MPA-ADAPT PROJECT

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Information resource on subregional vulnerability of MPAs in coastal areas

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INFORMATION RESOURCE ON SUBREGIONAL VULNERABILITY OF MARINE PROTECTED AREAS IN COASTAL WATERS

Introduction

The Mediterranean Sea is considered a hot spot for marine biodiversity (Coll et al. 2010). Covering less than 1% of world's oceans, it is home of about 10% of marine species with a high percentage of species that are only found in this enclosed sea. The Mediterranean marine ecosystems are key supporting the development of coastal and national wide socio-economic activities such as food provision, tourism industry and coastal protection. For instance, the Mediterranean area is one of the first tourist destinations in the world with more than 343 million annual visitors which are expected to increase by at least 20% during the next five years. However, the Mediterranean faces multiple pressures such as overfishing, pollution, arrival of non-indigenous species and climate change that are challenging the conservation of the rich biodiversity and the services they support.

The Mediterranean Sea is a temperate warm sea with mean annual sea surface temperature of 19.4 ± 1.3 °C (Figure 1). It exhibits important North to South and West to East environmental gradients, spanning over more than 6°C difference in yearly mean temperature (range 16 – 22.8°C). The Mediterranean coastal and shelf area can be subdivided into 7 ecoregions from Alboran to the West, to Levantine to the East (Spalding et al. 2007). The Mediterranean region is considered a hot-spot for climate change (Cramer et al. 2018). In fact, the entire Mediterranean Sea is extremely responsive to regional climate change. Over the 1982-2017 period, the Mediterranean Sea surface temperature has warmed by 1.4°C on average over the basin (see results section). These warming trends are associated to amplification of conditions now perceived as extreme, exacerbating the potential heat stress with multiple effects on marine ecosystems. Future evolution of Mediterranean Sea surface temperature has been evaluated using different modelling approaches. As shown in this document, the future trajectories of temperature conditions in coastal waters (from surface to 50 m depth and beyond) point to an unambiguously increase of mean temperatures and on the frequency on the occurrence of extreme events. Besides temperature modifications, combined effects with other stressor associated to climate change such as acidification and sea level rise have been as well observed (Cramer et al. 2018). In this way, Mediterranean Sea water pH is currently estimated to decrease by −0.018 to 0.0028 pH units per decade and during the last two decades, sea-level has risen by about 3 cm per decade.

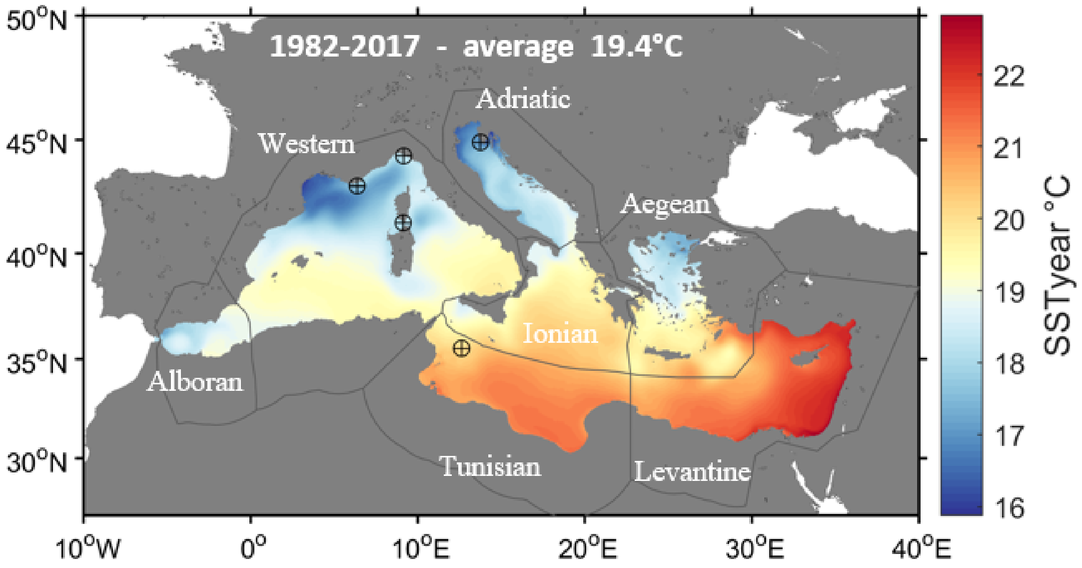


Figure 1. *Spatial maps of satellite derived sea surface temperature for the 7 Mediterranean ecoregions. Yearly average sea surface temperature calculated over the 1982-2017 period is displayed. The location of the 5 pilot Marine Protected areas participating in MPA-Adapt are indicated by circles. Figure generated using E.U. Copernicus Marine Service Information.*

The current and future climate change trajectory is considered one of the major concerns for the conservation of marine biodiversity (Hughes et al. 2017, Cramer et al. 2018). In the Mediterranean the observed warming is already affecting the marine ecosystems. Two main impacts are underway: i) the shift in species distribution (indigenous and non –indigenous) and ii) the occurrence of unprecedented mass mortalities events (MMEs). Besides these major impacts, other effects associated to warming are being reported as well, such as species proliferations and changes in species reproduction timing and migration patterns (Otero et al. 2013). Overall climate change is already dramatically affecting the abundance and distribution of species as well as the functioning of ecosystems (Givan et al., 2018, Sala et al. 2011, Cramer et al. 2018). It is difficult to foresee with precision to what extent the current climatic trends will affect marine ecosystems and key species in the Mediterranean Sea in the next decades. However, recent studies indicate that an increased extinction risk for endemic fauna, loss of habitat complexity and changes in ecosystem configurations is occurring (& Mouillot 2009, Lasram et al. 2010, Sala et al. 2011, Azzurro et al. 2019, Montero-Serra et al. 2019). In any case, management and conservation strategies of Mediterranean should therefore be wise enough to anticipate vulnerability to these new threats and to provide local communities with the adaptive capacity to cope with the related pressures (Fulton et al., 2015).

Marine Protected Areas (MPAs) are considered a primary tool for conservation biology for adapting and mitigating threats associated to climate change. In general, removing the impacts of local stressors in effectively managed MPAs demonstrated their effectiveness in the recovery of fish and coral populations (e.g. Linares et al. 2010, Edgar et al. 2014, Gill et al. 2017). Yet the effectiveness of MPAs to counteract global effects of climate change has been questioned (Coté & Darling 2010, Bruno et al. 2018), though there are evidences that MPAs may play a central role in enhancing the resilience of marine habitats to climate change (Micheli et al. 2012, Simard et al. 2016).

The main goal of MPA-Adapt was to enhance the role of MPAs as nature-based solutions for the implementation of EcAp to the adaptation and mitigation to ongoing climate change effects. To develop and efficient and cost-effective strategy for the full implementation, it is crucial to identify and prioritize key territorial challenges.

In this context, this document will provide the most updated and reliable information on current and expected environmental context associated to climate change at Mediterranean and eco-regions levels with special emphasis in the eco-region where the MPA-Adapt MPA are located. This information supported the assessment of the vulnerability of MPAs in view to develop the site specific adaptation plans.

As mentioned above there are multiple physico-chemical stressors as well as multiple ecological/biological impacts associated to climate change, however we decided to assess the vulnerability focusing in three main topics related with climate change impacts:

- Temperature conditions
- Shifts in species distributions (native and non –indigenous)
- Mass Mortality events

The main reason for this choice is to be in agreement with the main indicators monitored during the MPA-Adapt project by the five participating MPAs (Parc National de Port-Cros, Réserve Naturelle des Bouches de Bonifacio, Portofino AMP, Isole Pelagie AMP and Brijuni National Park; Figure 1). Besides, we contend that the chosen topics are already affecting most of the Mediterranean regions in a significant way.

Material and Methods

TEMPERATURE

TEMPERATURE DATASETS USED.

Ocean warming varies regionally and locally with impacts on ecosystems. The nearshore and coastal ocean is an area highly heterogeneous and with complex hydrodynamics, requiring high resolution information at spatial and temporal scale relevant for management and adaptation options, i.e typically from day to decades or beyond for local environmental variables.

In order to yield updated assessment of the evolution of regional sea surface temperature (SST) and site-specific thermal environment from recent past (back to 1982) to end of the 21st century, consistent analysis of the most recent observational and model data sets has been conducted.

Sea surface and sub-surface temperature can be measured with different sensors and instrumental platforms. While satellites provide good spatial and temporal coverage of the surface layer of the ocean, *in situ* measurements are needed to document the temperature variations beneath the surface. *In situ* data provide more reliable and accurate source of information on local conditions, though generally limited spatial and temporal coverage. When available, joint analysis of *in situ* time series with satellite derived SST provide unique opportunity to connect local observations to the (sub-) regional context and to enhance and validate spatial and temporal analysis in the coastal zone (Bensoussan et al. 2019ab). In MPA-Adapt we promoted the acquisition of high resolution temperature data series implementing the standardized protocol on temperature (Garrabou et al. 2018) (see below).

Recent evolution of Mediterranean Sea surface temperature has been evaluated over the 1982-2017 period using dedicated high-resolution observational data sets obtained from CMEMS. The Mediterranean reanalysis of AVHRR satellite derived SST at 4 km consist in daily, night-time, foundation temperature with improved accuracy and stability (Pisano et al. 2016).

Evolution of coastal thermal regimes, from the surface to 40 m depth, have been evaluated combining satellite derived SST with multi-year *in situ* observations acquired at high temporal (every hour) and vertical resolution obtained from the T-MEDNet regional observation network. The T-MEDNet database consists in 160 time series, mostly multi-year, originating from 67 monitoring sites in the Mediterranean Sea. Here we considered 4 decadal time series for trend and Marine Heatwave analysis (see Methods below).

The future evolution of Mediterranean SST under RCP8.5 has been evaluated using a dedicated ensemble of fully coupled Regional Climate System Models from the Med-CORDEX initiative (Darmaraki et al. 2019). The high-resolution simulations (10-20 km horizontal spatial resolution) from two different models were obtained from CNRM and CMCC, and considered for analysis representative of low and high model response to global warming respectively.

TEMPERATURE DATA ANALYSIS METHODS

The observational data were used to characterize thermal regimes and track changes in the marine thermal environment on the spatial horizontal and vertical dimensions. From the 36 years of daily satellite data, and available *in situ* data series, different statistics were calculated to analyze climatic trends as well as changes in daily T distribution relevant in both geophysical and ecosystem perspectives (Bensoussan et al. 2010, Lima and Wethey 2012, Hobday et al. 2016). High-resolution spatial maps have been produced over the entire Mediterranean Sea and ecoregions. Besides, local scale analyses have been conducted for pilot sites in the coastal zone considering nearest pixel.

Regarding thermal regimes: marine climatology allow through the analysis of large data sets to characterize normals and identify the main physical processes driving the various variability modes of the temperature conditions at depth (high frequency, seasonal, inter-annual).

Climatic trends and extreme warming events: warming trends were calculated over (multi-)decadal period depending on data availability, using Sen's regression on monthly anomalies to the climatology (Sen 1968). In our analysis we calculated changes in the number of warm and hot days defined from 75th and 90th percentile of the 30 years period 1982-2011 for satellite data, or considering the multi-year time series for *in situ* data. Beside Marine Heatwave (MHW) events were characterized using the approach of Hobday et al. (2016), over the length of the dataset, as fully described for satellite and *in situ* data in Bensoussan et al. (2019b). Spatial patterns were also analyzed from the satellite data, quantifying the spatial extent of MHW.

These analysis methods have been applied as well to the data sets obtained from CNRM and CMCC models (21st century simulations under RCP8.5) in order to evaluate future evolution of Mediterranean Sea surface temperature and marine heatwaves. This multi-model approach provides uncertainty estimates regarding the future trajectory of Mediterranean SST, which has also been evaluated through comparison with satellite observation over common periods.

SHIFTS IN SPECIES DISTRIBUTION

Climate change effects on the abundance and distribution of marine species are increasingly well documented and Mediterranean MPAs urgently need spatio-temporal assessments of these undergoing changes (Tulloch et al., 2015). Current warming trends ultimately favors the spread of warm-water affinity species while, due the geographic position and shape of the Mediterranean, cold-water affinity species are reducing their abundance and distribution areas. These changes, affecting many different taxa and through the different sub-regions of the basin (e.g. Bianchi 2007), also involve invasive species of tropical origin, which take advantage from novel climatic conditions to successfully spread over novel areas (Hiddink et al., 2012).

Population changes can be assessed on direct observations of single or multiple species, abundance of selected indicators or they can be inferred from changes in extent of occupied or suitable habitats.

Due to the nature of the observations made of invasive or range-expanding species, only occurrences data are often reported in the literature, while absences are usually not reported and are in many cases difficult to verify. When sightings have such an incidental character, they are known as presence-only records. Records in presence-only form may have several origins, as scientific records, citizen-science data and any other type of occasional or non-systematic observations. In the last years, due to the increasing need for managing, reporting, mapping and predicting biodiversity, this presence-only data have been increasingly generated by Mediterranean scientists providing new possibilities to map and model climate related changes in species distribution (e.g. Global Biodiversity Information Facility, GBIF; Ocean Biogeographic Information System, OBIS). In particular, Citizen Science can contribute with a large amount of data, even in traditionally data-poor areas (Bradter et al., 2018). Several citizen-related initiatives have been launched so far in the Mediterranean area (e.g. Mannino& Balistreri, 2018; Poursanidis & Zenetos., 2013; Bodilis et al., 2014), but so far only few systems provide geo-referenced observation on the regional scale making them visible and accessible by the general public (see www.seawatchers.org).

Predictions of shifts on species distributions can be made by two somewhat divergent groups of investigators: physiological ecologists and biogeographic modelers, using either mechanistic or correlative approaches, respectively (see Pacifici et al., 2015). One critical assumption of both approaches is that models developed at one location can be applied to novel conditions, either in space or in time.

Mechanistic methods relate environmental conditions to species' physiological responses. This approach has recently used by Marras et al. (2015) for analysing the energetics of habitat selection and to model the thermal habitat suitability of *Siganus rivulatus* (a tropical invader) and *Sarpa salpa* (a native temperate species) in relationship to current and future (2050) environmental conditions.

Correlative methods, the most used approach, relate environmental conditions to occurrence data to predict the geographical shift of suitable conditions for marine species under changing climate scenarios (see Lasram et al., 2010; Albouy et al., 2012, Coro et al., 2018 for the Mediterranean Sea). Species distribution models (SDMs) infer the spatial distribution of suitable habitats and estimate how the suitability would vary under changing environmental conditions.

SDMs application is particularly challenging in the context of invasion biology, because correlative models assume that species' niches (both fundamental, i.e. shaped by species' underlying abiotic requirements, and realized, i.e. the portion of the fundamental niche constrained by effects of biological interactions and environmental availability) are conserved through space and time (e.g. Li et al, 2014; Atwater, et al 2018). Conversely, the environmental space organisms occupy can change rapidly during invasion, due to evolved environmental tolerances in response to novel conditions in the new range, entailing a shift of the fundamental niche. The shift may also involve only the realized niche, e.g. due to the presence of novel biotic and abiotic conditions in the invaded range (Broennimann, et al., 2007). Indeed, recent studies (e.g. Parravicini et al., 2015) demonstrate that invasive species can occur in areas with different environmental conditions than experienced in their native ranges, violating the niche conservatism assumption. This may cause problems in projecting models from the native to the invaded range (transferability in space), with SDMs largely underestimating the invasion risk. To cope with this potential caveat, improved predictions of the invaded areas can be obtained by calibrating SDMs within both the native and invaded known ranges: this allows better characterizing species fundamental niche and producing improved forecasts for potential expansion under climate change. In addition, a recently presented advance consists in exploring univariate niche dynamics between native and invaded ranges to better assess the predictor set to be used during modelling. In fact, discarding those variables that show niche shift between invaded and native ranges, may allow to overcome SDM problems associated with transferability in space (D'Amen & Azzurro, 2019a in revision). Applying this methodology, in this document, we present a risk assessment for 142 Mediterranean Marine Protected Areas to the potential invasion of nine non-indigenous fishes of tropical origin in current conditions and under the 2050 RCP 26 future scenario (D'Amen and Azzurro, 2019b submitted).

MASS MORTALITY EVENTS

The first evidences of mass mortality events dated from the first half of ’80 years affecting the Western Mediterranean and the Agean Sea (Gaino and Pronzato 1989; Harmelin 1984; Bavestrello and Boero 1986, Voultsiadou et al. 2011). The most impressive phenomenon happened in 1999 when an unprecedented large scale MME impacted populations of more than 30 species from different phyla along the French and Italian coasts (Figure 2; Cerrano et al. 2000, Perez et al. 2000). Following this event, several other large scale MMEs have been reported, along with numerous other minor ones, which are usually more restricted in geographic extend and/or number of affected species (Garrabou et al. 2009, Rivetti et al. 2014, Marbà et al. 2015, Rubio-Portillo et al. 2015, authors’ personal observations). These events, in general, have generally been associated with strong and recurrent marine heat waves (Crisci et al. 2011, Kersting et al. 2013, Turicchia et al. 2018, Bensoussan et al. 2019ab) which are becoming more frequent globally (Smale et al 2019).

Gathering updated and comprehensive information on mass mortality events covering from regional to local scales is crucial to support scientific analysis of mortality events aiming to determine potential temporal and spatial patterns. This information will allow the analysis on the most vulnerable key species/habitats from the Mediterranean as well as geographic areas from ecoregions to local scales more susceptible of suffering mass mortality events. Overall such information is vital to guide management and conservation strategies that can then inform adaptive management schemes that aim to face the impacts of climate change.

To this end, within MPA-Adapt we developed a collaborative initiative involving more than 30 research institutions from 10 Mediterranean countries including EU and non-EU countries. This initiative aims to collect the information available (published in scientific journals and grey literature or still unpublished) on mass mortality events (MMEs) in the Mediterranean and facilitate the access to information related to Mediterranean MMEs.

The data from the MME-T-MEDNet database is deposited at Digital CSIC, the institutional repository of the Spanish National Research Council, and can be accessed via http://hdl.handle.net/10261/171445 (Garrabou et al. 2018). The database is also available in the T-MEDNet web platform which is devoted to tracking climate change effects in the Mediterranean Sea (http://t-mednet.org/mass-mortality/mass-mortality-events) where explanations for data upload, edition, exploration and download are detailed to enhance the collaborative effort in tracking MMEs in the basin.

The database was built from published records, predominantly from scientific journals and, to a smaller extent, from grey literature and technical reports. The database also benefited from previous reviews on MMEs (Rivetti et al. 2014; Marbà et al. 2015). To complete the database, we conducted a comprehensive literature search on ISI Web of Knowledge and Google Scholar using different search strategies combining the following different keywords: “mass mortality”, “mortality outbreak”, “necrosis”, “die-off”, “temperature anomaly”, “warming”, “climate change”, “heat wave”, “Mediterranean”, the names of different Mediterranean basins (e.g., Adriatic, Tyrrhenian, Aegean, Ionian) and the scientific names of affected species (e.g., *Paramuricea clavata*, *Corallium rubrum*). The final date available in our literature search was June 2017. For papers dealing with MMEs, we checked the cited references. Our search focused on macro- and mega-benthic species, while pelagic species (marine mammals and fish) are not included in the current version of the database.

Description of the mass mortality database

Field observations of mass mortality events in a specific geographic location (site) are the core of the MME-T-MEDNet database. One database record corresponds to the observation of abnormal (high) values of partial and/or total mortality (usually through quantitative indicators) in one local population at one specific time (or period). Here, we consider here a local population as a group of colonies or specimens/individuals of the same species (ranging from tens to thousands of depending on the species) dwelling in a specific geographic location that is defined by coordinates and depth range.

For each mass mortality event, the following information (main options in parenthesis) is provided:

- Geographic position (latitude and longitude in decimal degrees, datum WGS84);
- Ecoregion (following Spalding et al. 2007), basin, country;
- Year and season of the MME;
- Depth range in meters of the MME (minimum, maximum);
- Protection level of the affected site at the time of the MME event (protected, unprotected);
- Taxa/species affected;
- Degree of impact (sampling effort and % affected individuals);
- Biotic and abiotic parameters driving the mortality (e.g., high temperature, pathogens);
- Reference (published - paper in a scientific journal, conference proceedings, technical reports, or unpublished data);

A total of 196 papers were analyzed, of which 64 contained relevant information for the. Overall, we extracted information regarding 676 mass mortality events (one event corresponds to one species, one location and one period) observed between the years 1979 to 2017 throughout the Mediterranean Sea. This is the core of the information included in the MME-T-MEDNet database.

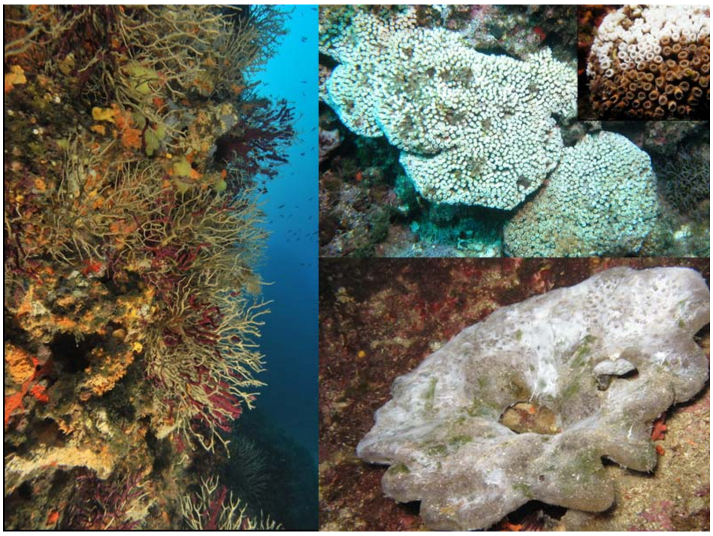


Figure 2. *Macrobenthic key species affected during mass mortality events in the Mediterranean Sea. From left the red gorgonian* Paramuricea clavata, *right up the scleractinian coral* Cladocora caespitosa *and right down the horny spong* Spongia lamella.

Main results and conclusions

TEMPERATURE WARMING TRENDS AND EXTREME EVENTS

WARMING TRENDS

Mediterranean and ecoregion scales. The Global ocean has stored over 90% of the excess heat (Earth energy imbalance) caused by continuous emission of greenhouse gases, mostly in the upper 700 m of the ocean, with largest warming observed near the surface (IPCC 5th AR). It is well known that European Seas, including the Mediterranean Sea are among the fast changing Large Marine Ecosystems of the world (Belkin et al. 2009). Updated analysis for the period 1982-2017 indicates that Mediterranean SST has warmed by 1.4°C on average, i.e. at a rate of 0.039°C per year which is 6.5 time faster than the mean warming rate of the word's ocean (0.006°C per year, Table 1). Within the Mediterranean, warming is uneven, showing the highest rates in the Adriatic, Aegean and Levantine ecoregions (1.5-1.8°C average, locally >2°C) and lowest in the Alboran and Western ecoregions (1.1-1.2°C average, locally > 1.5°C) (Figure 3).

Regional warming is known to display important spatial and temporal variability from decades to seasons (Skliris et al. 2011ab). In the NW Mediterranean, which is among the coldest area of the Mediterranean Sea, long-term (1982-2017) warming trend occurred at a rate of 0.024°C/year, with strongest warming observed in June (0.056°C/year). During the 2004-2017 period and when compared to the long-term trend, warming has accelerated by 80% on average over the NW Mediterranean Sea and by 30% at basin scale (Table 2).

In the context of rapid Mediterranean warming, important changes in temperature distribution are occurring. For instance, exposure to warm conditions (defined from 75th percentile of the 30 years period 1982-2011) has increased by 0.9 day per year in the NW Mediterranean Sea, i.e. a total of 32 days over the 1982-2017 period. This was primarily due to advance in the onset of warm conditions by 25 days, now starting in June, while the end date has been expanded by 1 week in October. These results, consistent with the highest warming rates observed for June over the area, are in agreement with recent local analysis conducted on the l'Estartit oceanographic time series (+40 years) in the Catalan Sea (Salat et al. in press).

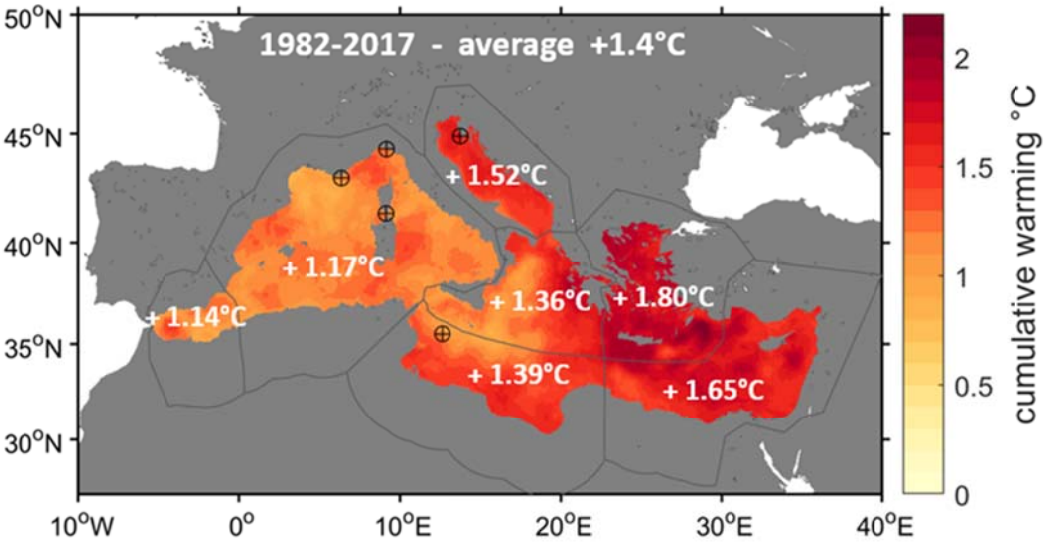


***Figure 3**. Mediterranean SST warming over the 1982-2017 period. Generated using E.U. Copernicus Marine Service Information.*

Table 1. SST Warming rate (°C/year) at global and regional scale over the 1982-2017 period depending on data sources. Data source: U.K. Hadley center SSTice global dataset at 1° resolution and CMEMS-AVHRR L4REP.

	SST warming 1982-2017		Ratio
	Global Ocean	Mediterranean Sea	Med. / Gobal
Hadl 1°	0.006	0.029	4.8
CMEMS		0.039	6.5

***Table 2**. SST warming rate (°C/year) over two different periods (1982-2017 vs. 2004-2017) to illustrate recent acceleration (Ratio >1) of SST warming at regional and sub-regional scale in the Mediterranean Sea. Data source: CMEMS-AVHRR*

	1982-2017	2004-2017	Ratio
Med. SST	0.038	0.050	1.31
NW-Med. SST	0.024	0.044	1.83

Warming rates in coastal waters - local scales.

Analysis of the 36 years of satellite data attest of rapid sea surface warming at local scale in the five pilot sites (Figure 4). The cumulative warming over the 1982-2017 period ranged from +1.1°C in Bonifacio to +1.6°C in Brijuni NP (N-Adriatic), being generally close or within 10% variation of average ecoregion warming rate, except in Lampedusa (Tunisian plateau) where significantly lower value, comparable to trends in the NW-Mediterranean Sea, was evidenced (Figure 4).

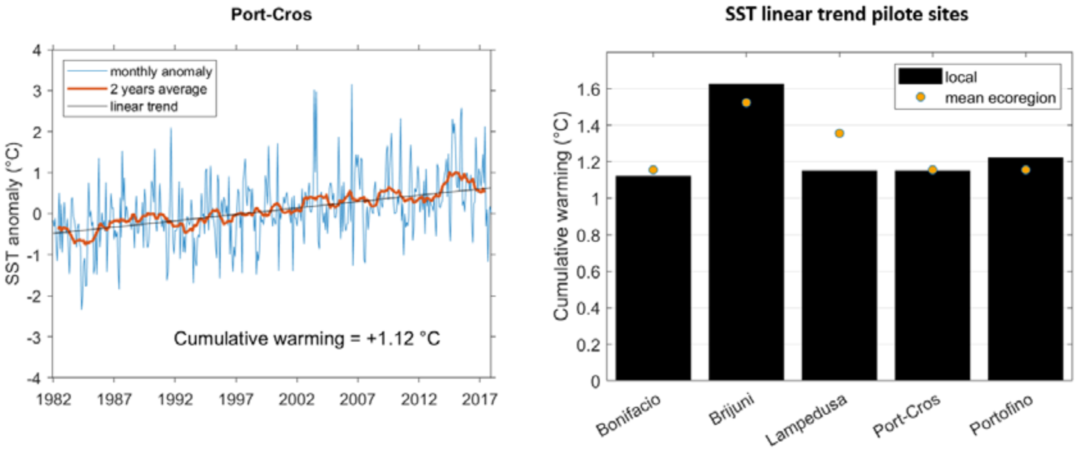


Figure 4. *Monthly SST anomalies over the 1982-2017 period, with 2 years running average (in red) and linear trend (Left panel). Summary of cumulative warming trends at the 5 pilot MPAs compared to the average value in their respective Ecoregions (orange dots) (Right panel).*

Rapid and accelerated coastal waters warming over the past decade was also confirmed by joint analysis of satellite and in situ data sets in different sites in the NW Mediterranean Sea (Bensoussan et al. 2019a). However, due to the scarcity of continuous observational data sets over the long-term (> 10 years), little is known about the propagation at depth of this warming signal. To investigate warming at the depth of marine coastal habitats, we have analysed the long-term series acquired in Port-Cros NP and in 3 other sites over the 2004-2017 period (complementary data obtained from T-MEDNet database). Figure 5 shows that the current warming trend is not limited to the surface, but propagates at depth with important variability along the depth gradient depending on local thermal regimes and seasonal stratification dynamics. Sustained observation effort in the pilot sites will provide important and complementary information to track sub surface warming trends.

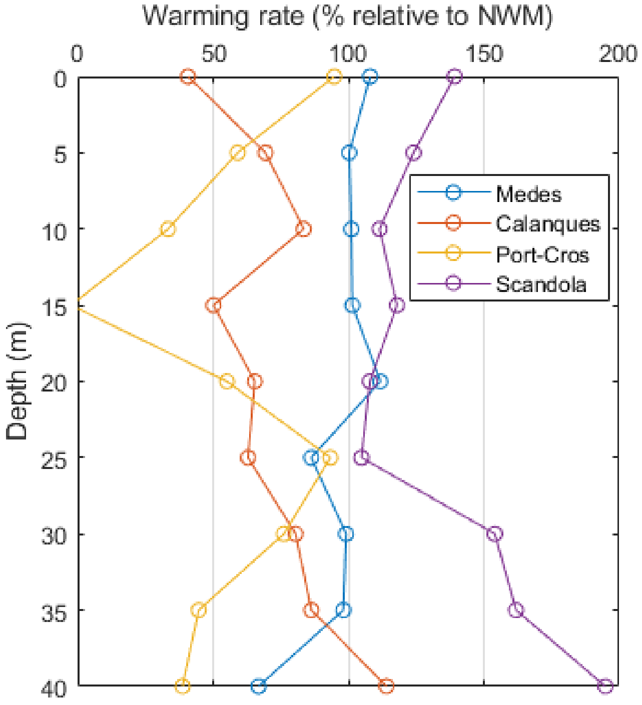


Figure 5. *Coastal waters (0-40 m) warming trend over the 2004-2017 period in different MPAs Port-Cros NP and 3 other MPAs along the coasts of Catalonia (Medes), Provence (Calanques NP), and Corsica (Scandola MPA) in the NW Mediterranean Sea . Warming trends are expressed in % relative to the average sea surface warming n the NW Mediterranean Sea. Figure generated using E.U. Copernicus Marine Service Information for satellite data and T-MEDNet daily time series for in situ data.*

MORE FREQUENT AND INTENSE MARINE HEAT WAVES (MHW)

Mediterranean and ecoregion scales. Extreme warming events from days to months, known as Marine Heatwaves, have increased in frequency and magnitude worldwide with impacts on ecosystems (Oliver et al. 2018, Smale et al. 2019). Over the past decades, the Mediterranean has been exposed to strong regional Marine Heatwaves, e.g. during summer 2003 and 2010 which peaked over the Western and Eastern basins respectively (e.g. Garrabou et al. 2009, Bensoussan et al. 2019b).

As for warming trends, important spatial variability has been evidenced for MHW events (e.g. Bensoussan et al. 2019ab). Strong spatial structuration of MHW was obvious at sub-regional scale, along the N-S and E-W gradients. Furthermore, variability in wind regimes and eddy activity are known to modulate MHW, locally exacerbating MHW conditions in the spatial horizontal and vertical dimensions (Bensoussan et al. 2019b). Though, strong increase in

MHW frequency has been evidenced in the different Mediterranean sub regions as illustrated here for the NW Mediterranean Sea, North of 41°N (Figure 6).

An average of 54 MHW events occurred at sub-regional scale during the months JJASON, among which 19 over the 1982-2000 period and 35 since then. Splitting the time series in two equal periods (1982-1999 vs. 2000-2017) indicates clear regime shift in MHW occurrence and severity between these 2 periods. Median number of MHW-days has increased from 7.5 to 26 days per year (Figure 6) due to the higher number of MHW events and also to the long duration (> season) of some events in fall-winter 2007 and 2014. Meantime, the intensity of MHW events has increased, showing maximum intensity > 5°C, and higher interquartile range after year 2000 when compared to the 1982-1999 period (3rd quartile value of 3.6°C vs 2.5°C, dashed lines in Figure 4).

Although Marine Heatwaves reach deeper layers and might be amplified at some depth (Schaeffer & Roughan 2017, Bensoussan et al. 2019b), the SST MHW regime shift is considered reliable sign of possible harmful conditions for coastal ecosystems.

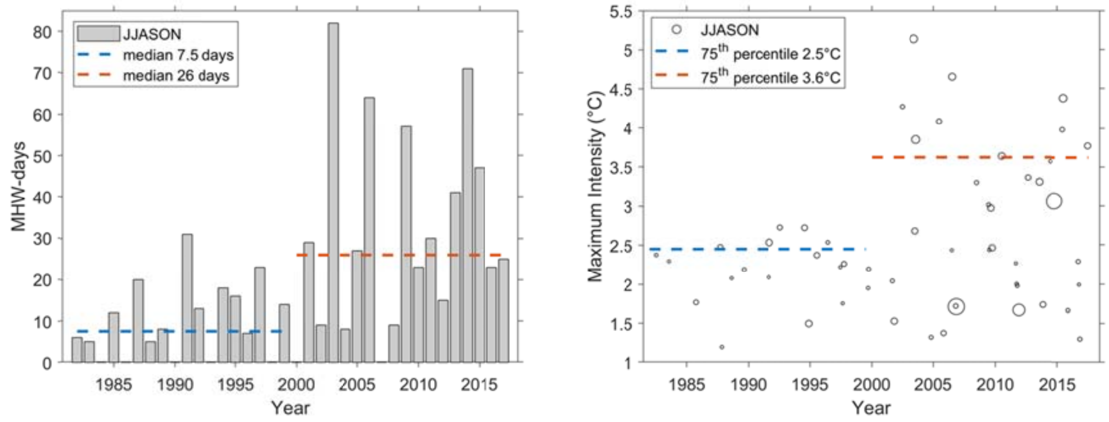


Figure 6. *Time series of Marine Heatwave days (left) and maximum intensity (right) during the 1982-2017 period. For each year, statistics were calculated considering events started between June and November.*

Coastal areas - local scales MHW observation.

Increasing thermal stress was also evidenced by analysis of available *in situ* time series. Interestingly, joint analysis of satellite and *in situ* data yielded consistent results for (near) surface MHW. Besides, Marine heatwaves have been shown to propagate along the depth gradient, and to reach also deep coastal ecosystems as illustrated for Port-Cros NP and 3 other coastal sites in the NW Mediterranean Sea (Figure 7). Consistently, MHW appear more frequent at the surface when compared to the depth of intermediate (20 m) or deep (40 m) coastal habitats where they generally occur in September or October with the deepening of the seasonal thermocline. Depending on sites and local oceanographic conditions, MHW occurred at depth under different breaking years, like in 2014 along the coasts of Provence, or 2017 in Corsica (Figure 7). This spatial horizontal and vertical variability was further investigated for year 2017, when strong MHW events occurred at regional scale, affecting the entire Mediterranean Sea (Bensoussan et al. 2019b). The temperature records and anomalies for year 2017 at 3 depth levels (shallow, intermediate and deep) in four of the pilot sites (Figure 8) highlight the very strong and long lasting anomalously warm conditions that prevailed over the entire water column in Bonifacio (Southern Corsica).

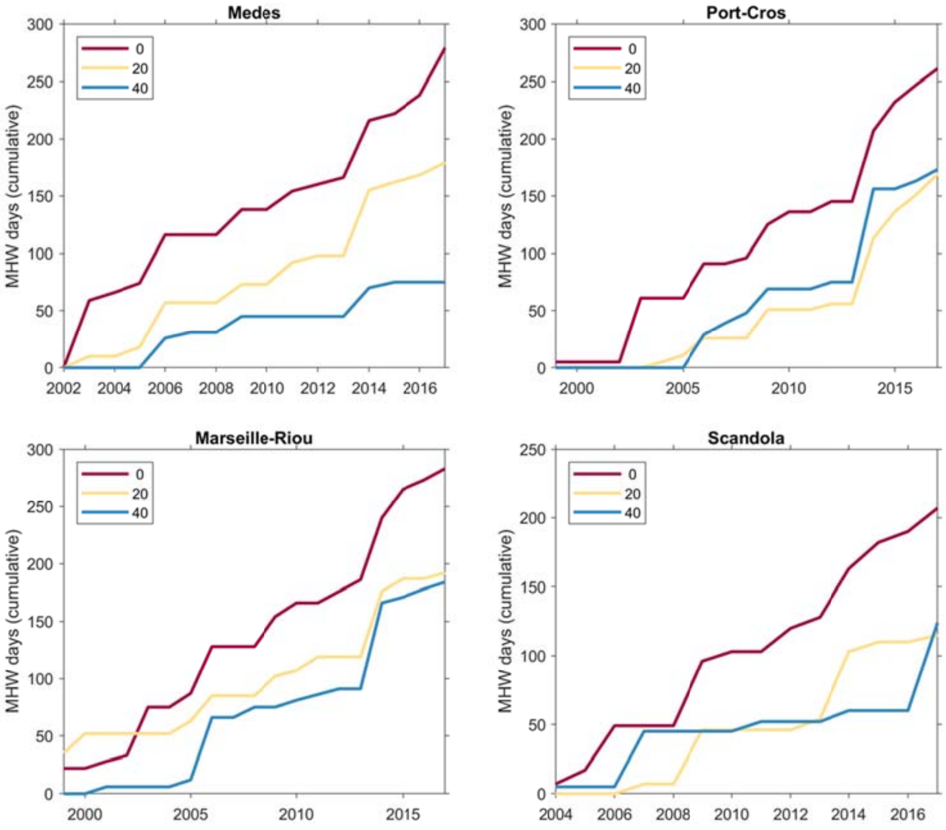


Figure 7. *Cumulative number of MHWdays during the warm period (JJASON) from the surface to 40 m depth in 4 sites along the coasts of N-Catalonia (Medes), Provence (Marseille and Port-Cros) and W-Corsica in the NW Mediterranean Sea. Figure generated using E.U. Copernicus Marine Service Information for satellite data and T-MEDNet daily time series for in situ data.*

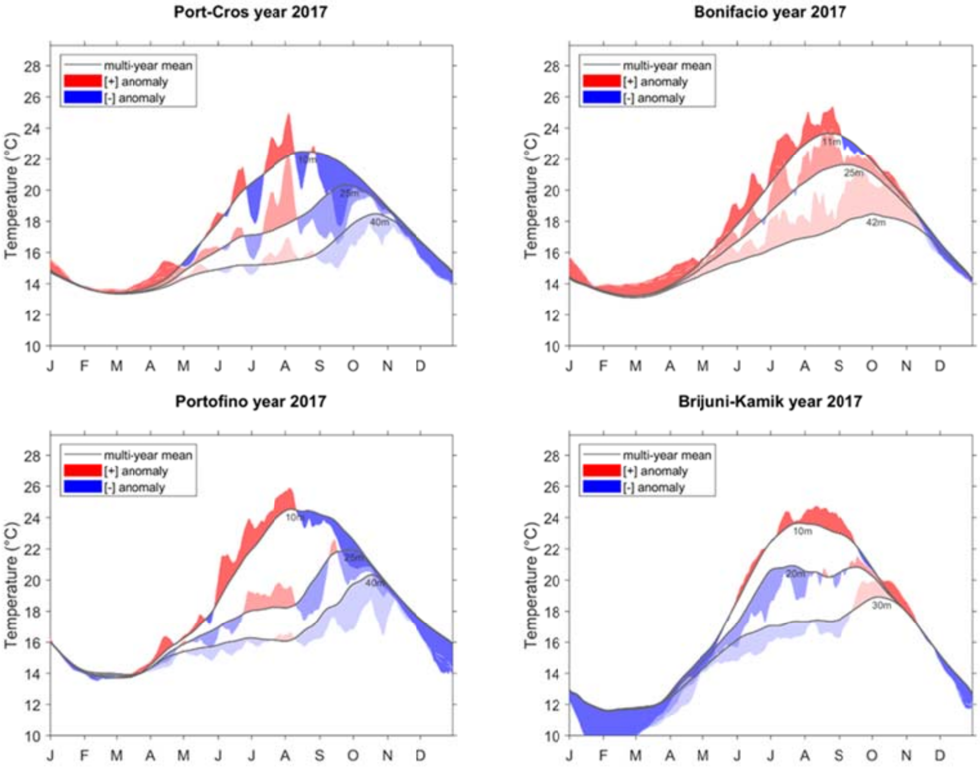


Figure 8. *Multi-year mean temperature (black lines) and year 2017 conditions at 3 depth level in four pilot MPAs from the NW Mediterranean (Port-Cros NP, Portofino, Bonifacio) and Adriatic (Brijuni NP) Seas.*

Overall, this updated analysis of satellite and *in situ* data sets provides clear evidence of increasing thermal stress for marine ecosystems, through accelerated warming and intensification of the perturbation regime associated to MHWs.

EXPECTED FUTURE TRENDS

Mediterranean and ecoregion scales

Considering the Med-CORDEX multi-model mean, average SST increase of 3°C is expected by the end of the century while temperature extremes 4°C warmer are projected (2071-2100 period compared to 1976-2005 period) (Darmaraki et al. 2019). In Figure 9, we show the modelled evolution of average Mediterranean SST for both Historical run (1950-2005) and 21st century scenario RCP8.5 obtained from CNRM and CMCC, together with satellite observations (in blue). The low and high response models show significant differences after 2050, and average warming of Mediterranean SST of 3 to 4°C by the end of the century. One can notice that the projected warming trends are inferior or equal to currently observed trends, which might thus be interpreted as low change hypothesis.

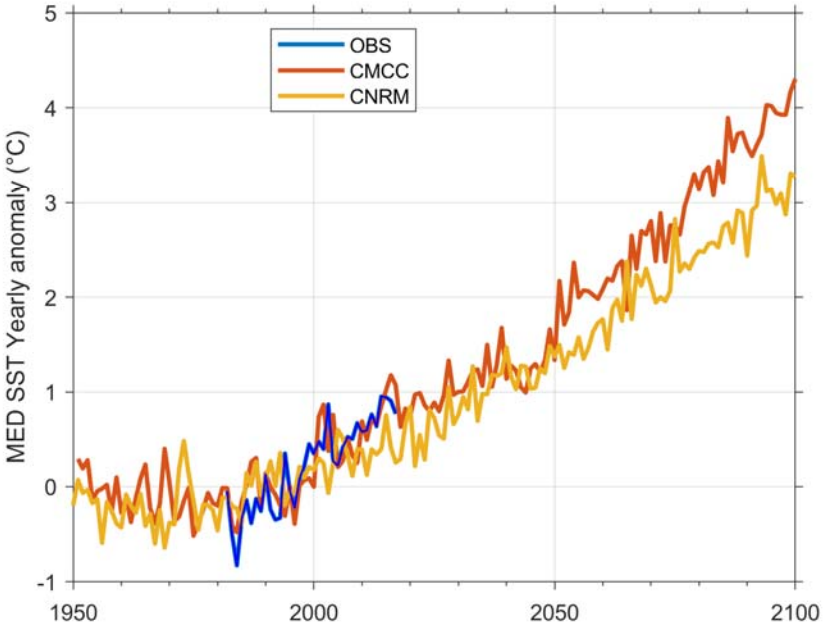


***Figure** 9. Evolution of Mediterranean SST from MedCORDEX models CNRM and CMCC under RCP8.5 and satellite observations.*

Regarding Marine Heatwaves (MHWs), different and complementary analysis were conducted, targeting the occurrence of extreme warm (90th threshold) or extreme hot (99th threshold) conditions.

By 2100 and under RCP8.5 scenario, long-lasting Marine Heatwave events are expected to occur every year, to be about 4 times more intense and to increase in duration, being up to 3 months longer than under present conditions when considering the 99th percentile threshold (Darmaraki et al. 2019) or lasting over entire seasons/year length after 2050 with the 90th threshold (Figure 10).

These SST trends over the Mediterranean Sea can be considered reliable signs of harmful conditions affecting the marine biota, leading to totally new configurations in coastal ecosystems diversity and function.

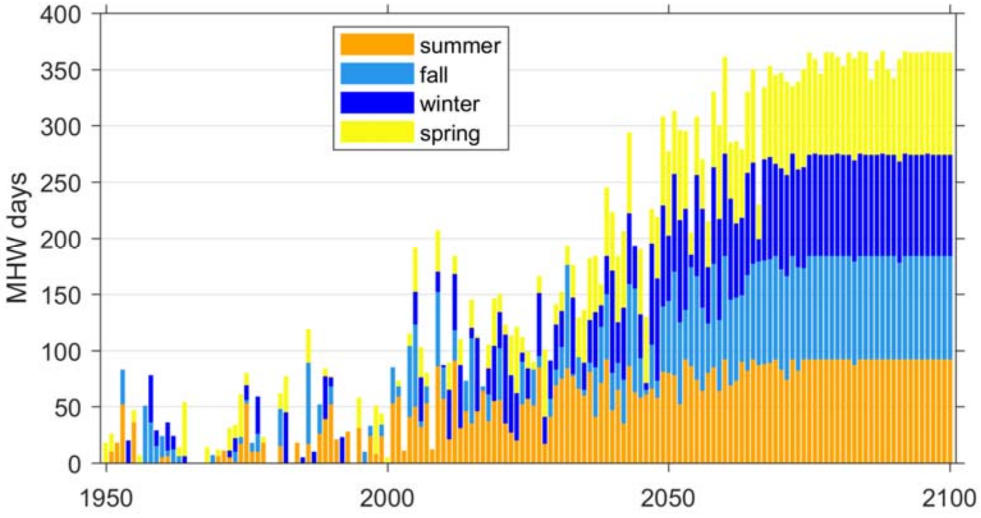


***Figure 10**. Evolution of Marine Heatwave days by season considering CNRM Historical run (1950-2005) and 21st century scenario (RCP8.5).*

Coastal areas - local scales

Local scale analysis of 21st century simulations has been conducted for pilot sites (Figures 11 and 12) considering the nearest grid points from RCP8.5 CNRM simulation. Results show local SST warming of ca. 3°C during the 21st century, i.e. around average projected warming for the Mediterranean Sea (Figure 11). Detailed analysis of the corresponding change in annual Marine Heatwave days and maximum intensity has been conducted as illustrated for Port-Cros (Figure 12). Increasing trend in frequency is obvious (+3 days per year) and goes along with increase in *imax* which might reach 9°C by the end of the century.

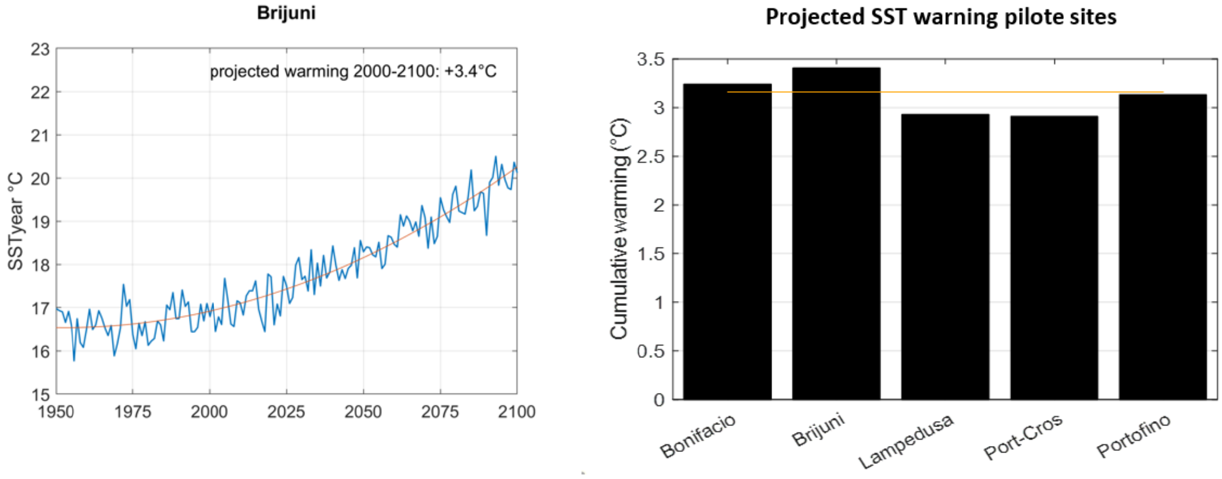


Figure 11. *Modelled evolution of Sea Surface Temperature at local scale for nearest grid point to pilot sites. Model results obtained from CNRM regional climate system model under RCP8.5 scenario. Left: yearly averaged SST evolution from 1950 to 2100 near Brijuni NP (N-Adriatic). Right: projected 21*st *century SST warming at the 5 pilot sites and average warming over the Mediterranean Sea (orange line).*

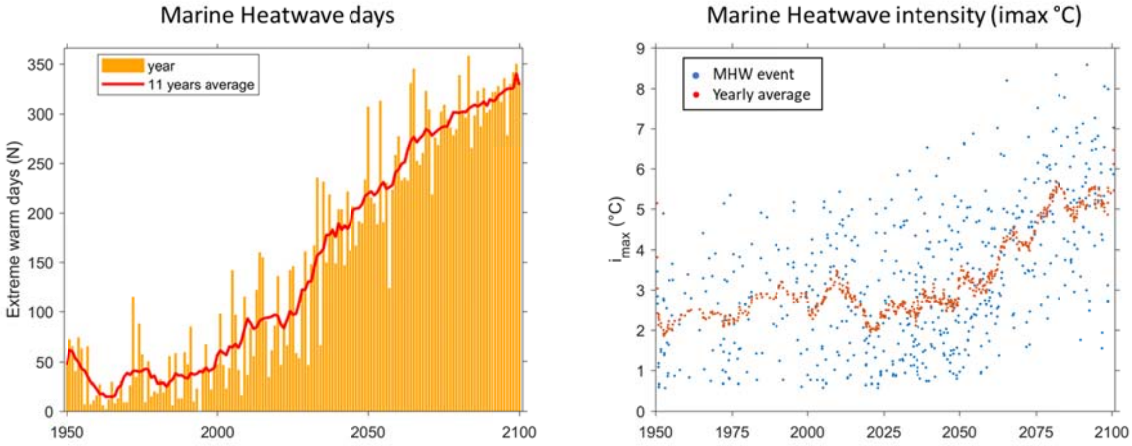
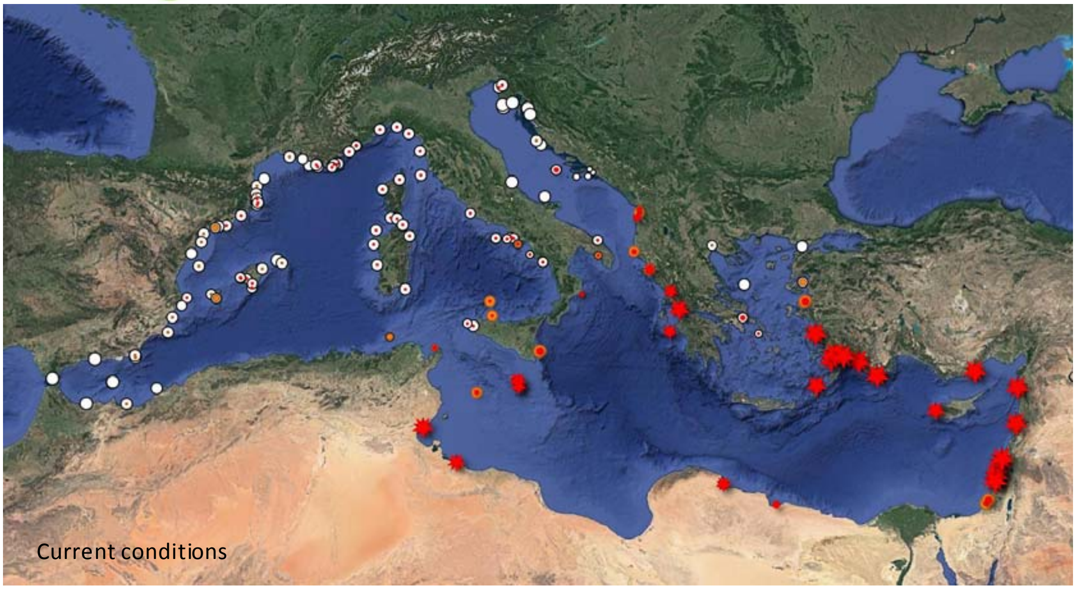


Figure 12. *Modelled evolution of Marine Heatwaves affecting the sea surface near Port-Cros NP. Left: Number of Marine Heatwave days for each year over the 1950-2100 period and 11 years running average (in red). Right: Marine Heatwaves maximum intensity (imax, in °C) and yearly average of imax of all events during the year (in red).*

SHIFTS IN SPECIES DISTRIBUTION

Mediterranean marine ecosystems are heading towards a climate-induced revolution in their biotic structure and functioning (Bianchi, 2007; Boero et al., 2008; Lejeune et al., 2010). This is mostly driven by rapid and profound changes in the abundance and distribution of species, which is known to be a direct and well-known consequence of climate change worldwide (e.g. Parmesan & Yohe, 2003). Warm water species of both exotic and native origin benefit from the novel climatic conditions and spread over novel areas with significant ecological and socio-economic consequences (e.g. Katsanevakis et al., 2014a,b). Among the tropical invaders that reached the MPA-Adapt area we can list the rabbitfishes *Siganus luridus* and *S. rivulatus* (Azzurro et al 2017a), the cornetfish *Fistularia commersonii* (Azzurro et al., 2013), the lionfish *Pterois miles* (Azzurro et al 2017b), the toxic *Lagocephalus sceleratus* (Rambla-Alegre et al., 2017), the Atlantic blue crab *Callinectes sapidus* (Mancinelli et al., 2017) and the Atlantic crab *Percnon gibbesii* (Suaria et al., 2017), just to mention some.

Climate change is making Mediterranean MPAs a more favourable environment for the invasion of non-indigenous species of tropical origin. In Figure 13 we showed the results of the risk assessment for 142 Mediterranean Marine Protected Areas to the potential invasion of nine non-indigenous fishes of tropical origin in current conditions and under the 2050 RCP 26 future scenario (D'Amen and Azzurro, 2019b submitted).



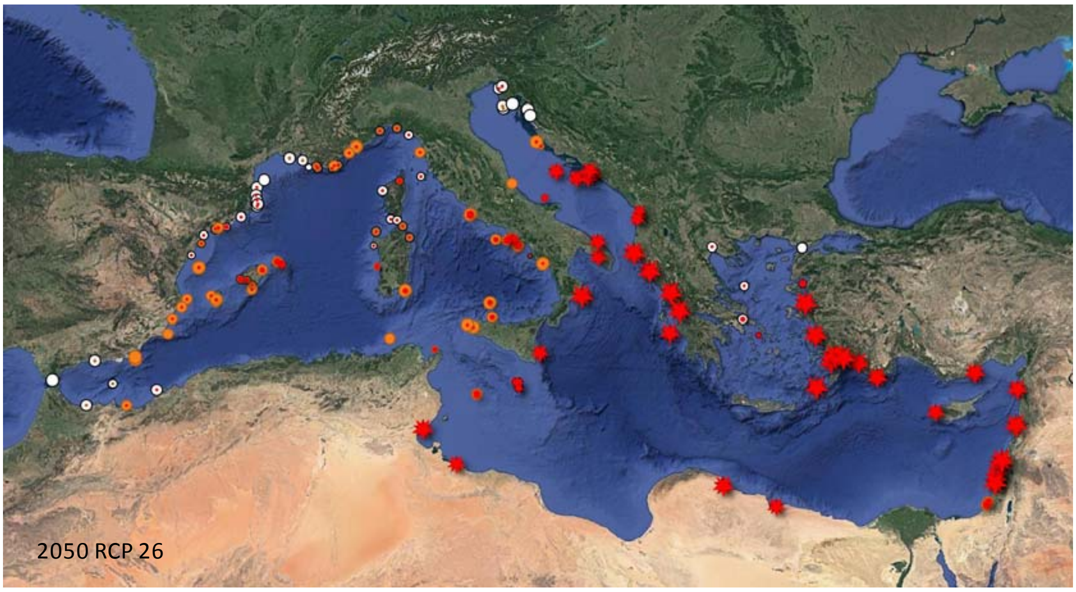


***Figure 13**. Risk assessment for 142 Mediterranean Marine Protected areas to the potential invasion of nine invasive fishes of tropical origin in in current conditions and under under the 2050 RCP 26 future scenario. White dots: low risk (i.e. species with HS<400). Orange dots: medium risk (i.e. species with 400<HS<800). Red stars: high risk (i.e. species with HS>800). The size of symbols is proportional to the number of species in the corresponding category. For each MPA symbols are visible in the following order: high -medium - low risk categories (From D'Amen and Azzurro 2019b, submitted). Species:* Fistularia commersoni*;* Lagocephalus sceleratus*;* Pterois miles*;* Siganus luridus*;* Siganus rivulatus*;* Stephanolepis diaspros*;* Upeneus moluccensis*;* Hemiramphus far*;* Sphyraena chrysotaenia.

The analysis of D'Amen & Azzurro (2019b in revision) provides a spatially-explicit evidence that climate change will substantially increase the number of MPAs vulnerable to Lessepsian fish invasion, following specific spatial gradients of "invasion risk".

We know that many Levantine MPAs are already dominated by tropical invaders and this is confirmed by model predictions. Instead, the MPAs located in the Western Mediterranean, as well as in the northern Adriatic Sea are currently at low risk of invasion, due to unfavourable environmental conditions. Nevertheless, by 2050, many tropical invaders are predicted to gain new suitable areas along the South Western coast of Italy and in the South Adriatic Sea. The West Mediterranean MPAs will generally become less resistant to these invaders. The bluespotted cornetfish, *F. commersonii* has already spread over most of Mediterranean coasts (Azzurro et al., 2011) and, in term of climatic requirements, is the only invasive fish, together with *P. miles*, that currently poses at risk more than half of the Mediterranean MPAs. Nevertheless by 2050, also *L. sceleratus* was projected to experience overall increases in climatic suitability over almost half of the current MPA network. This agreed with the predictions advanced by Coro et al. (2018), who suggested that *L. sceleratus* will continue its rapid spread, if any countermeasure is taken.

We know that invasive species can have profound ecological impacts through modification in species interactions and food web dynamics (Occhipinti-Ambrogi, 2007) compromising related ecosystem services. Yet, the major problem for conservationists is that invasive species cannot be directly kept out from protected areas (Simberloff, 2000) and this issue is increasingly stressed for Mediterranean MPAs (e.g. Otero et al., 2013; Mazaris & Katsanevakis, 2018, Giakoumy et al., 2019). Management should therefore be wise enough to anticipate the vulnerability to invasion and provide these areas with the adaptive capacity to cope with the related changes. When these species are settled in a new MPA, specific management actions, such as species-targeted removals, should be taken to effectively control these guests (Giakoumy et al., 2019)

Other striking examples for the MPA-Adapt area are those of the native warm-adapted native predators, such as the bluefish *Pomatomus saltatrix,* that has expanded northwards (Sabates et al., 2012), with reported socio-economical impacts (Azzurro et al in prep). In the NW sectors of the Mediterranean and in the Adriatic, local fishermen are well aware about the emergence of this 'novel' species in their fishing areas (Azzurro et al., 2019) and direct evidences have been also reported by the MPAs of Brijuni and Portofino through the monitoring activities implemented by the MPA-Adapt project. Many other thermophilic species, such as the ornate wrasse *Thalassoma* pavo (Sara et al., 2005) or the Asteroidea *Ophidiaster ophidianus* (Harmelin et al., 2010) have expanded their distribution, increasing the richness of species in the NW Mediterranean, but no information on related impact are available so far.

The expansion of thermophilic species is one of the most cited consequences of warming but we must also consider the native temperate or cold-adapted species that are contracting their distribution due to increasing temperatures. This is for instance the case of *Sarpa salpa,* a temperate Atlantic-Mediterranean species which is significantly losing suitable habitats by 2050 and it has already disappeared from the hottest and easternmost sector of the Mediterranean (Marras et al., 2015). Moreover, species interactions with exotic analogues (e.g. rabbitfishes) are expected to act as biotic multipliers of climate change effects (Marras et al., 2015) (Figure 14).

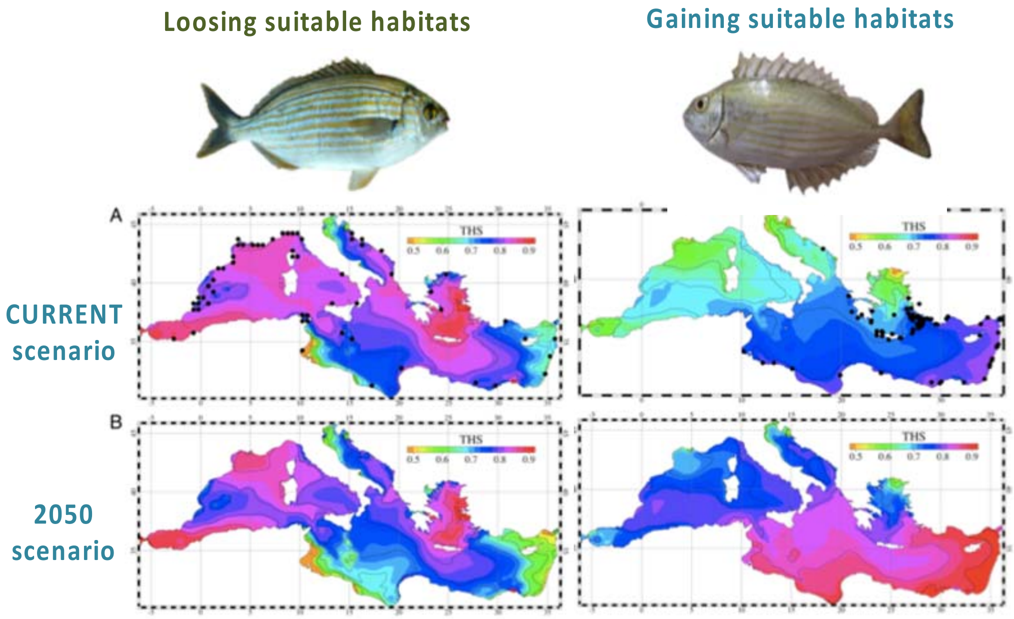


***Figure 14**. Thermal habitat suitability (THS) computed for the whole Mediterranean Sea from the basin-scale model results of the native* Salema Sarpa salpa *(on the left) and the rabbitfish* Siganus rivulatus *(on the right) (Modified from Marras et al., 2015). Red and pink colour stand for high THS; Yellow to green colors means unsuitable habitats.*

Other remarkable cases are the one of the sprat *Sprattus sprattus*, a cold water clupeid, typical of the northern Adriatic and the Gulf of Lyon, which declined in the 1990s. Similarly Anchovy stocks, showed a drastic reduction following years of maximal climatic anomaly in the 1980s, without any apparent evident link with overfishing (Boero et al., 2008).

Particularly alarming is the situation of many cold-adapted endemism (Malcolm et al., 2006), which are predicted to be extinct in the next future due to the loss of climatically suitable areas (Lasram and Mouillot, 2009; Lasram et al., 2010). Indeed, many cold water endemism are trapped in the northernmost, coldest parts of the basin, with no possibilities to track temperature changes by migrating or dispersing northwards. This is particularly clear for endemic fishes, which show their higher diversity in the Gulf of Lion, Adriatic and North Aegean Sea, with a hotspot in the north eastern Adriatic (Figure 15)

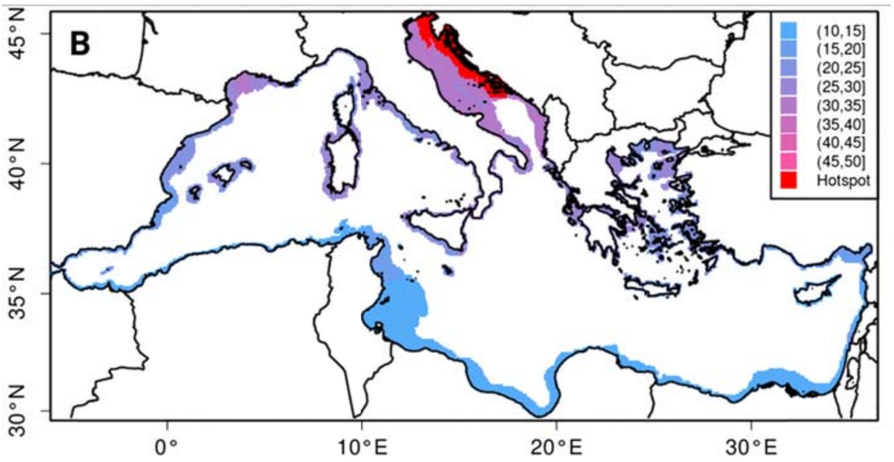


Figure 15. *Endemic species richness, as projected by Mouilliot et al. (2011). The coldest and northernmost areas (Gulf of Lion, North Adriatic and North Aegean Sea) exhibited a greater richness, and the eastern Adriatic appeared as a hot spot of endemism, with 42 species per cell.*

According to Lasram et al. (2010), by the end of the century, those areas were projected to become a ‘cul-de-sac’ that would drive those species towards extinction. In addition, the distribution of these species will undergo an extensive fragmentation, which is a potentially aggravating factor. Climatically endangered fishes mentioned by Lasram et al. (2011) are: *Gobius fallax, Gymnammodytes cicerelus,* and *Lipophrys adriaticus,* which all are projected to disappear from the Mediterranean Sea, though they may continue to survive in the Atlantic Ocean and in the Black Sea, thus, avoiding global extinction. Conversely, the loss of *Acipenser naccarii, Buenia affinis, Corcyrogobius liechtensteini, Didogobius schlieweni, Gobius geniporus, Microichthys coccoi, Opeatogenys gracilis, Paralepis speciosa*, and *Speleogobius trigloides* in the Mediterranean Sea will represent irreversible extinction, because these species are strictly endemic (sensu Quignard and Tomasini, 2000).

Concern also exist for algae and invertebrates. The cold-affinity *Fucus virsoides* is an Adriatic endemism and is considered a glacial relict. The Bay of Kotor, in the eastern Adriatic, was defined as the southernmost limits of this species. *F. virsoides* disappeared at some areas of the Dalmatian coast and at offshore islands (Boero et al., 2008). Also most of the *Cystoseira* species are Mediterranean endemics that have disappeared from several areas of the basin due to climatic factors (e.g. Serio et al. (2006). Invertebrates, such as the hydroids *Tricyclusa* *singularis* (known only from the Gulf of Trieste) and *Paracoryne huvei* are unrecorded from several decades (Boero et al., 2008).

MPAs located in the northernmost sectors of the Mediterranean and in the Adriatic Sea are therefore suggested to closely monitoring these endemisms, whose conservation should be prioritized and the arrival of warm-water species, which are expected to exacerbate the climatic impacts on cold water biota (Milazzo et al., 2013). Potential refuges for such species might be found at depth, but this hypothesis remains to be tested and not all taxa will find suitable habitats by moving deeper. After a proper evaluation of climate related risks, serious monitoring and management measures should be adopted by each Mediterranean MPA to adapt to these ongoing changes.

MASS MORTALITY EVENTS TRENDS AND PATTERNS

TAXA, SPECIES AND ECOREGIONS AFFECTED

These events encompassed 93 species from 9 major taxonomic groups (in order of importance, Cnidaria, Porifera, Bryozoa, Bivalvia, Chordata (Ascidiacea), Rhodophyta, Annelida, Chlorophyta, Echinodermata.

In terms of taxonomic groups, Cnidaria and Porifera accounted for 85% of the observations, with 47.4% and 37.6% of records, respectively. Mortality events for Porifera were recorded in a greater number of geographic areas compared to Cnidaria, including areas which have been historically harvested for commercial bath sponges (e.g. Aegean Sea and and Tunisian Plateau/Gulf of Sidra). Other taxonomic groups such as Bryozoa, Bivalvia and Ascidacea displayed a lower number of mortality events (Figure 16).

The reported mass mortality events mainly concerned the Western Mediterranean ecoregion, with 55.5% of observations (i.e. Liguro-Provençal: 25.4%, Balearic: 16.6%, and Tyrrhenian: 13.5% sub-ecoregions); followed by the Adriatic Sea with 23.5% %), the Aegean Sea (12.7%), and the Ionian Sea (0.4 %) (Figure 16). It is noteworthy that most information concerns the coast of EU countries while there is almost a complete lack of reports from the southern – eastern Mediterranean coasts, from Morocco to Lebanon.

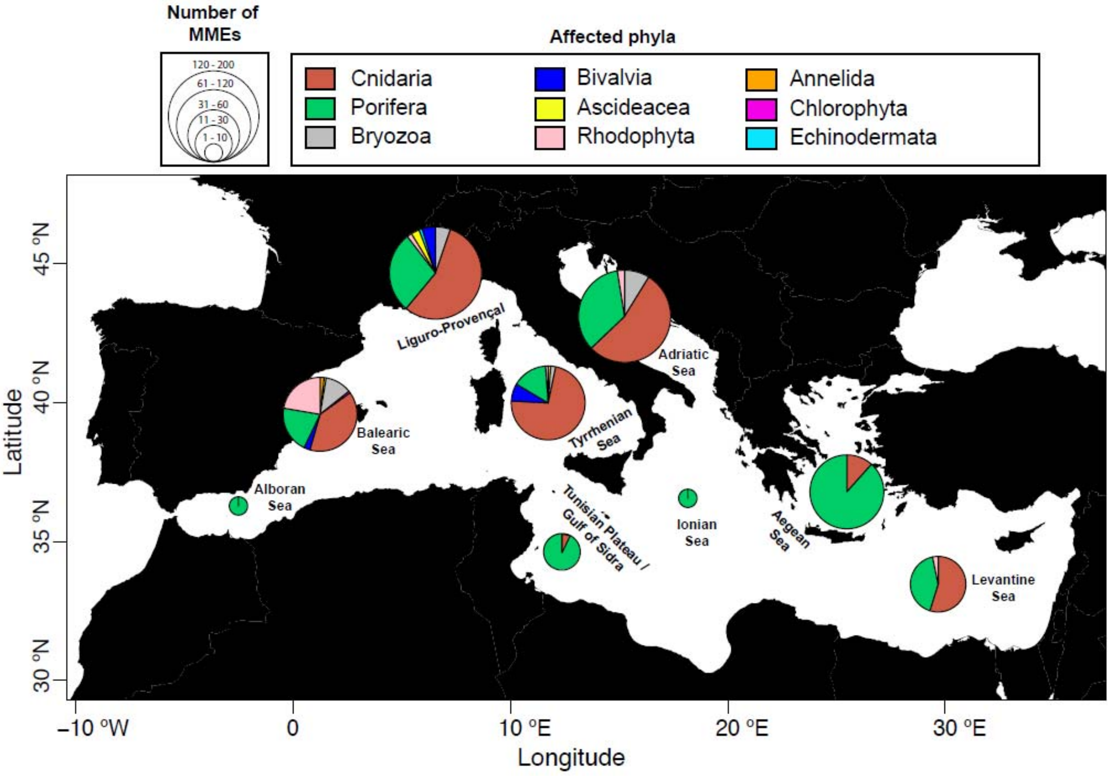


Figure 16. *Number of mass mortality events reported in the literature by geographic area and species phylum included MME-T-MEDNet database.*

TEMPORAL TRENDS AND RELATIONSHIP WITH TEMPERATURE CONDITIONS

Here we first focus our analysis on the NW Mediterranean Sea, N of 41°N, where several marine heatwave and mass mortality events occurred and which, for historical reasons, concentrate most of the *in situ* long time series on both physical (temperature) and biological indicators (conservation status) allowing to track changes in coastal ecosystems. Since most of MME affecting cnidarians took place in late summer/early spring, the period including June-July-August-September-October-November (hereafter JJASON) was considered for analysis. This period covers conditions of shallow stratification (typically <15m), generally from June to August, and subsequent deepening of the thermocline, generally observed in late summer or early fall under the influence of storms which can cause mixing events down to the seafloor in coastal zone (>40 m) (see Temperature section above).

The context of MHW intensification has been related to increasing number of MME affecting the coastal benthic biota (Crisci et al. 2011, 2017). In Figure 17 we show time series of MME for cnidarians, mostly octocorals, in the NW Mediterranean Sea since 1979 (data source: T-MEDNet Mass Mortality Data base). The cumulative time series shows increase in the perturbation regime, with major MME/strong perturbations affecting tens to thousands of km of coastline. In particular, 2003, 2006 and 2009 events and recent accelerated trend.

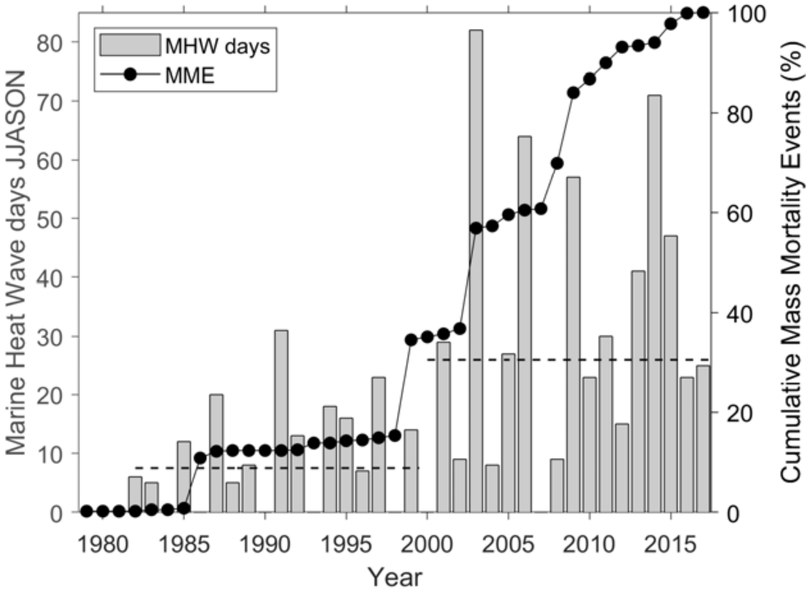


***Figure 17.**.Number of days experiencing Marine Heat Waves during the JJASON period in the W Mediterranean (bars) and the cumulative number of mass mortality events recorded in the area for octocral species (line).*

Main conclusions

Climate change effects are already affecting all Mediterranean regions. Temperature is warming, marine heat waves are affecting larger areas and longer periods both at surface and in the water column. These changes in temperature conditions are related to significant shifts in species distribution including native and non-indigenous species which are expected to impact larger areas in the next decades. Finally, mass mortality events affected a significant number of macro-benthic species and according to the information analyzed we are witnessing an acceleration of these dramatic events. These phenomena in the ecosystem structure are cascading in their functions in many Mediterranean areas, threatening marine biodiversity and the socio-economic activities they provides. The evolution scenarios examined indicate that changes already underway will accelerate and expand geographically during the coming decades.

The Mediterranean MPA network will not escape from the climate change impacts. In fact, many of them are already experiencing the effects including the ones participating in the MPA-Adapt project. In fact all MPA-Adapt MPAs experienced significant warming rates of the Sea Surface Temperature during the last decades and they displayed at some degree and extent the effects associated to climate change such as the arrival non indigenous species (e.g. rabbit fish *Siganus rivulatus* and *S. luridus*, Isole Pelagie MPA), native warm affinity expansion (e.g. *Pomatatus saltatrix* Brijuni National Park) and severe and repeated mass mortality events (e.g. different gorgonians Port-Cros National Park, Réserve Naturelle des Bouches of Bonifacio, Portofino MPA).

In conclusion, the vulnerability to climate change of MPAs in coastal areas is high and it is not expected to cease during the coming years. This is a strong call to implement effective adaptation action plans in the MPA at local scales and set a climate change strategy to define actions at the MPA network. These complementary actions should put MPAs in the frontline to face climate change in the Mediterranean.

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