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LETTER

Record-breaking persistence of the 2022/23 marine heatwave in the Mediterranean Sea

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Abstract

Since May 2022, the Mediterranean Sea has been experiencing an exceptionally long marine heatwave event. Warm anomalies, mainly occurring in the Western basin, have persisted until boreal spring 2023, making this event the longest Mediterranean marine heat wave of the last four decades. In this work, the 2022/2023 anomaly is characterized, using *in-situ* and satellite measurements, together with state of the art reanalysis products. The role of atmospheric forcing is also investigated; the onset and growth of sea surface temperature anomalies is found to be related to the prevalence of anticyclonic conditions in the atmosphere, which have also caused severe droughts in the Mediterranean region over the same period. Analysis of *in-situ* observations from the Lampedusa station and of ocean reanalyzes reveals that wind-driven vertical mixing led to the penetration of the warm anomalies below the sea surface, where they have persisted for several months, particularly in the central part of the basin. The evolution of the 2022/23 event is compared with the severe 2003 event, to put recent conditions in the context of climate change.

1. Introduction

Marine heatwaves (MHWs) are persistent and exceptional ocean warming events at a given location exceeding the 'expected' conditions, typically defined according to a reference climatology (Hobday *et al* 2016). MHWs occurrence is ubiquitous at the global scale, with severe events detected with increasing frequency in recent years in different regions, such as the Tasman Sea (Kajtar *et al* 2022), the north-west Pacific (Di Lorenzo and Mantua 2016, Li *et al* 2023), the southern Atlantic (Manta *et al* 2018), the Indian Ocean (Saranya *et al* 2022) and the Mediterranean Sea (Marullo and Guarracino 2003), among others. Nowadays, it is widely recognized that some of the properties (i.e. intensity, frequency, duration and spatial coverage) and trends of MHWs over time are strongly affected by global warming (Oliver *et al* 2021, Barkhordarian *et al* 2022, Xu *et al* 2022, He *et al* 2023). Recent literature (Amaya *et al* 2023, Martínez *et al* 2023) suggests a definition of MHWs relative to an evolving climatology or, in other words, based on the separation of the long-term warming trend from the total temperature signal.

The Mediterranean Sea, which is a hotspot for climate change (Giorgi 2006, Pisano *et al* 2020), has been subject to several intense MHWs, especially over the last decades (Darmaraki *et al* 2019a, Pastor and Khodayar 2023). Model projections (Darmaraki *et al* 2019b) indicate that Mediterranean MHWs will be longer lasting and more intense in the future due to global warming. MHWs in the Mediterranean Sea have caused substantial economic and ecological damages, such as loss of biodiversity and mass mortality events (Garrabou *et al* 2009, 2022), and therefore this marginal sea provides opportunities for testing mitigation strategies. Impacts are generally not limited to the uppermost water layers. Indeed, it has been shown that MHWs can alter conditions below the surface as well (Hu *et al* 2021, Dayan *et al* 2023), potentially amplifying circulation changes and affecting deep convection in the basin (Margirier *et al* 2020, Josey and Schroeder 2023).

The summer of 2022 set the record[3] as one of the hottest ever measured in the European region, concurrent with severe drought. These conditions have been associated to persistent atmospheric anticyclonic circulation especially over western Europe (Toreti *et al* 2022, Faranda *et al* 2023). While these conditions were documented in near real-time by the media and environmental agencies, a detailed description of the concurrent MHW is, to our knowledge, not available.

Here we describe the onset and evolution of the intense and unusually persistent Mediterranean sea surface temperature (SST) warm anomalies that started in May 2022, and assess their relationships with atmospheric conditions through the combined use of observational and model-based data. We also analyze this MHW event in the context of the SST increasing trend, comparing its exceptional characteristics with those of the very strong MHW of summer 2003.

2. Data and methods

2.1. Satellite data

Daily, gap-free (level-4), satellite-based SST data are provided by the Copernicus Marine Service covering, at the time of writing, the period from 25 August 1981 to the end of 2022 at 0.05° × 0.05° nominal grid resolution. The reprocessed (REP) product (Pisano *et al* 2016) is built from a consistent reprocessing of the collated merged single-sensor (level-3) climate data record provided by the ESA Climate Change Initiative and the Copernicus Climate Change Service (C3S) projects (Merchant *et al* 2019), and thus particularly suited for climate studies. The bias of this product is below 0.1 °C and the root mean square difference lower than 0.5 °C with respect to *in-situ* observations. Since year 2023 was not yet available at the time of writing, this product has been extended by using the Copernicus Mediterranean near real-time SST product, which is the operational counterpart of the REP one providing daily Mediterranean SST data up to one day before real-time (Buongiorno Nardelli *et al* 2013), but covering a shorter period (i.e. 2008-present).

2.2. *In-situ* data

In-situ measurements of wind and of ocean temperature are collected at the Lampedusa Oceanographic Observatory (OO; 35.49° N, 12.47° E). OO is located in the southern sector of the central Mediterranean, and the ocean depth at the site is 74 m. Further details are given by di Sarra *et al* (2019) and Marullo *et al* (2021). Measurements at OO were started in 2015, and include, in the atmospheric sector, meteorological, broadband and spectral radiation sensors. Underwater sensors are also operational, providing measurements of physical and biogeochemical parameters. In this study ocean temperature measurements at 1, 2, 5, and 18 m depths are used. During part of 2022 sonic anemometer measurements from OO were missing and were replaced with those from the Atmospheric Observatory (AO; 35.52° N, 12.63° E), 15 km North-East of OO on the island of Lampedusa. The wind at AO is measured with a sonic anemometer at 10 m above ground, and about 50 m above sea level. Differences in wind direction and intensity measured at OO and AO are reported to be small (Liberti *et al* 2020).

2.3. Reanalysis data

In order to have a consistent temporal record and vertical profiles, we consider the Mediterranean ocean reanalysis (Escudier *et al* 2021) that combines the multiyear and the near-real time datasets (1987–2020: multiyear, 2021-present: analysis-forecast) provided by the Copernicus Marine Service. The dataset is based on a high resolution hydrodynamic model (4–5 km horizontal resolution, 141 vertical levels), constrained by the assimilation of temperature and salinity profiles, as well as satellite altimetry data. We retrieved daily potential temperature data at four locations with fixed mooring stations: LION (42.06° N, 4.67° E), in the Gulf of Lyon (North Western Mediterranean), for which studies on windstress and vertical circulation are available (Ruti *et al* 2008, Margirier *et al* 2020); ODAS (43.79° N, 9.15° E), in the Northern Tyrrhenian, whose data were analyzed for the 2003 MHW (Sparnocchia *et al* 2006); LMP, near the island of Lampedusa in the Southern Mediterranean; and E1M3A (35.79° N, 24.92° E), north of Crete (Eastern Mediterranean), used for thermohaline circulation studies (Velaoras *et al* 2014). These locations were chosen for their representativeness of different Mediterranean subbasins. We note that as explained by Escudier *et al* (2021), data from moorings are not assimilated by the reanalysis.

Data retrieved from the European Centre for Medium Range Weather Forecasting ERA5 reanalysis (Hersbach *et al* 2020), for the period 1991–2023, were used to characterize atmospheric conditions. ERA5 combines a state-of-the-art weather model with an approximate spatial resolution of 30 km and 137 vertical levels from the surface to the upper stratosphere with the assimilation of a large amount of conventional and satellite observations, providing a strong constraint for the analysis. For this work we use daily mean fields (temperature, winds and sea level pressure) at the surface and geopotential at 500 hPa, and monthly mean surface fluxes (partitioned into

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[3] https://climate.copernicus.eu/copernicus-summer-2022-europes-hottest-record (last access, May 2023).

sensible and latent heat, net shortwave and longwave radiation).

2.4. Climatology definition

For all datasets, except *in-situ* data, we calculate anomalies with respect to a common 30 year climatology (following the World Meteorological Organization guidelines[4]) over the period 1991–2020. An updated reference period is in fact advised to better take into account the effects of the long-term warming trends. A shifting baseline approach as the one proposed by Amaya *et al* (2023) could be a solution but it would require a large (∼30 years) window around the period (Oliver *et al* 2021), which may be suitable for model outputs but not for the relatively short time series of observations.

3. Results

3.1. MHW evolution from satellite observations

Figure 1 shows the evolution of the daily SST and corresponding anomalies averaged over the whole Mediterranean basin for the period January 2022–April 2023, as derived from satellite data. The evolution of the climatological SST, and spatial maps for specific dates are also shown together with the distribution of the SST anomalies (i.e. differences with respect to the climatology). In early spring 2022 (date d1, figure 1(d1)), basin-averaged Mediterranean SSTs were close to their climatological values (median anomaly 0.08 °C). Starting from May, 8th (figure 1(d2)) positive SST anomalies developed in the north-western portion of the basin and in the Aegean Sea (Eastern Mediterranean Sea). As a consequence of the MHW onset, the basin-averaged SST raised by 1.5 °C above the climatology in less than a week (figures 1(b) and (d2)).

Around date d2 (19 May 2022), the distribution of anomalies started to get skewed toward positive values (figure 1(c2)). The event reached the first local maximum in the northwestern Mediterranean Sea very rapidly (4 °C in 9 days), by the second half of May (figure 1(d2)), while the eastern basin SSTs did not depart much from climatology. After this first maximum, a series of peaks modulated by wind events is observed in June in the SST anomaly time series (figure 1(b)). In July 2022 (date d3), the heatwave invaded the whole western Mediterranean and also moved to the Ionian sea in the central part of the basin, reaching values as high as 5 °C locally (figure 1(d3)). In this period, the contrast between western and eastern basins was marked, as seen from the bimodal distribution of the SST anomalies and from the negative anomalies observed in the Aegean Sea (figure 1(c3)).

After reaching their maximum in mid-July, the overall anomalies remained 1 °C–1.5 °C higher than normal until October, with some short-term fluctuations. After that, SSTs started to return to normal conditions, but the process ceased in December, when anomalies regained strength, to reach a new maximum in January 2023 (date d4). By the end of April 2023, a mean SST Mediterranean anomaly of more than 0.5 °C can still be seen, with local peak values well above 2 °C in the south western Mediterranean Sea (figure 1(d5)).

Hovmoeller diagrams showing meridionally averaged anomalies over all sea points as a function of time and longitude are given in figure 2, for the full time series (figure 2(a)) and for the 2003 and 2022–2023 events (figures 2(b) and (c), respectively). The diagram for the whole series (figure 2(a)) indicates a generalized warming trend at all longitudes. Episodic warm anomalies occupy a large fraction of the westernmost basins, and recurring MHWs can be observed. The intensity of the summer 2022 MHW, which interests the region between 0° and 20° of longitude, is comparable to that of the 2003 event, which is the most intense case ever occurred in the last decades (Darmaraki *et al* 2019a). Both events started in late spring/early summer, however substantial differences in duration and spatial extent are observed. These characteristics are robust to a detrending procedure (reported in figure S1), indicating that the different MHW properties cannot be explained by shifts in the climatology only.

A close-up view of the 2003 event (figure 2(b)) reveals that warm anomalies (up to 5 °C in June) were confined to the period June–September and then disappeared. For the 2022/23 event (figure 2(c)) the warm peak started in May, reached its maximum later in the summer season (July 2022), and positive anomalies persisted until the first months of 2023 in the western and central basins. In January 2023, when generally a maximum cooling is expected (Tomczak and Godfrey 2003), a large-scale intensification of the event took place (figure 1). Sub-monthly variability during these MHWs modulates the warm patches in summer, a process associated with vertical mixing and the propagation of SST anomalies to the mixed layer (see next section for details). Day-to-day evolution of the MHWs is also influenced by complex feedbacks between the lower atmosphere and the sea surface (Sen Gupta *et al* 2020).

3.2. Vertical mixing at selected observational sites

We now analyze *in-situ* data gathered at the Lampedusa OO, to assess the contribution of wind-driven mixing to the vertical propagation of anomalous warm SST to the mixed layer. While this process occurs seasonally in the whole basin (Bakun and Agostini 2001), in 2022/23 it led to sudden changes in seawater temperatures.

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[4] https://public.wmo.int/en/media/news/updated-30-year-reference-period-reflects-changing-climate (last access, May 2023).

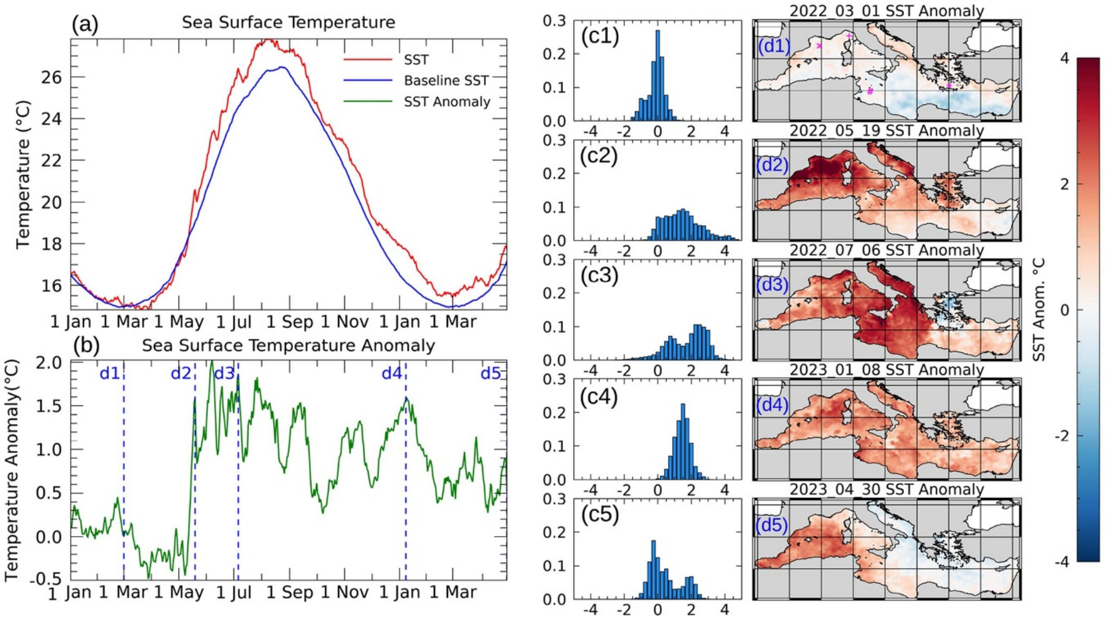

Figure 1. Overview of Mediterranean SST conditions in 2022/23 based on satellite data. (a) Daily mean Mediterranean basin SST time series (red line) and corresponding baseline 1991–2020 (blue line); (b) basin scale SST anomalies over the same period. Five dates (indicated as d1–5) are selected to represent pre-MHW conditions, the MHW onset, one of its summer peaks, the January peak and spring 2023. For each date, anomaly maps (panels (d1)–(d5)) and corresponding frequency histograms (panels (c1)–(c5)) are shown. The locations of mooring stations are indicated with pink markers (× for LION, + for ODAS, # for LMP, and ∗ for E1M3A) in (d1).

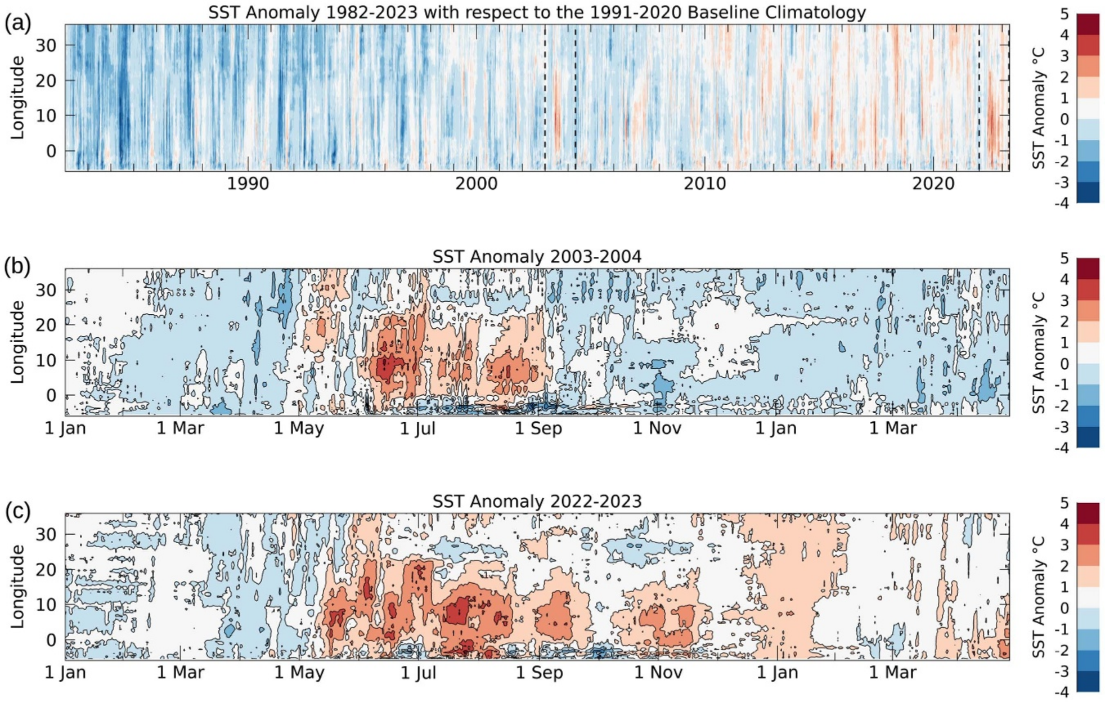

Figure 2. Evolution of meridionally averaged SST anomalies over the Mediterranean as a function of the longitude and time from January 1982 to April 2023 (a). Zoom over the 2003/04 (b), and over the 2022/23 (c) intervals, bounded by the dashed lines in plot (a).

Figure 3 shows daily averages of the squared 10 m wind speed and seawater temperature at 1, 2, 5 and 18 m depths, with SST observed by satellite also shown for comparison. The squared wind speed is proportional to the wind stress exerted on the sea surface and can therefore be used as a measure of vertical mixing intensity (Kondo 1975, Kara *et al* 2007). The wind stress also depends on the drag coefficient, which is in turn a function of wind speed, sea state and the difference between SSTs and atmospheric temperature

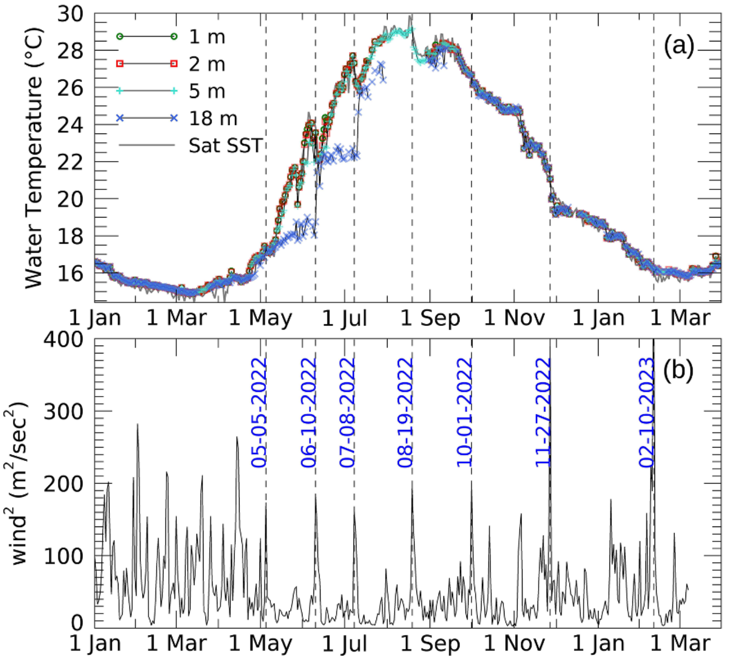

Figure 3. Time series of water temperature at different depths (a) and squared wind speed (b) measured at the Lampedusa mooring site. Temperature data at 18 m are missing between late July and August. Satellite-derived SSTs for the area are reported for reference in (a).

(Tomczak and Godfrey 2003). Temperatures in the first few meters increased progressively during the summer period, reaching their absolute maxima in mid-August (figure 3(a)), with high wind events triggering sudden cooling. Changes occurred with little or no delay in the first 5 m of the water column. Temperatures at 18 m depth also increased, but in a less continuous fashion, with a temporal evolution apparently decoupled from that of the other three sensors (up to 5 m). Figure 3 shows that in correspondence with wind intensification events, temperatures at 18 m abruptly increased, reaching values close to those measured by the upper sensors. As soon as the wind intensity decreased, the near-surface layer was decoupled from the lower layer, which remained at near constant temperatures until the next mixing event. Since early September, temperatures have been homogeneous throughout the vertical layer where measurements are available, as seasonal stratification is larger during summer. Sudden changes at all depths can be seen to occur especially in late November 2022, associated with an intense wind speed event (figure 3(b)). Meteorological conditions in the Mediterranean basin around this date are reported in figure S2(c), where northeasterly winds advecting cold air can be seen in the area, associated with a deep trough located between Libya and Egypt at the time.

These results highlight that warming at the surface, which can be enhanced by favorable atmospheric conditions (high insolation and calm winds), is then propagated to deeper layers by wind-induced vertical mixing. As strong wind conditions are sudden and relatively short-lived (i.e. peaks above 100 m^2 s^{-2} in figure 3(b) only last for a few days), in summer temperature changes in the mixed layer are less continuous than those at the surface, and step-like in appearance. As we discuss below, these anomalies can persist below the surface through the cold season and likely contribute to the exceptionally long-lasting MHW conditions.

We now assess if the downward propagation of temperature anomalies to about 20 m observed at the Lampedusa mooring site is a common feature across the Mediterranean basin. As buoy data are mostly available for shallow depths, we take advantage of Mediterranean ocean reanalysis data at four selected sites, ranging from the western to the eastern portions of the Mediterranean basin.

From May–June 2022, positive anomalies reaching 3 °C–4 °C above climatological values started to propagate from the surface down to 10–20 m depths in the areas of LION, ODAS and LMP (figure 4). By October and November surface anomalies weakened but propagated down to 40 m and reached depths of 70–80 m (not shown). Temperature dynamics in the Aegean Sea at the E1M3A site were distinctly different as weak positive anomalies are only seen in August but temperatures were otherwise colder than the climatology (figure 4(d)). Warm anomalies have been especially persistent at the LMP site, and in all sites they get vertically homogeneous in fall (consistent with the evolution of temperature at various depths in figure 3(a)). The shallow depth of the mixed layer in summer (∼20 m, Sparnocchia *et al* 2006) in fact prevents the vertical propagation of the anomalies, while

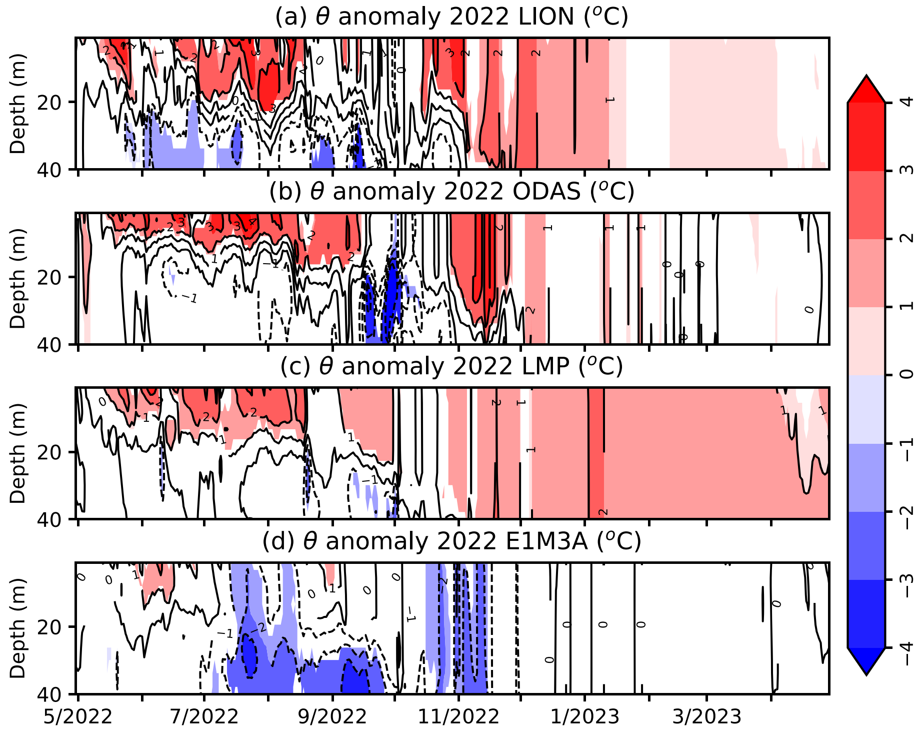

Figure 4. Temperature anomalies for grid-points of the Mediterranean Sea reanalysis close to LION (a), ODAS (b), LMP (c) and E1M3A (d) fixed moorings from May 2022 to April 2023. Anomalies below the lower and above the upper deciles are shaded.

in the fall and winter seasons, due to strong winds, the mixed layer depth increases and the warm anomalies can propagate further down below. In April 2023 the temperatures temporarily dropped (due to cold weather conditions in this period, not shown), but significant anomalies reappeared soon after. This phenomenon highlights the importance of subsurface anomalies for the re-emergence of warm SSTs over the next months. In 2022, the eastern Mediterranean Sea was not hit by a warm anomaly, and conditions were colder than usual in late summer and through fall.

Summer mean potential temperature profiles are reported in figure S3 for the four sites. Consistent with the above picture, water temperatures in 2022 were highest at the ODAS and LMP sites, while the 2003 event was more intense than 2022 in the LION area. Neither of these events was particularly intense at the E1M3A site. While the 2003 event (figure S4) was even more intense at the LION site (peak at 3 °C–4 °C above normal), the anomalies were eroded by November of the same year. These results agree with previous observational studies, such as Sparnocchia *et al* (2006) for the ODAS station.

3.3. Atmospheric circulation over the Mediterranean Sea

Atmospheric conditions can be determinant for the evolution of MHWs (Oliver *et al* 2018, 2021). Anticyclonic conditions persisted over western Europe during summer 2022 and were associated to the exceptionally warm and dry season over continental Europe (Faranda *et al* 2023), leading to severe droughts. To understand the cause of the warm SST anomalies shown in figure 1, we have investigated the atmospheric conditions during this period by using the ERA5 atmospheric reanalysis. The SST warm peaks were associated with anticyclonic ridges (figures S2(a), (b) and (d), date d3) extending from the North African coasts to the central Mediterranean area (Hatzaki *et al* 2014). Record-high geopotential heights were present in particular over western North Africa in July 2022 (figure S2(b)). The atmospheric circulation in 2022 was partly similar to that in 2003 (figure S5), but the anticyclonic anomalies were deeper over Europe and the North Atlantic, and the areas with cyclonic conditions were not as large, highlighting the hemispheric scale of the atmospheric forcing (Liu *et al* 2022, Li *et al* 2023, Oh *et al* 2023, Song *et al* 2023).

Anomalous anticyclonic conditions were present over continental Europe already in spring, between March and May 2022 (figure 5(a)), and covered most of the western and central Mediterranean Sea. Drought-inducing conditions continued through summer (figure 5(b)) especially over central and western Europe, with an east-west shift of the ridge axis. By fall (figure 5(c)), anomalous anticyclonic conditions were found over the Western Mediterranean and north Africa, and persisted until 2023 (figure 5(d)) but with a further shift towards the Central and Eastern basins during spring. The

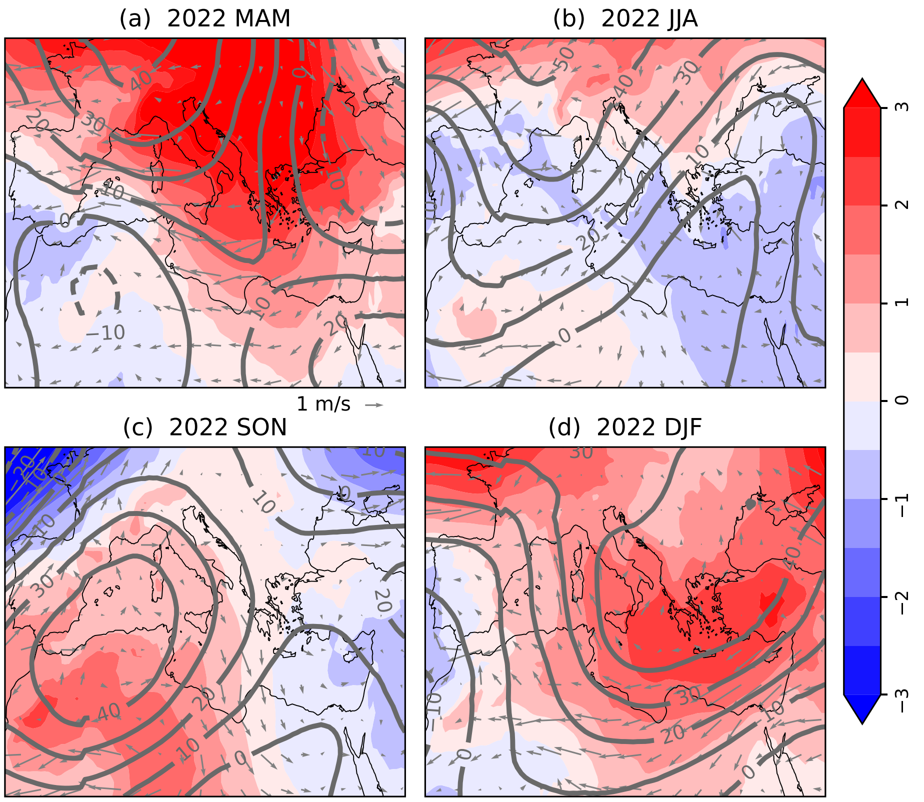

Figure 5. Seasonal average anomalies for geopotential height at 500 hPa (lines, units of m), 10 m winds (arrows, units of m s^{-1}) and surface pressure (shadings, units of hPa) for the MAM, JJA, SON and DJF seasons 2022/23.

analysis of atmospheric circulation indicates that these unfavorable conditions played against the development of MHW conditions in the eastern basins during the 2022 event (as seen in figure S2). By comparison, atmospheric conditions during the major 2003 Mediterranean MHW event are shown in figure S6.

Long-term increase in geopotential height can be linked to changes in surface conditions. Indeed, summertime geopotential height at 500 hPa and surface temperature anomalies for the western and central Mediterranean are well correlated (figure S7, $R \sim 0.8$). Both variables exhibit a clear increasing trend, and in June and July 2022 geopotential anomalies achieved their highest values (as seen figure S2(b)). In early summer, elevated peaks are also found in 2003 and 2017, years in which major MHWs over the Mediterranean area have been recorded (Darmaraki *et al* 2019a).

To better understand the atmospheric forcing of the 2022/23 MHW, we analyze the surface energy budget and its relationship with SST evolution, shown in figure 6, compared with climatological conditions. In the ERA5 convention, fluxes are positive downwards, and here quantities are averaged over the whole Mediterranean Sea. Climatologically, the net flux (figure 6(e)) changes sign between February and March (from negative to positive, meaning an energy gain) and in September (from positive to negative, i.e. a net heat loss). From the same plot we can see that the net flux was larger than climatological values from March 2022 through the summer (by ∼5 W m^{-2}), with a positive spike (reduced heat loss from the sea) in January 2023 (caused by the weak winds, figure 5(d)). The evolution of individual components in 2022/23 was more complex, as for example the longwave radiation (figure 6(b)) and latent heat fluxes (figure 6(d)) have feedbacks with cloudiness and near-surface atmospheric conditions. During summer the net shortwave radiation (figure 6(c)) was slightly above the climatology, contributing to the net heat excess, which is on average positive throughout 2022 (not shown). Anomalies of net radiative fluxes are shown in figure S8, with positive values between 5–10 W m^{-2} both in summer and winter months. As also found by Sen Gupta *et al* (2020), the role of latent heat fluxes has been important in both the MHW onset phase and in its winter persistence. However this combination may be event and region-specific, as local conditions modulate the effects from large scale forcings: for example, Lee *et al* (2022) stressed the importance of increased shortwave radiation in driving more frequent MHWs in East Asia. If we focus on the eastern Mediterranean Sea (not shown), where SST anomalies were more modest, flux anomalies in summer 2022 were modest

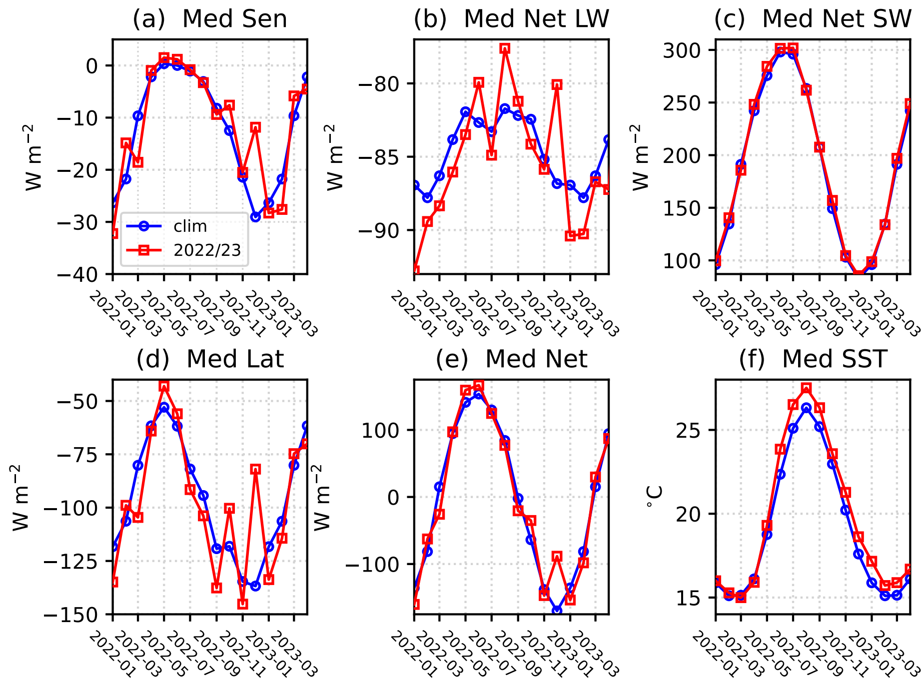

Figure 6. Monthly climatological mean (blue lines) and 2022/23 values (red lines) for (a) sensible heat flux, (b) net longwave (LW) radiation, (c) net shortwave (SW) radiation, (d) latent heat flux, (e) net flux (as the sum of these four components), and (f) SST (also shown in figure 1), averaged over the whole Mediterranean Sea.

or slightly negative, but the MHW intensity increase in January 2023 also affected this area.

4. Discussion and conclusions

A severe and long-lasting MHW has affected the Mediterranean Sea since spring 2022, attracting significant attention[5] from the public and the scientific community, given the possible impacts on ecosystems and related socio-economic activies (Garrabou *et al* 2022). While the MHW peak intensity was comparable with the exceptional event in summer 2003, its duration has been unprecedented. By combining satellite and *in-situ* sea water measurements with atmospheric and ocean reanalysis products, we characterize the basin-wide evolution of this event from its inception until present (spring 2023). The 2022/23 MHW started in the north-western Mediterranean basin around mid-May 2022 and moved south reaching its peak intensity and spatial extension by July, concomitant with a major atmospheric heatwave over Europe (Faranda *et al* 2023). Both the 2003 and 2022 MHWs started in NW Mediterranean following the suppression of the northerly winds in the area (figures 5(a) and S6(a)), linked with anticyclonic anomalies over western-central Europe.

We find that wind-induced vertical mixing reduced the intensity of the temperature anomaly at the surface, and led to propagation of the warming to deeper layers. This excess energy stored below the surface cannot be efficiently dissipated back to the atmosphere, and strong stratification inhibits further propagation to depths, thus favoring the persistence of warm anomalies for several months. From November on, the water column gets well mixed due to the effects of winds (Tomczak and Godfrey 2003). Indeed, significant temperature anomalies are still[6] observed especially in the southern Mediterranean in spring 2023. This exceptional MHW differs from the one occurred in 2003, which started in June but dissipated by November.

Differently from the 2003 summer MHW event, the anticyclonic conditions, manifesting in summer 2022 with large-scale conditions similar to the ‘western Europe’ cluster of Stefanon *et al* (2012), continued unabated during the following winter. Consequently, precipitation and snow in winter 2022/23 were also below average[7], increasing the risk of drought for southern European countries (Toreti *et al* 2022). The analysis of surface and mid-tropospheric seasonal anomalies from spring to winter 2022 (figure 5) provides a picture consistent with the assessment recently released by the Copernicus Climate Change Service (C3S 2023). In the cold season 2022/23, atmospheric circulation has been similar to the heatwave

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[5] www.mercator-ocean.eu/actualites/marine-heatwaves-mediterranean-summer-2022/; (last access, September 2023).

[6] The MHW was still ongoing during the review of this paper, as seen from https://t-mednet.org/visualize-data/marine-heatwaves (last access, September 2023).

[7] www.cimafoundation.org/en/news/april-italys-snow-deficit-is-64/ (last access, May 2023).

winter pattern conditions described by Holmberg *et al* (2023). In 2003 anomalies turned to cyclonic in fall and winter (figure S6(d)), thus helping to dissipate the accumulated marine warming to the atmosphere. While blocking conditions with stationary high pressure at the surface played a role in both the 2003 and 2022 cases (Feudale and Shukla 2011, Faranda *et al* 2023), the exceptional persistence of the anticyclonic anomalies in fall/winter months of 2022/23 helped to extend the MHW lifetime. In any case, the anomalous low wind speeds and high insolation conditions, together with the relatively weak mixing of the Mediterranean Sea, are key driving factors for the development of MHW conditions (Guinaldo *et al* 2023). The positive anomaly in the surface energy balance in 2022/23 was mostly due to reduced heat loss from the sea and higher than usual net shortwave radiation fluxes.

We note that during summer 2022 record high geopotential heights were found in the middle troposphere, a condition which is likely linked to anthropogenically forced trends (Christidis and Stott 2015). An increased occurrence of atmospheric anticyclonic conditions over the Mediterranean region plays an important role in leading the drying trends identified in projections (Seager *et al* 2019). Surface temperature variability is well correlated with tropospheric circulation over the western Mediterranean (figure S7). Interestingly, major MHWs in the recent decades occurred during a positive phase of the Atlantic Multidecadal Oscillation (Marullo *et al* 2011, Macias *et al* 2013), but more studies are needed to understand if and how global modes of variability influence Mediterranean MHWs, in analogy with their atmospheric counterparts (Liu *et al* 2022).

Further research is required to understand how such intense and long-lasting MHWs can influence ongoing circulation changes in the Mediterranean Basin (Schroeder *et al* 2016). Even if spatial scales are relatively smaller than those of major oceans (Hanawa and Talley 2001, Tak *et al* 2021), entrainment of MHW anomalies in the Western Mediterranean deep circulation and their further re-emergence could provide an opportunity for long-range forecasting of MHW conditions (Jacox *et al* 2022), whose predictability could otherwise be limited by high-frequency atmospheric forcing.

We stress that the characterization of MHWs is sensitive to the presence of underlying trends (Pisano *et al* 2020) and how they are accounted for (Frölicher *et al* 2018, Amaya *et al* 2023). This leads to quantitative differences when using different baseline periods, as for the 2003 case described by Sparnocchia *et al* (2006) compared with those in figure S4. Using for example the default Copernicus Marine Service climatology (1985–2005) for satellite SSTs would produce positive anomalies 0.5 °C stronger than those obtained with our baseline. A key challenge will thus be to elucidate drivers of MHW events in a changing climate, allowing a tailored detection for biological, physical or environmental impact studies.

Data availability statements

Satellite-based SST data are available at https://doi.org/10.48670/moi-00173 for the reprocessed dataset and https://doi.org/10.48670/moi-00172 for the near-real time (last access, May 2023). Mediterranean reanalysis data can be obtained at https://data.marine.copernicus.eu/product/MEDSEA_MULTIYEAR_PHY_006_004 and https://data.marine.copernicus.eu/product/MEDSEA_ANALYSISFORECAST_PHY_006_013 (last access, May 2023). The ERA5 reanalysis is available from the Copernicus Climate Data Store (https://doi.org/10.24381/cds.bd0915c6 and https://doi.org/10.24381/cds.adbb2d47, last access, May 2023). *In-situ* data from Lampedusa observatories are available at www.lampedusa.enea.it/dati/boa/index.php (last access, May 2023).

All data that support the findings of this study are included within the article (and any supplementary files).

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