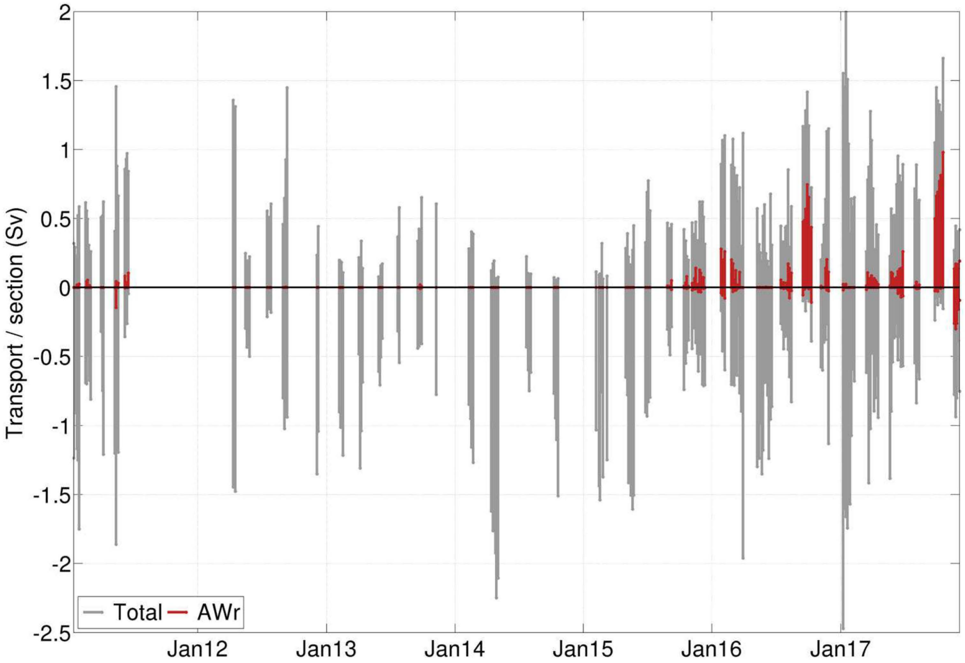

Figure 4.3.3. Northward (positive) and southward (negative) geostrophic transports in the Ibiza Channel integrated over the full water column (grey) and only considering recent Atlantic Water (red) obtained from product reference 4.3.2 during the glider missions from 2011 to 2017.

for the formation of the eddy event in 2017. These include the intense Mistral wind jets which could be responsible for the coastal detachment of the Northern Current. This in turn would favour the recent Atlantic Water coastal intrusion, and which would then gain negative vorticity due to the negative curl caused by wind in this area. High-resolution numerical model simulations will be used in the future to analyse this hypothesis and to improve our knowledge of the generation and permanence of these mesoscale eddies and their interaction with the mean flow.

Acknowledgements

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4.4. Insights on 2017 Marine Heat Waves in the Mediterranean Sea

Authors: Nathaniel Bensoussan, Jacopo Chiggiato, Bruno Buongiorno Nardelli, Andrea Pisano, Joaquim Garrabou

Statement of main outcomes: Overall, 99.6% of Mediterranean Sea surface experienced at least one Marine Heat Wave event during year 2017. Strong Marine Heat Wave events occurred at regional scale, in June, July and August. Analysis of sea surface temperature from CMEMS revealed unprecedented Marine Heat Wave total duration in the north-western sub-region (up to 225 days locally in the north Catalan Sea) and exceptionally long single event (entire summer) in the Eastern Levantine Sea. In all sub-regions examined, a long-term increasing trend in annual Marine Heat Wave duration is obvious over the 1982–2017 period. As for previous significant Marine Heat Wave events (e.g. summer 2003), mass mortality events affected the benthic biota in the north-western Mediterranean Sea in 2017. Unprecedented large-scale and long-lasting benthic mucilaginous bloom also occurred in the north Catalan Sea. Analysis of *in situ* temperature time series in Scandola Marine Protected Area showed sub-surface intensification of Marine Heat Wave events (both in intensity and duration) which could not be inferred from surface data only. Enhancing the monitoring framework on physical and biological indicators is thus required for good evaluation of Marine Heat Wave and their impacts on Marine Coastal Biodiversity at local and regional scale.

Products used:

Ref. No.	Product name and type	Documentation
4.4.1	SST_MED_SST_L4_REP_ OBSERVATIONS_010_021 Sea surface temperature data	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-OSI-PUM-010-021-022.pdf QUID: http://marine.copernicus.eu/documents/QUID/

(*Continued*)

Continued.

Ref. No.	Product name and type	Documentation
		CMEMS-OSI-QUID-010-021-022.pdf
4.4.2	T-MEDNet consolidated *in situ* temperature time series. www.t-mednet.org *In situ* temperature data	www.t-mednet.org/T-Database

Ocean warming is associated to large changes in daily temperature distribution with increase in the occurrence of conditions presently perceived as extreme (known as climate intensification, see for instance section 2.2). Extreme warm sea temperature events observed around the world have been termed Marine Heat Waves. The interest in the characterisation of Marine Heat Waves has increased in the recent years (Hobday et al. 2016, 2018; Frölicher and Laufkötter 2018). For this study we applied the approach proposed by Hobday et al. (2016) in which Marine Heat Waves can be qualitatively defined as prolonged periods (five consecutive days or more) of anomalously warm water conditions when compared to the climatological mean (Hobday et al. 2016, 2018; see below for more information). Their mean duration and frequency have increased significantly over the past century, resulting in a 54% increase in sea surface annual Marine Heat Wave days globally (Oliver et al. 2018).

Increasing thermal stress is already having a range of important impacts on marine ecosystems and the goods and services they provide (Frölicher and Laufkötter 2018). Increasingly, mass mortality events on the benthic biota are reported in both tropical and temperate ecosystems (e.g. Garrabou et al. 2009; Wernberg et al. 2016; Hughes et al. 2017). In the north-western Mediterranean Sea, anomalously warm conditions during summers 1999, 2003 and 2006 have been associated to unprecedented mass mortality events, which have affected macrobenthic engineer species along tens to thousands of km of the coastline of Spain, France and Italy (Garrabou et al. 2009; Crisci et al. 2011; Marbà et al. 2015). Since 1999, several Marine Heat Waves and new mass mortality events occurred, particularly during recent years, as was the case during year 2017. However, the linkage between surface Marine Heat Wave metrics and biological impacts in subsurface marine habitats is not straightforward, firstly due to seasonal stratification and the influence of wind on coastal hydrodynamics (Bensoussan et al. 2010; Schaeffer and Roughan 2017). Furthermore, relating the thermal anomalies to biological observations might be seen as a highly context-dependent issue (e.g. species depth distribution, life cycle, differential response to thermal stress) and overall relies on biological responses to temperature (among other climatic and non-climatic stressors) which are most often poorly constrained due to the lack of observation at the appropriate spatial and temporal scales.

In this context, we must note the importance of (i) a remote-sensing observing system to track the evolution of Marine Heat Wave events, (ii) sustained *in situ* observation over the long-term in marine coastal habitats, on both physical (temperature) and biological indicators, and (iii) a common analysis framework for comparison across temporal and geographic scales. Here, we analyse how such framework, when available, can allow good evaluation of Marine Heat Wave and better assessment of their ecological impacts. We provide insights on the 2017 Mediterranean marine heatwave, first with a view from the surface at regional and sub-regional scale in the Mediterranean Sea, considering CMEMS high resolution (4 km) satellite sea surface temperature (product reference 4.4.1). Then an inside view at local scale combining satellite and multi-year *in situ* data retrieved from T-MEDNet temperature series (product reference 4.4.2, see Section 3.6) recorded in a Marine Protected Area where biological impacts have been observed.

Identification and classification of MHW events

Marine heat waves have mostly been studied from the analysis of long-term satellite data sets over climatic time scale (30 years). Two different approaches can be conducted for their identification with respect to the long-term climatological mean for each location and day of year (Hobday et al. 2016) or with respect to an elevated temperature threshold (e.g. species specific thermotolerance threshold or upper percentiles of site temperatures, Marbà et al. 2015; Galli et al. 2017). While the later approach focus on extreme hot events, the former allows identification of strong anomalies (extreme warm events) throughout the entire annual cycle, which can prove relevant for a range of biological impacts, considering different biological processes and life stages of life cycle of marine organisms.

Relying on the definition of Hobday et al. (2016), Marine Heat Wave events, are identified as discrete and prolonged period of time (at least five consecutive days) with temperature above the site/day climatological 90th percentile. The method allows comparison of events duration and intensity across time and space from sites with different thermal regimes and we first analysed satellite sea surface temperature daily data from CMEMS (product reference 4.4.1). For each pixel, climatological mean and 90^{th} percentiles were calculated over the 1982–2011 period, using a 11-day centred window and additional smoothing on the climatology with a 30-day running mean (Hobday et al. 2016). The following primary metrics were used to describe the events: duration, maximum daily temperature (T_{max}), maximum intensity ($i_{max} = T_{max} -$ climatological mean), mean intensity and cumulative intensity ($i_{cum} =$ mean intensity × duration, in C° day). Total duration and total cumulative intensity were also calculated at different time scales, by aggregating duration or i_{cum} by month, season or year. The spatial extent of Marine Heat Wave events was computed at monthly and seasonal time scale from the satellite data of year 2017. In order to analyse the long-term trends at sub-regional scale, average daily temperature time series were calculated over three boxes shown in Figure 4.4.1(a). The Marine Heat Wave analysis was conducted over these spatially averaged time-series.

Classification of Marine Heat Wave events can be conducted by scaling their maximum intensity with respect to the degree to which temperature exceed the local climatology (Hobday et al. 2018). Categories of Marine Heat Waves are based on multiples of the value represented by the local difference between the climatological mean and the climatological 90th percentile. Multiples of this local difference describe different categories of Marine Heat Waves: defined as moderate (1–2×, Category I), strong (2–3×, Category II), severe (3–4×, Category III), and extreme (>4×, Category IV), based on their maximum intensity (i_{max}) at each point in space (Hobday et al. 2018).

The method is also suited for *in situ* time series (Hobday et al. 2016). Long-term (14 years) continuous (hourly) temperature time series has been acquired using vertical array of data loggers set at standard depth levels (every 5 m, between 5 and 40 m depth) in the no take zone of the Réserve Naturelle de Scandola (Parc Régional de Corse, France). Such oceanographic time series was obtained in the frame of sustained T-MEDNet network monitoring effort conducted jointly with Mediterranean Marine Protected Areas (see Section 3.6). The climatological mean and 90th percentile, were calculated for each depth over all daily averaged data available over the 2004–2016 period.

The 2017 Mediterranean MHW over the satellite record

Statistics computed from the CMEMS sea surface temperature data over the Mediterranean Sea show that 2017 was the sixth warmest year (mean SST = 19.86°C, anomaly + 0.65°C), and warmest spring on average since 1982 (Figure 4.4.1). During this warm year, significant Marine Heat Wave events occurred at regional scale in June, July and August (Figure 4.4.2) and at local to sub-regional scale across all four seasons, resulting in elevated total number of Marine Heat Wave days (Figure 4.4.2(a)). Overall, 99.6% of Mediterranean Sea surface experienced at least one Marine Heat Wave event and significant variability was evidenced at the various space scales (Figure 4.4.2). Marine Heat Wave days

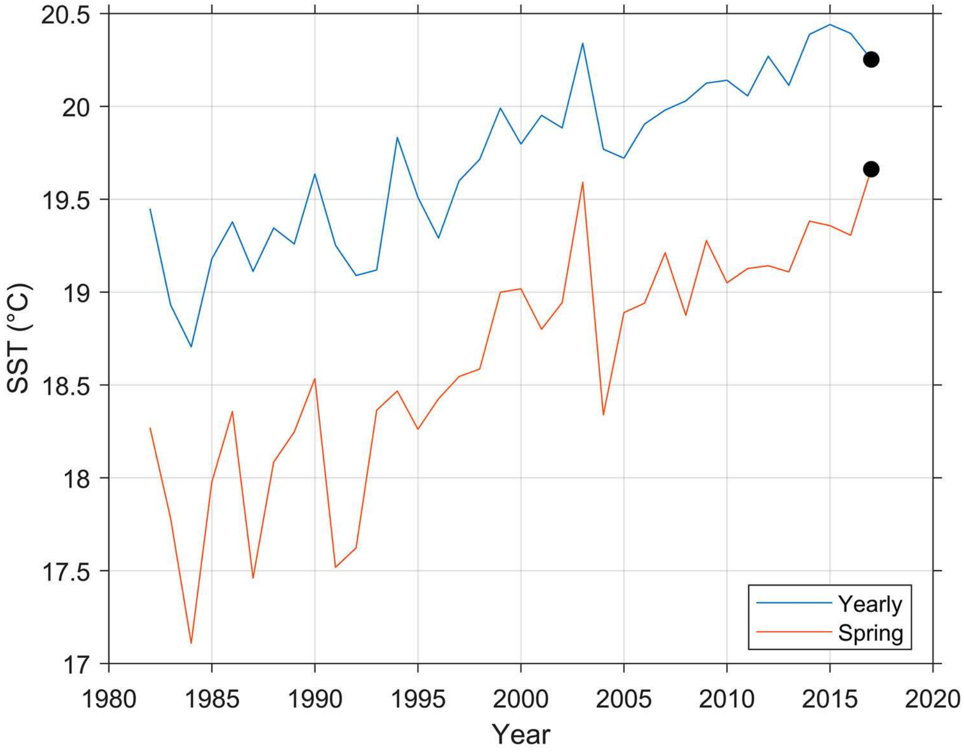

Figure 4.4.1. Time series of yearly and Spring (April, May and June) Mediterranean Sea surface temperature (SST) over the period 1982–2017. The black dots show results for year 2017. Reference number of the product used: 4.4.1.

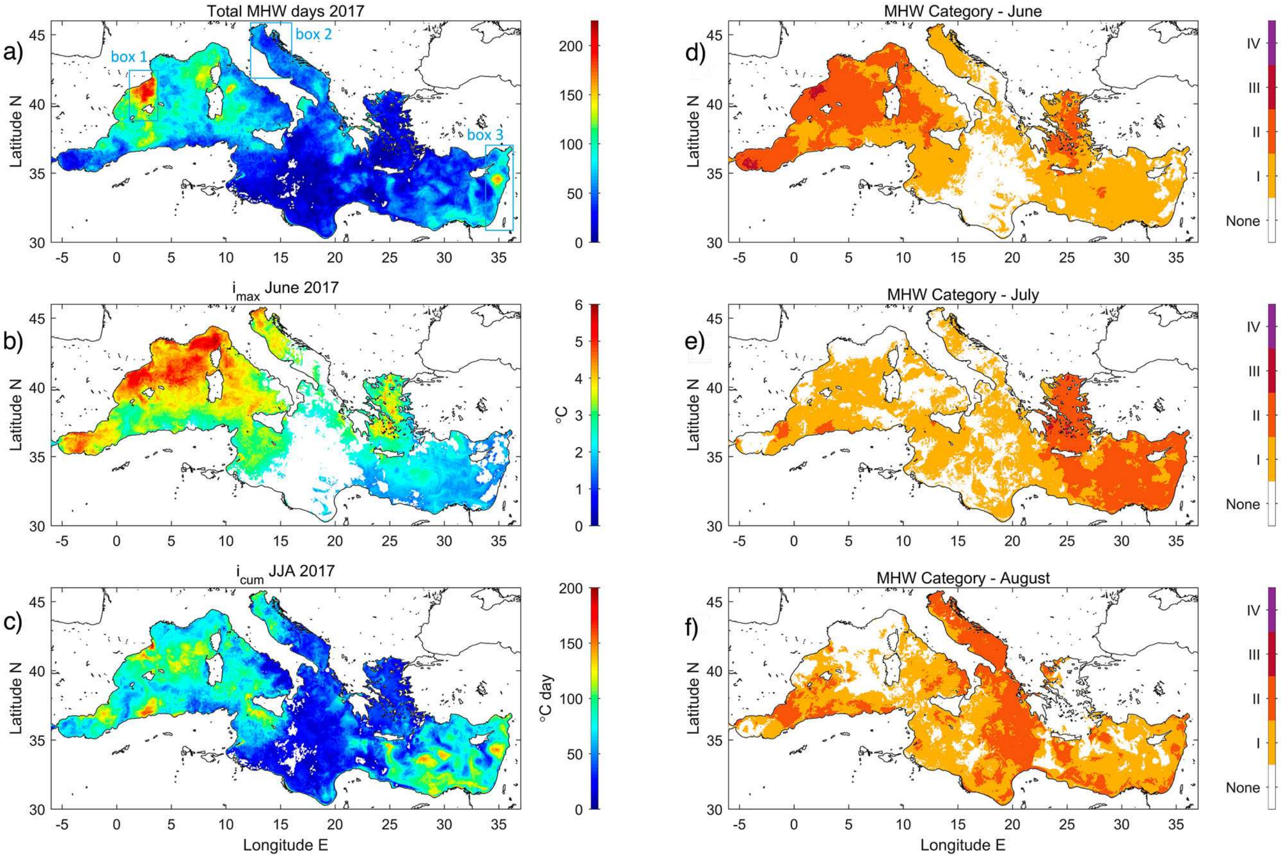

Figure 4.4.2. Maps showing different MHW metrics (left) and categorisation of MHW events by month (right). (a) Annual number of Marine Heat wave days in 2017, (b) MHW maximum intensity (i_{max}) during June 2017, (c) June to August 2017 MHW cumulative intensity (i_{cum}). (d, e, f) Highest MHW category by month, during the regional MHW events of June, July and August. Locations with no heatwave days are blanked out. Reference number of the product used: 4.4.1. Location of the three boxes considered for sub-regional analysis and of the Scandola Marine protected Area are shown in panel a.

were on average twice higher in the western than in the eastern basin (88 ± 31 vs. 43 ± 25 days, mean ± std). Total duration exceeded 6 months (max 225 days) in the northern Catalan-Balearic Sea and 4 months over 13% of the western basin surface, mainly from Algerian to Catalan Sea and from Sardinia to Ligurian Sea (Figure 4.4.2(a)). Similar amount of Marine Heat Wave days were not observed in the eastern basin, except locally in the eastern Levantine Sea.

A significant event at regional scale took place in June 2017, with a single long-lasting Marine Heat Wave (depending on the location, up to 20–25 days) in the western Mediterranean Sea. Figure 4.4.2(b) shows the very large spatial extent and elevated peak anomaly during this event. Maximum daily sea surface temperature anomalies up to 6°C were detected north of the Balearic-Corsica front but, in general, 4°C anomaly was reached in most part of the sub-basin and in the northernmost part of the eastern Mediterranean. We also analyse the cumulative intensity at the seasonal scale (here grouping June, July and August in order to account for different timing of observed events in the basin during the warm season). Combining both duration and intensity, Figure 4.4.2(c) shows overall elevated thermal stress in the western basin and adjacent Sicily channel, in the Levantine and northern Adriatic sub-basins. Significant spatial variability was observed with local extremes along the North Catalan coast, in the Algerian and Levantine seas which could be associated to seasonal or permanent circulation features, like eddy intensification in the Balearic-Catalan Sea (see Section 4.3) and permanent gyres (e.g. Ierapetra and Cyprus gyres), locally exacerbating the regional warm signal. It should be noted, on the other hand, that elevated i_{max} in the Aegean Sea (Figure 4.4.2(b)), when combined with locally short duration of the Marine Heat Wave, leads to a low cumulated intensity (Figure 4.4.2(c)). This example is suggestive of the relevance of considering both scores together with maximal temperature when interpreting Marine Heat Wave intensity. Adoption of a Marine Heat Wave scale was also found useful to communicate and raise scientific and public awareness on these extreme warm events (Hobday et al. 2018). Under this scheme, peak intensity of category II (strong) took place over most of the western Mediterranean in June, the Aegean-Levantine basin in July and the Adriatic-Ionian in August (Figure 4.4.2(d,e,f)).

Spatial and temporal variability of MHW events

We further focus our analysis to the Catalan-Balearic, northern Adriatic and eastern Levantine Sea, where relatively long event of category II occurred (Figure 4.4.3). In the north Catalan-Balearic area (Box 1, Figure 4.4.3(a)), sea surface temperature was overall warmer than average except in September. A sequence of eight Marine Heat Wave events took place between January and December, among which, the strong events of April and June ($T_{\max}$ 15 vs. 25°C) and the moderate but notably long fall event (78 days by the end of year, $i_{\text{cum}} = 113$°C day). This long event can be related to the intense anticyclonic eddy anomaly detected in fall-winter 2017 north of Mallorca Island, which blocked the general cyclonic circulation and enhanced the prevalence of Marine Heat Wave over the area (see Section 4.3).

In the warmer eastern Levantine Sea (Box 2, Figure 4.4.3 (b)), positive sea surface temperature anomaly prevailed from March to December and a notably long summer single event (97 days) occurred from 27 June to 1 October ($T_{\max} = 29$°C in July, $i_{\text{cum}} = 133$ C°day). In the northern Adriatic, six Marine Heat Wave events took place between late March and August (Figure 4.4.3(c)), out of which four were synchronous with events in the western Mediterranean (Box 1). Elevated $T_{\max}$ (28°C) was observed during the strong Marine Heat Wave event from 2 to 10 August.

Further analysis of the 36 years of satellite data attest of the unprecedented duration of the 2017 events (Figure 4.4.3(d,e,f)). In the western Mediterranean Sea (Box 1, Figure 4.4.3(d)), 2017 was the year with the highest annual number of Marine Heat Wave days since 1982. They were observed throughout the four seasons, as in 2015, but with only few days in summer compared to the years 2003, 2006 and 2015 (7 vs. 36–60 days respectively). Also, summer long event was evidenced in the eastern Levantine Sea for the second time since 1982 (as in 2012, Figure 4.4.3(e)). Interestingly in all areas, long-term increasing trend in Marine Heat Wave total duration (yearly) is obvious and longest total duration (>170 days per year) occurred during the past decade (2010 in the Levantine, 2014 in the Adriatic and 2017 in the Western). Splitting the observation period in two highlights contrasted Marine Heat Wave regimes. Since late nineties, Marine Heat Wave events have occurred every year in at least one season (except in 2005 in the N-Adriatic) and they last longer. This regime shift attest of the

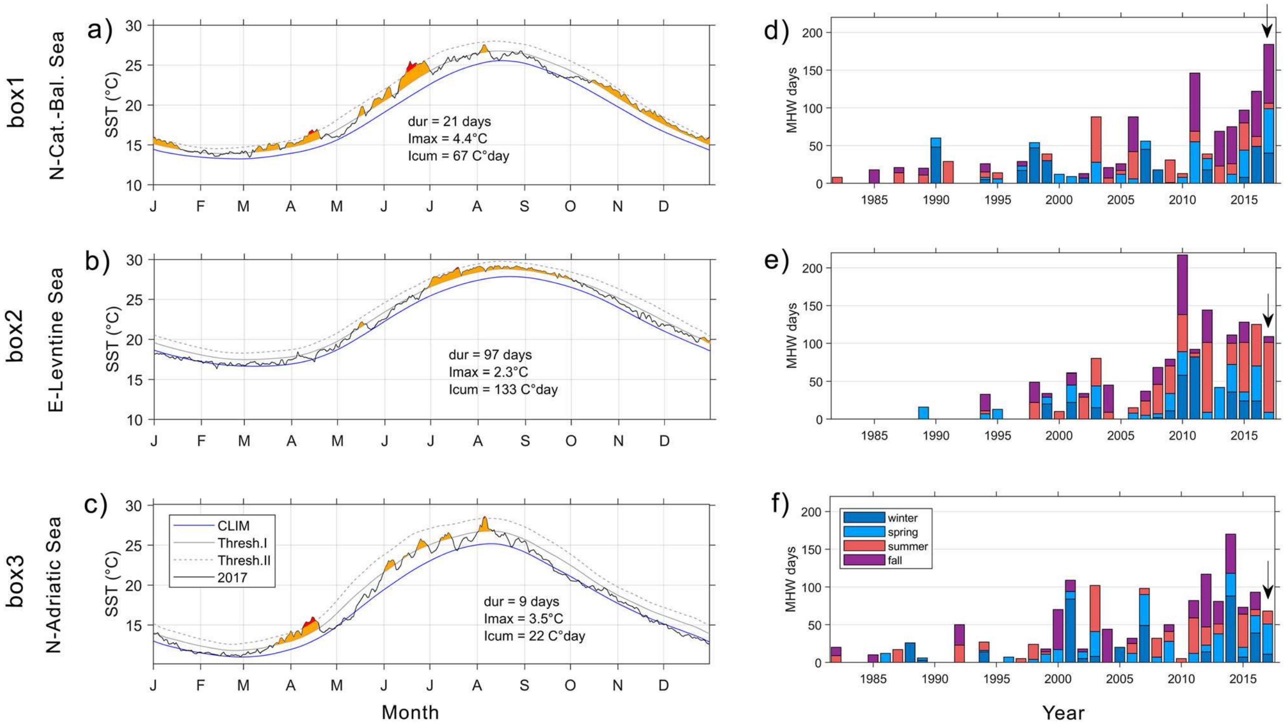

Figure 4.4.3. (a–c) Spatially averaged time series of daily sea surface temperature for the three boxes shown in Figure 4.4.2(a). The climatological mean (blue curve) and thresholds used to define MHW categories from moderate (dotted grey line) to strong (grey line) were calculated over the 1982–2011 period. MHW events are identified and filled with colours by categories (orange = moderate, red = strong). (d–f) Time series of the total number of marine heatwave days by year and by season since 1982, the arrow indicates the 2017 data. Reference number of the product used: 4.4.1.

important increase in the prevalence of extreme warm (upper decile) daily temperature under current warming trends (see Figure 4.4.1). Our results are in agreement with analysis conducted at global scale, which have been related to the acceleration of warming trends (Oliver et al. 2018).

Observed biological impacts

In 2017, concomitant with the thermal context, a range of biological impacts were observed. Firstly an unprecedented large-scale and long-lasting mucilaginous benthic algal bloom occurred along the French and Spanish coast of the northern Catalan Sea from spring till early fall (Figure 4.4.4). The mucilaginous algal blooms, mainly the Ectocarpal *Acinetospora crinita*, could cover all benthic habitats from 10 m down to 30 m depth. The cover of thick layers of mucilaginous algae dramatically affected even gorgonians which grow arborescent colonies up to 1 m in height depending on the species (Figure 4.4.4(b)). Subsequently, mass mortality on gorgonian species occurred in late Summer and Fall 2017 (mainly the red and white gorgonian *Paramuricea clavata* and *Eunicella singularis*, respectively). While in other areas of the north-western Mediterranean Sea mortality of gorgonians as well as other macrobenthic biota was observed, also in late summer. For instance, at the Réserve Naturelle de Scandola (Corsica) the yellow gorgonian *Eunicella cavolini* and several sponges species (*Spongia* spp. *Petrosia ficiformis*, *Ircina* spp.) dwelling between 10 and 25 m depth suffered from moderate to severe mortality impacts.

Surface and subsurface MHW in nearshore coastal waters (Scandola Marine Protected Area)

Proper knowledge on changes in environmental conditions, including marine heat waves, is needed to better assess potential impacts on ecosystem structure and function. Owing to the limited availability of long *in situ* data sets, it is not clear how accurate information can be obtained in the near-shore using satellite data (but see section 3.6). As satellite are restricted to the surface, *in situ* observations are required to cope with the important depth variability occurring during the seasonal stratification period, typically from April–May to Fall convective events. For instance the summer 2003 mega atmospheric heatwave over Europe was associated to extreme sea surface temperature in the central Ligurian Sea in August while cold anomaly prevailed below 10 m depth (Sparnocchia et al. 2006). Here we conduct further analysis from satellite data retrieved at local scale and *in situ* measurements conducted along the depth gradient from 5 to 40 m depth.

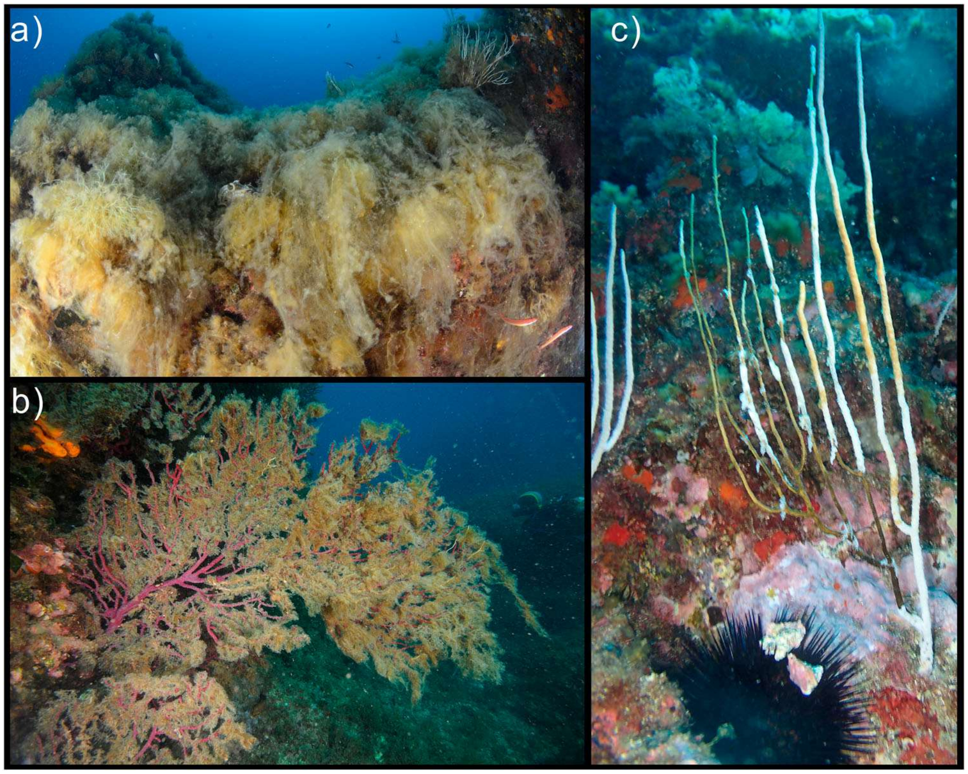

Figure 4.4.4. (a–b) Mucilaginous blooms covering different benthic assemblages (rocky infralittoral habitats and coralligenous) and species (the red gorgonian *Paramuricea clavata*) along the Catalan coast between Spring and Fall 2017, and (c) white gorgonian *Eunicella singularis* displaying signs of very recent necrosis (white tissue peeling off from the axis leaving denuded axis).

Local satellite data were retrieved from the closest pixel to the monitoring site considering the common years of data available (2004–2017). From the statistical analysis of the local satellite and *in situ*$_{5m}$ multi-year matchup database, high agreement was evidenced for Scandola, both in terms of correlation (0.988), bias (0.17°C) and round mean square difference (0.7°C). These results are in agreement with results shown in section 3.6 from analysis conducted in several Marine Protected Areas member of the T-MEDNet monitoring network. Figure 4.4.5(a,b) shows results from the Marine Heat Wave analysis conducted from June to October 2017 on the satellite and *in situ*$_{5m}$

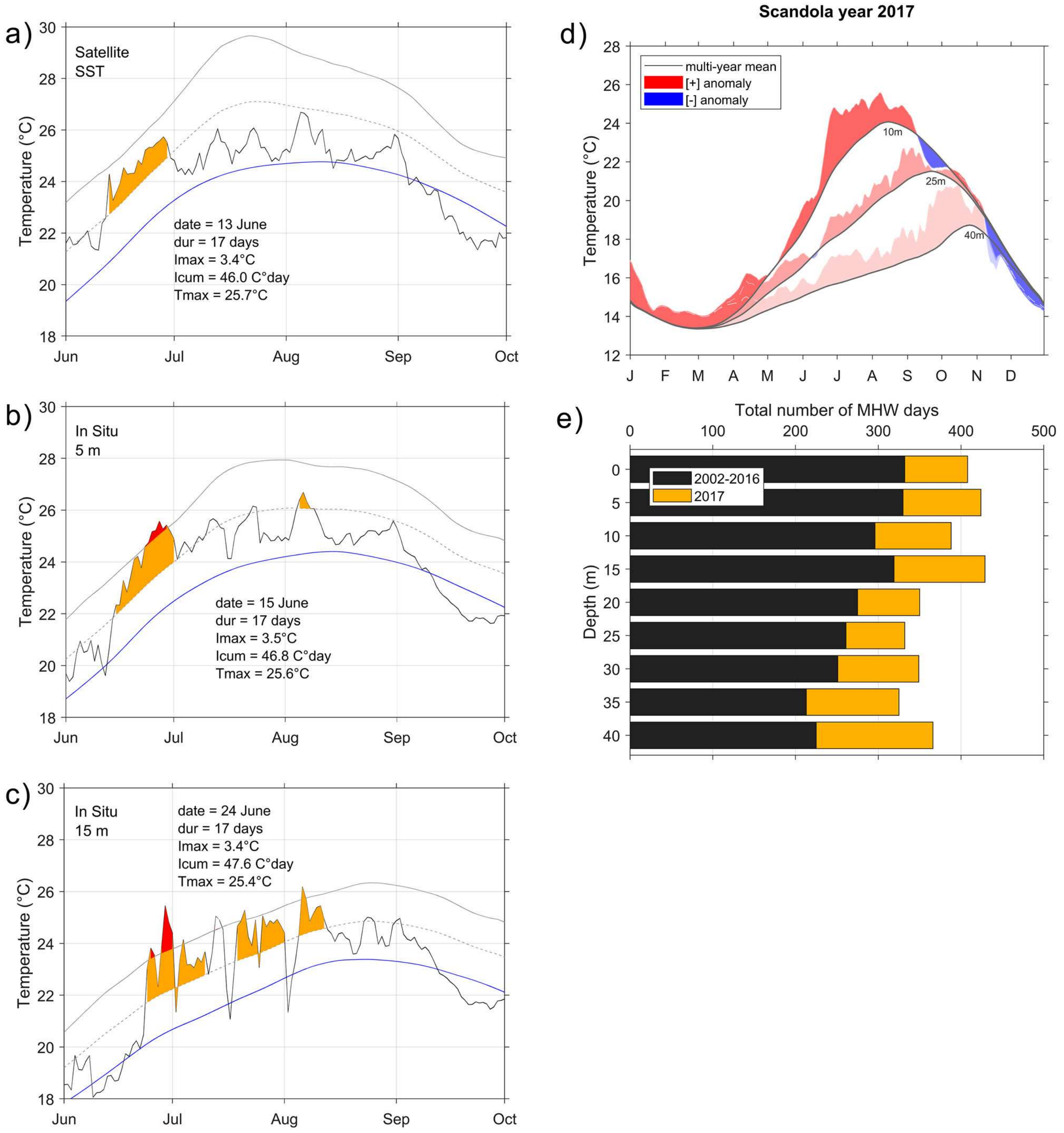

Figure 4.4.5. Information on MHW events in Scandola Marine Protected Area nearshore waters (Parc Régional de Corse, France). (a–c) Time series of daily satellite sea surface temperature and *in situ* temperature measured at 5 and 15 m depth. Climatology (blue line) and MHW thresholds (grey lines) calculated over the period 2004–2016 are also shown. MHW events are identified and filled with colours by categories (orange = moderate, red = strong). (d) *In situ* temperature anomalies relative to the multi-year mean at 10, 25 and 40 m depth. (e) Total number of MHW days from satellite (0 m) and *in situ* data (5–40 m depth). Reference number of the products used: 4.4.1 and 4.4.2.

data. The climatological mean and 90th percentile were slightly higher for the surface when compared to *in* $situ_{5m}$ (by typically <1°C). Also some differences arose regarding the number and category of detected events. Considering the strong June event however, high agreement was evidenced with negligible differences in terms of duration (17 days), $i_{\max}$ (3.5°C) and i_{cum} (46 C°day). This event reached deeper marine habitats, in fact, down to 15 m depth, with a time lag of ca. 10 days (Figure 4.4.5 (c)) while warm pulses occurred deeper (shorter than five days, not shown). Overall, over these 4 months, total number of Marine Heat Wave days was higher at 15 m (38 days) depth compared to 5 m (22 days) and surface (17 days), which can be seen as subsurface intensification of Marine Heat Wave, and largely depends on the seasonal stratification dynamics (Bensoussan et al. 2010; Schaeffer and Roughan 2017). Such anomalies were observed in late September and October at 40 m depth, as vertical mixing occurred and propagated the warm signal to depth (Figure 4.4.5(d)). Meanwhile, one might notice that cold to neutral anomaly prevailed at the surface.

Considering the 2004–2017 period (Figure 4.4.5(e)), elevate total number of Marine Heat Wave days was calculated over the depth range examined (325–429 days, maximum in the upper 15 m) from which a significant fraction occurred in year 2017. Interestingly, we can note the fair agreement between Marine Heat Wave days calculated from the local satellite and *in* $situ_{5m}$ data (0 vs. 5 m depth difference < 10%). Together with the high agreement evidenced for the June 2017 event, these results open new and interesting perspectives for satellite based analysis of Marine Heat Waves over climatic time scales (back to 1982) in the coastal zone.

Understanding the biological responses to warming and how changes in the thermal environment are driving changes in the marine biota is an active research field (see for instance Section 3.2 for fishes and Section 3.6 for the benthic biota). As introduced earlier in the section, different approaches might be used complementarily in order to assess such responses/impacts. In fact, metrics used to characterise Marine Heat Wave events (duration, $i_{\max}$, i_{cum}) could usefully be adapted to quantify more largely the positive anomalies (Figure 4.4.5(d)) occurring over given periods of interest, from days to month(s) and thus integrate the strong dynamics and variability modes of subsurface conditions (e.g. inertial oscillations, Bensoussan et al. 2010).

Mass mortality events are particularly strong disturbances affecting benthic habitats since they affect a wide range of macrobenthic species over large geographical scales (tens to thousands of kilometres of coastlines) as was the case in the 2017. However, mass mortality is only one of the impacts of climate change in the benthic coastal habitats. Overall climate change is severely modifying the structure and functions of marine coastal ecosystems to new configurations, which might no longer support the goods and services to people. In this context, we must note the importance of sustained observation effort on sub-surface temperature and biological indicators for comparison across temporal and geographic scales to enhance our understanding of ongoing changes and our forecasting abilities.

Acknowledgements

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4.5. Reversal of the Northern Ionian circulation in 2017

Authors: Giulio Notarstefano**,** Milena Menna, Jean-François Legeais

Statement of main outcome: A reversal of the surface circulation in the Northern Ionian Sea was observed in 2017. This changing of the circulation pattern seems to be periodic and it is critical for the redistribution of salt between the Eastern Mediterranean and the Northern Ionian – Southern Adriatic Seas. The periodicity of this reversal occurs on a quasi-decadal scale and, when it happens, it constitutes a special event because this phenomenon can deeply impact on the deep water formation sites and hence can affect the water masses distribution between the different Mediterranean sub-basins. Moreover, the shift of circulation mode can contribute to trigger abrupt events like the Eastern Mediterranean Transient that impacted the Mediterranean regional oceanography, shifting the deep water formation site from the South Adriatic to the Aegean/Cretan Sea.

Products used:

Ref. No.	Product name and type	Documentation
4.5.1	SEALEVEL_MED_PHY_L4_NRT_OBSERVATIONS_008_050 SEALEVEL_MED_PHY_L4_REP_OBSERVATIONS_008_051 Remote sensing	PUM: http://marine.copernicus.eu/documents/PUM/CMEMS-SL-PUM-008-032-051.pdf QUID: http://marine.copernicus.eu/documents/QUID/CMEMS-SL-QUID-008-032-051.pdf