https://doi.org/10.5194/sp-2023-22
Preprint. Discussion started: 28 August 2023

Forecasting the Mediterranean Sea Marine Heatwave of summer 2022

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Abstract. Early-warning of marine heatwaves requires short-term forecasts to provide precise information on timings, local-scale coverage and intensities of coming events. Here, we describe our successful efforts to track the onset, peak and decay of the Mediterranean Sea marine heatwave of summer 2022 with the Copernicus MedFS short-term (10-day) forecast system. First, we show that the 2022 event eclipses the economically and ecologically damaging event of 2003 in terms of MHW activity (a measure of intensity and duration). Forecasts of MHW area and activity provide a means of basin-wide validation, highlighting the capability of the system to capture regional behaviour. On local scales, we found that the MHW occurrence in the Ligurian Sea and Gulf of Taranto, two regions of economic and ecological importance, was also reliably forecast. Encouragingly, we note that the forecast has demonstrated skill in capturing not just the season-long MHW cycle but also breaks in MHW persistence and abrupt changes in local activity. Subseasonal forecasts do not yet demonstrate the capacity to predict MHW response to short-lived weather patterns, but this study confirms that short-term forecasts, at least in the Mediterranean Sea, can fill this gap.

1 Introduction

Disease outbreaks, mass mortality events and the redistribution of species induced by marine heatwaves (MHWs) lead to economic losses to fisheries and aquaculture farms, and hamper conservation efforts (Smith et al., 2021; Garrabou et al., 2022; Smith et al., 2022). The need to prepare for and mitigate these MHW-induced impacts has driven developments in understanding the drivers and predictability of MHWs (Holbrook et al., 2019; Rodrigues et al., 2019; Sen Gupta et al., 2020; Zi et al., 2020; Schlegel et al., 2021), and in quantifying the skill of forecasts of MHWs (Benthyusen et al., 2021; Jacox et al., 2022; McAdam et al., 2023). The Mediterranean Sea is a particular "hot-spot" for MHWs, with much literature documenting the increases in intensity, duration, frequency and impacts (Darmaraki et al., 2019; Ibrahim et al., 2019; Juza et al., 2022; Dayan et al., 2023). Despite this, there is currently less information on forecasting capability and event predictability in the Mediterranean region than in others (e.g. the North Pacific: Jacox et al., 2019; de Boisesson et al., 2022). With marine services projected to play an ever-increasing role in global sustainability and economic security (Rayner et al., 2019), early-warning systems of heat extremes can aid their planning and day-to-day management (Hartog et al., 2023).

While inter-annual variability of MHW occurrence and characteristics is derived from ocean warming and preconditioning (de Boisesson et al., 2022), ENSO (Jacox et al., 2022) and atmospheric teleconnections (e.g. Rossby wave trains, Rodrigues et al., 2019), short-lived atmospheric processes and weather systems can disrupt MHW persistence or halt their continuation completely (Benthyusen et al, 2021). The definition of MHWs assumes persistent conditions are harmful to marine life if the duration is 5 days or longer (Hobday et al., 2016), and the average duration of MHWs across most of the global ocean, as well as in the Mediterranean Sea, falls within the definition of short-term forecasting (< 2 weeks) (Oliver et al., 2021; Dayan et al., 2023). A short-term view of MHWs is therefore crucial to understanding their predictability and their impacts.

Short-term forecasting of MHWs has a range of potential roles in marine activities. While some contingency plans for extreme heat events in the aquaculture and fishing industries require several months notice (e.g. relocating or switching species), others should be performed at the latest possible moment in order to avoid minimise losses (e.g. early harvesting, or cooling of farm water) (Holsman et al., 2019; Galappaththi et al., 2020). In these cases, accurate information on daily timescales is crucial. Short-term forecasts are also useful for marine protected areas (MPAs), allowing them to prepare to monitor ecosystem damage (e.g. coral bleaching) and recovery, which in turn helps assess the effectiveness of their conservation efforts (McLeod et al., 2008). Forecasts of SST can also, in theory, be coupled to distribution models to forecast changes in species habitat for highly-mobile species (Abrahms et al., 2019). “Early-warnings” are a key means of climate resilience for marine services (Galappaththi et al., 2020); an assessment of their ability to track MHWs will contribute to further uptake by these services and unlock potential socio-economic benefits.

During the summer of 2022, the Copernicus Marine Service Mediterranean Physical Forecasting system was employed to monitor and forecast sea surface temperature (SST) increases which eventually evolved into a record-breaking MHW for the region. Here, we provide a basin-wide description of the event and demonstrate the ability of the Mediterranean Physical Forecasting system to accurately predict many facets of the event (e.g. the onset, spread, persistence and decay). First, we introduce the high-resolution regional forecast system and the satellite-derived SST data used to identify MHWs. Then, the record-breaking characteristics (intensity, geographic extent) of the 2022 event are described. We demonstrate the system's ability to predict the MHW spread across the basin and daily temperature variability in regions of key economic and ecological importance. Finally, we explore the potential role of short-term forecasting in the early-warning of MHWs compared to other forecasting time scales.

2. Dataset & Methods

Here, MHWs are detected with a 0.05° resolution reprocessing of a blend of satellite-derived products provided by the ESA Climate Change Initiative (CCI) and the Copernicus Climate Change Service (C3S) initiatives, including AVHRR Pathfinder dataset version 5.3 to increase the input observation coverage (Product ref. no. 1). The dataset provides daily SST of the Mediterranean Sea from January 1st 1982 to present (currently, up to six months before real time).

The Mediterranean Near Real Time Analysis and Forecast is a 3D coupled hydrodynamic-wave modelling system implemented at 1/24o (~4 km) horizontal spatial resolution, which produces analysis and 10-day forecasts of the main ocean essential variables (Product ref. no. 2). The analysis system assimilates satellite sea level anomalies and in-situ temperature and salinity observations, and nudges SST towards an ultra-high resolution satellite product. The same model framework is used to provide a multi-decadal reanalysis of the ocean, extending from 1987 to the present (Product ref. no. 3). Forecasts are made daily; once a week (on Tuesdays) an analysis is used to initialise forecasts, while on other days a hindcast is used. A schematic of the provision of forecast and analysis data is found in the QUID/PUM of the product.

MHWs are defined as SSTs which persist above the 90th-percentile for 5-days or longer (Hobday et al., 2016). Here, the 90th-percentile threshold corresponds to the 33 year baseline period 1987-2021 calculated individually for satellite derived and model-derived data, and smoothed with an 11-day moving window. MHWs in the forecast system are defined relative to the climatology of the physical reanalysis.

We use the MHW activity as a means to describe the event on a basin-scale, and to validate the forecast ability to capture the spatial scale of the event. Previously, activity has been defined as the product of event intensity, duration and area over a target period (Simon et al., 2022). Here, in order to study basin-wide spread at daily resolution, we define activity as the sum of the intensity over the area undergoing a MHW in the Mediterranean Basin. We assume that all MHW activity in the basin corresponds to the same event, unlike more novel methods of MHW tracking which employ spatial clustering (Bonino et al, 2023). Nonetheless, the activity metric used here identifies very similar phases of MHW activity during the 2003 event as the more advanced clustering method (Fig 1a; Bonino et al., 2023).

Product Table

Product ref. no	Product ID & type	Data Access	Documentation
1	SST_MED_SST_L4_REP_OBSERVATIONS_010_021; Satellite observations	EU Copernicus Marine Service Product (2022a)	PUM: Pisano et al. (2022a) QUID: Pisano et al. (2022b)

2	MEDSEA_ANALYSISFORECAST_PHY_006_013; Numerical models	EU Copernicus Marine Service Product (2022c)	PUM: Lecci et al. (2022b) QUID: Goglio et al. (2022)
3	MED_MULTIYEAR_PHYS_006_004; Numerical models	EU Copernicus Marine Service Product (2022b)	PUM: Lecci et al. (2022a) QUID: Escudier et al. (2022)

3. Results

First, we describe the event on a basin scale using satellite observations. We remind the reader that references to specific dates are for indication only, as the precise timings of peaks and onsets may differ when using different datasets and climatologies. In 2022, the onset of summer MHW conditions began in mid-May; by 23rd May, 35% of the area of the Mediterranean Sea was already experiencing MHW conditions (Fig. 1c). Maps of temperature anomaly confirm that the onset occurred mostly in the western regions and the Adriatic Sea (Fig. 2a). The geographic extent of MHW extended into the central and eastern parts of the basin (e.g. Fig. 2b), and conditions remained above a third of the basin area until the decay at the end of September. Peak area (70%) was reached on June 6th, while notable peaks of activity occurred later, on June 29th, July 6th and July 27th (Fig. 1a). The peak temperature anomaly of 6.45 oC (above the 1987-2019 average) was reached in the Gulf of Lion on July 18th.

Prior to 2022, the MHWs of the summers of 2003, 2015 and 2018 had been found to have the highest activities on record (using a slightly different definition of activity, but which is still based on intensity and duration; Simon et al., 2022). Here, we find that the activity in 2022 clearly eclipses that of 2015 and 2018, in terms of both maxima and persistence of activity (Fig. 1a). Though the summer of 2003 reached similarly high peaks of activity (twice, in mid-June and at the end of August), the total overall activity (defined as the area under the curve) is lower (82 x 106 oC.km2) than for 2022 (139 x 106 oC.km2). While in 2003 the MHW activity returned to zero in late May and mid-July, in 2022 it persisted throughout the summer above at least 0.5oC.km2 each day. By this measure, the summer of 2022 now holds the record for MHW activity.

Using the MHW activity provides an efficient, if not complete, means of validating the forecast system on the basin-scale. It is important to remember that activity time series cannot identify where and when MHWs are occurring (we study forecast ability in specific regions later). Here, we show both the activity (Fig. 1b) and the area (Fig. 1c) predicted, to infer whether

https://doi.org/10.5194/sp-2023-22
Preprint. Discussion started: 28 August 2023

forecast inaccuracies are caused by an inability to capture the geographic extent or the temperature intensity. Overall, we find that the forecast system was able to forecast the evolution of basin-wide MHW activity (Fig. 1b). In particular, we highlight the accurate predictions of the timings of the May onset, the various peaks throughout the summer, the two stages of the decay and the September rebound. On several occasions, MHW activity rapidly increases, often doubling or tripling over the period of less than a week; this activity is accurately predicted by the forecasts in mid-May, early-June, mid-June (twice) and mid-July. Declines in activity are accurately forecast on all occasions. Moreover, the start of declines are often accurately predicted even with lead times of 5 days or more (e.g., early June). The area of MHW conditions was also well predicted; accuracy in capturing the activity and the area implies accuracy in capturing the intensity as well, although this analysis does not yet determine the geographic distribution of MHW intensity.

There are indeed forecast inaccuracies to highlight. Firstly, there are instances of activity growth being overestimated and of false alarms about growth being raised (Fig. 1b). Generally, these are found for longer lead times, and it is expected for a forecast to experience a decay in skill with forecast time. In the first half of the summer, area is accurately forecast while activity is overestimated (e.g. at the end of June), implying an overestimation of intensity. In the latter half of the summer, area is typically overestimated, partially explaining the overestimation of activity. Then, there are instances in which MHW area tendencies follow the activity but are overestimated (late July to early August); given that activity continues to increase while area decreases (e.g. early September), there is an implied overestimation of the temperatures.

Elsewhere, we see fluctuations in activity on daily timescales which dominate over the longer-term growth tendencies (e.g., during the growth period beginning at the end of June). Throughout the summer of 2022, we see various examples of the forecast activity being unable to detect this higher-frequency variability; area forecasts, instead, generally follow the tendencies. In summary, the forecasts sometimes persist or increase temperature anomalies for too long, suggesting that they fail to capture sporadic cooling. Candidate drivers for short term cooling mechanisms not captured by the forecasts include cloud cover changes or winds.

It is important also to consider the ability to capture the spread of MHW occurrence. The geographical distribution of intensity in key phases of the MHW life cycle in forecasts agrees well with observations (Fig. 2). During the onset, forecasts capture the basin-wide patterns, with MHW occurrence at this stage correctly forecast in the Tyrrhenian Sea, Gulf of Lion and parts of the Adriatic Sea. The spread of the MHW conditions during the peak was correctly predicted to cover the south part of the Alboran Sea, the Ionian and southern regions of the Levantine Basin. Meanwhile, the Aegean Sea was predicted to be shielded from MHWs and instead experience cold anomalies, most likely caused by cooling related to the Etesian winds (Poupkou et al., 2011). Lastly, the first decay phase at the end of August produced very inhomogeneous MHW conditions across the basin. This “patchiness”, indicative of local-scale processes acting to cool the ocean such as increased cloud cover, was indeed predicted, but how well the forecast matches observations depends greatly on the local regions of interest and the exact day

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and lead time considered. Although it is not possible to draw rigorous conclusions from snapshots, the accuracy of basin-wide activity (Fig. 1b) suggests that forecast ability to capture MHW patterns and spread was generally high across the entire summer.

While basin-scale analysis allows an overview of forecasting skill, local-scale testing is imperative as forecasting tools are expected to be used on local-scale analysis (Dayan et al., 2023). Here, we also provide MHW forecasts for two key areas of maritime activity in the Mediterranean Sea: the Ligurian Sea and the Gulf of Taranto (Fig. 3). Each region experienced MHW conditions at different times during the summer, and in each case the forecasts accurately predicted the onset, persistence, intensity and decays. The Ligurian Sea, bordered by Italy and France, is a crucial location for marine conservation; it doubles as a marine protected area (the Pelagos Sanctuary for Mediterranean Marine Mammals) which is home to unique species of fin whales and striped dolphins, amongst other species (Notarbartolo-de-Sciara et al., 2008). The Ligurian Sea experienced 115 days of MHWs throughout the summer, and temperature anomalies reached a maximum of 4.46oC above the 1987-2019 average at the end of July, coinciding with the peak temperature of the summer (28.74oC). This activity is indicative of the conditions experienced by the rest of the western part of the Mediterranean basin. For an indication of forecast reliability, we highlight the false alarms (MHW days forecast but not observed) and misses (MHW days observed but not forecast). First we note that in the vast majority of days the correct conditions are forecast with few, sporadic exceptions. For example, the forecast made on May 10th captured the sharp rise in SST but not the MHW conditions at the end of the week. However, reducing the lead time (i.e. checking forecasts made on the 12th or 13th) correctly forecast the MHW state.

The Gulf of Taranto, situated in the Northern Ionian Sea, is one of the most productive areas of shellfish (mussels) farming in Italy (Prioli, 2004) but there is not yet data on MHW-induced mass-mortality or economic loss in this region (Garrabou et al., 2019). Unlike the Ligurian Sea, the Gulf of Taranto experienced three short but intense periods of MHW activity in June and July, adding up to 61 days of MHWs in total. The peak temperature anomaly was 4.76oC on 6th June, though peak temperatures occurred later in the season. As in the Ligurian Sea, the forecasts reliably captured the MHW state, with few false alarms and misses. The continuation of the start of the heatwave in early May was missed by the forecast of May 17th, while the forecast of 2nd August missed several days of MHW activity. In both cases, however, the observations show the temperature was only very slightly over the MHW threshold, and upon visual inspection the forecast temperature was very similar to the observed.

So far we have studied accuracy of the entire forecast period but, in some applications, it might be necessary or of more interest to have a specific warning time (e.g. 3 days). As the forecasts system produces forecasts every day, we now study forecast accuracy for the summer of 2022 at different lead times (Fig. 4). The overestimation of MHW activity in July and August occurred after a lead time of one day. In many instances, lead time 1 and lead time 4 are similarly far from the observed values, while lead time 7 further overestimates the peaks in activity.

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4. Discussion & Summary

The MHW of summer 2022 in the Mediterranean Sea was record-breaking, eclipsing 2003 in terms of basin-wide activity (defined as the integral of intensity, duration and area). Other contributions to this report also define the MHW of 2022 as a record-breaking event, using various other definitions. Here, we provide a basin-wide view of the MHW conditions. The Copernicus Mediterranean Physical forecasting system was used to track this event, serving as the first validation of MHW prediction for this system. Forecasts accurately captured the full life cycle of the MHWs several days in advance: onset (mid-May) in the Western part of the basin; spread into the Adriatic and Ionian Sea; sporadic local-scale occurrences in the Levantine Basin; persistence of peak conditions throughout July and August; and the gradual decay (September). The forecasts also identified regions shielded from MHWs e.g. during cooling in the Aegean Seas.

The system has already demonstrated skill in detecting past extreme events in the Mediterranean Sea: the “aqua alta” flooding in Venice in 2019 (Giesen et al., 2020), and Medicane Ianos (Clementi et al., 2022) and Storm Gloria (Alvarez-Fanjul et al., 2022) in 2020. While these and MHWs are all considered “extreme events”, their natures and formations are quite different, meaning that, once again, the forecast system has demonstrated the ability to capture a wide range of concurrent conditions (e.g. high surface air temperatures, moisture, atmospheric instability for medicanes; Cavicchia et al, 2014). Unlike the other events, the common drivers of MHWs in the Mediterranean are yet to be identified. The MHW of 2022, as well as the concurrent and record-breaking atmospheric heatwave which occurred over western Europe, appears to be linked to the northward extension of the subtropical ridge (Barriopedro et al., 2023). Meanwhile, model studies have suggested that mid-latitude MHWs in summer typically arise from reduced ocean heat loss to the atmosphere and reduced vertical diffusion (Vogt et al, 2022), but the link between these mechanisms has yet to be demonstrated in the Mediterranean. Encouragingly, however, we note that the forecast has demonstrated skill in capturing not just the season-long MHW cycle but also breaks in MHW persistence and abrupt changes in local activity. Subseasonal forecasts do not yet demonstrate the capacity to predict MHW response to weather patterns (Benthuysen et al., 2018), but this study confirms that short-term forecasts, at least in the Mediterranean Sea, can fill this gap.

The time scale of forecasting determines the information that can be provided and the type of response to that information. Here, we make the case for using short-term forecasting in MHW tracking tools and studies. Seasonal forecasting informs management decisions and contingency plans, while subseasonal forecasting can update these plans (White et al, 2017). Short-term forecasting, on the other hand, can then be used to determine the precise timings of events and instruct users on when to implement urgent response actions. Longer-term forecasts are typically global in scale and have a relatively low model resolution, while short-term forecasting centres, benefitting from the reduced time scale, can put more computational power towards regional-scale forecasting at a finer scale more relevant to stakeholders. In principle, for MHWs, this means the following: seasonal forecasts forewarn of extreme summer temperatures (e.g. seasonal averages above the 90th percentile, identification of ocean basins affected); sub-seasonal forecasts then update this to forewarn of MHW occurrence (e.g. daily temperatures persisting above 90th percentile, greater detail on geographic spread); finally, short-term forecasts can provide key details such as the start date, onset rate and breaks in activity on a local-to-regional scale. Currently, more effort is being placed on seasonal forecasting of MHWs (Liu et al., 2018; Jacox et al., 2022). With the level of accuracy for local-scale MHW indicators shown here, such tools should be complemented with daily, short-term updates.

In particular, we found that the MHW occurrence in the Ligurian Sea and Gulf of Taranto, two regions of economic and ecological importance, was also reliably forecast. There is, though, a need to include subsurface temperatures or heat content to report MHWs occurring at depth (Dayan et al., 2023; McAdam et al., 2023). For example, caged fish have been observed to avoid the top of cages when surface temperatures increase (Gamperl et al., 2021), meaning truly stakeholder-relevant tracking tools need a 3D view. The near-real-time analysis, as well as the forecast system, provides 3D temperatures and can track subsurface propagation of MHWs (unlike satellite observations). The MHW record in the analysis aligns exceptionally well with satellite observations for the two target regions shown (Fig 3), suggesting its accuracy (the same is found for the basin-scale MHW activity; not shown). However, a subsurface validation with in-situ data will be performed in the near-future, before using the analysis and forecast to track subsurface MHWs.

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Code Availability

Codes used to analyse data and produce figures in this study are available at https://github.com/RJMcAdam.

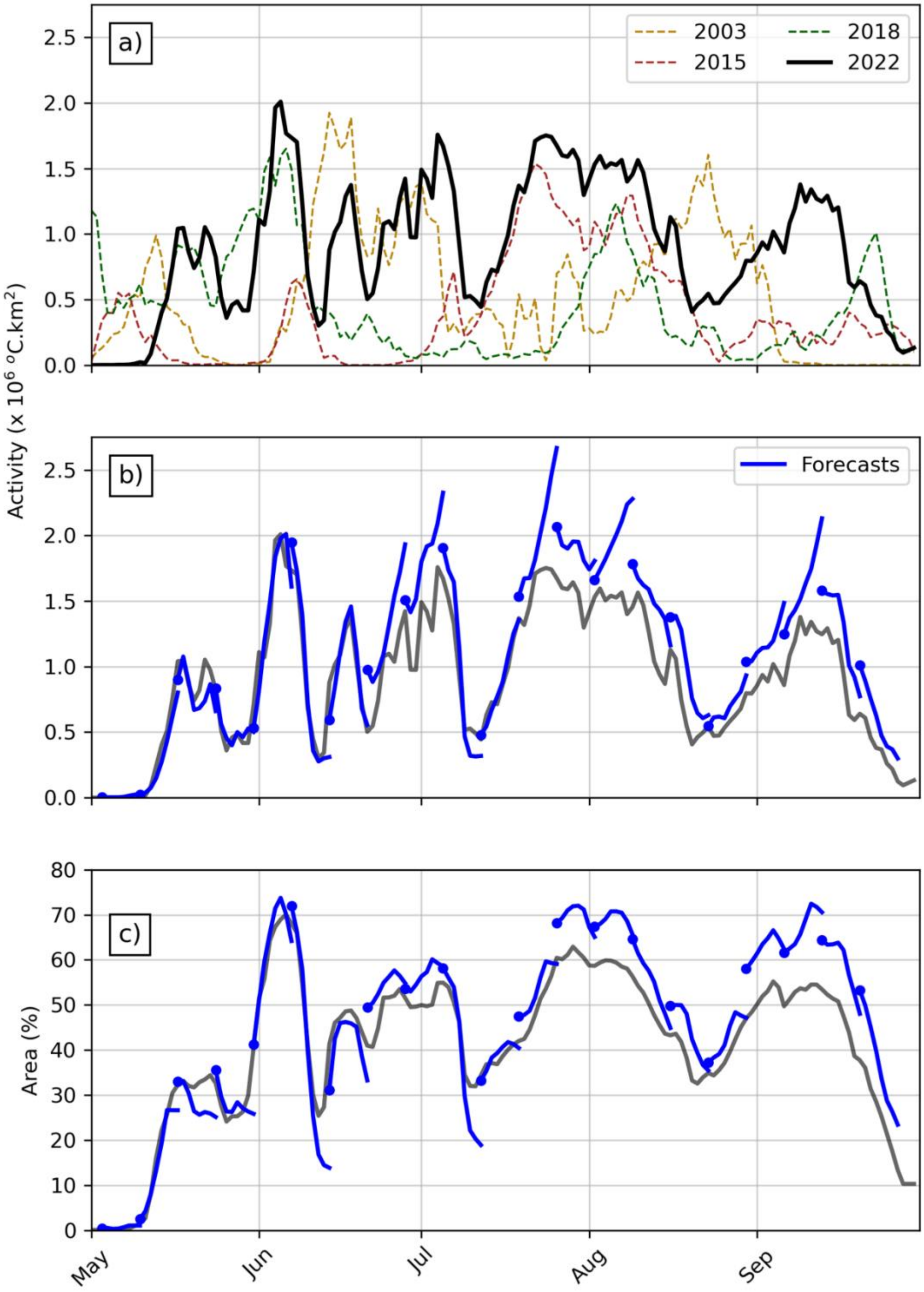
Author Contributions

R.M., G.B., S.M. and E.C. conceived the study. R.M. and G.B. performed the analysis and prepared the figures. R.M wrote the manuscript. G.B., S.M., E. C contributed to the interpretation of the results and to the paper writing. R.M., G.B., S.M. and E.C reviewed the manuscript.

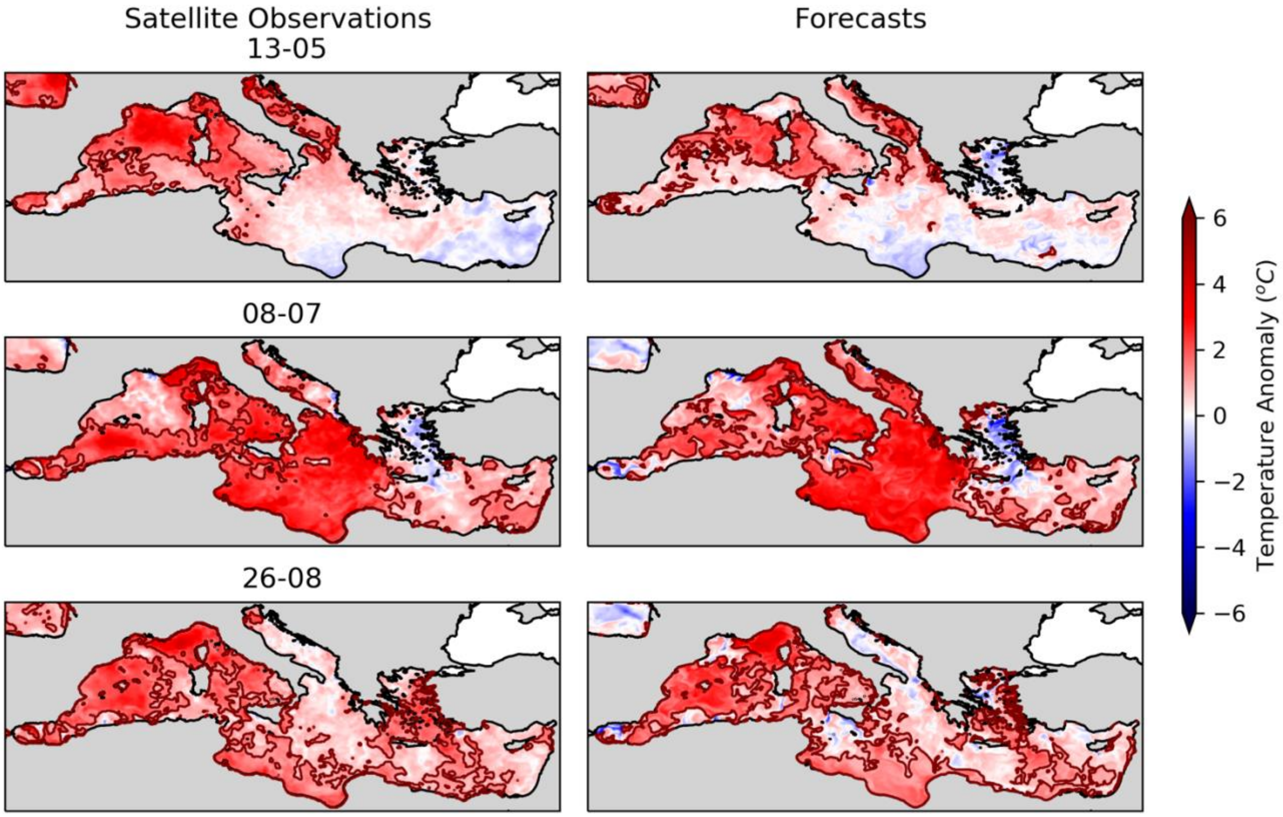
Competing Interests

The authors no competing interests.

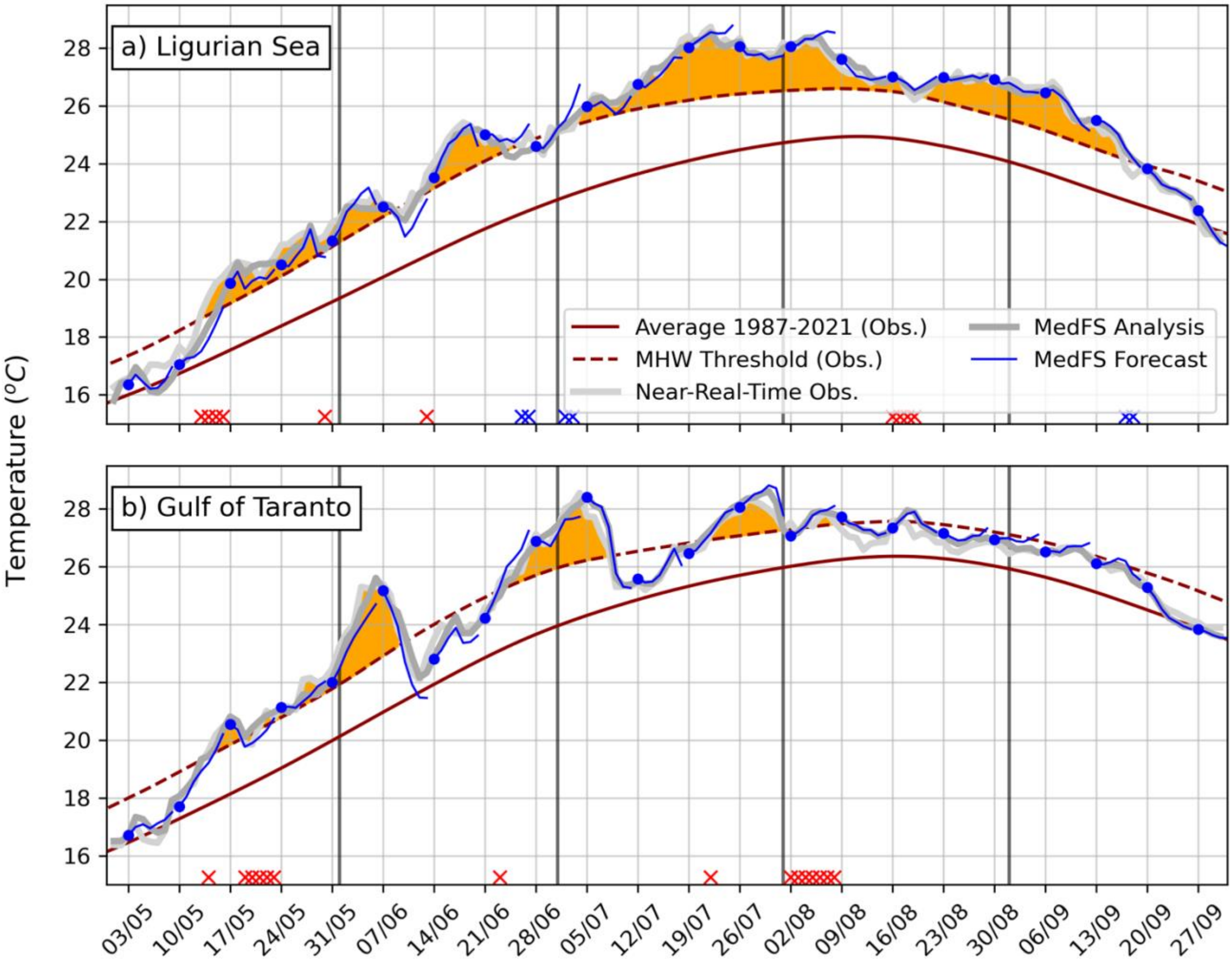
https://doi.org/10.5194/sp-2023-22
Preprint. Discussion started: 28 August 2023



420 **Figure 1: MHW activity across the Mediterranean Sea.** (a) MHW activity defined by satellite observations for 2022 and the three previous record years according to Simon et al, (2022). (b) Comparison between satellite observations and forecasts of 2022 MHW activity. (c) Area of Mediterranean Sea experiencing a MHW (as a percentage of total basin area). Activity is defined as the daily product of area and intensity. Shown here are the first 8 days of forecasts initiated on Tuesdays. Forecast start dates are shown by the blue dots.

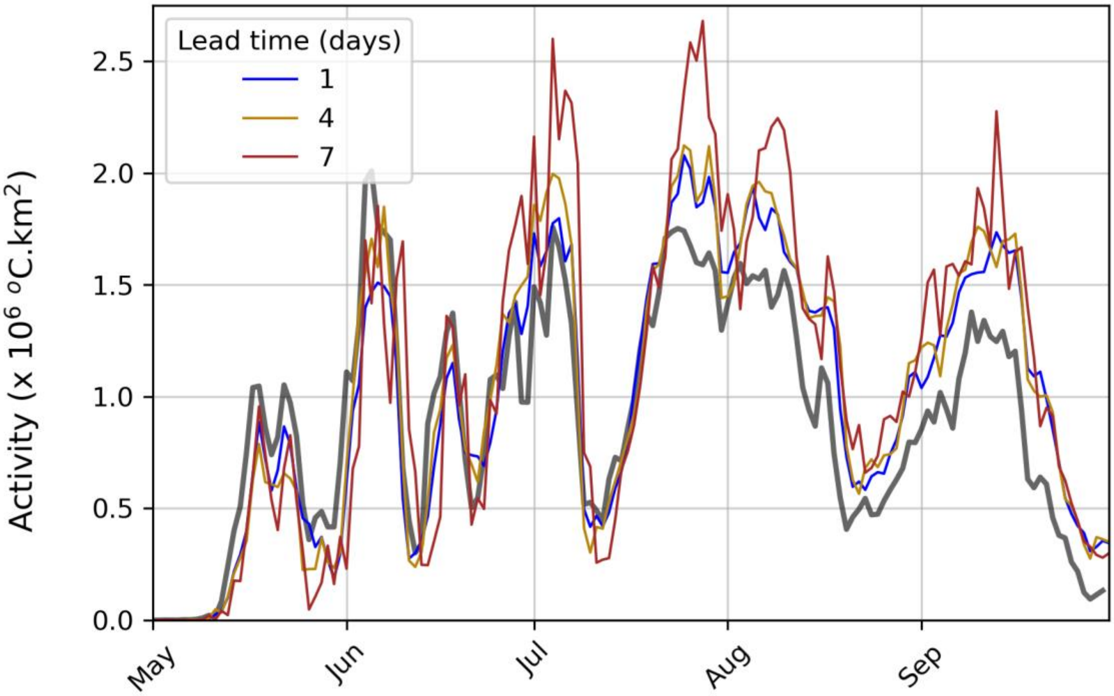


425 **Figure 2: Snapshots of SST anomalies and MHW occurrence during the different stages of the 2022 MHW.** Left: satellite observations. Right: forecasts with a lead time of 4 days. Areas in which SST is above the 90th-percentile threshold is indicated by the dark red contour. The 13th May highlights the MHW onset, the 9th July highlights the peak activity, and the 26th August highlights the (first) decay.



430 **Figure 3: Time series of SST and MHW occurrence in summer 2022**. Orange (yellow) shading highlights MHW (MHS) occurrence in satellite observations. Forecast start dates are shown by the blue dots. Definitions of the Ligurian Sea (a) and Gulf of Taranto (b). Note that the climatology lines (red) do not correspond to the satellite data, not to the model output (analysis and forecasts). Crosses correspond to misses (red) and false alarms (blue) in the forecast output.

https://doi.org/10.5194/sp-2023-22
Preprint. Discussion started: 28 August 2023



435 **Figure 4: Effect of lead time on forecasts of MHW activity**. Comparison between satellite observations (Fig. 1) and forecasts of 2022 MHW activity. Each forecast time series corresponds to a different lead time (I.e. how many days in advance the forecast was made). Forecasts of MHW activity was calculated for forecasts initiated every day; the lead time from each forecast was extracted to construct the time series.

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