MARINE HEAT WAVES DETECTION IN CLIMATE WARMING SEAS: THEIR EVOLUTION IN THE NW MEDITERRANEAN SEA

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RESUMEN

El aumento extremo y prolongado de la temperatura del mar, una ola de calor marina (MHW), se detecta por comparación con los valores históricos en cada localización y época del año. Así, el correcto establecimiento de los valores de referencia es una tarea clave en la detección de MHW. Al comparar diferentes épocas es necesario considerar dos contribuciones a la evolución de los episodios extremos: la tendencia subyacente de la temperatura y los cambios súbitos de la misma. Siguiendo la definición de Hobday (2016), comparamos las MHW detectadas en caso de corregir o no la tendencia climatológica en la definición de los valores de referencia. Para ello empleamos 38 años de temperatura superficial del mar Mediterráneo proporcionados por el servicio Copernicus. El trabajo se centra alrededor de la reserva marina de las islas Columbretes, donde existe una estación costera de medición de la temperatura del mar integrada en la red T-MedNet. Esto permite vislumbrar el efecto a diferentes profundidades aunque con series temporales más cortas. El resultado es que no corregir la tendencia al definir la referencia subestima el número de eventos detectados en los primeros años de la serie y los sobreestima en los últimos, independientemente de la longitud de la serie. La influencia del cambio climático en la alteración de los ecosistemas marinos debido a las MHW no parece deberse al incremento en la frecuencia de las mismas, sino a que éstas tienen lugar en un mar cada vez más caliente, actuando sobre sistema biológicos con mayor estrés térmico.

Palabras clave: eventos extremos, temperatura del mar, olas de calor, climatología.

ABSTRACT

Extreme and prolonged increases in the sea temperature, a marine heatwave (MHW), are detected by comparison with historical values at each location and time of year. Thus, the correct estimation of reference values is key in detecting marine heatwaves. In temporally separated epochs comparison, it is necessary to consider two contributions to the evolution of extreme events: the underlying trend in temperature and its sudden changes. Following the definition of Hobday (2016), we compare the detected MHW in case of correcting or not the climatological trend in the definition of the reference values. We use 38 years of the surface temperature of the Mediterranean Sea provided by the Copernicus service. This work is centered around the Columbretes Islands marine reserve, where there is a coastal sea temperature measurement station integrated into the T-MedNet network. This allows us to have a glimpse of the effect at different depths but with shorter time series. The results show that if the long-term trend is not removed from the reference, then the number of events is underestimated in the first years of the series and overestimated in the last ones regardless of the length of the series. The influence of climate change on the alteration of marine ecosystems caused by the MHWs does not seem to be caused by the increased frequency of MHWs, but rather by the fact that the MHWs take place in an increasingly hot sea, acting on biological systems having greater thermal stress.

Key words: extreme events, sea temperature, marine heatwaves, climatology.

1. INTRODUCTION

The concept of heatwave is usually associated with the atmosphere. They correspond to periods of extremely high temperatures. Heatwaves can also occur in the ocean and are known as marine heatwaves (MHW). In the same way that heatwaves on land can have a negative impact on wildlife, forests, and crops, the MHW can alter marine ecosystems (Cerrano *et al.*, 2000; Garrabou *et al.*, 2009; Wernberg *et al.*,2013).

Heatwaves can be understood as anomalous warm states, prolonged in time and discrete (*i.e.* with a defined start and end times). This qualitative description of heatwaves was quantified for MHW by Hobday *et al.* (2016, 2018) based on the atmospheric heatwaves characterization performed by Perkins and Alexander (2013). The ecological relevance of a given MHW depends not only on the ecosystem under study but on the duration, and the intensity of the MHW. However, the Hobday *et al.* (2016) recommendation is to consider as MHW those warming events having persistence of at least five days. The degree of anomaly is obtained by comparing the temperature with the historical registers. With this aim, they considered as rare events those anomalies having permanence in the upper 10% range (*i.e.* beyond the 90 percentile) of the climatology during at least five consecutive days. With this definition, the start and end times are well-defined. Nevertheless, two MHW separated by a gap of two days or less are considered the same MHW.

The MHWs can be produced by atmospheric and/or oceanographic processes; absorption of atmospheric heat and advection of warmer waters are the more evident examples. It is known that climate change produces sustained oceans warming. This means that climate change is introducing a positive trend in the temperature temporal series. Therefore, the comparison with climatologic values should be carefully performed because most of the increase in extreme values could be explained by the mean temperature rise. When comparing epochs separated in time, two contributions need to be considered to study the evolution of extreme episodes: the underlying trending of the variable, and sudden changes. In a continuously warming sea, such as the Mediterranean Sea, the temperature registers will be closer to the 90 percentile of the climatologic values as we move forward in time even in the absence of extreme events. The cause won't be extreme sudden events but the subjacent warming. The MHW should be isolated by substrating the accumulated climatic warming (the trend) before the computation of the climatology (Tebaldi *et al.* 2012, 2021; IPCC 2013, page 50). The accumulated increase in the temperature due to the trend should be accounted for to elucidate the biological impact only after MHW detection. On the other hand, the trend in a time series has a larger effect on the number and duration of the detected MHWs than dealing with short time series or missing values in the data (Schlegel, 2019).

In this work, we perform a comparison between the main MHWs detected with and without applying the detrending before the climatology computation. The trend is computed using the Singular Spectral Analysis (Golyandina and Zhigljavsky 2013; Macias *et al.*, 2014). Apart from this new approach, the methodology used to detect and characterize the MHWs is the same developed in Hobday (2016). The data used corresponds to two sources: the sea surface temperature from satellite, and in situ temperature values collected through the T-MEDNet initiative (https://t-mednet.org/). The area under consideration surrounds the Columbretes Islands marine reserve (figure 1), where the in situ values were collected, and mortality of endemic species due to MHW has been registered in recent years (Kersting *et al.*, 2013). The methodology is described in section 2, including a description of the data sets. Sections 3 and 4 are devoted to presenting the results and the discussion respectively.

2. DATASETS AND METHODS

2.1. Datasets

To perform this study we have considered two datasets: in situ data, and satellite observations. The in situ data correspond to the site "*Columbretes (Illa-Grossa)*" provided by the regional temperature observation network T-MEDNet (http://t-mednet.org). This station is located at 39º53’30’’N, 0º40’16’’E (see figure 1) in the Islas Columbretes Marine Reserve of Fishing Interest and provides hourly sea temperatures at 5, 10, 15, 20, 25, 30, 35, and 40 meters since 2007 for some of these depths. The data covers the range from October 20, 2007, to October 19, 2019 (both included) providing 12 years of data. Nevertheless, the times series is not continuous and not uniform in in-depth (*i.e.* not always the data is available at all the depths at the same time). However, to perform our study it is desirable a dataset for as long as possible. Therefore, gaps shorter than 48 hours have been filled using the average of the days and hours of the rest of the series at the same depth. The resulting coverage for the time series is shown in table 1

The satellite data is the “Mediterranean Sea - High Resolution L4 Sea Surface Temperature Reprocessed” (available at 10.48670/moi-00173). It has been created from the global L3 ESA CCI SST with the add-on that the observation coverage is increased by including an adjusted version of the AVHRR Pathfinder dataset (Pisano *et al.,* 2016; Merchant *et al.*, 2019). This dataset is freely distributed through Copernicus Marine Service (https://marine.copernicus.eu). The dataset used here is a subset of the original product and includes data from 1982 to 2019 (both included) and the area covered is delimited by coordinates (38º45’N, 0º37’30’’W) - (41º00’, 3º00’E). This area includes part of the Balearic Sea and the Columbretes station (see figure 1). The data is distributed with a daily frequency and resolution of 0.05º.

Depth (m)	Start date	Years	Gaps - Larger (hours)
5	2007-10-20	12	10 - 43
10	2009-10-20	10	3 - 6
15	2007-10-20	12	10 - 43
20	2007-10-20	12	6 - 26
25	2007-10-20	12	10 - 43
30	2007-10-20	12	6 - 26
35	2009-10-20	10	7 - 43
40	2008-10-20	11	8 - 43

Table 1: Continuous temporal coverage of the in the situ data from Columbretes site after discarding missing periods larger than 48 hours. The time series finish on October 20, 2019, for all the depths. The last column indicates the number of gaps with the duration of the larger one in hours.

2.1. Methods

In order to have a uniform temporal resolution with the satellite product, as well as to reduce the noise of the in situ data, the Columbretes dataset has been daily averaged. To increase the statistics over each geographical point and reduce the noise of the resulting distribution at each point for the satellite product, the grid resolution is downsampled by a factor of three and finally gridded into a 1/8º resolution.

The first step in the proposed MHW detection consists of computing the trend τ(t) of the temporal series. The second one is to construct the detrended temporal series by subtracting it from the original one. Finally, we apply the MHW detection method proposed by Hobday *et al.* (2016).

The trend can be estimated using different approaches: applying a moving average window (X, X-11 methods, Pezzulli *et al.*, 2005; Pisano *et al.*, 2020), parametric regression, or using non-parametric methods. The Singular Spectrum Analysis (SSA) is a non-parametric and objective method (Hassani, 2007; Golyandina and Nekrutkin, 2013, Macias *et.al.*, 2014). Therefore, no assumptions about the involved processes are necessary. It is based on the decomposition of the temporal series into the eigenvalues of the covariance matrix and not in the frequency domain as is the case of Fourier time series decomposition. The code used to perform the SSA uses the python kernel provided by D’Arcy (2018). Once the trend is obtained for each temporal series of interest, they are detrended and the MHWs detection is performed.

The MHWs detection (Hobday *et al.*, 2016; 2018) is performed using the python module created by Olivier (2020). The daily climatologic series is computed from the whole period of continuous data obtaining one climatologic value for each day of the year (*i.e.* 365 values). In the case of the satellite product, this period covers from the year 1982 to 2019 (included), and the computation is performed point-wise. For the in situ data, the climatology is computed using the periods shown in table 1. The daily climatology and 90 percentile are computed for every day of the year by applying a centered window of 11 days width. Therefore, for a given day of the year, not only all the occurrences in the time series of the given day are included but also the corresponding five days before and after. Finally, the climatologic and 90 percentile daily values are smoothed by applying a convolution with a 31 days width uniform window. Once the daily climatology and 90 percentile are computed, MHWs are defined for periods of time accomplishing these two rules: the temperature for a given day is above the 90 percentile for the same day of the year, and this condition is sustained at least for five consecutive days. Additionally, two MHW separated by only one or two days are considered the same MHW.

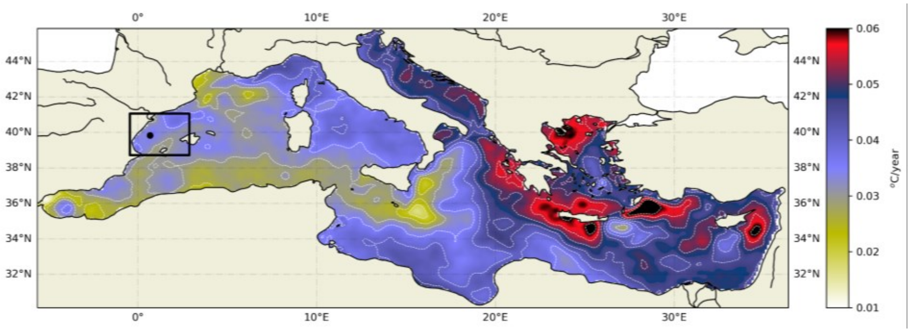

Fig. 1: Sea surface temperature trends in the Mediterranean Sea in the 1982-2019 period. The black square indicates the zone under study and the black spot corresponds to the location of the Columbretes temperature measurement station. White isolines are plotted every 0.005ºC/year.

The MHWs at each point are characterized by their duration, intensity, and spatial coverage. The temperature anomaly stands for the intensity of the MHW. A categorization of the MHWs is performed using four degrees of intensity (Hobday *et al.*, 2018): I, moderate; II, strong; III, severe; and IV, extreme. The category is computed as how many multiples of the difference between the climatologic value and the 90 percentile lie in the anomaly $C = \lfloor (T - T_{clim})/(T_{90} - T_{clim}) \rfloor$.

In order to determine the change in time of magnitudes related to MHW (number of MHW in a year, mean MHW duration, mean and maximum MHW intensity, etc.) by estimating their trend, we will use the Mann-Kendall (MK) test (Mann. 1945; Kendall, 1948). This is a non-parametric test for monotonic trends that determines if the trend exists inside a level of significance.

3. RESULTS

3.1. Satellite time series.

The trend has been computed using SSA method for the Mediterranean for the period 1982-2019 obtaining a good linear agreement. The results are similar to those obtained by Pisano (2020) using X-11 method.

The study was centered on the zone around Columbretes and the temperature was detrended as $T_d(x, y, t) = T(x, y, t) - \tau(x, y, t) \times t$ where t is given in days since January 1, 1982, and τ is the trend. The MHWs are detected point-wise. Therefore, to avoid detection of MHW affecting only a few points of the area, only those covering more than 15% of the sea area are accounted for.

In the case that no detrending is performed, the number of days having MHWs by year (see figure 2) increases by about 15.7 days/decade (p-value=8.8×10^{-7}) as well as the portion of the affected area (5.7%/decade, p-value=0.003), mean duration of the MHW (1.2 days/decade, p-value=0.019), and intensity of the MHWs. However, the average maximum intensity has a small trend (0.13ºC/decade, p-value=0.039). The situation is very different when the temporal series is detrended. In this case, only the average maximum intensity shows a small trend (0.11ºC/decade, p-value=0.014).

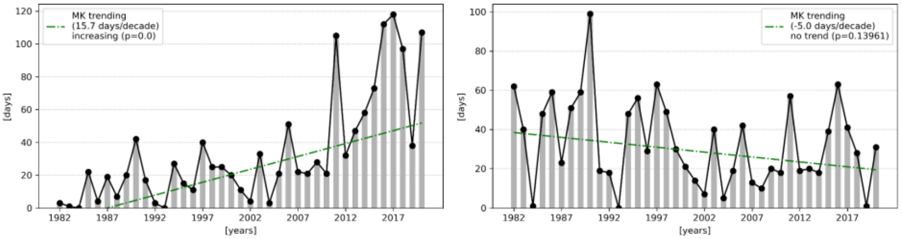

Fig. 2: Total days by year having MHWs affecting more than 15% of the area. Left: the not detrended case. Right: the detrended case. Green dashed line: MK adjust.

3.1. The Columbretes in situ time series.

The trend at different depths has been computed using averaged daily values for the periods indicated in table 1. Applying the MK test with a significance level of 0.05 we obtain a similar temperature trend for all ranges of depths between 5 and 40 meters (0.132, 0.163, 0.144, 0.142, 0.160, 0.130, 0.090, and 0.134 ºC/year respectively). The Kendall's Tau (KT) is 1.0 or close to 1.0 (1.0 for the 5-20 meters range, and 0.97, 0.94, 0.99, and 0.97 for 25, 30, 35, and 40 meters respectively. We have used also the satellite data at 0.05º for the period 2009-2019 (the most similar to the in situ data period) to compute the trend in the surface as close as possible to the station location. obtaining 0.095 ºC/year (KT=1.0).

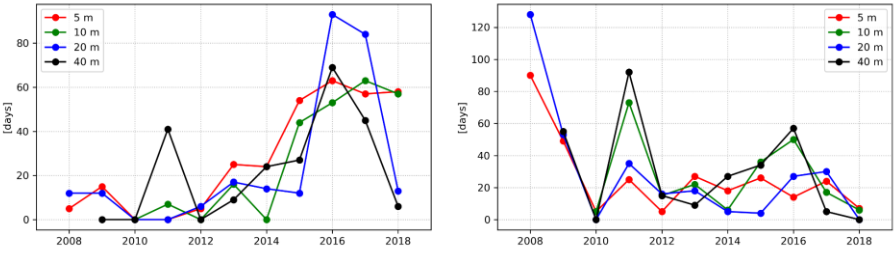

Fig. 3: Total days by year having MHWs at different depths. Left: the not detrended case. Right: the detrended case.

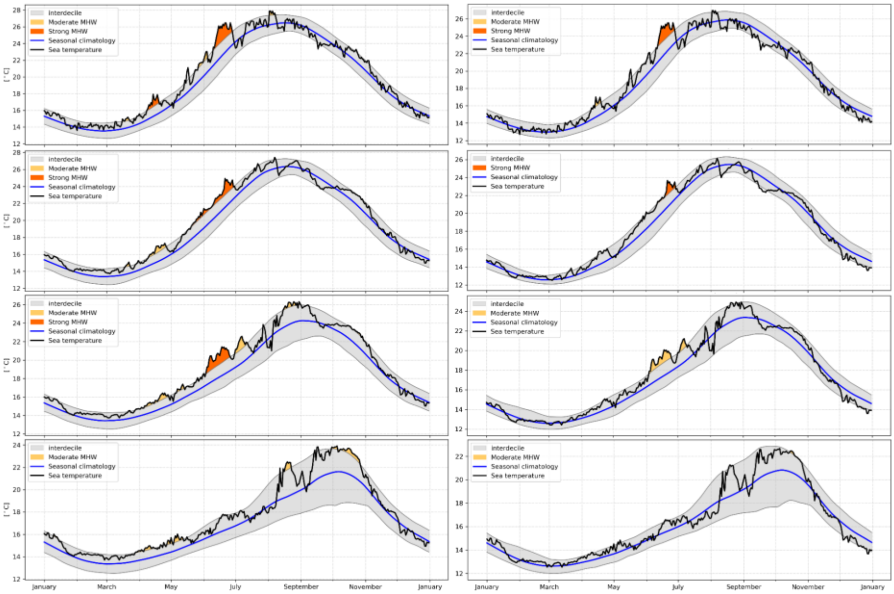

Fig. 4: MHW during the year 2017. From top to bottom: 0, 10, 20, and 30-meter levels. Left: the not detrended case. Right: the detrended case. The level at 0 meters has been computed using satellite data.

In this case, to discern between the evolution of the MHWs magnitudes using detrended series or the original ones is a tricky question because the number of available years is close to the minimum necessary sample size (~10 measures). However, the MK test provides a positive trend for the total days having MHWs by year at 5 meters (70 days/decade, p-value=0.005), 10 meters (90 days/decade, p-value=0.01), and 15 meters depth (55 days/decade, p-value=0.04) depths. This trend is not present in detrended temporal series (see figure 3).

Intense MHW took place in the Columbretes in the year 2017. The effect is visible in the upper 20 meters of the column water. Figure 4 shows the MHWs detected in 2017 including their category. The surface layer (0 meters) has been computed using satellite data and detrended using the trend computed for the period 2007-2019.

4. DISCUSSION

As can be seen from figure 3, trends obtained from small sample sizes can be highly influenced by the beginning (2008 on the right for 5 and 20 meters) and end years (2018 on the left for 30 and 40 meters). However, the satellite long term temporal series reinforces the conclusion that the main contribution to the growing impact of MHWs on ecosystems is not the increased frequency, duration, or extent of the MHWs, but rather the fact they take place in a warming sea, which emphasizes its impact on biological systems increasingly thermally stressed. It is worth noting the importance of performing the detrending of the temperature series before studying MHWs, even for short-size temporal series. As expected, the detrending of the

temperature standardizes the treatment of the entire period under study by separating the contributions of sustained warming and that of sudden temperature changes at any depth. In this way, the number of detected MHW during the last years of the series is not overestimated to the detriment of those that occurred in the initial years.
Detailed knowledge of the influence of MHWs below the surface is out of the scope of this study, but as expected the depth of the mixing layer seems to play an important role in the MHW distribution. In general, MHWs are mitigated below this layer and the advection process could explain some hot anomalies at such depths.

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