 2016) the claim that Mediterranean MHWs are generally rising in frequency (Laufkötter *et al*. 2020). When interpreting this claim however, the reader must again keep in mind that shifts the Figure 6 are to an extent (see Simon, 2024 in this volume) a reflection of the temperature trend. This however does not mean that this shift is not an actual reflection of a real environmental stressor for marine organisms, namely the warming seas.

Another type of panoramic or spatially-dependent regional view of this increase of cumulative MHW intensity can be obtained by calculating *CI* (λ, ϕ) for the entire Mediterranean sea. After doing this for every year, and averaging over the five-year periods 1989-1993 and 2015-2019, we obtain the top two panels in Figure 7.

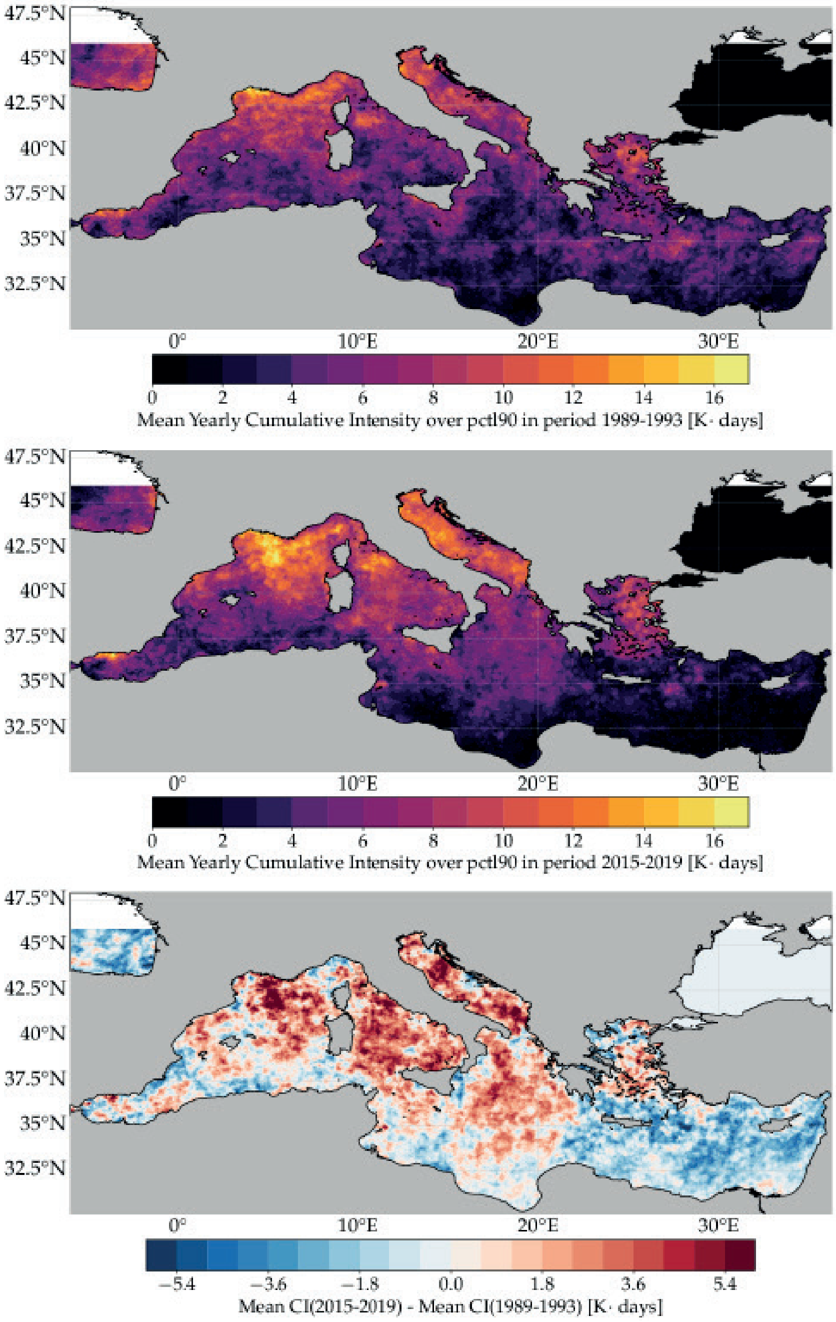


Figure 7. Yearly cumulative intensity averages [K - days] over periods 1989-1993 (top panel), 2015-2019 (middle panel) and their arithmetic difference (bottom panel).

These depict yearly cumulative intensity averages [◦K - days] over periods 1989-1993 (top panel), 2015-2019 (middle panel), while their arithmetic difference is shown in the bottom panel.
During both time windows, the areas most prone to MHWs seem to be the Gulf of Lion, the Ligurian sea, the Adriatic and Aegean seas, which is consistent with the results presented by Simon *et al*. (2022), while the least heat accumulation occurs in the Levantine basin and along the shores of Egypt, Libya and Tunisia. However the 2015-2019 period indicates a visible rise in MHW-related cumulative intensity, most glaringly in the Gulf of Lion, Ligurian, Tyrrhenian, Adriatic and Ionian seas. On the other hand, the Levantine basin that shows a decline in cumulative intensity.

3 Conclusions

We have analyzed basic statistic properties and return periods of MHWs from a multidecadal time series of satellite observations in the Mediterranean Basin. We show in the northern Adriatic there is a seasonality in the SST anomaly, with most MHWs and MCS occurring in the summer. We further show that for a number of locations around the Basin, the MHWs are getting more frequent in the 2010s compared to the 1990s. We show this following two distinct methodologies, one tracking frequency of SST anomalies with respect to a fixed 30-year climatological baseline (Hobday *et al*. 2016) and another through making no assumptions about the climatology, but rather focusing on fitting identified local extremes to a GEV distribution (Rypkema and Tuljapurkar 2021). An alternative approach to Hobday *et al*. (2016) was chosen because recent studies (Rosselló *et al*. 2023, Martínez *et al*. 2023) suggested that a fixed baseline likely leads to a misrepresentation of MHWs and MCSs frequencies in the presence of a warming trend in the ocean.

We further present regional maps of cumulative MHW intensity from the periods 1989-1993 and 2015-2019. The difference between the two fields indicates an increase in MHW related cumulative intensity in most of the Mediterranean, and with a decline of cumulative intensity in the Levantine basin. Attribution of these changes should be further investigated through analyses of atmospheric forcing, available for example in ERA5 reanalysis, and offers a possible trajectory for further research.

Our study also sheds light on the importance of considering long-term temperature trends in assessing the frequency of MHWs. While detrending the data might suggest a stable frequency of MHWs, retaining the trend provides a more ecologically relevant picture of increasing thermal stress on marine organisms.
We discussed the potential fast and slow adaptations of marine organisms to rising temperature trends and extreme heatwaves. These insights are crucial for predicting the resilience of marine ecosystems to ongoing climate change and informing conservation strategies. It is imperative to integrate these findings into regional and global climate adaptation and mitigation strategies so as to protect and sustain the Mediterranean marine environment and the communities that depend on it.

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References

Barbeaux S. J., Holsman K. and S. Zador. 2020. Marine heatwave stress test of ecosystem-based fisheries management in the gulf of Alaska pacific cod fishery. *Frontiers in Marine Science*, 7.

Brown C. J., Mellin C., Edgar G. J., Campbell M. D., and R. D. Stuart-Smith. 2021. Direct and indirect effects of heatwaves on a coral reef fishery. *Global Change Biology*, 27(6) :1214–1225.

Darmaraki S., Somot S., Sevault F. and Nabat, P. 2019. Past variability of Mediterranean Sea marine heatwaves. *Geophysical Research Letters*, 46(16): 9813-9823.

Garrabou J., Gómez Gras D., Medrano A., Cerrano C., Ponti M., Schlegel R., et al. 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Glob. Chang. Biol.*, 28(19): 5708-5725, doi:10.1111/gcb.16301

Gómez-Gras *et al*. 2021a. Climate change transforms the functional identity of Mediterranean coralligenous assemblages. *Ecology Letters*, 24(5):1038–1051.

Gómez-Gras D., Linares C., López-Sanz A., Amate R., Ledoux J.-B., Bensoussan N., Drap P., Bianchimani O., Marschal C., Torrents O., Zuberer F., Cebrian E., Teixidó N., Kipson S., Kersting D., Montero Serra, I., Pagès Escolà M., Medrano A., Frleta-Valić M. and J. Garrabou. 2021b. Population collapse of habitat-forming species in the Mediterranean: A long-term study of gorgonian populations affected by recurrent marine heatwaves. Proceedings of the Royal Society B: *Biological Sciences*, 288, 20212384. https://doi.org/10.1098/rspb.2021.2384

Hamdeno M., and A. Alvera-Azcaráte. 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Front. Mar. Sci*., 10, 1093760. doi:10.3389/FMARS.2023.1093760/BIBTEX.

Harris R., Beaumont L., Vance T., Tozer C., Remenyi T., Perkins-Kirkpatric K, S., Mitchell P., Nicotra A., McGregor S., Andre X. N., Let- nic M., Kearney M., Wernberg T., Hutley L., Chambers L., Fletcher M., Keatley M., Woodward C., Williamson G., Duke N., and D. Bowman. 2018. Biological responses to the press and pulse of climate trends and extreme events. *Nature Climate Change*, 8(7):579–587. Correction at Harris, R.M.B., Beaumont, L.J., Vance, T.R. *et al.* 2018 Author Correction: Biological responses to the press and pulse of climate trends and extreme events. *Nature Clim Change 8*, 840. https://doi.org/10.1038/s41558-018-0237-3.

Hobday A. J., Alexander L. V., Perkins S. E., Smale D. A., Straub, S. C., Oliver E. C., Benthuysen J. A., Burrows M. T., Donat M. G., Feng M., Holbrook N. J., Moore P. J., Scannell H. A., Sen Gupta A., and Wernberg T. 2016. A hierarchical approach to definin marine heat waves. *Progress in Oceanography*, 141:227– 238.

Hobday A.J., Oliver E.C., Gupta A.S., Benthuysen J.A., Burrows M.T., Donat M.G., Holbrook, N.J., Moore P.J., Thomsen M.S., Wernberg T. and Smale D.A., 2018. Categorizing and naming marine heatwaves. *Oceanography*, 31(2):173.

Laufkötter C., Zscheischler J., and T. L Frölicher. 2020. High-impact marine heat waves attributable to human-induced global warming. *Science*, 369(6511):1621–1625

Martínez J., Leonelli F. E., Garcia-Ladona E., Garrabou J., Kersting D., Bensoussan N., and A. Pisano. 2023. Evolution of marine heatwaves in warming seas: the Mediterranean Sea case study. *Front.Mar.Sci*,10:1193164

Oliver E. C. J. 2016. Marine heatwaves detection code. https://github.com/ecjoliver/marine HeatWaves.

Pastor F. and S. Khodayar. 2023. Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of The Total Environment*, 861, 160621.

Rosselló P., Pascual A., and Combes V. 2023. Assessing marine heat waves in the Mediterranean sea: a comparison of fixed and moving baseline methods. *Frontiers in Marine Science*, 10:1168368.

Rypkema D. and S. Tuljapurkar. 2021. Chapter 2 - modeling extreme climatic events using the generalized extreme value (gev) distribution. pages 39–71. In Data Science: Theory and Applications [Srinivasa Rao A. S. and Rao, C., Eds], volume 44, Handbook of Statistics. Elsevier.

Sen Gupta A., Thomsen M., Benthuysen J. A., Hobday A. J., Oliver E., Alexander L. V., et al. 2020. Drivers and impacts of the most extreme marine heatwaves events. *Sci. Rep.*, 10, 19359. doi:10.1038/s41598-020-75445-3.

Simon A., Plecha S.M., Russo A., Teles-Machado A., Donat M.G., Auger P-A. and R.M Trigo. 2022. Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. *Front. Mar. Sci*. 9: 892201 [12 p.]

Verdura J., Linares C., Ballesteros E., Coma R., Uriz M. J., *et al.* 2019. Biodiversity loss in a Mediterranean ecosystem due to an extreme warming event unveils the role of an engineering gorgonian species. *Scientific Reports*, 9, 5911. https://doi.org/10.1038/s41598-019-41929-0.

Yeruham E., Rilov G., Shpigel M. and A. Abelson. 2015. Collapse of the echinoid Paracentrotus lividus populations in the Eastern Mediterranean - result of climate change? *Scientific reports,* 5:13479.

The need to adopt process-based or impact-based definitions for marine heatwaves

Giovanni Liguori

Dpt. of Biology, Geology and Environmnt, Univ. of Bologna, Italy

Abstract

The oceanographic and climate research communities are actively working to establish a common definition for Marine Heatwaves (MHWs), but the lack of consensus poses a significant challenge for retrospective comparisons among different MHW studies. This obstacle is crucial for gaining a mechanistic understanding of MHWs' role in marine ecosystems.
The difficulty in characterizing and defining MHWs arises from the absence of a singular, distinct dynamical mechanism responsible for the persistence of heat anomalies in the ocean. In contrast to phenomena like large oceanic eddies, oceanic fronts, upwelling systems, tropical cyclones, or climate modes, prolonged heat anomalies lack characteristic time or spatial scales. Therefore, existing MHW definitions group together temperature anomalies lasting from days to years and spanning from a few kilometers to thousands of kilometers.

Analysis of sea surface temperature (SST) anomalies through power spectra reveals a «red» power spectrum without a uniquely discernible time scale. Similarly, spatial analysis shows a lack of specific scales. Due to the absence of emergent scales, a suggested solution is to adopt a process-based or an impact-based definition for MHWs (a combination of the two might work even better). This approach would categorize all events into a smaller number of groups, each linked to a specific impact, driver or dynamical process operating on certain spatiotemporal scales. This shift could significantly reduce subjectivity in selecting temporal and spatial scales, ultimately advancing our understanding of MHWs.

Keywords: *extreme marine environments; temperature extremes; marine heatwaves; MWH definitions; Mediterranean Sea.*

Introduction

In recent years, the escalating frequency and intensity of marine heatwaves (MHWs) have become a prominent subject of research (Darmaraki *et al*. 2019 ; Dayan *et al*. 2023; Oliver *et al*. 2018). The scientific literature on MHWs offers valuable insights into their ecological, environmental, and socio-economic impacts (Benthuysen *et al*. 2020). A key focus is the profound influence of MHWs on marine ecosystems, leading to consequences such as mass mortality in benthic communities (Coma *et al*. 2009; Garrabou *et al*. 2009; also 2024 in this volume), coral bleaching events (Le Nohaïc *et al*. 2017), disruptions in fishery yields (Mills *et al*. 2013), and shifts in species distributions (Sorte *et al.* 2010). While the long-term ecological implications of these disruptions are still under investigation, they are expected to be extensive.

However, the absence of a universally accepted definition for MHWs has led to variations across studies. Generally, MHWs are described as prolonged discrete periods of unusually warm sea surface temperatures in a specific region. Definitions vary, with some emphasizing deviation from a long-term mean temperature, identifying MHWs as periods exceeding a certain threshold above the historical average (Hobday *et al*. 2016). Others consider the absolute temperature anomaly, requiring temperatures to reach a specific value above the local climatology. With regard to duration, definitions differ, with some specifying a minimum consecutive number of days with elevated temperatures (Hobday *et al.* 2016), while others focus on the cumulative heat content anomaly over a specified period. Spatially, MHWs can be defined at different scales, from localized small events (Hamdeno and Alvera-Azcaráte 2023) to broader regional or basin-wide occurrences, such as the 2015 «warm blob» event in the North Pacific (Bond *et al*. 2015; Di Lorenzo and Mantua 2016).

The lack of unanimous agreement among scientists regarding a shared definition for MHWs goes beyond a technical issue, as seen with defining and counting tropical cyclones (Hart et al. 2016). Instead, it stems from a fundamental characteristic of MHWs: they do not represent distinct phenomena or possess a fixed set of dynamics. Rather, they emerge from the complex, turbulent nature of the oceanic fluid, exhibiting temporal scales spanning from days to years (and longer) and spatial extents that can range from confined coastal areas to large oceanic regions. When examining the physical and dynamic aspects, the absence of clearly defined scales for marine heatwaves challenges the viability of an approaches for defining that depends on arbitrary choices for temporal and spatial scales, as illustrated by the commonly used criterion of five consecutive days (Hobday *et al*. 2016). Therefore, we propose two alternative approaches to defining MHWs: an impact-based approach (i) and a process-based approach (ii).

The impact-based approach delves into the inherent connection between temperature and a specific system it affects, whether it be a local marine ecosystem, a fish farm, or any other relevant system. This approach is particularly suitable when the objective is not an exhaustive or in-depth physical understanding but rather a practical method for efficiently managing marine resources. The process-based approach defines MHWs in relation to the underlying mechanisms driving them, such as anomalous atmospheric conditions, upwelling suppression (vertical heat exchange), ocean currents (horizontal heat exchange), or specific climate modes or sets of dynamics. This approach enables a more profound comprehension of the distinct physical mechanisms governing various types of marine heatwaves, with the potential to advance predictive methodologies. In contrast to many existing MHW definitions, which hinge on arbitrary temporal and spatial scales (e.g., the 5-day consecutive temperature anomaly rule), a process-based approach establishes these scales on a solid understanding of the underlying physical processes. This significantly reduces the arbitrary nature of scale selection.

Upon examining commonly accepted definitions of MHWs, we highlight the contrast between these definitions and the absence of distinct spatial and temporal scales for MHWs, which largely exhibit a red-noise spectrum in both time and space. In pursuit of this, we conducted a series of analyses using daily mean sea surface temperature (SST) anomalies over the Mediterranean Sea, a region we consider to be an excellent test region due to its spatial constraints and numerous dynamic features mirroring those of the world Ocean (Bethoux *et al*. 1999).

Subsequently, we establish the foundation for a process-based definition that, following years of rigorous discussions within the scientific community, aims to develop standardized classification methods. These methods hold great promise, offering significant advantages such as facilitating quantitative comparisons across diverse studies and shedding light on the ocean processes that enhance the predictability of such extreme events.

Lack of characteristic spatial and temporal scales

As previously noted, marine heatwaves (MHWs) demonstrate significant diversity in both their temporal and spatial scales. Temporally, MHWs can be brief, lasting for a few days to a few weeks, often influenced by local conditions. An example of such events is the series of MHWs that occurred in the Mediterranean Sea during the summer of 2019 (Hamdeno and Alvera-Azcaráte 2023). Intermediate-term MHWs persist for weeks to several months, often associated with regional climate patterns. Long-term MHWs, extending for several months to multiple years, are linked to large-scale climate phenomena. Spatially, MHWs range from localized events impacting small coastal areas, driven by factors like local ocean currents or coastal geography. Regional MHWs cover broader coastal regions and oceanic zones, often influenced by regional climate patterns (Bond *et al*. 2015; Di Lorenzo and Mantua 2016). In rare instances, global-scale MHWs occur, affecting multiple ocean basins concurrently, often associated with the positive phase of El Niño-Southern Oscillation (ENSO). For a visual representation of this wide range of spatiotemporal scales associated with MHWs, we direct the reader to a recent review article by Oliver and co-authors (2021). This broad spectrum in spatial and temporal scales underscores the absence of a singular set of dynamics underlying all MHW events. Therefore, envisioning a unified framework for achieving physically-grounded predictions of MHW events, akin to what is done for tropical cyclones or ENSO events, is challenging. We contend that the typical «counting exercise» (i.e., statistical characterization) undertaken in MHW studies is unlikely to yield any new theoretical understanding of these types of oceanic extremes.

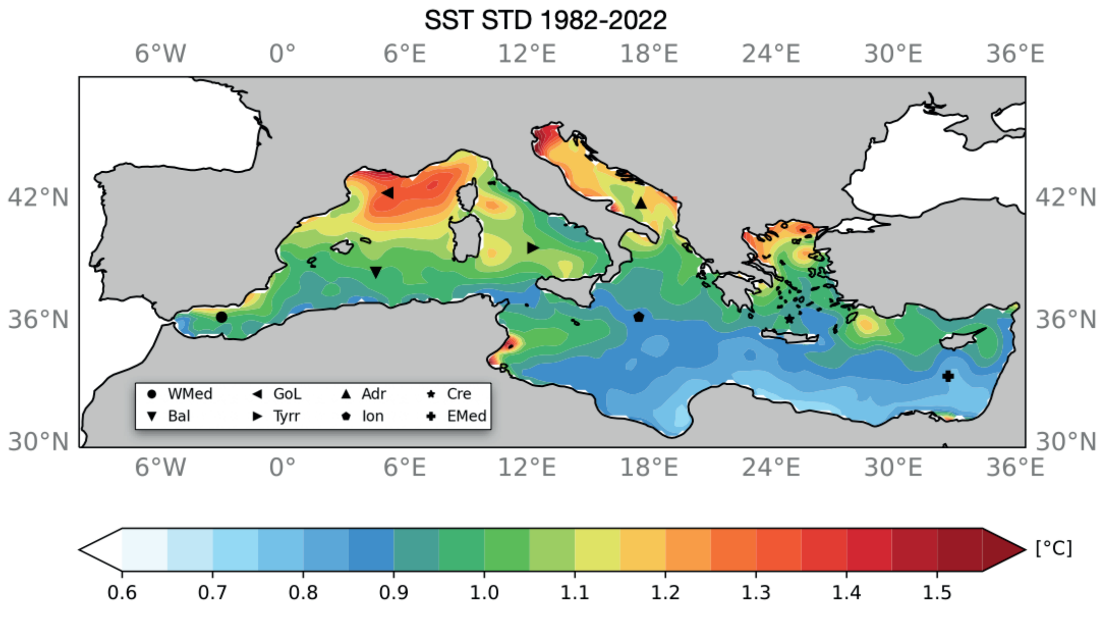

Figure 1. Map of SST standard deviation computed from observational daily mean anomalies over the period 1982-2022. The SST data were sourced from the National Oceanic and Atmospheric Administration's Optimum Interpolation Sea Surface Temperature dataset version2 (OISSTv2), as described by Reynolds et al. in 2007. This dataset covering the world ocean involves the interpolation of sea surface temperature values derived from AVHRR imagery into a consistent grid format with a spatial resolution of 0.25° x 0.25° and a daily temporal resolution. The marks indicate the locations that were chosen for the power spectra analysis presented in Figure 2: Western Mediterranean Sea (WMed), Gulf of Lion (GoL), Balearic Islands (Balea), Tyrrhenian Sea (Tyrr), Adriatic Sea (Adr), Ionian Sea (Ion), Cretan Sea (Cre) and Eastern Mediterranean Sea (EMed).

Being extreme in temperature, MHWs are inherently linked to Sea Surface Temperature (SST) variability. Therefore, one might initially assume that areas with high SST variability are more susceptible to MHW events. In the case of the Mediterranean Sea basin, which we will use as a testbed to illustrate our main point about the lack of a characteristic temporal and spatial scale, this assumption holds to some extent. An uncomplicated map (Fig. 1) depicting the standard deviation (STD) of daily SST anomaly (SSTa) computed over the period 1928-2022 mirrors the map of MHW occurrence frequency (Fig. 3), calculated using a common methodology (Hobday *et al*. 2016). The pattern exhibits a distinct latitudinal component, even after eliminating the seasonal cycle by subtracting the long-term daily mean from 1971-2000, suggesting that SSTa variability is still influenced by the seasonal cycle.

In general terms, the spatial distribution of prolonged extremes in SSTa (i.e., MHW events) tends to align with the STD of SSTa, which supports the hypothesis that SSTa variability results from a red-noise process driven by randomness in the atmosphere, with the ocean serving as a heat capacity that integrates atmospheric heat fluxes. This well-established paradigm for climate variability (Song and Wu 2022) explains a significant portion of the observed variance in the Mediterranean Sea. In fact, an examination of the frequency domain through a power spectral analysis (Fig. 2) for eight representative locations within the basin reveals that the only clear features not accounted for by the red-noise hypothesis are the remnants from the seasonal cycle (considering the dataset has been de-seasoned). Depending on the specific location, the power spectra for periodicities between 4 days and 2 months may appear distinct from the red-noise confidence interval of 95%. However, upon closer inspection, this might simply be a result of the relatively short time series used for calculating the power spectra, preventing a smooth estimation of each frequency's power.

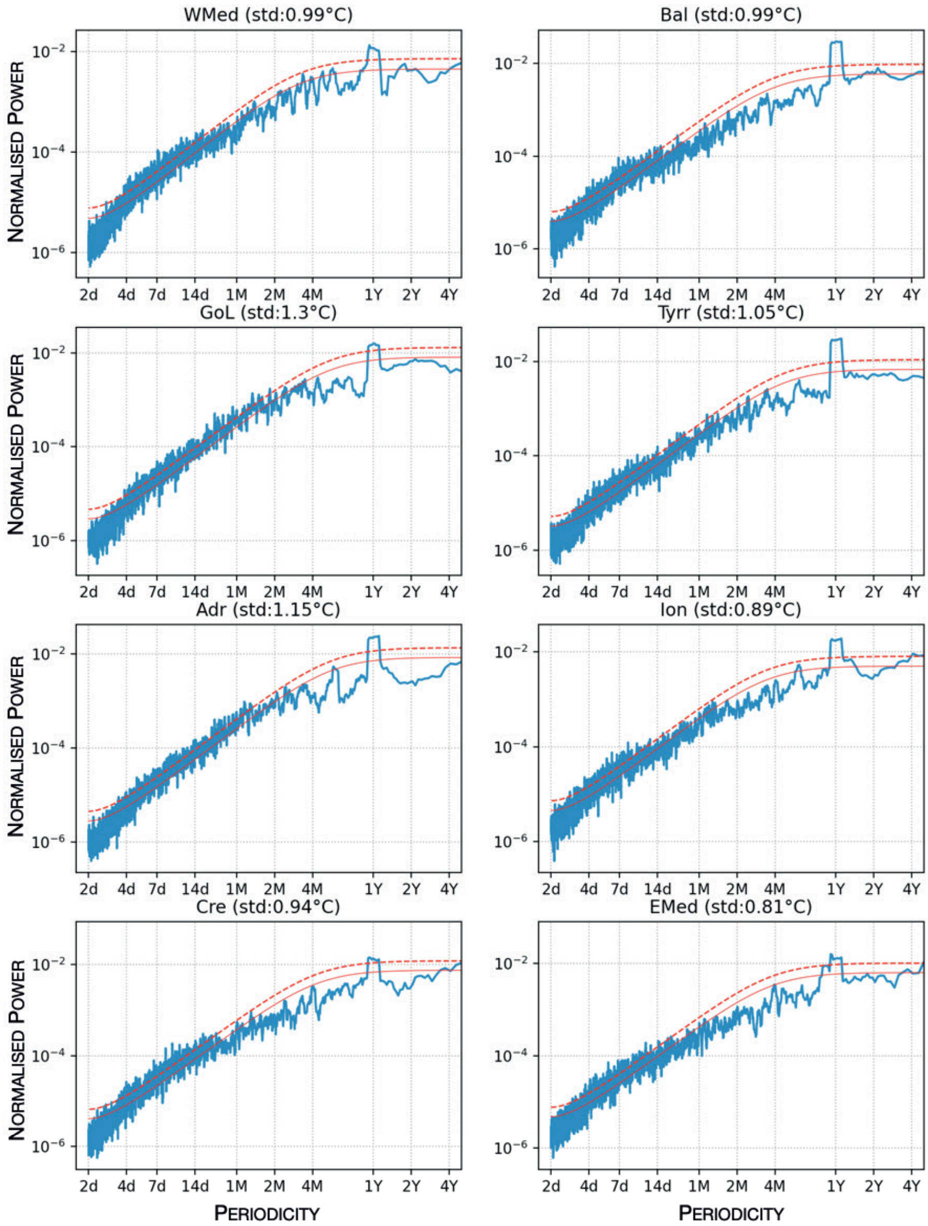

Figure 2. Power spectral density (solid blue) of daily sea surface temperature anomaly for the location shown in Fig. 1. The dataset covers the years from 1982 to 2022. Figures also depict the best fit for a red-noise process (solid red) with the same lag-1 autocorrelation as the temperature time series, and the red-noise 95% confidence interval (dashed red).

The absence of a preferred timescale for the duration of oceanic temperature anomalies indicates that definitions of MHWs relying on specific temporal thresholds are not only arbitrary but also result in MHW statistics that are highly sensitive to the chosen threshold.

Since the term «Marine Heatwaves» first appeared in the scientific literature in 2011 (Pearce *et al*. 2011), numerous quantitative definitions have been proposed to identify and characterize the spatial-temporal statistics of these marine extreme events. Currently, one of the most commonly used definitions for MHWs was introduced by Hobday *et al*. 2016. This definition describes marine heatwaves as prolonged periods of unusually warm ocean conditions lasting at least five consecutive days, with sea surface temperatures (SST) surpassing the seasonally varying 90th percentile threshold. To establish this threshold, climatological averages and the 90th percentile are calculated for each grid cell on a daily basis throughout the year, utilizing historical daily SST data typically spanning a reference period of at least 30 years. Additionally, when two MHW events occur within a gap of two days or less, they are considered a single continuous event. These MHW events are characterized by key metrics, including duration, frequency, mean intensity, maximum intensity, cumulative intensity, and total days.

Despite its widespread use, this definition relies on a fully arbitrary assumption regarding the minimum time length of an MHW event, set to 5 days. The significant drawback of this arbitrariness in the minimum temporal scale lies in the fact that MHW statistics computed with different thresholds can exhibit substantial disparities. This, in turn, makes it challenging to draw robust and universally applicable conclusions regarding the spatial characteristics of such marine extreme events. To illustrate this issue, we examined the frequency of MHW occurrences (expressed as events per decade) in the Mediterranean Sea from 1982 to 2022 using various minimum length thresholds. Our results (see Fig. 3) reveal noteworthy variations in the patterns, exemplified by the North Adriatic Sea. It appears as a prominent MHW hotspot when the minimum length threshold is set at 5 days, but this characterization does not hold when the threshold is adjusted to 3 days or extended to 14 days or more. It is clearly challenging to definitively determine whether this area qualifies as a hotspot for MHW events.

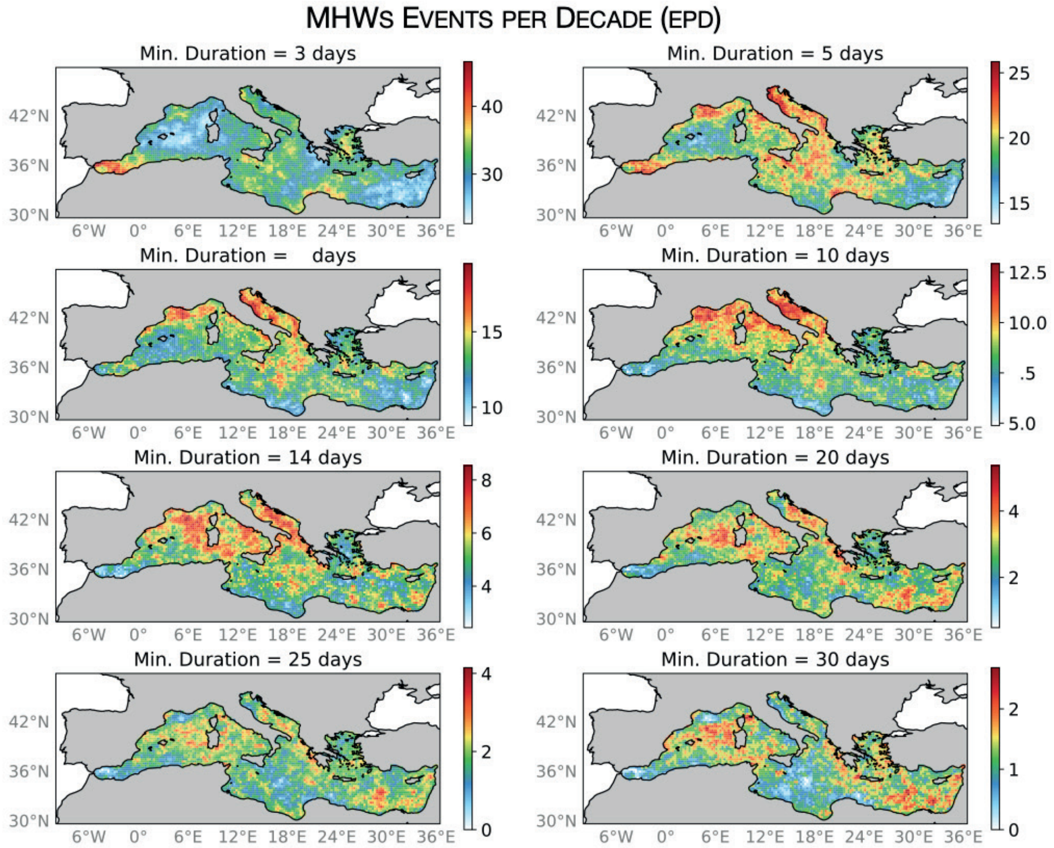

Figure 3. Frequency of occurrence for marine heatwaves in the Mediterranean Sea during the study period (1982-2020) using the detection algorithm from Hobday *et al.* (2016) for several threshold values for MHW minimum length. Unit is events per decade (EPD).

A process-based definition for MHW

A mere statistical characterization of ocean temperature extremes does not contribute to a deeper understanding of the drivers and causes behind these extremes, nor does it significantly improve predictive accuracy. The reliance on forecasting the full three-dimensional ocean limits the effectiveness of current approaches. Hence, we advocate for a transition to a marine heatwave classification that categorizes events according to their underlying physical processes. This shift has the potential to diminish the subjectivity in defining marine heatwaves, as the criteria would be grounded in our comprehension of the involved physical mechanisms. Several drivers contribute to the occurrence of MHWs, encompassing factors such as elevated air temperatures, intensified solar radiation, reduced cloud cover, shallower mixed layers above colder deep ocean regions, diminished wind speeds leading to reduced evaporative cooling, changes in ocean currents and upwelling systems, the influence of large-scale climate patterns like El Niño-Southern Oscillation, and the overarching impact of climate change. For certain drivers, the spatiotemporal scales involved are reasonably known, providing fundamental information to establish a definition for specific categories of marine heatwaves. For instance, in cases where MHWs are associated with persisting warm core eddies or are generated by the weakening of a climatological upwelling system, the characteristic timescales may range from weeks to months.

Various factors contribute to the occurrence of marine heatwaves (Sen Gupta *et al.* 2020). These influencing factors include elevated air temperatures, increased solar radiation, reduced cloud cover, shallower mixed layers above colder deep ocean regions, diminished wind speeds leading to decreased evaporative cooling, changes in ocean currents and upwelling systems, the impact of large-scale climate patterns such as El Niño-Southern Oscillation, and the overarching influence of climate change. Some of these drivers already have associated knowledge regarding the spatiotemporal scales involved, providing valuable insights for developing specific categories for MHWs.

As an example, for MHWs linked to persistent warm core eddies (Zhao *et al.* 2022), the characteristic timescale may vary from weeks to months. Similar timescales are observed in MHWs resulting from the weakening of a climatological upwelling system. By taking into account these underlying physical processes and their associated spatiotemporal scales, we can establish a more precise and informative framework for the classification of marine heatwaves. This approach has the potential to enhance both the understanding and prediction of these critical oceanic events.

Conclusion

We contend that relying solely on statistics for defining Marine Heatwaves may not yield fruitful results due to the absence of a singular, specific dynamical mechanism responsible for persistent heat anomalies in the ocean. Unlike phenomena such as large eddies, oceanic fronts, and upwelling systems, MHWs lack characteristic time and spatial scales, as indicated by power spectral analyses of sea surface temperature anomalies. Focusing solely on temperature statistics may not contribute to gaining new insights into MHW drivers or assessing multifactor impacts.

To illustrate this point, let us draw an analogy to the investigative work of a doctor treating a patient. Informing the doctor of a high fever alone is insufficient to establish a diagnosis, prescribe a treatment plan, and forecast the patient's health progress. However, when the goal is to study or assess the impact of prolonged extreme temperatures, a case-specific MHW definition can be very helpful in understanding the relationship between specific temperature levels and the variable or system of interest. Nevertheless, when examining the consequences of prolonged, extreme temperatures on, for example, the marine ecosystem, a case-specific definition for MHW becomes invaluable in comprehending and assessing the connection between specific temperature extremes and the variable or system under investigation.

However, within a context focused on specific impacts the relevance of the concept of MHW events might diminish, as restricting impact assessments solely to temperature extremes may no longer be necessary. Instead, a multivariate approach should be embraced, encompassing all pertinent variables associated with a particular impact. For instance, when assessing the ideal conditions for a fish farm to thrive, additional factors such as salinity, oxygen and pH should be considered. Furthermore, considering the diverse array of drivers leading to MHW events, it becomes apparent that enhancing their prediction, typically achieved through forecast models, necessitates an improved understanding of a wide range of oceanic and atmospheric processes. This can be summarized as the need for better models, a platitude that is not particularly helpful.

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References

Benthuysen J. A., Oliver E. C. J., Chen, K. and T. Wernberg. 2020. Editorial: Advances in Understanding Marine Heatwaves and Their Impacts. *Frontiers in Marine Science*, *7*, Article 147. https://doi.org/10.3389/fmars.2020.00147

Bethoux J.P., Gentili B., Morin P., Nicolas E., Pierre C., and D. Ruiz-Pino. 1999. The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. *Progress in Oceanography*, *44*(1-3), 131-146. https://doi.org/10.1016/s0079-6611(99)00023-3

Bond N.A., Cronin M.F., Freeland H., and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, *42*(9), 3414-3420. https://doi.org/10.1002/2015gl063306

Coma R., Ribes M., Serrano E., Jiménez E., Salat J., and J. Pascual. 2009. Global warming-enhanced stratification and mass mortality events in the Mediterranean. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(15), 6176-6181. https://doi.org/10.1073/pnas.0805801106

Darmaraki S., Somot S., Sevault F., Nabat P., Cabos Narvaez W. D., Cavicchia and D. V. Sein. 2019b. Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, 53, 1371-1392. https://doi.org/10.1007/s00382-019-04661-z

Dayan H., McAdam R., Juza M., Masina S., and S. Speich. 2023. Marine heat waves in the Mediterranean Sea: An assessment from the surface to the subsurface to meet national needs. *Front. Mar. Sci*., 10, 142, doi:10.3389/fmars.2023.1045138

Di Lorenzo, E. and Mantua, N. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, 6(11):1042-1047. https://doi.org/10.1038/nclimate3082

Garrabou J., Coma R., Bensoussan N., Bally M., *et al*. 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, 15: 1090–1103. https://doi.org/10.1111/j.1365-2486.2008.01823.x

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Hamdeno M., and A. Alvera-Azcaráte. 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Front. Mar. Sci.*, 10, 1093760. doi:10.3389/FMARS.2023.1093760/BIBTEX.

Hart R. E., Chavas D. R., and M.P. Guishard. 2016. The arbitrary definition of the current Atlantic major hurricane landfall drought. *Bulletin of the American Meteorological Society*, 97(5): 713-722. https://doi.org/10.1175/bams-d-15-00185.1

Hobday A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Moore, P. J., Scannell, H. A., Sen Gupta, A., and Wernberg, T. 2016. A hierarchical approach to define marine heat waves. *Progress in Oceanography*, 141: 227– 238. https://doi.org/10.1016/j.pocean.2015.12.014

Le Nohaïc M., Ross C.L., Cornwall C.E., Comeau S., Lowe R., McCulloch M.T., and V. Schoepf. 2017. Marine heatwave causes unprecedented regional mass bleaching of thermally resistant corals in northwestern Australia. *Scientific Reports*, 7, Article 14999. https://doi.org/10.1038/s41598-017-14794-y

Oliver E. C. J., Benthuysen J. A., Darmaraki S., Donat M. G., Hobday A. J., Holbrook N. J. and A. Sen Gupta. 2021. Marine Heatwaves. *Annual Review of Marine Science, 13*: 313-342. https://doi.org/10.1146/annurev-marine-032720-095144

Oliver E.C., Donat M.G., Burrows M.T., Moore P.J., Smale D.A., Alexander L.V., *et al.* 2018. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.*, 9:1324, https://doi.org/10.1038/s41467-018-03732-9

Pearce A., Lenanton R., Jackson G., Moore J., Feng M. and Gaughan D. 2011. The “marine heat wave” off Western Australia during the summer of 2010/11. Fisheries Research Report No. 222. Department of Fisheries, Western Australia. 40pp.

Reynolds R.W., Smith T. M., Liu C., Chelton D. B., Casey K. S. and M.G. Schlax. 2007. Daily high-resolution-blended analyses for sea surface temperature. *J. Clim.* 20 5473–96.

Sen Gupta A., Thomsen M., Benthuysen J. A., Hobday A. J., Oliver E., Alexander L. V., *et al.* 2020. Drivers and impacts of the most extreme marine heatwaves events. *Sci. Rep*. 10, 19359. https://doi:10.1038/s41598-020-75445-3

Song, F. F., and L. X. Wu. 2022. The 2021 Nobel Prize in Physics: Discussion on the contributions of Klaus Hasselmann. *Chinese Science Bulletin-Chinese*, 67(6): 557-560. https://doi.org/10.1360/tb-2021-1211

Sorte, C.J.B., Fuller, A., and Bracken, M.E.S. 2010. Impacts of a simulated heat wave on composition of a marine community. *Oikos*, 119(12): 1909-1918. https://doi.org/10.1111/j.1600-0706.2010.18663.x

Zhao Z. J., Holbrook N. J., and E. C. J. Oliver. 2022. An eddy pathway to marine heatwave predictability off eastern Tasmania. *Frontiers in Climate*, 4, Article 907828. https://doi.org/10.3389/fclim.2022.907828

Marine heatwave research:
A path forward via the Mediterranean and the Arctic

Robert W. Schlegel

Sorbonne Univ, CNRS, LOV, Villefranche-sur-mer, France

Abstract

Extreme ocean temperature events, now often referred to as marine heatwaves (MHWs), are not a new phenomenon. They have been occurring naturally as far back as written human records exist. However, the anthropogenic forcing of the global climate system has aggravated this natural phenomenon so severely that the philosophical underpinning for how to define these events has become hotly debated. Because the global rate of warming is so advanced, defining these events based on historical data will lead to the occurrence of never-ending MHWs (e.g. annual durations of 365 days). A solution to this paradox is to remove the warming trend before detecting events. Unfortunately this renders these results sub-optimal for bio/ecological research. With no clear resolution in sight for this issue, it is proposed here to pivot away from the general definition of MHWs towards a mechanistic one. The argument being that, because the extreme values within seawater temperature time series no longer adhere to the standard 'climate normal' (*sensu* WMO), we can no longer define extreme temperature events via temperature data alone. Evidence from the Mediterranean and the Arctic is given in support of this debate, and a roadmap on the next steps is discussed.

Keywords: *marine heatwaves, MWH definitions, Mediterranean, Arctic, Sea-Surface Temperature (SST)*

The path behind

A marine heatwave (MHW) is generally regarded as an event during which seawater temperature at a given location exceeds a locally relevant threshold for a given period of time. Even though a need for a quantitative definition had existed for years, it wasn't until the publications of Hobday *et al*. (2016, 2018) (hereafter referred to as the 'general' definition) that a central methodology for the detection of these saw broad use. The now familiar five day minimum length for temperatures above a 90th percentile seasonally varying threshold, based on a fixed 'climate normal' baseline (WMO 2023), has become synonymous with MHWs from South Africa to Southampton. For many years (and many more PhD theses) this quantitative approach reigned; however, it could never be that every facet of a concept so broad and complex as the cause and effects of extreme temperature events could be completely understood with a single algorithm (see Liguori 2024; Ličer 2024 for further argument, in this volume).

The first shortcomings in the utility of the general MHW definition surfaced a couple of years after the algorithm was published. Not long after the workshop that led to the publication of Hobday *et al*. (2016), a team consisting of many of the same authors analysed CMIP5 ensemble data to see what the state of MHWs would be in 2100 given different emissions scenarios (Oliver *et al*. 2019). What they found was surprising in that, regardless of the scenario, by 2050 the global ocean would be experiencing at least 300+ MHW days per year

(Figure 3 in Oliver *et al.* 2019). With large swathes of the surface of the ocean entering into permanent MHW states within a couple generations. This finding can be easily replicated (see Fig. 1 below). Using a fixed baseline of 1982-2011, one can see how many more MHW days there are on average between the first (Figure 1A) and last (Figure 1B) five year period of a global sea-surface temperature (SST) dataset (Huang *et al.* 2021). One may also see that the majority of the global ocean already started to experience regions with at least 183 MHW days in a given year (i.e. more than half the year was in a MHW state) from the 2010s to the 2020s (Figure 1C). Notable exceptions include the Southern Ocean, the Arctic Ocean (see below), and the equatorial Pacific (i.e. the el niño signal). On top of this, the rate of increase of MHW days per year is itself advanced, with much of the global ocean experiencing 4 to 8 more days per year (Figure 1D).

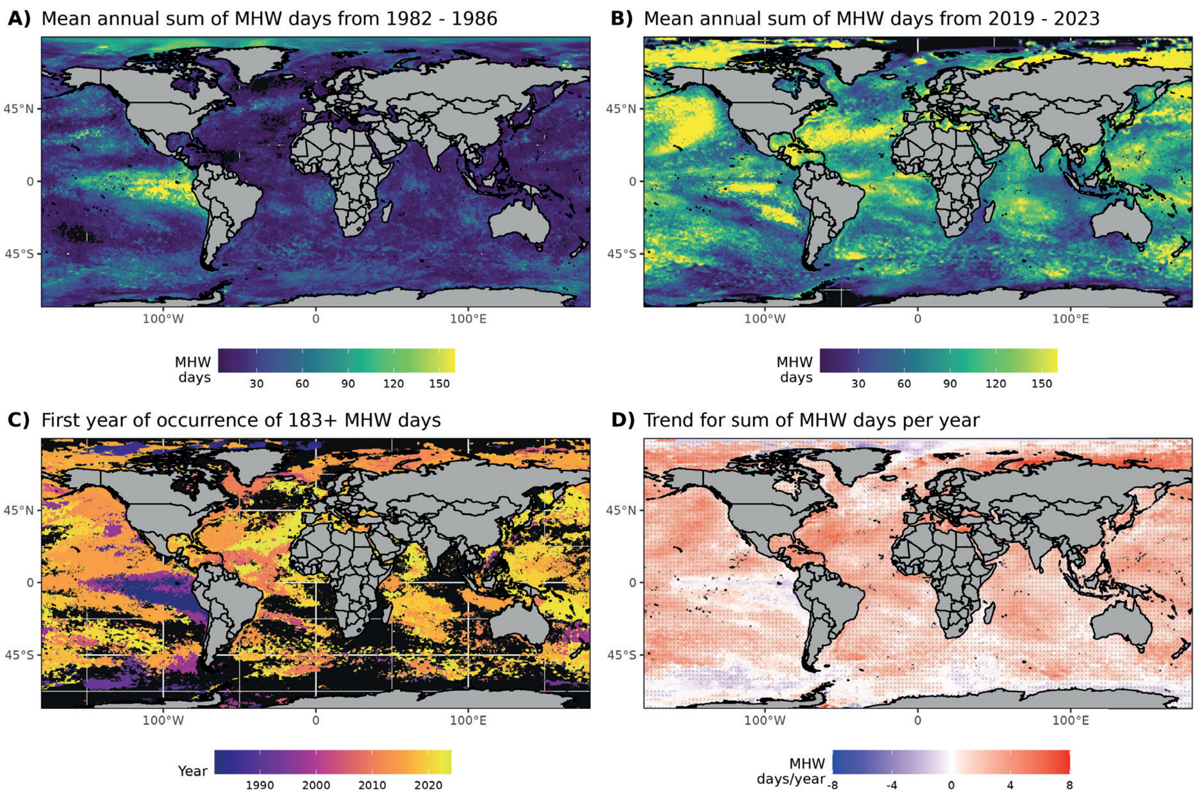

Figure 1: Historical (1982-2023) detection of marine heatwaves (MHWs) in the World ocean when applying the standard thresholds of the Hobday *et al.* (2016, 2018) definition to the NOAA OISST product (Huang *et al.* 2021) with a fixed baseline of 1982-2011. A) Average annual MHW days over the first five years of the data (1982-1986). B) Average annual MHW days over the last five years of the data (2019-2023). C) First year during which 183 MHW days or more occurred (i.e. more than half the year was in a MHW state). D) Linear trend of MHW days per year from 1982-2023. Stippling shows significant trends (p-value <= 0.05).

This brings us to the first issue which is that, philosophically, a MHW is at its core defined as an event. Meaning, if the majority of the year is spent in a MHW state, or worse, there is no end in sight for a MHW (*i.e.,* 365 day duration): what we have is a new normal state, not an extreme "event". Therefore, this approach to defining extreme temperature events via a fixed baseline must be addressed.

The proposed fix to the issue of dominant/permanent MHWs did not take long because many physical oceanographers and climate scientists were able to intuit that the issue causing the algorithm to detect constant MHW states was caused by the anthropogenic warming signal within a given seawater temperature time series interacting with the fixed baseline period. It was therefore decided by certain research teams to simply detrend their time series and use the full length of the time series as the baseline. The additional reasoning for this was that when one seeks to understand the physical forces that drive a MHW, one must separate the anthropogenic warming signal from the background variance in order to pinpoint what is causing an anomalous temperature fluctuation over a given series of days. Many studies have since been performed using this altered methodology, and many papers have been published. Often with the results of the original and detrended data side by side.

Whereas detrending and full baseline periods may address the issue of the constant MHW state from a numerical point of view, any biologist or ecologist will be very quick to point out that the anthropogenic warming of the planet matters for organisms and ecosystems, and one cannot simply remove it from an analysis. Whether or not marine life will be able to adapt to temperatures as the climate warms has yet to be seen in the long run, but already there have been many winners and losers (see Garrabou *et al*. ; Ghanem *et al*. ; Rilov *et al*. 2024 all in this volume). If one were to remove anthropogenic warming from a seawater temperature time series and then compare the MHWs detected therein with a record of bio/ecological damage in a given area, one would likely (and incorrectly) not see much of a relationship.

This divergence of views over the general definition has engaged the community, and a heated debate on the subject has been raging since at least 2019. Even though scientific researches, and opinion pieces, have been published arguing for each side, no real conclusion lies in sight because both arguments are valid for their own reasons. A deeper background on how exactly the current MHW algorithm responds to these changes may be found in Oliver *et al.* (2021). Suffice it to say that the MHW algorithm in its current state is likely reaching the end of its development. In order to create new methodologies for the quantification of MHWs we will likely need to shift into another way of thinking.

The Mediterranean path

A focus on the Mediterranean will be useful to frame the importance of the debate on how to define MHWs. Due to the rapid rate at which this region is warming, it is beginning to experience the numeric conundrum of dominant/constant MHW presence. Conversely, it is also home to many organisms that appear unable to adapt to this warming. We therefore discover a situation in which both approaches to detect MHWs are necessary, but neither set of results will suffice to fully investigate the situation.
For example, the Mediterranean (in conjunction with the Black Sea) is the fastest warming marine ecoregion on the planet. Already this body of water regularly has years with more than 80 MHW days averaged across the Basin (Fig. 2A). At the current rate of warming this

sea will have regions approaching the constant MHW state within 50 years. Indeed, nearly the entire surface (+90%) of the Mediterranean has already been experiencing at least one MHW almost every year since 2001 (Fig. 2B). What is perhaps even more striking is the increase in the coverage of category II "strong" MHWs over the last decade (Fig. 2B), and the emergence of the widespread and very worrying presence of category III "severe" events. The increasing rate of warming within the Mediterranean is itself visible, and numerically problematic. One should not simply detrend this time series with a linear model, because the trend itself is not linear (Wang *et al*. 2022). This same issue further complicates the choice of the baseline period.

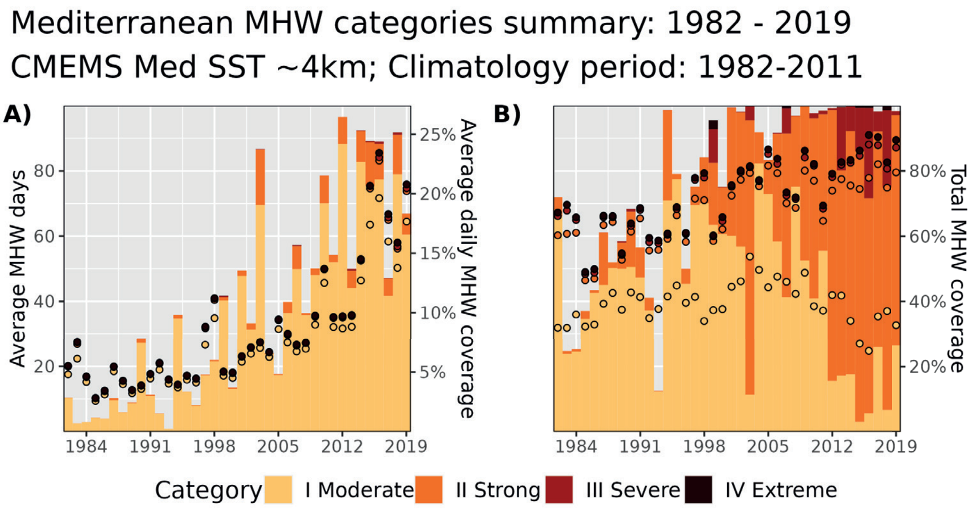

Figure 2. Summary MHW statistics from the Mediterranean, with colours showing the highest category detected for the given time period.
A) Stacked barplots showing the average MHW days occurring throughout the Mediterranean per year (left y-axis). The right y-axis shows the same value expressed as the percent surface of the Mediterranean that would have been experiencing a constant MHW for that year.
B) The total surface of the Mediterranean that experienced at least one MHW for a given year. The dots in panels A and B show the same statistics for the global ocean values, with the colour of the dots showing the category. Note that most dots in panel A are either yellow or black because, on a global scale, there is relatively little contribution to the daily MHW count other than category I, and a bit of category II. Therefore the dots for categories III and IV appear on top of the dots for category II. Barplots from CMEMS data (Merchant *et al.* 2019) with dots from NOAA data (Huang *et al.* 2021).

Regardless of the numeric issues one may face when handling the anthropogenic warming rate within one's data, the warming is critically important for understanding the biology. It has been known for years that Gorgonian sea fans, one of the ecosystem engineers of the Mediterranean, are extremely susceptible to MHWs (Garrabou *et al.* 2009). It is therefore no surprise that a recent study of mass mortality events across the Mediterranean from 2015 - 2019 found that Gorgonians, as well as many other important species, were experiencing mass mortalities annually (Garrabou *et al*. 2022). Were we to remove the warming trend from the data, there would be a mismatch between the physics and the biology. It would appear as if the endemic species of the Mediterranean were dying off from mysterious causes, detached from the reality of the anthropogenic thermal forcing to which they have been submitted.

Consider 1983, roughly the start of the satellite era and the lowest year on record in the Mediterranean for MHWs (Fig. 3A). In that year these events were not long lasting nor intense (Fig. 3B). Only ~20% of Mediterranean surface waters experienced a MHW on that year (Fig. 3C), and on average the Basin only endured 2.5 days of anomalous heat (Fig. 3D). This is what we tend to consider the "normal" environmental background against which the evolution of species has occurred. That is of course not completely accurate, as the planet had already warmed quite a bit before 1983, but it is what we have to work with. Now consider 2018 (Fig. 4A). While the choice of the colour palette does make the surface of the Mediterranean appear to be a hellscape, the research on the biology supports this perception. We now see periods of time in which as much as 80% of the surface of the Mediterranean is experiencing a MHW on the same day (Fig. 4B), with ~30% experiencing category III "severe" events (Fig. 4C), and averages of 80 MHW days across the Basin (Fig. 4D). This is *far* ahead of what we are seeing in the global ocean. The thermal regime of the Mediterranean is itself changing (Tuel & Eltahir, 2020), evidenced biologically by the influx of Red Sea species (CIESM Atlas of Exotic Fishes, 2021).

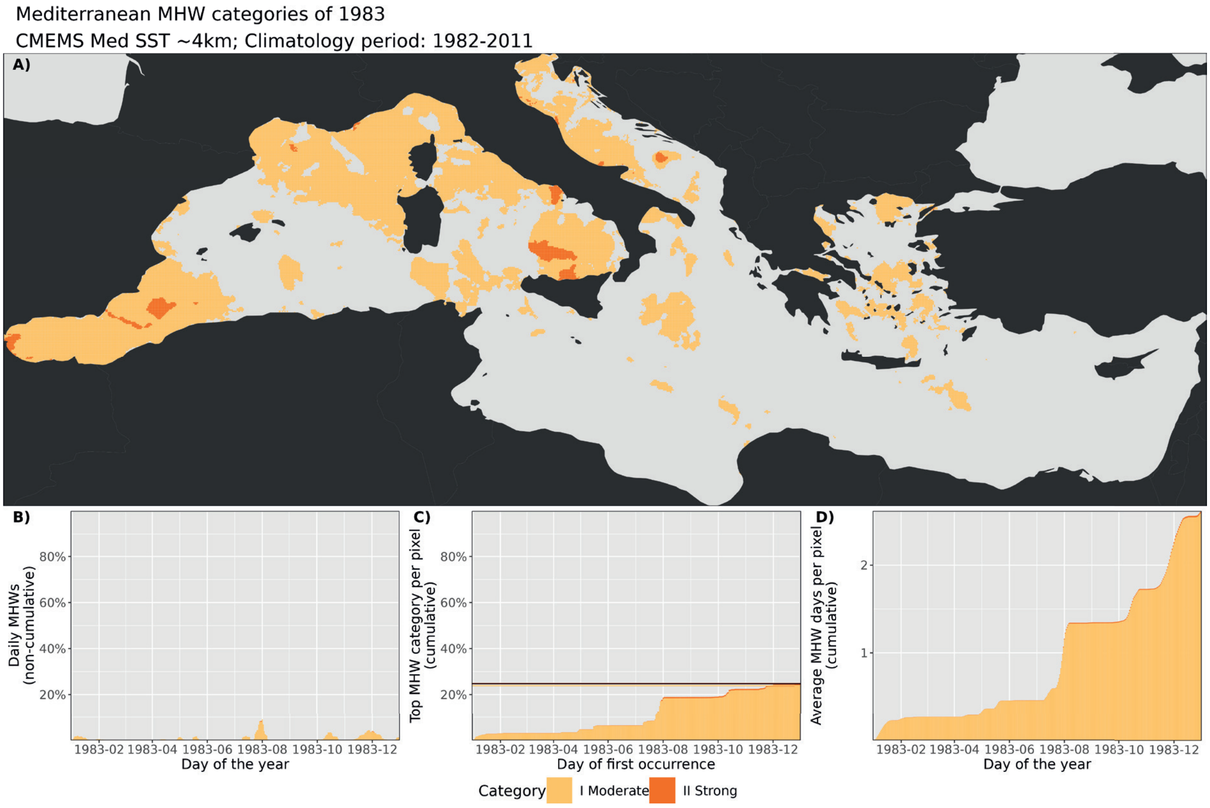

Figure 3. Map of marine heatwave (MHW) occurrence for the Mediterranean in 1983. Colours show the highest category detected for the given time period, and all values are weighted to the surface area of the pixels (i.e. pixels closer to the equator are larger).

A) The location of MHW occurrence during the year.

B) Surface area experiencing a MHW on a given day.

C) Cumulative surface area that experienced at least one MHW over the year. No area is counted more than once.

D) The average cumulative MHW days experienced over the course of the year when averaged across the Basin. Data from CMEMS (Merchant *et al.* 2019).

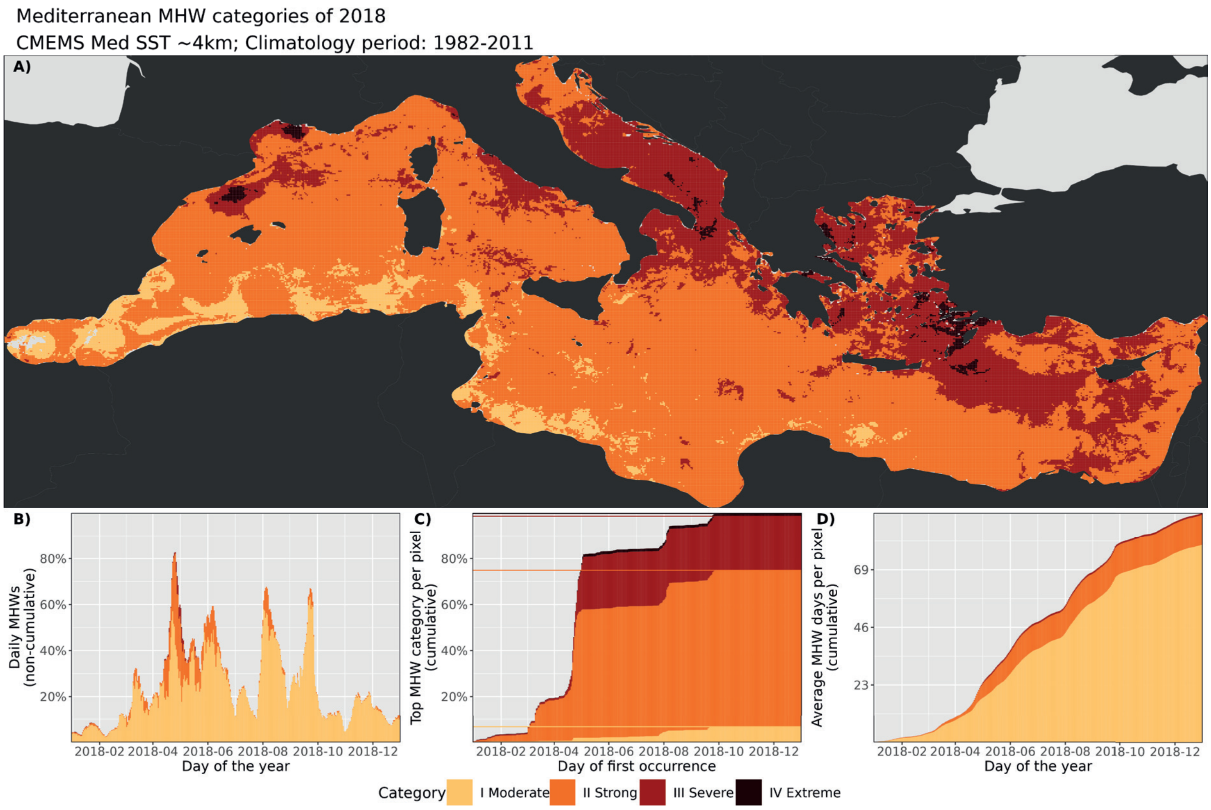

Figure 4. The same information as Figure 3, but for 2018. Note the difference in the y-axis for panel D between Figures 3 and 4.

This then frames the paradox: what good is it to understand the physical drivers of MHWs if they cannot be used to explain the biological impacts, but what good is relating the biology to the temperature if we do not develop a precise understanding of the physics?

The Arctic path

The focus of the argument presented here is the importance of accurately defining MHWs for research within any given body of seawater. However, examples from the Arctic (and Antarctic) provide a more concise tableau to highlight the current shortcomings in the general definition for detecting and quantifying MHWs. This is because the nature of the extreme temperatures in the Arctic naturally lend themselves to testing the rigour of any numeric definition of extreme temperatures. That was an intentional tautology, and one that helps to highlight the cyclical nature of the issue. To break out of this cycle we may adopt a social science stance and argue that much of what are viewed as the different facets of natural science (e.g. physics, biology, chemistry) are in fact 'community approved' collections of frequently used statistical analyses. One may encounter physical oceanographers enamoured with PCAs, while ecologists flock towards ordination.

This is all to say that due to fundamental reliance on statistics in the natural sciences, certain routine assumptions are made, and not often questioned. A common example is that values within a time series are normally distributed. But what do we do when the data are not ?
In many fields of natural science we revert to non-parametric tests of some sort. When using

percentile values, such as those in the general definition, non-normal data are not a disaster, but they are *not an issue* either. Equatorward of 60°N/S, most time series of seawater temperature are normal enough that a researcher can happily ignore the numeric quagmire that quietly roosts beneath. Once we move up into the Arctic (or down into Antarctica, but likely for different reasons; see Siegert *et al*. 2023) the data begin to pose challenges. It is for this reason that studies of extreme temperatures in the Arctic need to develop some sort of addendum to the standard definition (see Hu *et al*. 2020; Schlegel *et al.* 2021; Lo *et al.* 2023). This is inescapable because the seawater temperature data themselves are no longer sufficient for determining the background state against which a researcher may detect MHWs (Fig. 5). In Arctic research a solution employed to address this issue is the inclusion of sea-ice cover data. As the planet warms, it will increasingly become a common issue for the global ocean that the seawater data themselves will no longer be enough. The inconvenient truth is that we need to start considering the use of data external to seawater temperature when defining what a MHW is.

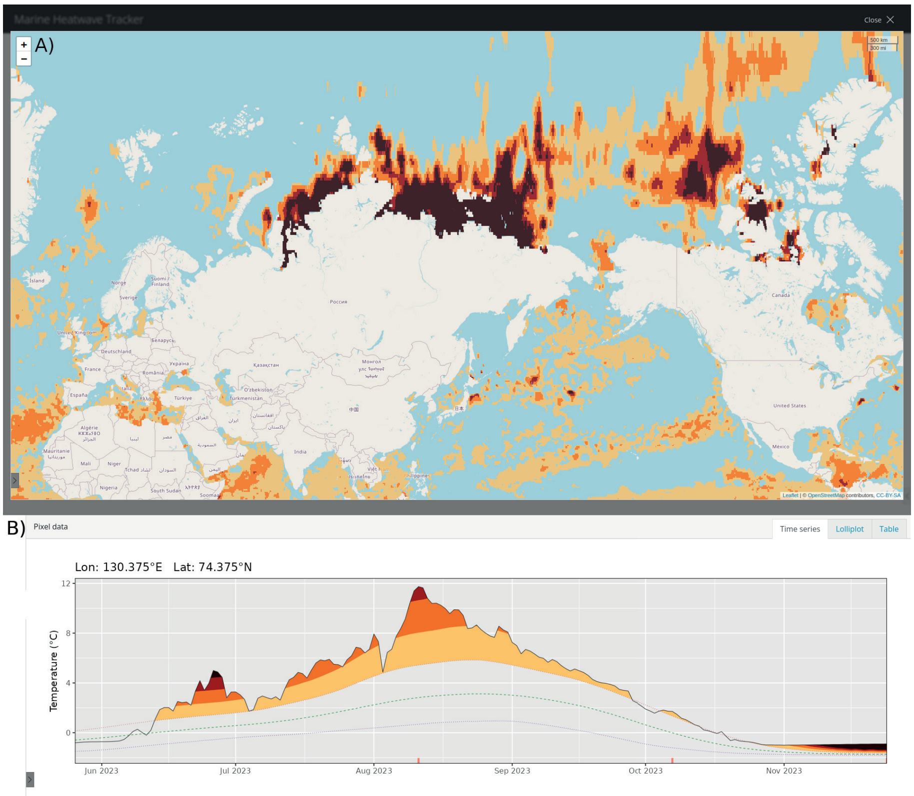

Figure 5. Screenshots from the Marine Heatwave Tracker (https://www.marineheatwaves.org/tracker.html; Schlegel, 2020) showing the problematic use of the general MHW definition in the Arctic.

A) The surface of the Laptev sea on 2023-11-12.

B) Time series showing daily temperature values (black) 90th percentile threshold (dotted red), and MHW categories (yellow to dark red). Note that the events shown to be "IV Extreme" in panel A are only temperature anomalies of ~0.5 degrees in panel B.

The path forward

The future will be hotter. We must therefore assume that time series of seawater temperature will become more and more irregular over time (i.e. right skewed). Thereby exacerbating the issues described above regarding contrasting approaches to the general definition of MHWs.

This is why it is proposed here to adopt a new method for the detection of MHWs. A meeting of the french network ILICO (Infrastructure de recherche littorale et côtière) gathered a few months ago in Toulouse to discuss the current state of knowledge on MHWs, and where to go from there. One outcome was the classification of the different approaches on the detection of MHWs into three types (Fig. 6). The first type - the general definition - is that around which the current debate rages as discussed in this paper. MHWs detected with this approach are useful when performing global analyses but contain a paradox with no clear solution. The second type of definition – specific – has been used for decades: temperature thresholds are based on the known thermal limits of a given species. This approach will always be useful, and necessary, but is inherently limited to the species of interest. The third type of definition embraces a mechanistic understanding of MHWs.

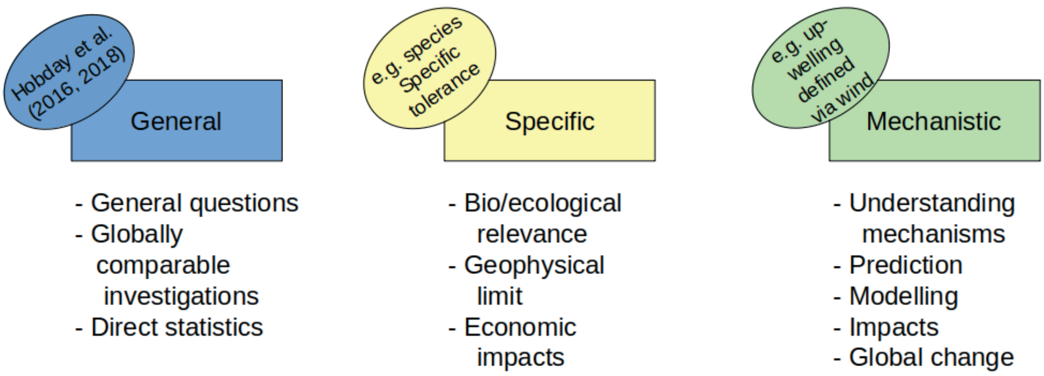

Figure 6. Schematic classification of MHW definitions, and their uses, into three distinct types.

The pursuit of the mechanistic understanding of extreme temperature is not new and has been a subject of interest for physical oceanography for decades. However, what has been lacking is the focus on discrete events, and how they may be impacting biology and society.
A priority now is to understand from a physical perspective what sets extreme temperature events apart from whatever "normal" may be. This must be done in such a way that changes with season, depth, or anything else that may be accounted for. Additionally, the biological, ecological, economic, and societal impacts of these events cannot be relegated to a concluding sentence. Much work has already been done on understanding the physical drivers of MHWs, and a fast expanding published record is available that can say which drivers are the most relevant, when, where, and to what extent (e.g. latent heat flux at depth in the winter vs shortwave radiation at the surface in the summer).

In order to move this avenue of research forward, deeper investigations into the constituent components of the surface heat flux budget are required, that will not simply classify events as having one cause, but take a more holistic approach to looking at the contribution of all considered heat flux components. Additionally, this must be considered in the context of the local- to synoptic-scale oceanic and atmospheric conditions in the region, as well as the relevant climate indexes. This may sound like an insurmountable task, but all of these facets of research are already very well developed at this point. It is time to start merging them. The purpose of doing so is to allow for the necessary complexity of the system to be accounted for in order to better relate the MHW records with their potential impacts on the biology, ecology, and broader society. Such a multi-layered approach would also allow for the integration of essential work on potential species and ecosystem adaptations to the changing climate.

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Schlegel R.W. Marine heatwave research: A path forward via the Mediterranean and the Arctic. pp 51 - 62 In CIESM Monograph 51 [F. Briand, Ed.] Marine heatwaves in the Mediterranean Sea and beyond. CIESM Publisher, Paris, Monaco, 174 p.

References

CIESM Atlas of Exotic Fishes fishes in the Mediterranean Sea. Golani, D., E. Azurro, J. Dulčić, E. Massutí and L. Orsi-Relini, 2021. Second edition. [F. Briand, Ed.]. CIESM Publishers, Paris, Monaco, 365 pages.

Garrabou J., Coma R., Bensoussan N., Bally M., *et al*. 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, 15: 1090–1103. https://doi.org/10.1111/j.1365-2486.2008.01823.x

Garrabou J., Gómez Gras D., Medrano A., Cerrano C., Ponti M., Schlegel R., *et al.* 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Glob. Chang. Biol*., 28(19): 5708-5725, doi:10.1111/gcb.16301. https://doi.org/10.1111/gcb.16301

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Ghanem R., Ben Souissi J., Ledoux J.B., Linares C. and J. Garrabou. 2024. Marine Heatwaves and benthic communities: Changes features of the assemblages and alarming consequences on biodiversity in Tunisian waters. pp 155 - 162 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Hobday A.J., Alexander L.V., Perkins S.E., Smale D.A., Straub S.C., Oliver E.C., and T. Wernberg. 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, *141*: 227-238. https://doi.org/10.1016/j.pocean.2015.12.014

Hobday A.J., Oliver E.C., Gupta A.S., Benthuysen J.A., Burrows M.T., Donat M.G., Holbrook, N.J., Moore P.J., Thomsen M.S., Wernberg T. and Smale D.A., 2018. Categorizing and naming marine heatwaves. *Oceanography*, 31(2):162-173.

Hu S., Zhang L., and S. Qian. 2020. Marine heatwaves in the Arctic Rrgion: Variation in different Ice Covers. *Geophysical Research Letters*, 47(16), e2020GL089329. https://doi.org/10.1029/2020GL089329

Huang B., Liu C., Freeman E., Graham G., Smith T., and H-M Zhang. 2021. Assessment and intercomparison of NOAA daily optimum interpolation sea surface temperature (DOISST) Version 2.1. *Journal of Climate*, 34(18): 7421–7441. https://doi.org/10.1175/JCLI-D-21-0001.1

Lo Y.T.E., Mitchell D. M., Watson P.A.G., & Screen J.A. 2023. Changes in winter temperature xtremes from Future Arctic sea-ice loss and ocean warming. *Geophysical Research Letters*, 50(3), e2022GL102542. https://doi.org/10.1029/2022GL102542

Merchant C. J., Embury O., Bulgin C. E., Block T., Corlett G. K., Fiedler E., *et al.* 2019. Satellite-based time-series of sea-surface temperature since 1981 for climate applications. *Sci. data*, 6(1): 1-18, doi:10.1038/s41597-019-0236-x

Oliver E.C.J., Burrows M.T., Donat M.G., Sen Gupta A., Alexander L.V., Perkins-Kirkpatrick S.E., Benthuysen J.A., Hobday A.J., Holbrook N.J., Moore P.J., Thomsen M.S., Wernberg T and D.A Smale. 2019. Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Front. Mar. Sci*. 6: 734. doi: 10.3389/fmars.2019.00734

Oliver E.C.J., Benthuysen J. A., Darmaraki S., Donat M.G., Hobday A.J., Holbrook N.J. and A. Sen Gupta. 2021. Marine Heatwaves. *Annual Review of Marine Science, 13*: 313-342. https://doi.org/10.1146/annurev-marine-032720-095144

Rilov G. and collaborators. 2024. Ocean warming, marine heatwaves and the thermal vulnerability of the increasingly tropicalized Levant coast ecosystems. pp 141-154. In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Schlegel R. W. 2020. Marine Heatwave Tracker (v1.0.0) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.37878

Schlegel R.W., Darmaraki S., Benthuysen J.A., Filbee-Dexter K., and E.C.J. Oliver. 2021. Marine cold-spells. *Progress in Oceanography*, 198, 102684. https://doi.org/10.1016/j.pocean.2021.102684

Siegert M. J., Bentley M. J., Atkinson A., Bracegirdle T. J., Convey P., Davies B., Downie R., Hogg A. E., Holmes C., Hughes K. A., Meredith M. P., Ross N., Rumble J., and J. Wilkinson. 2023. Antarctic extreme events. *Frontiers in Environmental Science*, 11, 1229283. https://doi.org/10.3389/fenvs.2023.1229283

Tuel A., and E.AB. Eltahir. 2020. Why is the Mediterranean a climate change Hot Spot? *Journal of Climate*, 33(14): 5829–5843. https://doi.org/10.1175/JCLI-D-19-0910.1

Wang S., Jing Z., Sun D., Shi J., & Wu L. 2022. A new model for isolating the Marine Heatwave changes under warming scenarios. *Journal of Atmospheric and Oceanic Technology*, 39(9): 1353–1366. https://doi.org/10.1175/JTECH-D-21-0142.1

WMO. 2023. *Guide to Climatological Practices* (100). WMO. https://library.wmo.int

Marine heatwaves in the Mediterranean Sea: the latest insights from multi-platform observations

Mélanie Juza[1], Emma Reyes[1], Joaquín Tintoré[1,2]

[1] *Balearic Islands Coastal Observing and Forecasting System (SOCIB), Palma, Spain*
[2] *Mediterranean Institute for Advanced Studies (IMEDEA) (CSIC-UIB), Esporles, Spain*

Abstract

The existing multi-platform observing capabilities enable characterizing marine heatwaves (MHWs) in the Mediterranean Sea at local and sub-regional scales from open to coastal ocean waters, from surface to subsurface and from physical to biogeochemical properties. In this study, recent updates on surface MHWs highlight the extremely strong thermal stress conditions that the Mediterranean Sea is experiencing, particularly in 2022 and 2023 compared to the last four decades. Further analysis combining multi-platform remote and *in situ* observations over the last decade also show the different responses to extreme events in the coastal ocean, the propagation of surface MHWs into the ocean interior as well as the possible impacts on the biogeochemical ocean. The results strongly support the necessary continuous monitoring of the three-dimensional ocean to better understand and predict MHWs and their impacts on the physical and biogeochemical oceans. In the context of the accelerating climate change, it is crucial to increase the scientific knowledge and its transfer to society to better support marine conservation, policy decision-makings and adaptation strategy implementation.

Keywords: *marine heatwaves, Mediterranean Sea, multi-platform observations, monitoring applications, coastal response, vertical propagation*

1. Introduction

As a consequence of human-induced global warming, marine heatwaves (MHWs) are expected to be more common, threatening marine ecosystems and pushing them to the limits of resilience (IPCC 2019). MHWs are caused by anomalous atmospheric conditions that increase the solar radiation into the ocean and reduce the ocean heat losses or by ocean processes that transport warm water (Holbrook *et al.* 2019). MHWs have multiple impacts on (i) the ocean system, changing ocean properties and circulation which can in turn modify the nutrient supply from subsurface to euphotic zone or the heat and carbon absorption into the deep ocean, (ii) the marine ecosystems at the surface and in subsurface such as coral bleaching, declines in kelp forests or seagrass meadows, harmful algal blooms, mass mortalities of marine organisms, and location shift of species (see Garrabou *et al.* 2022; 2024 in this volume; Rilov *et al.* 2024 in this volume), and (iii) the socio-economic system affecting key sectors of the Blue Economy (e.g. marine living resources or tourism) with economic consequences that already run into billions of US dollars or contributing to the intensification of storms and flooding with warmer ocean waters. Such impacts are affecting the achievement of several UN Sustainable Development Goals such as “Zero Hunger”, “Decent work and economic growth”, “Responsible consumption and production”, “Climate action” and “Life below water” (Smith *et al.* 2021).

The Mediterranean Sea is a basin severely affected by climate change (Giorgi 2006; CIESM 2008; Lionello and Scarascia 2018) and relevant for climate change-related research and adaptation strategy. The Mediterranean Sea responds rapidly to global warming with a surface warming rate more than twice higher than in the global ocean (Juza and Tintoré 2021a). This oceanic basin has a large coastal zone which offers essential goods and services for human societies *et al.* It is a hotspot of biodiversity with a high number of endemic species (Coll *et al.* 2010), which is increasingly threatened by extreme temperature events (see for ex. Guerrero-Meseguer *et al.* 2017; Bensoussan *et al.* 2019 ; Verdura *et al.* 2021; Garrabou *et al.* 2024 ; Ghanem *et al.* 2024 in this volume). Although MHWs in the Mediterranean Sea have been mainly related to large-scale anomalous atmospheric conditions (Sparnocchia *et al.*, 2006 ; Guinaldo *et al.* 2023 ; Hamdeno *et al.* 2023 ; Simon *et al.* 2024 in this volume), the ocean response shows strong spatial variations in both ocean warming and MHW events, at the surface and in subsurface, in coastal and open ocean waters (Juza and Tintoré 2021a ; Juza *et al.* 2022, 2023 ; Dayan *et al.* 2023). This spatial variability requires specific consideration to understand the processes involved and consequences of global warming and extreme events on the physical and biogeochemical components of the ocean. The existing ocean observing capabilities allow studying ocean changes at different spatial and temporal scales, as scientifically required to respond to societal needs.

This paper provides a review updated till November 2023 of MHWs in the Mediterranean Sea at the surface, as detected by satellites. It further highlights the added value of multiplatform *in situ* observations for enabling the characterization of MHWs from open to coastal oceans, from surface to subsurface and from physical to biogeochemical properties, critically contributing to the characterization of Earth's climate. Finally, it discusses the lessons learnt and to be learnt from observing and modelling systems, and the strategy to be implemented to contribute to the achievement of the UN Decade challenges.

2. Datasets and methodology

2.1. Ocean observations

The multi-platform observing systems now provide a large amount of ocean data at various spatial and temporal scales (Tintoré *et al*. 2019a) which enables the characterization of MHWs in the Mediterranean Sea at local and sub-regional scales, from surface to subsurface and from open to coastal ocean waters. In particular, as illustrated in Figure1:

(i) **Satellite products** provide continuous daily monitoring of sea surface temperature (SST) since the last four decades. Daily reprocessed[1] and near real-time[2] optimally interpolated estimates of SST with regular horizontal grids of 1/20º and 1/16º spatial resolutions, respectively, from 1982 to present (Merchant *et al.* 2019 ; Pisano *et al.* 2016 ; Buongiorno Nardelli *et al.* 2013) are distributed by the Copernicus Marine Service[3].

(ii) **Fixed moorings** provide locally hourly temperature time series, in particular in coastal waters. For coastal MHW analyses (Juza *et al.* 2023), 10 shallow-water moorings with limited temporal gaps over the period 2013-2022 along the western Mediterranean coast have been used. Such datasets are available through European data aggregator and institutional data portals (e.g. Copernicus Marine In Situ[4], Balearic Islands Coastal Observing and Forecasting System (SOCIB)[5] and Puertos del Estado[6]).

1 SST_MED_SST_L4_REP_OBSERVATIONS_010_021: doi:10.48670/moi-00173
2 SST_MED_SST_L4_NRT_OBSERVATIONS_010_004: doi:10.48670/moi-00172
3 Copernicus Marine Service: https://marine.copernicus.eu/
4 CMEMS In Situ TAC:http://www.marineinsitu.eu/
5 SOCIB thredds catalog: https://thredds.socib.es/thredds/catalog.html
6 Puertos del Estado: https://www.puertos.es/es-es/oceanografia/Paginas/portus.aspx

(iii) **Profiling floats**, which drift with ocean currents generally at a parking depth of 350m in the Mediterranean Sea, collect vertical hydrographic profiles from 2000m depth to surface every 5 to 10 days. Quality-controlled temperature and salinity profiles have been extracted over the last decade from the EN4.2.2 dataset[7] (Gouretski and Reseghetti 2010; Good *et al.*, 2013), which is distributed by Met-Office. A total of 67.861 vertical profiles are available over the period 2012-2022 in the Mediterranean Sea. Over the period 2012-2020, 16% of the profiles coincided locally with MHW events (Juza *et al.* 2022).

(iv) **Autonomous underwater vehicles** collect high-resolution physical and biogeochemical data along transects from surface to deep ocean. In the Balearic Channels, SOCIB has operated gliders deployed along a semi-continuous endurance line since 2011 (Heslop *et al.* 2012 ; Tintoré *et al.* 2013). 83 missions have been performed collecting 358 completed transects in the Ibiza Channel, providing high-resolution data between depths of 20 and 950 m with a horizontal resolution of approximately 2 km (Tintoré *et al.* 2019b).

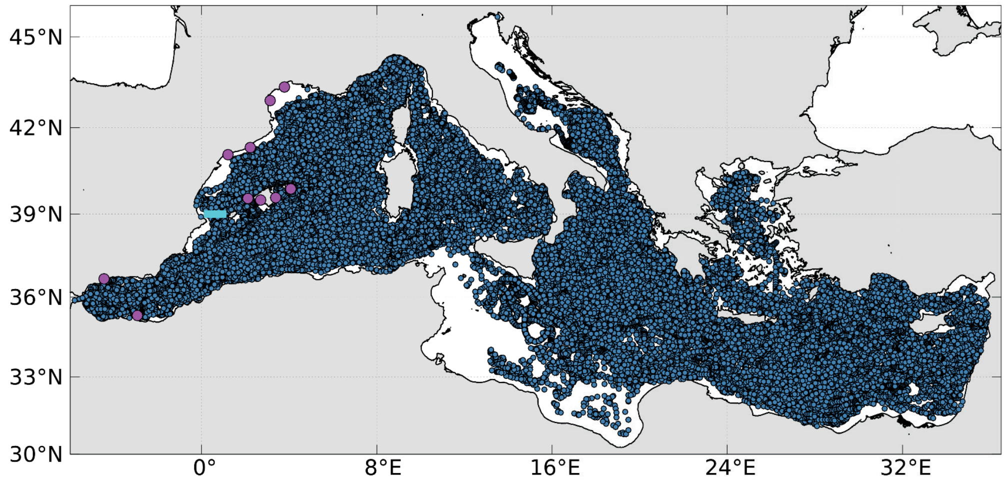

Figure 1. Profiling floats over the period 2012-2022 in the Mediterranean Sea (blue dots). Shallow-water moorings with limited temporal gaps over the period 2013-2022 in the western Med (pink dots). Glider endurance-line in the Ibiza Channel since 2011 (cyan line).

2.2 Model forecasting

Analysis and 10-day forecasts of SST from the Copernicus Marine Service Mediterranean Sea Physics Analysis and Forecast model (Clementi *et al.* 2021)[8] are also used over the current year for the prediction of MHWs in the Mediterranean Sea implemented in the SOCIB application (Section 3.3).

2.3. Methodology

- **Definition**. Following the commonly used methodology from Hobday *et al.* (2016), MHWs occur when SST is warmer than the daily 90th percentile of the local SST distribution over a long-term reference period during five consecutive days or more. Hobday *et al.* (2016) recommended using at least a 30-year period for climatology and smoothing time series using a 30-day moving window.

7 Met-Office EN4 dataset: www.metoffice.gov.uk/hadobs/en4/

8 MEDSEA_ANALYSISFORECAST_PHY_006_013: doi:10.25423/CMCC/MEDSEA_ANALYSISFORECAST_PHY_006_013_EAS7

● **Baseline period**. In a warming ocean, the reference periods for climatology affect quantitatively the estimations in MHW intensity, duration and frequency although results remain qualitatively in agreement (Juza *et al.* 2022 ; Dayan *et al.* 2023). In this paper, MHWs as detected by satellite products are computed with respect to the period 1982-2015 as done in previous studies (Juza and Tintoré 2021a ; Juza *et al.* 2022, 2023) and implemented in operational applications (Juza and Tintoré 2020, 2021b). MHWs as detected by fixed moorings are characterized using a shorter and more recent period, due to the data availability. In a warming ocean, using more recent periods leads to underestimations of MHWs indices (Juza *et al.* 2022, 2023).

● **MHW indices.** Annual indices are also computed to characterize MHWs and estimate long-term changes of their properties over the last four decades: MHW mean and maximum intensities (above the mean), mean duration, number of events and total days.

● **Sub-regional approach**. To properly analyse MHWs in the Mediterranean Sea, sub-regions have been distinguished, as defined by Manca *et al.* (2004) according to the schematic representation of the upper ocean dynamics and allowing also to consider the spatial variability of the surface ocean warming rate (Juza *et al.* 2022).

● **Open science**. This work is aligned with the Open Science principles, including open methodology, open source code, open research data, open access publishing and open educational resources (UNESCO 2021).

3. Marine heat waves at surface

MHWs are first detected at the surface, using satellite data which enable their characterization from local to sub-regional scales from 1982 to 2023.

3.1. Recent situation (2022, 2023)

Averaged in the Mediterranean Sea, annual mean SSTs were the warmest over the last six years ever registered since 1982 (Juza and Tintoré 2020)[9]. In 2022, SST was the warmest on record before 2023 with an annual mean of 20.73ºC corresponding to a mean anomaly of 1.13ºC (Fig. 2). After this very abnormally warm year, 2023 also experienced new records in the Mediterranean Sea with the warmest annual mean SST of 20.97ºC (anomaly of 1.36ºC) and the highest seasonal values ever registered over the last 42 years. In the western Mediterranean Sea (WMed), spring 2023 was the warmest spring ever registered at sea in the region while in the eastern Mediterranean (EMed) autumn 2023 was the warmest autumn on record. In both the WMed and EMed, winter and summer 2023 were the second warmest on record. These records for SST have been associated with records on MHW total days in 2022 (2023), reaching regionally averaged values of 145 (208), 177 (212) and 113 (205) days in the Mediterranean Sea, WMed and EMed, respectively (Fig. 2).

9 https://apps.socib.es/subregmed-indicators/ocean_temperature.htm

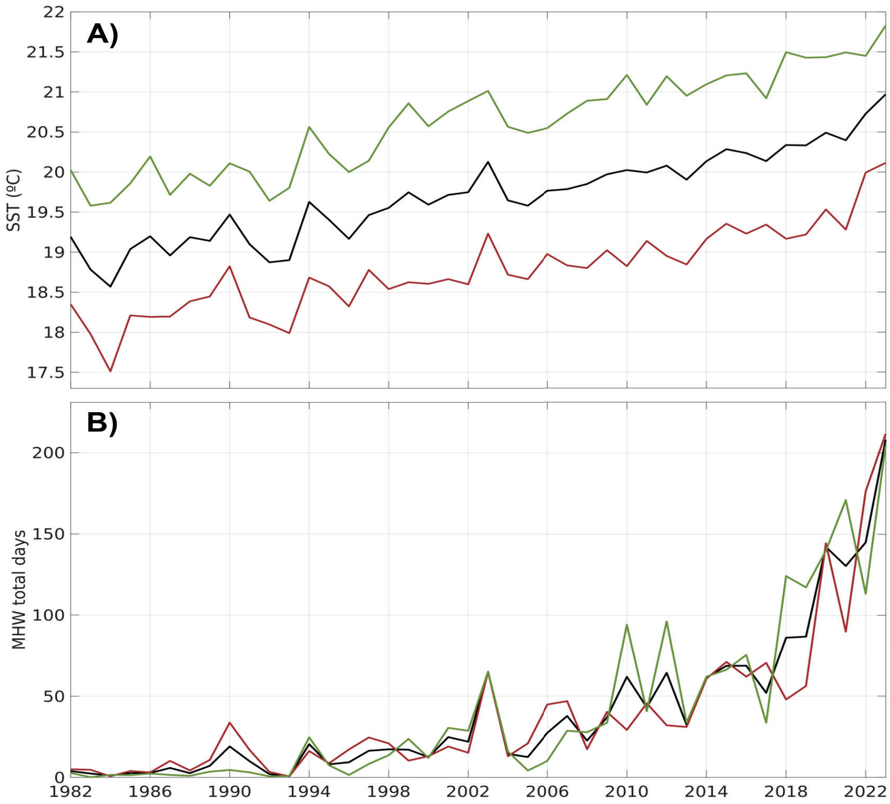

Figure 2. Annual mean SST (A) and annual MHW total days (B) averaged in the Mediterranean Sea (black), western (red) and eastern (green) sub-basins from 1982 to 2023.

Table 1: MHW properties show strong spatio-temporal variations at sub-regional scales.

Year	Annual MHW indices	Mean intensity	Max. intensity	Mean duration	Frequency	Total days
2022	Sub-regional values (associated sub-region)	1.48-2.73ºC (max DF3)	2.71-5.29ºC (max DF3)	13-51 days (max DS2)	4-9 events (max DL2)	79-232 days (max DS2)
	Local maximum	3.32ºC (max coast DI3, Sfax)	6.78ºC (max DF2)	237 days (max DS2, south Mallorca)	15 events (max DF2)	281 days (max DS2, coast west IC)
2023	Sub-regional values (associated sub-region)	1.67-2.32ºC (max DJ1)	3.24-5.18ºC (max DI1)	19-58 days (DL3)	5-10 events (max DT1)	143-256 days (max DL3)
	Local maximum	3.16ºC (north DH1)	6.18ºC (conv DF2)	176 days (westG DS1)	15 events (DT1-DT2)	351 days (westG DS1)

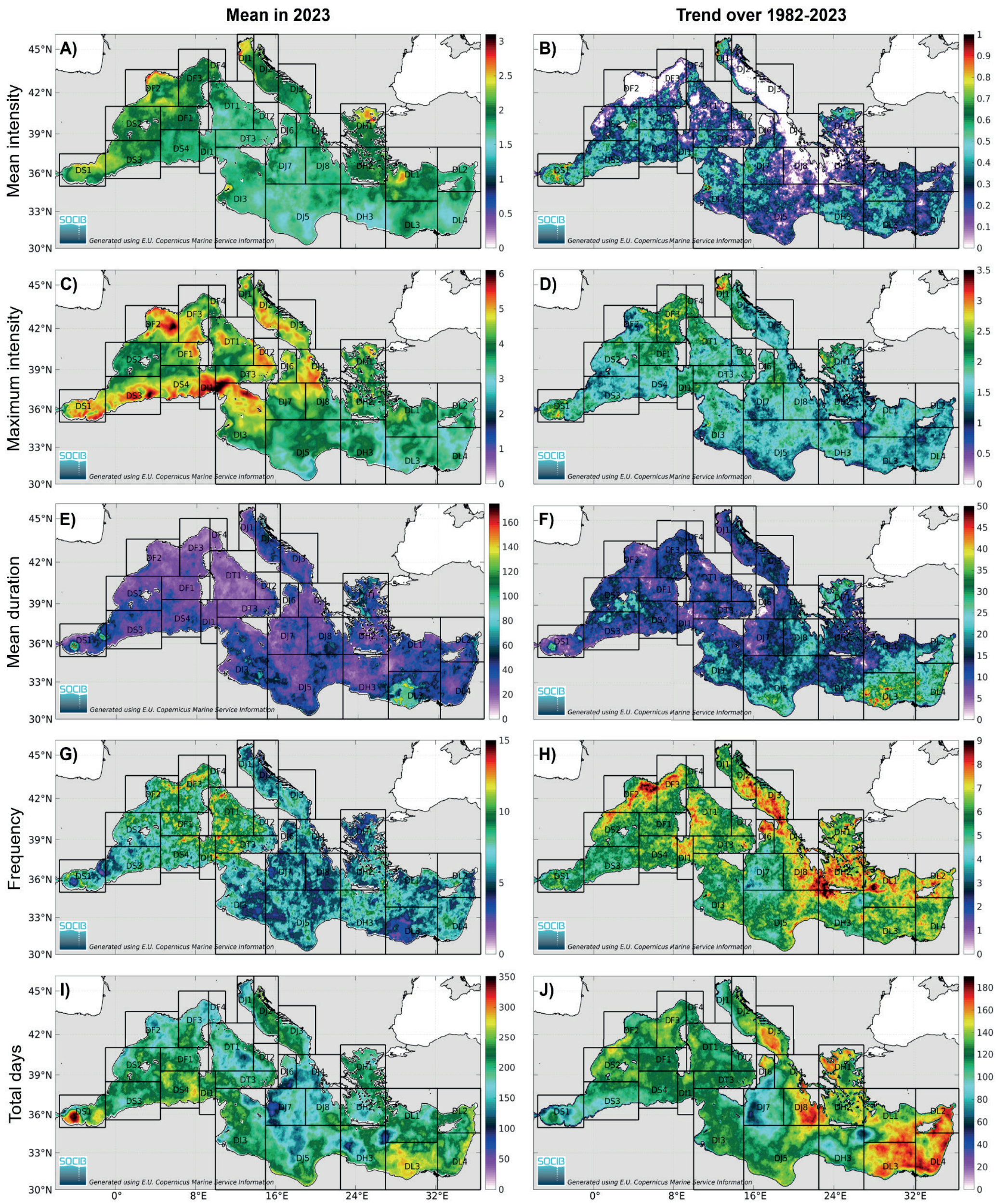

Figure 3. MHW mean and maximum intensities in ºC; mean duration (in day); frequency and total days (from top to bottom) in the Mediterranean Sea: annual mean in 2023 (A,C,E,G,I) and linear trends over the period 1982-2023 (B,D,F,H,J).

In 2022, the sub-regional MHW mean and maximum intensities (above the mean), mean duration, frequency and total days ranged over 1.48-2.73ºC, 2.71-5.29ºC, 13-5 days, 4-9 events and 73-232 days, respectively. The maximum sub-regional intensities, duration and total days as well as all local maxima of the MHW indices were reached in the northern WMed. The annual MHW intensities locally reached extremely high values in the northern WMed while MHWs occurred until almost 77% of the year locally in the Balearic Sea along the Spanish coast. 2022 was a year of many records in the WMed.

Still 2023 reached new records, with. MHW indices also reaching very high values with sub-regional mean and maximum intensities, mean duration, frequency and total days varying over

1.67-2.32ºC, 3.24-5.18ºC, 19-58 days, 5-10 events and 143-256 days, respectively, with the highest values. in the north Adriatic, Sardinia Channel, south Levantine, Ligurian-Provencal and the Alboran Sea, respectively. Locally, MHW mean and maximum intensities, mean duration, frequency and total days reached maximum values of 3.16ºC, 6.18ºC, 176 days, 15 events and 351 days, respectively (Fig. 3).

The Alboran Sea, which is the region connecting with the Atlantic Ocean, suffered unprecedented warm SSTs and strong MHWs reaching category 2, as defined by Hobday *et al.* (2018), and during several weeks reaching the highest sub-regional and local MHW total days (Fig. 3 and 4). Differently from the WMed, but also subjected to extreme temperatures, the EMed also experienced intense and long-lasting MHWs in winter, summer and autumn 2023 (Fig. 4).

Very stressful thermal conditions were observed in 2022 and 2023. In addition to very intense and long-lasting MHW events, SST values locally reached thresholds that strongly threaten ecosystems. For example, averaged in the Balearic Sea, daily SST values reached 29.1 ºC and 29ºC in 2022 and 2023, respectively, while the mooring at Dragonera (in the Balearic Islands) observed local temperatures warmer than 31ºC in August 2022 and 2023 (Juza *et al.* 2024). The maximum local SST associated with a MHW event in 2022 and 2023 was reached in the Tunisian waters (off Sfax) with a local value of 32.67 ºC on 31-July-2022 and on 23-July-2023.

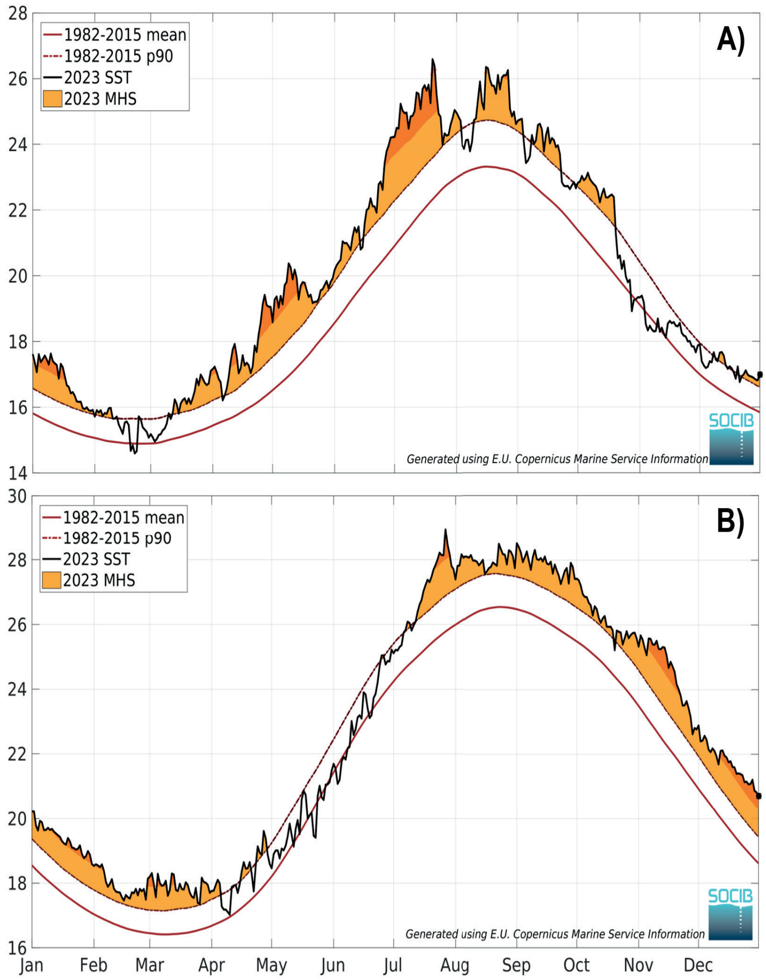

Figure 4. Daily SST for 2023 averaged (A) in the Alboran Sea, western Mediterranean ; (B) in the south Levantine sea, eastern Mediterranean. MHWs are indicated in orange.

3.2. Long-term changes (1982-2023)

As seen, all sub-regions are experiencing increasing trends in all MHW characteristics (Fig. 3). These trend estimates in MHW properties include ocean warming and will be discussed in Section 5. Annual MHW indices increased over 1982-2023 in all sub-regions with spatial variations. The linear trends over the period 1982-2023 in mean and maximum intensities, mean duration, frequency and total days reached local values up to 0.44 ºC/decade, 1.15 ºC/decade, 21.4 days/decade, 2.4 events/decade and 50.1 days/decade, being higher than over 1982-2022 (Vargas-Yáñez *et al.* 2023). The trends of the different MHW indices show important spatial variations, and different spatial patterns between indices. The highest increases in MHW intensity are found in the north Adriatic, while the trends in MHW duration and total days are the highest in the Levantine basin in the EMed. The time series of the annual MHW total days from 1982 to 2023 at sub-regional scale show both the events and the strong increase over the last four decades and particularly in the last decade, and highlight the unprecedented MHWs that occurred in 2022, particularly in the sub-regions of the WMed and in 2023 in the whole Mediterranean Sea.

Satellite products have allowed estimating long-term variations of surface MHWs at local and sub-regional scales but they are limited to the surface and less accurate near the coast. So, to go further, they have been combined with *in situ* observational networks (Section 4).

3.3. User-oriented application

The strong spatio-temporal variability of MHWs highlights the role of the dynamical processes at sub-regional and local scales, suggesting the diversity of the MHW impacts over the whole basin and calling for providing information at these scales to the diverse stakeholders. In this context, SOCIB has implemented an open access application[10] to monitor and visualize continuous information on MHWs in the Mediterranean Sea at local and sub-regional scales (Juza and Tintoré 2021b ; Juza *et al.* 2022). This application enables the detection of MHWs in real-time using satellite observations and with 10-day prediction using model forecasts. It also monitors annual MHW indicators to follow their long-term variations. This application has been generated using E.U. Copernicus Marine Service information, including open access, quality-controlled, historical and near real-time data from satellite observations and modeling systems. It has been designed to share timely information understandable to multiple stakeholders and has contributed to enhance the link with national, regional and local end-users in several strategic sectors such as: (i) the scientific community (e.g. physical oceanographers, marine biologists), (ii) environmental organizations (e.g. Marilles Foundation in the Balearic Islands), (iii) the academic community and education in marine science (e.g. summer schools), (iv) the policy-decision making (e.g. managers of the Maritime-Terrestrial National Parks, General Directorate of Emergency Response), (v) marine living resources (e.g. fishery through interactions with the BlueFin Tuna community or aquaculture through emerging private-public collaborations), and (vi) the general public. Such an application has also promoted the generation of new research projects (e.g. TIAMAT[11], TUNAWAVE).

10 SOCIB web app https://apps.socib.es/subregmed-marine-heatwaves/
11 TIAMAT observatory www.observatoriotiamat

4. New insights from multi-platform observations

New insights have been provided by the multi-platform observing capabilities. Combining satellites with fixed moorings, profiling floats and gliders enables to characterize MHWs from open to coastal ocean waters, from surface to subsurface and from physical to biogeochemical properties.

4.1. Coastal ocean response

Coastal marine events have been addressed using *in situ* data. In a case study, Juza *et al.* (2020) used data from two moorings located in the near-shore waters of the Balearic Islands from 2012 to 2020. Comparing MHWs detected at the mooring, at the closest and offshore satellite points, the authors showed a higher occurrence and maximum intensity of MHWs in near-shore areas than in the open ocean as well as strong variability in near-shore waters from surface to subsurface and from one site to another even in nearby area. Recently, the coastal MHW analyses have been extended to the WMed over the last decade using 10 shallow water moorings along the Spanish and French coasts (Fig. 1, Juza *et al.* 2023). MHWs were observed from 2013 to 2022 in many locations with strong spatio-temporal variations in intensity, duration and frequency. Unprecedented MHWs in 2022 were also clearly identified in the coastal WMed with observed MHW temperatures warmer than 28ºC in several locations. Such temperatures threaten sensitive ecosystems in the shallow coastal waters such as seagrass meadows of the endemic *Posidonia oceanica,* which is both an enormous carbon sink and a vital nursery for fishes (Guerrero-Meseguer *et al.* 2017). Finally, the authors demonstrated the importance of high-resolution and accurate time series along the coast from moorings, to complement satellites.

4.2. Ocean interior response

Hydrographic profiles from profiling floats have been used to investigate how MHWs propagate below the surface (Juza *et al.* 2022). After having identified MHWs at surface using satellite data, their propagation in subsurface was analysed over the period 2012-2020, using temperature and salinity profiles that coincide locally with MHW. The analyses of MHW anomaly profiles showed the propagation in depth of surface MHWs as well as its strong seasonal and sub-regional variability, suggesting a contribution of local ocean processes (e.g. convection, downwelling and mesoscale eddy) in the propagation of the surface anomaly to subsurface. The resulting enhanced upper-ocean stratification was also highlighted when comparing the hydrographic properties at surface and 150m depth.

4.3. Biogeochemical ocean response

Repeated sections of gliders in the Ibiza Channel have collected physical and biogeochemical data since 2011 (see Fig. 1). Several transects coincided with MHWs. Preliminary studies are now conducted to analyse the possible impacts of MHWs and the resulting enhanced-stratification on chlorophyll-a concentration (CHL) and dissolved oxygen. In addition, satellite products of ocean colour (Volpe *et al.* 2019) show episodes of abnormally low winter CHL coinciding with MHW and low wind conditions in the Balearic Sea (as in early-March 2022). But after river discharges increased by storms, MHW may boost CHL (as in January 2020 after the storm Gloria around the Ebro delta). Such preliminary results illustrate the need to combine ocean and atmosphere drivers to predict CHL during MHWs.

5. Conclusions and next steps

5.1. Lessons learnt

In the Mediterranean Sea, (i) MHWs have substantially increasing from 1982 to 2023 in mean intensity, duration and frequency in all sub-regions, particularly in the last decade; (ii) unprecedented MHWs in 2022 have been observed in coastal and open ocean, with temperatures exceeding 28ºC, causing high thermal stress for the ecosystem; and (iii) the year 2023 reached new records in ocean temperatures and MHWs in particular in the western Mediterranean Sea; (iv) MHW indices have shown strong spatio-temporal variability in surface, subsurface and coastal oceans, highlighting the role of the dynamical processes at sub-regional and local scales; and (v) MHWs have to be combined with atmospheric conditions to better understand and predict the biogeochemical ocean responses to MHWs.

5.2. Ocean observing and prediction systems

In the Mediterranean Sea, the multi-platform observing system enables to characterize MHWs at local and sub-regional scales as well as to capture their strong variability in the surface, subsurface and coastal oceans. The need for sustainable observing systems of the three-dimensional ocean is also verified for the MHW monitoring, understanding and prediction. Existing and emerging multi-sensor observational platforms combining physical and biogeochemical information (e.g. gliders, saildrones) will also support the investigations on these extreme events and their impacts. New coastal high-resolution products will be developed (e.g. FOCCUS project) to improve pan-European innovative coastal observations in response to society and EU policy needs.

Providing four-dimensional and regular ocean data, reliable modelling systems are essential tools: (i) to complement the observing systems in under-sampled areas such as the coastal and deep oceans, (ii) to perform long-term changes in these areas and process studies, (iii) to perform Observing System Experiment and Observing System Simulation Experiment to evaluate the current observing systems and to better design observing systems, and (iv) to address key variables for MHWs such as subsurface temperature, ocean heat content (Dayan *et al.* 2023), mixed layer properties. Finally, models have the prediction capability from weekly to seasonal time scales (McAdam *et al.* 2023).

5.3. Discussion about methodology

The estimations of MHW properties and variations depend on factors such as the regions and baseline period. Since ocean temperatures show strong spatial variations, working on large or dynamically inhomogeneous sub-regions may provide inappropriate estimations or different results between studies. In addition, in a warming ocean the use of different reference periods for climatology leads to different estimations in MHW properties although they are qualitatively in agreement (Juza *et al.* 2022 ; Dayan *et al.* 2023). The use of a fixed baseline period includes ocean warming in detection and characterization of extreme events. Using a shifting baseline or detrended SST allows separating the trend component (long-term warming) to abrupt changes (extreme event) (Amaya *et al.* 2023 ; Martínez *et al.* 2023). Amaya *et al.* (2023) proposed a redefinition distinguishing the abrupt change as MHW and the total heat exposure, both indicators being necessary to understand how the ecosystems are facing ocean warming and extreme events. The thermal stress threshold, as a temperature at 28ºC (Juza *et al.* 2023), which is kept with the total heat exposure, is also an essential indicator for some marine species and habitats. Finally, the criterion of minimum duration fixed at 5 days in the commonly used MHW definition established by Hobday *et al.* (2016) can be discussed (see Liguori 2024 ; Schlegel 2024 in this volume).

5.4. Transfer of knowledge

The SOCIB application for MHWs in the Mediterranean Sea has been a first step towards the transfer of knowledge to various stakeholders at regional, national and local levels. Its targeted end-users are the scientific community, education in marine science, environmental organizations, policy decision-makers, some sectors of the Blue Economy and the general public. Also, in the framework of the EuroSea project, information about the Mediterranean MHWs has been generated in the Exclusive Economic Zones (Dayan *et al.* 2023) to foster the actions and to support policy-making at national scale. The strong variability of MHWs in the surface, subsurface and coastal oceans calls for implementing new functionalities in the existing web-based application extending to coastal areas (using fixed moorings and models) and subsurface (using models) in order to better respond to end-user needs.

5.5 Adaptation strategy

In order to support the building and increase of resilience and to define / implement strategies for a better adaptation and management of the oceans in the context of climate change, it is crucial (i) to foster the continuous monitoring of physical and biogeochemical essential ocean variables from sub-regional to local scales, from surface to subsurface and from open to coastal ocean; (ii) to improve the modelling and prediction systems; (iii) to facilitate the access to the information for all stakeholders through open access data and user-oriented applications; (iv) to consolidate the interdisciplinary collaboration and to engage the stakeholders; (v) to contribute to the achievement of key challenges aiming at protecting our oceans and fostering sustainable practices for a healthier marine environment, aligned with the UN Decade Challenges for collective impact; and vi) to include the monitoring and forecasting of MHWs in regional Digital Twins for helping to identify areas and time periods of extreme ocean temperature, so as to be alert to the possible impacts on human health (e.g. infection diseases or jellyfish proliferation) and on meteorological phenomena intensification.

Acknowledgments

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References

Amaya D. J., Jacox M. G., Fewings M. R., Saba V. S., Stuecker M. F., Rykaczewski R. R., *et al.* 2023. Marine heatwaves need clear definitions so coastal communities can adapt. *Nature*, 616(7955): 29-32, doi:10.1038/d41586-023-00924-2

Bensoussan N., Chiggiato J., Buongiorno Nardelli B., Pisano A. and Garrabou J. 2019. Insights on 2017 marine heat waves in the Mediterranean Sea. Copernicus marine service ocean state report: issue 3. *J. Oper. Oceanogr.*, 12: 101–108, doi:10.1080/1755876X.2019.1633075

Buongiorno Nardelli B., Tronconi C., Pisano A., and R. Santoleri. 2013. High and Ultra-High resolution processing of satellite Sea Surface Temperature data over Southern European Seas in the framework of MyOcean project. *Rem. Sens. Env.*, 129: 1-16, doi:10.1016/j.rse.2012.10.012

CIESM. 2008. Climate warming and related changes in Mediterranean marine biota. CIESM Workshop Monograph n° 35 [F. Briand, Ed.]. CIESM Publisher, Paris, Monaco 152 p.

Coll M., Piroddi C., Steenbeek J., Kaschner K., Ben Rais Lasram F., Aguzzi J., *et al.,* 2010. The Biodiversity of the Mediterranean Sea: Estimates, Patterns, and Threats, *PLoS One*, 5, e11842, doi:10.1371/journal.pone.0011842

Dayan H., McAdam R., Juza M., Masina S., and S. Speich. 2023. Marine heat waves in the Mediterranean Sea: An assessment from the surface to the subsurface to meet national needs. *Front. Mar. Sci.*, 10, 142, doi:10.3389/fmars.2023.1045138

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129-140. In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Ghanem R., Ben Souissi J., Ledoux J.B., Linares C., and J. Garrabou. 2024. Marine Heatwaves and benthic communities: Changes features of the assemblages and alarming consequences on biodiversity in Tunisian waters. pp 155-162. In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Giorgi F. 2006. Climate change hot-spots. *Geophys. Res. Lett*. 33(8), doi:10.1029/2006GL025734

Good S. A., Martin M. J., and N. A. Rayner. 2013. EN4: quality controlled ocean temperature and salinity profiles and monthly objective analyses with uncertainty estimates. *J. Geophys. Res*., 118: 6704–6716, doi:10.1002/2013JC009067

Gouretski V., and F. Reseghetti. 2010. On depth and temperature biases in bathythermograph data: development of a new correction scheme based on analysis of a global ocean database. *Deep Sea Res*., 57: 812–833.

Guerrero-Meseguer L., Marín A., and C. Sanz-Lázaro. 2017. Future heat waves due to climate change threaten the survival of Posidonia oceanica seedlings. *Environ. Pollut.*, 230: 40-45, doi:10.1016/j.envpol.2017.06.039

Guinaldo T., Voldoire A., Waldman R., Saux Picart S., H. Roquet. 2023. Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer. *Ocean Sci.*, 19(3): 629-647, doi:10.5194/os-19-629-2023

Hamdeno M., A. Alvera-Azcaráte. 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Front. Mar. Sci*., doi:10.3389/fmars.2023.1093760

Heslop E.E., Ruiz S., Allen J., López-Jurado J.L., Renault L., and J. Tintoré. 2012. Autonomous underwater gliders monitoring variability at “choke points” in our ocean system: a case study in the Western Mediterranean Sea. *Geophys. Res. Lett*., 39: L20604.

Holbrook N.J., Scannell H.A., Gupta A.S., Benthuysen J.A., Feng M., Oliver E.C., *et al.,* 2019. A global assessment of marine heatwaves and their drivers. *Nat. Commun.*, 10: 2624, doi: 10.1038/s41467-019-10206-z

Hobday A.J., Alexander L.V., Perkins S.E., Smale D.A., Straub S.C., Oliver E.C., *et al.,* 2016. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr.*, 141: 227–238, doi: 10.1016/j.pocean.2015.12.014

Hobday A.J., Oliver E.C., Gupta A.S., Benthuysen J.A., Burrows M.T., Donat M.G., *et al.,* 2018. Categorizing and naming marine heatwaves. *Oceanogr.*, 31(2): 162-173, https://www.jstor.org/stable/26542662

IPCC. 2019. IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, eds H.-O. Pörtner, D. C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, *et al.,* Available online at: https://www.ipcc.ch/srocc/ (accessed September, 2023).

Juza M., J. Tintoré. 2020. Sub-regional Mediterranean Sea Indicators [Web app]. Balearic Islands Coastal Observing and Forecasting System, SOCIB. https://apps.socib.es/subregmed-indicators (accessed September, 2023)

Juza, M., and J. Tintoré. 2021a. Multivariate Sub-regional ocean indicators in the Mediterranean Sea: From event detection to climate change estimations. *Front. Mar. Sci.*, 8, 610589, doi:10.3389/fmars.2021.610589

Juza, M., and J. Tintoré. (2021b). Sub-regional Mediterranean Marine Heat Waves [Web app]. Balearic Islands Coastal Observing and Forecasting System, SOCIB. https://apps.socib.es/subregmed-marine-heatwaves (accessed September, 2023).

Juza M., Fernández-Mora A., and J. Tintoré. 2022. Sub-regional marine heat waves in the Mediterranean Sea from observations: long-term surface changes, sub-surface and coastal responses, *Front. Mar. Sci.*, doi:10.3389/fmars.2022.785771

Juza M., de Alfonso M., and Á Fernández-Mora. 2024. Coastal ocean response during the unprecedented marine heat waves in the western Mediterranean in 2022, *State Planet Discuss. [preprint]*, doi:10.5194/sp-2023-18, accepted.

Liguori G. 2024. The need to adopt process-based definitions for marine heatwaves. pp 41 - 50 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Lionello P., and L. Scarascia. 2018. The relation between climate change in the Mediterranean region and global warming. *Reg. Environ. Chang.*, 18: 1481-1493, doi:10.1007/s10113-018-1290-1

Manca B., Burca M., Giorgetti A., Coatanoan C., Garcia M.J., and Iona A. 2004. Physical and biochemical averaged vertical profiles in the Mediterranean regions: an important tool to trace the climatology of water masses and to validate incoming data from operational oceanography. *Journal of marine systems*, 48(1-4): 83-116.

Martínez J., Leonelli F. E., García-Ladona E., Garrabou J., Kersting D., Bensoussan N., *et al,*. 2023. Evolution of marine heatwaves in warming seas: the Mediterranean Sea case study, *Front. Mar. Sci.*, 10:1193164, doi:10.3389/fmars.2023.1193164

McAdam R., Masina S., and Gualdi S. 2023. Seasonal forecasting of subsurface marine heatwaves. *Commun. Earth Environ.*, 4(1): 225, doi:10.1038/s43247-023-00892-5

Merchant C. J., Embury O., Bulgin C. E., Block T., Corlett G. K., Fiedler E., *et al.,* 2019. Satellite-based time-series of sea-surface temperature since 1981 for climate applications. *Sci. data*, 6(1): 1-18, doi:10.1038/s41597-019-0236-x

Oliver E.C., Donat M.G., Burrows M.T., Moore P.J., Smale D.A., Alexander L.V., *et al.,* 2018. Longer and more frequent marine heatwaves over the past century. *Nat. Commun.*, 9:1324, doi:10.1038/s41467-018-03732-9

Pisano A., Nardelli B.B., Tronconi C., R. Santoleri. 2016. The new Mediterranean optimally interpolated pathfinder AVHRR SST Dataset (1982–2012). *Rem. Sens. Environ.*, 176: 107-116, doi:10.1016/j.rse.2016.01.019

Schlegel R.W. 2024. Marine heatwave research: A path forward via the Mediterranean and the Arctic. pp 51 - 62 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Simon A. 2024. Summer 2023 MHW main features and trend in air-sea interactions related to the long-term evolution of MHW in the Mediterranean., pp 77 - 84 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Smith K.E., Burrows M.T., Hobday A.J., Sen Gupta A., Moore P.J., Thomsen M., *et al.,* 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Sci.*, 374(6566), doi:10.1126/science.abj3593

Smith K.E., Burrows M.T., Hobday A.J., King N.G., Moore P.J., Sen Gupta A., *et al.,* 2023. Biological impacts of marine heatwaves. *Annu. Rev. Mar. Sci.*, 15: 119-145, doi:10.1146/annurev-marine-032122-121437

Sparnocchia S., Schiano M. E., Picco P., Bozzano R., and A. Cappelletti. 2006. The anomalous warming of summer 2003 in the surface layer of the Central Ligurian Sea (Western Mediterranean). *Ann. Geophys.*, 24: 443-452, doi:10.5194/angeo-24-443-2006

Tintoré J., Pinardi N., Alvarez Fanjul E., Balbin R., Bozzano R., Ferrarin C., *et al.,* 2019a. Challenges for sustained observing and forecasting systems in the Mediterranean Sea. *Front. Mar. Sci.*, 6:568, doi:10.3389/fmars.2019.00568

Tintoré J., Heslop E., Ruiz S., Muñoz C., and J. Allen. 2019b. SOCIB Glider - Canales Endurance Line (Version 1.0) [Data set]. Balearic Islands Coastal Observing and Forecasting System, SOCIB. doi:10.25704/JD07-SV9 (accessed September, 2023)

Tintoré J., Vizoso G., Casas B., Heslop E., Pascual A., Orfila A., *et al.,* 2013. SOCIB: the Balearic Islands coastal ocean observing and forecasting system responding to science, technology and society needs. *Mar. Technol. Soc. J.*, 47: 101–117. doi:10.4031/mtsj.47.1.10

Vargas-Yáñez M., Moya F., Serra M., Juza M., Jordà G., Ballesteros E., *et al.,* 2023. Observations in the Spanish Mediterranean Waters: A Review and Update of Results of 30-Year Monitoring. *J. Mar. Sci. Eng.*, 11(7), 1284, doi:10.3390/jmse11071284

Verdura J., Santamaría J., Ballesteros E., Smale D. A., Cefalì M. E., Golo R., *et al.,* 2021. Local scale climatic refugia offer sanctuary for a habitat forming species during a marine heatwave. *J. Ecol.*, 109(4), 1758-1773, doi:10.1111/1365-2745.13599

Volpe G., Colella S., Brando V. E., Forneris V., Padula F. L., Cicco A. D., *et al.,* 2019.. Mediterranean ocean colour Level 3 operational multi-sensor processing. *Ocean Sci.*, 15(1): 127-146, doi:10.5194/os-15-127-2019

UNESCO. 2021. UNESCO Recommendation on Open Science, doi:10.54677/MNMH8546

Main features of summer 2023 MHWs and trends in air-sea interactions related to the long-term evolution of MHWs in the Mediterranean

Amélie Simon

IMT Atlantique, Lab-STICC, UMR CNRS 6285, Brest, France

Abstract

This paper aims to describe the features of the recent MHWs in summer 2023 and to document the air-sea heat fluxes related to the long-term evolution of MHWs in the Mediterranean. We show that the summer of 2023 presented high values of MHW activity (index combining the number of events, duration, intensity and spatial extent of MHWs) in the entire Mediterranean Basin, with maximum in the Alboran and Balearic Seas. Regarding MHW activity, the year 2023 was by far the most extreme of the last four decades in autumn and winter, and autumn was the season with the highest trend over the last four decades (+~200 °C x days x10^6 km²). Analysis of the significant trend of the four components of air-sea heat flux suggests that summer MHWs in the Mediterranean are associated with increased surface solar radiation in the western, central and Adriatic regions and in the eastern region with decreased upward surface thermal radiation. This study calls for a better understanding of whether atmospheric variability has changed in recent decades and how it is linked to MHW generation.

Keywords: *marine heatwave, atmospheric drivers, satellite data, extreme event, climate change.*

Introduction

The Mediterranean has a relatively long history with MHWs as one of the first MHWs on record was reported in the summer 2003 in the northwestern Mediterranean Sea with SSTs around 4 °C above the 1982–2016 reference period (Grazzini *et al.* 2003; Garrabou *et al.* 2009; Frölicher and Laufkötter 2018; Juza *et al.* 2022). More recently, the summer 2022 set a new record with SST up to 5 °C above the seasonal mean in the Mediterranean northwestern sector (Cutroneo and Capello 2023; González-Alemán *et al*. 2023; Guinaldo *et al*. 2023; Simon *et al*. 2023 ; Juza 2024 in this volume). Since 2001 90% of the Mediterranean has experienced at least one MHW every year or quite (Schlegel, 2024 in this volume) and long-lasting events have been recorded, for example up to 80 days events in the Marmara Sea (Tokat and Besiktepe 2024 in this volume) and an increasing trend of MHWs days of 21.3 days/decade in the Aegean, Ionian, and Cretan Seas (Androulidakis 2024 in this volume).

Long-term ocean warming is the main driver of this increase in MHWs features in the Mediterranean (Oliver *et al*. 2021; Ciappa *et al*. 2022; Mohamed 2024 in this volume) and is projected to be in the future (Daramaraki *et al.* 2019). Changes in temperature variability also account for the long-term evolution of MHWs. Liguori (2024 in this volume) showed that the spatial distribution of MHW events tends to match the standard deviation (variability) of SST anomalies with satellite data. Still with satellite data Simon *et al*. (2023) estimated that SST variability changes contribute to about a third of the MHW long-term trend in the western, central and Adriatic Mediterranean region whereas in the eastern and Aegean sub-basins, the variability of SST acts to diminish this trend. This last study showed via joint Principal Component Analysis that the long-term trend (over the period 1982-2022) in MHW activity was associated in the western, central and Adriatic regions with increased downward short-wave radiation and in the eastern Mediterranean with decreased upward long-wave radiation.

This paper addresses a double question: what are the MHW features for the last summer of 2023 and what are the physical processes driving the long-term evolution of summer MHWs in the Mediterranean? To do so, an extended version of the MHW ranking in the Mediterranean of Simon *et al.* (2022), now ranging from 1982 to 2023, was produced. Also, by calculating the trend of the four components of air-sea heat flux, we further diagnose the result of Simon *et al.* (2023) that summer MHWs in the Mediterranean are associated in the western, central and Adriatic regions with increased downward short-wave (solar) radiation and in the eastern Mediterranean with decreased upward long-wave (terrestrial) radiation.

Data and Methodology

The increasing interest in characterizing and ranking the main MHW events around the world has prompted several attempts to develop appropriate metrics for an objective characterization of MHWs. Nevertheless, most of these metrics do not take into account the spatial extent of each individual MHW event. The MHW activity index (Simon *et al*. 2022) combines the number of events, duration, intensity and spatial extent of MHWs occurring in each extended summer (JJAS) in the Mediterranean, between 1982 and 2021. This method allows a year-to-year comparison of the physical importance of MHWs for a specific season and region. Based on the same idea as the cumulative intensity which combines the duration and intensity of one event (Hobday *et al*. 2016), the activity combines the duration and intensity of all area-weighted events over a time range (here the summer months). One should note that we account explicitly for the area (in km²) in the index, as in most SST products a grid cell area differs from one latitude to another and MHW can expand over large areas. The activity index is calculated as follow:

$$Activity = \sum_{EE \subset Time\ Range} mean\ intensity_{EE} \cdot duration_{EE \cap Time\ Range} \cdot area_{EE}$$

The EE denotes the discrete (at a given grid cell) extreme events (EE) that occur within the selected time range of analysis; (in ° C) is the mean temperature anomaly with respect to the climatology; the (in days) is the duration of the event that remains within the considered time range, and (in km²) is the area affected by the discrete extreme event (that is to say, the grid cell area).

The detection of events is made beforehand using the standard method and available script of Hobday *et al*. (2016) using observed SST for the whole period of study. Daily sea-surface temperature (SST) was obtained from NOAA OISSTV2 (Reynolds *et al*. 2007; Huang *et al*. 2020) spanning from 1st January 1982 to 30 September 2022 at a regular resolution of 0.25° x 0.25° (1440 x 720 number of cells). We therefore define an MHW locally (for each grid point) when the daily SST exceeds the 90th percentile for at least five consecutive days. The local thresholds are computed using the 41 years of data spanning between 1 January 1982 and 30 September 2022.

A python script is available (https://github.com/amelie-simon-pro/marine-extreme-event) to compute the activity index over a domain based on the grid-cell detection script (https://github.com/ecjoliver/marineHeatWaves) introduced in Hobday *et al*. (2016).

Results

Main features of MHWs in summer 2023

Figure 1 clearly shows an accelerated increment of summer (JJA) MHW activity since the beginning of the century when compared with the two previous decades, and also that the top three events in terms of MHW activity (for the entire Mediterranean basin) correspond to the summer of 2022, followed by summer 2003 and summer 2023. The evolution is similar when considering the extended summer (JJAS; Simon *et al.* 2022) for the period 1982-2021 with the summers 2003, 2012, 2015 and 2018 peaking.

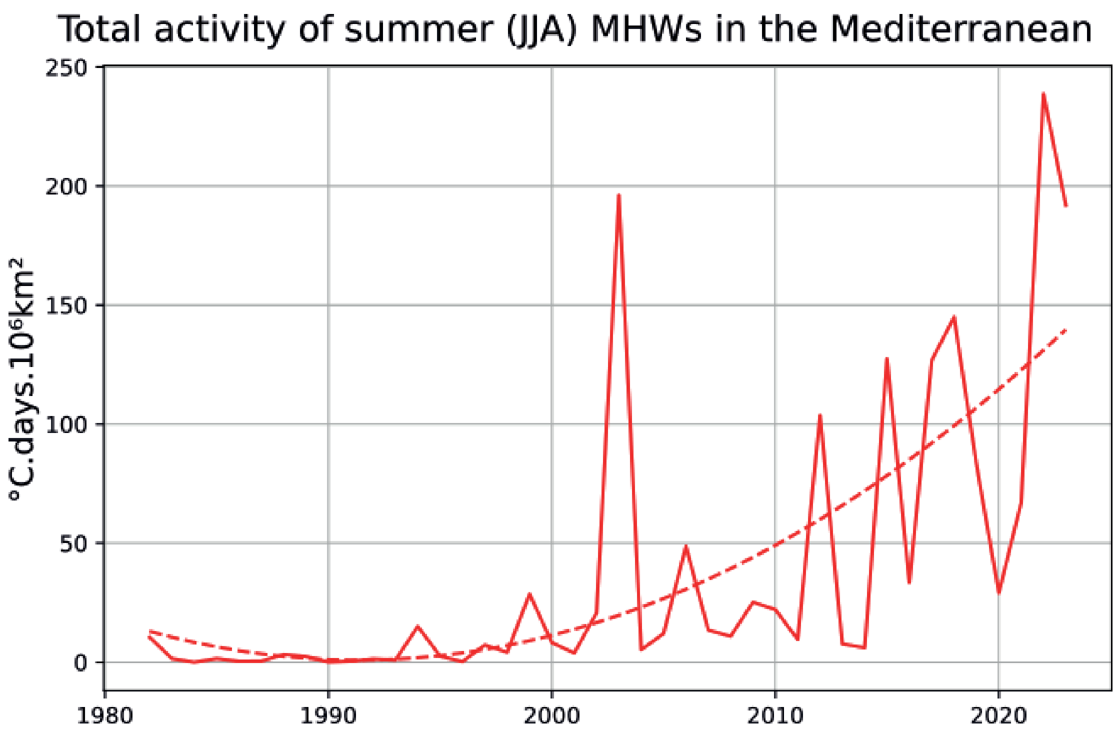

Figure 1. MHW activity in summer (JJA) for the period 1982-2023. Updated figure of Simon *et al.* (2022) with two more years.

Figure 2 shows the MHW mean properties in summer 2023. The mean intensity was maximum in the Gulf of Lion (~ 4 °C). This pattern follows the averaged mean intensity for all detected MHWs over the last four decades, as seen in Simon *et al*. (2022) and Ličer (2024 in this volume). The number of events was highest in the Gulf of Lion-Genova and the north Balearic Seas (~ 3 events). The duration was maximum in two distant regions (~ 40 days): the south Balearic/Alboran Seas and western/eastern (not central) Levantine Sea.

By combining these features, the summer of 2023 presents activity mostly in the Alboran and Balearic Seas (~100 °C. days.10^3km²), the rest of the Basin having a roughly equal MHW activity value (~ 40 °C. days.10^3km²). The summer MHWs recorded in 2023 were somewhat different from the summers of 2003 and 2022, both characterized by strong activity in western/central and also from the summer 2018 that showed a basin-wide MHW activity (Simon *et al*. 2023).

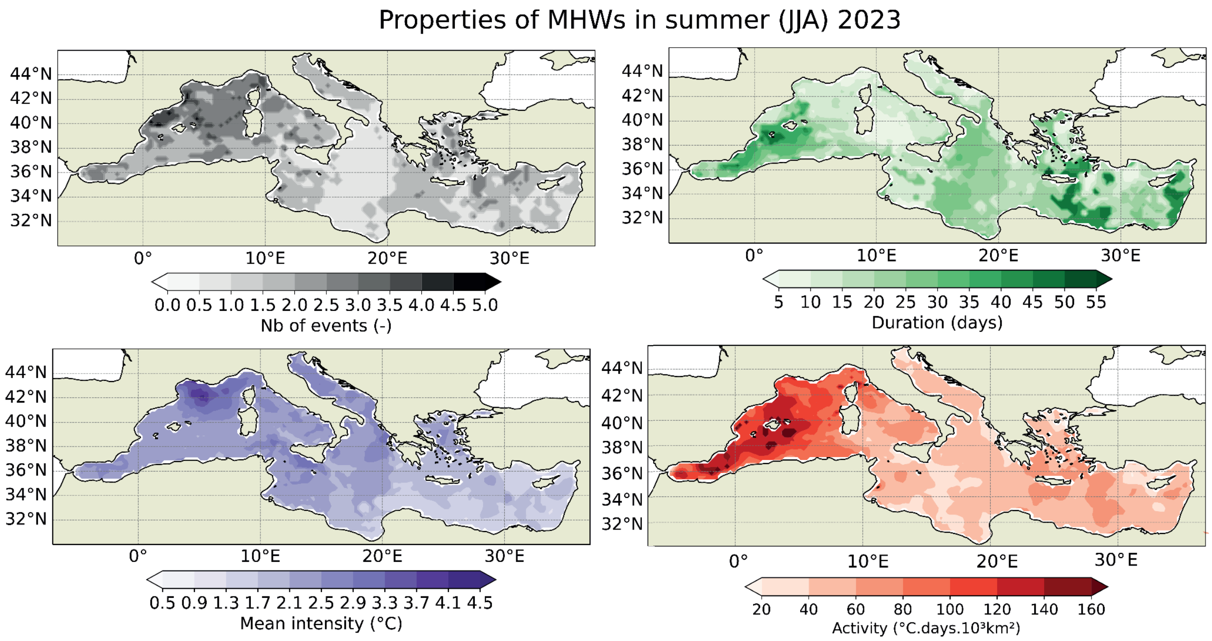

Figure 2. (Top) number of events, average duration (in days). (Bottom) average intensity (°C) and activity (°C x days x 10^3 km²) of the 2023 summer (JJA) MHW in the Mediterranean.

Figure 3 shows the MHW total activity in the Mediterranean in the autumn, winter and spring. Like in summers (Fig. 1), every season shows an accelerated increase. Since 1982 the maximum trend occurs in autumn (+~200 °C x days x 10^3 km²), then summer (+~140 °C x days x 10^3 km²) and winter (+~120 °C x days x10^3 km²), with a minimum trend in the spring (+~80 °C x days x 10^3 km²). The year 2023 was, by far, the most extreme of the last four decades in autumn and winter. The second most extreme autumn was in 2021, with MHW activity around one third less than the year 2023 while the winter 2016 had an activity about half less than in 2023.

In the autumn 2023, the MHWs occurred mostly in the Levantine Sea and west of Corsica, which was not seen in the previous spring or summer, only in the previous winter. This could partly be explained by a reemergence of subsurface warm water, trapped in winter and released in autumn.

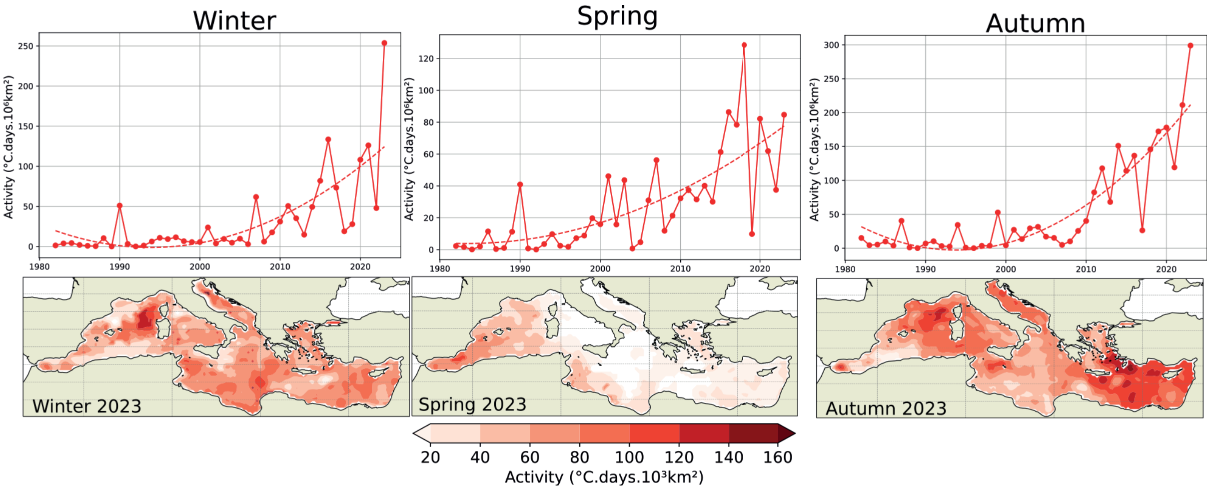

Figure 3. (Top) Time series of MHW total activity in the Mediterranean in autumn (SON), winter (DJF) and spring (MAM) for the period 1982-2023. (Bottom) Map of MHW activity of the 2023 autumn (SON), winter (DJF) and spring (MAM). For each winter (DJF), December of the previous year is considered.

Trend in air-sea interactions related to the long-term evolution of MHW in the Mediterranean

The second objective of this paper is to diagnose the air-sea interactions related to the long-term increase of MHWs. Figure 4 illustrates the main findings of Simon *et al*. (2023). Integrating Principal Component Analysis (PCA) on the summer (JJAS) MHW activity, geopotential height at 500 hPa and the four components of air-sea heat fluxes (shortwave radiation, long-wave radiation, latent heat flux and sensible heat flux revealed how their main modes co-vary together. In brief, the long-term MHW warming trend covaries increased downward short-wave radiation in the western Mediterranean and decreased upward long-wave radiation in the eastern Mediterranean. The warm MHW interannual variability reduced upward latent heat flux and increased downward sensible heat flux possibly due to intrusion of warm and humid air. Here, air-sea heat fluxes are suggested to drive the MHW evolution. Which raises the question of what is the significant trend of the four air-sea heat fluxes components.

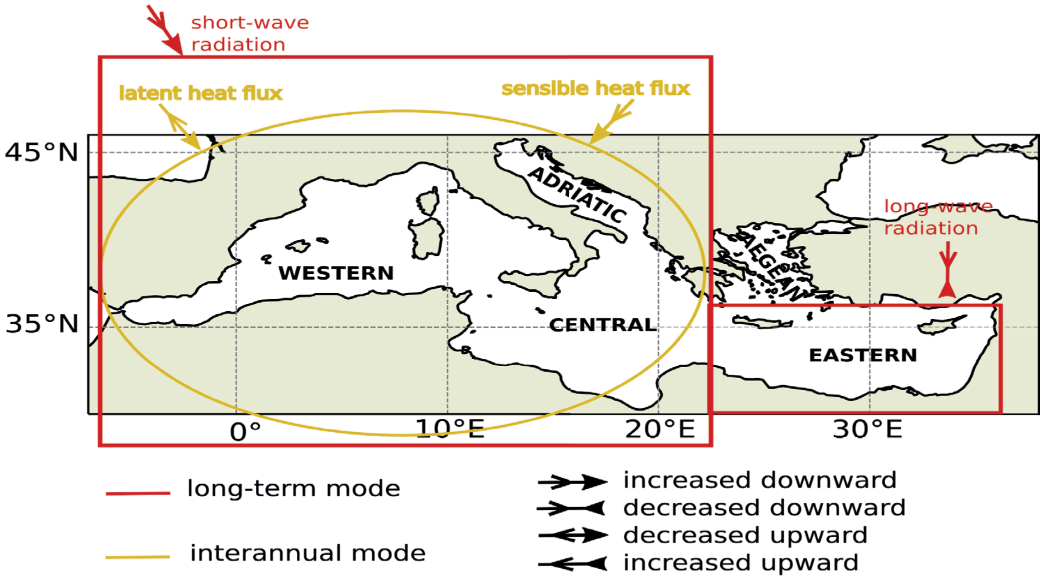

Figure 4. Illustration of the main air-sea fluxes and atmospheric circulation associated with the long-term and interannual mode of summer MHWs in the Mediterranean over the period 1982-2022. [Adapted from Figure 7 of Simon *et al.* 2023].

Figure 5 shows the significant trend at 95% using the Mann-Kendall test over the summers (JJAS) 1982-2022 for the four air-sea components in the Mediterranean. The short-wave and long-wave radiations significantly increased by about 0.2 (W/m2)/summer respectively in the western/central/Adriatic sub-basins and the eastern/Aegean sub-basins. The latent and sensible heat fluxes significantly decreased (by about 0.7 and 0.07 (W/m2)/summer over wide regions in the Mediterranean (except in the Adriatic and Alboran Seas for sensible heat fluxes).

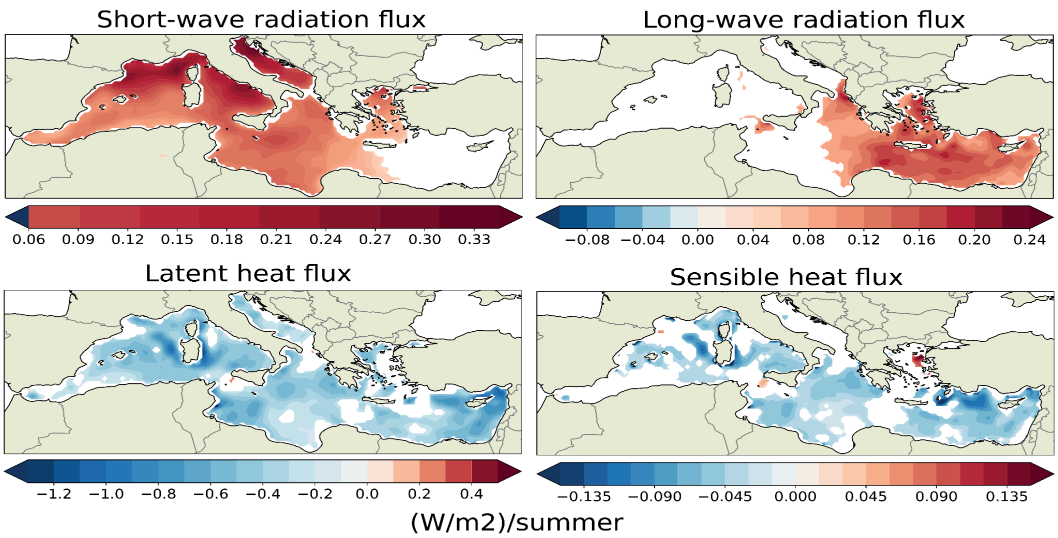

Figure 5. Summer (JJAS) trend for the short-wave radiation (top-left panel), long-wave radiation (top-right panel), latent heat flux (bottom-left panel), sensible heat flux (bottom-right panel) in the Mediterranean over the 1982-2022 period (in (W/m2)/summer). For the top panels, results are shown only when the trend is significant at 95% using the Mann-Kendall test.

Figure 6 presents the time series of the mean evolutions for the cells having a significant trend (coloured pixels in Figure 5) of each air-sea heat flux component. The long-term evolution of the short-wave and long-wave radiation fluxes are monotonic, increasing while the latent and sensible heat fluxes show two distinct periods. They both decreased from 1982 until around 2000-2005, then remained stable until 2022. These two periods show contrasted variability with a lower variability in the last 20 years. The interannual variability remains stable for the short-wave and long-wave radiation fluxes.

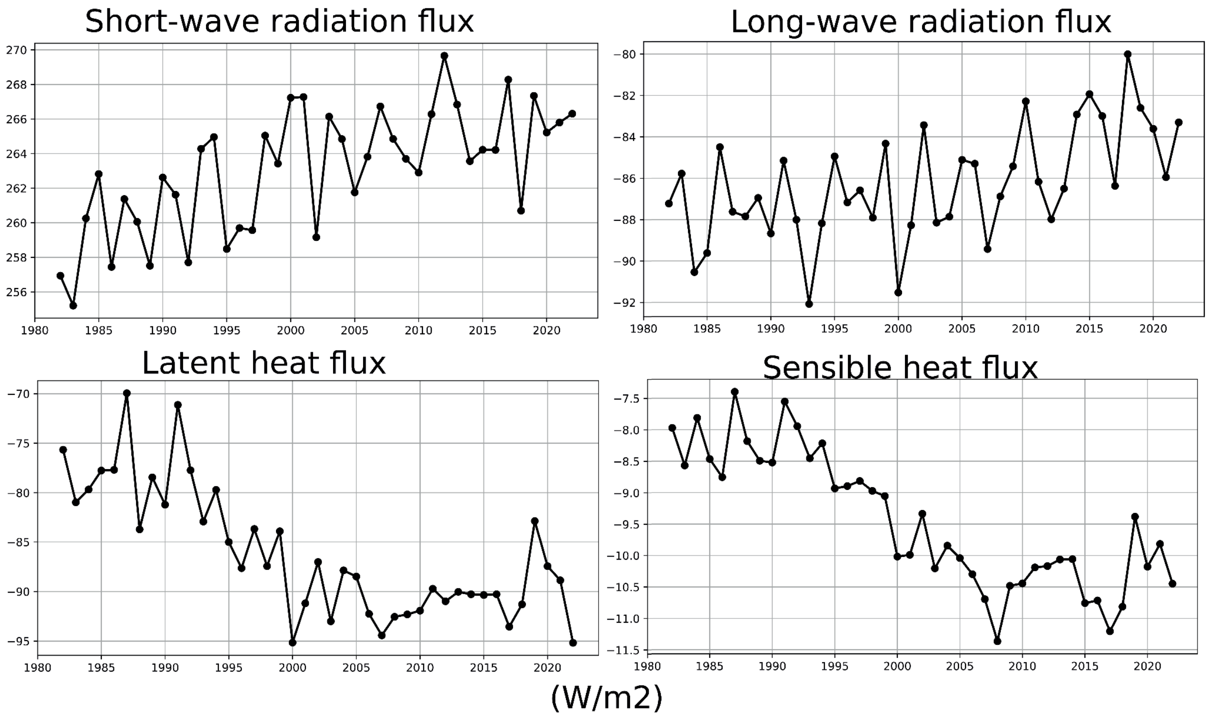

Figure 6. Time series of the mean over the cells where the trend is significant at 95% using the Mann-Kendall test (coloured cells in Figure 4) for the short-wave radiation (top-left panel), long-wave radiation (top-right panel), latent heat flux (bottom-left panel), sensible heat flux (bottom-right panel) (in W/m2/ summer).

Conclusion

This analysis updates our MHW ranking in the Mediterranean, now ranging from 1982 to 2023. By considering the MHW activity, the year 2023 was, by far, the most extreme of the last four decades in autumn and winter, and autumn was the season with the highest trend over the last four decades (+~200 °C x days x 10^3 km²). By calculating the significant trend of the four components of air-sea heat flux, we suggest that summer MHWs in the Mediterranean are associated in the western, central and Adriatic regions with increased downward short-wave radiation and with decreased upward long-wave radiation in the eastern region.

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References

Ciappa A.C. 2022. Effects of Marine Heatwaves (MHW) and Cold Spells (MCS) on the surface warming of the Mediterranean Sea from 1989 to 2018. *Progress in Oceanography*, *205*, 102828.

Cutroneo L. and M. Capello 2023. The Cold Waters in the Port of Genoa (NW Mediterranean Sea) during the Marine Heatwave in Summer 2022. *Journal of Marine Science and Engineering*, *11*(8), 1568.

Darmaraki S., Somot S., Sevault F., Nabat P., Cabos Narvaez W. D., Cavicchia and D. V. Sein. 2019b. Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, *53*: 1371-1392.

Frölicher T. L. and C. Laufkötter. 2018. Emerging risks from marine heat waves. *Nature communications*, *9*(1), 650.

Garrabou J., Coma R., Bensoussan N., Bally M., Chevaldonné P., Cigliano M. and C. Cerrano. 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global change biology*, *15*(5), 1090-1103.

González-Alemán J. J., Insua-Costa D., Bazile E., González-Herrero S., Marcello Miglietta M., Groenemeijer P. and M.G. Donat. 2023. Anthropogenic Warming Had a Crucial Role in Triggering the Historic and Destructive Mediterranean Derecho in Summer 2022. *Bulletin of the American Meteorological Society*, *104*(8), E1526-E1532.

Grazzini F. and P. Viterbo. 2003. Record-breaking warm sea surface temperature of the Mediterranean Sea. *ECMWF Newsletter*, 98: 30–31.

Guinaldo T., Voldoire A., Waldman R., Saux Picart S. and H. Roquet. 2023. Response of the sea surface temperature to heatwaves during the France 2022 meteorological summer. *Ocean Science*, 19(3): 629-647.

Hobday A. J., Alexander L. V., Perkins S. E., Smale D. A., Straub S. C., Oliver E. C. and T. Wernberg. 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*, *141*: 227-238.

Huang B., Liu C., Banzon V., Freeman E, Graham G., Hankins B., Smith T. and H.-M. Zhang. 2020. Improvements of the Daily Optimum Interpolation Sea Surface Temperature (DOISST) Version 2.1, *Journal of Climate*, 34, 2923-2939. doi: 10.1175/JCLI-D-20-0166. (Accessed on 03-10-2022).

Juza M., Fernández-Mora À. and J. Tintoré. 2022. Sub-regional marine heat waves in the Mediterranean Sea from observations: long-term surface changes, sub-surface and coastal responses. *Frontiers in Marine Science*, 9:785771, doi.org:10.3389/fmars.2022.785771.

Oliver E. C., Benthuysen J. A., Darmaraki S., Donat M. G., Hobday A. J., Holbrook N. J. and A. Sen Gupta. 2021. Marine heatwaves. *Annual Review of Marine Science*, *13*, 313-342.

Reynolds R.W., Smith T. M., Liu C., Chelton D. B., Casey K. S. and M.G. Schlax. 2007. Daily high-resolution-blended analyses for sea surface temperature. *J. Clim*. 20 5473–96.

Simon A., Plecha S.M., Russo A., Teles-Machado A., Donat M.G., Auger P-A. and R.M Trigo. 2022. Hot and cold marine extreme events in the Mediterranean over the period 1982-2021. *Front. Mar. Sci.* 9:892201 [12 p.].

Simon A., Pires C., Frölicher T.L. and A. Russo. 2023. Long-term warming and interannual variability contributions to marine heatwaves in the Mediterranean. *Weather and Climate Extremes*, 100619, https://doi.org/10.1016/j.wace.2023.100619.

Marine Heatwaves: comparative analysis between low and high latitude regional seas in the northern Hemisphere

Bayoumy Mohamed[1,2,*] **and Aida Alvera-Azcárate**[1]

[1] *GeoHydrodynamics and Environment Research (GHER), University of Liège, Liège, Belgium*
[2] *Oceanography Department, Faculty of Science, Alexandria University, Alexandria, Egypt*
* *Correspondence: Bayoumy Mohamed* ba.mohamed@uliege.be

Abstract

While the frequency, duration and spatial extent of marine heatwaves (MHWs) have increased worldwide, this increase is neither temporally nor spatially uniform, but varies depending on the time and geographical region under consideration. Therefore, this study examined the characteristics of MHWs and their spatio temporal variability over the past four decades (1982-2022) in five warming hotspots of the Northern Hemisphere - the Red Sea, the eastern Mediterranean, the Black Sea, the North Sea and the Barents Sea. We found accelerated warming and high spatio temporal trend variability in MHW frequency in these regional seas, with an average trend (event/decade) ranging from 0.84 in the Red Sea to 1.12 in the eastern Mediterranean Sea. These results are consistent with observed SST warming rates. The occurrence of these events was influenced by large-scale climate patterns such as the El Niño-Southern Oscillation (ENSO) and the East Atlantic Pattern (EAP), with ENSO having the greatest influence on the Red Sea and Black Sea and EAP on the North Sea and Barents Sea. We also found that atmospheric forcing plays a larger role in the formation of MHWs, especially in shallow seas (e.g. North Sea and Barents Sea). These results suggest that as climate change progresses, more intense MHW episodes can be expected in these regional seas, with far-reaching implications for marine ecosystems.

Keywords: *marine heatwaves, Regional Seas, climate change, MHW regional variability,WHW trends.*

1 Introduction

Anthropogenic global warming has a profound impact on the occurrence of extreme events such as marine heatwaves (IPCC 2021), which have a destructive impact on the marine environment and ecosystems. Marine heatwaves (MHWs) are generally defined as extremely anomalous warm ocean temperatures lasting five consecutive days or longer (Hobday *et al*. 2016), although there is mounting debate over the relevance of this definition (see Liguori; Schlegel 2024 in this volume). Atmospheric and marine heatwaves have become an important issue for many climate scientists, governments, policy and decision-makers, stakeholders, and even individuals because of the recent increase in the frequency of this phenomenon and its impact on marine life (Selig *et al.* 2010 ; Mills *et al*. 2013 ; Frölicher and Laufkötter, 2018; Smale *et al.* 2019; Sen Gupta *et al.* 2020). Major consequences of these events for the marine environment include coral bleaching, mass benthic mortality, harmful algal blooms, reduced chlorophyll concentrations, and changes in species behavior and fishing practices (Mills *et al*. 2013 ; Bond *et al*. 2015; Smale *et al.* 2019 ; Holbrook *et al.* 2020 ; see Garrabou *et al.* 2024 in this volume for details).

Over the last decade, MHWs and their driving mechanisms have been quantified at global and regional scales (Frölicher *et al.* 2018; Oliver *et al.* 2018 ; Holbrook *et al.* 2019 ; Roberts *et al.* 2019 ; Sen Gupta *et al*. 2020 ; Schlegel *et al.* 2021 ; Smith *et al.* 2021, 2023 ; Yao *et al.* 2022 ; Aboelkhair *et al.* 2023). These studies concluded that MHWs have become more frequent and prolonged worldwide in recent decades. They also concluded that the main reasons for this phenomenon could be oceanic or atmospheric in nature and could be modulated by large-scale climate modes of teleconnection patterns, such as the El Nino Southern Oscillation (Li and Han 2015), the Atlantic Multidecadal Oscillation (Kerr 2000), the Eastern Atlantic Pattern (Barnston, A. G. and Livezey 1987) etc. (Holbrook et al. 2019, 2020 ; Hobday *et al.* 2023; Mohamed *et al.* 2023). The frequency and intensity of MHWs are predicted to increase over the next century (Frölicher et al. 2018).

This study focuses on five regional seas in the Northern Hemisphere that are considered warming hotspots - the Red Sea, the eastern Mediterranean Sea, the Black Sea, the North Sea, and the Barents Sea (see maps in Fig. 1). These regional seas are heavily populated near the coast, and MHWs could severely impact the livelihoods and several important economic and geopolitical activities of surrounding countries, such as fisheries and tourism. The North Sea and Barents Sea are considered the most fisheries-rich areas in Europe (Guiet *et al*. 2019; Eriksen *et al*. 2020) and a large marine ecosystem (Ducrotoy *et al*. 2000; Olsen *et al*. 2010).

MHW characteristics have been studied in these five regions (Ibrahim *et al.* 2021; Mohamed *et al.* 2021, 2022a, 2022b, , 2023; Hamdeno and Alvera-Azcaráte 2023; Pastor and Khodayar, 2023) and our aim here is to compare them to assess the impact of large-scale coupled atmospheric/oceanic climate modes on MHW occurrence. We further examine long-term interannual variability and trends in SST and MHW characteristics (e.g, frequency and number of days) based on satellite data (1982-2022).

2 Materials and Methods

In this study, we used the NOAA daily Optimum Interpolation SST Version 2.1 (NOAA_OISST V2.1, Reynolds *et al.* 2007) to determine MHWs and their characteristics in the five selected regional seas. This global product with daily and ¼ degree spatial resolution covers the period from 1982 to present and was created by combining observations from multiple platforms (satellites, ships, and buoys) to produce a daily gap-free product (Banzon *et al.* 2016). The atmospheric parameters (e.g., wind, atmospheric pressure and temperature) were obtained from the ECMWF-ERA5 reanalysis dataset (Hersbach et al. 2020). The large-scale climate mode data were obtained from the NOAA Physical Sciences Laboratory website (https://psl.noaa.gov/gcos_wgsp/Timeseries/, accessed August 2023). Here, MHWs were determined according to the standard method described by Hobday *et al.* (2016). A marine heatwave is defined herein as an extreme positive SST anomaly that lasts for five consecutive days or longer, where the SST is above the seasonally fluctuating 90th threshold for that time of year. Baseline climatology should be based on 30 years or more (Hobday *et al.* 2016). Here, the baseline climatology and the MHW thresholds are calculated for each grid cell for each calendar day of the year, using daily SST data over the entire period studied (1982-2022). When two consecutive MHW events occur less than two days apart, they are considered a single event (Hobday *et al.* 2016). Once MHW events are identified, two indices are used in this study to represent MHW characteristics, namely MHW frequency (the number of MHW events in each year) and MHW days (the total number of MHW days in each year).

3 Results and Discussion

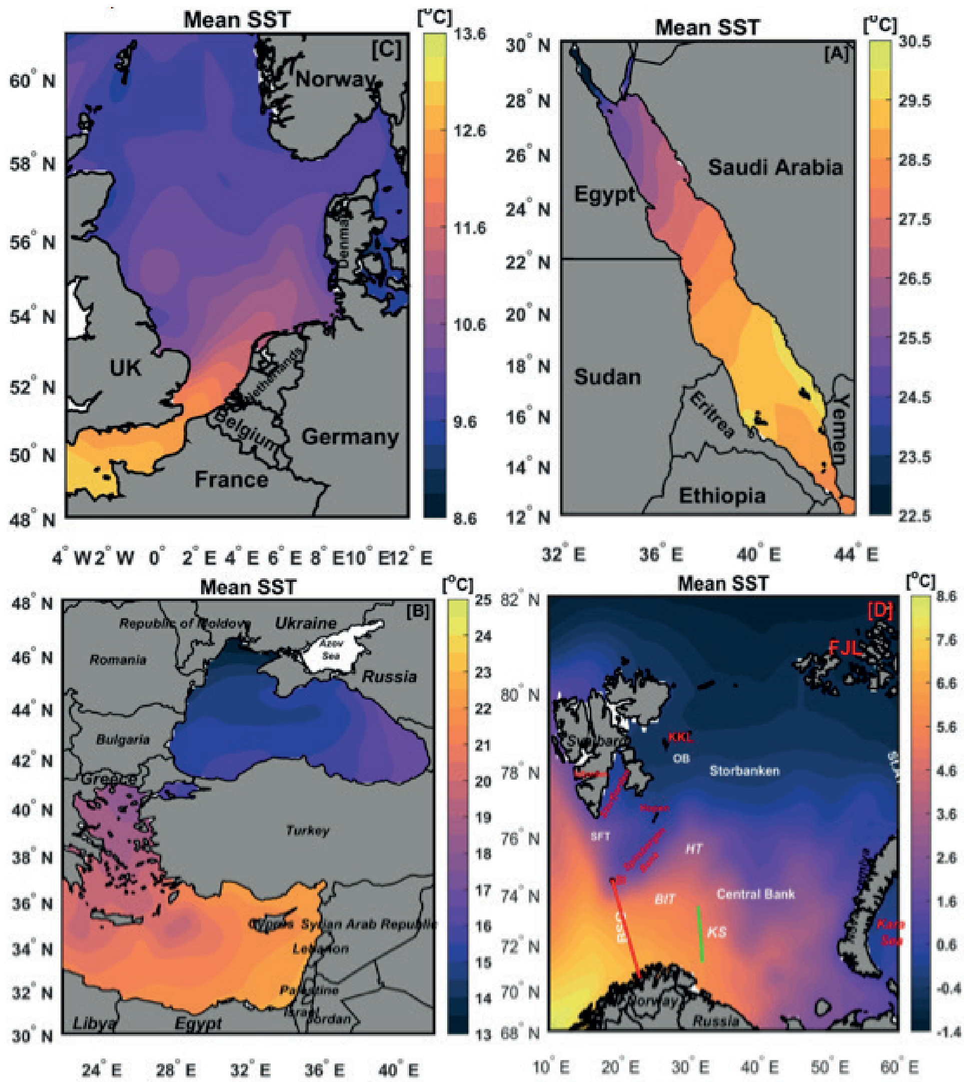

Figure 1. Geographic location and climatological mean sea surface temperatures between 1982 and 2022 for (A) the Red Sea, (B) the eastern Mediterranean and Black Seas, (C) the North Sea, and (D) the Barents Sea. Abbreviations in panel D stand for Barents Sea Opening (BSO), Bear Island Trough (BIT), Hopen Trough (HT), Bear Island (BI), Storfjorden Trough (SFT), Kong Karls Land (KKL), Olga Basin (OB), Franz Joseph Land (FJL), and St. Anna Trough (St.AT). The Kola Section (KS) is marked with a straight green line.

3.1 SST climatological mean and trend

The regional climatological averages (1982-2022) of SST over the five selected regional seas are shown in Figure 1. The climatological mean SST exhibits a clear meridional gradient (i.e., SST increases from south to north). SST ranged from -1.4 °C in the northern Barents Sea (Fig. 1D), which is influenced by sea ice, to 30.5 °C in the southern Red Sea (Fig. 1A), which is influenced by the influx of warm water from the Indian Ocean via the Gulf of Aden (Nagy *et al.*, 2021). Both the North Sea and the Barents Sea have higher SST in their southern and southwestern regions (Figs. 1C, 1D), which is due to the influx of warm Atlantic water. A zonal gradient is also observed in the eastern Mediterranean and Black Sea, this time with the highest values in the east and the lowest in the west. The SST minimum in the Black Sea was found in the northwestern shelf, near the Dnieper and Dniester estuaries (Fig. 1B), while the highest values were found in the eastern part, which is influenced by the permanent anticyclonic Batumi Gyre (Buongiorno Nardelli *et al*. 2010; Gunduz *et al*. 2020 ; Mohamed *et al*. 2022a).

Statistically significant ($p < 0.05$) rates of SSTA warming are observed over each grid cell of the five regional seas (Fig. 2), except for the northern sector (above 80°N) of the Barents Sea and the Spitsbergen Bank (see Fig. 1d for location), which show an insignificant SST trend ($p > 0.05$) influenced mainly by sea ice in these regions (Mohamed *et al.* 2022b). High spatial variability in the observed SST trend is found not only between these different regional seas, but also within the same basin. For the Red Sea, the highest SST trends are observed in the northern sector, and the lowest values in the southern sector (Fig. 2A). For both the North Sea and the Barents Sea, the highest SST trends are found in the regions affected by the accumulation of warm Atlantic water (i.e., the central and eastern areas of the North Sea and the southwestern sector of the Barents Sea) (Figs. 2 C, D). The Black Sea shows the highest SST trend among the regional seas examined, with the highest trend of up to 0.6 ^{o}C/decade observed along the Russian coast (Fig. 2B). In the eastern Mediterranean, the strongest SST trends are observed west and south of Cyprus (Fig. 2B), and the lowest in the Ierapetra Gyre (southeast of Crete).

The time series and temporal linear trend of spatial mean SSTA in these sub-basins between 1982 and 2022 are shown in Figure 3 and Table 1. The highest SSTA in the low-latitude seas (i.e., Red Sea, Eastern Mediterranean, and Black Sea) were observed in 2010, 2013, 2016, 2018, and 2020, which coincide with the years when the ENSO index showed a strong warming phase (i.e., El Niño conditions). The highest SSTA values in the North Sea were recorded in 2014 and 2022, and in 2013, 2016 and 2022 in the Barents Sea. It is worth noting that the SSTA in the North Sea and Barents Sea show opposite fluctuations, which requires further analysis to determine the reason. The overall temporal trends of SSTA are 0.25 ± 0.015, 0.36 ± 0.017, 0.47 ± 0.027, 0.37 ± 0.026, 0.31 ± 0.029 ° C/decade for the Red Sea, Eastern Mediterranean, Black Sea, North Sea, and Barents Sea, respectively (Fig. 3 and Table 1).

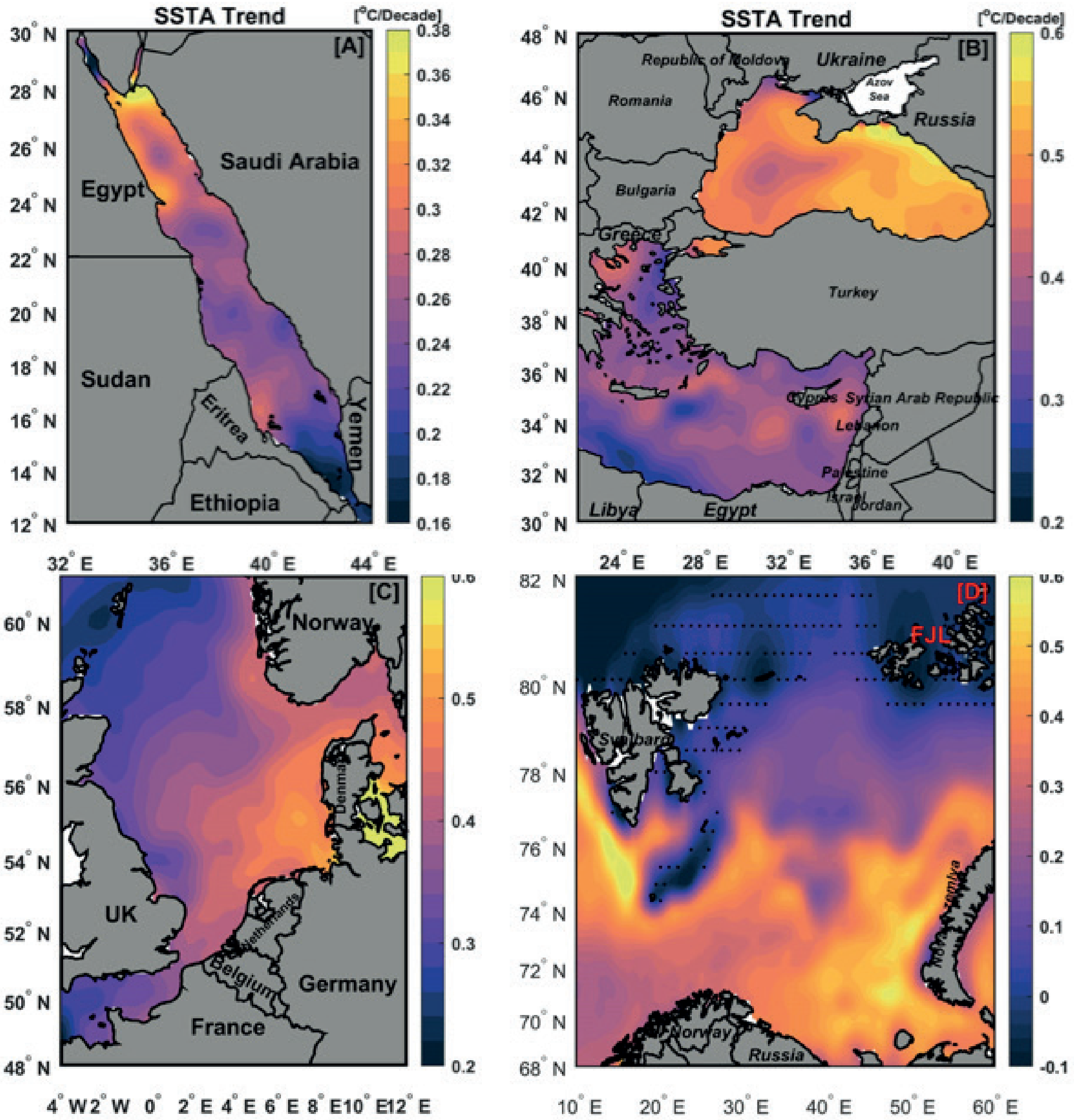

Figure 2. Trend maps (°C/decade) of sea surface temperatures over (A) the Red Sea, (B) the eastern Mediterranean and Black Sea, (C) the North Sea, and (D) the Barents Sea between 1982 and 2022.

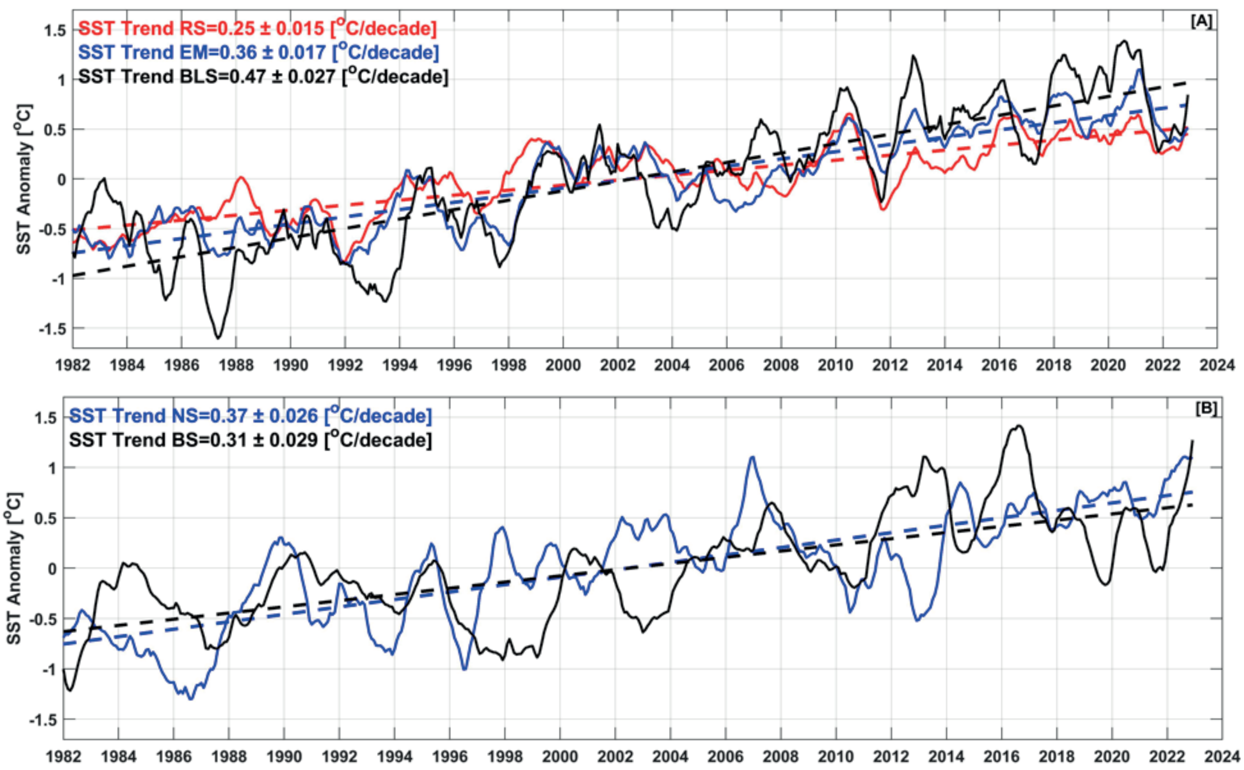

Figure 3. Temporal variations and linear trends (°C/decade) of sea surface temperature anomaly (SSTA) between 1982 and 2022; for (A) the Red Sea (red line), eastern Mediterranean (blue line), and Black Sea (black line), (B) the North and Barents Seas (blue and black lines). Linear trends are shown by dashed lines for the entire period. All-time series were low-pass filtered with a 13-month period to highlight interannual variability and improve visualisation.

3.2. Spatial Trends of MHW Characteristics

Figures 4 and 5 show the spatial trends in MHW frequency and total number of days in the five regional seas between 1982 and 2022. Both MHW frequency and total number of MHW days showed a statistically significant ($p > 0.05$) trend in all regional seas, except for the Spitsbergen Bank and the northern sector of the Barents Sea (Figs. 4D and 5D), where a non-significant trend was found due to the influence of sea ice in these regions. High spatial variability is also observed in MHW frequency and total day trends, not only between these different regional seas, but also within the same basin. The highest trends in MHW frequency (up to 1.8 events/decade) and MHW days (up to 28 days/decade) are observed in the Black Sea and Barents Sea, especially in southwestern Svalbard and the southernmost part of the Barents Sea, and in the northeastern Black Sea (mainly in the Caucasus-Anticyclone Gyre off the Russian coast) (Figs. 4B,D and 5 B,D). For the Red Sea, the highest trend in both MHW frequency and total days is in the northern Red Sea (Figs. 4A and 5A). In the North Sea, the highest trend of MHW frequency and total days are found in the southern section and in the English Channel (Figs. 4C and 5C), which are affected by the warm Atlantic Water. In general, the highest trends of MHW characteristics (Figs. 4 and 5) mainly coincide with the trend of SST (Fig. 2), confirming the role of long-term warming in the formation of MHWs.

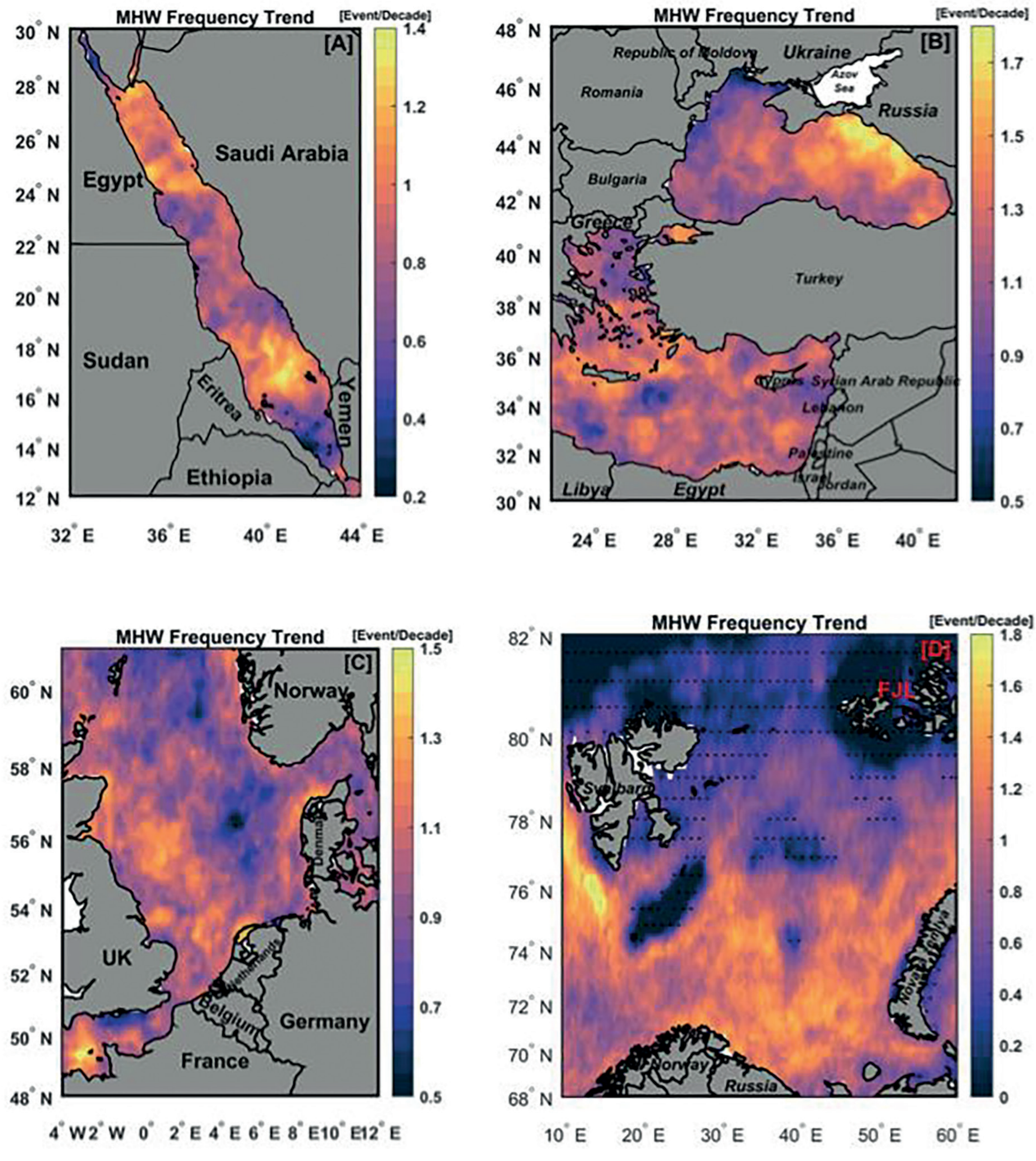

Figure 4. MHW frequency trend maps (event/decade) between 1982 and 2022 for (A) the Red Sea, (B) the eastern Mediterranean and Black Seas, (C) the North Sea, and (D) the Barents Sea. Black dots indicate areas where trends are not statistically significant based on the modified Mann-Kendall method with a 95% confidence interval.

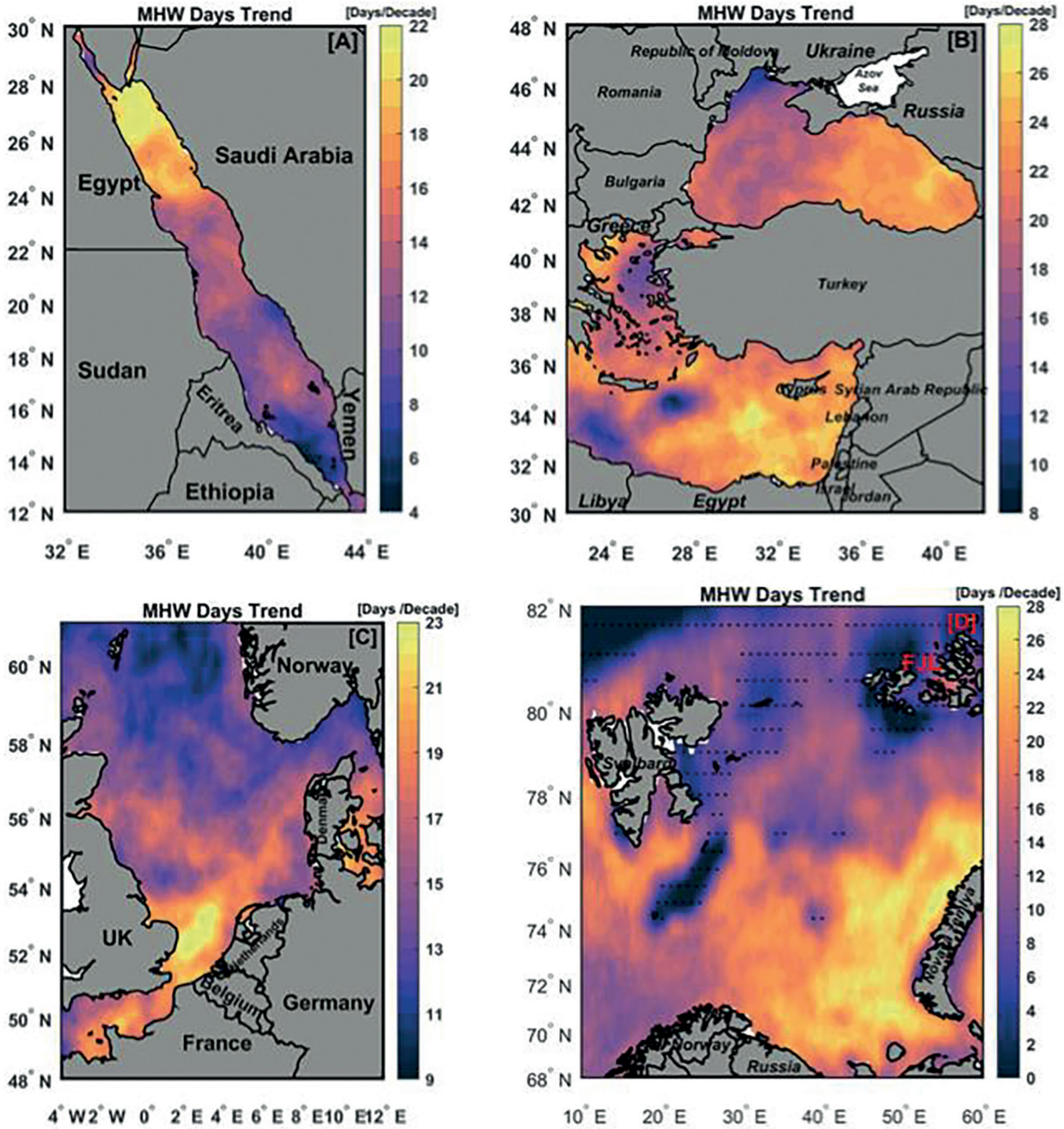

Figure 5. MHW total days trend maps (days/decade) for (A) the Red Sea, (B) the eastern Mediterranean and Black Seas, (C) the North Sea, and (D) the Barents Sea between 1982 and 2022. Black dots indicate areas where trends are not statistically significant based on the modified Mann-Kendall method with a 95% confidence interval.

3.3 Interannual Variation of MHW

The interannual variability and temporal trends of MHW frequency for the different sub-basins between 1982 and 2022 are shown in Figure 6 and Table 1. The highest MHW frequency (more than 4 events) that occurred in the Red Sea, Eastern Mediterranean, and Black Sea was observed in 2010, 2016, 2018, and 2020 (Fig. 6A), which were the warmest years in these regions (see Fig. 3A). This could be due to the effects of the strong positive/warm ENSO phase recorded in the same years (Fig. 7), especially in the Red Sea. For the North Sea and Barents Sea (Fig. 6B), the most frequent MHW events (more than 6 events) were recorded in 2014 and 2016, respectively. In the North Sea, the frequency was also high (more than 5 events) in 2020 and 2022 (Fig. 6B).

The overall temporal trends of MHW frequency (total days) are 0.84 ± 0.29 (13.45 ± 4.53), 1.17 ± 0.26 (20.60 ± 5.32), 1.12 ± 0.30 (19.02 ± 6.05), 0.99 ± 0.33 (16.22 ± 6.55), 0.89 ± 0.34 (17.32 ± 8.33) event/decade (days/decade) for the Red Sea, Eastern Mediterranean, Black Sea, North Sea, and Barents Sea, respectively (Fig. 7 and Table 1). The highest trends of the frequency and total days are found in the Eastern Mediterranean and Black Sea, which have the highest SST trend among all sub-basins.

In general, MHW frequency and total days have increased in all five regional seas, especially in the last decade (2012–2022). Figure 8 shows an example of the relationship between MHW frequency and maximum intensity in the Black Sea. The correlation of MHW frequency with maximum MHW intensity and total days was 0.62 and 0.90, respectively, indicating that as MHW frequency increases, intensity and total days also increase (i.e., MHWs become more frequent, intense, and last longer). Each year in the last decade (red circles in Fig. 8) has a higher MHW frequency than the average climatological mean of 1.9 events (vertical black dashed line) and also higher intensity than the climatological mean of 2.5 °C (horizonatal blue dashed line). The only year in which there was no MHW is 1987 (Figure 8).

Table 1. Summary of the long-term trend in SST (°C/decade), MHW frequency (events/decade), and MHW days (days/decade) for the Red Sea, Eastern Mediterranean Sea, Black Sea, North Sea, and Barents Sea between 1982 and 2022.

Region	SST	MHW Frequency	MHW Days
Red Sea	0.25 ± 0.015	0.84 ± 0.29	13.45 ± 4.53
Eastern Mediterranean	0.36 ± 0.017	1.17 ± 0.26	20.60 ± 5.32
Black Sea	0.47 ± 0.027	1.12 ± 0.30	19.02 ± 6.05
North Sea	0.37 ± 0.026	0.99 ± 0.33	16.22 ± 6.55
Barents Sea	0.31 ± 0.029	0.89 ± 0.34	17.32 ± 8.33

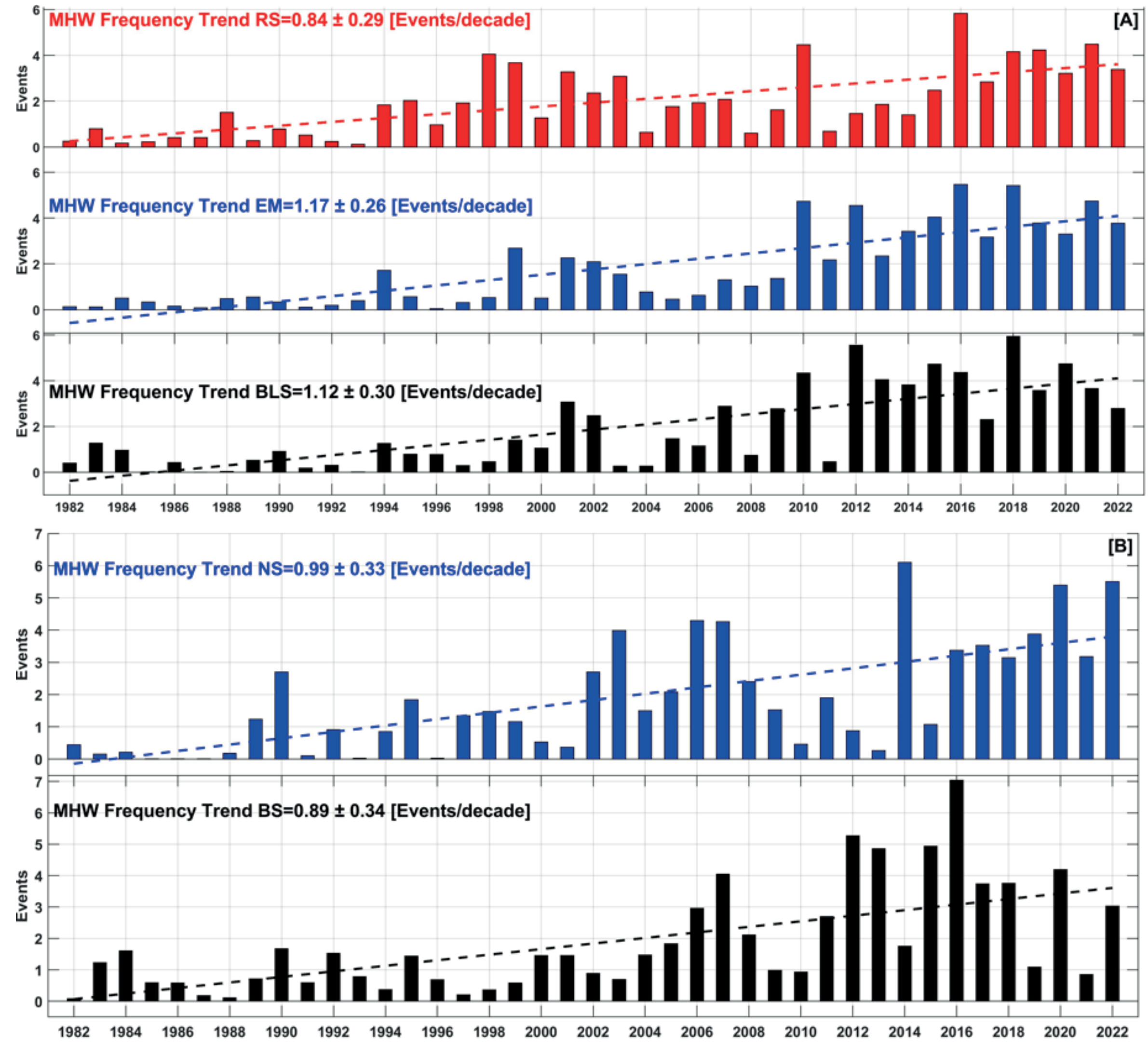

Figure 6. Regionally averaged annual MHW frequency from 1982 to 2022 for (A) low-latitude seas (i.e., Red Sea, eastern Mediterranean, and Black Sea), (B) high-latitude seas (i.e., North Sea and Barents Sea). Note that trend values are also displayed at the top of each subgraph.

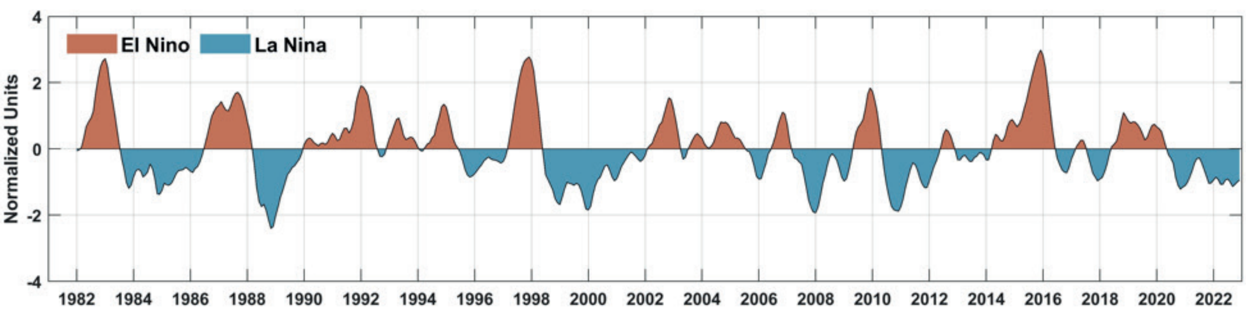

Figure 7. Normalized 3- months runing mean values of the El Niño Southern Oscillation (ENSO) index from 1982 to 2022. The warm ENSO phase (El Niño) and the cold ENSO phase (La Niña) are represented by red and blue shading, respectively.

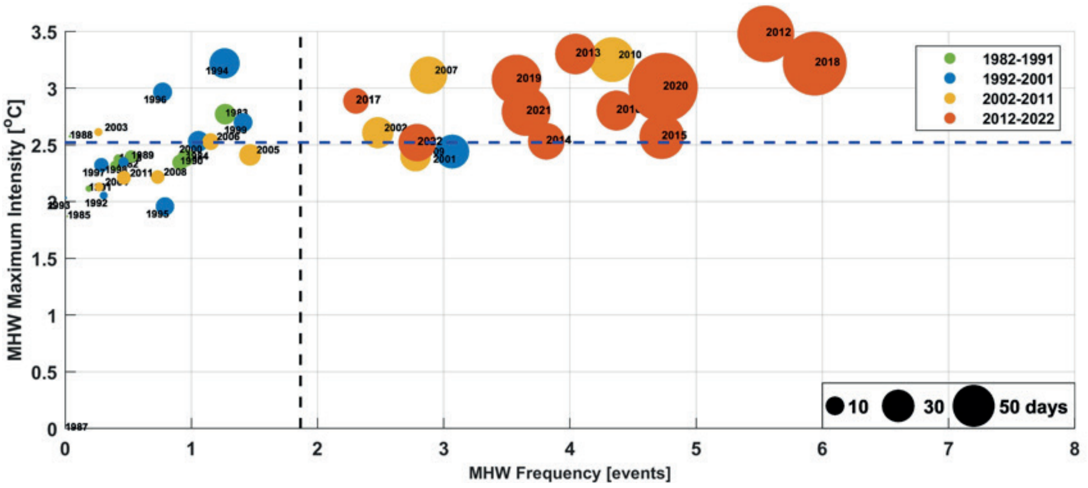

Figure 8. Annual mean maximum intensity of MHW versus frequency and total number of days in the Black Sea by decade. The dashed lines indicate the mean values for maximum intensity (horizontal) and frequency (vertical). The size of the colored circles indicates the annual average of total days. The black circles in the southeast corner represent the reference size of the circle for 10, 30, and 50 days.

3.4. Marine Heatwaves 2016 (MHW16) in the Barents Sea

The warmest year on record in the Barents Sea was 2016, with a record of seven MHWs (Fig. 9). Here we examine the strongest MHW event, which lasted for about two months (from 28 June and 29 to August 2016) over the southern Barents Sea, and then examine the role of atmospheric conditions in the development of this event and its impacts. The mean and maximum MHW intensities during this event were 2.96 °C and 4.13 °C, respectively. The average SSTA over the whole Barents Sea during this MHW event is shown in Figure 10A. The average SSTA in the southern Barents Sea was 2.9 °C. Marine species and fish stocks responded to this MHW event by shifting their geographic distribution (Eriksen *et al*. 2020). For example, the densest cod and herring assemblages shifted eastward, while capelin assemblages shifted northward. Species such as capelin, haddock, herring, and long rough dab were more abundant than the long-term average (1980-2016), while the stock of polar cod was significantly lower and had almost disappeared in the core area of the MHW event (i.e., the southeastern Barents Sea).

During this event, atmospheric conditions showed warm air temperature anomalies over the entire Barents Sea (shaded in Fig. 10B), with the highest positive anomaly in the core area of the MHW event (i.e., the southeastern Barents Sea), with higher atmospheric pressure anomalies (up to +2hPa) in the same region (Fig. 10B). This high pressure system over the ocean reduces cloud-cover, increases solar radiation, and reduces surface wind speed, resulting in hot and dry weather that contributes to SST warming (Holbrook *et al*. 2020). The southerly wind anomalies over the southernmost Barents Sea enhanced the transport of heat and moisture from the south to the northern Barents Sea, causing a strong summertime MHW over the entire Barents Sea. This combination of unusual southerly winds (i.e., negative anomalies) and higher atmospheric pressure over the southeastern Barents Sea most likely resulted in an intense positive loop of surface heating and stratification that could not be broken because wind stress was insufficient to mix up colder water from below. In addition, this event coincided with the strongest positive EAP phase, which is usually associated with southerly wind anomalies and above-average surface temperatures over northwestern Europe.

Thus, the main cause of this strong MHW event was most likely atmospheric overheating associated with a southerly wind and unusually high pressure (Mohamed *et al*. 2022c).

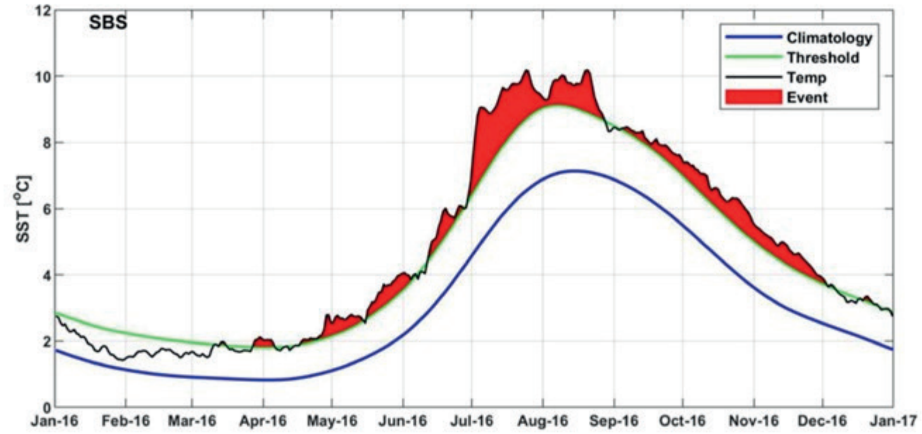

Figure 9. Evolution of the daily SST time series (black line) over the southern Barents Sea (SBS) from January to December 2016. The blue and green lines indicate the climatological mean and 90th percentile, respectively. The red shaded regions indicate the period associated with the identified MHW.

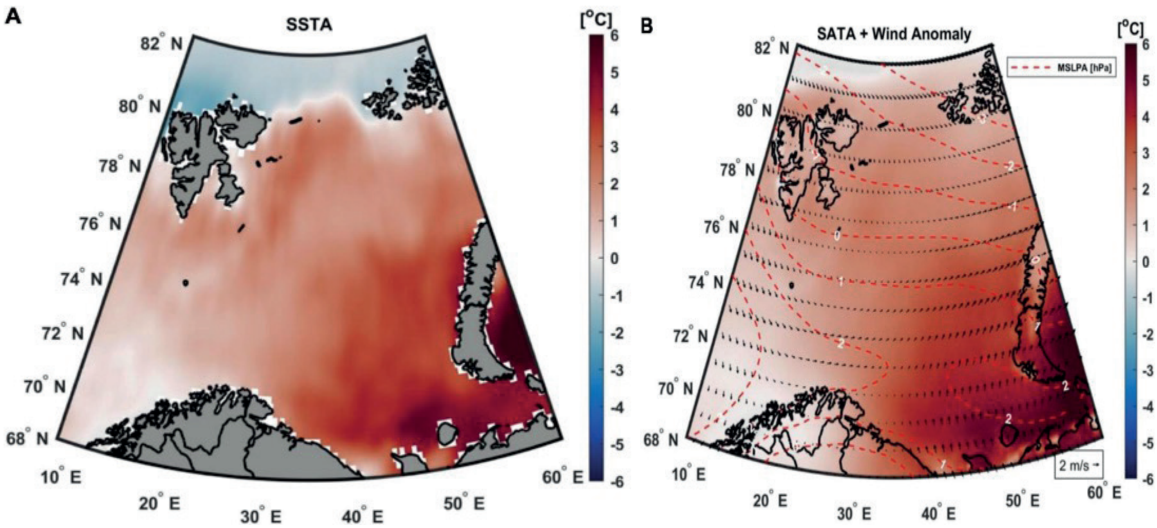

Figure 10. (A) Spatial map of the mean SST anomaly (SSTA) in the Barents Sea during the most intense MHW event (June 28-29-August 2016), (B) corresponding anomalies of air temperature (SATA, shaded), mean sea level pressure (MSLPA, dashed red line contours, units: hPa), and wind speed anomalies (black arrows denote magnitude and direction of wind anomaly, scale arrow bottom right, units: m/sec).

4 Summary and conclusions

This study examines spatio-temporal variations and trends in SST and the frequency and number of days of marine heatwaves in the context of a comparison of five regional seas in the northern Hemisphere which are considered climate change hotspots.

Over the past 41 years (1982-2022) significant SST warming was observed in the five regional seas studied - the Red Sea, Eastern Mediterranean, Black Sea, North Sea and Barents Sea - accompanied by increases in MHW frequency and total days. These trends are not uniform and vary from basin to basin. The strongest trends in MHW frequency and total days were observed in the eastern Mediterranean and Black Sea, where the strongest SST trends were also observed. This confirms the role of long-term warming in the generation of MHWs.

Atmospheric conditions play an important role in the formation of MHWs, especially in shallow seas such as the North and Barents Seas. As shown by the two case studies of MHWs in 2014 in the North Sea and 2016 in the Barents Sea, these were associated with higher atmospheric pressure and a reduction in wind speed, which is considered a favorable condition for MHW occurrence. Moreover, the comparison between the large-scale climate modes and the temporal variability of MHWs suggests that not only long-term warming but also the large-scale natural climate modes seem to play a significant role in the occurrence of MHWs. For example, as shown here in the Red and Black Seas, the probability of MHW occurrence increases with the positive warm phase of the El Nino Southern Oscillation (El Nino). The same is true in the North Sea and Barents Seas, this time with the East Atlantic Pattern (EAP).

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References

Aboelkhair H., Mohamed B., Morsy M. and H. Nagy. 2023. Co-occurrence of atmospheric and oceanic heatwaves in the Eastern Mediterranean over the last four decades. *Remote Sensing*, 15:1841.

Banzon V., Smith T.M., Chin T.M., Liu C., and W. Hankins. 2016. A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth Syst. Sci*., Data 8, 165–176. doi:10.5194/essd-8-165-2016.

Barnston A.G. and R.E. Livezey. 1987. Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon. Weather Rev*. 115: 1083–1126.

Bond N. A., Cronin M. F., Freeland H., and N. Mantua. 2015. Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophys. Res. Lett*., 42, 3414–3420. doi:10.1002/2015GL063306.

Buongiorno Nardelli B., Colella S., Santoleri R., Guarracino M., and A. Kholod. 2010. A re-analysis of Black Sea surface temperature. *J. Mar. Syst*., 79: 50–64. doi:10.1016/J.JMARSYS.2009.07.001.

Ducrotoy J. P., Elliott M., and De Jonge V. N. 2000. The North Sea. *Mar. Pollut. Bull.*, 41: 5–23. doi:10.1016/S0025-326X(00)00099-0.

Eriksen, E., Bagøien, E., Strand, E., Primicerio, R., Prokhorova, T., Trofimov, A., *et al*. 2020. The recordwarm Barents Sea and 0-group fish response to abnormal conditions. *Front. Mar. Sci*., 0, 338. doi:10.3389/FMARS.2020.00338.

Frölicher T. L., Fischer E. M., and N. Gruber. 2018. Marine heatwaves under global warming. *Nature*. 560: 360–364, doi:10.1038/s41586-018-0383-9

Frölicher T. L., and C. Laufkötter. 2018. Emerging risks from marine heat waves. *Nat. Commun*, 2018 91 9: 1–4. doi:10.1038/s41467-018-03163-6.

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Guiet J., Galbraith E., Kroodsma D., and B. Worm. 2019. Seasonal variability in global industrial fishing effort. PLoS One 14. doi:10.1371/JOURNAL.PONE.0216819.

Gunduz M., Özsoy E., and R. Hordoir. 2020. A model of Black Sea circulation with strait exchange (2008-2018). *Geosci. Model Dev*. 13: 121–138. doi:10.5194/GMD-13-121-2020.

Hamdeno M., Nagy H., Ibrahim O., B. Mohamed. 2022. Responses of satellite Chlorophyll-a to the extreme sea surface temperatures over the Arabian and Omani Gulf. *Remote Sens*., 14, 4653. doi:10.3390/RS14184653.

Hamdeno M., and A. Alvera-Azcaráte. 2023. Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Front. Mar. Sci*., 10, 1093760. doi:10.3389/FMARS.2023.1093760/BIBTEX.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., et al. 2020. The ERA5 global reanalysis. Q. J. R. *Meteorol. Soc*., 146: 1999–2049. doi:10.1002/qj.3803.

Hobday A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Moore, P. J., Scannell, H. A., Sen Gupta, A., and Wernberg, T. 2016. A hierarchical approach to definin marine heat waves. *Progress in Oceanography*, 141:227– 238.

Hobday A. J., Burrows M. T., Filbee-Dexter K., Holbrook N. J., Sen Gupta A., Smale D. A., *et al.* 2023. With the arrival of El Niño, prepare for stronger marine heatwaves. *Nature*, 2023 6217977 621: 38–41. doi:10.1038/d41586-023-02730-2.

Holbrook N. J., Scannell H. A., Gupta A. S., Benthuysen J. A., Feng M., Oliver E. C., *et al.* 2019. A global assessment of marine heatwaves and their drivers. *Nat. Commun*., 10: 2624, doi: 10.1038/s41467-019-10206-z

Holbrook N.J., Sen Gupta A., Oliver E.C.J. *et al*. 2020. Keeping pace with marine heatwaves. *Nat. Rev. Earth Environ*., 1: 482–493. https://doi.org/10.1038/s43017-020-0068-4

Ibrahim O., Mohamed B., and H. Nagy. 2021. Spatial variability and trends of marine heat waves in the eastern mediterranean sea over 39 years. *J. Mar. Sci. Eng*., 9: 1–22. doi:10.3390/jmse9060643.

IPCC 2021. Summary for policymakers. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, et al. (Eds.), Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the intergovernmental panel on c. Cambridge Univ. Press. Available at: https://www.ipcc.ch/report/ar6/wg1/chapter/summary-for-policymakers/ [Accessed May 25, 2023].

Kerr R. A. 2000. A North Atlantic climate pacemaker for the centuries. Science, 288, 1984–1986. doi:10.1126/SCIENCE.288.5473.1984.

Li Y., and Han W. 2015. Decadal sea level variations in the Indian Ocean investigated with HYCOM: Roles of climate modes, ocean internal variability, and stochastic wind forcing. *J. Clim*. 28, 9143–9165. doi:10.1175/JCLI-D-15-0252.1.

Liguori G. 2024. The need to adopt process-based definitions for marine heatwaves. pp 41 - 50 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Mills K.E., Pershing A.J., Brown C.J., Chen Y., Chiang F.S., Holland D.S., Lehuta S., Nye J.A., Sun J.C., Thomas A.C. and Wahle R.A., 2013. Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography*, 26(2): 191-195. doi:10.5670/OCEANOG.2013.27.

Mohamed B., Nagy H., and O. Ibrahim. 2021. Spatiotemporal variability and trends of marine heat waves in the Red Sea over 38 Years. *J. Mar. Sci. Eng*; 9, 842. doi:10.3390/JMSE9080842.

Mohamed B., Ibrahim O., and H. Nagy. 2022a. Sea surface temperature variability and marine heatwaves in the Black Sea. *Remote Sens*; 14, 2383. doi:10.3390/RS14102383.

Mohamed B., Nilsen F., and R. Skogseth. 2022b. Interannual and decadal variability of sea surface temperature and sea ice concentration in the Barents Sea. *Remote Sens*. 14, 4413. doi:10.3390/RS14174413.

Mohamed B., Nilsen F., and R. Skogseth. 2022c. Marine heatwaves characteristics in the Barents Sea Based on high resolution satellite data (1982–2020). *Front. Mar. Sci*. 9. doi:10.3389/FMARS.2022.821646.

Mohamed B., Barth A., and A. Alvera-Azcárate. 2023. Extreme marine heatwaves and cold-spells events in the Southern North Sea: classifications, patterns, and trends. *Front. Mar. Sci*. 10. doi:10.3389/fmars.2023.1258117.

Nagy, H., Mohamed, B., and Ibrahim, O. 2021. Variability of heat and water fluxes in the Red Sea using ERA5 data (1981–2020). *J. Mar. Sci. Eng;* 9, 1276. doi:10.3390/JMSE9111276.

Oliver E.C., Donat M.G., Burrows M.T., Moore P.J., Smale D.A., Alexander L.V., *et al.* 2018. Longer and more frequent marine heatwaves over the past century. *Nat. Commun*., 9:1324, doi:10.1038/s41467-018-03732-9

Oliver E. C. J. 2019. Mean warming not variability drives marine heatwave trends. *Clim. Dyn.* 2019 533 53, 1653–1659. doi:10.1007/S00382-019-04707-2.

Olsen E., Aanes S., Mehl S., Holst J. C., Aglen A., and H. Gjøsæter. 2010. Cod, haddock, saithe, herring, and capelin in the Barents Sea and adjacent waters: a review of the biological value of the area. ICES. *J. Mar. Sci*. 67, 87–101. doi:10.1093/ICESJMS/FSP229.

Pastor F. and S. Khodayar. 2023. Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of The Total Environment*, 861, 160621. doi:10.1016/J.SCITOTENV.2022.160621.

Reynolds R.W., Smith T. M., Liu C., Chelton D. B., Casey K. S. and M.G. Schlax. 2007. Daily high-resolution-blended analyses for sea surface temperature. *J. Clim*., 20: 5473–96.

Roberts S. D., Van Ruth P. D., Wilkinson C., Bastianello S. S., and M.S. Bansemer. 2019. Marine heatwave, harmful algae blooms and an extensive fish kill event during 2013 in south Australia. Front. Mar. Sci., 6, 610. doi:10.3389/fmars.2019.00610.

Schlegel R. W., Oliver E. C. J., and K. Chen. 2021. Drivers of marine heatwaves in the Northwest Atlantic: the role of Air–Sea interaction during onset and decline. *Front. Mar. Sci.:* 8, 217. doi:10.3389/FMARS.2021.627970/BIBTEX.

Schlegel R.W. 2024. Marine heatwave research: A path forward via the Mediterranean and the Arctic. pp 51 - 62 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Selig E. R., Casey K. S., and J.F. Bruno. 2010. New insights into global patterns of ocean temperature anomalies: Implications for coral reef health and management. *Glob. Ecol. Biogeogr*., 19, 397–411. doi:10.1111/J.1466-8238.2009.00522.X.

Sen Gupta A., Thomsen M., Benthuysen J. A., Hobday A. J., Oliver E., Alexander L. V., *et al.* 2020. Drivers and impacts of the most extreme marine heatwaves events. *Sci. Rep*. 10, 19359. doi:10.1038/s41598-020-75445-3.

Smale D. A., Wernberg T., Oliver E. C. J., Thomsen M., Harvey B. P., Straub S. C., *et al.* 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Change*, 9, 306–312. doi: 10.1038/s41558-019-0412-1

Smith, K. E., Burrows, M. T., Hobday, A. J., Sen Gupta, A., Moore, P. J., Thomsen, M., *et al*. 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*: 374. doi:10.1126/science.abj3593.

Smith K.E, Burrows M.T., Hobday A.J., King N.G., Moore P.J., Sen Gupta A., Thomsen M.S.,Wernberg T., Smale D.A. 2023. Biological impacts of marine heatwaves. *Ann. Rev. Mar. Sci.*15(1): 119–145

Yao Y., Wang C., and Y. Fu. 2022. Global marine heatwaves and cold-spells in present climate to future projections. *Earth's Future.* 10, e2022EF002787. doi:10.1029/2022EF002787.

Marine heatwaves over different coastal environments: findings from the NE Mediterranean Sea to south Florida

Yannis S. Androulidakis[1,2], Yannis Krestenitis[1], Vassiliki Kourafalou[3], Marios Krestenitis[4]

[1]*Laboratory of Maritime Engineering and Maritime Works, School of Civil Engineering, Aristotle University of Thessaloniki, Greece*
[2]*Laboratory of Physical and Chemical Oceanography, Department of Marine Sciences, University of the Aegean, Greece*
[3]*Department of Ocean Sciences, University of Miami/Rosenstiel School of Marine, Atmospheric and Earth Science, USA*
[4]*Information Technology Institute, Centre for Research & Technology Hellas, Greece*

Abstract

Marine Heatwaves (MHWs) are increasingly recognized as an important parameter in the sustainability of coastal environments (both natural and urban) in the context of climate change. We investigated the formation of MHW events during prolonged periods (past decades) and focused on their relationship with spatial and temporal sea surface temperature (SST) variability over two different coastal regions: NE Mediterranean (Aegean, Ionian, Cretan Seas/AICS) and south Florida. The methodology is based on continuous high-resolution satellite observations, field observations, meteorological data, and numerical hydrodynamic simulations. The interannual variability and the spatial differences between coastal regions with different socioeconomic and environmental characteristics are examined. We also evaluated the ocean climate factors that are responsible for the SST variability and trends of each coastal area, focusing on the formation of MHWs and their interannual variability. Ocean dynamics and circulation features like the low salinity Black Sea Waters spreading over parts of the AICS region and the Gulf Stream in the vicinity of south Florida coasts contribute to the variability of MHWs. For south Florida, the interannual positive trend of the MHWs was 0.75 events/decade with 7.4 days/decade duration increase and was associated to the general increasing SST trend over the entire region (0.19^{o}C/decade), following the respective atmospheric temperature (0.21^{o}C/decade) and the heat flux (~5000 J/m^2/decade) increases. In the AICS, the interannual trends of MHWs were stronger (1.7 events/decade) with 21.3 days/decade increase in the total annual duration. The cumulative intensity of MHWs was higher over the northern Aegean Sea, which includes several “hot spot” areas such as Thermaikos Gulf. Finally, a novel deep-learning method was also developed and tested over the AICS region to predict the ocean temperature evolution over the interim future (from months to year), useful for the detection of future MHWs.

Keywords: *SST variability, interannual trends, ocean circulation, stratification, deep-learning*

1. Introduction

Marine Heatwaves (MHWs) as defined by Hobday *et al.* (2016; 2018) are extreme climatic episodes affiliated with warm Sea Surface Temperature (SST) values that persist for days to months, over a specific oceanic area. The interannual distribution of the SST is related both to the variability of the atmospheric conditions and to ocean circulation dynamics. MHW events may affect the vulnerability of marine organisms and ecosystems (see Garrabou *et al*. 2024 in this volume) and have been observed in all major ocean basins (i.e., Pearce *et al*. 2013; Wernberg *et al*. 2013 ; Mills *et al*. 2013 ; Di Lorenzo and Mantua 2016 ; Oliver *et al*. 2017; Darmaraki *et al*. 2019; see also Mohamed, Rilov *et al*. 2024 in this volume). Over the coastal ocean, where the majority of the global population, environmentally sensitive areas, and the majority of human activities are located, the impact of MHWs is more important and requires further evaluation and assessment. In this paper, we describe the formation and evolution of MHWs over two different coastal environments: i) the Aegean, Ionian and Cretan Seas (AICS) in the northeastern Mediterranean Sea (Fig. 1a; Androulidakis and Krestenitis 2022); and ii) the south Florida region in the west tropical Atlantic Ocean (Androulidakis and Kourafalou 2022; Fig. 1b). Although prevailing atmospheric conditions are the main forcing factors at the two coastal areas, they are both characterised by specific ocean circulation patterns (e.g. Black Sea Waters (BSW) plume in the Aegean Sea and Gulf Steam in the Straits of Florida) that play a determining role on the temporal and spatial distribution of SST and thus the variability of MHWs.

2. Methods and data

The data used in the study consist of SST satellite observations, atmospheric modeling data, ocean field observations, and model-derived ocean data. The satellite SST observations data set used here, distributed by the E.U. Copernicus Marine Service (CMS; https://www.copernicus.eu/), covers the entire study period from 1982 to 2022 (0.05^{o} spatial resolution). The satellite-derived data consist of the daily mean gap-free (L4) horizontal fields. They were used to analyze the SST temporal and spatial variability, and to detect the MHWs. The meteorological conditions for our domains and study periods were derived from the ERA5 hourly data on single levels distributed by the Copernicus Climate Data Store (0.25^{o}; https://cds.climate.copernicus.eu/). Field (e.g., Poseidon System Buoys; Soukissian *et al.* 2002; https://poseidon.hcmr.gr/) and numerical simulations (e.g., Florida Keys Hybrid Ocean Circulation Model: FKEYS-HYCOM; Kourafalou and Kang, 2012; https://coastalmodeling.earth.miami.edu/) were also used to evaluate the variability of the ocean conditions covering the same study periods.

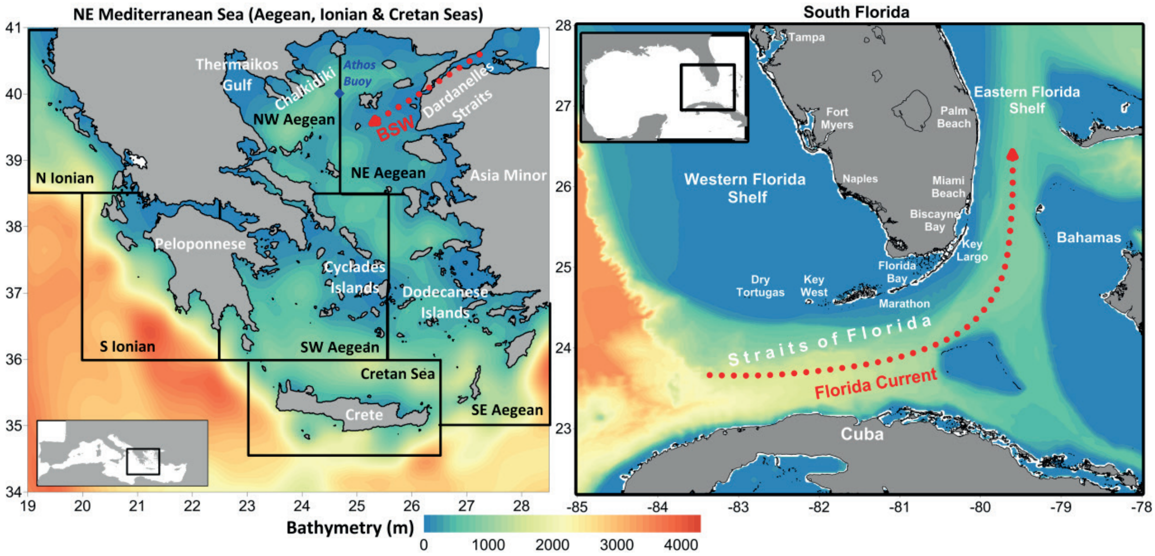

Figure 1. Bathymetry (m) of (a) Aegean, Ionian and Cretan Seas (AICS), divided at seven sub-basins, and (b) South Florida domain. The main geographical locations are also marked. The red dashed lines indicate (a) the Black Sea Waters (BSW) and (b) the Florida Current patterns.

Our methodology adopts the definition proposed by Hobday *et al*. (2016) to determine MHW events, based on abrupt SST increases above a "climatologic" value (the baseline temperature) for a certain time period. This method has been broadly used to evaluate the MHW variability in both global ocean (i.e. Oliver *et al*. 2018, Holbrook *et al*. 2019) and regional basins (i.e. Oliver *et al*. 2017 ; Darmaraki *et al*. 2019). To define a baseline temperature, Hobday *et al*. (2016) proposed a period of 30 years, which is associated to the time scale variability of ocean drives (e.g., El Nino). Herein, we use a long dataset with satellite-derived SST high-resolution fields. The baseline temperature used in the present study is defined by the varying 90th climatological temperature percentile, derived from the satellite-derived data. Moreover, the duration (the time between the start and end dates; ≥5 days) was also computed for all detected MHW events. Finally, the cumulative intensity was derived based on the SST anomaly over the 90th climatological temperature percentile over an entire time interval of interest that includes the MHW events during this interval (see Licer, 2024 in this volume).

3. Results

3.1 Aegean, Ionian, and Cretan Seas

The mean annual SST levels were averaged over the entire study region and for each sub-region separately (Fig. 2). The mean SST of the entire study region reveals a clear increasing trend derived from annual means (0.47 °C/decade; Sen's Slope) with significantly high annual means after 2012 (>20.5 °C; Fig. 2a). The respective annual mean was approximately 19 °C in 1982 and 20 °C in 2008 (Androulidakis and Krestenitis, 2022). The annual 99th percentiles, representing the highest 1% of the SST values and averaged over the entire region, show a respective interannual increase (Fig. 2b) of about 0.56 °C/decade. The strengthening of the warming conditions through the last four decades increased the annual frequencies of extreme SST levels (>median + 2x standard deviation) in almost all sub-regions (Fig. 2c) with significantly high frequencies in the northern Aegean (e.g. 8.5% and 9.6% of 2021 in NE and NW Aegean, respectively). The north Aegean areas revealed the strongest trends among all sub-regions for the mean (0.052°C) and maximum (0.071°C) levels. The trends (residuals) of the seasonal SST Anomalies (SSTA) derived from the Empirical Mode Decomposition (EMD) analysis confirm the different distribution of each season especially in the beginning and at the end of the study period (Fig. 2d); after 2010, the cold season (spring and winter) anomalies sharply increased while the summer and especially the warm season SSTA is characterised by a milder rise (see Androulidakis and Krestenitis (2022). However, the overall linear 41-year trend over the entire AICS region is stronger for the summer SSTAs (0.53°C/decade).

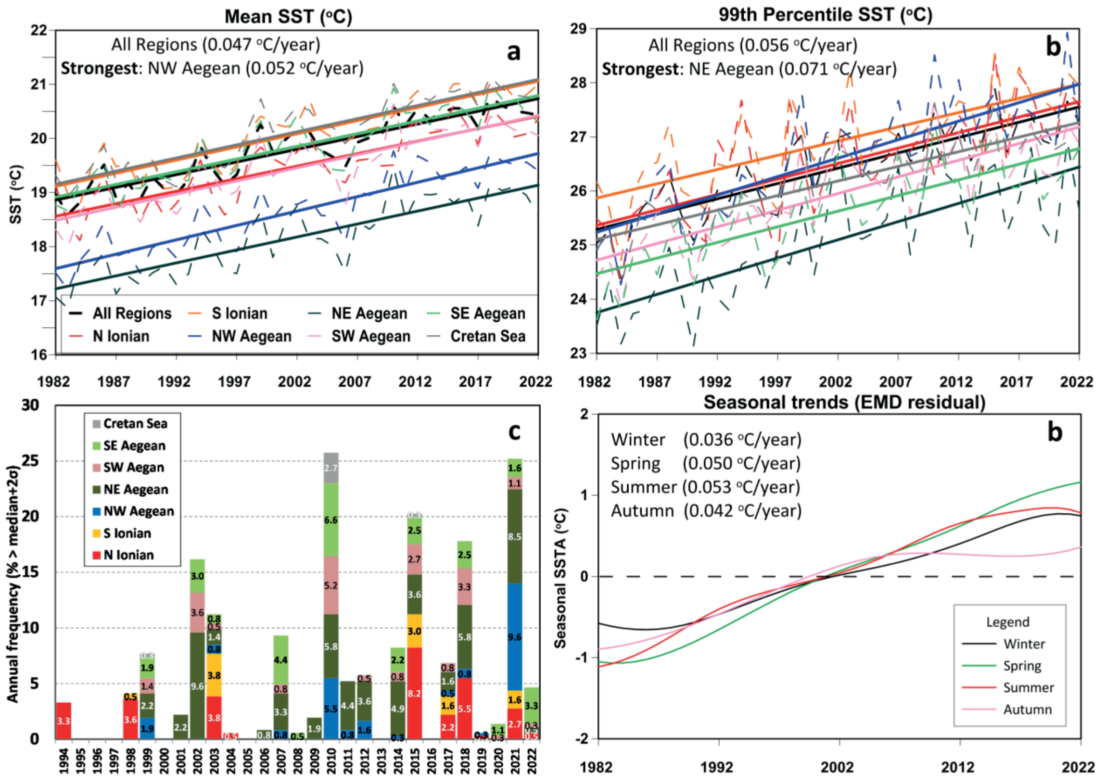

Figure 2. Annual variability and trends of (a) the mean SST, and (b) the 99th percentile of SST, averaged over eight regions (Figure 1a) for the 1982-2022 period (extension of the time series presented by Androulidakis and Krestenitis 2022). (c) Annual frequencies (%) of the 99th percentiles over the median+2x standard deviation (2σ) threshold, derived for each sub-region (data before 1994 are not shown due to zero frequencies in all areas). (d) Trends (residuals) derived from the Empirical Mode Decomposition (EMD) of the seasonal SST anomalies for all AICS. The respective linear Sen's Slopes (°C/year) are also shown.

Androulidakis and Krestenitis (2022), based on a higher resolution (0.01°) SST satellite product showed that the annual number of MHW events and their total annual duration (days) revealed an increasing trend over the AICS region during the recent 14-year period (2008-2021). The increase of the MHWs days was 21.3 days/decade and the respective increase of the MHWs events was 1.7 events/decade in agreement with the trend derived by Darmaraki *et al*. (2019) for the whole Mediterranean Sea. Herein, we extend the study period covering the last four decades, from 1982 to 2022. The strongest interannual SST trends (>0.6°C; Fig. 3a) were detected in areas over the northern Aegean Sea, the central Ionian Sea and south of Rhodes island (SE Aegean). The highest cumulative intensities of MHWs were also computed over the northern Aegean coastal areas (Figure 3b). The broader Thermaikos Gulf (NW Aegean) and the coastal area around Chalkidiki peninsula are considered as "hot spots" of MHW formation, affecting the ecological state of the marine environment (Lattos *et al*. 2022; Antoniadou *et al*. 2022). In fact the prolonged extreme sea temperature conditions (>31°C) in the summer of 2021 affected the entire water column of Thermaikos (Androulidakis *et al*. 2022) and led to extended mussels' mortality (Lattos *et al*. 2022). MHWs were not very frequent and intense over the southern regions, especially over the Cretan Sea (Fig. 3b) that showed the lowest extreme SST annual frequencies (Fig. 2c). The prevailing ocean conditions over the northern Aegean, favourable for MHW formation, are discussed below in section 3.3.1.

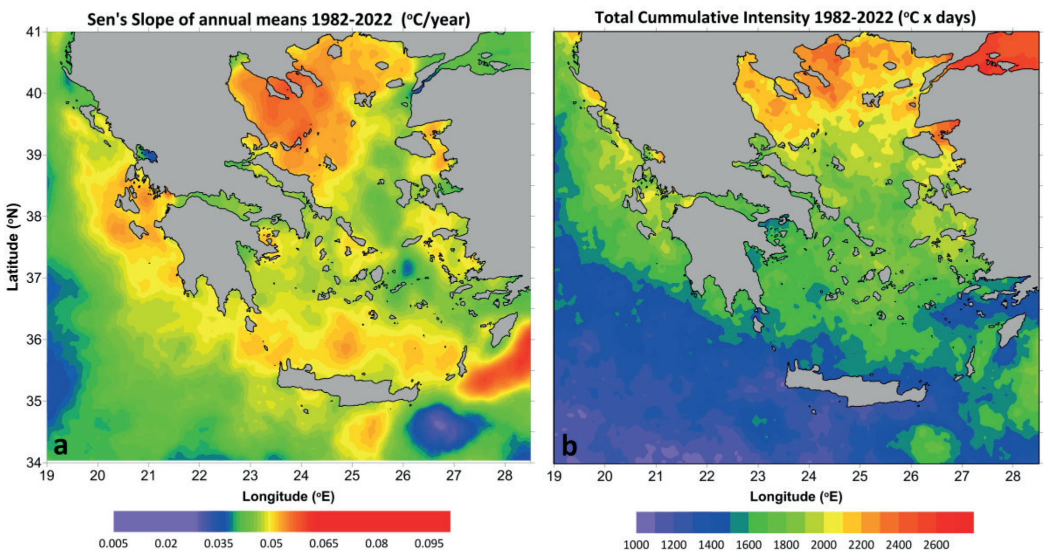

Figure 3. Spatial distribution of: (a) the Sen's slopes (°C/year) of annual SST means; and (b) the total cumulative intensity of MHWs, derived from the 1982-2022 period.

The highest cumulative intensities were computed after 2018 consistent with the large number of MHWs events and long periods during 2018-2021 shown by Androulidakis and Krestenitis (2022). The detection of abrupt changes during specific years in the long-term timeseries was also assessed with the homogeneity test of Pettitt (1979) which detects shifts in the average and calculates their significance in a hypothesis test. The null hypothesis is that the data are homogeneous, as against the alternative hypothesis that there is a datum at which there is a change in the data. The year 2002 is the datum of an upward shift, dividing the 41-year period in two separate periods; the cumulative intensity difference between the two periods is around 8.5 °C x days. The slope of the linear increasing trend is 4.6 °C x days/decade while the EMD residual reveals a sharper increase during the 1990s and 2000s. The 2022 MHW intensity was the lowest among the last five years (2018-2022) over the AICS region, contrary to the western Mediterranean basin, where significantly intense heat episodes occurred during that year (see Juza *et al*. 2024 in this volume). The summer and autumn of 2023 are also considered as extreme warm periods with high MHW intensity (not shown).

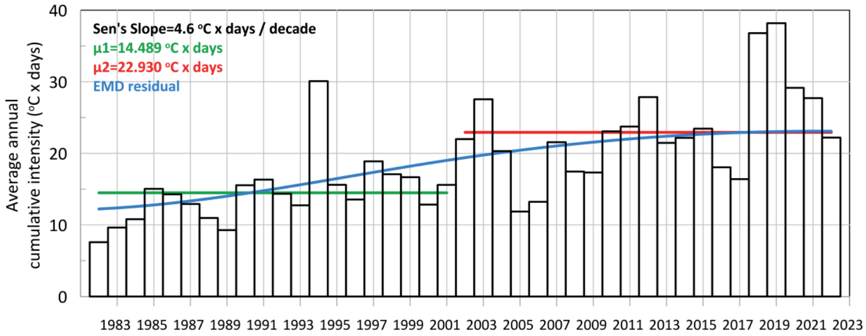

Figure 4. Yearly average cumulative intensity (°C x days) of MHWs (bars) over the entire AICS region from 1982 to 2022. The Pettitt's test for homogeneity shows the potential shift in the mean levels (μ1, μ2). The p_{value} of the homogeneity test is less than 0.0001 (<alpha=1%) confirming that there is a date at which there is a change in data. The EMD residual trend is marked with a blue line.

3.2 South Florida

South Florida is a marine environment where offshore ocean dynamics plays an important role on the hydrography and physical variability of coastal waters. A unique characteristic is the close proximity of a major, warm, oceanic current (the Gulf Stream), which manifests itself as the Loop Current/Florida (LC/FC) Current system around south Florida (Johns and Scott, 1987). The formation of MHWs was computed and analyzed over south Florida for the 1982-2021 period (Androulidakis and Kourafalou 2022). Both the annual number of MHW events, averaged over the entire domain (see Fig. 1b), revealed an increasing trend during the 40-year period and are statistically significant (p_{value}<0.01; Fig. 5). The increase of the total annual MHW days was 7.4 days/decade, and the respective increase of the MHW events was 0.75 events/decade. The prolonged period of lower SST levels reported during the 2004-2013 decade (Fig. 5) agrees with the relatively lower number of MHWs events (<4) and days (<40). The last seven years (2015–2021) revealed the highest number of events and durations among all study years. Three large peaks were computed in 2015, 2019, and 2020, respectively, with more than eight MHWs lasting around 70 to 110 days in total (Androulidakis and Kourafalou, 2022). The net heat flux (4839 Joule m^{-2}/decade) and especially the air temperature (0.21°C/decade) are both well correlated (R_p) with the formation of MHWs showing all significant increasing trends (Fig. 5). The highest air temperatures and the strong positive (downward) heat fluxes generally coincide with the MHW peaks.

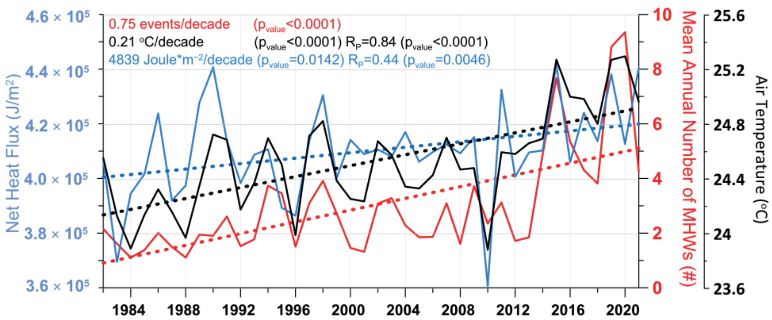

Figure 5. Annual variability (continuous lines) and trends (dashed lines) of the mean annual number of all MHWs (red line), air temperature (°C; black line), and surface net heat flux (J/m²; blue line). The Sen's Slopes, the Pearson correlation coefficients, and the respective $p_{values,}$ between atmospheric variables (air temperature and heat flux) and the number of MHWs are presented (adapted from Androulidakis and Kourafalou 2022).

The spatial distribution total cumulative intensity of MHWs over the entire study domain is presented in Figure 6a. The highest intensity levels were computed over the Western Florida Shelf, along the northern coasts of the Florida Keys and inside the Florida Bay. The Straits of Florida, where the warmer waters of the Florida Current (FC; part of the Gulf Stream in the Straits of Florida; Figure 1b) prevail, are characterized by fewer events with smaller durations due to the constant high 90th percentile levels that were used as thresholds in the MHW detection. The meandering of the FC (Kourafalou and Kang 2012) and its approach toward the Florida coasts play an important role on both local circulation over the coastal region and hydrographic characteristics (see section 3.3.2). The shallow coastal region of the Bahamas can also be considered as a «hot spot» for MHWs with a high number of events (>100) and long durations (>1000 days) during the 1982-2021 period (Androulidakis and Kourafalou 2022). The Pearson correlation coefficients (R_p) between the SST and air temperature show strong spatial variability with high values over the shallow areas of the inner Western Florida Shelf and Bahamas. The impact of air temperature on SST gradually reduces towards the shelf slopes (R_p=0.85–0.75), especially over the areas where the Gulf of Mexico mesoscale ocean circulation patterns (LC/FC) evolve (Weisberg *et al*. 2003). The smaller coefficients mainly occurred over the southern and eastern coastal areas where the FC flows, controlling the distribution of physical properties and thus the formation of MHWs. The coastal area of Miami Beach revealed the weakest correlation between SST and atmospheric conditions (R_p< 0.75).

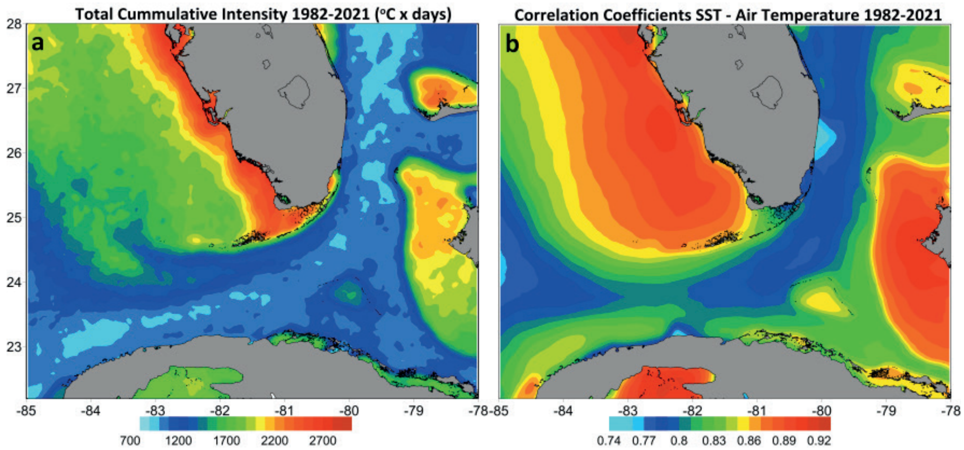

Figure 6. Spatial distribution of: (a) the total cumulative intensity of MHWs; and (b) Pearson correlations coefficients (R_p) between daily SST and air temperature for the whole 1982-2021 period.

3.3 Effects of ocean dynamics on MHWs formation

The main environmental factors for the formation of MHWs are the atmospheric conditions, and especially the high air temperatures, the weak winds and solar radiations. However, their impact is not the same over all coastal areas, especially over regions where specific ocean circulation conditions may also control the distribution and variability of sea temperature and thus the evolution of MHWs in the coastal environment. Herein, we investigate two different ocean processes that may control the temperature variability in the northern Aegean (AICS) and in the Eastern Florida Shelf (south Florida), respectively.

3.3.1 Black Sea Waters (BSW)

The main buoyant water mass over the northern Aegean region is the BSW that flows through the upper-layer of the Turkish Straits and exits into the Aegean (Fig. 1a; Androulidakis and Kourafalou 2011). This water mass forms a low salinity barrier layer in the upper-ocean that typically ranges between 0 to 50 m. The hypothesis is that this shallow and less saline BSW layer is subject to increased heating resulting in higher SST levels (Amaya *et al*. 2021). We used available field measurements (2008-2021) collected between the NE and NW Aegean Sea at Athos Poseidon Buoy (https://poseidon.hcmr.gr/) to investigate the evolution of the upper-ocean stratification characteristics. During 12 periods of high SST peaks (SSTA>2σ), the surface salinity showed very low values while the sub-surface layer (20 m) was characterized by more saline waters resulting in high ΔSalinity (Salinity anomaly 1-20m) and peaks of the stratification frequency (Fig. 7).

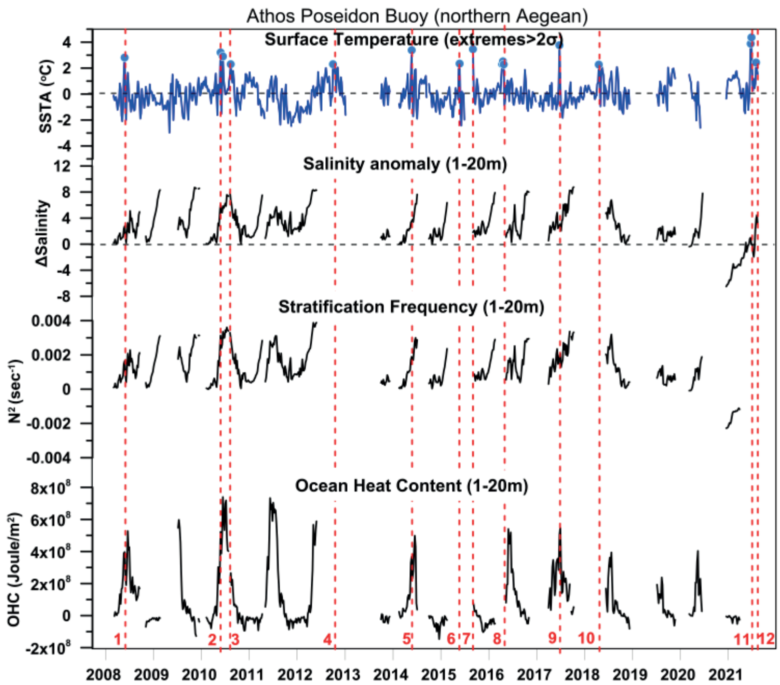

Figure 7. Weekly means of SST anomaly, salinity anomaly between the two layers (1 m and 20 m), Brunt-Väisälä stratification frequency between 1 and 20 m (N^2), and Ocean Heat Content (OHC) of the upper 20 m, derived from Athos Buoy daily values without the seasonal cycle (adapted from Androulidakis and Krestenitis 2022). The red dashed lines represent 12 events when surface temperature anomaly was higher than the 2x σ threshold (2.21°C).

The Ocean Heat Content (OHC), that represents the energy stored in the upper-ocean revealed very high values during all these study events. Our results, derived from available field observations, confirm the hypothesis that shallow mixed layers may contribute to the warming of the surface layer in agreement with Amaya *et al*. (2021).

3.3.2 Gulf Stream

The branch of the Gulf Stream in the Straits of Florida, namely the Florida Current (FC), is known to meander between Florida and the Bahamas; the position of its axis has been calculated here as the 20 °C temperature contour line at 150 m along 26° N (Kourafalou and Kang, 2012), based on 9-year Florida Keys Hybrid Ocean Coordinate Model (FKEYS-HYCOM) archives (Fig. 8). Although the areas of Miami Beach and Biscayne Bay reveal similar correlations between atmospheric conditions (air temperature and winds) and SST variability (not shown), the MHWs (7.2 MHW/decade for Biscayne Bay and 10 MHW/decade for Miami Beach) and SST (0.1 °C/decade for Biscayne Bay and 0.15 °C/decade for Miami Beach) trends revealed significant differences between the two areas (Androulidakis and Kourafalou 2022). During the 2012-2020 period, there is a clear interannual trend of the FC shift toward the eastern Florida coast, moving to the nearest shore location in 2019 (79.78°W; Fig. 8). The furthest offshore positions (easternmost) were computed for 2012. The mean annual SST anomaly and the mean annual number of MHWs showed increasing trends at both Biscayne Bay (Fig. 8a) and Miami Beach (Fig. 8b). However, the interannual variations of the mean SST and MHW number for Miami Beach follow the FC variability, indicating stronger FC relation to the ocean temperature variability over this area (insert in Figure 8b), which is more exposed to the offshore ocean dynamics, compared to the enclosed Biscayne Bay (see insert in Fig. 8a). More information about this effect is described by Androulidakis and Kourafalou (2022).

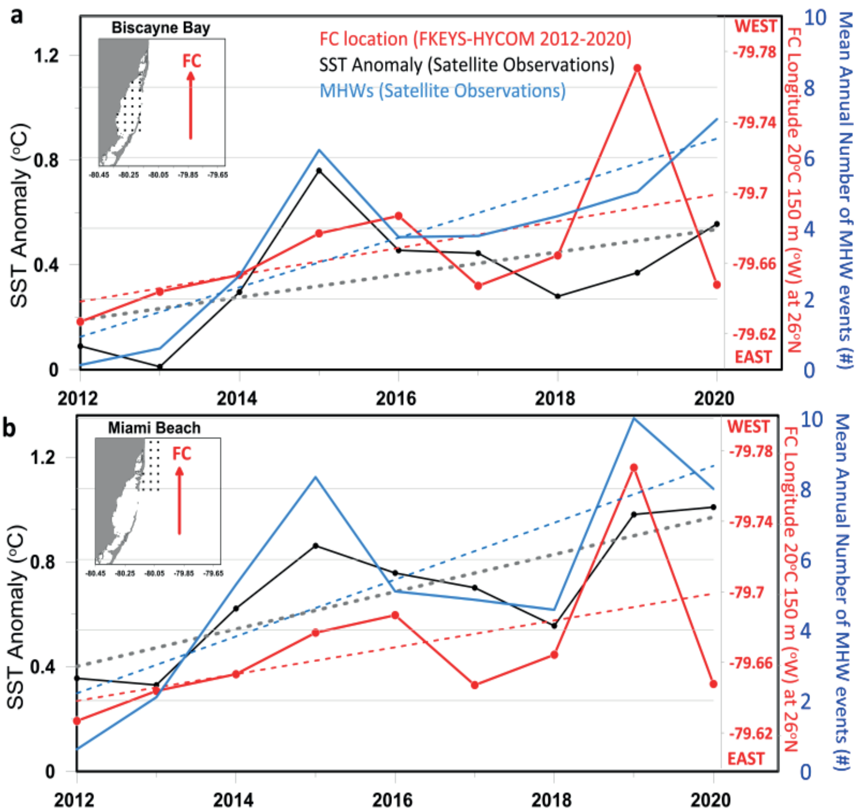

Figure 8. Annual mean of SST anomaly (black line), mean annual number of MHW events (blue line), and FC longitude (red line) for (a) Biscayne Bay, and (b) Miami Beach during the 2012-2020 period. The linear trend (dashed line) for each case is also presented (adapted from Androulidakis and Kourafalou 2022).

4. Predictions based on a Deep Learning technique

The accurate prediction of MHW events in the near-term (from hours to a few days) and even more in the distant-future (from years to decades) is a critical but challenging task. Although the short term SST forecasts are very useful for the very near-future management and the assessment of the high temperature impacts on the marine environment, they do not provide accurate interim predictions (from months to year). Similarly, although climatic projections may provide long-term ocean predictions, they are not capable to accurately (e.g. daily) estimate SST levels in specific future periods (e.g. temperature levels during the next months or year). The widespread expansion of Deep Learning (DL) techniques and their application across various fields has also significantly impacted the domain of SST forecasting. Despite the variety of the existing methods (i.e., Zhang *et al*. 2017 ; Xiao *et al*. 2019 ; Xie *et al*. 2019), the majority of them is oriented to provide short-term SST predictions (from a few days to a month).

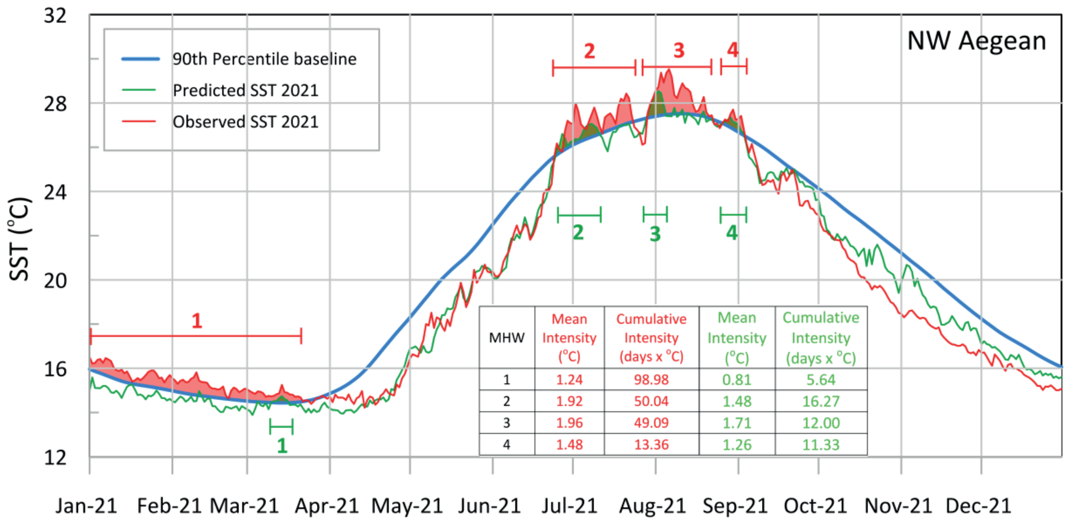

Figure 9. SST observed (red) and predicted (green) results over the NW Aegean for the year 2021. The climatological 90th percentile baseline (blue), the detected MHW events and their characteristics (insert table), based on the observed and predicted series, are also presented (adapted from Krestenitis *et al.* 2022).

Herein, we present a novel DL-based approach that uses the long-term satellite-derived observations of SST (Copernicus) and respective atmospheric fields (ERA5) to provide accurate estimations of temperature levels of the interim future. The proposed method utilizes robust DL techniques and is based on a dual-stream network, capable to process multi-regional data spatio-temporally, and forecast SST time series for multiple regions, simultaneously (Krestenitis *et al*. 2023). The method was developed and tested over the AICS region to predict the SST variability over 2021, using training data (SST, air temperature, winds, radiations) derived from the previous 13-year period (2008-2020). The DL technique finally provides SST values of the AICS regions for the “unknown” year of 2021. Results imply that the developed method can efficiently process the input data and accurately predict the spatio-temporal SST sequence. It should be noted that even in cases of extreme SST values that can be related to MHWs, especially during the summer periods (NW Aegean), the model can provide predictions close to reality. The reported results for year 2021 (1st year after the training period 2008-2020) imply that the developed method is capable to efficiently forecast one year ahead timeseries deviating less than 1◦C from the observed values. The number of MHWs derived from the observed values over the NW Aegean is the same with the events detected based on the predicted time-series (Fig. 9). The DL method output was efficient to detect four MHW events (one during winter and three during summer). Although the MHW durations and accumulative intensities were underestimated, the mean intensities and the formation dates were adequately predicted by the model, especially during the summer. Extending the dataset with additional ocean parameters (besides atmospheric conditions), such as currents speed, mixing and vertical structure conditions, lateral fluxes of neighbouring water bodies, etc., could further increase the model accuracy. Beyond satellite, long-term field observations without gaps could also be used as training input providing information about sub-surface MHW formation.

5. Discussion and concluding remarks

The general increasing SST trend observed over the AICS is 0.47 ° C/decade, with stronger local gradients over the northern Aegean regions (0.52 ° C/decade). The overall trend (1982-2022) over the northern Aegean is stronger than the relevant trend derived from an older period (1985-2008; Skliris *et al*. 2011). Extreme conditions have recently affected the ecological state of the marine environment of the northern basins: coral mortality around Chalkidiki peninsula (Antoniadou *et al*. 2023), decline of seagrass (Litsi-Mizan *et al.* 2023), mussels mortality in Thermaikos Gulf (Lattos *et al.* 2022), invasion of thermophilous alien species (Ragkousis *et al*. 2023). 2002 is the datum of an upward shift, dividing the period studied in two periods. The increasing trends, especially during the last decade, are also associated with the cold seasons, a sign that the winter surface waters also became warmer in recent years (Androulidakis and Krestenitis 2022). The most-recent four-year period studied (2018-2021) revealed the highest number of MHWs with the longest durations (high cumulative intensity). The 2022 temperature levels were lower for AICS than the levels for the western Mediterranean (see Juza *et al*. 2024 in this volume; lower cumulative intensities of MHWs). Several environmental parameters, besides atmospheric conditions, may affect SST variability. The strong upper-ocean stratification, related to buoyant barrier layers at the surface (e.g., Black Sea waters in the northern Aegean), is a pre-condition of MHWs, increasing the heat storage capacity of the upper layers, contributing to the further warming of the surface water masses. Similarly, the proximity of warm ocean currents to the coast, such as the Gulf Stream evolution along the coasts of south Florida, is also an ocean-oriented pre-condition of MHW formation, while the Gulf Stream offshore shift away from the coast results in colder coastal waters, unfavourable for MWH formation. Accurate forecasting of SST allows the prediction of temperature peaks and MHW formations, supporting the efficient handling of their impact. We presented a novel method, based on a robust Deep Learning model, capable to forecast SST in the interim future of at least one year ahead.

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Androulidakis Y.S. Marine heatwaves over different coastal environments: findings from the NE Mediterranean Sea to south Florida. pp 103-116 In CIESM Monograph 51 [F. Briand, Ed.] Marine heatwaves in the Mediterranean Sea and beyond. CIESM Publisher, Paris, Monaco, 174 p.

References

Amaya D.J., Alexander M.A., Capotondi A., Deser C., Karnauskas K.B., Miller A.J. and N.J. Mantua. 2021. Are long-term changes in mixed layer depth influencing North Pacific marine Heatwaves? *Bulletin of the American Meteorological Society*, 102(1): S59-S66.

Androulidakis, Y.S. and V.H Kourafalou. 2011. Evolution of a buoyant outflow in the presence of complex topography: the Dardanelles plume (North Aegean Sea). *Journal of Geophysical Research: Oceans*, 116(C4).

Androulidakis Y.S. and V. Kourafalou. 2022. Marine heat waves over natural and urban coastal environments of south Florida. *Water*, 14(23), p.3840.

Androulidakis Y.S. and Krestenitis Y.N., 2022. Sea surface temperature variability and marine heat waves over the Aegean, Ionian, and Cretan Seas from 2008–2021. *Journal of Marine Science and Engineering*, 10(1), p.42.

Antoniadou, C., Pantelidou, M., Skoularikou, M. and Chintiroglou, C.C., 2023. Mass mortality of shallow-water temperate corals in Marine Protected Areas of the North Aegean Sea (Eastern Mediterranean). *Hydrobiology*, 2(2): 311-325.

Darmaraki S., Somot S., Sevault F. and Nabat, P. 2019. Past variability of Mediterranean Sea marine heatwaves. *Geophysical Research Letters*, 46(16): 9813-9823.

Di Lorenzo, E. and Mantua, N. 2016. Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, 6(11): 1042-1047.

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Hobday A. J., Alexander, L. V., Perkins, S. E., Smale, D. A., Straub, S. C., Oliver, E. C., Benthuysen, J. A., Burrows, M. T., Donat, M. G., Feng, M., Holbrook, N. J., Moore, P. J., Scannell, H. A., Sen Gupta, A., and Wernberg, T. 2016. A hierarchical approach to definin marine heat waves. *Progress in Oceanography*, 141: 227-238.

Hobday A.J., Oliver E.C., Gupta A.S., Benthuysen J.A., Burrows M.T., Donat M.G., Holbrook, N.J., Moore P.J., Thomsen M.S., Wernberg T. and Smale D.A., 2018. Categorizing and naming marine heatwaves. *Oceanography*, 31(2): 162-173.

Holbrook N. J., Scannell H. A., Gupta A. S., Benthuysen J. A., Feng M., Oliver E. C., *et al.* 2019. A global assessment of marine heatwaves and their drivers. *Nat. Commun.*, 10:2624, doi: 10.1038/s41467-019-10206-z

Juza M., Reyes E., and J. Tintore. 2024. Marine heatwaves in the Mediterranean Sea: 2023 latest insights from multi-platform observations. pp 63 - 76 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Kourafalou, V.H. and Kang, H., 2012. Florida Current meandering and evolution of cyclonic eddies along the Florida Keys Reef Tract: Are they interconnected? *Journal of Geophysical Research: Oceans*, 117(C5).

Krestenitis M., Androulidakis Y. and Y. Krestenitis. 2024. Deep learning-based forecasting of sea surface temperature in the interim future: application over the Aegean, Ionian, and Cretan Seas (NE Mediterranean Sea). *Ocean Dynamics*, 74: 149-168. https://doi.org/10.1007/s10236-023-01595-3

Lattos A., Papadopoulos D.K., Feidantsis K., Karagiannis D., Giantsis I.A. and B. Michaelidis. 2022. Are Marine Heatwaves Responsible for Mortalities of Farmed *Mytilus galloprovincialis*? A Pathophysiological Analysis of Marteilia Infected Mussels from Thermaikos Gulf, Greece. *Animals*, 12(20), p.2805.

Ličer, M., 2024. Seasonality, return periods and intensity of surface marine heat waves in the Mediterranean basin. pp 27 - 39 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Litsi-Mizan, V., Efthymiadis, P.T., Gerakaris, V., Serrano, O., Tsapakis, M. and Apostolaki, E.T., 2023. Decline of seagrass (*Posidonia oceanica*) production over two decades in the face of warming of the Eastern Mediterranean Sea. *New Phytologist*, 239(6): 2126-2137.

Mills K.E., Pershing A.J., Brown C.J., Chen Y., Chiang F.S., Holland D.S., Lehuta S., Nye J.A., Sun J.C., Thomas A.C. and Wahle R.A., 2013. Fisheries management in a changing climate: lessons from the 2012 ocean heat wave in the Northwest Atlantic. *Oceanography*, 26(2), pp.191-195. doi:10.5670/OCEANOG.2013.27.

Mohamed B., and A. Alvera-Azcarate. 2024. Marine Heatwaves: Comparative analysis between low and high latitude regional seas in the Northern Hemisphere. pp 85 - 101 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Oliver, E.C., Benthuysen, J.A., Bindoff, N.L., Hobday, A.J., Holbrook, N.J., Mundy, C.N. and Perkins-Kirkpatrick, S.E., 2017. The unprecedented 2015/16 Tasman Sea marine heatwave. *Nature communication*s, 8(1): 1-12.

Oliver E.C., Donat M.G., Burrows M.T., Moore P.J., Smale D.A., Alexander L.V., *et al.* 2018. Longer and more frequent marine heatwaves over the past century. *Nat. Commun*., 9:1324, doi:10.1038/s41467-018-03732-9

Pearce A.F. and M. Feng. 2013. The rise and fall of the “marine heat wave” off Western Australia during the summer of 2010/2011. Journal of Marine Systems, 111: 139-156.

Pettitt, A.N., 1979. A non‐parametric approach to the change‐point problem. Journal of the Royal Statistical Society: Series C (Applied Statistics), 28(2):126-135.

Ragkousis M., Sini M., Koukourouvli N., Zenetos A. and S. Katsanevakis. 2023. Invading the Greek Seas: spatiotemporal patterns of marine impactful alien and cryptogenic species. Diversity, 15(3), p.353.Skliris, N., Sofianos, S.S., Gkanasos, A., Axaopoulos, P., Mantziafou, A. and Vervatis, V., 2011. Long-term sea surface temperature variability in the Aegean Sea. *Advances in oceanography and limnology*, 2(2): 125-139.

Ragkousis M., Sini M., Koukourouvli N., Zenetos A. and S. Katsanevakis. 2023. Invading the Greek Seas: spatiotemporal patterns of marine impactful alien and cryptogenic species. Diversity, 15(3), p.353.

Skliris, N., Sofianos, S.S., Gkanasos, A., Axaopoulos, P., Mantziafou, A. and Vervatis, V., 2011. Long-term sea surface temperature variability in the Aegean *Sea. Advances in oceanography and limnology*, 2(2), pp.125-139.

Soukissian, T.H., Chronis, G.T., Nittis, K. and Diamanti, C., 2002. Advancement of operational oceanography in Greece: The case of the Poseidon system. The Global atmosphere and ocean system, 8(2-3): 93-107.

Weisberg, R.H. and Liu, Y., 2017. On the Loop Current penetration into the Gulf of Mexico. *Journal of Geophysical Research: Oceans,* 122(12): 9679-9694.

Wernberg T., Smale D. A., Tuya F., Thomsen M.S., Langlois T. J., De Bettignies T., Bennett S. and C. S. Rousseaux. 2013. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Clim. Change* 3:78-82.

Xiao, C., Chen, N., Hu, C., Wang, K., Gong, J., and Chen, Z. 2019. Short and mid-term sea surface temperature prediction using time-series satellite data and lstm-adaboost combination approach. *Remote Sensing of Environment*, 233:111358.

Xie J., Zhang J., Yu J., and L. Xu. 2019. An adaptive scale sea surface temperature predicting method based on deep learning with attention mechanism. IEEE Geoscience and Remote *Sensing Letters*, 17(5): 740–744.

Zhang Q., Wang H., Dong J., Zhong G., and X. Sun. 2017. Prediction of sea surface temperature using long short-term memory. IEEE geoscience and remote sensing letters, 14(10): 1745–1749.

Marine heatwaves characteristics in the Marmara Sea 1982-2021

Erdal Tokat and Şükrü T. Beşiktepe

Institute of Marine Sciences and Technology, Dokuz Eylül University, Izmir, Turkey

Abstract

This study investigates the characteristics of marine heatwaves (MHWs) in the Marmara Sea and southwestern Black Sea from 1982 to 2021. The Sea of Marmara, part of the Turkish Straits System connecting the Black Sea and the Mediterranean Sea, experiences unique oceanographic conditions due to its geography and interactions between different water masses. This study analyzes 40 years of high-resolution sea surface temperature (SST) data to identify and understand MHWs in this region. The data analysis includes the calculation of MHW metrics and trends, allowing for a comprehensive examination of MHW characteristics. In both regions, typical MHWs lasted between 5 and 15 days, but notable differences emerged in extreme MHW durations. The Black Sea exhibited MHWs lasting from 50 to 170 days, whereas the Marmara Sea recorded durations ranging from 50 to 79 days. We also found that MHWs in both regions increased in frequency and duration after 2006, with a significant rise post-2012. Specificities in the Marmara Sea oceanographic conditions do impact the characteristics of MHWs.

Keywords : *Marine heatwaves, Marmara Sea, Black Sea, trends, sea surface temperature*

1. Introduction

The Turkish Straits System (TSS) consists of the Marmara Sea and the Straits of Istanbul (Bosphorus) and Çanakkale (Dardanelles) located between the continents of Europe and Asia, connecting the Black Sea to the Aegean basin of the Mediterranean Sea and then to the ocean. In a physical sense, the TSS connects the Black Sea to the Aegean Sea through two bottleneck straits and one buffer zone. The basic dynamics creating the two-way exchange flows of the TSS are the density and pressure differences between the Black Sea and the Aegean Sea. In the Black Sea the freshwater flux (a riverine discharge and precipitation) exceeds the evaporation, resulting in a net outflow of the brackish waters through the Bosphorus which is a long (30 km) and narrow (1 km) strait. The flow from the Black Sea to the Aegean throughout the Turkish Straits is mainly due to the sea level differences between these seas. The outflow from the Bosphorus has been calculated as 635 km^3 yr based on long term salinity data (Besiktepe *et al.* 1994). While Black Sea waters flow into the Marmara Sea via the Bosphorus, denser Mediterranean water flows into the Marmara Sea via the Dardanelles. The two different water masses are separated by a strong pycnocline at a depth of approx. 25 m. Low salinity - approx. 18 ppt - Black Sea waters occupy the upper 25 meters of the basin and the rest of the basin is occupied by salty - approx. 38.5 ppt - Aegean waters (Besiktepe *et al.* 1994). As the upper layer of the Marmara Sea is occupied by the brackish water of the Black Sea coming through the Bosphorus and the renewal time of the upper layer is short (≈4 months), the biochemical

structure of Marmara Sea surface waters reflects Black Sea coastal water characteristics. However, the main hydrodynamic and biochemical properties of the Marmara upper layer are determined both by the water flowing in from the Bosphorus and by the water entrained from the lower layer by vertical mixing.
The Bosphorus upper layer flow enters the Bosphorus - Marmara Sea junction in the form of a shallow, buoyant turbulent jet and entrains Mediterranean originated lower layer water; further downstream wind stirring mixes upper- and lower-layer waters. Hence the incoming Black Sea water is modified before exiting to the Aegean Sea. This unique setting is one of the rare, enclosed basins of the world subjected to strait and surface atmospheric forcing, as well as interactions of two different water masses. Throughout history, the Marmara Sea has endured substantial human utilization and impact. This has caused a decline in the ecological health of the Marmara Sea, resulting in unanticipated and unparalleled changes in recent years (Demirel *et al.* 2023). Most notably, the occurrences of mucilage outbreaks in 2007 and 2020 inflicted damage to the overall ecosystem structure and led to subsequent economic losses. While some studies on the observed mucilage events have suggested a connection to rising surface temperatures in the Marmara Sea, there are few published scientific studies demonstrating the extent of temperature increase and its correlation with global warming.

In this paper, we analyze 40 years of high-resolution Sea Surface Temperature (SST) data in the Marmara Sea and in the Bosphorus Black Sea Junction to determine the characteristics of marine heatwaves (MHWs). Then, by comparing these characteristics in both regions, we aim to explain how the unique oceanographic settings of the Marmara Sea do affect MHWs.

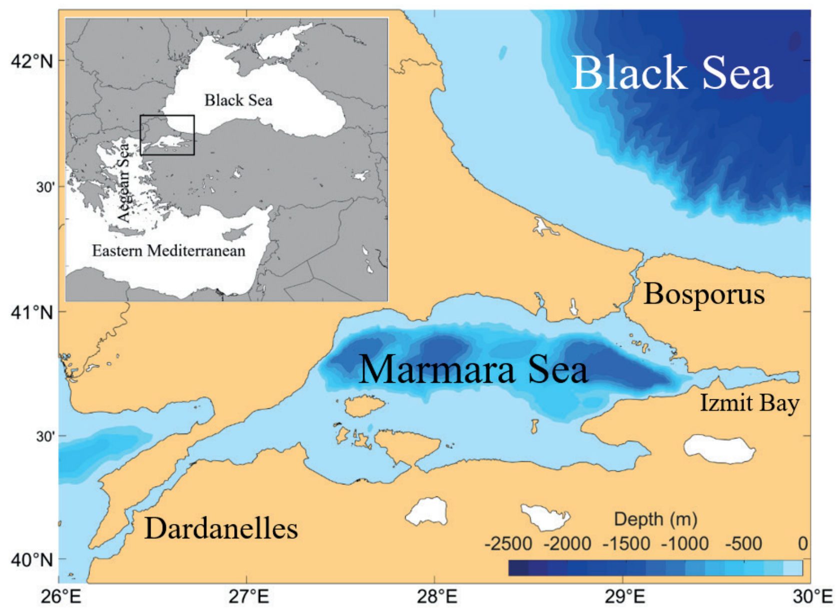

Figure 1. Study area and its bathymetry. Bathymetry was created by using ETOPO high resolution data (https://www.ncei.noaa.gov/products/etopo-global-relief-model).

2. Data and methods

2.1 Data

We used Optimum Interpolation Sea Surface Temperature version 2.1 (Huang *et al.* 2020). This high-resolution SST dataset was developed by the National Oceanic and Atmospheric Administration (NOAA), using an optimum interpolation technique. It combines data from various sources, such as satellites, ships, buoys, and Argo floats. The data have a spatial grid resolution of 0.25 degree and temporal resolution of one day, spanning from September 1981 to present. We extracted the data for the study area from January 1982 to December 2021.

2.2 Methods

In this paper, we use the standard Marine Heatwave definition introduced by Hobday *et al.* (2016) to detect MHWs in daily SST data. According to their definition, a marine heatwave is characterized as an unusual period of warm water that persists for a minimum of five consecutive days. During such events, the SST surpasses the seasonally varying 90th percentile threshold. To determine this threshold, the climatological mean and 90th percentile values are calculated for each grid point daily throughout the year, using SST data collected over a 40-year period (1982-2021). Each MHW event is described by a set of five metrics:

1. Duration (measured in days) represents «the time elapsed between the start and end dates of an event.»

2. Frequency (measured in events) signifies «the count of MHW events occurring within each year and month.»

3. Total days (measured in days) quantifies «the cumulative sum of MHW days across each year and month.»

4. Total events (measured in events) represent «the count of MHW events across each year and month.»

5. The Ratio of Total days/Total events represents «the duration of MHW events across each year and month.»

We normalized the total days and total events for each basin by dividing these metrics with the corresponding total number of grid points in order to better compare the Black Sea with the Marmara Sea.

We employed the MATLAB toolbox (M_MHW) to calculate all the above metrics (Zhao and Marin 2019). We computed yearly and monthly statistics and time series for the frequency and duration of MHWs for the Marmara Sea and southwestern Black Sea region spanning the years 1982 to 2021. We determined the linear trends in SST and MHW characteristics by applying the least squares method using MATLAB. To assess the statistical significance of these trends, we utilized the Modified Mann-Kendall test at a 95% confidence level.

3. Results and Discussions

3.1 An example of marine heatwave in the Black Sea and Marmara Sea

An example of MHW events identified in our analysis from Bosphorus-Black Sea Junction and the Bosphorus-Marmara Sea Junction is presented in Figure 2.

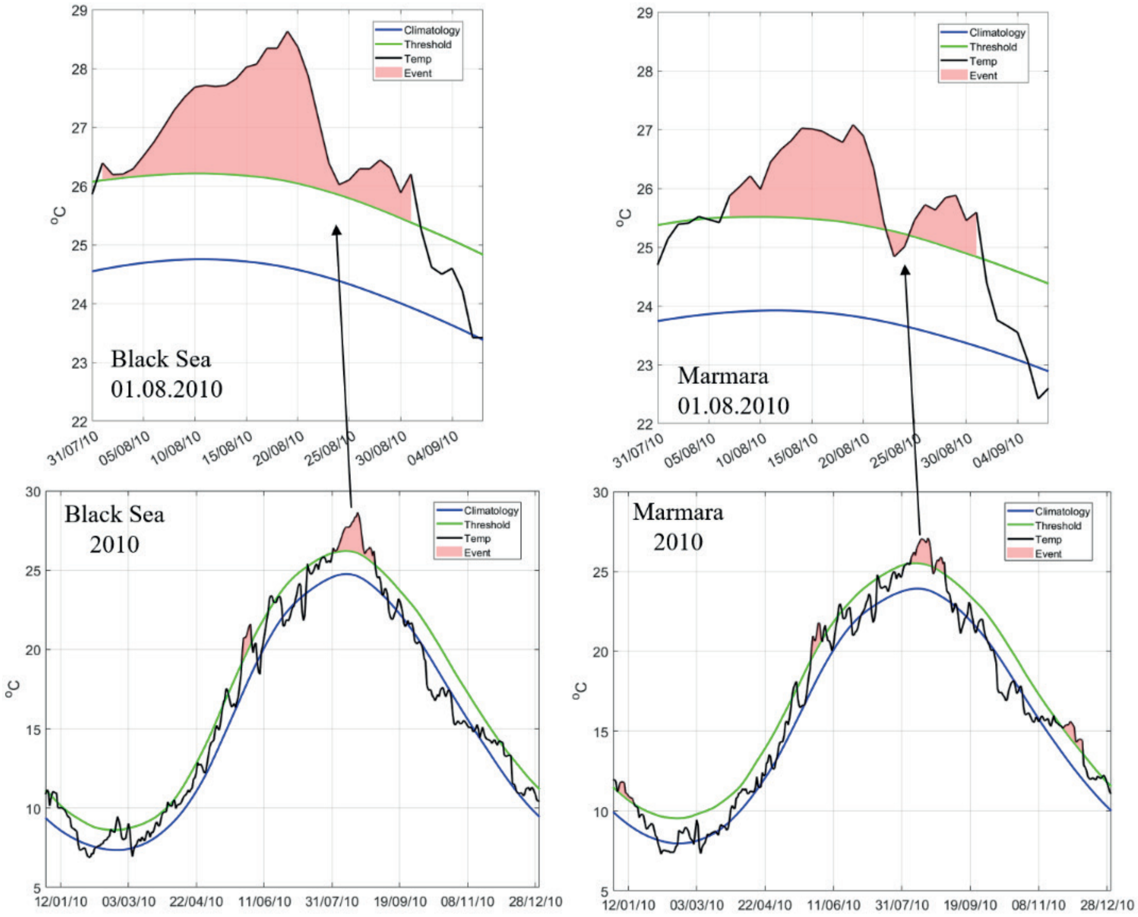

Figure 2. Detected marine heatwaves in the Black Sea and Marmara Sea in August 2010.

As seen from the SST climatology (blue line), Black Sea surface waters are approx. 0.6 °C warmer than the Marmara Sea waters in summer months; a contrario Black Sea waters are approx. 0.6 °C cooler than the Marmara Sea waters in winter months. While the durations of the MHWs detected in both regions in August 2010 were about the same, intensity of the event was 1.5 °C higher in the Black Sea than in the Marmara Sea. Furthermore, there is a 1-day lag in the occurrence and the development of the MHWs between the Black Sea and the Marmara Sea. There may be different explanations of the intensity difference and the lag. One hypothesis is that MHW occurred in the Black Sea and warmed waters were transported into the Marmara Sea through the Bosphorus and that mixing of the Black Sea waters with Marmara Sea lower layer waters decreased the temperature of the heated waters.

3.2 Duration of marine heatwaves in the Black Sea and Marmara Sea

Our analysis detected 1683 MHW events in the 22 grid points in the Black Sea and 1204 events in the 16 grid points in the Marmara Sea (Fig. 3). The normalized total number of events which almost represent the events occurred in each region are nearly equal, with 76.5 in the Black Sea and 75.25 in the Marmara Sea. The typical duration of MHWs lasts between 5 and 15 days in both regions. There is however a considerable difference in the extreme MHW durations: in the Black Sea, the longest duration MHWs extend from 50 days to 170 days, versus 50 to 79 days in the Marmara Sea.

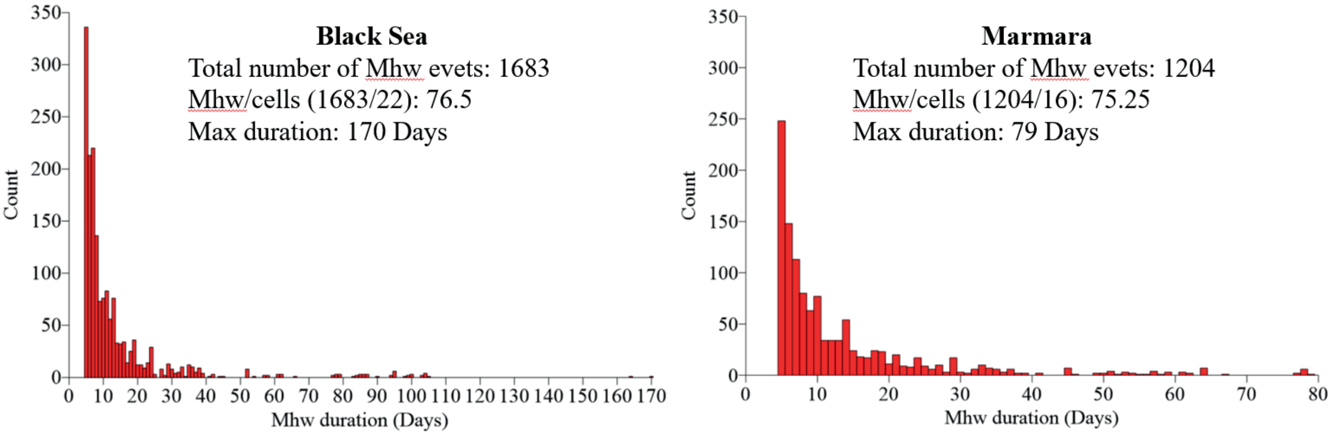

Figure 3. Distribution of marine heatwave event durations for the period 1982-2021.

3.3 Interannual variability of marine heatwaves

Monthly MHW total days over 1982-2021 are presented in Figure 4, illustrating their long-term evolution. One sees that the frequency and duration of MHWs increased after 2006 and rose considerably after 2012. Most of the time, MHWs occurred synchronously in both regions except in a few cases. Events observed in December 2009 - January 2010 and in November - December 2010 only concerned the Marmara Sea. This could result either from a micro climatological characteristic of the region or from local specific oceanographic conditions of the Marmara Sea.

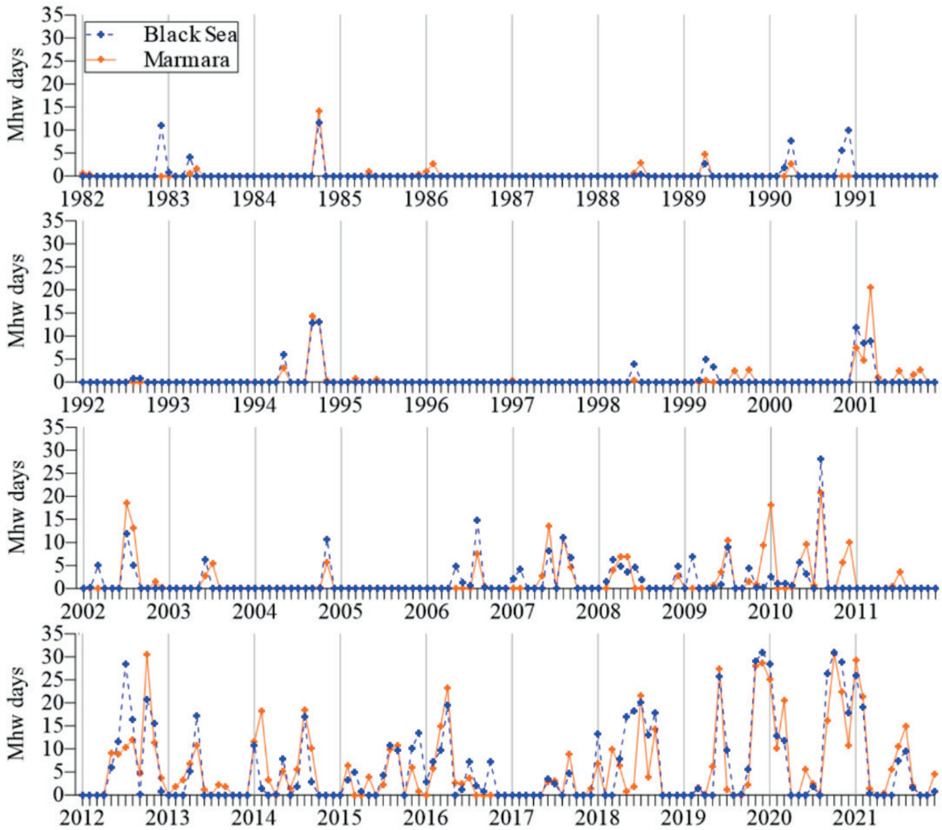

Figure 4. Monthly marine heatwave total days over the period 1982-2021.

3.4 Seasonal variability of the SST and marine heatwaves

The SST data exhibit a clear annual pattern for both regions, with lower values in February to March and higher values in the summer, especially in August, as illustrated in Figure 5A.

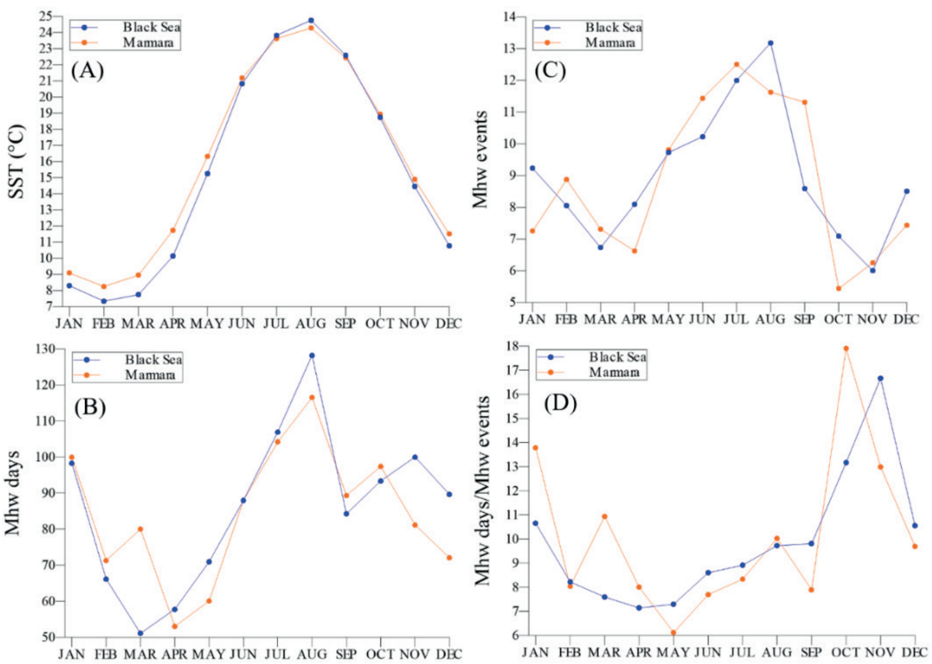

Figure 5. Monthly climatology: (A) Mean sea surface temperature; (B) regionally integrated marine heatwave days; (C) active marine heatwave events; (D) ratio of marine heatwave days over marine heatwave events for the period 1982-2021.

The average maximum value, above 24 ° C for both regions, was observed in August, while the average minimum value, below 9 ° C, was found in February. As noted above, while Marmara Sea waters were warmer in winter and spring, Black Sea waters are warmer in summer months. It is observed from the seasonal cycle of the total MHW days (Fig. 5B) that the minimum total MHW days is observed in March for the Black Sea and in April for the Marmara Sea. From this minimum point MHW days increase gradually and reached their maximum in August for both regions. From August to September there is a sharp decrease in the MHW days. Seasonal variability of the number of events (Fig. 5C) followed a similar structure with the seasonal cycle of the MHW days. As clearly seen from these distributions, the occurrence of MHWs was much higher during summer months. Hence, it can be said that seasonal variability of the occurrence MHWs was mostly following seasonal variability of the SST. The ratio shown in Figure 5D is a metric that represents MHW duration. The maximum duration was observed in November in the Black Sea and in October in the Marmara Sea.

3.5 Effects of global warming and marine heatwaves

The mean annual SST values show 0.048 ^{0}C/yr increasing trend for both regions (Fig. 6A). Annual values of the SST in the Marmara Sea were always higher than in the Black Sea. In the last decade, all SST values were at record high except in the year 2017 when there was a 0.7 ^{0}C decrease in annual mean SST compared to the previous year. Such marked decreases were also noted in 1987, 1997 and 2011. However, these decreases did not change the general trend of increasing SST in both regions.

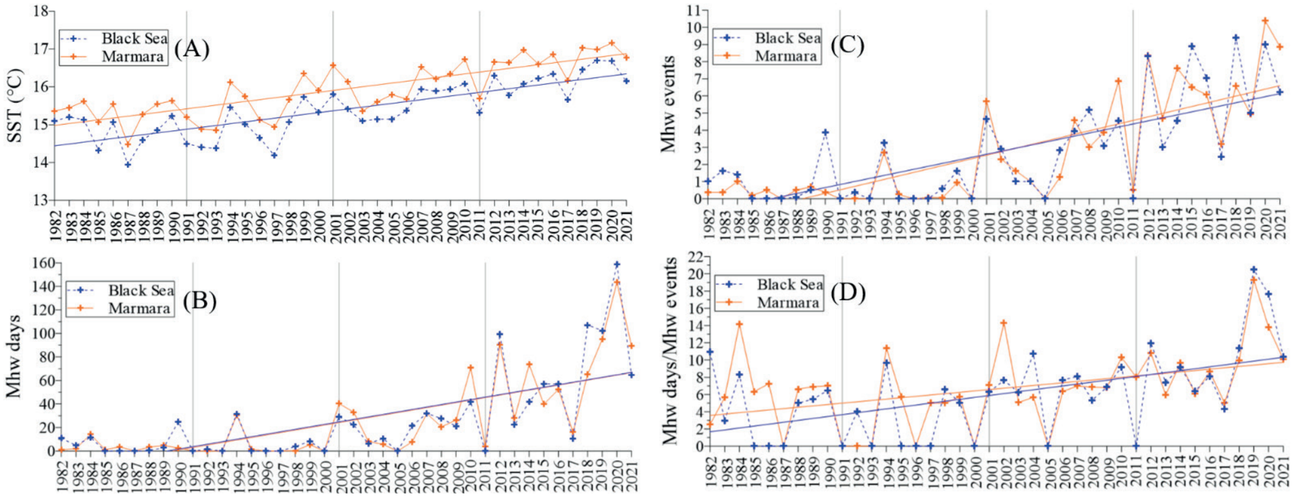

Figure 6. Time series of annual (A) mean sea surface temperature; (B) regionally integrated marine heatwave days; (C) marine heatwave events and (D) ratio of marine heatwave days over marine heatwave events for the period 1982-2021.

All MHW metrics presented in Figures 6B-D show statistically significant increasing trends for both regions. Trend values observed on MHW days are 2.10 days/yr in the Black Sea and 2.12 days/yr in the Marmara Sea. Generally, MHW days in both the Black Sea and the Marmara Sea follow a similar pattern and show a robust relationship with a correlation coefficient of 0.94 ($p < 0.01$). However, MHW days are higher in the Marmara Sea than the Black Sea in the years 2001, 2002, 2010, 2014, 2021. These differences can be explained by the peculiarity of the Marmara Sea oceanographic conditions. Similar patterns were also evident in the MHW total events (Fig. 6C). The ratio presented in Figure 6D is a metric that shows the duration of the MHW events. The duration of the MHW events observed in 2019 is the maximum during the analysis period. On the other hand, MHW total days and events reached their maximum values in 2020. This shows that the characteristics of the MHWs differ interannually.

3.6 Example of extreme marine heatwave events

The longest MHW durations were detected (Fig. 7) in 2020 for the Black Sea and in 2019 for the Marmara Sea respectively. The longest MHW lasted 170 days (September 2020-February 20201) in the Black Sea and 79 days (November 2019-January 2020) in the Marmara Sea. During this period, SST reached values 2-3 ^{0}C above the climatological value in both regions. These longer events are expected to have implications on the water mass structure and on marine biodiversity (see CIESM 2009) as this period corresponds to the autumn bloom and the dense water formation.

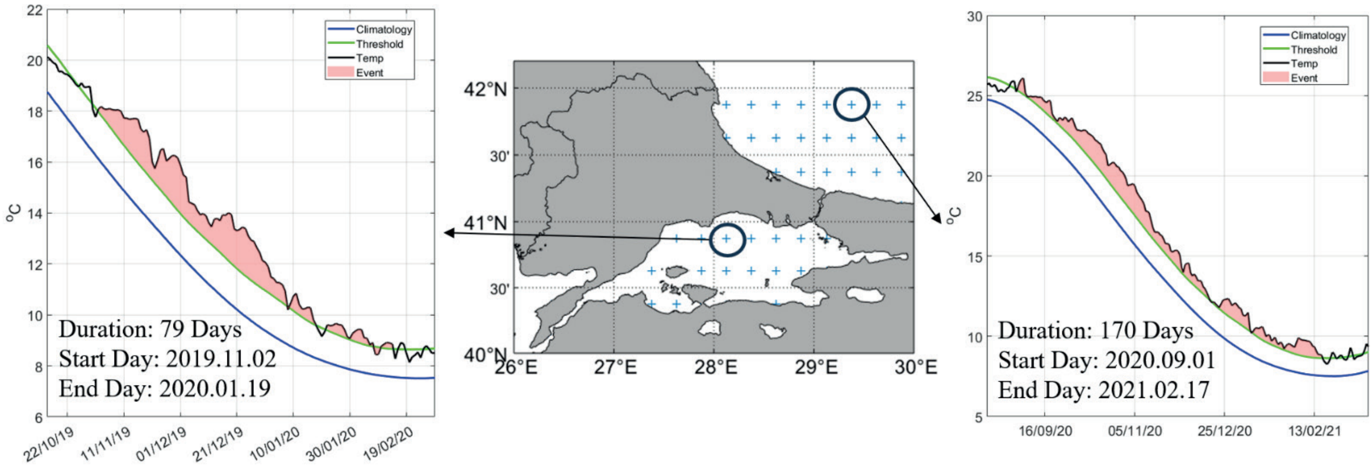

Figure 7. Longest duration marine heatwaves registered in the Black Sea and Marmara Sea.

4. Conclusion

In this study we investigated for the first time the characteristics of marine heatwaves in the Marmara Sea and compared them with the MHWs in the Black Sea for the period 1982-2021. Notably, there is a trend of increasing frequency and duration of marine heatwaves, particularly in the post-2012 period. It is expected that this increase will have a significant impact on the ecosystem structure of the Marmara Sea where adaptive strategies and further research will be needed to better understand and mitigate the effects of these heatwaves.

In both the Black Sea and the Marmara Sea, typical MHWs lasted between 5 and 15 days but notable differences were observed in extreme MHW durations, from 50 to 170 days in the Black Sea versus 50 to 79 days in the Marmara Sea. The longest-lasting MHWs occurred in the Black Sea in 2020 and in the Marmara Sea in 2019. While there was a close correlation between MHW days in the Black Sea and the Marmara Sea, differences in MHW characteristics were noted which could be attributed to the unique oceanographic conditions of the Marmara Sea.

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Tokat E. Marine heatwaves characteristics in the Marmara Sea 1982-2021. pp 117- 125 In CIESM Monograph 51 [F. Briand, Ed.] Marine heatwaves in the Mediterranean Sea and beyond. CIESM Publisher, Paris, Monaco, 174 p.

References

Beşiktepe Ş.T., Sur H. İ., Özsoy E., Latif M.A., Oğuz T. and Ü. Ünlüata. 1994. The circulation and hydrography of the Marmara Sea. *Prog. Oceanogr.* 34 (4): 285–334. https://doi.org/10.1016/0079-6611(94) 90018-3.

CIESM 2009. Climate forcing and its impact on the Black Sea marine biota. CIESM Workshop Monographs n°39 [F. Briand, Ed.], 152 p., CIESM Publisher, Paris, Monaco.

Demirel N., Akoglu E., Ulman A., Ertor-Akyazi P., Gül G., Bedikoğlu D., Yıldız T. and I.N Yilmaz. 2023. Uncovering ecological regime shifts in the Sea of Marmara and reconsidering management strategies, *Mar. Env. Res*. 183, 105794, https://doi.org/10.1016/j.marenvres.2022.105794.

Hobday A.J., Alexander L.V., Perkins S.E., Smale D.A., Straub S.C., Oliver E.C.J., *et al.,* 2016. A hierarchical approach to defining marine heatwaves. *Prog. Oceanography* 141: 227–238. doi: 10.1016/j.pocean.2015.12.014.

Huang B., Liu C., Banzon V.F., Freeman E., Graham G., Hankins W., Smith T.M. and H.-M Zhang. 2020. NOAA 0.25-degree Daily Optimum Interpolation Sea Surface Temperature (OISST), Version 2.1 dataset for 1982-2021. NOAA National Centers for Environmental Information. Accessed on 11-05-2022. https://doi.org/10.25921/RE9P-PT57.

Zhao Z. and M. Marin. 2019. A MATLAB toolbox to detect and analyze marine heatwaves. *J. Open Source Software* 4, 1124. doi: 10.21105/joss.01124.

WORKSHOP COMMUNICATIONS

B) BIOLOGICAL RESPONSES

24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios

Joaquim Garrabou[1]*, Jean Baptiste Ledoux[2], Sandra Ramirez-Calero[12], Yanis Zentner[3,4], Laura Figuerola-Ferrando[3,4], Daniel Gómez-Gras[3,4,13], Cristina Linares[3,4], Massimo Ponti[5], Eva Turicchia[5], Torcuato Pulido[6], Carlo Cerrano[6], Núria Teixidó[7,8], Jérémy Carlot[8], Marc Jou[1], Lucia Millan[1], Emma Cebrian[9], Cristina Galobart[9], Jorge Santamaría[9], Maria Sini[10], Vasilis Gerovasileiou[11,12], Nathaniel Bensoussan[1] and **T-MEDNet network**

[1] Departament de Biología Marina, Institut de Ciències del Mar (CSIC), Barcelona, Spain
[2] CIIMAR-Interdisciplinary Centre of Marine and Environmental Research, University of Porto, Matosinhos, Portugal
[3] Dept de Biologia Evolutiva, Ecologia i Ciències Ambientals, Universitat de Barcelona (UB), Barcelona, Spain
[4] Institut de Recerca de la Biodiversitat (IRBio), Universitat de Barcelona (UB), Barcelona, Spain
[5] Dipartimento di Scienze Biologiche, Geologiche e Ambientali, Università di Bologna, Ravenna, Italy
[6] Department of Life and Environmental Sciences, Polytechnic University of Marche, Ancona, Italy
[7] Stazione Zoologica Anton Dohrn, Ischia Marine Center, Ischia, Naples, Italy
[8] Sorbonne Université, CNRS, Laboratoire d'Océanographie de Villefranche, Villefranche-sur-mer, France
[9] Departament Ecologia Marina, Centre d'Estudis Avançats de Blanes (CEAB-CSIC), Girona, Espanya.
[10] Department of Marine Sciences, University of the Aegean, Mytilene, Greece.
[11]Department of Environment, Faculty of Environment, Ionian University, Zakynthos, Greece
[12] Hellenic Centre for Marine Research, Inst. Marine Biology, Biotechnology & Aquaculture, Heraklion, Greece
[13] Hawaii Institute of Marine Biology, University of Hawai'i at Mānoa, Kaneohe, HI, USA
Correspondence (*): Joaquim Garrabou garrabou@icm.csic.es

Abstract

The Mediterranean Sea is considered a climate change hotspot exhibiting warming rates and marine heatwaves (MHWs) events higher than in the global ocean. Among others, these conditions have already resulted in the onset of widespread mass mortality events (MMEs) across the Basin during the last 24 years. Since the first observation of an unprecedented MME in 1999, several international collaborative initiatives devoted to track the impacts and quences of MHWs and promoting solutions to support the resilience of coastal habitats in the face of climate change have been developed. Herein, we review how the Mediterranean scientific community has been tackling the challenges associated with MMEs in the Mediterranean. Focusing on the experience of building the T-MEDNet, a collaborative observation network dedicated to track climate change impacts, we present the main research issues and outcomes, and provide insights into new scientific avenues. Up to now, through this collective effort, we have revealed that severe ecological impacts of MHWs are unfolding at an unexpectedly accelerated pace. This acceleration, along with the interacting effects of other climate change stressors, poses an unprecedented threat to the Mediterranean ecosystems' health and functioning. In this context, it is critical to reinforce and upscale ongoing collaborative efforts at different levels aiming to increase the resolution of empirical observation networks, experimental studies, and interdisciplinary research. Such concerted efforts are essential for enhancing our ability to thoroughly comprehend and effectively manage the consequences of climate change and associated extreme climatic events such as marine heatwaves.

Keywords: *ocean warming, mortality outbreaks, ocean observation, long-term ecological monitoring, evolution and ecology*

Introduction

The Mediterranean Sea is experiencing an increase in the frequency, extent, and intensity of marine heatwaves (hereafter MHWs) associated with anthropogenic climate change. One of the macroscopic measurable impacts of MHWs is the onset of mass mortality events (hereafter MMEs). While barely recognized by society at large, marine MMEs are one of the most predominant biological impacts of anthropogenic climate change and associated MHWs in the Mediterranean coastal ecosystems (Rivetti *et al*. 2014 ; Marbà *et al*. 2015 ; Cramer *et al*. 2018). Indeed, Mediterranean MHWs have triggered extensive climate-driven MMEs during the last decades and their occurrence and severity are expected to increase in the coming decades (Darmaraki *et al*. 2019 ; Garrabou *et al*. 2019).

Since the observation of the unprecedented mass mortality event in 1999, which affected both the French and Italian coasts of the northwestern Mediterranean, different research teams and programs have focused their efforts toward analyzing the different eco-evolutionary dimensions of MMEs. The ultimate goals of these efforts were to: i) enlarge our observation capacity at large-scale and long-term on MMEs; ii) provide a better understanding on the drivers triggering the MMEs; iii) analyze the consequences of MMEs at different biological organization levels; and iv) enhance our predictive capability on the future trajectories of coastal habitats in the face of anthropogenic climate change.

During the study of the 1999 MME, we realized the lack of high-resolution temperature series in the Mediterranean coastal habitats. To fill this knowledge gap, a monitoring strategy to track thermal conditions using underwater temperature data loggers was proposed and gradually deployed (Bensoussan *et al.* 2019). This was the origin of the collaborative T-MEDNet network devoted to track climate change effects in the Mediterranean coastal ecosystems (www.t-mednet.org). Over the past two decades, T-MEDNet has supported the implementation of cost-effective monitoring of seawater temperature conditions, as well as the ecological impacts of anthropogenic climate change in Mediterranean coastal ecosystems. This collaborative effort, in alliance with other pan-Mediterranean initiatives, such as the CIESM Tropical Signals program, resulted in the most comprehensive datasets of coastal temperature conditions and MMEs records across the Mediterranean Sea. This observational effort provided a robust basis to engage in fruitful research activities for the analysis of MMEs and MHWs.

In this study, we provide a summary of the main outcomes obtained during the last two decades from different research projects on mass mortality events and marine heatwaves. We also discuss potential key observation activities and new scientific avenues. The main objective is to provide a panoramic understanding of the current state of knowledge concerning both MHWs and MMEs, thus supporting evidence-based decisions aimed at strengthening the resilience of Mediterranean coastal ecosystems in the face of anthropogenic climate change.

Methods

To characterize the spatial and temporal patterns of MMEs in the Mediterranean Sea, we compiled the most comprehensive dataset on these events from an extensive literature review analysis, besides the compilation of unpublished data from more than 30 research teams across eleven Mediterranean countries. The dataset contains a total of 1240 climate-driven mass mortality records. Mass mortality records were obtained from quantitative or semi-quantitative benthic surveys using different methods to assess the mortality impacts on local populations. A 'local' population is considered a group of colonies/individuals, (ranging from tens to hundreds of colonies/individuals depending on the species), dwelling in a specific geographic location defined by spatial coordinates and depth range. The surveys provided the percentage of colonies/individuals affected by mass mortality, *i.e.* indicating signs of necrosis over a relevant surface of the specimens (*e.g.,* hexa and octocorals, sponges, and bryozoans) or being dead (*e.g.,* mollusks). When the percentage of affected specimens was higher than 10%, the local population was considered to be affected by a MME. To facilitate a standardized monitoring approach for MMEs throughout the Mediterranean region, we developed a full toolkit including different training materials and database management within the T-MEDNet network (Garrabou *et al*. 2022a).

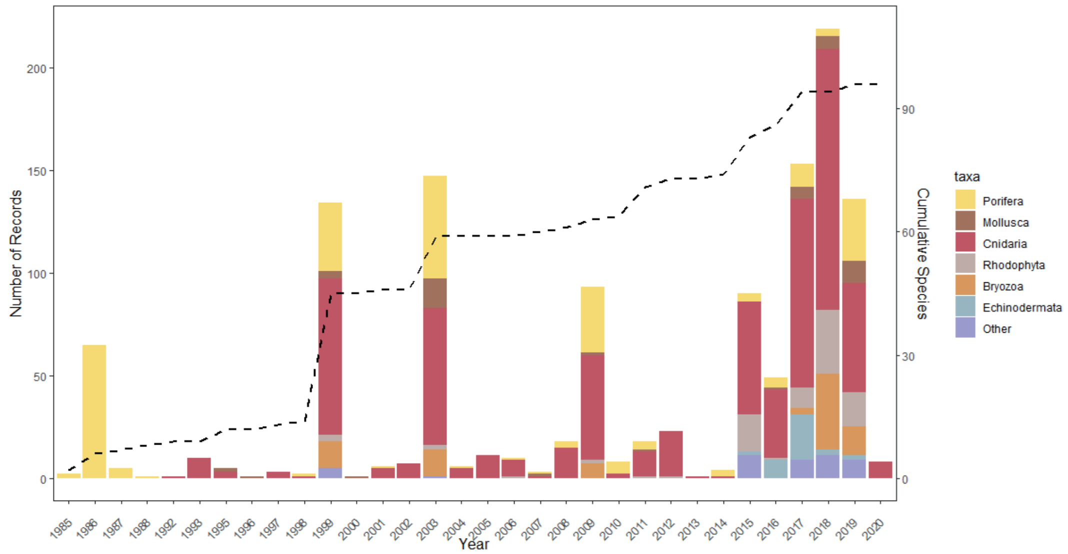
Besides providing an overview of the spatial-temporal patterns of MMEs at a Mediterranean level, we summarized the main research outcomes of the involved teams to provide up to date knowledge on their effects at different biological levels.

Results and discussion

Mediterranean mass mortality events - overview

The first large MMEs were reported in the mid '80s and affected few commercial sponge species in the southern and eastern Mediterranean regions (Fig. 1). The most dramatic events reported in terms of geographic extent and number of affected species occurred in 1999 and 2003 along the northwestern Mediterranean Sea (Cerrano *et al*. 2000; Perez *et al.* 2000; Garrabou *et al.* 2009). These two events affected more than 40 species from various taxa (*e.g.,* Porifera, Cnidaria, Bivalvia, Bryozoa, Ascidiacea) across thousands of kilometers of coastline. Following these main events, the mass mortality records indicate that MMEs had impacted smaller geographic areas and fewer species almost every year until the 2015-2019 period, when the Mediterranean Sea experienced exceptional thermal conditions resulting in the onset of five consecutive years of MMEs widespread across the Basin (Garrabou *et al*. 2022b). Finally, during the summer 2022, the Western Mediterranean experienced temperature breaking records associated to one of the most severe MHW (Juza *et al*. 2024), which resulted in one of the strongest ever observed MME in the northwestern Mediterranean Sea with up to 80% affected colonies across 26 locations (Estaque *et al*. 2023).

Overall, the number as well as the diversity of species affected by MMEs have been increasing over the last two decades. MMEs have affected a total of 96 species belonging to 10 different phyla (Fig. 1). Cnidaria, Porifera, and Bryozoa account for most of the impacted species, with octocorals (among cnidarians) being the most affected. Regarding the depth range, in general the MMEs affected the species dwelling from 0 to 40 m depth, with the intermediate depths (15-25m) being the most impacted. Finally, as mentioned above, over the last decades MMEs have become more frequent and have affected larger geographic areas (Fig. 1). According to the dataset collected the literature review, there is a lack of information from the southern and eastern Mediterranean coasts. Likewise, our review revealed the absence of consolidated MMEs monitoring efforts in the Mediterranean Sea (Garrabou *et al*., 2019, 2022b). The T-MEDNet network and other similar initiative should be promoted to fill these gaps and enhance our observation capabilities.



N Ecoregions	1	4	2	1	1	1	3	1	2	1	3	1	4	2	2	3	2	2	3	2	3	2	3	3	1	2	3	3	6	4	6	2
N Taxa	1	1	1	1	1	1	2	1	1	2	6	1	2	1	6	2	1	3	3	2	5	2	4	2	1	2	6	5	8	8	7	1
N Species	2	6	3	1	1	1	3	1	1	2	39	1	4	4	34	4	4	5	3	6	25	7	14	10	1	4	23	15	31	26	34	2

Figure 1. Bars indicate the number of mass mortality records per main taxa reported during the period 1985 to 2020 (1985 was the first year for which information on MMEs was found). Dashed line shows the cumulative number of species affected by mass mortality during the 1985-2020 period. Data were collected from literature review and monitoring activities conducted by the T-MEDNet network. The table indicates the number of ecoregions (according to Garrabou *et al.* 2022b), number of taxa and number of species affected across years.

Regarding the life-history and functional traits, the species affected by MMEs correspond to long-lived species, with low growth rates and massive-arborescent growth forms, such as gorgonians and perennial seaweeds. In most cases, these species are considered foundation or habitat-forming species, playing a key structural and ecological role in the habitats in which they thrive. In the following sections a summary of the main findings on the consequences of MMEs at different biological levels is provided.

Consequences of MMEs at population level

According to our literature review, most studies on the consequences of MMEs in the Mediterranean at population level have focused on foundation species (*e.g.*, Turicchia *et al.* 2018 ; Garrabou *et al.* 2019 ; Chimienti *et al.* 2021 ; Verdura *et al.* 2021 ; Gómez-Gras *et al.* 2021a ; Ghanem *et al.* 2024). These studies were mostly based on demographic surveys quantifying the immediate impacts, which resulted in an increase of both total and partial mortality rates. They revealed that differential impacts at all biological levels (*i.e.,* among species, populations, individuals, and even within colonies) are one of the main characteristics of the MMEs (Cerrano *et al.* 2000 ; Garrabou *et al.* 2009, 2022b).

At population levels, after the 1999 event, the percentage of dead colonies in red coral *Corallium rubrum* populations from the southeastern coast of France varied from less than 2% to more than 40% (Garrabou *et al.* 2001). After the 2003 MME, populations of *Paramuricea clavata* from the same area showed percentages of colonies affected by necrosis ranging from 2 to 80% (Garrabou *et al.* 2009). In general, studies monitoring population dynamics after MMEs showed null or quite limited recovery capacity (Cerrano *et al.* 2005 ; Santangelo *et al.* 2015 ; Gómez-Gras *et al.* 2021a). This lack or limited recovery is the result of the combination of slow population dynamics (slow growth and limited recruitment, Linares *et al.* 2007 ; Montero-

Serra *et al*. 2018), and low connectivity characterizing these species (Ledoux *et al*. 2010 ; Arizmendi-Mejía *et al*. 2015a), and the recurrent onset of MHWs during the last decades. These observations clearly point out to a collapse trajectory for most populations dwelling between surface and 30 m depth (Garrabou *et al*. 2021 ; Gómez-Gras *et al*. 2021a ; Bramanti *et al*. 2023). Bearing in mind the severity and the recurrent impacts, some populations can be considered already ecologically extinct, and, in the most dramatic cases, local extinctions have even been reported (e.g. Gómez-Gras *et al*. 2021a).

Community level consequences of MMEs

The ecological extinctions observed at the population level can lead to widespread structural and compositional changes at the community level, and to subsequent changes in ecosystem functioning, especially when lost species are functionally unique (Loya *et al*. 2001 ; Bellwood *et al*. 2004 ; Bianchi *et al*. 2014 ; Harvey *et al*. 2022). This is the case for octocorals and other habitat-forming species, which are among the most affected by MMEs (Garrabou *et al*. 2022b). These species dominate many diverse and abundant rocky habitats, such as coralligenous assemblages. They are considered to be functionally unique in the Mediterranean Sea because they provide a high structural complexity that is needed for many other associated species to thrive (Ponti *et al*. 2014, 2016, 2018 ; Verdura *et al*. 2019 ; Gómez-Gras *et al*. 2021b).

As extreme climatic events unfold, the populations of these species are likely to experience further declines in their distribution range across various spatial dimensions, encompassing vertical (from surface to deep ranges) and horizontal (from north to south and west to east) distribution at local, regional, or even at pan-Mediterranean scale. These declines will have significant consequences for the functioning of Mediterranean benthic ecosystems (Gómez-Gras *et al*. 2021b) and, subsequently, for the provision of associated services to human societies (Smith *et al*. 2021).

Exploring future trajectories of Mediterranean habitats under MHWs

During the last decades, research efforts were focused on the factors and processes that shape inter- and intra-specific differential responses (sensitivity) to heat stress associated to MHWs. The outcomes of these efforts are fundamental to develop climate resilience conservation and restoration tools and to better predict the vulnerability of benthic species to the expected increase in the MHWs regime.

Several studies contributed to fill the gap of knowledge on basic information, such as the identification of thermotolerance thresholds in affected species, mainly octocorals, bryozoans, and fucalean seaweeds (*e.g.,* Pagés-Escolà *et al*. 2018 ; Gómez-Gras *et al*. 2019 ; Verdura *et al.* 2021). Likewise, for some species, experimental studies allowed to identify the main factors modulating the differential responses within and between populations, such as sex, maturity, symbiosis, physiological condition, microbiome and diseases (Bally & Garrabou, 2007 ; Linares *et al*. 2008 ; Cebrian *et al*. 2011; Ledoux *et al*. 2015 ; Arizmendi-Mejía *et al*. 2015b ; Crisci *et al*. 2017 ; Gómez-Gras *et al*. 2022 ; Bonacolta *et al*. 2023, Rilov 2024). Besides, combining these studies with population genetics and transcriptomics allowed to explore the eco-evolutionary dynamics in some of the affected species. Overall these studies confirmed the sensitivity to warm temperatures, with important inter-individual and inter-population thermotolerance variations, across the tested populations and species. Yet, as our understanding of the underlying evolutionary processes remains scarce, whether or not one can expect these species to adapt to the current and expected warming conditions remains an open question. For instance, in the red gorgonian *Paramuricea clavata*, the differential response observed among populations in one experiment in controlled conditions involving eight populations from the French and Catalan coasts (Crisci *et al*. 2017) was related to genetic drift. In another study which focused on eleven populations from the northwestern Mediterranean Sea and the Adriatic Sea, some populations did show adaptive potential and /or adaptive phenotypic plasticity to future warming (Gómez-Gras *et al*. 2022).

Despite such efforts, most studies concerned a very limited number of populations over a limited geographic area. Only few studies have considered populations over a wide distributional species range (*e.g.,* Gomez-Gras *et al*. 2022). There is an urgent need to span our experimental efforts to cover a larger number of species and to test larger numbers of populations coming from the whole distribution range. This is the required step to enhance our capacity to inform on the transformation of the structure and functioning of coastal Mediterranean habitats face due to the observed and predicted increase of MHWs regime.

<u>Relationship between MMEs and MHWs</u>
Unraveling the intricate interplay between the biological responses of marine biodiversity and the diverse gradients of heat exposure stands as a rarely explored challenge (Cheung *et al*. 2021 ; Hughes *et al*. 2021). Indeed, the high variability of responses observed among different species and populations across spatial and temporal scales, as well as the lack of empirical datasets on these extreme (rare) events, undermine our ability to understand this relationship.

In spite of this, several studies have confirmed the relation between MHWs and MMEs using both MHWs derived from satellite sea surface and *in situ* temperature data in the Mediterranean (*e.g.,* Verdura *et al*. 2021; Garrabou *et al*. 2022b). However, as mentioned above, these studies have also shown a high variability in the level of mortality impact for a similar heat exposure. The main component explaining this variability could be linked to: i) properties of the MHWs such as timing, duration, maximum, and cumulative intensity (Hodbday *et al*. 2016; Elzahaby *et al*. 2021); ii) species physiology and taxonomy (*i.e.,* differences among species and populations, including their specific thermal niche, thermotolerance, and physiological status) (see for example Arizmendi-Mejía *et al*. 2015b; Crisci *et al*. 2017; Gómez-Gras *et al*. 2019); and iii) the ecological memory on the recurrence of MHWs or other adaptative or acclimatization processes over the same geographic areas, which may alter the response of populations re-exposed to MHWs (Kersting and Linares, 2019 ; Turner *et al*. 2020 ; Hughes *et al*. 2021).

To bolster our predictive capacity concerning the ecological impacts of MHWs, needed measures encompass: i) persistent advocacy for recording long-term series of *in situ* temperature and for monitoring mass mortality series across the Mediterranean, so as to facilitate the construction of an extended historical record essential for precise MHWs identification and the potential onset of MMEs (Garrabou *et al*. 2022b ; Juza *et al.* 2024); ii) advancing our comprehension of the physical mechanisms propelling MHWs, both on the surface and at depth (Elzahaby *et al*. 2021); iii) the formulation of more comprehensive heat stress indicators adeptly considering both exposure duration and intensity (Cheung *et al.* 2021; Hughes *et al.* 2021, Lacer, 2024, Liguori 2024, Schlegel 2024, Simon 2024) and iv) engaging interdisciplinary research focused in understanding the factors and mechanisms responsible for the observed contrasted responses of species and populations across multiple spatial and temporal scales.

Conclusion

The increase in frequency, intensity, and spatial scales of MHWs is driving major ecological changes in marine ecosystems worldwide (Smith *et al*. 2021). Our results clearly indicate that the Mediterranean Sea is experiencing an acceleration of anthropogenic climate change impacts and reveal worrisome signals that large-scale MMEs and MHWs are no longer the exception but might become the new “normal”.

As the global ocean, in general, and the Mediterranean Sea, in particular, are entering in unchartered territories, it is critical to reinforce and upscale ongoing collaborative efforts to increase the resolution of empirical observation networks, experimental settings, and interdisciplinary research. Such concerted efforts are essential for enhancing our ability to thoroughly comprehend and effectively manage the consequences of climate change.

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References

Arizmendi-Mejía R., Linares C., Garrabou J., Antunes A., Ballesteros E., Cebrian E., Diaz, D. and J.B. Ledoux. 2015a. Combining genetic and demographic data for the conservation of a Mediterranean marine habitat-forming species. *PLoS ONE* 10(3): e0119585. https://doi.org/10.1371/journal.pone.0119585

Arizmendi-Mejía R., Ledoux JB., Antunes A., Thanopoulou Z., Garrabou J. and C. Linares. 2015b. Demographic responses to warming: reproductive maturity and sex influence vulnerability in an octocoral. *Coral Reefs*, 34: 1207-1216. https://doi.org/10.1007/s00338-015-1332-9h

Bally M. and J. Garrabou. 2007. Thermodependent bacterial pathogens and mass mortalities in temperate benthic communities: a new case of emerging disease linked to climate change. *Global Change Biology,* 13: 2078-2088. https://doi.org/10.1111/j.1365-2486.2007.01423.x

Bellwood D.R., Hughes T.P., Folke C. and M. Nyström. 2004. Confronting the coral reef crisis. *Nature*, 429: 827–833. https://doi.org/10.1038/nature02691

Bensoussan N., Cebrian E., Dominici J.M., Kersting D.K., Kipson S., Kizilkaya Z., Ocaña O., Peirache M., Zuberer F., Ledoux JB., Linares C., Zabala M., Nardelli B.B., Pisano A. and J. Garrabou. 2019. Using CMEMS and the Mediterranean Marine protected Area sentinel network to track ocean warming effects in coastal areas. In: Copernicus Marine Service Ocean State Report, 3, *J. of Operational Oceanography*.

Bianchi C. N., Corsini-Foka M., Morri C. and A. Zenetos. 2014. Thirty years after-dramatic change in the coastal marine habitats of Kos Island (Greece), 1981–2013. *Mediterranean Marine Sciences*, 15(3), 482–497. https://doi.org/10.12681/mms.678

Bonacolta A.M., Miravall J., Gómez-Gras D., Ledoux J.B., Garrabou J., Massana R. and del Campo, X. 2023. Differential apicomplexan presence predicts thermal stress mortality in the Mediterranean coral *Paramuricea clavata*. *Environmental Microbiology* DOI: 10.1111/1462-2920

Bramanti L., Manea E., Giordano B., Estaque T., Bianchimani O., Richaume J., Mérigot B., Schull Q., Sartoretto S., Garrabou J. G. and K. Guizien. 2023. The deep vault: a temporary refuge for temperate gorgonian forests facing marine heat waves. *Mediterranean Marine Science*, 24(3): 601–609. https://doi.org/10.12681/mms.35564

Cebrian E., Uriz MJ., Garrabou J. and E. Ballesteros. 2011. Sponge Mass Mortalities in a Warming Mediterranean Sea: Are Cyanobacteria-Harboring Species Worse Off? *PLoS ONE* 6(6): e20211. https://doi.org/10.1371/journal.pone.0020211

Cerrano C., Arillo A., Azzini F., Calcinai B., *et al.* 2005. Gorgonian population recovery after a mass mortality event. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 15(2), pp.147-157. https://doi.org/10.1002/aqc.661

Cerrano C., Bavestrello G., Bianchi C. N., Cattaneo-vietti R., *et al.* 2000. A catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (northwestern Mediterranean), summer 1999. *Ecology Letters*, 3: 284–293. https://doi.org/10.1046/j.1461-0248.2000.00152.x

Cheung M.W.M., Hock K., Skirving W. and P.J. Mumby. 2021. Cumulative bleaching undermines systemic resilience of the great Barrier reef. *Current Biology*, 31(23), 5385–5392.e4. https://doi.org/10.1016/j.cub.2021.09.078

Chimienti G., De Padova D., Adamo M., Mossa M., Bottalico A., *et al.* 2021. Effects of global warming on Mediterranean coral forests. *Scientific Reports*, 11: 20703 https://doi.org/10.1038/s41598-021-00162-4

Cramer W., Guiot J., Fader M., Garrabou J., *et al.* 2018. Climate change and interconnected risks to sustainable development in the Mediterranean. *Nature Climate Change,* 8: 972–980. https://doi.org/10.1038/s41558-018-0299-292

Crisci C., Ledoux J-B., Mokhtar- Jamaï K., Bally M, Bensoussan N., *et al.* 2017. Regional and local environmental conditions do not shape the response to warming of a marine habitat-forming species. *Scientific Reports*, 7: 50-69. https://doi.org/10.1038/s41598-017-05220-4

Darmaraki S., Somot S., Sevault F., Nabat P., *et al.* 2019. Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics*, 53: 1371–1392. https://doi.org/10.1007/s00382-019-04661-z

Elzahaby Y, Schaeffer A., Roughan M. and S. Delaux. 2021. Oceanic circulation drives the deepest and longest marine heatwaves in the East Australian Current system. *Geophysical Research Letters*, 48(17): e2021GL094785. https://doi.org/10.1029/2021GL094785

Estaque T., Richaume J, Schull Q, Merigot B., *et al.* 2023. Marine heatwaves on the rise: One of the strongest ever observed mass mortality event in temperate gorgonians. *Global Change Biology*, 29(22): 6159–6162. https://doi.org/10.1111/gcb.16931

Garrabou J., Gómez-Gras D., Ledoux J.B. Linares C., *et al.* 2019. Collaborative Database to Track Mass Mortality Events in the Mediterranean Sea. *Front. Mar. Sci*. 6: 707. https://doi.org/10.3389/fmars.2019.00707

Garrabou J., Bensoussan N., Di Franco A., Boada J., Cebrian E., Santamaria J., Guala I., Grech D., Cerrano C., Pulido T., Jou M., Marambio M. and E. Azzurro. 2022a. Monitoring Climate-related responses in Mediterranean Marine Protected Areas and beyond: ELEVEN STANDARD PROTOCOLS. 74 pp. Edited by: Institute of Marine Sciences, Spanish Research Council ICM-CSIC. https://doi.org/10.20350/digitalCSIC/14672

Garrabou J., Coma R., Bensoussan N., Bally M., *et al.* 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology*, 15: 1090–1103. https://doi.org/10.1111/j.1365-2486.2008.01823.x

Garrabou J., Gómez-Gras D., Medrano A., Cerrano C., Ponti M., *et al.* 2022b. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology*, 28(19): 5708–5725. https://doi.org/10.1111/gcb.16301

Garrabou J., Ledoux J.-B., Bensoussan N., Gómez-Gras D. and C. Linares 2021. Sliding toward the collapse of Mediterranean coastal marine rocky ecosystems. In J. G. Canadell and R. B. Jackson (Eds.), Ecosystem collapse and climate change (pp. 291–324). *Springer International Publishing*. https://doi.org/10.1007/978-3-030-71330-011

Garrabou J., Pérez T., Sartoreto S. and J.G Harmelin. 2001. Mass mortality event in red coral (*Corallium rubrum*, Cnidaria, Anthozoa, Octocorallaria) populations in the Provence region (France, NW Mediterranean). *Marine Ecology Progress Series,* 217: 263-272

Ghanem R., Ben Souissi J., Ledoux J.B., Linares C. and J. Garrabou. 2024 Marine Heatwaves and benthic communities: Changes features of the assemblages and alarming consequences on biodiversity in Tunisian waters. CIESM pp 155-162 Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Gómez-Gras D., Bensoussan N., Ledoux J.B., López-Sendino P., Cerrano C., Ferretti E., Kipson S., Bakran-Petricioli T., Serrao E.A., Paulo D., Coelho M.A.G., Pearson G.A., Boavida J., I. Montero-Serra I., Pagès-Escolà M., Medrano A., López-Sanz A., Milanese M., Linares C., and J. Garrabou. 2022. Exploring the response of a key Mediterranean gorgonian to heat stress across biological and spatial scales. *Scientific Reports* 12: 21064 https://doi.org/10.1038/s41598-022-25565-9

Gómez-Gras D., Linares C., De Caralt S., Cebrian E., Frleta-Valić M., *et al.* 2019. Response diversity in Mediterranean coralligenous assemblages facing climate change: insights from a multi-specific thermotolerance experiment. *Ecology and Evolution*, 9(7): 4168-4180. https://doi.org/10.1002/ece3.5045

Gómez-Gras D., Linares C., Dornelas M., Madin J. S., Brambilla V., *et al.* 2021a. Climate change transforms the functional identity of Mediterranean coralligenous assemblages. *Ecology Letters*, 24(5), 1038-1051. https://doi.org/10.1111/ele.13718

Gómez-Gras D., Linares C., López-Sanz A., Amate R., Ledoux J.-B., Bensoussan N., Drap P., Bianchimani O., Marschal C., Torrents O., Zuberer F., Cebrian E., Teixidó N., Kipson S., Kersting D., Montero Serra, I., Pagès Escolà M., Medrano A., Frleta-Valić M. and J. Garrabou. 2021b. Population collapse of habitat-forming species in the Mediterranean: A long-term study of gorgonian populations affected by recurrent marine heatwaves. *Proceedings of the Royal Society B: Biological Sciences*, 288, 20212384. https://doi.org/10.1098/rspb.2021.2384

Harvey B. P., Marshal K. E., Harley C. B. P. and B.D Rusell. 2022. Predicting responses to marine heatwaves using functional traits. *Trends in Ecology & Evolution*, 37(1), 20-29. https://doi.org/10.1016/j.pocean.2015.12.014

Hobday A.J., Alexander L. V., Perkins S. E., Smale D. A., Straub S. C., *et al.* 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography*. 141:227-238. https://doi.org/10.1016/j.pocean.2015.12.014

Hughes T. P., Kerry J. T., Connolly S. R., Álvarez-Romero J.G., Eakin C. M., *et al*. 2021. Emergent properties in the responses of tropical corals to recurrent climate extremes. *Current Biology*, 31(23): 5393-5399. https://doi.org/10.1016/j.cub.2021.10.046

Juza M., Reyes E. and J. Tintoré. 2024. Marine heat waves in the Mediterranean Sea: 2023 update and new insights from multi-platforms observations. In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Kersting DK and C. Linares. 2019. Living evidence of a fossil survival strategy raises hope for warming-impacted corals. *Science Advances,* 5(10), eaax2950. https://doi.org/10.1126/sciadv.aax2950

Ledoux JB., Mokthar-Jamai K., Roby C., Feral JP., *et al.* 2010. Genetic survey of shallow populations of the Mediterranean red coral [*Corallium rubrum* Linnaeus, 1758]: new insights into evolutionary processes shaping nuclear diversity and implications for conservation. *Molecular Ecology* 19: 675–690. https://doi.org/10.1111/j.1365-294x.2009.04516.x

Ličer M. 2024. Seasonality, return periods and intensity of surface marine heat waves in the Mediterranean basin. pp 27 - 39 In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Liguori G. 2024. The need to adopt process-based definitions for marine heatwaves. pp 41 - 50 In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Linares C., Doak D., Coma R., Díaz D., and M. Zabala. 2007. Life history and viability of a long-lived marine invertebrate: The octocoral *Paramuricea clavata*. *Ecology* 88: 918-928.

Linares C., Coma R. and M. Zabala. 2008. Effects of a mass mortality event on gorgonian reproduction. *Coral Reefs*, 27(1): 27-34. https://doi.org/10.1007/s00338-007-0285-z

Loya Y., Sakai K., Yamazato K., Nakano Y., Sambali H. and R. Van Woesik. 2001. Coral bleaching: The winners and the losers. *Ecology Letters*, 4(2): 122–131. https://doi.org/10.1046/j.1461-0248.2001.00203.x

Marbà N., Jordà G., Agusti S., Girard C. and , C. M. Duarte. 2015. Footprints of climate change on Mediterranean Sea biota. *Frontiers in Marine Science*, 2: 00056. https://doi.org/10.3389/fmars.2015.00056

Montero-Serra,I., Linares C., Doak D.F., Ledoux J.B. and J. Garrabou. 2018. Strong linkages between depth, longevity and demographic stability across marine sessile species. Proceedings of the Royal Society of London B, 285: 20172688

Pagès-Escolà M., Hereu B, Garrabou J, Montero-Serra I, Gori A, Gómez-Gras D, Figuerola B. and Linares C. 2018. Divergent responses to warming of two common co-occurring Mediterranean bryozoans. *Scientific reports*, 8(1): 17455. https://doi.org/10.1038/s41598-018-36094-9

Perez T., Garrabou J., Sartoretto S., Harmelin, J. G., *et al.* 2000. Mortalité massive d'invertébrés marins: un événemnt sans précédent en Méditerranée nord-occidentale. *Comptes Rendus de l'Académie des Sciences - Series III Life Sciences*, 323: 853–865. https://doi.org/10.1016/S0764-4469(00)01237-3

Ponti M., Grech D., Mori M., Perlini R.A., Ventra V., Panzalis P.A. and C. Cerrano. 2016. The role of gorgonians on the diversity of vagile benthic fauna in Mediterranean rocky habitats. *Mar Biol* 163(5):1-14 https://doi.org/10.1007/s00227-016-2897-8

Ponti M., Perlini R. A., Ventra V., Grech D., Abbiati M. and C. Cerrano. 2014. Ecological shifts in Mediterranean coralligenous assemblages related to gorgonian forest loss. *PLoS ONE*, 9(7): e102782. https://doi.org/10.1371/journal.pone.0102782

Ponti M., Turicchia E., Ferro F., Cerrano C. and M. Abbiati. 2018. The understorey of gorgonian forests in mesophotic temperate reefs. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 28(5): 1153-1166. https://doi.org/10.1002/aqc.2928

Rilov G. and collaborators. 2024. Ocean warming, marine heatwaves and the thermal vulnerability of the increasingly tropicalized Levant coast ecosystems. pp 141 - 154 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Rivetti I., Fraschetti S., Lionello P., Zambianchi E. and F. Boero. 2014. Global warming and mass mortalities of benthic invertebrates in the Mediterranean Sea. *PLoS ONE*, 9(12): e115655. https://doi.org/10.1371/journal.pone.0115655

Santangelo G., Cupido R., Cocito S., Bramanti L., Priori C., Erra F. and M. Iannelli. 2015. Effects of increased mortality on gorgonian corals (Cnidaria, Octocorallia): Different demographic features may lead affected populations to unexpected recovery and new equilibrium points. *Hydrobiologia*, 759, 171–187. https://doi.org/10.1007/s10750-015-2241-1

Schlegel R.W. 2024. Marine heatwave research: a path forward via the Mediterranean and the Arctic. pp 51 - 62 In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Simon A. 2024. Summer 2023 MHW main features and trend in air-sea interactions related to the long-term evolution of MHW in the Mediterranean. pp 77 - 84 In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Smith K. E., Burrows M. T., Hobday A. J., Sen Gupta A., Moore P. J., Thomsen M., Wernberg T. and D.A Smale. 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science,* 374, 6566. https://doi.org/10.1126/scien ce.abj3593

Turicchia E., Abbiati M., Sweet M. and M. Ponti. 2018. Mass mortality hits gorgonian forests at Montecristo Island. *Disease of Aquatic Organisms*, 131(1): 79-85. https://doi.org/10.3354/dao03284

Turner M. G., Calder W. J., Cumming G. S., Hughes T. P., Jentsch A., *et al.* 2020. Climate change, ecosystems and abrupt change: science priorities. Philosophical Transactions of the Royal Society B: *Biological Sciences*, 375(1794): 20190105. https://doi.org/10.1098/rstb.2019.0105

Verdura J., Linares C., Ballesteros E., Coma R., Uriz M. J., *et al.* 2019. Biodiversity loss in a Mediterranean ecosystem due to an extreme warming event unveils the role of an engineering gorgonian species. *Scientific Reports*, 9, 5911. https://doi.org/10.1038/s41598-019-41929-0.

Verdura J., Santamaría J., Ballesteros E., Smale D.A., Cefalì M.E., Golo R., Caralt S., Vergés A. and E. Cebrian. 2021. Local-scale climatic refugia offer sanctuary for a habitat-forming species during a marine heatwave. *J. Ecol*. 109, 1758–1773. https:// doi.org/10.1111/1365-2745.13599.

Ocean warming, marine heatwaves and the thermal vulnerability of the increasingly tropicalized Levant coast ecosystems

Gil Rilov[1,2], **Erez Yeruham**[1,2], **Simona Noè**[1,3]

[1] *Israel Oceanographic & Limnological Research, National Inst. of Oceanography, Haifa, Israel*
[2] *Leon H. Charney School of Marine Sciences, Marine Biology Department, Univ. of Haifa, Israel*
[3] *Stazione Zoologica Anton Dohrn, Integrative Marine Ecology Department, Naples, Italy*

Abstract

The Levantine coastal biodiversity has transformed considerably in the past century towards increased domination of thermophilic alien species, as well as loss of native biodiversity in a few major taxonomic groups. A main driver of this transformation is suspected to be the rapid warming of coastal waters but the role of marine heatwaves (MHWs) in the loss of native species remains unclear. We have evidence of only one clear mass mortality event -of a dominant alien mussel- since systematic ecological monitoring started in 2009 on the rocky Israeli coast. Recent analysis of coastal temperature trends in the southeast Levant indicates that MHWs are becoming more frequent, that some can last for months, but that most are moderate and occur during the spring season. Experimental testing of the thermal tolerance of macrophytes and invertebrates shows that most but not all tested native species are sensitive to future warming or prolonged MHWs. In some invertebrates, where the impact of exposure length was tested, it was shown that with increasing exposure to extreme heat stress, the thermal optimum and performance are reduced. The intriguing difference between the eastern and western Mediterranean sub-basins in terms of both MHW trends and their ecological impacts is discussed, as well as the need to better define MHWs in the face of future fast warming.

The threat of climate change and marine heatwaves to marine biodiversity

Climate change, and specifically ocean warming and the increase in the frequency, intensity and duration of marine heatwaves (MHWs), are rapidly becoming considerable threats to the integrity of marine populations in many ocean regions (IPCC 2019). This is because water temperature is the most important abiotic variable affecting physiological performance in aquatic ectotherms (Brown *et al.* 2004). Every species has its own temperature range within which its physiological performance is optimal – the so-called thermal envelope (Portner and Farrell 2008). When thermal thresholds are exceeded, the species performance will be hindered, which may affect the species abundance and then distribution. Gradual ocean warming can lead to major shifts in species distributions; this may include the local elimination of thermal-sensitive species or their migration towards colder climes (Bates *et al.* 2014). Severe regional MHWs had led to rapid localized collapse of marine communities (e.g., kelp forests in Western Australia, Wernberg *et al.* 2013) or mass mortality events (e.g., benthic invertebrate communities in the Western Mediterranean, Garrabou *et al.* 2009) of various scales and magnitude (Smith *et al.* 2023) -not necessarily at distributional edges. Obviously, both gradual ocean warming and intensification of MHWs can occur simultaneously in the same region, increasing thermal risk considerably.

MHWs have been recently defined as *discrete* anomalously-prolonged warming **events** that last five days or more with sea surface temperatures (SST) above the 90th percentile of the local daily climatology that was ideally measured over 30 years or more (Hobday *et al.,* 2016). Then, the intensity of MHWs was categorized into four levels of severity from moderate to extreme (Hobday *et al.* 2018). MHWs are considered the result of the "interaction of many local and remote atmospheric and oceanic processes and phenomena acting across a large range of temporal and spatial scales" (Holbrook *et al.* 2019). The two prevailing mechanisms for the development of a MHW in the mixed-layer of the ocean are (1) the geostrophic advection of warmer water from elsewhere in the region, or (2) considerable change in air-sea heat flux, i.e., exceptional warming of the air often associated with a reduction in wind speed and in cloud cover (Oliver *et al.* 2021). When defining MHWs, deciding as a function of the research question which climatological baseline to use -fixed or moving- will have a bearing on the metrics, trends and forecasts. In principle the same intensity and frequency of heat events superimposed over gradual warming can turn these events into MHWs without even an actual increase in the degree of the anomalies (Fig. 1). Further, if the summer months become much warmer than the previous baseline very rapidly, they can be defined as MHW events without actually being discrete "events" but rather as part of the seasonal trend due to the statistical nature of the current, popular definition of Hobday *et al.* (2016).

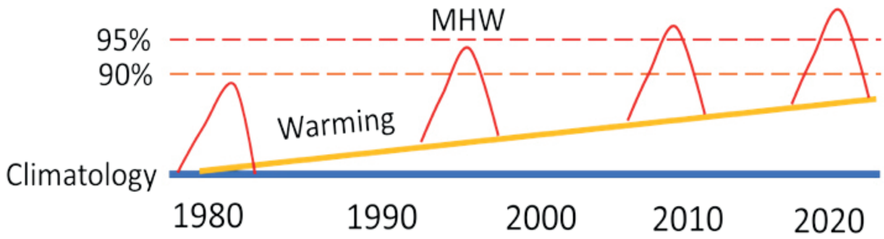

Figure 1. Natural warming events can theoretically turn into MHWs when superimposed on top of the gradual warming trend as illustrated here. The blue bottom line represents the thirty-year average (climatology) temperature, the dashed lines represent the 90th and 95th percentiles above it and the curves represent warming events. When the peaks of similar-sized events (similar warming above ambient temperatures) cross the 90th percentile, the event become a moderate MHW by definition. It can even be considered a strong event when crossing the 95th percentile, while in fact there was no change in the frequency and intensity of the event.

This evidently is true not only for the Mediterranean but also for many other areas in the global ocean (Xu *et al.* 2022). Furthermore, gradual rise in water temperature can also affect MHW detection in past decades. On one hand this can under-estimate the threshold value in the later period of a given time series (post-warming), causing an artificial inflation of MHWs. On the other hand, this method of analysis will overestimate the calculated threshold in the earlier (pre-warming) period of the time series, resulting in an artificial scarcity of such events in the past. This statistical anomaly is well evident in the analysis of MHWs along the Israeli coast (Fig. 2), where analysis of satellite derived SST time series (1982-2023) revealed an unlikely scarcity of extreme warming events (MHWs) between 1982-2000, with only a single event in that period, compared to their hyper-abundance in most years after 2010.

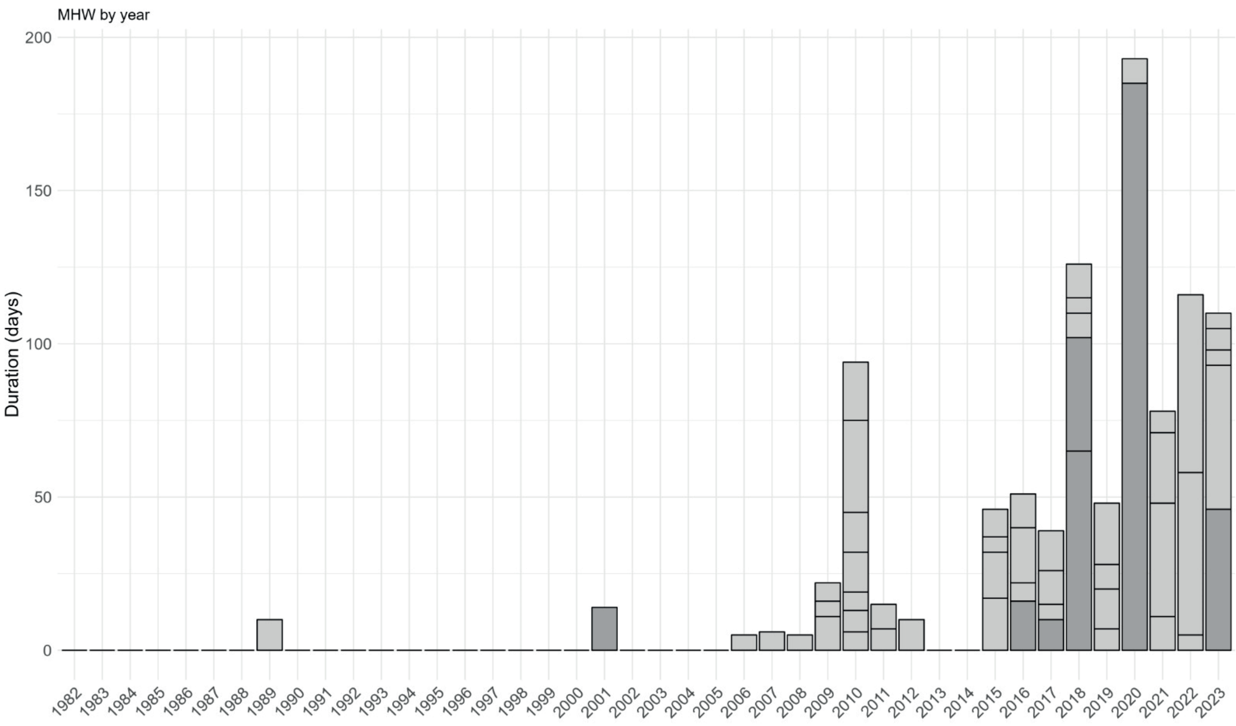

Figure 2. Discrete marine heatwaves and their durations between 1982-2023 as detected for SST time series for the coastal area near Haifa. Light gray indicates moderate events and darker gray indicates strong events. Events that started in a specific year and lasted into the next year are present in whole in the earlier year.

Mediterranean MHWs

Global analysis of the occurrence of MHWs -as they have been defined- reveals an increase in their frequency and intensity (Oliver *et al.* 2018) , with impacts on biodiversity and ecosystem services that can be profound (Smale *et al.* 2019 ; Smith *et al.* 2023). Among oceanic regions, the Mediterranean Sea is one of the hottest hotspots of climate change and specifically ocean warming (IPCC 2019). In this marginal sea, although there were previous reports on MHW impacts (Garrabou *et al.* 2001), the first exceptional, large scale, documented MHW occurred in the northwest Mediterranean in 2003, with air temperature records 3–6^{o}C above the seasonal average, and water surface anomalies of 2–3^{o} C. This event had considerable impacts on the marine biota, including extensive mass mortalities (Garrabou *et al*. 2009). Since then, MHW events have occurred increasingly frequently (29 events between 1982-2017, Darmaraki *et al*. 2019a), accompanied by increasing frequency of mass mortality events across the Basin, as shown for the years 2015-2019 (Garrabou *et al.* 2022 ; Garrabou *et al.* ; Ghanem *et al.* in this volume). Most events in these five years occurred between July and September. MHWs are projected to increase further into the future under different scenarios; in particular under the business-as-usual IPCC scenario (RCP8.5), models forecast at least one, several months long, highly intense MHW every year by 2100 (Darmaraki *et al.* 2019b). This will no longer be an anomalous event but rather the norm. Darmaraki *et al.* (2019a), based on both observed SST data and models, revealed a strong spatial pattern in the intensity and duration of Mediterranean MHWs. While the northern sectors of the Mediterranean displayed the most intense MHW (expressed as surface *Imean* ~1^{o}C), the Levantine displayed events with the longest durations

(~20–70 days). Recent studies (Simon *et al.* 2024, also in this volume) using a new index that accounts for MHW intensity, duration as well as area covered, confirm that MHW activity is higher in the western basin where MHWs are more intense while they are longer and less intense in the eastern basin).

They also show that long-term warming provides most of the contribution to summer MHW activity but only in the western basin. This suggests that the mechanisms behind the increase in MHW activity are different between sub-basins. We may argue that in the southeastern basin real, discrete MHW events are much rarer today than in the northwest basin, and the long and weak MHWs documented in the east are mostly a statistical product of the very fast warming in the region as seen in future projections for the world ocean in coming decades (Oliver *et al.* 2019).

The analysis by Darmaraki *et al.* (2019a) also revealed that in the western Mediterranean Sea the most intense but infrequent events occurred from the surface down to 23 m depth, with specific spots in the Alboran, Ionian and Tyrrhenian Seas kept under MHW influence for 60–167 days. This is confirmed by *in-situ* data (Garrabou *et al.* 2022) showing strong MHW signature at this depth and beyond. Further, Juza *et al.* (in this volume), report till present MHW events lasting up to 197 days. This suggests that in the Mediterranean Sea, MHW intensity and duration are highly patchy and that there are distinct MHW (or warming) hotspots and possibly some less thermally-changing areas that may be considered as climate change refugia (Doxa *et al.* 2022).

Ocean warming and MHW impacts in the Mediterranean Sea

Clearly, both general warming trends and MHW events impacts on specific species can vary considerably depending on the location in the Mediterranean of a particular species and on the width of its physiological thermal niche. Ecological impacts will further depend on the species degree of phenotypic (thermal) plasticity as well as the degree of local thermal adaptation of different populations across the species' range. Such local adaptation (driven mostly by local genetic selection) is known to exist in many marine species (e.g., Gaitán-Espitia *et al.* 2017 ; King *et al.* 2018). In principle, the degree of thermal stress a species will experience depends on how close it is to the cold or warm edge of its distribution or to warm or cold spots when the thermal environment is a mosaic (see, Helmuth *et al.* 2002, Helmuth *et al.* 2006). Let's take the purple sea urchin, *Paracentrotus lividus*, an important Mediterranean reef herbivore, as an example. Its northwestern Mediterranean populations were shown to have a thermal optimum (CT_{opt}) of 22°C and a CT_{Max} (lethal temperature) of 29°C (Pages *et al.* 2018). This CT_{max} was probably far from the urchin's thermal danger zone three decades ago, but today the urchin in the region possibly got much closer to its thermal maximum with the combination of gradual warming and intense MHWs (Fig. 3, green curve). Populations in the southeast Mediterranean with an assessed CT_{opt} of 25°C and a known CT_{Max} of 30.5°C (Yeruham *et al.* 2015), on the other hand, were already much closer to their thermal maximum in the peak of summer in the 1970s when summer temperatures reached ~29°C (Dothan 1977) (Fig. 3, blue curve). Summer temperatures started repeatedly crossing the CT_{Max} during the 1990s (Rilov 2016) through gradual warming, and today peak coastal water summer temperatures on the Israeli shore are ~31.5°C. As a result, the urchin population probably collapsed sometimes between the 1990s and the early 2000s; when extensive surveys and the routine monitoring started (2010-2012) they were already ecologically extinct on the Israeli coast (Yeruham *et al.* 2015, 2020 ; Rilov 2016). Therefore, the exact progression of their population decline, whether abrupt of gradual, cannot be determined. But it is also possible that the urchin population started to be affected already earlier by extreme heat events in the 1980s and 1990s, leading to their eventual collapse sometimes in the early 2000s. Due to the lack of historical population density time series, we cannot determine when exactly this collapse occurred in this region. It is also important to note that, at least for this species, field experiments suggest that competition for food with invasive fish grazers (rabbitfish) most probably also contributed to its decline.

It is possible that the fate of the purple sea urchin was shared by many other thermally sensitive species in the southeast Levant, as is primarily evident in mollusca assemblages in the region, where most native species disappeared and the assemblage today is dominated by tropical no-native invasive species (Rilov 2016, Albano *et al.* 2021). Of course, many other, presumably more thermally resilient, native species are still present in the southeast Mediterranean, but they may also be close to the danger zone (Fig. 3, orange curve), as was exemplified in TPC experiments wit and (Amsalem and Rilov 2021, Mulas *et al*. 2022, Rilov *et al*. 2022).

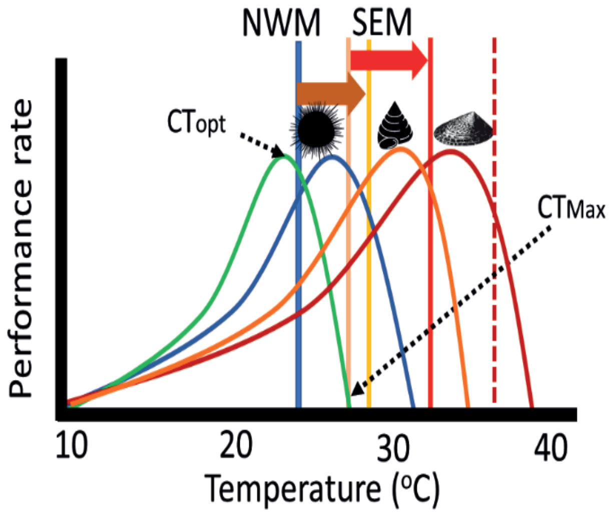

Figure 3. Illustration of a theoretical thermal curves (TPC) of cross-Mediterranean species (green curve) assuming regional adaptation with optimum and maximum temperatures at higher values in the southeast basin (blue curve). This may represent the situation of the purple sea urchin *Paracentrotus lividus* which has been disappearing from the Levantine basin over the past three decades, first from the warmest coast of Israel (see Yeruham *et al.,* 2015, 2019). The orange curve represents a TPC of a native Levant species that is still present but its optimum is close to current summer maxima (e.g., the intertidal topshell snail *Phorcus*).The red curve represents a tropical invader (e.g., the Indopacific limpet *Cellana rota*, See Rilov *et al.,* 2022). The vertical lines represent maximum summer or heatwave temperatures in the northwestern Mediterranean (NWM) in the recent past (blue) and present (yellow), and in the southeastern Mediterranean (SEM) in the recent past (pink), present (red), as well as predicted future (dashed dark red). CT_{opt} = temperature at optimum (maximum) performance, CT_{Max} = temperature when a species loses it functionally and eventually dies; both indicated on the green curve.

Tropical non-native invasive with much higher thermal optimum, like the limpet *Cellana rota* with the highest metabolic rates at 35°C (Rilov *et al.,* 2022), may be much further away today from that danger zone (Fig. 3, red curve), but they might as well get close to it with further gradual ocean warming, and occasional MHWs may help push them over the cliff even earlier. It is important to note that the TPC for the same species can take very different shapes and have different optimums and CT_{Max} depending on the performance measured. Some traits that are very important for fitness (like growth or reproduction) can fit within the permissive range and thus may have a much lower optimum compared to others that affect a species survival like standard metabolic rates and are found within the stressful range where homeostasis is disrupted (Ørsted *et al.* 2022).

Evidence of CC and MHW and their impacts in the Levantine basin

Recent SST analysis of MHW trends in the eastern Mediterranean shows that the mean MHW frequency and duration increased in the region by 40% and 15%, respectively (Ibrahim *et al.* 2021) (and Mohamed *et al.* in this volume). During the last decade (2010-2020), the shortest event occurred in the southern Aegean Sea and lasted 10 days, and the longest one occurred on the Israeli coast and exceeded 27 days. Further, the maximum significant MHW event was 6.35°C above the 90th SST climatology threshold. It lasted 7 days and occurred in 2020 and was related to increased air temperature, reduced wind and increase in air pressure south of the island of Rhodes (Ibrahim *et al.* 2021). Another study showed a clear correlation between MHWs and atmospheric heatwaves in this region over the same study period (Aboelkhair *et al.* 2023), suggesting that most MHWs in the region are driven by air-sea heat flux processes and not by advection.

When absolute temperatures are considered, for example for developing species habitat suitability models for current and future distributions (Lavender *et al.* 2021), information based only on satellite-driven SST for shallow coastal regions could be missing important variability and thermal extremes (Meneghesso *et al.* 2020). This bias can be critical for the prediction of the resilience of thermally sensitive shallow water species under climate change. In the Levantine basin, for the Israeli coast at least, analysis of monthly averages has shown that indeed satellite data are consistently under estimating (by about 2°C) both average and maximum surface temperatures measured *in-situ* by nearshore buoys (Rilov 2016). The difference can be even larger when examining the data on a daily resolution (up to +4°C and -6°C at the extremes) as exemplified when comparing temperatures that were measured in the very nearshore over the past 14 years by loggers set at 0.5 m depth on subtidal rocks in Haifa to satellite driven values for the pixel on that shoreline (Fig. 4).

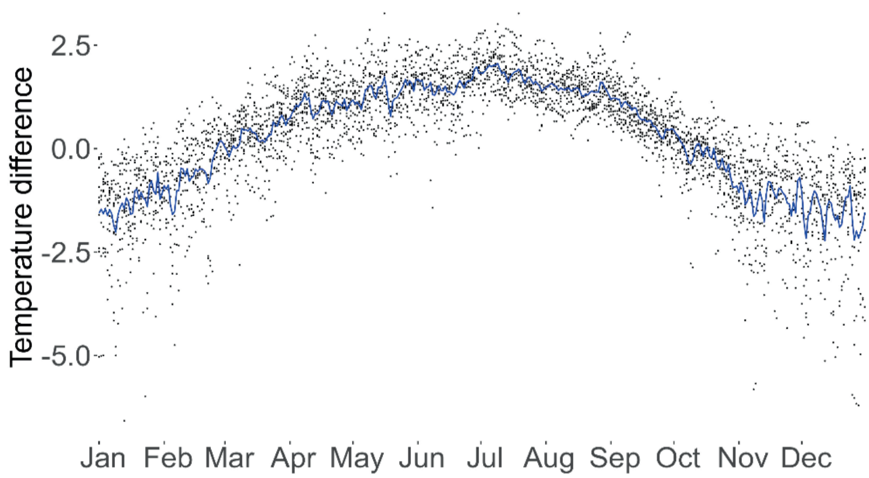

Figure 4. The difference between in-situ measured temperatures at 0.5m on the shoreline near Haifa, Israel, and satellite driven SST values for the same pixel on the shore along the year. Data are for the years 2009-2023. Blue line indicates running mean.

This dynamic "ocean weather" (different from ocean climate) that shows very high thermal variability at many different spatial and temporal scales is often ignored by biologists (Bates *et al.* 2018), but acknowledging it can be critical for our understanding of the dynamics of life in the ocean, and for projections of trends in the future. For example, these two degrees (or more) difference between modeled data from the satellite and that measured in-situ on the Israeli coast, can mean life or death for a species living at the warm edge of its distribution; and this bias can be critical for the usefulness of model projections as well. More specifically, peak satellite driven SST values for the Israeli coast in mid-summer (August) were normally between 29.5-30.2^{o}C (unpublished data), a temperature still below the thermal maximum of the sea urchin *Paracentrotus lividus* in this region which was determinated experimentally as 30.5^{o}C (Yeruham *et al.* 2015). This means that this urchin should still thrive in the region. However, *in-situ* loggers deployed on offshore buoys (Rilov 2016) and on the rocky shore at 0.5 m depth (Rilov *et al.* 2022), show that the actual nearshore temperature normally exceeds 31^{o}C in the peak of summer, which is beyond the species thermal maximum of 30.5^{o}C , meaning that it cannot actually survive the Israeli summer today (Yeruham *et al.* 2015). In the 1970s, when the urchin's populations were still large, summer temperatures in the region peaked around 29^{o}C (Dothan 1977).

A further critical issue to consider is the fact that a species resilience to thermal stress will erode with increasing exposure to this stress. The longer the exposure to stressful temperatures lasts, the more the thermal optimum temperature reduces, and the maximum performance, even at this temperature, may reduce as well. This is clearly exemplified (Fig. 5) in experiments testing the thermal performance curve (TPC) of two coastal native Mediterranean species living on the Israeli coast (Amsalem and Rilov 2021, Rilov *et al.* 2022).

SST analysis for the coastal waters near one of our monitoring sites in Haifa, Israel, shows indeed an increase in MHW frequency and duration. Besides 2010 which had many short events, the main increase in the frequency and durations of continuous days above the regional climatology started in 2015 with four years reaching above 100 days of "MHWs" (in 2020 lasting almost 200 days, although this event lasted well into 2021, Fig. 2). Figure 5 shows summer (July-October) "MHWs" of the last four years. It is interesting that in 2020 warming above the 90th percentile threshold occurred later in the season, in 2021, in the middle, in 2022, early in the season, and in 2023 – throughout the entire summer. All these "events" were moderate (yellow color) except for a small peak into the "strong" category (orange) in August 2023. If we consider the fact that these prolonged "events" are superimposed on the long-term warming trend (Fig. 3), we could argue that these are in fact not discrete events but just an expression of that warming trend.

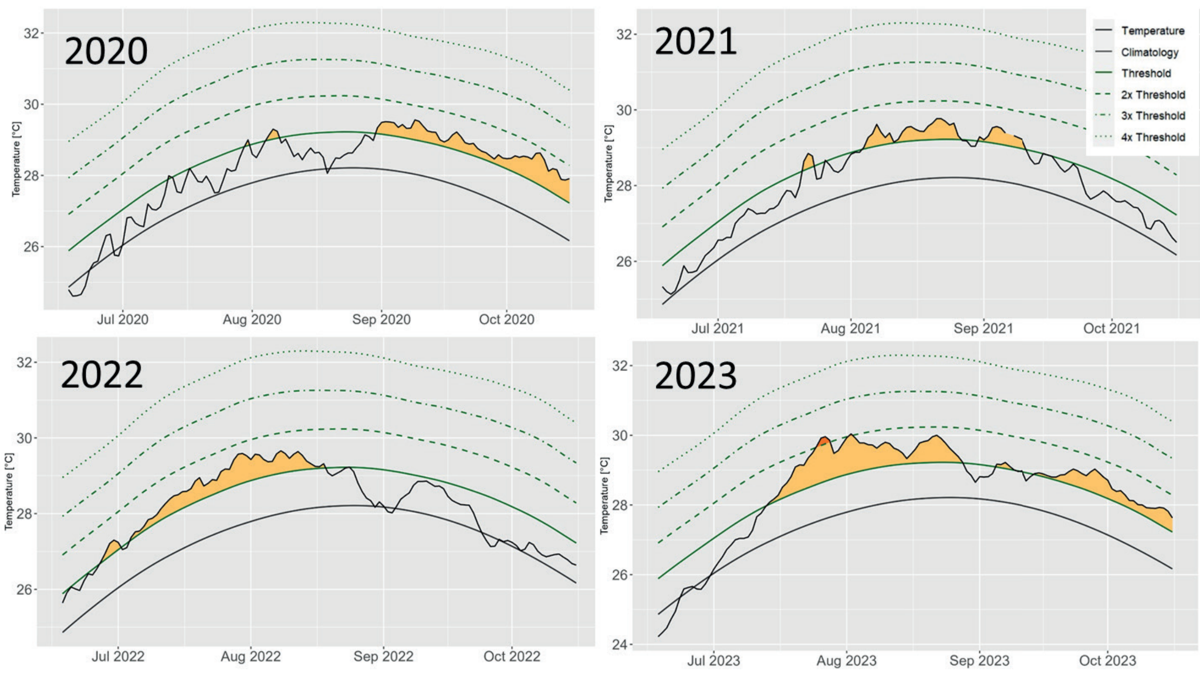

Figure 5. Marine heatwave "events" in the coastal waters near Haifa, Israel, detected from satellite SST data during the summers of 2020-2023 by using the Hobday definition and the Marine Heatwave R program.

Timing of MHWs is important

The impact of a specific MHWs can depend a lot on its timing within the seasonal cycle and the degree of the phenology /seasonality (some species have stronger seasonal fluctuations in their growth and reproduction, for example, than others) of a particular species (Smale 2015). If the MHWs occurs when ambient temperatures are well below the thermal optimum, a heatwave may not have a dramatic impact on the species performance or survival; it may in fact enhance performance rather than reduce it. Within an ecological community in a specific area, there will normally be a spectrum of more cold-affinity and more warm affinity species, and species with more or less thermal phenotypic plasticity, or stronger and weaker seasonality. This implies that when experimentally testing the impact of a simulated MHW, the time of the year and the ambient temperature over which a rapid warming is imposed, and the identity (and traits) of the tested species are highly important and will determine the results and the relevance of the results for models and predictions. For example, we tested the impact of a short MHW on two species coexisting on shallow reefs of the Israeli coast: a cold-affinity native forest-forming brown alga, *Sargassum vulgare,* with a thermal optimum of 21.4°C (unpublished data), and a tropical alien bushy red alga, *Galaxaura rugosa*, with a thermal optimum of 31.7°C (unpublished data). We applied a week-long mild (+2°C) or strong (+5°C) heatwave in early April (spring) when the ambient temperature was 20°C.

Photosynthesis and growth rates were used to assess performance. We expected to find a reduction in performance in the native species and an increase in the alien species. Rather surprisingly, the results showed that photosynthetic rates were almost identical across all treatments in both species, although there is a slight (non-significant) indication of stress under the strong heatwave for *Sargassum* (Fig. 6A). Similar results were seen in growth rates (not shown). It is likely that, although abrupt, an increase in temperature of 5ºC magnitude or less does not produce a significant reduction in macroalgal performance when occurring during the early spring season (when temperatures are rather far from the cold or warm annual extremes). Even the native *Sargassum* was still far enough from its thermal danger zone (between 27-30ºC) under the strong heatwave temperature (25ºC), or that exposure to the extreme temperature was not long enough to impose stress that would lead to measurable reduced performance. We can assume that conducting the experiment later in the season when the ambient conditions are closer to the detrimental temperature for the native species, even a short heatwave could cause significant stress on the species. This will need to be tested in future studies. Why performance did increase in the tropical alien species *G. rugosa* under elevated temperatures was also surprising (Fig. 6B), and requires further investigation.

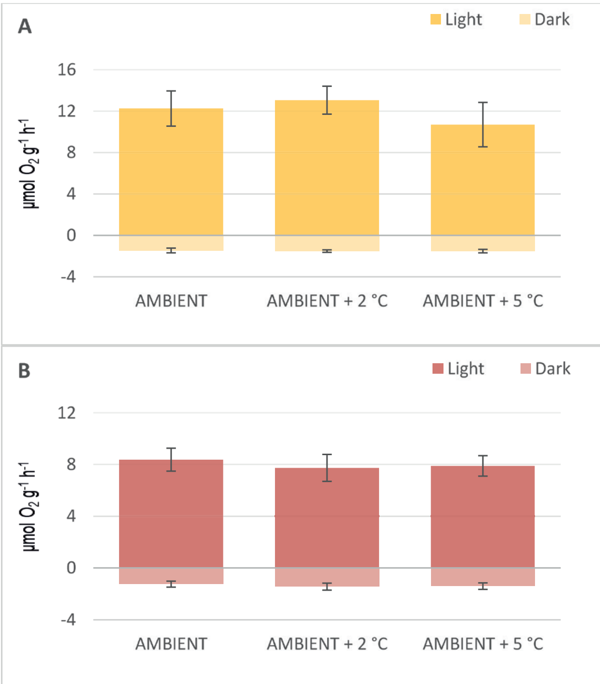

Figure 6. Photosynthesis (light) and respiration (dark) expressed in µmol O_2 g^{-1} WW h^{-1} for the seaweeds (A) *Sargassum vulgare* and (B) *Galaxaura rugosa*, under ambient, mild (AMBIENT + 2°C) and strong (AMBIENT + 5°C) heatwave treatments after one-week exposure to the target temperatures.

East vs. west

The impacts of ocean warming on the marine biota appear to differ in the western and eastern basins and more specifically between its northwest and southeast (Levant) corners.

While both basins are exposed to MHWs, the most severe seem to occur in the northwest and so do current mass mortalities while longer lasting but milder ones occur in the east. This may be related to the fact that in the northwest, interannual variability in SST is much greater than in the southeast where there is more gradual but faster warming with less interannual variability and extreme, discrete, events (see Liguori; Simon; both in this volume). Stronger variability with intense and rapid warming can lead to major mass mortalities but with possible recovery, at least for some species, while gradual but persistent warming can lead to range contraction at the warm distributional edges of many thermally sensitive species. Indeed, the most pronounced, documented, recent mass mortalities in general are those of sessile invertebrates like corals, bryozoans and sponges; but such mortalities were mostly reported in the west and much less in the southeast (Garrabou *et al.* 2022). Nonetheless, the severity (percent mortality) of the mass mortality events in the east was higher. On the other hand, total, regional collapse of species is mostly reported in the east (we are not aware of such reports in the northwest) and seems to have occurred before systematic observation started with some noted exceptions like the predatory snail *Stramonita haemastoma* (Rilov *et al.* 2001, Rilov 2016, Albano *et al.* 2021).

Unlike the rapidly increasing and well documented cases of recent (2015-2019) mass mortalities (mostly in the western Mediterranean), since systematic ecological monitoring started on the rocky Israeli coast, about a decade and a half ago, there is evidence of only one clear mass mortality event - of the dominant alien mussel *Brachidontes pharaonis* in the summer 2016 (Rilov *et al.* 2020 ; Garrabou *et al.* 2022). This species has been since slowly recovering (Rilov unpublished data). It is possible that MHWs were responsible for more distant past mass mortalities in the early stages of ocean warming in the second half of the 20th century, which caused the collapse of native species before systematic ecological monitoring started in the Levant. However, if MHW occurrence was lower in the past, this scenario becomes less likely. It is therefore quite possible that the observed gradual, but also faster, warming (Pisano *et al.* 2020) may be the main driver of native collapse in the Levantine region, and not MHWs.

Conclusions

In conclusion, we have shown here that MHWs can have different characteristics depending on the region, and the possibility that at least in the southeast Mediterranean Sea the repeated long (over a month) summer MHWs may be in fact a statistical expression of rapid summer warming in the region in the past three decades and not discrete MHW events. This appears to contradict the documentation of long MHWs in the Levant (see Fig. 6 and other chapters in this volume). This, we believe, is part of the "baseline problem" raised and discussed by Schlegel (in this volume). Together with Schlegel and Liguori (in this volume) we call for a more refined, updated, definition of MHWs that will be based on better statistics or a processed base approach. We also stress the need and importance to use *in-situ* temperature data to evaluate exposure of coastal organisms to heat stress because satellite-driven SST can underestimate cold and warm temperature extremes which can be critical for the local species. Further, we emphasize that when we experimentally examine a species thermal vulnerability, this trait can vary across a species distributional range due to local adaptation, and it can also vary as a function of exposure to the target temperatures and even the tested season.
Finally, the timing (e.g. season) of testing the impact of MHWs on an organism can influence a lot the results.

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References

Albano P. G., Steger J., Bošnjak M., Dunne B., Guifarro Z., Turapova E., Hua Q., Kaufman D. S., Rilov G. and M. Zuschin. 2021. Native biodiversity collapse in the eastern Mediterranean. *Proc.Royal Soc.* London B, 288: 20202469.

Amsalem E. and G. Rilov. 2021. High thermal plasticity, and vulnerability, in extreme environments at the warm distributional edge: The case of a tidepool shrimp. *Journal of Experimental Mar. Biol. Ecol*., 545:151641.

Bates A. E., Helmuth B., Burrows M. T., Duncan M. I., Garrabou J., Guy-Haim T., Lima F., Queiros A. M., Seabra R., Marsh R., Belmaker J., Bensoussan N., Dong Y., Mazaris A., Smale D. A., Wahl M. and G. Rilov. 2018. Biologists ignore ocean weather at their peril. *Nature,* 590: 299-301.

Bates A. E., Pecl G. T., Frusher F., Hobday A. J., Wernberg T., Smale D. A., Sunday J. M., Hill N. A., Dulvy N. K. and K. Colwell. 2014. Defining and observing stages of climate-mediated range shifts in marine systems. *Global Environmental Change,* 26:27-38.

Brown J. H., Gillooly J. F.,. Allen A. P., Savage V. M. and G. B. West. 2004. Toward a metabolic theory of ecology. *Ecology,* 85:1771-1789.

Darmaraki S., Somot S., Sevault F. and P. Nabat. 2019a. Past variability of Mediterranean Sea marine heatwaves. *Geophysical Research Letters,* 46: 9813-9823.

Darmaraki S., Somot S., Sevault F., Nabat P., Narvaez W. D. C., Cavicchia L., Djurdjevic V., Sannino L. Li, G and D. V. Sein. 2019b. Future evolution of marine heatwaves in the Mediterranean Sea. *Climate Dynamics,* 53: 1371-1392.

Dothan A. 1977. Communities of sessile animals in the region of Shahaf and Nachliely Islands. Tel Aviv University, Tel Aviv.

Doxa A., Kamarianakis Y. and A. D. Mazaris. 2022. Spatial heterogeneity and temporal stability characterize future climatic refugia in Mediterranean Europe. *Global Change Biology,* 28: 2413-2424.

Gaitán-Espitia J. D., Bacigalupe L. D., Opitz T., Lagos N. A., Osores S. and M. A. Lardies. 2017. Exploring physiological plasticity and local thermal adaptation in an intertidal crab along a latitudinal cline. *Journal of Thermal Biology* 68:14-20.

Garrabou J., Coma R., Bensoussan N., Bally M., Chevaldonne P., Cigliano M., Diaz D., Harmelin J. G., Gambi M. C., Kersting D. K., Ledoux J. B., Lejeusne C., Linares C., Marschal C., Perez T., Ribes M., Romano J. C., Serrano E., Teixido N., Torrents O., Zabala M., Zuberer F. and C. Cerrano. 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biology,* 15: 1090-1103.

Garrabou J., Gómez–Gras D., Medrano A., Cerrano C., Ponti M., Schlegel R., Bensoussan N., Turicchia E., Sini M., Gerovasileiou V., Teixido N., Mirasole A., Tamburello L., Cebrian E., Rilov G. and *et al.*, 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Global Change Biology.*

Garrabou J., Perez T., Sartoretto S. and J. Harmelin. 2001. Mass mortality event in red coral Corallium rubrum populations in the Provence region (France, NW Mediterranean). *Marine Ecology Progress Series,* 217: 263-272.

Helmuth B., Broitman B.R., Blanchette C.A., Gilman S., Halpin P., Harley C.D. G., O'Donnell M.J., Hofmann G.E., Menge B. and D. Strickland. 2006. Mosaic patterns of thermal stress in the rocky intertidal zone: Implications for climate change. *Ecological Monographs,* 76: 461-479.

Helmuth, B., Harley C. D. G., P. M. Halpin, M. O'Donnell, G. E. Hofmann. and C. A. Blanchette. 2002. Climate change and latitudinal patterns of intertidal thermal stress. *Science,* 298: 1015-1017.

Hobday A. J., Alexander L. V., Perkins S. E., Smale D. A., Straub S. C., Oliver E. C., Benthuysen J. A., Burrows M. T., Donat M. G. and M. Feng. 2016. A hierarchical approach to defining marine heatwaves. *Progress in Oceanography,* 141: 227-238.

Hobday A. J., Oliver E. C., Gupta A. S., Benthuysen J. A., Burrows M. T., Donat M. G., Holbrook N. J., Moore P. J., Thomsen M. S and T. Wernberg. 2018. Categorizing and naming marine heatwaves. *Oceanography,* 31: 162-173.

Holbrook N. J., Scannell H. A., Sen Gupta A., Benthuysen J. A., Feng M., Oliver E. C. J., Alexander L. V., Burrows M. T., Donat M. G., Hobday A. J., Moore P. J., Perkins-Kirkpatrick S. E., Smale D. A., Straub S. C. and T. Wernberg. 2019. A global assessment of marine heatwaves and their drivers. *Nature communications,* 10: 2624.

Ibrahim O., Mohamed B. and H. Nagy. 2021. Spatial variability and trends of marine heat waves in the eastern mediterranean sea over 39 years. *Journal of Marine Science and Engineering,* 9: 643.

IPCC. 2019. Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate.

King N. G., McKeown N. J., Smale D. A and P. J. Moore. 2018. The importance of phenotypic plasticity and local adaptation in driving intraspecific variability in thermal niches of marine macrophytes. *Ecography,* 41: 1469-1484.

Lavender E., Fox C. J., and M. T. Burrows. 2021. Modelling the impacts of climate change on thermal habitat suitability for shallow-water marine fish at a global scale. *PLoS One* 16:e0258184.

Meneghesso C., Seabra R., Broitman B. R., Wethey D. S., Burrows M. T., Chan B. K., Guy-Haim T., Ribeiro P. A., Rilov G., Santos A. M., Sousa L. L. and F. Lima. 2020. Remotely-sensed L4 SST underestimates the thermal fingerprint of coastal upwelling. *Remote Sensing of Environment,* 237: 111588.

Mulas M., Silverman J., Guy-Haim T., Noé S. and G. Rilov. 2022. High climate vulnerably of the Levantine endemic and endangered habitat-forming macroalga, Gongolaria rayssiae: implications for reef carbon budget. *Frontiers in Marine Science,* 9: 1447.

Oliver E.C., Benthuysen J.A., Darmaraki S., Donat M.G., Hobday A.J., Holbrook N.J., Schlegel R.W. and A. Sen Gupta. 2021. Marine heatwaves. *Annual Review of Marine Science,* 13: 313-342.

Oliver E.C., Donat M.G., Burrows M.T., Moore P.J., Smale D. A., Alexander L.V., Benthuysen J. A., Feng M., Gupta A.S. and A.J. Hobday. 2018. Longer and more frequent marine heatwaves over the past century. *Nature communications,* 9: 1324.

Oliver E.C., Burrows M.T., Donat M.G., Sen Gupta A., Alexander L.V., Perkins-Kirkpatrick S.E., Benthuysen J.A., Hobday A.J., Holbrook N.J. and P.J. Moore. 2019. Projected marine heatwaves in the 21st century and the potential for ecological impact. *Frontiers in Marine Science,* 6: 734.

Ørsted M., Jørgensen L. B. and J. Overgaard. 2022. Finding the right thermal limit: a framework to reconcile ecological, physiological and methodological aspects of CTmax in ectotherms. *Journal of Experimental Biology,* 225: jeb244514.

Pages J. F., Smith T. M., Tomas F., Sanmarti N., Boada J., De Bari H., Perez M., Romero J., Arthur R. and T. Alcoverro. 2018. Contrasting effects of ocean warming on different components of plant-herbivore interactions. *Marine Pollution Bulletin,* 134: 55-65.

Pisano A., Marullo S., Artale V., Falcini F., Yang C., Leonelli F.E., Santoleri R. and B. Buongiorno Nardelli. 2020. New Evidence of Mediterranean Climate Change and Variability from Sea Surface Temperature Observations. *Remote Sensing,* 12: 132.

Portner H.O. and A.P. Farrell. 2008. Ecology Physiology and Climate Change. *Science*, 322: 690-692.

Rilov G., Benayahu Y. and A. Gasith. 2001. Low abundance and skewed population structure of the whelk *Stramonita haemastoma* along the Israeli Mediterranean coast. *Marine Ecology Progress Series,* 218: 189-202.

Rilov G. 2016. Multi-species collapses at the warm edge of a warming sea. *Scientific reports,* 6, 36897.

Rilov G., Peleg O., Guy-Haim T and E. Yeruham. 2020. Community dynamics and ecological shifts on Mediterranean vermetid reefs. *Marine Environmental Research,* 160.

Rilov G., Klein L., Iluz D., Dubinsky Z and T. Guy-Haim. 2022. Last snail standing? superior thermal resilience of an alien tropical intertidal gastropod over natives in an ocean-warming hotspot. *Biological Invasions*: 1-17.

Simon A., Pires C., Frölicher T. L. and A. Russo. 2023. Long-term warming and interannual variability contributions' to marine heatwaves in the Mediterranean. *Weather and Climate Extremes,* 42: 100619.

Smale D.A., Yunnie A.L., Vance T. and S. Widdicombe. 2015. Disentangling the impacts of heat wave magnitude, duration and timing on the structure and diversity of sessile marine assemblages. Peer J 3:e863.

Smale D.A., Wernberg T., Oliver E.C., Thomsen M., Harvey B.P., Straub S.C., Burrows M.T., Alexander L.V., Benthuysen J.A. and M.G. Donat. 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change,* 9: 306-312.

Smith K.E., Burrows M.T., Hobday A.J., King N.G., Moore P.J., Sen Gupta A., Thomsen M.S., Wernberg T. and D.A. Smale. 2023. Biological impacts of marine heatwaves. *Annual Review of Marine Science,* 15: 119-145.

Wernberg T., Smale D. A., Tuya F., Thomsen M.S., Langlois T.J., De Bettignies T., Bennett S. and C.S. Rousseaux. 2013. An extreme climatic event alters marine ecosystem structure in a global biodiversity hotspot. *Nature Clim. Change,* 3: 78-82.

Xu T., Newman M., Capotondi A., Stevenson S., Di Lorenzo E. and M.A. Alexander. 2022. An increase in marine heatwaves without significant changes in surface ocean temperature variability. *Nature communications,* 13: 7396.

Yeruham E., Rilov G., Shpigel M. and A. Abelson. 2015. Collapse of the echinoid *Paracentrotus lividus* populations in the Eastern Mediterranean - result of climate change? *Scientific reports,* 5: 13479.

Yeruham E., Shpigel M., Abelson A. and G. Rilov. 2020. Ocean warming and tropical invaders erode the performance of a key herbivore. *Ecology,* 101: e02925.

Marine Heatwaves and benthic communities: Changes features of the assemblages and alarming consequences on biodiversity in Tunisian waters.

Raouia Ghanem[1,2], Jamila Ben Souissi[1,2], Jean-Baptiste Ledoux[3,4], Cristina Linares[5], Joaquim Garrabou[4]

[1]*Laboratoire Biodiversité, Biotechnologies et Changements climatiques, Faculté des Sciences, Tunis El Manar*
[2]*Institut National Agronomique de Tunisie, 43, Avenue Charles Nicolle, 1082 Tunis, Tunisie.*
[3]*CIIMAR/CIMAR, Centro Interdisciplinar de Investigação Marinha e Ambiental, Univ do Porto, Portugal.*
[4] *Institut de Ciències del Mar CSIC, Passeig Maritim de la Barceloneta, Barcelona, Spain.*
[5]*Dept de Biologia Evolutiva, Inst de Recerca de la Biodiversitat, Univ de Barcelona, Avda. Diagonal 643, Spain.*

Abstract

The Mediterranean Sea stands out as a hostspot for climate change, exhibiting higher warming rates and more frequent marine heatwaves (MHWs) compared to the global ocean. MHWs are increasingly recognized as significant events impacting marine ecosystems worldwide. This paper discusses their impact on benthic communities and the alarming consequences for biodiversity in Tunisian waters. Between 2015 and 2021, over 100 instances of mass mortality events were documented in Tunisian waters through scuba diving and surveys based on Local Ecological Knowledge at depths ranging from 0 to 80 m. Each event corresponds to a specific species, location, and time period.. These occurrences involved 25 species distributed across six significant taxonomic groups, ranked in order of importance as follows: Cnidaria, Porifera, Bivalvia, Bryozoa, Echinodermata, and Rhodophyta. The findings highlight the vulnerability of benthic communities to MHWs and the urgent need for comprehensive conservation and management strategies in order to enhance resilience in the face of ongoing climate change. Addressing the impacts of MHW on benthic communities is crucial for preserving the biodiversity and ecological integrity of Tunisian marine ecosystems in the context of global climate change.

Keywords: *Climate change, Mass mortality events, Cnidaria, MHW, Central Mediterranean.*

Introduction

The Mediterranean Sea is undergoing a rapid warming compared to any other marine region globally, resulting in increasingly severe consequences for marine ecosystems (Albano *et al.* 2021 ; Garrabou *et al*. 2021) and the crucial services they offer to our societies.
Analysis of satellite data for Mediterranean sea surface temperatures (SST) over the past four decades reveals a notable upward trend. This trend is characterized by temperatures persisting at higher levels for more extended periods throughout the annual cycle, accompanied by an increase in the frequency and intensity of extreme SST events (Pastor *et al*. 2020 ; Pisano *et al*. 2020). This SST warming has led to the increasing occurrence of marine heatwaves (MHWs) in the last decades in the Mediterranean (Ciappa 2022).
Across the entire Mediterranean Basin, the period from 2015 to 2019 stands out as the warmest since the beginning of satellite records in 1982, witnessing a dramatic rise in the frequency and intensity of MWHs (see details in Schlegel 2024, this volume). The impacts of MHWs can vary

in nature, depending on trends in their duration, frequency, intensity, and cumulative intensity (Pastor and Khodayar 2023). This is particularly significant when given their effects on marine biota where MHW days are considered the primary drivers of heat stress exposure (Smale *et al*. 2019).
In this study a preliminary overview of the MMEs that occurred in Tunisia from 2015 to 2021 is provided.

MMEs in the Mediterranean Sea

In the Mediterranean Sea, there is a recurring occurrence of MHWs that frequently lead to severe mass mortality events (MMEs) impacting a wide range of benthic macro-invertebrates from various phyla (see Garrabou; Rilov, 2024 in this volume).

The first documented evidence of an MME in this region dates back to the 1980s in the Western Basin and the Aegean Sea (Harmelin 1984 ; Cerrano *et al*. 2000). One of the most notable occurrences took place in 1999 when an exceptionally large-scale MME affected more than thirty species from different phyla along the French and Italian coastlines. Subsequently, several other large-scale MMEs have been reported, along with numerous smaller ones, which tend to be more localized in terms of geographic extent and the number of affected species (Garrabou *et al.* 2009 ; Marbà *et al.* 2015 ; Rubio-Portillo *et al.* 2016). These events are generally linked to the presence of strong and recurrent marine heatwaves (Crisci *et al.* 2011 ; Turicchia *et al.* 2018; Bensoussan *et al.* 2019) a trend that is increasingly observed on a global scale (Smale *et al.* 2019).

A database of 196 papers, documenting these events between 1979 and 2017, highlights the severe impacts that MHWs can have on benthic invertebrates (Garrabou *et al*. 2019): more than 676 MMEs involving over 93 species from 9 major taxonomic groups were recorded during this period throughout the Mediterranean Sea, predominantly linked to periods of unusually warm temperatures (Garrabou *et al.* 2019). Mass mortality events were predominantly observed in the Western Mediterranean ecoregion, with subsequent occurrences in the Adriatic Sea, the Aegean Sea, and the Ionian Sea. The available information primarily pertains to the coastal regions of European countries, while there is a glaring absence of reports from the southern and eastern Mediterranean coastlines.
Benthic surveys conducted by 33 research teams from 11 Mediterranean countries showed evidence of 567 MMEs during the 2015–2019 period, a significant increase compared to the preceding years (Garrabou *et al*. 2022). This data set, which represents the most comprehensive inventory of MME records for benthic species, encompassed 50 taxa from 8 phyla. These events were correlated to the heat exposure linked to marine heatwaves observed at sea surface and throughout various depths.

MMEs in Tunisian waters

Overall, more than 100 MMEs (one event corresponds to one species, one location and one period) were observed between the years 2015 to 2021 in Tunisian waters at depths ranging from 0- 80m by scuba diving and Local Ecological Knowledge surveys. These events encompassed 25 species from six major taxonomic groups. In order of importance: Cnidaria, Porifera, Bivalvia, Bryozoa, Echinodermata, Rhodophyta (see Fig. 1).

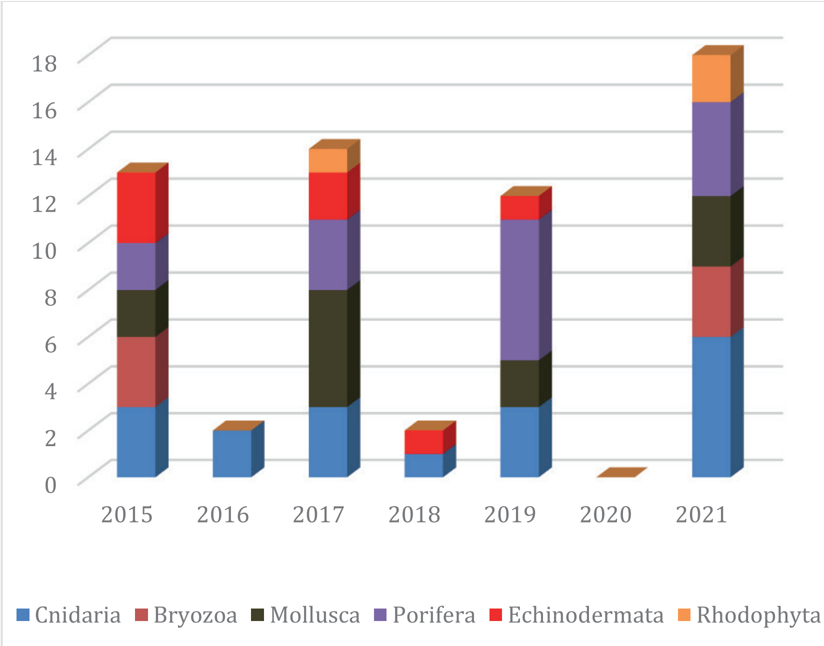

Figure 1. Number of affected taxa per phylum

The reported MMEs mainly concerned cnidarians. In fact, numerous cases of bleaching of the scleractinian coral *Astroides calycularis*, resulting in the total or partial death of colonies, were observed, especially in the Cape Bon Peninsula and in the Marine Protected area of Zembra, where this species is abundant (Ghanem *et al*. 2019a, b). Other scleractinian species *Cladocora caespitosa, Caryophyllia inornata, Balanophyllia europaea, Leptosammia pruvoti* and the presumably introduced *Oculina patagonica* also suffered bleaching (Fig. 2).

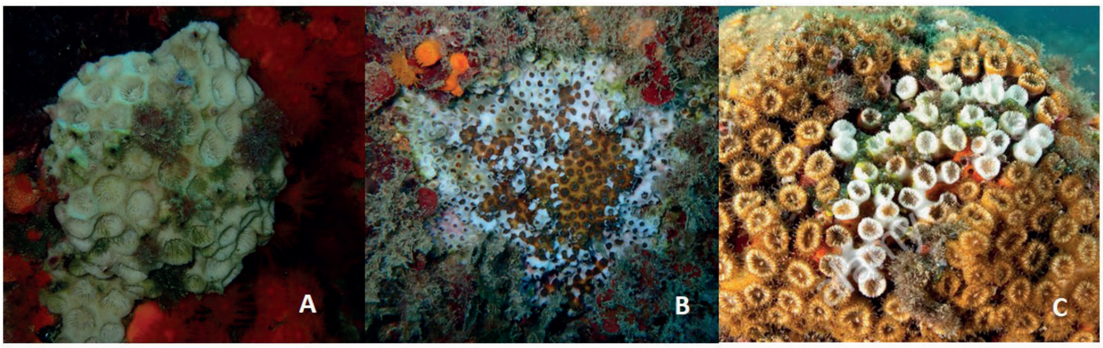

Figure 2. Corals bleaching; A: *Astroides calycularis*; B: *Oculina patagonica*; C: *Cladocora caespitosa*

With regard to gorgonians, many species suffered spectacular and extensive damage. The white gorgonian *Eunicella singularis* which is very abundant on the northern and eastern Tunisian coasts, showed a high level of injury (between 10% and 99%) (Ghanem *et al*. 2021). Other gorgonian species, such as *Eunicella cavolini* showed extensive damage with mortality rates reaching 50% at some sites (unpublished data).

Local Ecological Knowledge survey conducted with divers showed that *Pramuricea clavata* and the red coral *Corallium rubrum* have suffered injuries and mortalities during the five last years (Fig. 3).

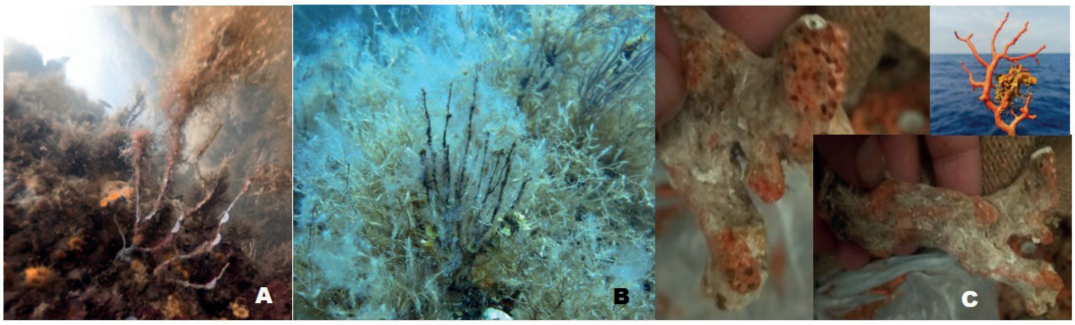

Figure 3. Mortality of gorgonians in Tunisian waters
A: *Eunicella cavolini*; B: *Eunicella singularis*; C: *Corallium rubrum*

Among sponges, the keratose species were the most damaged. Scuba diving surveys carried out in the southern part of Tunisia showed that the commercial sponges *Spongia officinalis* (Fig. 4) and *Hippospongia communis* were dramatically affected (Garrabou *et al*. 2022). In addition, *Cacospongia mollior* and *Ircinia* spp showed a high percentage of damaged colonies up to 70%.

Regarding Bryozoans, three species were affected by MMEs in Tunisia, namely *Schizobrachiella sanguinea*, *Reteporella* spp. and *Myriapora truncata* (Fig. 4) observed particularly in coralligenous habitats of northern Tunisia.
Among Echinoderms abnormal death rates were recently reporded for the sea urchins *Paracentrotus lividus, Arbacia lixula* and the sea cucumber *Holothuria poli.*

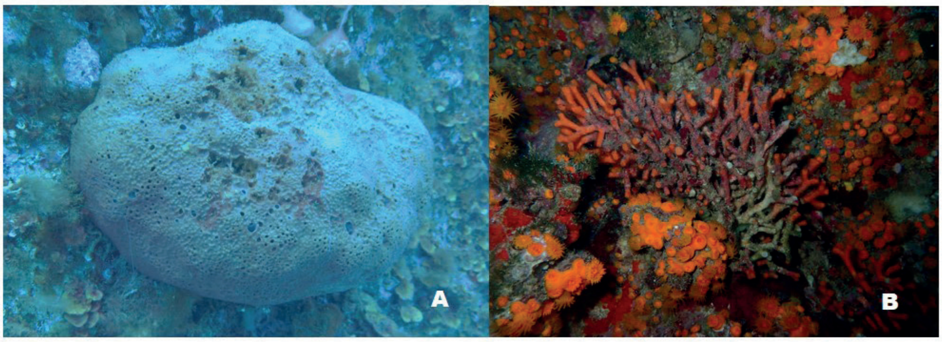

Figure 4. Injuries of Spongia officinalis (A) and Myriapora truncata (B)

High temperatures and the presence of bacterial or fungal infections can coexist. When the host is under stressful conditions, such as elevated seawater temperatures or other environmental stressors, this will often render the microbe more virulent or make the host more susceptible, increasing the mortality rate (Cerrano *et al*. 2000). This is the case of the endangered bivalve *Pinna nobilis* which experienced severe mass mortality events that drastically impacted its populations in the Mediterranean Sea.
Tunisian populations were not spared: surveys conducted in Kerkennah Island (eastern Tunisia) and Bizerte lagoon (northern Tunisia) showed that populations were drastically damaged with a mortality rate of 100% in many Tunisian sites (Unpublished data). A recent study carried out

by Labidi *et al*. (2023) did reveal the presence of *Haplosporidium pinnae* and *Mycobacterium* sp. in living specimens sampled in Bizerte Lagoon.
MMEs also concerned Non-Indigenous bivalves. This is the case of *Fulvia fragilis*, with severe mortalities observed in the north of the country, particularly in the Bizerte lagoon and Tunis lagoon. Similarly, the pearl-oyster *Pinctada radiata* showed dramatic mortality rates in the gulf of Gabès.

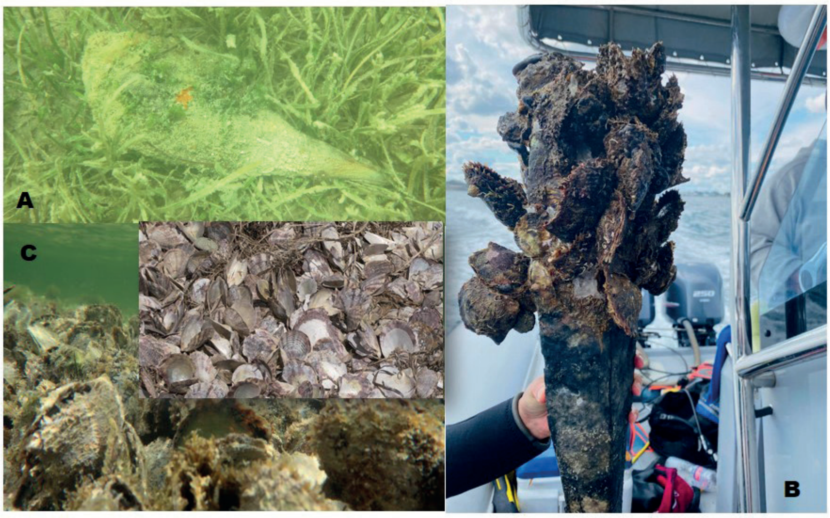

Figure 5. Mortalities of *Pinna nobilis* (A: Kerkennah island; B: Bizerte lagoon) and *Pinctada radiata* (C: Bibane lagoon).

Conclusion

We are facing a very complex scenario where many factors are involved and where stress levels experienced by populations in the past could play a crucial role in determining the effects on mortality. The increased frequency, severity, and geographical scope of Marine Heatwaves are causing significant ecological transformations in marine ecosystems globally (Smith *et al*. 2021). In the Mediterranean Sea, climate change impacts are accelerating, but our understanding of their implications for socioecological systems remains limited. Indeed, our ability to predict how MHWs will impact marine species and habitats is hampered by significant knowledge gaps.

The prospects for the recovery of affected populations are uncertain because many of these species exhibit slow dynamics, including slow rates of growth, recruitment, and mortality. Thus it could take several decades for gorgonian populations to achieve full recovery, and even then, such recovery may not occur if new outbreaks occur in the same area.

Unfortunately, this grim scenario is not far-fetched. Therefore, we strongly believe that standardized monitoring programs should be enhanced to understand the interactions among various stressors, the role of ecological memory, the significance of species' functional traits and to evaluate the recovery ability and better identify the causes of such events. In this way, we might be able to anticipate the future occurrence of new outbreaks and propose adequate management strategies.

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References

Albano P.G., Steger J., Bošnjak M., Dunne B., Guifarro Z., Turapova E. *et al.,* 2021. Native biodiversity collapse in the Eastern Mediterranean. *Proc. R. Soc B*, 288(1942)20202469. doi: 10.1098/rspb.2020.2469

Bensoussan N., Chiggiato J., Buongiorno Nardelli B., Pisano A. and J. Garrabou. 2019. Insights on 2017 Marine Heat Waves in the Mediterranean Sea. Copernicus Marine Service Ocean State Report #3 *Journal of Operational Oceanography.*

Cerrano C., Bavestrello G., Bianchi C. N., Cattaneo-Vietti R., Bava, S. *et al.,* 2000. Catastrophic mass-mortality episode of gorgonians and other organisms in the Ligurian Sea (North-western Mediterranean), Summer 1999. *Ecol. Lett*. 3: 284–293. doi: 10.1046/j.1461-0248.2000.00152.x

Ciappa A. C. 2022. Effects of Marine Heatwaves (MHW) and Cold Spells (MCS) on the surface warming of the Mediterranean Sea from 1989 to 2018. *Progress in Oceanography*, 205, 102828.

Crisci C., Bensoussan N., Romano J.C. and J. Garrabou 2011. Temperature anomalies and mortality events in marine communities: insights on factors behind differential mortality impacts in the NW Mediterranean. *PLoS ONE* 6:e23814. doi: 10.1371/journal.pone.0023814

Garrabou J., Coma R., Bensoussan N., Bally M., Chevaldonné P.et al., 2009. Mass mortality in Northwestern Mediterranean rocky benthic communities: effects of the 2003 heat wave. *Global Change Biol*. 15: 1090–1103. doi: 10.1111/j.1365-2486.2008.01823.x

Garrabou J., Gómez-Gras D. Ledoux J.B., Linares C., Bensoussan N. *et al*. 2019. Collaborative database to track mass mortality events in the Mediterranean Sea. *Frontiers in Marine Science*, 6: 478167.

Garrabou J., Gómez Gras D., Medrano A., Cerrano C., Ponti M., Schlegel R., *et al.* 2022. Marine heatwaves drive recurrent mass mortalities in the Mediterranean Sea. *Glob. Chang. Biol*., 28(19), 5708-5725, doi:10.1111/gcb.16301

Garrabou J., Ledoux J.-B., Bensoussan N., Gómez-Gras D. and C. Linares. 2021. Sliding toward the collapse of Mediterranean coastal marine rocky ecosystems. In J. G. Canadell and R. B. Jackson (Eds.), Ecosystem collapse and climate change (pp. 291–324). *Springer International Publishing*. https://doi.org/10.1007/978-3-030-71330-011

Garrabou J., and 22 others. 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Ghanem R., Ben Souissi J., Ledoux J-B., Linares C. and J. Garrabou. 2021. Population structure and conservation status of the white gorgonian *Eunicella singularis* (Esper 1791) in Tunisian waters (Central Mediterranean). *Mediterranean Marine Science*. In press.

Ghanem R., Ben Souissi J., Linares C., Ledoux J.B. and J. Garrabou. 2019a. Occurrence of Corals Bleaching in Tunisian Waters (Central Mediterranean). 42nd CIESM Congress. Cascais, Portugal, 7-11 Octobre 2019.

Ghanem R., Soufi-Kechaou E., Ben Souissi J., Linares C., Ledoux J.B. and J. Garrabou. 2019b. Demography and disturbance levels of the Coral *Astroides calycularis* (Pallas, 1766) In The Tunisian Marine Protected Area of Zembra (Central Mediterranean). Proceedings of the 3rd Mediterranean Symposium on the conservation of Coralligenous & other Calcareous Bio-Concretions. Antalya, Turkey, 15-16 January 2019. Pp. 52-56.

Harmelin J. G. 1984. Biologie du corail rouge. Paramètres de populations, croissance et mortalité naturelle. Etat des connaissances en France. FAO Fishery Rep. 306, 99–103.

Labidi S., Vázquez-Luis M. A. I. T. E., Catanese G., Grau A., Khammassi M., Youssef S.B. and M.S. Achouri. 2023. First detection of the invasive protozoan Haplosporidium pinnae in the critically endangered bivalve *Pinna nobilis* in the Southern Mediterranean Sea (Bizerte Lagoon, Tunis) and update of its current status. *Mediterranean Marine Science*, 24(3): 470-481.

Marbà N., Gabriel J., Agusti S., Girard C. and C.M. Duarte. 2015. Footprints of climate change on Mediterranean Sea biota. *Front. Mar. Sci*. 2: 56. doi: 10.3389/fmars.2015.00056

Pastor F. and S. Khodayar. 2023. Marine heat waves: Characterizing a major climate impact in the Mediterranean. *Science of The Total Environment*, 861, 160621.

Pastor F., Valiente J. A. and S. Khodayar. 2020. A warming Mediterranean: 38 years of increasing sea surface temperature. *Remote sensing*, 12(17): 2687.

Pisano A., Marullo S., Artale V., Falcini F., Yang C., Leonelli F. E. and B. Buongiorno Nardelli. 2020. New evidence of Mediterranean climate change and variability from sea surface temperature observations. *Remote Sensing*, 12(1), 132.

Rilov G. and collaborators. 2024. Ocean warming, marine heatwaves and the thermal vulnerability of the increasingly tropicalized Levant coast ecosystems. pp 141 - 154 In Marine Heatwaves in the Mediterranean Sea and Beyond. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Rubio-Portillo E., Izquierdo-Muñoz A., Gago J. F., Rosselló-Mora R., Antón J. and A.A. Ramos-Esplá 2016. Effects of the 2015 heat wave on benthic invertebrates in the Tabarca Marine Protected Area (southeast Spain). *Mar. Env. Res*. 122, 135–142. doi: 10.1016/j.marenvres.2016.10.004

Schlegel R. 2024. Marine heatwave research: a path forward via the Mediterranean and the Arctic. pp 51 - 62 In *Marine Heatwaves in the Mediterranean Sea and Beyond*. CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Smale D. A., Wernberg T., Oliver E. C. J., Thomsen M., Harvey B. P., Straub S. C., *et al.* 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Change 9*: 306–312. doi: 10.1038/s41558-019-0412-1

Smith K.E., Burrows M.T., Hobday A.J., Sen Gupta A., Moore P.J., Thomsen M., Wernberg T. and D.A. Smale. 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, 374: 6566. https://doi.org/10.1126/science.abj3593

Turicchia E., Abbiati M., Sweet M. and M. Ponti. 2018. Mass mortality hits gorgonian forests at Montecristo Island. *Dis. Aquat. Org.* 131: 79–85. doi: 10.3354/dao03284

Mining the published record on the biological impacts of marine heatwaves

Niki Chartosia

University of Cyprus, Department of Biological Sciences, Nicosia

Keywords: *marine heatwaves; bibliometric analysis; text mining; marine biology, metrics*

Introduction

In the last decades climatic extremes have become more frequent, therefore more common. Marine heatwaves (MHWs) – defined by Hobday *et al*. (2016) as local, prolonged periods of anomalously high sea temperatures- are part of these climatic extremes. If, along with increased human pressures, global warming persists at current rates under the highest emission scenarios projected by IPPC (Giorgi and Lionello 2008), it is widely expected to lead inter alia to deep changes in marine biodiversity and marine ecosystems (Guiot and Cramer 2016).
As the subject receives increasing public attention, larger efforts are invested by the scientific community to study the impacts of these events on the marine biota, covering a large spectrum of topics ranging from climatic drivers, models, to environmental and socioeconomic impacts (see for example Holbrook *et al*. 2020 and references therein; Smith *et al.* 2021). The observed increase in MHWs has broad, various consequences for marine ecosystems (e.g. Smale *et al*. 2019) and seems correlated with coral bleaching, decreased kelp biomass and seagrass, etc. (Smale *et al*. 2019 ; Garrabou *et al*. 2024 ; Ghanem *et al.* 2024 in this volume).

The Mediterranean Sea is warming faster than the global ocean and the majority of forecasts project a higher frequency and duration of MHWs for the near future (Giorgi and Lionello 2008). In the Mediterranean Sea which is considered a biodiversity hotspot, the annual mean SSTs in recent years were the warmest ever registered. Further, in the last decades the Mediterranean Sea registered an increase at an average (± SD) rate of 0.03 ± 0.008 ° C yr–1 in the western basin and 0.05 ± 0.009 °C yr–1 in the eastern basin (Soto-Navarro *et al*. 2020). The importance of this geographical region though, is not reflected in the available literature regarding the impacts of MHWs on the Mediterranean biota.

Much material has been published on the biological impacts of climate change on the Mediterranean biota – for example CIESM Monograph n° 35 (2008) or other reviews (like Marbà *et al.* 2015), but far less on the impacts of MHWs on global marine ecosystems (see review by Smith *et al.* 2023).
Bibliometric analysis is a well-known, widely utilized method for analysing in research publications on a given subject which scientific terms are cited most frequently and their inter-relations (Tang *et al.* 2023). There is a large number of bibliometric analysis tools now available.

For this study we used VOSviewer, an open-source software that can analyse a significant amount of data and provide excellent network data mapping (Bukar *et al*. 2023). VOS is the acronym for visualization of similarities - a concept developed less than two decades ago for analysing and visualizing patterns within data (Eck and Waltman 2007).

Bibliometric analysis

Initially, a retrieval of published sources containing the term "Impacts of Marine Heatwaves" was conducted, using a search in Web of Science. This retrieved a total of 798 publications. Then the data were exported from the Web of Science database in a RIS (reference manager file) format to be able to assess the bibliometric maps of terms in VOSviewer (1.6.20 edition). The terms that were chosen referred to different geographical areas and to the most common biological traits studied. The minimum number of occurrences of a term which was found in the Abstract and Title of the reference was 5 for the traits and 10 for the regions. Regarding the biological traits, the terms were selected to strictly concern biology, while only the sources referring to a specific region were retained for the geographic map analysis.

Results

Our search query on the impacts of MHWs found 798 documents published between 2007 and 2023 inclusive. The growth of publications showed a steep increase after 2017 (see Fig. 1), with a record number of 244 publications in 2023 alone.

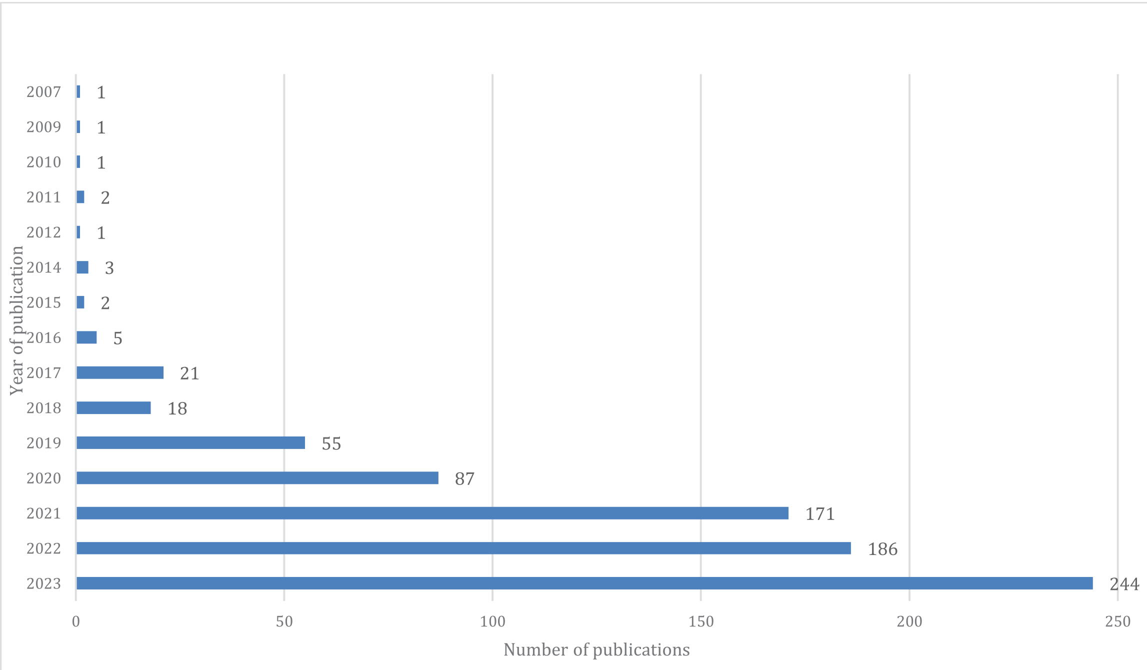

Figure 1. Number of published articles retrieved per year referring to the impacts of MHWs.

A bibliometric map of pre-selected terms commonly studied and found in the literature regarding MHWs and marine organisms, is shown in Figure 2. One notes that corals attract the highest number of publications regarding the impacts of MHWs in the World ocean. Not surprisingly a number of MHW studies relate to fish populations and fisheries, along with seagrasses and macroalgae. For these groups and for others less often reported (e.g., birds, bivalves, sponges) the connecting lines, i.e., the co-occurrence of terms, indicate that the most studied life traits are mortality, abundance, growth, and survival; while traits like thermal tolerance, recruitment, density, metabolic activity, were studied to a lesser extent. For corals the major connection was with mortality, while for kelp and other algae it was with the term abundance. For the fish most of the connections concerned recruitment, age, survival, and thermal tolerance.

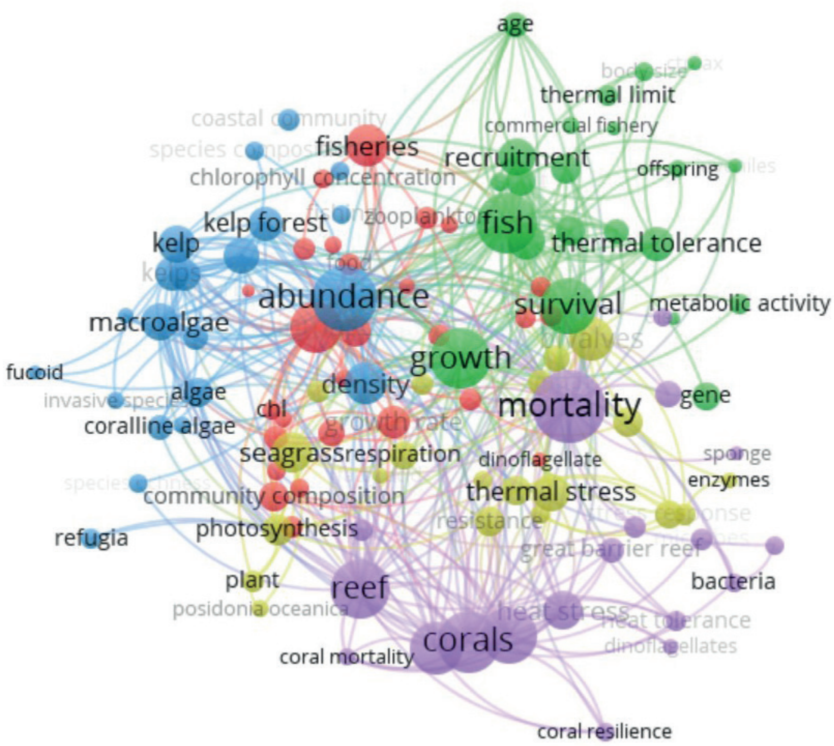

Figure 2. Network visualization map of terms found in abstracts / titles of documents on biological impacts of MHWs. Node size represents the frequency of occurrence of the term. The thicker the lines, the more frequently the connected terms appeared in the same article. Nodes of similar colour represent a cluster of related terms. The map was created by VOSviewer.

In comparison to the high number (798) of publications retrieved for the period 2007-2023 from the scientific record concerning the world ocean, a further Web of Science geographical analysis, focused this time on MHWs impacts in the Mediterranean Sea, retrieved only 62 articles.
The low number of MHW studies citing the Mediterranean Sea was far too limited to be treated statistically or even discussed in depth. Suffice to say that biomass, growth and photosynthetic activity of seagrasses such as *Posidonia oceanica* were rather common in that restricted sample.
Figure 3 offers a graphic representation of the geographic areas studied by the 798 publications retrieved. The most studied ocean region in that regard was the Pacific Ocean (both north and south), as could be expected given its vast surface area and the fact that it is where the world's most extensive coral reef ecosystems lie (Great Barrier Reef, south Pacific Ocean). The northeast Pacific is not forgotten either, and a probable credit for that can be given to «the Blob» phenomenon that started in 2013 and persisted for two years. The Indian Ocean is also well represented, likely related to the importance of threatened coral reefs and mariculture resources. There again the Mediterranean Sea appears very much at the periphery.

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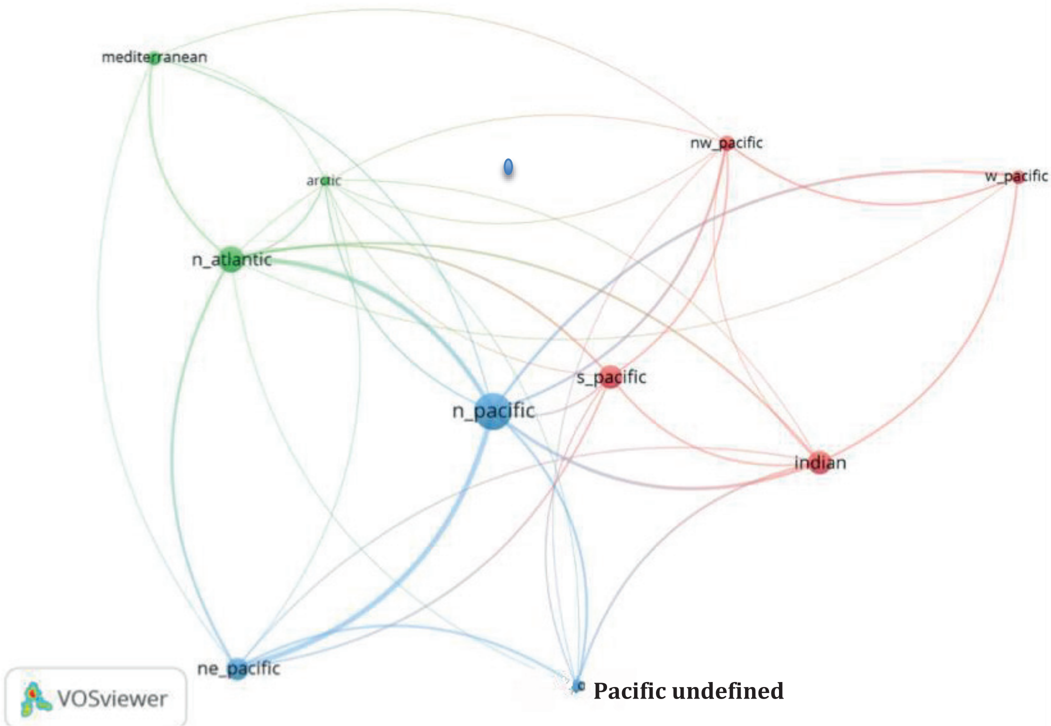

Figure 3. Network visualization map, grouped by geographic region, of co-occurring terms found in abstracts / titles of documents on impacts of MHWs. Explanation as in Figure 2.

Discussion

This study was performed to retrieve published sources on the biological impacts of MHWs and present their inherent properties and inter-relations in a visual fashion.
As could be expected, most of the taxa investigated in MHW studies are benthic, sessile organisms inhabiting hard bottom substrates, thus unable to move away from unusually warm waters. Corals are particularly well represented in that group, as MHWs combined with other stressors can drive these species to bleaching and mass mortalities which do not go unnoticed. The species most affected by mass mortalities events (MMEs) correspond to long-lived species, with low growth rates and massive-arborescent growth forms, and they are considered as foundation or habitat-forming species, which play a key structural and ecological role in the habitats where they flourish (see Garrabou *et. al.* 2024 in this volume). Information regarding seagrass meadows and seaweeds like kelp, which often act as foundation species and modify their environments in creating unique habitats, will also be found often in the published record.

Thermal stress, tolerance, and resistance appear as another subject that attracts scientific interest, but to a lesser extent as can be seen in Figure 2. Different species and populations will naturally exhibit different responses to warming, and these responses are highly variable at regional scales (Verdura *et al,* 2021). Furthermore, not all impacts from MHWs will be "negative" as warm-adapted species, species with high mobility, and organisms found near their colder poleward range edge should experience a competitive advantage under MHWs and may therefore increase in abundance. The thermal tolerance of native vs alien species is another issue; recent experimental testing on macrophytes and invertebrates indicates that most - but not all - tested native species are more sensitive to warming or prolonged MHWs (Rilov *et al*. 2024 in this volume).

Among the subjects that appear worthy of more scientific attention, we may cite (a) how certain species interactions like the pathogens of corals or sponges are affected by MHWs (see Mueller *et al*. 2023) ; (b) the alteration of marine food webs due to differential mortality at various trophic levels (Oliver *et al*. 2019 and references therein); or (c) species redistributions following MHWs and the availability of refugia (see Verdura *et al*. 2021). The more knowledge we get on this subject, the better will be our ability to manage populations and habitats under future extreme events.

The very low number (62) of publications on MHWs impacts in the Mediterranean is certainly linked as well to the consistent under-representation affecting publications from the Mediterranean Basin, which is due to a number of causes – editorial policy against regional reports, poor visibility of papers not written in English, etc. - that are detailed elsewhere (Maslin 2006; Stergiou and Tsikliras 2006). In addition, the considerable media attention given in recent years to the phenomenon of coral bleaching caused by global warming did nothing to stimulate Mediterranean research on MHWs, since coral reefs are quite rare and small in the Mediterranean, except for white corals in deep waters. Further, the analysis of MME records retrieved from the literature by Garrabou *et al*. (2024 in this volume) reveals a serious deficit of information from the southern and eastern Mediterranean coasts.

Through the current analysis, it is apparent that higher attention is given to the impacts of MHWs on corals and especially to the deterioration of coral reefs, which are among the most diverse and valuable ecosystems on our planet and are found in majority in the Pacific Ocean. On the other hand, the Mediterranean Sea lacks such habitats although hosting others of equal importance that are currently in danger of ecological extinction due to extreme events (Garrabou *et al.* 2024 this volume). In addition «the Blob» - an unprecedented MHW in its magnitude and duration that started in late 2013 in the NE Pacific Ocean and persisted for over two years - was a very anomalous alarm event that attracted high scientific interest and generated devastating ecological impacts with socioeconomic implications for coastal communities (Schmeisser *et al*. 2019). This is another reason why the Pacific Ocean, and especially the North and NE Pacific Ocean, appear prominently in Figure 3.

The latest peak of interest shown for MHWs by the scientific community in the past three years (see Fig. 1), appears triggered by their higher and higher frequency and duration (see Juza *et al.* 2024 in this volume). However, the available information regarding MHWs impacts on the marine biota remains very heterogenous geographically, with a clear deficit of Mediterranean studies. Keeping in mind the importance of the Mediterranean Basin as a biodiversity hotspot under siege (Coll *et al.* 2012), it is urgent to put more effort on experimental, observational, and modelling studies to understand how Mediterranean species and ecosystems will be impacted by more extensive and more frequent MHWs, so as to preserve important habitats and species.

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Chartosia N. 2024. Mining the published record on the biological impacts of marine heatwaves. pp. 163 - 169 In CIESM Monograph 51 [F. Briand, Ed.] Marine heatwaves in the Mediterranean Sea and beyond. CIESM Publisher, Paris, Monaco, 174 p.

References

Bukar U.A., Sayeed M.S., Razak S.F.A., Yogarayan S., Amodu O.A. and Mahmood R.A.R. 2023. A method for analyzing text using VOSviewer. *MethodsX*, 11, 102339.

CIESM. 2008. Climate warming and related changes in Mediterranean marine biota. CIESM Monograph n° 35 [F. Briand, Ed.], 152 p., CIESM Publisher, Paris, Monaco.

Coll M., Piroddi C. , Albouy C., Lasram F., Cheung W., Christensen V., Karpouzi V. *et al*. 2012. The Mediterranean Sea under siege: spatial overlap between marine biodiversity, cumulative threats and marine reserves. *Global Ecology and Biogeography* 21: 465–80.

Eck N. and L. Waltman. 2007. VOS: a new method for visualizing similarities between objects, in: Advances in Data Analysis: Proceedings of the 30th Annual Conference of the Gesellschaft für Klassikation eV, Freie Universität Berlin, 299–306.

Eck N. and L. Waltman. 2022. Vosviewer manual. Manual for VOSviewer version 1 6 18.

Gao G., Zhao X., Jiang M., Gao L. 2021. Impacts of marine heatwaves on algal structure and carbon sequestration in conjunction with ocean warming and acidification. *Front. Mar. Sci*., 8:758651.

Garrabou J., and 22 others 2024. 24 years tracking mass mortality events and marine heatwaves: when observations overcome the worst scenarios. pp 129 - 140 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Ghanem R., Ben Souissi J., Ledoux J.B., Linares C. and J. Garrabou. 2024. Marine Heatwaves and benthic communities: Changes features of the assemblages and alarming consequences on biodiversity in Tunisian waters. pp 155 - 162 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Giorgi F., and P. Lionello. 2008. Climate change projections for the Mediterranean region, Global and Planetary Change, 63 (2–3): 90-104, https://doi.org/10.1016/j.gloplacha.2007.09.005.

Guiot J. and W. Cramer. 2016. Climate Change: The 2015 Paris Agreement thresholds and Mediterranean Basin ecosystems. *Science* 354(6311): 465–8.

Hobday A.J., Alexander L.V., Perkins S.E., Smale D.A., Straub S.C., Oliver E.C. 2016. A hierarchical approach to defining marine heatwaves. *Prog. Oceanogr*., 141: 227–238. doi: 10.1016/j.pocean.2015.12.014

Holbrook N.J., Sen Gupta A., Oliver E.C.J. *et al.* 2020. Keeping pace with marine heatwaves. *Nat Rev Earth Environ* 1, 482–493. https://doi.org/10.1038/s43017-020-0068-4

Juza M., Reyes E., and J. Tintore. 2024. Marine heatwaves in the Mediterranean Sea: 2023 latest insights from multi-platform observations. pp 63 - 76 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Maslin M. 2006. Research skewed by stress on highest-impact journals. *Nature,* 440: 408

Mueller J., Grammel BN., Rohde S., Schupp PJ., *et al*., 2023 Mass mortality event of the giant barrel sponge *Xestospongia sp*.: population dynamics and size distribution in Koh Phangan, Gulf of Thailand. *Peer J*. 2023 11 p.e16561

Oliver E.C.J., Burrows M.T., Donat M.G., Sen Gupta A., Alexander L.V., Perkins-Kirkpatrick S.E., Benthuysen J.A., Hobday A.J., Holbrook N.J., Moore P.J., Thomsen M.S., Wernberg T and D.A Smale. 2019. Projected Marine Heatwaves in the 21st Century and the Potential for Ecological Impact. *Front. Mar. Sci.* 6: 734. doi: 10.3389/fmars.2019.00734

Rilov G., Yeruham E. and S. Noè. 2024. Ocean warming, marine heatwaves and the thermal vulnerability of the increasingly tropicalized Levant coast ecosystems. pp 141 - 154 In *Marine Heatwaves in the Mediterranean Sea and Beyond.* CIESM Workshop Monograph n°51 [F. Briand, Ed.], 174 p., CIESM Publisher, Paris, Monaco.

Schmeisser L., Bond N.A., Sidelecki S., Ackerman T.P. 2019. The role of clouds and surface heat fluxes in the maintenance of the 2013–2016 Northeast Pacific marine heatwave." Journal of *Geophysical Research: Atmospheres,* 124: 10772 - 10783. https://doi.org/10.1029/2019JD030780

Smale D.A., Wernberg T., Oliver E. C. J., Thomsen M., Harvey B. P., Straub S. C. *et al.* 2019. Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nat. Clim. Chang*. 9, 306–312. doi: 10.1038/ s41558-019-0412-1.

Smith K. E., Burrows M. T., Hobday A. J., Sen Gupta A., Moore P. J., Thomsen M., Wernberg T and D.A Smale. 2021. Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science,* 374(6566). https://doi.org/10.1126/science.abj3593

Smith K.E, Burrows M.T., Hobday A.J., King N.G., Moore P.J., Sen Gupta A., Thomsen M.S., Wernberg T., Smale D.A. 2023. Biological impacts of marine heatwaves. *Ann Rev Mar Sci* 15(1): 119–145.

Soto-Navarro J., Jordá G., Amores A., Cabos W., Somot S., Sevault F. *et al.* 2020. Evolution of Mediterranean Sea water properties under climate change scenarios in the med-CORDEX ensemble. *Climate Dynamics*, 54 (3): 2135–2165. doi: 10.1007/s00382-019-05105-4

Stergiou K. and A.C. Tsikliras. 2006. Underrepresentation of regional ecological research output by bibliometric indices. *Ethics in Sc. Env. Politics*, 15-17.

Tang Jing-Qian, Qian-Hui Shen, Yao-Yao Han, Yang Wu, Xiang-Feng He, Da-Wei Li, Yong Huang. 2023. Analysis of research status and trends on marine benthic dinoflagellate toxins: A bibliometric study based on web of science database and VOSviewer, Environmental Research, Volume 238, Part 2, 117179.

Verdura J, Santamaría J, Ballesteros E. *et al.* 2021. Local-scale climatic refugia offer sanctuary for a habitat-forming species during a marine heatwave. *J Ecol*., 109: 1758–1773. https://doi.org/10.1111/1365-2745.13599

LIST OF PARTICIPANTS

Yannis Androulidakis
Lab. of Marine Engineering
University of Thessaloniki
Greece
iandroul@civil.auth.gr

Ernesto Azzurro
Chair, CIESM Committee 6
Reseach Director
CNR Inst. Mar. Biol. Res.
Ancona, Italy
ernesto.azzurro@cnr.it

Sukru Besiktepe
Inst. Marine Sc. & Technology
Dokuz Eylul University
Izmir, Turkey
sukru.besiktepe@deu.edu.tr

Frédéric Briand
CIESM Headquarters
fbriand@ciesm.org

Niki Chartosia
Dpt. of Biological Sciences
Univ. Of Cyprus
Nicosia, Cyprus
chartosia.niki@ucy.ac.cy

Joaquim Garrabou
Dpt. of Marine Biology
Institut de Ciències del Mar-CSIC
Barcelona, Spain
garrabou@icm.csic.es

Raouia Ghanem
Biodiversity Laboratory
Univ. El Manar
Tunis, Tunisia
raouia-ghanem@hotmail.fr

Laura Giuliano
CIESM Headquarters
lgiuliano@ciesm.org

Mélanie Juza
Coastal Obs. & Forecasting System
SOCIB
Palma de Malloca, Spain
mjuza@socib.es

Matjaž Ličer
Marine Biology Station
Piran, Slovenia
matjaz.licer@nib.si

Giovanni Liguori
Dpt. of Biolo, Geol., Env. Science
Univ. of Bologna
Bologna, Italy
g.liguori@unibo.it

Bayoumy Mohamed
Geo Hydrodynamics
Univ. of Liège, Belgium and
Univ. of Alexandria, Egypt
Bayoumy.Mohamed@uliege.be

Paula Moschella
CIESM Headquarters
pmoschella@ciesm.org

Gil Rilov
Head, Marine Ecology Lab.
National Inst. of Oceanog.
Haifa, Israel
rilovg@ocean.org.il

Robert Schlegel
Laboratoire d'Océanographie
IMEV - CNRS
Villefranche-sur-mer, France
robert.schlegel@imev-mer.fr

Katrin Schroeder
Chair, CIESM Commitee 2
Ist. Science Mar. ISMAR – CNR
Venice, Italy
katrin.schroeder@ismar.cnr.it

Amélie Simon
IMT Atlantique
Sc. & Tech. Info. & Knowledge
Brest, France
amelie.simon@imt-atlantique.fr

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