A Spatiotemporal Analysis of Marine Heatwave Frequency Around Malta

Emily Kelley

A Capstone Project submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

And

UNIVERSITY OF MALTA

In Partial Fulfillment of the Requirements

for the degree of

Master of Science in Integrated Science and Technology

Concentration in Environmental Management & Sustainability

July 2025

Supervisor: Dr. Adam Gauci

Co-Supervisor: Dr. Tobias Gerken

L-Università ta' Malta

FACULTY/INSTITUTE/CENTRE/SCHOOL Earth Systems

DECLARATIONS BY POSTGRADUATE STUDENTS

(a) Authenticity of Dissertation

I hereby declare that I am the legitimate author of this Dissertation and that it is my original work.

No portion of this work has been submitted in support of an application for another degree or qualification of this or any other university or institution of higher education.

I hold the University of Malta harmless against any third party claims with regard to copyright violation, breach of confidentiality, defamation and any other third party right infringement.

(b) Research Code of Practice and Ethics Review Procedures

I declare that I have abided by the University's Research Ethics Review Procedures. Research Ethics & Data Protection form code IES - 2025 - 00030.

As a Master's student, as per Regulation 77 of the General Regulations for University Postgraduate Awards 2021, I accept that should my dissertation be awarded a Grade A, it will be made publicly available on the University of Malta Institutional Repository.

Abstract

As global climate change intensifies due to anthropogenic influences, marine heatwaves (MHWs) have increased in both frequency and duration, posing significant risks to marine ecosystems. These extreme warming events occur not only at the ocean surface but also at subsurface depths, where their dynamics and ecological impacts remain less understood. This study analyzes in-situ buoy data, sea surface temperature (SST) satellite data, and reanalyzed subsurface temperature model data from the Marine Copernicus Service in the central Mediterranean Sea to investigate MHW occurrence across vertical profiles over more than a decade. Using the 95^{th} percentile temperature threshold for each grid cell and a minimum event duration of five to ten days, MHW counts were calculated spatially and complied annually to assess temporal patterns. Surface MHWs showed some correlation with atmospheric heatwaves during the same years, indicating the influence of atmospheric conditions on ocean surface warming. However, the comparison between surface and subsurface temperature anomalies revealed the presence of subsurface MHWs that often persisted independently from surface events. These subsurface heatwaves retained temperatures for extended periods, even at depths approaching 500 meters. These findings show the growing significance of subsurface MHWs and emphasize the need of increased monitoring and research of the vertical extent and duration of these events. Understanding these deeper warming events is important to prevent damage to the marine ecosystems, both pelagic and benthic. This study highlights the importance of integrating subsurface data in MHW research to improve predictions, ecological impact assessments, and inform sustainable marine management practices in a world affected by warming temperatures.

Table of Contents

Table of Figures

Abbreviations

CMEMS: Copernicus Marine Environment Monitoring Service

EAP: East Atlantic Pattern

ENSO: El Niño Southern Oscillation

EU: European Union

LSTM: Long Short-Term Memory

MHW: Marine Heatwave

ML: Machine Learning

MPA: Marine Protected Area

MSFD: Marine Strategy Framework Directive

NAO: North Atlantic Oscillation

SST: Sea Surface temperature

UNSDGs: United Nations Sustainable Development Goals

1. Introduction

As global temperatures rise in the face of climate change, the negative effects become increasingly evident on both land and sea. Marine heatwaves (MHWs) are linked to climate change and are occurring more often. Similar to how atmospheric heatwaves on land are damaging to humans and the environment, the marine environment is also suffering due to the MHWs. There are several different thresholds for how to define a MHW depending on which literature is being reviewed, the most general definition being "periods of extreme warm sea surface temperature that persist for days to months" (Frölicher et al. 2018). A highly cited study suggests that it is temperatures at or exceeding the 90^{th} percentile for five days or more (Hobday et al. 2016). MHWs cause harm to the ocean and its inhabitants by inducing shifts in ecosystem configuration, causing mass die offs, and reducing ocean productivity among other issues (Smale et al. 2019). They also harm human livelihoods by the loss of ecosystem services due to the temperature increase (Smith et al. 2021).

1.1 MHWs in the Mediterranean

Marine heatwaves in the Mediterranean Sea have become increasingly frequent. This area is vulnerable to MHWs due to its semi-enclosed nature and reduced mixing with the Atlantic Ocean. Regional climate patterns such as the East Atlantic Pattern (EAP) and North Atlantic Oscillation (NAO) are connected to the frequency and intensity of MHWs (Hamdeno & Alvera-Azcaráte 2023). The largest cause being the increase in sea surface temperature (SST) over the past few decades within the Mediterranean Sea (Martínez et al. 2023). The increase in SST being linked with atmospheric forcing, where high-pressure conditions lead to reduced wind and increase solar radiation and cause the sea surface to heat up rapidly (Marullo et al. 2023). These factors combine to make the region a global hotspot for marine heatwaves, with significant ecological and socioeconomic impacts.

Understanding the underlying causes of MHWs is important for learning how to remediate the issue. Studying MHWs supports two of the United Nation's Sustainable Development Goals (SDGs), SDG 13 on Climate Action, and SDG 14 on Life Below Water. Creating policy that mitigates the harm caused by these high temperatures relies on scientific data about MHWs to develop resilience plans for the marine environment, such as informing the design of marine protected areas (MPAs). MHWs threaten ecosystem services like fisheries and carbon storage, which need to be preserved for the health of future generations. They also directly affect ocean ecosystems making studying them important for protecting biodiversity within water.

The wider environmental management implications are challenging to address and sensitive within the region because the Mediterranean Sea is a highly used resource for many different countries. Monitoring these events is hard because they develop quickly, thus creating policy relies on accurate scientific data processing methods that are not currently available. In addition to ecological impacts, MHWs pose serious socioeconomic risks. Coastal communities, small-scale fishers, and other groups who depend directly on marine ecosystems for their livelihoods are particularly vulnerable. These populations may lack the resources or institutional support needed to adapt to sudden changes in marine conditions, such as shifts in fish populations or mass mortality events. In the EU context, marine environmental governance is shaped by frameworks such as the Marine Strategy Framework Directive (MSFD) and the EU Biodiversity Strategy for 2030. While these policies emphasize ecosystem-based management and climate resilience, MHWs are not yet integrated into national or regional marine strategies.

1.2 Knowledge Gaps and Research Objectives

Currently, there are gaps in the understanding of MHWs and their causes and effects. The interconnecting roles of local processes and large-scale climate modes are not fully unified in understanding, especially in ocean-climate complex regions like the Arctic (Oliver et al. 2021). There is still an ongoing debate on defining MHWs that makes it difficult to track them uniformly within research. The full impact that these events will have on ecosystems, especially years down the line, is still not fully understood. Most studies focus on surface temperatures and do not address subsurface temperature warming. There is a lack of good quality high-resolution data to use when making subsurface observations. The vertical and three-dimensional dynamics of MHWs are poorly understood because of this (Holbrook et al. 2020). Addressing these gaps is crucial for improving prediction, management, and adaptation to the growing threat of MHWs.

In addressing the lack of subsurface studies, the aim of the project is to perform a time series analysis of surface and subsurface temperatures over the course of 11 to 12 years within the region of the Mediterranean Sea surrounding the country of Malta. Focusing on the frequency, spatial distribution, and temperature anomalies across different depths up to approximately 500 meters below sea level. Understanding the dynamics of MHWs in a climate change hot spot is essential for informing climate adaptation strategies and guiding effective marine environmental management. Unlike surface MHWs, subsurface MHWs have been far less studied, and they may have a significant ecological impact. Through the application of statistical tools, the study will identify MHW events based on their intensity and duration, particularly emphasizing the vertical variability.

The research objectives of the study aim to answer the following questions:

- In which locations and how frequently have marine heatwaves occurred in the Maltese region over the past decade?
- Are marine heatwaves also occurring at subsurface depths, and how do they compare to surface events?

To address these questions, the study will analyze temperature datasets from both surface and subsurface layers, allowing for a comparative assessment of MHW characteristics across vertical gradients. Timeseries datasets obtained from in-situ, remote sensing, as well as numerical models were analyzed and compared. Research will expand knowledge on the occurrences of MHWs in the region and lead to a more thorough look at high subsurface temperatures.

1.3 Outline

Following this introduction, a literature review that explores the various definitions and classifications of MHWs, followed by a focused discussion on why the Mediterranean Sea is particularly vulnerable to these events, is presented in Chapter 2. The review also examines the ecological and socioeconomic consequences of MHWs in this region. In Chapter 3, the methodology section then details the data sources, Python-based tools, and processing techniques used to analyze sea temperature trends and identify heatwave events. The results and discussion sections in Chapter 4, presents the generated maps, tables, and other visual outputs, interpreting the spatial and temporal patterns of MHWs in the Mediterranean. Finally, in Chapter 5, the conclusion summarizes the key findings, reflects on their broader implications, and suggests potential areas for future research.

2. Literature Review

The yearly average duration of marine heatwaves has doubled from 2008 to 2023 (Schuckmann et al. 2024). Furthermore, with rising global atmospheric temperatures, the severity of MHWs is projected to accelerate, leading to larger spatial extents and even longer durations (Frölicher et al. 2018). Beyond global warming, local oceanographic processes and large-scale climate modes also drive the increasing occurrence of MHW events. The detrimental effects of marine heatwaves on socioeconomic factors and marine ecology explain the importance of their consistent monitoring and categorization to preserve human and environmental well-being.

2.1 Defining Marine Heatwaves

Hobday et al. 2016 aims to provide a definition for MHWs as previously the definitions were too broad. They referenced other definitions of MHWs being “long periods of warmer than average temperatures”. They looked at guidelines from atmospheric heatwaves and applied those to a marine context. Figure 1 shows a visual example from Hobday et al. (2016)’s definition of MHWs, particularly the difference between a “heat spike” and a heatwave of prolonged higher temperatures. The context of marine heatwaves makes it more challenging to quantify metrics, as different ocean regions exhibit varying spatial characteristics and diverse MHW properties that must be taken into account. To enable effective comparison and communication of MHW events, their identification from in-situ or remotely sensed data must rely on consistent categorization.

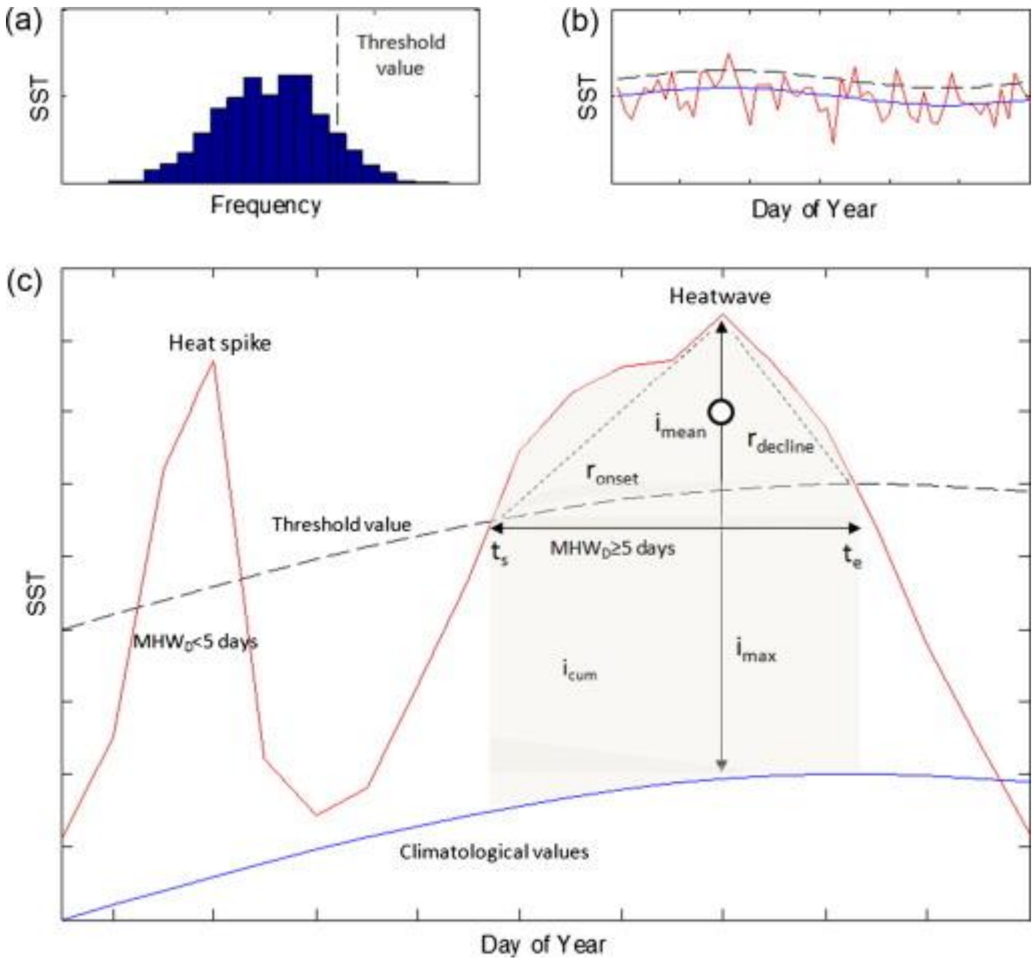

Figure 1 *Hobday et al. 2016's MHW definition representation.*

2.2 MHWS in the Mediterranean

The Mediterranean Sea hosts a high level of biodiversity and has the highest rate of endemism in the world according to the United Nations Environment Programme. Millions of people live along its coasts, making it a vital resource for both coastal communities and regions beyond. Due to its relatively small size and semi-enclosed basin, the Mediterranean is particularly vulnerable to the negative impacts of climate change (Figure 2). Anthropogenic influences, such as overexploitation and pollution, have a worse effect on the region because of the dense coastal population and the infrastructure required to support it (Dayan et al. 2023).

Hamdeno & Alvera-Azcaráte (2023) examine the specific characteristics of marine heatwaves (MHWs) in the Mediterranean and explore how the frequency of these events is connected to broader weather patterns. Their findings indicate that extreme events, such as atmospheric heatwaves, often coincide with MHWs in certain parts of the Sea. These atmospheric heatwaves cause heat transfer to the ocean, triggering MHWs. The authors link the prolonged atmospheric heatwaves of 2019 in western Europe, to a concurrent MHW, which contributed to the formation of a "Medicane" on the eastern side of the Sea due to elevated SSTs. Understanding these connections is crucial for predicting future anomalies in ocean temperatures and improving emergency preparedness for extreme weather events.

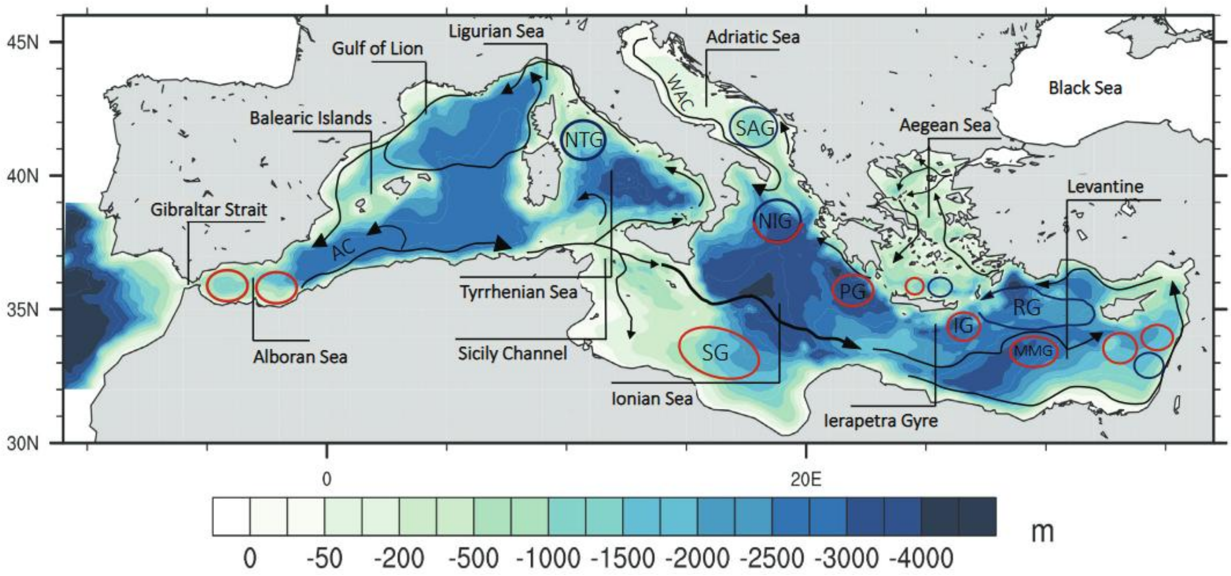

Figure 2 *The Mediterranean Sea its sub-basins and surface circulation from Darmaraki et al. (2024). Acronyms: AC, Algerian Current; NTG, North Tyrrhenian Gyre; SG, Sidra Gyre; WAC, Western Adriatic Current; SAG, Southern Adriatic Gyre; NIG, Northern Ionian Gyre; PG, Pelops Gyre; IG, Ierapetra Gyre; RG, Rhodos Gyre; MMG, Mera-Matruh Gyre.*

2.3 Subsurface MHWs

There are different and similar dynamics that create surface and subsurface MHWs. Both oceanographic processes and local climate modes affect the spatial extent and timing of both kinds of MHW. According to Holbrook et al. (2019) MHWs within the Mediterranean are associated with atmospheric anomalies that cause reduced wind speed and increased heat flux, which in turn causes higher temperature. This is in line with the findings of Hamdeno & Alvera-Azcaráte (2023), so we can infer that the changes in climate patterns due to anthropogenic global warming is causing the SST of the Mediterranean to increase to extreme levels.

A study by Schaeffer & Roughan (2017) found that off the coast of Australia, marine heatwaves occurred year-round below the surface and extended to the bottom of the water column, primarily due to weak stratification. While many subsurface MHW events are correlated with surface events, some of the events in this study did not correlate with surface MHWs. Elzahaby & Schaeffer (2019) also correlate findings that there are MHWs in the same region that extend far below the surface with no surface detectable features. One of the driving factors taken away from these studies is that deeper MHWs are driven by anticyclonic warm-core eddies, and they reflect changes in the temperature and salinity of the water. Local bathymetry, weak stratification, and vertical mixing are all factors in developing these events as well. The El Niño Southern Oscillation (ENSO) has been linked to increased downwelling, sending Kelvin waves that push warm water downward within the Mediterranean (Fernández-Barba et al. 2024). These deeper MHWs also have longer duration periods than surface events (Schaeffer & Roughan 2017, Fernández-Barba et al. 2024).

2.4 Ecological and Socioeconomic Impacts

The rise in marine heatwaves (MHWs) is directly contributing to the decline of vital ecosystem services. According to Smith et al. (2021), 34 major marine heatwave events over the past 25 years have negatively affected four categories of ecosystem services, namely provisioning, regulating, habitat and cultural. It was found that in the Mediterranean Sea, MHWs have been linked to mass mortality events among native marine species, as well as an increase in invasive species and marine pathogens, disrupting ecological balance. These disruptions are especially harmful to fisheries, a key provisioning service, as they reduce the capacity of the ocean to provide food. This not only threatens biodiversity but also causes economic hardship for coastal communities dependent on fishing for their livelihoods. While Free et al. (2023) echo the findings of Smith et al. (2021) regarding the negative effects of MHWs on fisheries, they also report that certain events may have beneficial outcomes, such as increased bluefin tuna size.

Thermal stress from MHWs can exceed species' tolerance limits, altering their distribution. Guibourd de Luzinais et al. (2024) report shifts in species biogeography toward cooler, deeper waters and higher latitudes. Beyond redistribution, increased thermal stress can cause mass mortality events and disrupt food webs, particularly at lower trophic levels (Gomes et al., 2024). While evidence of MHW impacts is growing, especially in surface and coastal systems, data on subsurface and deep-sea ecosystems remain limited. Documented effects like coral bleaching and seagrass die-offs (Genevier et al., 2019; Strydom et al., 2020) highlight benthic vulnerability, but impacts on deeper communities are still poorly understood.

2.5 Advances in MHW Detection and Prediction

Analysis of MHWs has developed rapidly in the past few years. Traditional statistical detection, machine learning (ML), and paleoclimate reconstruction, are just some of the methods that have been used. Current approaches are focused on detecting, predicting, and understanding MHWs using observational data and modeling. Schlegel et al. (2019) demonstrated that long-term marine heatwave patterns can be effectively detected even with relatively short datasets. Their findings showed that useful observations were achievable with as little as 10 years of data, challenging the previously held assumption that a minimum of 30 years was required for reliable detection. They also found that datasets with up to 25% missing values did not significantly impact the results, as the gaps could be reliably addressed using linear interpolation. This suggests that research based on suboptimal datasets can still yield robust findings, which is particularly relevant given the scarcity of continuous observational data. However, it should be noted that Schlegel et al. (2019) based their analysis solely on SST data and did not assess the applicability of these findings to subsurface observations.

Commonly, reanalysis models are used to study the spatiotemporal dimensions of subsurface MHWs. One of the most widely used methods in the literature involves satellite-derived data to track SST and do statistical analysis on the data as in Hobday et al. (2019). In Sun et al. (2023) they used several reanalysis datasets to identify MHWs in four-dimensions using Hobday et al. (2016)'s definition of a MHW as well as applying a nearest-neighbor smoothing method to the data. Bonino et al. (2023) tested out different ML models, such as random forest, long short-term memory (LSTM), and convolution neural networks, and compared them to the current forecast system used by the Copernicus Marine Service, the Mediterranean Forecasting System (MedFS). MedFS is a computational ocean forecasting system created and maintained by the Euro-

Mediterranean Center on Climate Change, which generates analyses and short-range predictions covering the Mediterranean Sea and nearby regions of the Atlantic Ocean. Their study found that a hybrid approach combining random forest and LSTM yielded promising results for short-term MHW predictions. By integrating spatiotemporal data with known climatic drivers of MHWs, these ML models can be trained to recognize patterns and improve forecasting accuracy.

2.6 Adaptation and Mitigation Strategies

As marine heatwaves become more frequent and pose growing threats to marine ecosystems and ecosystem services, the development and implementation of effective adaptation and mitigation strategies is becoming increasingly critical. Since MHWs have been found to frequently extend into deeper waters, fish farming infrastructure such as sea cages are directly affected. In some cases, cages can be submerged into deeper, cooler layers to protect fish stocks, but this solution is only viable where the bathymetry permits. In shallower regions this adaptation is limited or unfeasible (Atalah et al., 2024). Improved spatial planning for aquaculture and marine development is essential. This includes identifying and avoiding ecologically sensitive areas and minimizing potential conflicts with other marine users, such as tourism or small-scale fisheries. Since rising MHWs are linked to climate change, global mitigation efforts must focus on reducing greenhouse gas emissions (Frölicher et al. 2018). The ability of MPAs to buffer MHW impacts remains uncertain, though targeting areas with steep depth gradients may improve resilience (Smith et al., 2021). Combining MPAs with other conservation tools and adopting cross-boundary, multidisciplinary strategies is critical to prevent irreversible damage.

2.7 Gaps in Subsurface MHW Research

There is a gap in literature when it comes to subsurface MHWs, most studies focus on surface-based metrics and SST anomalies. Surface MHWs have better documentation than subsurface MHWs. Subsurface MHW frequency, vertical extent, and interaction with ocean stratification and bathymetry is understudied (Fernández-Barba et al. 2024). Part of the gap is a lack of long-term, depth-resolved observational datasets, especially in coastal and shelf regions. These gaps can lead to underestimation of the negative effects that MHW events will have on marine ecology and the socioeconomic needs of people. To help address these limitations, integrated depth modeling approaches are needed to assess MHW frequency through the entire water column.

2.8 Copernicus Marine Service

The Copernicus Marine Environment Monitoring Service (CMEMS) is part of the European Union's Copernicus Programme, providing information on ocean conditions through real-time data, forecasts, and historical records (reanalysis). Managed by Mercator Ocean International since 2015, CMEMS supports maritime safety, marine resource management, and climate forecasting. It combines satellite and in-situ observations with advanced ocean modeling (Le Traon et al., 2019).

For this study, two CMEMS products were used: daily sea surface temperature fields for the Mediterranean Sea at high (~6 km) and ultra-high (~1 km) resolution, produced by Consiglio Nazionale delle Ricerche – Gruppo di Oceanografia da Satellite using satellite observations and statistical interpolation. The SST product is validated through consistency checks across sensors, cloud masking, and estimation of analysis errors, with comparisons to in-situ measurements and climatological anomalies. The 'Mediterranean Sea Physics Reanalysis', produced by the Euro-Mediterranean Center on

Climate Change with OceanVAR data assimilation, which provides 3D ocean fields at approximately 4–7 km horizontal resolution and 141 vertical layers. This reanalysis is validated through comparison with independent in-situ temperature and salinity profiles, satellite sea level and SST observations, and long-term climatologies, ensuring temporal consistency and minimizing model bias across the 1987–present record.

3. Materials and Methods

The aim of this study was to investigate the frequency and temporal evolution of marine heatwaves in the Mediterranean Sea, with a focus on the area surrounding Malta. The analysis applies the five-day threshold definition from Hobday et al. (2016) but uses the 95th percentile instead of the 90th percentile because of the variation in the literature. It also looks at changes when the threshold is increased to 10 days. The methodology involves computing MHWs using three datasets: ultra-high-resolution satellite-derived SST data from the Copernicus Marine Environment Monitoring Service (CMEMS), numerical model reanalysis data from CMEMS for subsurface temperature variability, and in-situ buoy measurements. The approach compares MHW characteristics across datasets with differing spatial and temporal resolutions to examine how these differences influence event detection. The detection of MHWs was carried out using a percentile threshold consistent with most definitions of MHWs on both surface and subsurface data.

Table 1 *- Table showing the resolution differences between the data.*

Dataset	Mediterranean Sea High Resolution and Ultra High-Resolution Sea Surface Temperature Analysis	Mediterranean Sea Physics Reanalysis	Buoy
Spatial Resolution	0.01° × 0.01°	0.042° × 0.042°	Point measurement
Temporal Resolution	January 2012 - December 2024	January 2012- May 2023	August 2020 – November 2021

3.1 Study Area

Figure 3 *Approximate study area location, created in ESRI's ArcGIS Pro.*

The study focuses on the marine environment surrounding the Maltese Islands and the southern part of Sicily in the Mediterranean Sea (Figure 3) between approximately 37.25 ° N to 34.5 ° N latitude and 12.6 ° E to 16 ° E longitude. This region represents a transitional zone between the Western and Eastern Mediterranean basins, making it sensitive to both local oceanographic processes and basin climate variability. Malta's coastal waters have diverse marine ecosystems, with important habitats such as the *Posidonia oceanica* seagrass meadows, which are a protected habitat and vulnerable to marine warming events. The region's economy relies heavily on fisheries and tourism, highlighting the importance of understanding marine heatwave variability here to safeguard both ecological health and human livelihoods.

3.2 Preliminary Validation

Before applying the full analysis to the Copernicus dataset, a preliminary validation step was conducted using in-situ temperature data from a buoy located off the coast of Gozo. This dataset was in CSV format and contained hourly sea surface temperature data from August 2020 through November 2021. It was used to test and refine the marine heatwave detection code in a simplified context with a single point. Using the five-day 95th percentile threshold, one MHW was detected over this period. This step not only helped verify the detection logic before scaling up to gridded datasets but also provided a reference point for comparison with the satellite-derived SST at an approximately colocated grid cell.

3.3 Surface Analysis

The primary data source for this study was ultra-high resolution satellite data from CMEMS. The specific product used was the Mediterranean Sea High Resolution and Ultra High-Resolution Sea Surface Temperature Analysis, which provides daily SST measurements from 2008 until the current date with a spatial resolution of approximately 0.01° × 0.01°, this high spatial and temporal resolution allows for detailed tracking of thermal variability in the study period. The parameter used from the SST data set was called 'analysed_sst'.

For the first step of processing through the SST data, descriptive statistics were taken from each grid cell and then the overall statistics were calculated for the entire surface of the study area using the xarray library. The individual grid cell statistics were exported into a CSV file. A custom Python script was developed to analyze the satellite data from CMEMS covering the period from 2012-2024. This analysis aimed to detect MHW events within each individual grid cell by identifying periods of 5 days or more where SST values exceeded the 95th percentile for that grid cell. The dataset contained 4,749 daily timestamps across 330 latitude and 408 longitude grid points. It was loaded and processed using the netCDF4 and numpy libraries. A full time series was extracted from each grid cell and the 95th percentile was calculated based on the entire 12-year period. A Boolean array was generated to identify which days exceeded this threshold. The script iterated through the time series to detect stretches of five or more consecutive days above the 95th percentile, which then classified the event as a MHW. The number of MHW events was counted and stored for each grid cell, and a map was created visualizing the frequency over the 12-year period. A second version of this SST analysis was conducted using a 10-day minimum to make a MHW event, and a map visualizing the frequency of events at this threshold was also created.

To investigate the temporal evolution of MHWs in the study area, the SST data were analyzed on a yearly basis to compute the number of heatwave events per year within each grid cell. The same percentile method used in the overall analysis was applied but the script grouped the SST time series by year and looked at annual event counts. The

95th percentile was still calculated over the full 12-year time series. The SST data were organized into annual segments using the 'pandas' library. Only the five-day threshold was examined in this analysis. The yearly counts were stored in a dictionary structure, indexed by year, enabling temporal comparisons. The output was visualized with the 'matplotlib' library which provided a static map and an animation.

3.4 Subsurface Analysis

The data source used for subsurface data was reanalysis data also from CMEMS. The specific product used was the 'Mediterranean Sea Physics Reanalysis', which provides hourly, daily, and monthly measurements of potential temperature down to around 5000 meters below sea level at a lower spatial resolution of 0.042° × 0.042°. The 'Mediterranean Sea Physics Reanalysis' is produced using a high-resolution ocean model, Nucleous for European Modelling of the Ocean (NEMO) combined with a data assimilation system (OceanVAR) that integrates satellite and in-situ observations to reconstruct past physical conditions of the Mediterranean Sea. Only the daily measurements were used for the analysis. The reanalysis spans from 1987 until mid-2023. This dataset provides a four-dimensional array of temperature values across time, depth, latitude, and longitude. A similar approach to the SST analysis was used. Nine different depths were analyzed, ranging from 1.02m to 513.29m below sea level and were processed in individual files. The parameter used within the subsurface datasets was called 'thetao'. The data is on a slightly smaller time scale than the SST data because the available CMEMS data ended on May 31, 2023, while the SST data is available to the current date. Each depth file contained 4,169 daily time stamps,1 depth, 66 latitudes, and 81 longitudes. Descriptive statistics for each grid cell at every depth were taken and put into a CSV file and overall statistics for each depth were also measured.

The method used to detect marine heatwaves in the reanalysis dataset largely mirrored the procedure described for the SST analysis. The five-day, 95th percentile threshold was applied to identify marine heatwave events, defined as consecutive periods exceeding this threshold. In this analysis, the methodology was extended to incorporate multiple vertical layers, enabling the detection of heatwave events at various depths within the water column. A complete time series from 2012 to May 2023 was processed at each latitude–longitude–depth coordinate, resulting in a three-dimensional matrix of heatwave frequency. As with the SST analysis, both the full time series and annual datasets were extracted for further examination. The same analysis was performed using the 10-day threshold as well. Maps were generated using the 'matplotlib' library to visualize the results. Annual counts of marine heatwave events were calculated using the same methodology as applied in the SST analysis. These results were used to produce both static maps and an animation, and were subsequently compared with the bathymetry of the study area to explore spatial patterns in relation to seafloor topography. A visual representation of the workflow used to process both sets of data can be seen in Figure 4.

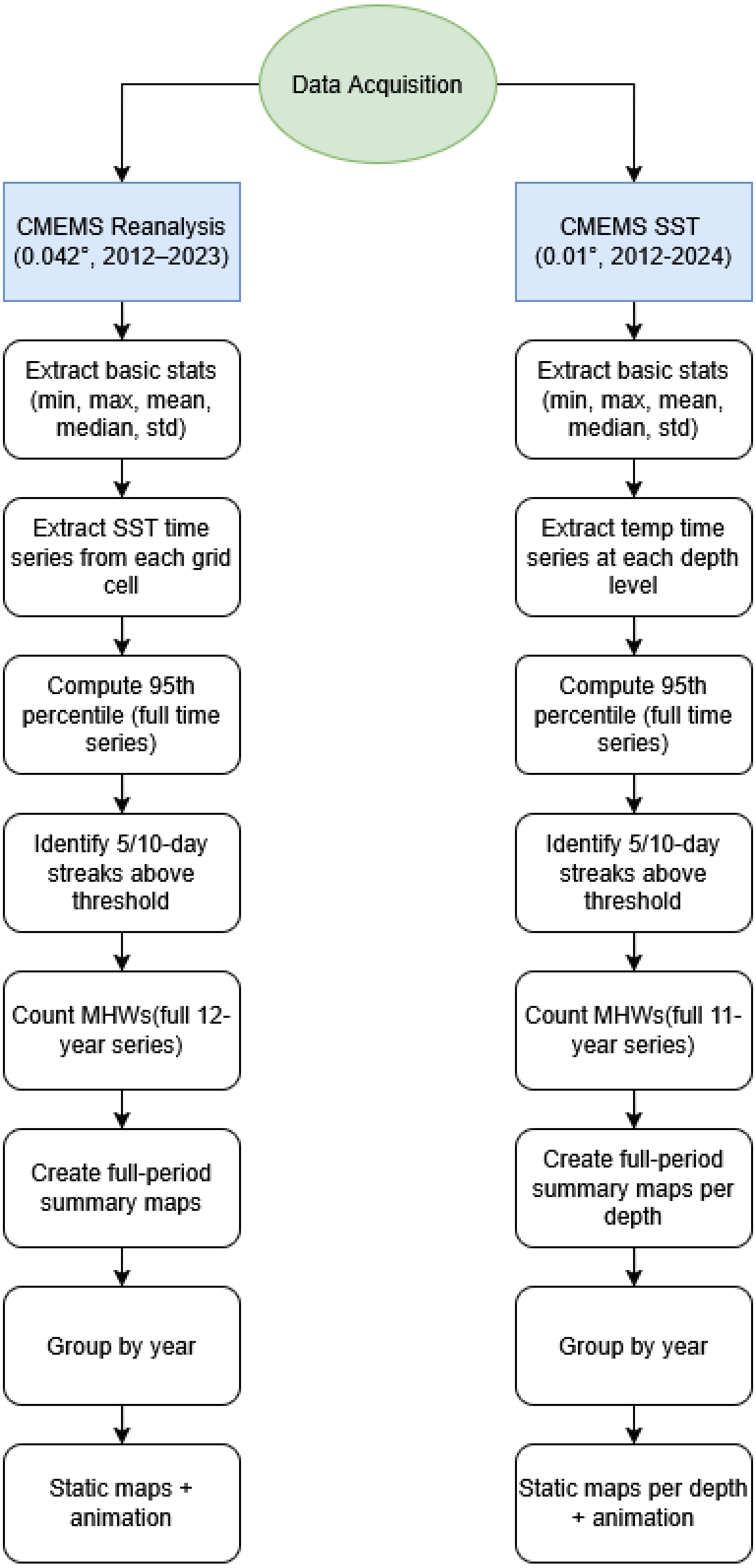

Figure 4 *A chart showing the workflow process for each set of data.*

3.5 Computational Environment

All the data were accessed in netCDF format and processed using the Python library netCDF4. Due to the size and resolution of the datasets involved, processing times varied. The ultra-high-resolution CMEMS SST data required approximately 27 hours to complete the full 12-year MHW count, with an additional 40 hours needed to process the annual breakdown. In contrast, the lower-resolution reanalysis dataset took only about 90 minutes to process the nearly 11-year MHW count at each depth, with the yearly breakdown requiring approximately the same amount of time. All data processing was carried out locally on a personal laptop equipped with an AMD Ryzen 9 7940HS processor (8 cores, 16 threads, 4.0 GHz base clock) and 16 GB of RAM, running Python 3.11 within a Jupyter Notebook environment. These processing times show the computational tradeoffs between high-resolution and coarser datasets.

4. Results and Discussion

Following the methodology described earlier, this section presents the results and discussion of MHW frequency, depth distribution, and temporal variability in the central Mediterranean Sea. The analysis includes surface and subsurface trends, supported by comparisons across datasets, to provide a multidimensional understanding of MHW dynamics.

4.1 Statistics

Descriptive statistics were computed across the study area, including global temperature metrics (Table 2). The analysis reveals a clear vertical gradient in water temperature, with values decreasing with depth. At the surface, the mean temperature is approximately 20.9°C, ranging from 12.2°C to 31.3°C, reflecting substantial variability likely driven by diurnal and seasonal fluctuations. In the upper ten meters, mean temperatures gradually decline from 20.8°C to 20.3°C, suggesting a relatively well-mixed surface layer. Correspondingly, the standard deviation also decreases slightly with depth, indicating reduced thermal variability compared to the surface.

At mid-depths (approximately 19 to 51 m), mean temperatures drop from 19.7°C at 19.4 m to 17.2°C at 51.4 m, with a further reduction in variability. Below 100 m, temperatures stabilize around 16°C at 105 m and reach 14 to 15°C between 200 and 500 m. These deeper layers exhibit very low standard deviations, implying minimal temperature fluctuations. Although cooler, the reduced variability at depth suggests that these waters retain heat for longer periods, potentially supporting marine heatwaves of extended duration.

Table 2 *Statistics calculated for each depth level globally.*

Depth (m)	Mean (°C)	Median (°C)	Min (°C)	Max (°C)	Std. Dev.
0.0	20.90	20.33	12.19	31.29	4.55
1.02	20.76	19.83	12.66	30.57	4.55
3.17	20.65	19.72	12.66	30.35	4.49
5.46	20.54	19.61	12.66	30.14	4.43
10.54	20.30	19.37	12.84	30.06	4.27
19.4	19.68	18.73	13.28	29.36	3.88
51.38	17.20	16.65	13.06	25.84	1.99
104.94	16.00	15.91	13.65	21.47	0.82
203.17	14.98	14.94	13.59	16.76	0.39
513.29	14.20	14.20	13.45	15.00	0.14

4.2 Preliminary Validation

Using the in-situ buoy data, a preliminary validation was conducted to assess the accuracy of the satellite SST data. The buoy, located off the coast of Gozo (approximately 36.08° N, 14.25° E), recorded hourly sea surface temperature measurements from August 2020 through November 2021. Corresponding coordinates and the matching time window were extracted from the ultra-high SST data for comparison. Both datasets showed the presence of a single marine heatwave event during this period and had a similar measurement of the 95th percentile at 28.37 °C from the buoy data and 28.23 °C from the satellite-derived grid cell. A time series plot was created (Figure 5) and shows temperature trends and indicates where values exceeded the 95th percentile, demonstrating the similarities between datasets. This validation supports the reliability of the satellite data and MHW detection method used in this analysis.

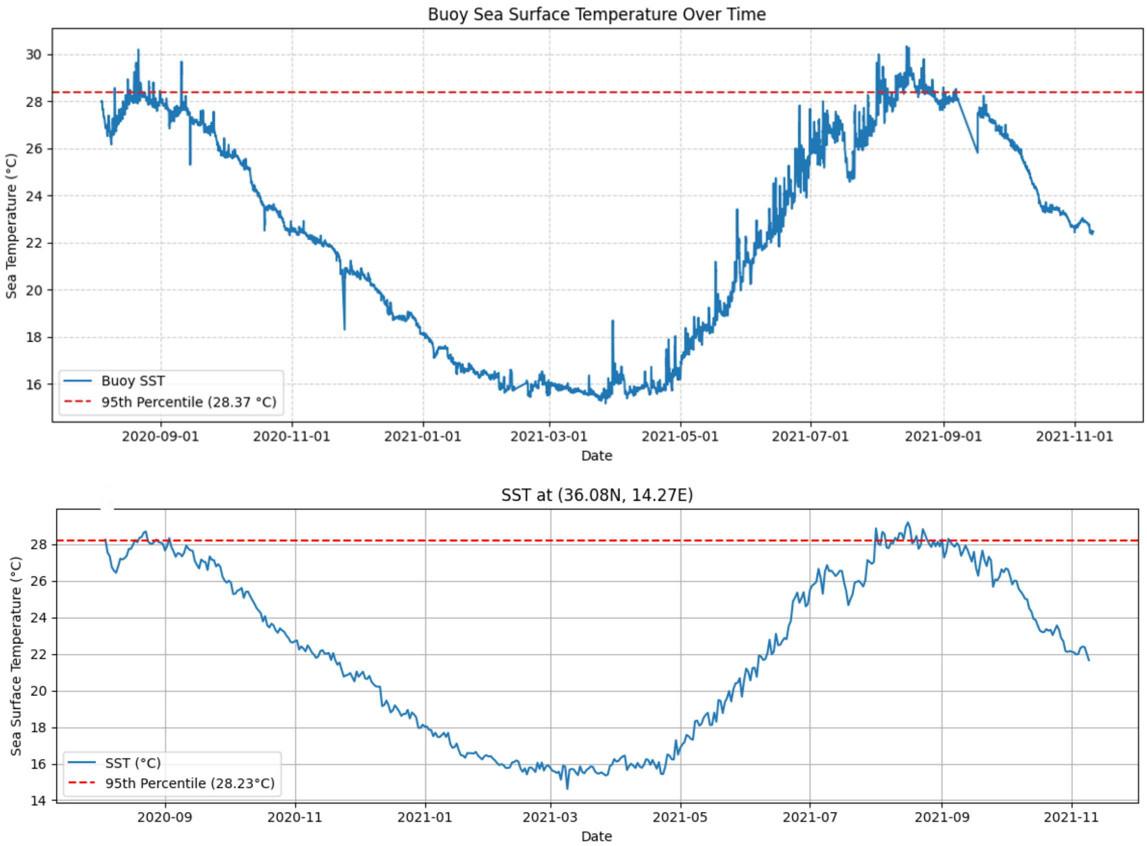

Figure 5 *Time series plots comparing the in-situ and satellite data (buoy data on top, satellite data on the bottom).*

4.3 Overall MHW Analysis of SST

The ultra-high resolution SST analysis revealed widespread MHW activity across the study area between 2012 and 2024. Using the five-day 95th percentile threshold, MHWs were detected in every grid cell across the study area, indicating the frequency of extreme thermal events in the central Mediterranean Sea, however, the intensity of the spatial frequency varied across the region. The Malta Channel, located between Sicily and Malta, the southwestern coast of Sicily, and the northwestern sector of the domain, had a higher MHW frequency comparatively to the rest of the study area. These areas had higher intensity shading on the 12-year cumulative map (Figure 6), with some grid cells reaching 25 detected events over the study period. This pattern indicates frequent and persistent MHW occurrences, that could be influenced by local circulation dynamics and oceanographic features that contribute to surface heat retention.

Lower MHW activity was seen in regions near the Malta Escarpment and southeastern Sicily, as well as in the waters to the south of Malta. There is less intensity shading on the cumulative map, suggesting reduced MHW frequency. However, even in these areas, MHWs are still present in every grid cell, at a minimum over the 12-year period one heatwave occurred. The reduced frequency in these areas could be because of stronger vertical mixing and deeper bathymetry which can help limit the persistence of anomalously warm surface layers. For example, the waters after passing the Malta Escarpment dip to 3,000 meters and deeper, which could contribute to cooler water upwelling or inhibit stratification, in turn reducing long-duration heat anomalies on the surface.

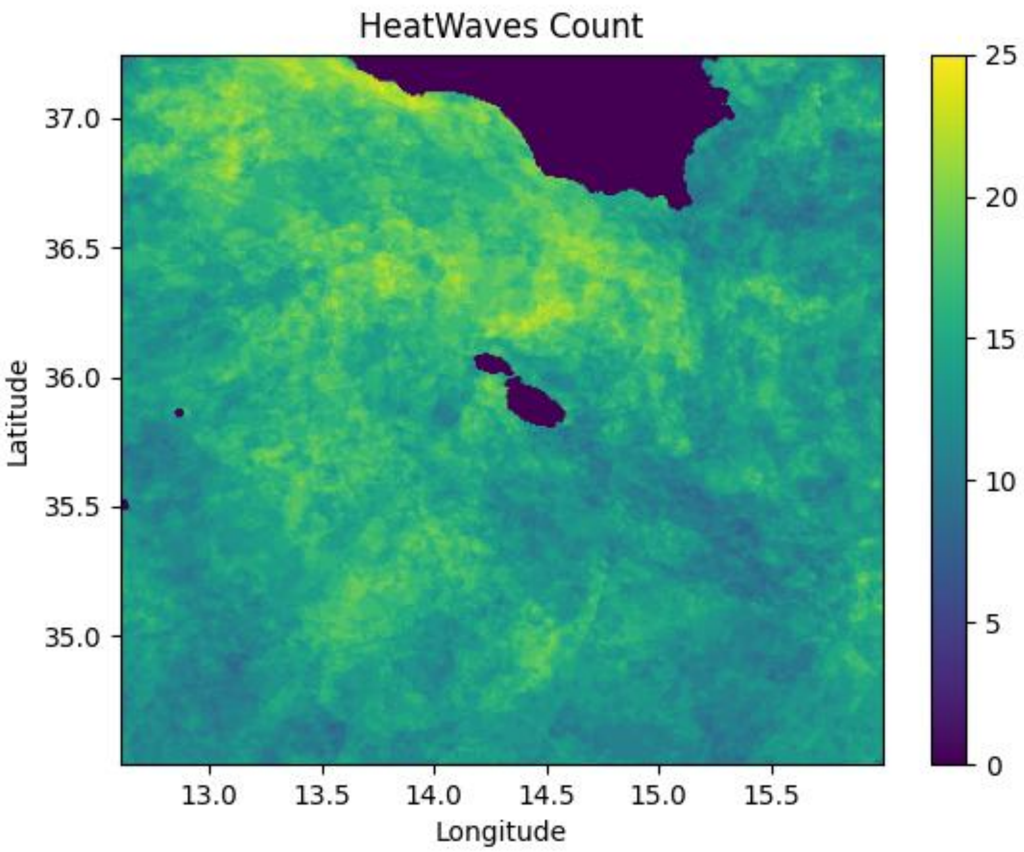

Figure 6 *Ultra high resolution MHW count map (2012-2024).*

To assess the influence of event duration on MHW detection, a second analysis was conducted using a 10-day threshold (Figure 7). The number of events per grid cell decreased by around half compared to the 5-day threshold, indicating that a significant portion of heatwaves in the region are shorter. The overall spatial distribution was consistent with the 5-day threshold, with higher frequencies occurring in the northwestern part of the study area and off the southwestern coast of Sicily. The Malta channel exhibited a change when the 10-day threshold was introduced, where there was a sharper decline in MHWs using the 10-day threshold compared to other parts of the study area. This suggests that while the channel experiences frequent heatwaves, they may not last beyond five to nine days. This could be due to the hydrography of the channel, where surface warming may be disrupted more quickly by local current systems or exchanges between the eastern and western Mediterranean basins.

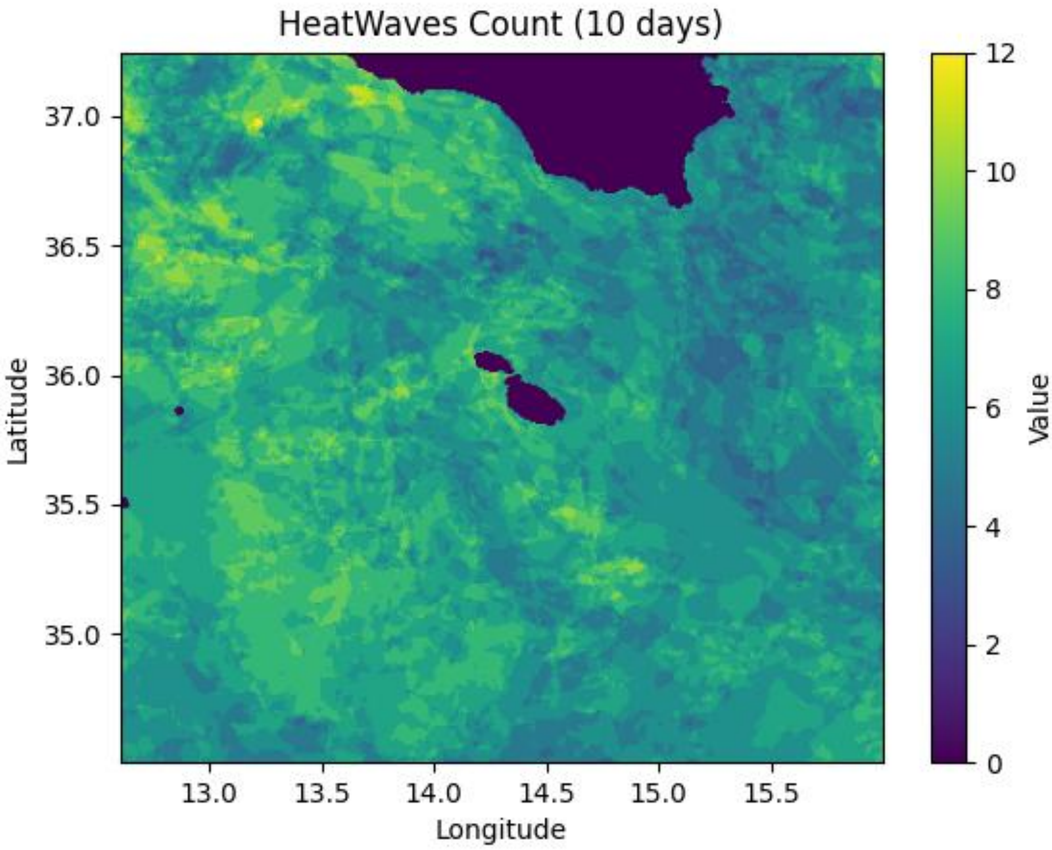

***Figure** 7 Ultra high resolution MHW count map for a 10-day threshold (2021-2024).*

These findings have ecological implications. Regions with frequent MHW activity, particularly off the coast of Sicily, are home to *Posidonia oceanica* meadows which are vulnerable to heat stress. There are also fisheries in the region that could be affected negatively by the increased MHWs. Lower intensity areas south of Malta could be seen as thermal refuges, there are already MPAs located of the coast of Malta in this area, but this assumption would require further ecological validation.

These cumulative maps show the spatial complexity of MHW behavior in the region. Regions like the Malta channel may be exposed to more frequent but transient

MHWs, while areas like the coast off southwestern Sicily could be more vulnerable to sustained extreme warming.

4.4 Yearly Sea Surface Temperature

The yearly analysis of MHWs (Figure 8) in SST across the study area from 2012 through 2024 reveals some interannual variability in both the frequency and spatial distribution of events. Using the 5-day 95th percentile threshold for detection, the data shows a clear pattern of fluctuating MHW intensity and extent, with several years exhibiting heightened activity and others marked by absence of heatwaves evets.

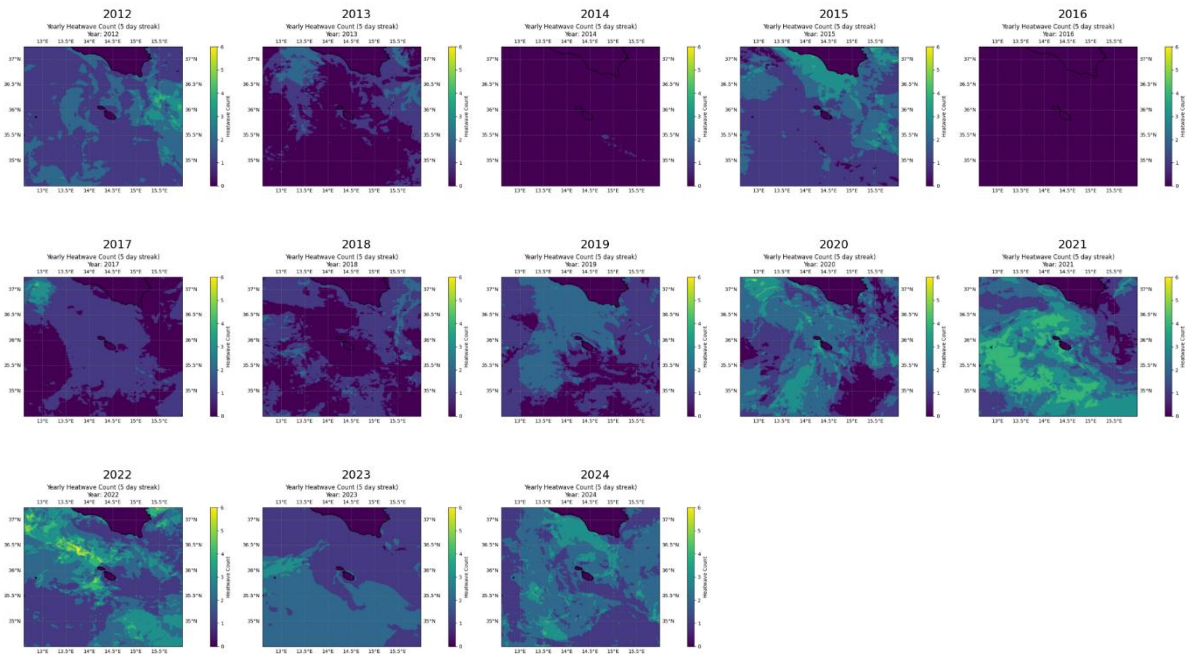

Figure 8 *Ultra high resolution MHW count variations per year.*

In 2012, almost every grid cell experienced at least one MHW event, with concentration of up to four events in a hotspot around the Malta Escarpment, southeast of Sicily. The following two years, 2013 and 2014, saw a significant reduction in MHW activity with 2014 being quite sparse, only one event in the southeastern part of the study area was counted. In 2015 MHWs increased from the previous year, multiple events were detected off the Sicilian coastline, the Malta Channel, and again near/past the Malta Escarpment. This increase aligns with warming trends in the Mediterranean during the mid-2010s. However, in 2016 there were no MHWs recorded at all, which could be connected to the transition that year from El Niño to La Niña, bringing cooler sea surface temperatures to the region.

From 2017 onward, frequency of events increased. Both 2017 and 2018 showed moderate activity with around half the study area experiencing at least one event. The northwestern part of the study area was highly affected by a large heatwave event. These spread around temperatures within the two years could be correlated to the two cyclones that passed through the area, Cyclone Numa in 2017 and Cyclone Zorbas in 2018, which could alter local oceanographic conditions. In 2019 the frequency continued to rise, particularly off the Sicilian coast and within the Malta Channel, this is could have been due to the intense western European atmospheric heatwave that occurred that year.

In 2020, up to four MHW events occurred in large areas of the northwest study area, with more events in the waters south of Malta. The southeast was unaffected this year, showing the spatial variability in heatwave persistence. The subsequent year 2021 was the worst within the dataset. It had extensive heatwave coverage spanning from Malta to Linosa. The widespread nature and duration of these events coincide with the rising atmospheric temperatures that are being experienced across continental Europe, the ocean temperatures also being driven by climate change. Although 2022 had less intensity in MHWs than 2021, it maintained high activity, especially in the northwest extending down to Gozo and along the Sicilian coast. 2023 showed a decrease in activity, but there was still at least one event per grid cell over almost the entire study area, with more multi-event areas in the south. By 2024, MHW event count increased again, with scattered areas of four count events and concentrations of events in the south, off the coast of Sicily, and within the Malta Chanel, there is a slight swirling pattern in the event counts in the channel, which could indicate the influence of local currents in MHW dynamics.

Overall, the yearly SST analysis reveals the dynamic nature of MHWs in the study area, influenced by a combination of atmospheric forcing and oceanographic processes. The spatial hotspots appearing around the Malta Channel and off the coast of Sicily. The interannual variability observed in the data indicates the importance of continuous monitoring to capture both shorter- and longer-term trends. The temporal patterns show a worrying increase in extreme events leading up to the present and may continue to rise in the future.

4.5 Subsurface Temperature Analysis

The subsurface analysis spanned nine depths ranging from 1.02 m to 513.29 m, it is important to note that this dataset has a lower spatial resolution, and a slightly shorter timespan (2012-2023) compared to the surface SST dataset. These limitations must be considered when interpreting patterns of MHW frequency and extent at depth. Despite these limitations, MHWs were detected at every depth level and in almost every grid cell where bathymetric conditions permitted valid data. Overall, the maximum number of MHWs reached across all depths was 21 years over the course of the 11-year period (Figure 9). The presence of MHWs vertically confirms that these events are not just limited to the surface but also occur deeply into the water column, in agreement with findings from Schaeffer & Roughan (2017) and Elzahaby & Schaeffer (2019).

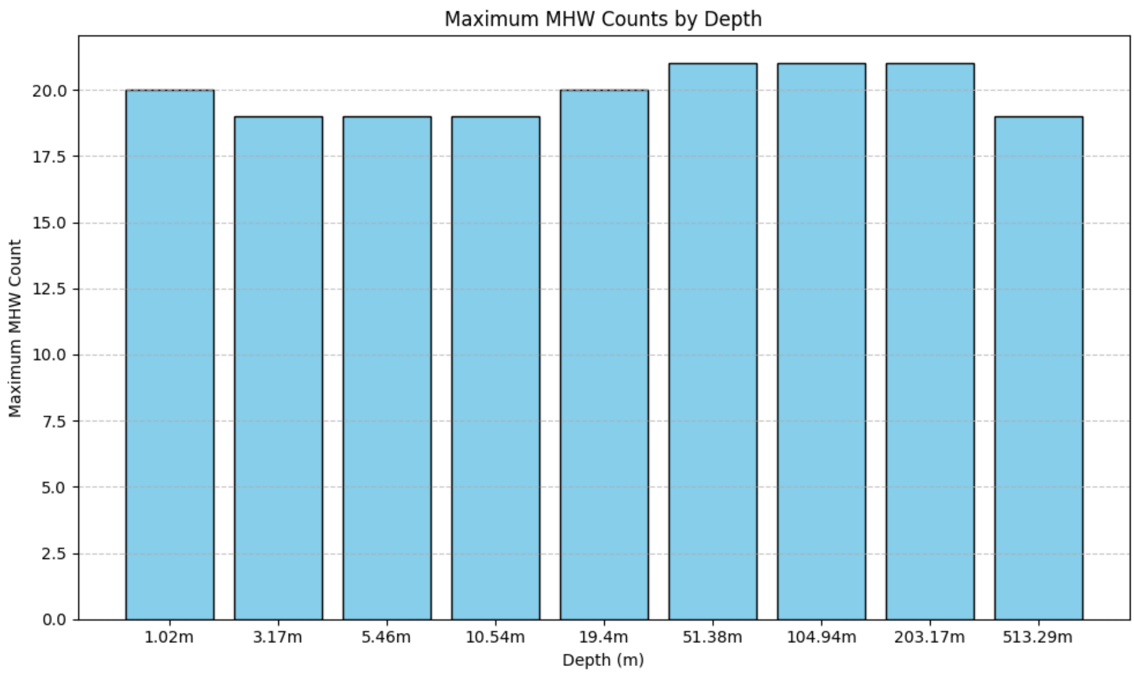

Figure 9 *Histogram comparing the maximum number of MHWs at each depth level.*

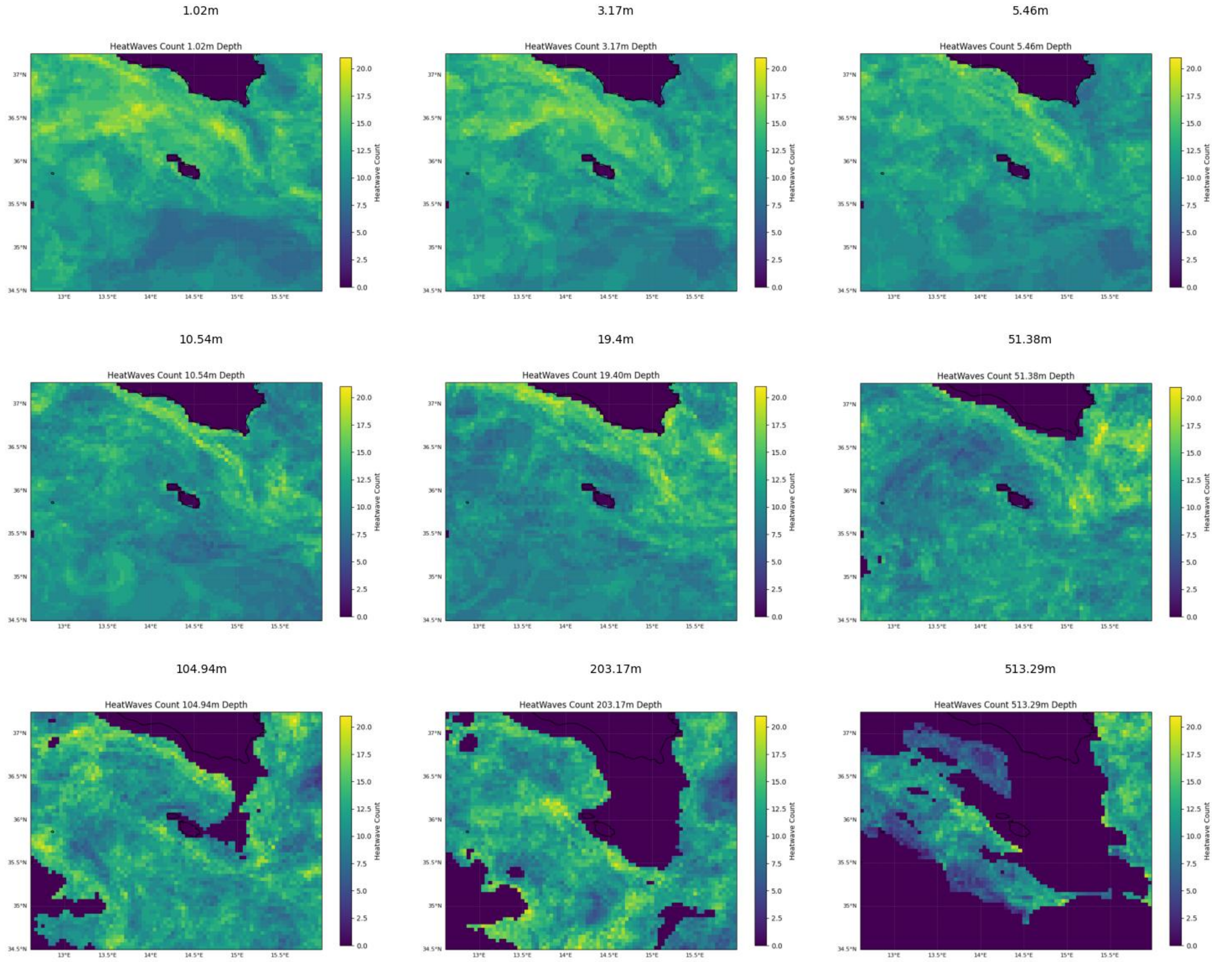

Figure 10 *All nine measured depths showing spatial variation at the five-day threshold.*

Within the shallower layers (1.02 m and 3.17 m) spatial patterns closely mirrored surface SST results. High MHW counts of up to approximately 20 per grid cell, were concentrated in the northwestern part of the study area, including the Malta Channel and southwestern coast of Sicily, areas previously identified as hotspots (Figure 10). At 5.46 m and 10.54 m, a subtle eastward shift in MHW hotspots shows up. The Malta Channel remains a hotspot, but higher activity appears to expand further along the eastern coastline of Sicily. Additionally, the area past the Malta Escarpment begins to show increased MHW presence, indicating warming influences extending into deeper waters. At 19.4 m, this pattern continues with elevated counts along the eastern and southeastern portions of the area, including more activity in the coastal zones of southern Sicily. This could support the idea of a vertical continuity or downward propagation of heat, possibly driven by local oceanography.

At 51.36 m there is a reduction in MHWs being detected, there are still events in almost every depth-valid grid cell but there are not any large hot spots occurring. Within the grid cells that have no MHWs detected this is because of the local bathymetry. Much of the shallow coastal shelf around Sicily does not reach this depth and the resulting gaps in the data are where the seafloor is too shallow (Figure 11). Some higher count areas persist, particularly in the northeastern portion of the study area. The 104.94 m depth layer shows a dispersed distribution of MHWs with higher numbers of events scattered throughout the study area. At 203.17 m it shows a similar pattern to the 104.94 m depth with no particularly large hotspots, aside from one area to the west of Gozo.

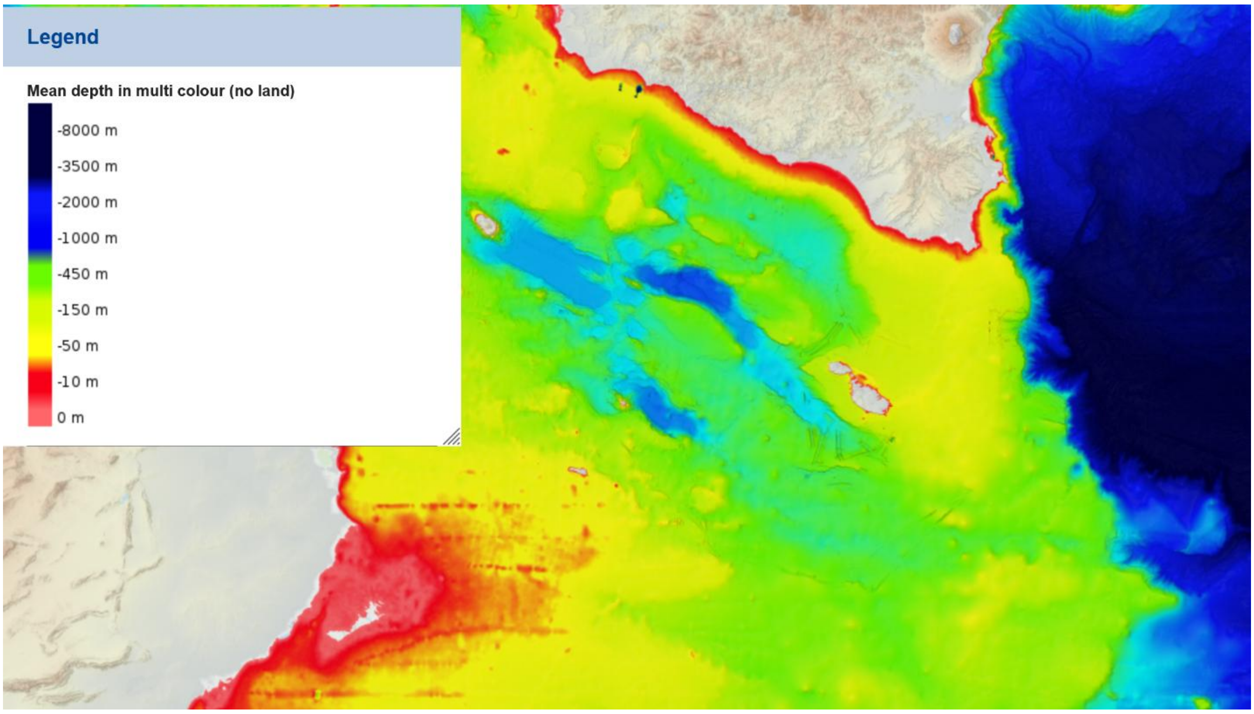

Figure 11 *Estimated bathymetry of the study area from the European Marine Observation and Data Network (EMODnet).*

At the deepest level analyzed, 513.29 m, MHWs are still detectable, especially in areas beyond the Malta Escarpment, within the Ionian Sea basin. This is concerning because it reveals that extreme thermal anomalies penetrate into the deep ocean. Spatial patterns at this differ from the surface, supporting findings from Fernández-Barba et al. (2024) that deeper MHWs may be governed by different mechanisms than surface anomalies.

There is a visual pattern here that shows a gradient of events happening, where once the MHW events are measured at a depth that is close to the sea floor, a higher number of events occur in that area. For example, looking at the 19.4 depth, there is a high count around the coastline of Sicily where the seafloor depth is approximately 20 – 30 m, indicating a higher intensity of events as the water gets closer to the sea floor. This creates the impression of a vertical gradient where heat accumulates near the bottom in some areas, perhaps due to weak stratification or downwelling processes.

Applying the 10-day threshold to the subsurface analysis produced a reduction in MHW frequency across all depths, as is consistent with the surface findings. The events are reduced to about half, but every grid cell still indicated at least one event over the study period. So, longer duration is less common but subsurface waters throughout the region are consistently impacted (Figure 12).

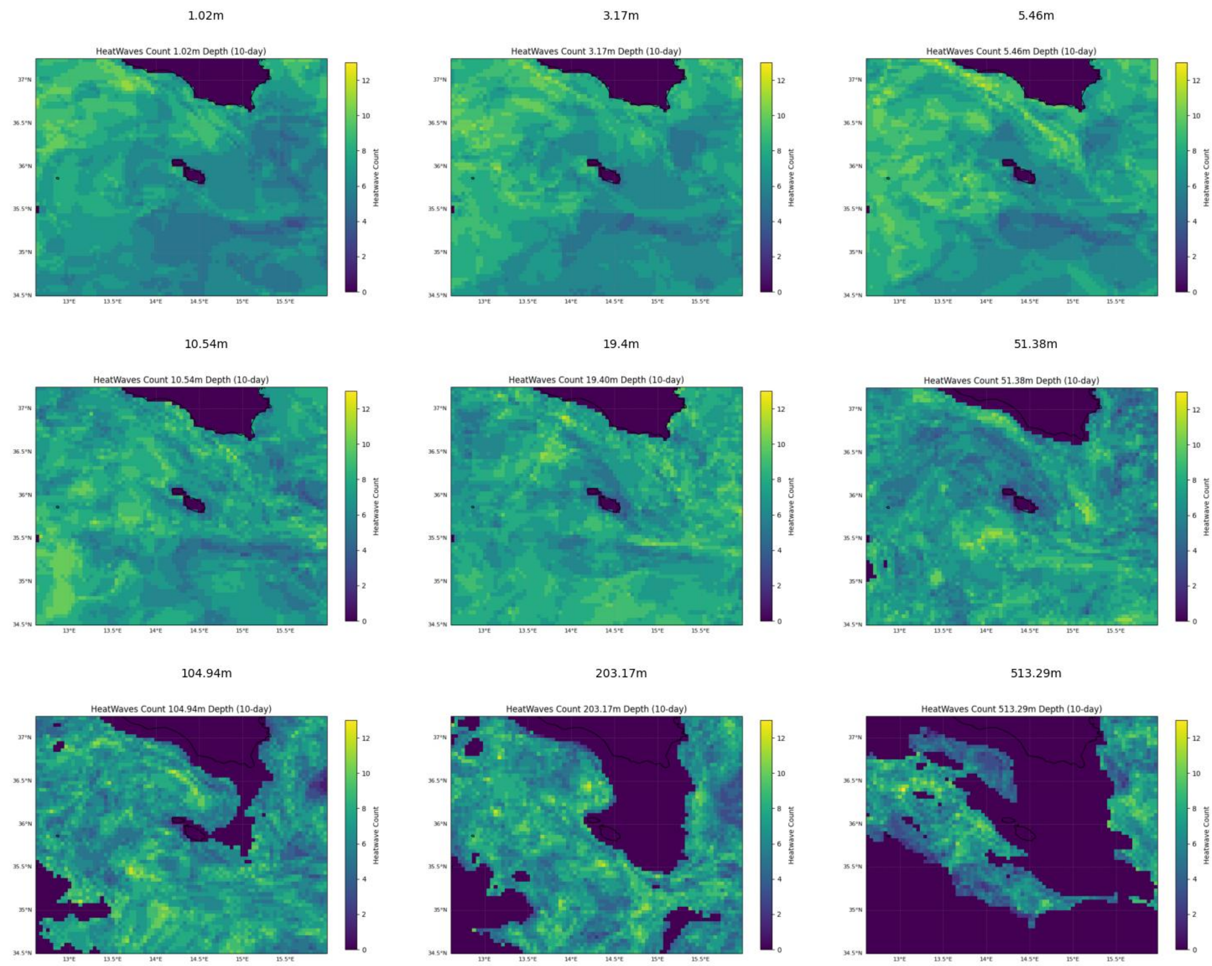

Figure 12 *MHW counts at nine different depths for the 10-day threshold.*

The spatial distribution under the 10-day threshold differed from the 5-day threshold results at certain depth levels. For example, at 19.4 m hot spot locations shifted, showing potential variability in local oceanographic drivers at longer durations. In other layers spatial clustering is broader, with fewer concentrated hotspots but larger contiguous regions experiencing the same number of MHWs. This could indicate that deeper layers maintain elevated temperatures for longer across wider areas.

In 51.38 m there is a higher number of hotspots than under the 5-day threshold, even though the total number of events was lower. The deepest layers of the analysis, 203.17 m and 513.29 m showed strong pattern similarity to their 5-day counterparts. This analysis shows that while intensity decreases with a higher threshold, longer subsurface MHWs are still occurring extensively throughout the region.

Deep water MHWs are frequent, particularly in the offshore regions and may pose hidden risks to benthic ecosystems that rely on these habitats. These findings show that it is important to integrate vertical MHW assessments in both ecological risk modeling and regional ocean management strategies.

4.6 Yearly Subsurface Analysis

Three depths, 10.54 m, 51.38 m, and 203.17 m were selected to represent shallow, mid, and deeper subsurface dynamics yearly. The 10.54 m layer closely reflects surface variability but begins to diverge in spatial distribution, while the 51.38 m layer is the first that is significantly influenced by bathymetry. The 203.17 m layer captures changes past the Malta Escarpment and into the Ionian Sea, where surface and deep anomalies can differ.

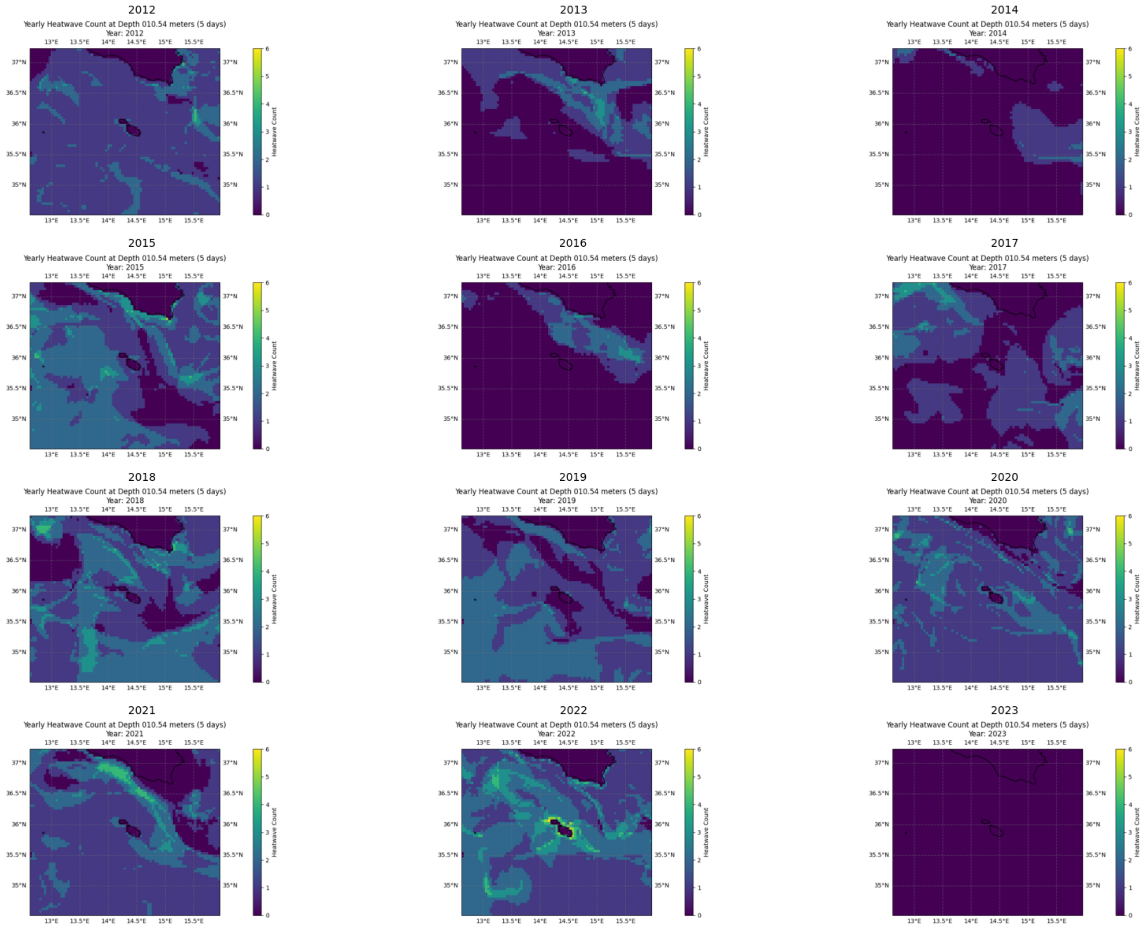

Figure 13 *Yearly variations of MHW count at 10.54 meters deep.*

At 10.54 m, patterns are similar to the surface. 2012 showed widespread MHWs across the study area (Figure 13). 2013-2014 saw a sharp decline in events, follow by increased activity in 2015, particularly along the Sicilian coast and in the Malta Channel. 2016-2018 had patch distributions, with localized hotspots appearing in the northwest. The most intense periods occurred in 2020 and 2021, with many grid cells showing multiple MHWs. 2022 remained active especially along the Maltese coastline, though 2023 showed no events, this is likely due to limited data coverage (ending May 31, 2023).

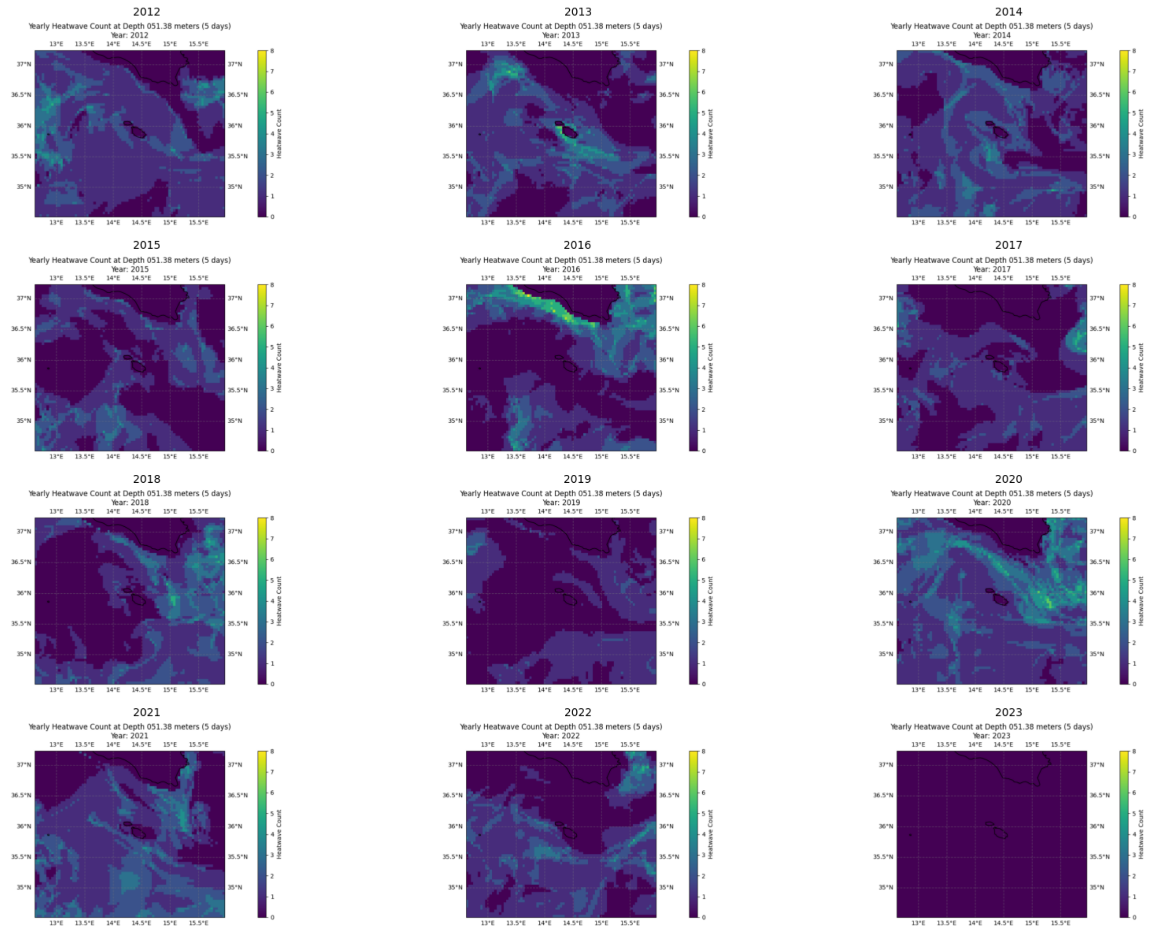

Figure 14 *Yearly variations of MHW count at 51.38 meters deep.*

At 51.38 m, the spatial distribution of MHWs shifted in response to seafloor depth (Figure 14). 2012-2014 saw relatively broad distribution, especially in deeper western and southwestern areas. A distinct hotspot emerged past the escarpment in 2017-2018 where up to five MHWs were recorded in some grid cells. 2020-2021 again marked high activity with events concentrated along the southwest coast of Sicily and extending towards the Malta Channel. Bathymetric dimensions were evident in areas like Sicily's immediate coast, where depths shallower than 50 m were not detected.

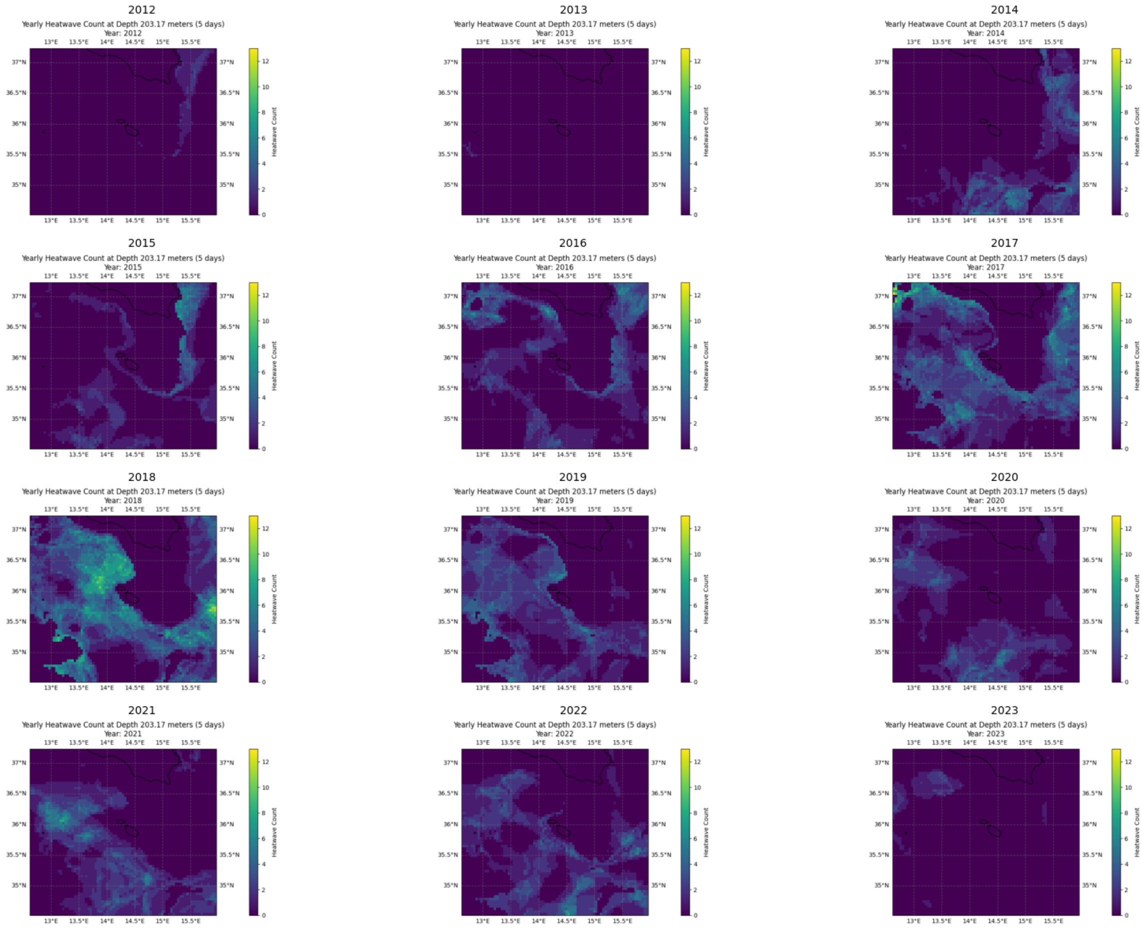

Figure 15 *Yearly variations of MHW count at 203.17 meters deep.*

At 203.17 m heatwaves were confined to areas where sufficient depth existed (Figure 15). 2015-2018 were highly active with up to 10-12 MHWs in some cells. With the highest count and spatial distribution occurring in 2018. These years also showed consistent hotspots east past the escarpment and west of Malta. Activity remained elevated through 2020-2021, especially in the western and southwestern corners. 2023 still showed early-year MHWs, despite the partial data. Notably, the 203.17 m depth exhibited a higher count of marine heatwave events compared to shallower depths, indicating that heatwave activity persists and can even intensify at greater depths.

4.7 Surface Vs Subsurface

While comparing the surface and subsurface MHW data across the study area, it reveals both consistent patterns and notable differences in MHW behavior throughout the water column. Surface waters, analyzed from 2012 to 2024, showed MHW activity in every grid cell, with particularly high frequencies in the Malta Channel, along the southwestern Sicilian coast, and in the northwestern portion of the study area.

Subsurface data similarly exhibited MHW events in nearly every depth-valid grid cell. The shallowest layers mirrored the SST patterns, confirming vertical adherence to surface warming. However, as depth increased, the spatial distribution of MHWs began to diverge. At depths like 10.54 m and 19.4 m, MHW hotspots shifted east and extended into deeper regions past the Malta Escarpment, indicating possible downward propagation of heat or influence of subsurface current systems. The mid-depth layers showed changes driven by bathymetry, MHWs were absent in shallower zones not reaching depth, while deeper offshore regions retained high event counts. Marine heatwave events were still detected in the deepest layers analyzed, particularly within deep basins located beyond the escarpment. The presence of these events at depth may indicate the influence of physical processes such as downwelling or vertical heat transport.

Temporal patterns also varied. Surface data showed interannual variability with high event years such as 2020 and 2021 which were marked by broad spatial impact, while low activity years like 2016 and 2014 showed minimal to no surface warming. Subsurface layers reflected similar temporal trends in the shallow and mid-level depths but also showed that deeper events can persist even during years with fewer surface anomalies.

When applying a longer ten-day threshold, both surface and subsurface datasets showed a reduction of MHW frequency by about half. However subsurface patterns became broader and more diffuse, especially at deeper levels. This indicates that longer duration MHWs can span large volumes of the water column.

Surface MHWs capture the immediate expression of marine heat extremes while subsurface analysis reveals a picture that includes delayed or persistent warming. The two perspectives together emphasize the importance of vertical MHW monitoring, especially given the ecological implications for both pelagic and benthic systems. Understanding these dynamics is crucial for assessing long-term thermal stress.

4.8 Limitations

While this analysis provides insight into the spatial and vertical patterns of marine heatwaves in the central Mediterranean, there are several limitations to consider. Constraints related to computing power, disk space, and processing time restricted the size of datasets used, especially for longer term, higher resolution datasets. These limitations may have affected some of the results, particularly for the subsurface datasets. However, the strength of this approach is its reproducibly.

5. Conclusions

This study aimed to investigate where and how MHWs have occurred in the Maltese region over the past decade and to determine whether these events also occur at subsurface depths. Using satellite-derived SST and CMEMS reanalysis data, supported by in-situ validation, the study revealed clear spatial and vertical patterns in MHW frequency and intensity. Events were widespread, with hotspots in the Malta Channel and southwest of Sicily. Subsurface analysis showed that MHWs extend below the surface, often persisting across multiple depth layers, with deep-water events displaying distinct spatial patterns and longer durations. A notable increase in MHW frequency was observed in recent years (especially 2020–2021), along with strong spatial variability in event duration. While shallow subsurface layers reflected surface trends, deeper layers diverged, likely influenced by local oceanographic and bathymetric features. These results are consistent with previous studies (e.g., Schaeffer & Roughan, 2017; Fernández-Barba et al., 2024) and emphasize the need for continued multi-depth monitoring.

Several limitations affected this study. Differences in spatial resolution and temporal coverage between surface and subsurface datasets limited direct comparisons. The number of depth levels was restricted by processing time. Future work should expand vertical resolution, incorporate longer time series, and explore the ecological consequences and drivers of subsurface MHWs. Despite its limitations, this study contributes valuable, region-specific insight into the vertical structure of MHWs using openly available datasets and provides a foundation for future marine climate monitoring in the central Mediterranean.

References

Atalah, J., Ibañez, S., Aixalà, L., Barber, X., & Sánchez-Jerez, P. (2024). Marine heatwaves in the western Mediterranean: Considerations for coastal aquaculture adaptation. *Aquaculture*, *588*, 740917. https://doi.org/10.1016/j.aquaculture.2024.740917

Biological diversity in the Mediterranean | UNEPMAP. (n.d.). Www.unep.org. https://www.unep.org/unepmap/resources/factsheets/biological-diversity

Bonino, G., Giuliano Galimberti, Masina, S., McAdam, R., & Clementi, E. (2024). Machine learning methods to predict sea surface temperature and marine heatwave occurrence: a case study of the Mediterranean Sea. *Ocean Science*, *20*(2), 417–432. https://doi.org/10.5194/os-20-417-2024

Darmaraki, S., Denaxa, D., Theodorou, I., Livanou, E., Rigatou, D., Raitsos E., D., Stavrakidis-Zachou, O., Dimarchopoulou, D., Bonino, G., Mcadam, R., Organelli, E., Pitsouni, A., & Parasyris, A. (2024). Marine Heatwaves in the Mediterranean Sea: A Literature Review. *Mediterranean Marine Science*, *25*(3), 586–620. https://doi.org/10.12681/mms.38392

Dayan, H., McAdam, R., Juza, M., Masina, S., & Speich, S. (2023). Marine heat waves in the Mediterranean Sea: An assessment from the surface to the subsurface to meet national needs. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1045138

Elzahaby, Y., & Schaeffer, A. (2019). Observational Insight Into the Subsurface Anomalies of Marine Heatwaves. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00745

EMODnet Map Viewer. (2023). Europa.eu; emodnet-central-portal. https://emodnet.ec.europa.eu/geoviewer/#

Fernández-Barba, M., Huertas, I. E., & Navarro, G. (2024). Assessment of surface and bottom marine heatwaves along the Spanish coast. *Ocean Modelling*, *190*, 102399. https://doi.org/10.1016/j.ocemod.2024.102399

Free, C. M., Anderson, S. C., Hellmers, E. A., Muhling, B. A., Navarro, M. O., Richerson, K., Rogers, L. A., Satterthwaite, W. H., Thompson, A. R., Burt, J. M., Gaines, S. D., Marshall, K. N., J. Wilson White, & Lyall Bellquist. (2023). Impact of the 2014–2016 marine heatwave on US and Canada West Coast fisheries: Surprises and lessons from key case studies. *Fish and Fisheries*, *24*(4), 652–674. https://doi.org/10.1111/faf.12753

Frölicher, T. L., Fischer, E. M., & Gruber, N. (2018). Marine heatwaves under global warming. *Nature*, *560*(7718), 360–364. https://doi.org/10.1038/s41586-018-0383-9

Genevier, L. G. C., Jamil, T., Raitsos, D. E., Krokos, G., & Hoteit, I. (2019). Marine heatwaves reveal coral reef zones susceptible to bleaching in the Red Sea. *Global Change Biology*, *25*(7). https://doi.org/10.1111/gcb.14652

Gomes, D. G. E., Ruzicka, J. J., Crozier, L. G., Huff, D. D., Brodeur, R. D., & Stewart, J. D. (2024). Marine heatwaves disrupt ecosystem structure and function via altered food webs and energy flux. *Nature Communications*, *15*(1), 1988. https://doi.org/10.1038/s41467-024-46263-2

Guibourd de Luzinais, V., Gascuel, D., Reygondeau, G., & Cheung, W. W. L. (2024). Large potential impacts of marine heatwaves on ecosystem functioning. *Global Change Biology*, *30*(7). https://doi.org/10.1111/gcb.17437

Hamdeno, M., & Alvera-Azcaráte, A. (2023). Marine heatwaves characteristics in the Mediterranean Sea: Case study the 2019 heatwave events. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1093760

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

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., & Wernberg, T. (2019). A global assessment of marine heatwaves and their drivers. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-10206-z

Holbrook, N. J., Sen Gupta, A., Oliver, E. C. J., Hobday, A. J., Benthuysen, J. A., Scannell, H. A., Smale, D. A., & Wernberg, T. (2020). Keeping pace with marine heatwaves. *Nature Reviews Earth & Environment*, *1*(9), 482–493. https://doi.org/10.1038/s43017-020-0068-4

Le Traon, P. Y., Reppucci, A., Alvarez Fanjul, E., Aouf, L., Behrens, A., Belmonte, M., Bentamy, A., Bertino, L., Brando, V. E., Kreiner, M. B., Benkiran, M., Carval, T., Ciliberti, S. A., Claustre, H., Clementi, E., Coppini, G., Cossarini, G., De Alfonso Alonso-Muñoyerro, M., Delamarche, A., & Dibarboure, G. (2019). From Observation to Information and Users: The Copernicus Marine Service Perspective. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00234

Martínez, J., Leonelli, F. E., García-Ladona, E., Garrabou, J., Kersting, D. K., Bensoussan, N., & Pisano, A. (2023). Evolution of marine heatwaves in warming seas: the Mediterranean Sea case study. *Frontiers in Marine Science*, *10*. https://doi.org/10.3389/fmars.2023.1193164

Marullo, S., Serva, F., Iacono, R., Napolitano, E., Alcide di Sarra, Meloni, D., Monteleone, F., Damiano Sferlazzo, Lorenzo De Silvestri, Vincenzo de Toma, Pisano, A., Bellacicco, M., Landolfi, A., Emanuele Organelli, Yang, C., & Santoleri, R. (2023). Record-breaking persistence of the 2022/23 marine heatwave in the Mediterranean Sea. *Environmental Research Letters*. https://doi.org/10.1088/1748-9326/ad02ae

Oliver, E. C. J., Benthuysen, J. A., Darmaraki, S., Donat, M. G., Hobday, A. J., Holbrook, N. J., Schlegel, R. W., & Sen Gupta, A. (2021). Marine Heatwaves. *Annual Review of Marine Science*, *13*(1), 313–342. https://doi.org/10.1146/annurev-marine-032720-095144

Schaeffer, A., & Roughan, M. (2017). Subsurface intensification of marine heatwaves off southeastern Australia: The role of stratification and local winds. *Geophysical Research Letters*, *44*(10), 5025–5033. https://doi.org/10.1002/2017gl073714

Schlegel, R. W., Oliver, E. C. J., Hobday, A. J., & Smit, A. J. (2019). Detecting Marine Heatwaves With Sub-Optimal Data. *Frontiers in Marine Science*, *6*. https://doi.org/10.3389/fmars.2019.00737

Schuckmann, von, Moreira, L., Cancet, M., Gues, F., Autret, E., Baker, J., Bricaud, C., Bourdalle-Badie, R., Castrillo, L., Cheng, L., Chevallier, F., Ciani, D., de Pascual-Collar, A, Toma, D., Drevillon, M., Fanelli, C., Garric, G., Gehlen, M., Giesen, R., & Hodges, K.

(2024). The state of the global ocean. State of the Planet, 4-osr8, 1. https://doi.org/10.5194/sp-4-osr8-1-2024

Smale, D. A., Wernberg, T., Oliver, E. C. J., Thomsen, M., Harvey, B. P., Straub, S. C., Burrows, M. T., Alexander, L. V., Benthuysen, J. A., Donat, M. G., Feng, M., Hobday, A. J., Holbrook, N. J., Perkins-Kirkpatrick, S. E., Scannell, H. A., Sen Gupta, A., Payne, B. L., & Moore, P. J. (2019). Marine heatwaves threaten global biodiversity and the provision of ecosystem services. *Nature Climate Change*, *9*(4), 306–312. https://doi.org/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., & Smale, D. A. (2021). Socioeconomic impacts of marine heatwaves: Global issues and opportunities. *Science*, *374*(6566). https://doi.org/10.1126/science.abj3593

Strydom, S., Murray, K., Wilson, S., Huntley, B., Rule, M., Heithaus, M., Bessey, C., Kendrick, G. A., Burkholder, D., Fraser, M. W., & Zdunic, K. (2020). Too hot to handle: Unprecedented seagrass death driven by marine heatwave in a World Heritage Area. *Global Change Biology*, *26*(6), 3525–3538. https://doi.org/10.1111/gcb.15065

Sun, D., Li, F., Jing, Z., Hu, S., & Zhang, B. (2023). Frequent marine heatwaves hidden below the surface of the global ocean. *Nature Geoscience*, *16*(12), 1099–1104. https://doi.org/10.1038/s41561-023-01325-w

Data Sources

Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis. *E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS).* DOI: https://doi.org/10.48670/moi-00172

Mediterranean Sea Physics Reanalysis. *E.U. Copernicus Marine Service Information (CMEMS). Marine Data Store (MDS).* DOI: https://doi.org/10.25423/CMCC/MEDSEA_MULTIYEAR_PHY_006_004_E3R1