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Surface Temperature trends in the Mediterranean Sea from MODIS data during years 2003–2019

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ABSTRACT

Sea Surface Temperature is a variable recognized as an Essential Climate Variable (ECV) by the Global Climate Observation System (GCOS), due to its determinant influence on climate dynamics, from micro scale to global levels The aim of this paper is to estimate Sea Surface Temperature trends in the Mediterranean Sea during years 2003–2019 by using the MODIS Level 3 SST Thermal IR 8 Day 4km V2019.0. Results show an SST increase of 0.040 ± 0.001 °C/yr. The seasonal maximum trend is associated to summer 0.070 ± 0.001 °C/yr, followed by winter, (0.040 ± 0.001) °C/yr, autumn 0.030 ± 0.001 °C/yr and spring, 0.020 ± 0.001 °C/yr. The total period analyzed has been divided into ten-year time spans, showing a stable increase of 0.055 °C/yr in average, from period 2005–2014 onwards. In absolute SST values terms, the parameter range is of 0.85°C from year 2005 to 2019. We have also analyzed the spatial variability of the parameter by dividing the Mediterranean Sea into nine sub-basins: Alboran Sea, Balearic Sea (Iberian Sea), Mediterranean Western Basin, Mediterranean Eastern Basin, Ligurian Sea, Tyrrhenian Sea, Ionian Sea, Adriatic Sea and Aegean Sea. The results show warming trends from 0.02 °C/yr for the Alboran Sea to 0.07°C/yr for the Adriatic Sea. Results have been validated by using data from a local observational buoy system, obtaining a coefficient of determination of 0.97.

1. Introduction

Sea Surface Temperature (SST) is an Essential Climate Variable (ECV) with a crucial role in energy, momentum, humidity and gases ocean–atmosphere exchanges (Manabe and Stouffer, 1988) and which are fundamental in climate regulation. These reasons justify the importance of an accurate measure of the variable, as a basic input for meteorological models, and the necessity of being monitored through time.

Satellite-derived data provide a global, homogeneous and continuous coverage of this variable, characteristics that allow it to be considered as an alternative to the traditional *in situ* data (Sobrino et al., 2020a,b), measured with heterogeneous instruments and irregularly distributed in space.

The interest in acquiring a broad knowledge about the SST behavior in the Mediterranean Sea is gaining importance, as it is associated with the characteristic precipitation cycles in the area, in which both torrential rains and drought periods can be observed (Sousa et al., 2011). These phenomena have increased their frequency in the last decades (Hoerling et al., 2012). SST variability has also been reported to influence fisheries variability in the area, by inducing phytoplankton and zooplankton changes (Coll et al., 2018; Carbonell et al., 2018), which is the basis of the marine food chain.

This increasing interest has triggered an international concern on the necessity of monitoring the Mediterranean Sea SST. The Intergovernmental Panel on Climate Change (IPCC) included the Mediterranean Sea in the sub-region of Semi-Enclosed Seas, calculating a trend of 0.084 °C/decade over the period 1950–2009 (Field et al., 2014). They used a monthly 1 × 1 degree SST data grid extracted from the Hadley Centre HadISST1 data set. Moreover, the Third Issue of the Copernicus Marine Service Ocean State Report also has approached the topic and has established an SST warming of 0.04 °C/yr, as the trend from 1993 to 2017 (Karina von Schuckmann et al., 2019).

In the same line, previous literature suggests a positive trend of SST for this region. Sakalli (2017) computed a lineal trend of 0.04 °C/yr for the period 1985–2015. Their work was based on the AVHRR Pathfinder Version 5.2 (PFV52) data set. Pastor et al. (2018) used the data set GRHSST AVHRR_OI Level 4 and analyzed the period 1982–2016, estimating trends for several time spans: 0.060 ± 0.019 °C/yr for the 1982–1992 decade, 0.103 ± 0.017 °C/yr for the decade 1993–2004 and 0.110 ± 0.017 °C/yr for the decade 2005–2016. During this last

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period, the estimated trend corresponds to an increase of 1.35 °C in absolute terms.

Because previous literature has consistently focused on using the AVHRR sensor for studies related to the Mediterranean Sea, this paper aims to analyze SST estimations for this region of interest derived from MODIS observations. There are multitude of time series datasets for several parameters that are largely unexploited. The MODIS SST product is one of them. This study is our contribution in this area by analyzing a product which has been scarcely applied to the subject of interest.

The correlation between SST and one of the major phenomena of the global climatic system, the North Atlantic Oscillation (NAO), has been a subject of study for years. Traditionally, the NAO is defined as the normalized pressure difference between a station on the Azores (Ponta Delgada- 37.7N, 25.7W) and on Iceland, where two stations are used: Akureyri, 65.7N, 18.1W and Stykkisholmur, 65.0N, 22.8W. (Jones et al., 1997). This NAO index can be positive or negative. For the Mediterranean region, positive NAO indexes mean a cool and dry winter weather (Rafferty, 2019), whereas the northern Europe support mild, stormy and wet winter conditions (Met Office, 2019).

Skliris et al. (2012) correlated the NAO index and SST anomalies derived from AVHRR observations considering years 1985–2008. Their results show positive correlations between the NAO index and the Mediterranean Western Basins: 0.15. For the Eastern Basins and the whole Mediterranean Sea, their correlations are negative: −0.23 and −0.10, respectively. However, their results are not statistically significant.

Despite the existence of other climatic indices, such as El Niño South Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), Atlantic Multidecadal Oscillation (AMO) or the Western Mediterranean Oscillation (WeMO), the index selected for developing this study is the NAO index. This index is identified as the major factor in oceanic variability in several areas of the northern hemisphere, including the Mediterranean Sea (Lionello and Galati, 2008). Moreover, there are several papers which analyze the links between the NAO index and sea level changes (Mohamed et al., 2019; Lionello and Sanna, 2005), which have been proven to be related to changes in sea surface temperature (Vigo et al., 2011; Fenoglio-Marc, 2002). For these reasons, the paper is focused on finding the relationships between the NAO index and the Mediterranean Sea SST.

The main objective of this study is to estimate the SST evolution in the Mediterranean Sea by using the MODIS SST retrievals during years 2003 to 2019 and then, calculate the SST trend during this period, annually and seasonally. A sub-basins' analysis, considering the Alboran Sea, Balearic Sea (Iberian Sea), Mediterranean Western Basin, Mediterranean Eastern Basin, Ligurian Sea, Tyrrhenian Sea, Ionian Sea, Adriatic Sea and Aegean Sea, is also provided. Complementarily, we have used data from a local observational buoy system to validate the results and have analyzed possible relations between the NAO index and the SST behavior. In the following sections, we present the material and methods used, the results computed to accomplish our objectives and the conclusions reached.

2. Material & methods

2.1. Data sets

The MODIS Level 3 SST Thermal IR 8 Day 4 km V2019.0 product has been used in this study, fully available on https://podaac.jpl.gov since January 2020. Daily, 8-days composites, monthly and annual images are available at a processing Level 3 (L3). We have selected 8-days composites to develop computations and obtain the results shown in the paper. Each composite is obtained by averaging 8 daily images so we have considered them as an optimum option, as there is an appropriate balance between the representativeness of the measures and the reduction of both the storage capacity and the computation time needed. Furthermore, the lack of information due to cloud presence is reduced.

A total of 3100 MODIS SST images for the time span 2003–2019 have been computed (1555 MODIS-Aqua images and 1545 MODIS-Terra images). The product spatial resolution is 4.63 km, resulting on global images of 8640 × 4320 pixels dimensions. Each L3 image is a gridded global dataset, so it has been cropped to select the Mediterranean Sea region, as detailed in the methodology section.

The MODIS SST product Algorithm Technical Background Document (ATBD) (Brown and Minnett, 1999) establishes uncertainties of 0.45 K at nadir and 0.56 K at 45°. Several studies have validated the MOD25 product at a regional level. Thus, Qin et al. (2014) defined an error ranging from 0.58 °C to 0.65 °C for the South China Sea during the period 2008–2012; Ghanea et al. (2016) established uncertainties of 0.53 °C for MODIS-Aqua and 0.44 °C for MODIS-Terra in the northern Persian Gulf from June 2011 to June 2015.

The long wave algorithm applied to SST retrieval uses MODIS' 31 and 32 bands and requires calibrating coefficients which are dynamic and periodically estimated and validated by the Rosenstiel School of Marine and Atmospheric Science (RSMAS) at the University of Miami (Brown and Minnett, 1999).

Results are validated with the Puerto del Estado's REDEXT (external buoy net) buoy system dataset, composed of 16 fixed buoys distributed along the waters of the Iberian Peninsula. The REDEXT buoys offer both oceanographic and atmospheric parameters. Measurements are provided hourly, averaged over 10 min periods. Sea temperature is measured at a 3 m depth (Ministry of Development, 2015). Four fixed buoys, located in the Mediterranean Sea, have been selected to develop the results validation: Tarragona (40.68°N, 1.47°E), Cabo de Palos (37.65°N, 0.33°O), Valencia Copa (39.52°N, 0.20°E) and Dragonera (39.95°N, 2.10°E).

The NAO Index used in this study is the one developed by the Climatic Research Unit (CRU) of the University of East Anglia. This index is an extended version of the traditional NAO index, which is defined as the normalized pressure difference between a station on the Azores and one on Iceland. The extended NAO index includes a station in the south-western part of the Iberian Peninsula: Gibraltar (Jones et al., 1997).

2.2. SST estimation for the Mediterranean Sea

Annual SST averages have been computed for the Mediterranean Sea. First, the region of interest has been delimited by applying a mask to the global SST MODIS images. An example of the masked product for year 2018 is shown in Fig. 1.

Furthermore, the Mediterranean Sea has been divided into the following sub-basins, which have already been defined by the International Hydrographic Organization (IHO): Alboran Sea, Balearic Sea (Iberian Sea), Mediterranean Western Basin, Mediterranean Eastern Basin, Ligurian Sea, Tyrrhenian Sea, Ionian Sea, Adriatic Sea and Aegean Sea (Fig. 2). An IHO Sea Areas mask, in its Version 3, developed by the Flanders Marine Institute, has been used for sea delimitation (Flanders Marine Institute, 2018).

Following the methodology proposed by Sobrino et al. (2020a,b), SST annual means have been computed, normalized by pixel area, as shown in Eq. (1), where SST_{ij}^{t} is the SST for each pixel i,j at time t, with i as the column pixel dimension, j as the raw pixel dimension. A_{ij} is the area of each considered pixel of the Mediterranean Sea with indices i and j and A_{MedSea} is the total

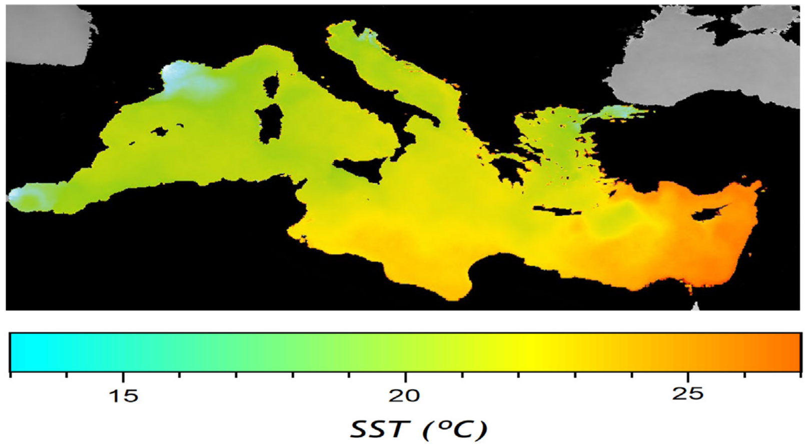

Fig. 1. SST average for 2018 from the MODIS Level 3 SST Thermal IR 8 Day 4 km V2019.0 product after applying the Mediterranean Sea mask.

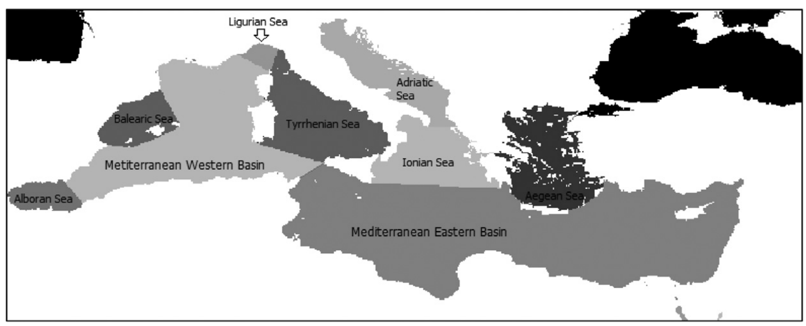

Fig. 2. IHO Sub-basins delimitation in the Mediterranean Sea: Alboran Sea, Balearic Sea, Mediterranean Western Basin, Mediterranean Eastern Basin, Tyrrhenian Sea, Ligurian Sea, Adriatic Sea, Ionian Sea.

area of the Mediterranean Sea, obtained by including only cloud free pixels.

$$SST^{t}_{MedSea} = \frac{1}{A_{MedSea}} \sum_{1}^{m} \sum_{1}^{n} A_{ij} SST^{t}_{ij} \quad (1)$$

Four temperature images for each 8-day period (both Terra and Aqua, day – 10:30, 13:30 respectively – and night – 22:30, 01:30 respectively – observations) are used to calculate averages for the period 2003–2019 according to Eq. (2) (Mao et al., 2017). Years 2001 and 2002 have not been considered because only Terra data were available for that period. Aqua satellite was launched in 2002 and did not provide valid data until 2003. For this reason, the analysis starts in year 2003, with the aim of being homogeneous in the methodology applied on every pixel average.

$$SST^{t}_{ij(2003\_2019)} = \left(SST^{(01:30)}_{ij(mean)} + SST^{(10:30)}_{ij(mean)} + SST^{(13:30)}_{ij(mean)} + SST^{(22:30)}_{ij(mean)} \right) /4 \quad (2)$$

Quality Control (QC) has been used to select pixels with an appropriate quality to be considered into computation. The criterion has been a QC value of 0 and 1, meaning good and acceptable quality (Brown and Minnett, 1999), respectively. Missing data have not been interpolated through any gap-filling method. Outliers have been removed by using the Z-score method. Linear regression has been used to estimate trends, complemented by Sen's slope method for the general sub-basins trends. Trend significance has been estimated with the Mann–Kendall trend test.

Results have been validated using as reference the *Puertos del Estado's in situ* time series provided by the REDEXT buoy system. As buoys data are associated to bulk SST, transformations have been done in order to obtain skin SST, in order to be compared with the estimated satellite SST. The MN-11 model (Minnett et al., 2011) has been used for this purpose, which assumes an exponential dependence of bulk-skin difference (ΔT) on wind speed for winds above 2 m s^{-1} (Alappattu et al., 2017) and follow Eq. (3).

$$\Delta T = a + b\, exp(-\frac{U_0}{U}) \quad (3)$$

Coefficients in Eq. (3) are: a, 0.133, b, 0.637, and U_0, 3.279. In order to meet the wind requirement, only *in situ* temperature data with an associated wind value superior to 2 m s^{-1} have been taken into consideration.

A total of 7839 *in situ* measures, from year 2005 onwards, have been used in the validation, provided by four fixed buoys: Tarragona (40.68°N, 1.47°E), Cabo de Palos (37.65°N, 0.33°O), Valencia Copa (39.52°N, 0.20°E) and Dragonera (39.95°N, 2.10°E). These *in situ* data have been filtered by their Quality Control associated value: only good quality values have been included on computations (QC = 0, QC = 1). Each measurement has been compared to the corresponding image pixel. The comparison is also shown by buoys during the satellite passing times.

3. Results & discussion

3.1. Results validation

Our MODIS SST results have been validated by using *in situ* data provided by *Puertos del Estado*. The general validation includes measurements of the four buoys considered (Tarragona, Dragonera, Valencia Copa and Cabo de Palos) at the time associated to Terra and Aqua passing times (13:30, 01:30, 22:30,

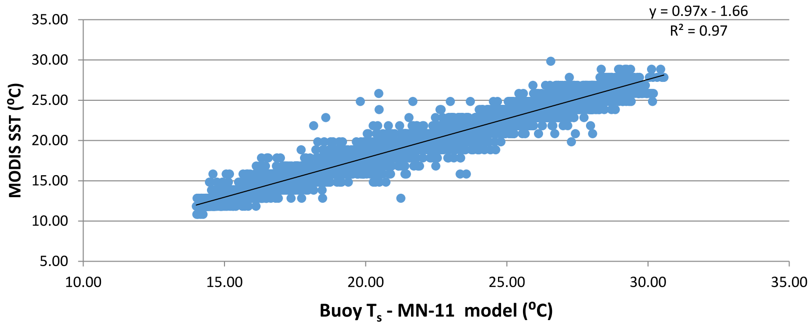

Fig. 3. MODIS SST validation with Puertos del Estado's in situ buoy temperature data. In situ surface temperatures (Ts) obtained by applying MN-11 model have been compared to MODIS SST.

10:30) and for the MN-11 model is shown in Fig. 3. These *in situ* sources are independent from the ones included in the MODIS SST Temperature Algorithm Matchup Databases, provided by the US National Data Buoy Center (NDBC), the Japanese Meteorological Agency, NOAA and the Canadian Marine Environmental Data Service (Brown and Minnett, 1999).

As commented in Section 2.1, buoy data is taken hourly, whereas passing times occur at half past. For the case of Aqua night data, for example, we have compared buoy data measured at 01:00 with satellite data observed at 01:30. This may slightly decrease our correlation values.

In Fig. 3, high correlations are observed between the estimated buoy surface temperature and satellite SST: the coefficient of determination (R^2) is 0.97 and the coefficient of correlation (r), 0.98. This high correlation between *in situ* and satellite data confirms the high potential of satellite observations in climatic studies.

Several validations have been previously carried out at a narrower spatial level, with correlations in the line of our results. Androulakis et al. (2020) made a comparison between in situ data and MODIS Aqua and Terra SST data for the years 2014–2018, using a methodology similar to ours. They extrapolated in situ bulk data to a sea surface level (SST skin) within ± 1 h from the satellite overpass. They obtained a squared Pearson correlation coefficient of 0.9689. The validation was developed on the Underwater Biotechnological Park of Crete, an in-situ infrastructure located 2 km offshore the northern Cretan coast. Hao et al. (2017) validated the coastal waters in the Yellow Sea by using *in situ* buoy data. They found correlation coefficients of 0.989 for Terra and 0.987 for Aqua. Bernardello et al. (2016) compared MODIS SST observations with in situ data collected with data loggers at 5 locations in the western Mediterranean Sea, finding high correlations ($r > 0.98$).

The regression equation obtained in Fig. 3 shows an intercept of −1.66. This is explained by the presence of clouds, which influences satellite SST estimations but not buoy measurements. It has been demonstrated that MODIS SST retrievals are biased with respect to in situ measurements but are sufficiently valid for estimating trends over time (Sobrino et al., 2020a,b).

Results for each buoy and time are shown in Table 1. The MN-11 model shows a high correlation between in situ surface temperature and the estimated satellite SST, with values ranging between 0.97 and 0.99, while regression slopes are between 0.93 and 0.98.

Results offer similar statistical parameters for the four buoy stations analyzed. Each buoy-SST comparison has taken into consideration a minimum of 343 points (Dragonera – 10:00) and a maximum of 616 points (Tarragona – 10:00), depending on the number of data days' available and the filters of Quality Control and wind speed (>2 m s^{-1}). For the total 7839 pairs analyzed, MODIS SST has demonstrated to be highly accurate with correlation values close to 1.

Table 1
SST validation with Tarragona, Dragonera, Valencia Copa and Cabo de Palos buoy data. For each point and time, the coefficients of determination, R^2, correlation, r, and regression slope are shown.

Buoy	Time	MN-11 model			N pairs
		R^2	r	Slope	
Tarragona	13:00	0.98	0.99	0.98	601
	01:00	0.97	0.99	0.97	604
	10:00	0.95	0.98	0.95	616
	22:00	0.98	0.99	0.98	599
Dragonera	13:00	0.87	0.97	0.93	355
	01:00	0.97	0.99	0.96	355
	10:00	0.97	0.99	0.97	343
	22:00	0.93	0.97	0.95	359
Valencia Copa	13:00	0.97	0.99	0.97	485
	01:00	0.97	0.99	0.98	477
	10:00	0.97	0.98	0.97	506
	22:00	0.98	0.99	0.98	500
Cabo de Palos	13:00	0.97	0.99	0.97	516
	01:00	0.98	0.99	0.97	510
	10:00	0.98	0.99	0.97	507
	22:00	0.98	0.99	0.98	506

3.2. Absolute SST and trends estimation

The average surface temperature of the Mediterranean Sea obtained from MODIS data during years 2003–2019 is 19.7 ± 0.3 °C. Shaltout and Omstedt (2014) determined an SST average of 19.7 ± 1.3 °C for the period 1982–2012 from AVHRR data. This value is a reference but cannot fully be compared to our MODIS results, as the time span considered is different. The annual evolution of the parameter is shown in Fig. 4, allowing an SST range of 0.85 °C to be appreciated, from 2005 to 2019. The maximum value of the averaged Mediterranean Sea SST, 20.16 °C, is reached in year 2019.

In year 2003, a 0.5 °C value higher than the one obtained for years 2004 and 2005 is found (19.8 °C). It is related to the intense drought cycle of years 2001–2003 (Acuña et al., 2005). Nevertheless, from year 2012 onwards, except in 2013, the SST annual averages are higher than the one associated to year 2003, showing the magnitude of the warming which is currently taking place in this regional Sea.

In Fig. 5, SST is analyzed seasonally. In summer, the maximum SST value is reached in 2018 (25.86 °C), followed by the one associated to 2003 (25.75 °C). As it can be found in Almarza et al. (2004) and Feudale and Shukla (2010) works and the MITECO's global change evaluation report (2011), during 2003, August was registered as one of the hottest ever. As for spring, the maximum is found in year 2003 (18.86 °C), only reached in 2018. Winter shows the least SST variability in time with a standard deviation of 0.32 °C (standard deviations for Spring: 0.36 °C, Autumn: 0.71 °C, and Summer: 0.83 °C).

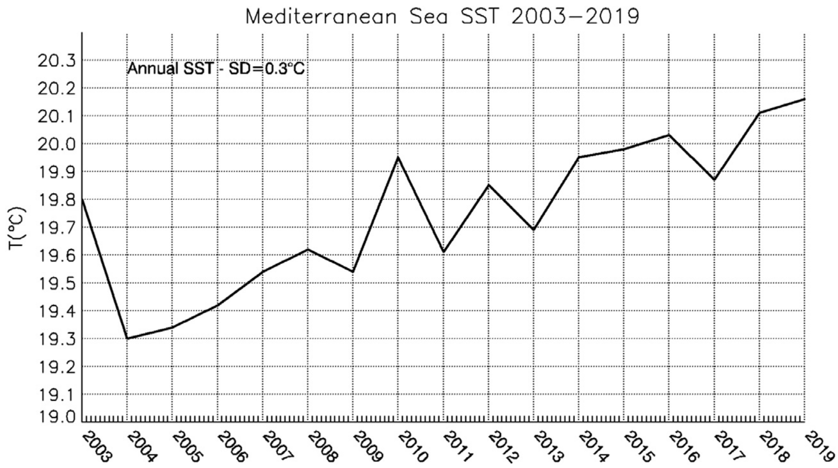

Fig. 4. SST evolution in the Mediterranean Sea during years 2003–2019.

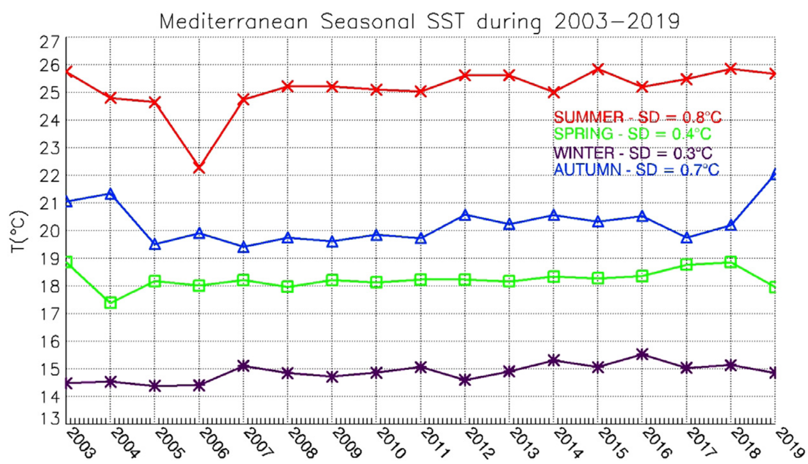

Fig. 5. Seasonal SST evolution in the Mediterranean Sea during years 2003–2019.

When considering these results, it is important to point out that thermal sensors, such as MODIS, on board NASA's Terra and Aqua satellites, make observations of the *skin* SST (Schlussel et al., 1990). This is a factor to consider when comparing measurements from these two different databases and for understanding possible biases. Furthermore, cloudiness should be considered when interpreting satellite estimations, as thermal radiometers are not able to observe through clouds.

The SST trend for the whole Mediterranean Sea during 2003–2019 is 0.040 ± 0.001 °C/yr (Table 2). This trend value agrees with Mohamed et al. (2019) research, in which a 0.036 ± 0.001 °C/yr SST trend was estimated for the period 1993–2017, by using AVHRR derived data. We observe seasonal behavior, as the highest trend is associated to summer with 0.070 ± 0.001 °C/yr, followed by winter 0.030 ± 0.001 °C/yr, autumn (0.030 ± 0.001) °C/yr and spring, 0.020 ± 0.001 °C/yr. The same order in seasonal trend variability was established between 1986 and 2006 (Nykjaer, 2009), meaning that the seasonal patterns are remaining stable over time. In the introduction section, a study of Pastor et al. (2018) was referenced. They estimated a 0.110 °C/yr for the decade 2005–2016, using the data set GRHSST AVHRR_OI Level 4. To compare with our results, over the same period, we obtain a 0.06 °C/yr trend. Sen's slope trends estimation method has also been applied in order to obtain the results significance. All trends are significant at the 95% confidence level ($p < 0.05$), except for the autumn trend.

Trend values are positive for the annual and seasonal analysis (Fig. 6). However, this warming rate is not homogeneous for the whole area of interest, ranging between 0.02 °C/yr and 0.07 °C/yr These results are similar to Shaltout and Omstedt (2014), which estimated a significant trend distribution ranging from 0.017 °C/yr to 0.05 °C/yr, with an average value of (0.035 ± 0.007) °C/yr, considering the years 1982–2012 and using AVHRR derived data.

For further knowledge of this spatial SST variability, the Mediterranean sub-basins' SST trends have been estimated and are shown in Table 3. The highest trends are found along sub-basins situated at the East of the Strait of Sicily, the Ionian Sea, the Adriatic Sea, the Aegean Sea, which represent a 19.9% of the total Mediterranean Sea area, and the Ligurian Sea, representing a 0.7% of the total area. The largest sub-sea is the Mediterranean Eastern Basin, which represents a 46.5% of the total area and has a 0.04 °C/yr trend, equal to the global Mediterranean warming rate. At the West of the Strait of Sicily, we find the lower warming trends. The Alboran Sea has the lowest SST trend associated, as can be observed in Table 3. Our results agree with the ones obtained by Skliris et al. (2012). As the confidence level selected is 95%, all trends are significant, except in the Alboran Sea case, which significance is of 88.3%.

The highest mean SST during years 2003–2019 is found in the Mediterranean Eastern Basin (21.1 ± 0.2 °C), while the lower SST is associated to the Ligurian Sea (17.9 ± 0.4 °C), followed by the Adriatic Sea (18.2 ± 0.4 °C) and the Alboran Sea (18.2 ± 0.4 °C). These low absolute SST values are associated to the presence of winds, which are parallel to the coast, generating a wind-driven

Table 2
Mean SST and trends during years 2003–2019 for seasonal periods and annually. Significance is obtained by applying the Mann–Kendal test.

Timespan: 2003–2019		Mean SST (°C)	Linear trend (°C/yr)	Sen's slope trend (°C/yr)	Mann–Kendall test (%)
Annual	Natural year	19.7 ± 0.3	0.040 ± 0.001	0.050*	99.99
Spring	21st March–20th June	18.2 ± 0.4	0.020 ± 0.001	0.028*	95.66
Summer	21st June–22nd September	25.1 ± 0.8	0.070 ± 0.001	0.065*	97.66
Autumn	23rd September–20th December	20.3 ± 0.7	0.030 ± 0.001	0.047	69.70
Winter	21th December–20th march	14.9 ± 0.3	0.040 ± 0.001	0.042*	99.42

Significant trends at a 95% confidence level.

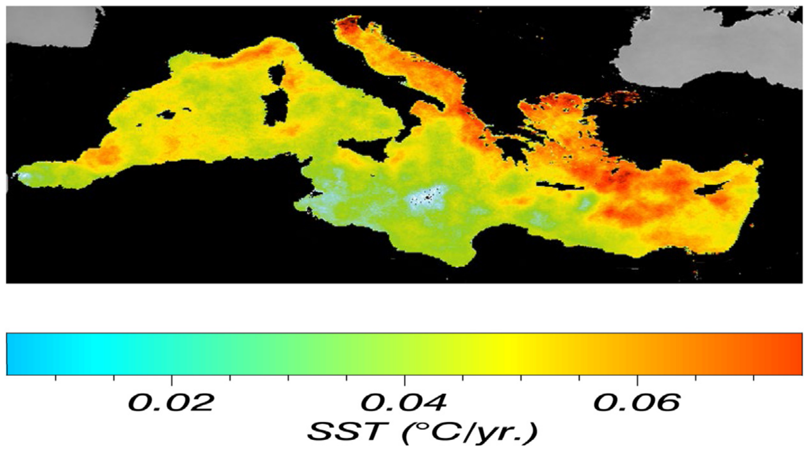

Fig. 6. SST trend estimated for years 2003–2019 in the Mediterranean Sea.

Table 3
Sub-basins' absolute SST means, trends during years 2003–2019 estimated by the linear and Sen's slope methods, significance and associated area proportion.

Sub-basins	Mean SST (°C)	Linear trend (°C/yr)	Sen's slope trend (°C/yr)	Mann–Kendall test (%)	Area (%)
Alboran Sea	18.3 ± 0.3	0.02	0.02	88.3	2.2
Balearic Sea	18.7 ± 0.4	0.04	0.05*	99.6	3.2
Mediterranean Western Basin	18.9 ± 0.3	0.04	0.06*	99.9	18.9
Mediterranean Eastern Basin	21.1 ± 0.2	0.04	0.04*	99.8	46.5
Tyrrhenian Sea	19.2 ± 0.3	0.04	0.05*	99.9	8.6
Ionian Sea	19.7 ± 0.3	0.05	0.06*	99.6	6.8
Aegean Sea	19.2 ± 0.4	0.06	0.06*	99.3	7.6
Ligurian Sea	17.9 ± 0.4	0.06	0.07*	99.9	0.7
Adriatic Sea	18.2 ± 0.5	0.07	0.07*	99.2	5.5

Significant trend at a 95% confidence level.

Ekman transport. This phenomenon leads to the upwelling of deep waters (Bakun and Agostini, 2001), which are colder than surface waters, and have a cooling effect on mean values.

The highest SST interannual variability, represented by the standard deviation of the annual values during the years 2003–2019, is found in the Adriatic Sea, with 0.5 °C, followed by the Ligurian and Aegean Sea, with 0.4 °C. The Adriatic Sea is defined as a dilution basin, so this thermal variability is explained by the presence of riverine freshwater inputs with inflows that can reach 1500 m^3/s and have a cooling effect on its water during the winter season (Gacic et al., 1997). The Ligurian Sea SST dynamic is determined by the water and heat exchanges with its neighbor, the Thyrrenian Sea: the greater the cooling during the winter, the larger the volume of the warmer flow carried northward by the Tyrrhenian Current (Astraldi and Gasparini, 1995). The Aegean Sea undergoes intense water exchanges with the Black Sea that occur through the Dardanelles Strait (Androulidakis et al., 2012) and which induce a marked seasonal behavior. On the other hand, the lowest variability is associated to the Mediterranean Eastern Basin, 0.2 °C. The minimum annual SST values are observed in the Ligurian Sea (17.3 °C), and the maximum, in the Mediterranean Eastern Basin (21.5 °C). By years, the higher differences between both sub-basins, which are the highest overall, occur in 2010, with 4 °C difference.

Differences in absolute SST means between the sub-basins located in the Western or Eastern sides along the Strait of Sicily are detected. The mean SST, weighted by its area proportion, of those situated in the Western side is 18.9 °C, while the mean SST for the ones located in the Eastern side, is 20.5 °C, showing a difference of 1.6 °C. SST trends are 0.04 °C/yr for both basins, when estimated by the linear method. This is in agreement with other studies, such as the one developed by Mohamed et al. (2019), which established a 0.041 °C/yr trend for the Western Basin and 0.038 °C/yr, for the Eastern Basin.

Rhoads et al. (2013) state that the mechanisms which generate these facts need to be investigated, and may be driven by changes in annual latent heat losses and by the variability in regional wind speeds. Axaopoulos and Sofianos (2010) established that the difference in the SST evolution in the two sub basins can be related to the Eastern Mediterranean Transient (EMT), a phenomenon which influenced deep water formations during the 90 s along the Eastern Mediterranean. Artale et al. (2006) quantified heat exchanges through the Gibraltar Strait that also may have an effect on these differences.

SST trends have also been estimated for a sliding window over a ten-year time period over the whole Mediterranean Sea and the defined sub-basins (Table 4), with the aim of graphing their

Table 4
SST trend evolution in 10 years' time intervals during 2003 and 2019.

SST trends (°C/yr)	2003–2012	2004–2013	2005–2014	2006–2015	2007–2016	2008–2017	2009–2018	2010–2019
Mediterranean Sea	0.029	0.050	0.055	0.055	0.056	0.055	0.056	0.054
Eastern Basin	0.041	0.052	0.052	0.040	0.040	0.028	0.040	0.028
Western Basin	0.014	0.031	0.037	0.047	0.073	0.086	0.066	0.071
Alboran Sea	0.012	0.019	0.026	0.035	0.046	0.059	0.020	0.011
Aegean Sea	0.084	0.109	0.122	0.114	0.072	0.024	0.021	0.014
Adriatic Sea	0.025	0.076	0.105	0.119	0.103	0.086	0.111	0.106
Tyrrhenian Sea	0.007	0.046	0.047	0.058	0.057	0.063	0.073	0.077
Balearic Sea	−0.009	0.001	0.015	0.035	0.074	0.109	0.103	0.102
Ligurian Sea	−0.004	0.022	0.039	0.066	0.083	0.082	0.106	0.122
Ionian Sea	0.017	0.060	0.070	0.080	0.084	0.069	0.076	0.074

trend evolution through time. The results show a progressive increase of the SST warming rate from the period between 2003–2012 and 2010–2019 in the Mediterranean Sea. From this period onwards, the SST trend keeps constant around a mean value of 0.055 °C/yr. The maximum trend is 0.056 °C/yr during both periods 2007–2016 and 2009–2018. Further monitoring of SST through time should be carried out, as new MODIS data becomes to be available, to enlarge the number of years considered and have a better perspective of the parameter evolution through time.

The Sub-basins' SST trends have different behaviors: the Ligurian Sea and Tyrrhenian Sea trends increase gradually in time, reaching their maximum during the period 2010–2019, with 0.122 °C/yr and 0.077 °C/yr, respectively. The maximum trend for the Balearic Sea, the Alboran Sea and the Mediterranean Western Basin are observed during the period 2008–2017, with values of 0.109 °C/yr and 0.059 °C/yr, respectively. In the Balearic Sea and Western Basin cases, the trend remains practically stable while in the Alboran Sea case, the trend has decreased down to a 0.011 °C/yr value in the period 2010–2019. The Aegean Sea and the Adriatic Sea reached their maximum value trend before the previous sub-basins mentioned; this is during periods 2005–2014 (0.122 °C/yr) and 2006–2015 (0.119 °C/yr), respectively. Afterwards, the Aegean Sea trend decreases during the following years' periods while the Adriatic Sea maintains a 0.106 °C/yr trend over the years 2010–2019. The Mediterranean Eastern Basin has slightly decreased its 10 years' trend since the first period considered, with a 0.017 °C/yr value during the period 2010–2019. Finally, the Ionian Sea reaches its maximum trend in the period 2007–2016, 0.084 °C/yr to get later established.

3.3. Correlation between the NAO index and the Mediterranean Sea SST

The yearly NAO index data from year 2003 to 2019 has been downloaded from the Climatic Research Unit of the University of East Anglia website (CRU, 2020) and correlated with our SST results for the same period of time. Spearman's and Kendall's correlation coefficients are shown in Table 5.

In Section 1, the Skliris et al. (2012) work is pointed out as a reference in this field. They found positive correlations between the NAO index and the yearly SST anomalies and the Western sub-basins and, negative correlations with the Eastern Sub-basins. They used AVHRR derived data for the period 1985–2008. Our results agree with the Western sub-basins results: the Mediterranean Western basin Spearman's correlation coefficient is 0.52, for the Alboran Sea is 0.49, for the Balearic Sea is 0.63 and the Ligurian Sea is 0.47, while the one obtained by Skliris et al. (2012) for the group of western basins is 0.15. In this way, the positive correlation obtained by Skliris et al. (2012) for years 1985–2008 has been improved by our results, although they remain non-significant. Therefore, further investigations should be carried out to achieve a better understanding of the relation between both parameters.

Table 5
Correlation coefficients between the NAO index and the Mediterranean Sea SST and its sub-basins.

Sub-basin	Spearman's correlation		Kendall's correlation	
	Coefficient	Significance	Coefficient	Significance
Mediterranean Sea	0.50	0.04	0.29	0.11
Eastern Basin	0.15	0.56	0.09	0.62
Western Basin	0.52	0.03	0.36	0.04
Alboran Sea	0.49	0.04	0.39	0.03
Adriatic Sea	0.60	0.01	0.43	0.02
Aegean Sea	0.21	0.41	0.15	0.41
Tyrrhenian Sea	0.46	0.06	0.32	0.08
Balearic Sea	0.63	0.01	0.49	0.01
Ligurian Sea	0.49	0.05	0.35	0.05
Ionian Sea	0.47	0.05	0.33	0.07

It is clear that the periods compared are different: 1985–2008 for the Skliris study versus 2003–2019 for this MODIS study, so this difference must be considered, when interpreting the comparison. There is little literature on the subject, so this is a field of research to be considered in future studies.

Conclusions

The MODIS SST trend in the Mediterranean Sea is 0.040 ± 0.001 °C/yr for the timespan 2003–2019, with an amplitude of 0.85 °C from year 2005 to 2019. By seasons, the highest trend is associated to summer, 0.070 ± 0.001 °C/yr, followed by winter, 0.040 ± 0.001 °C/yr, autumn, 0.030 ± 0.001 °C/yr, and spring, 0.020 ± 0.001 °C/yr. The sub-basins analysis shows the spatial variability of SST in the Mediterranean Sea, with warming trends ranging between 0.02 °C/yr in the Alboran Sea and 0.07 °C/yr in the Aegean Sea.

Our results strengthen the previously identified positive warming trend of the Mediterranean Sea surface. The most important climate reports, referenced along the text, allude to this topic: the Copernicus Ocean State Report establishes a 0.04 °C/decade trend for the period 1993–2017 and the IPCC's 2014 Assessment Report shows a 0.084 °C/decade trend for years 1950–2009. For years 2005–2016, and in terms of (°C/yr), the MODIS estimated SST trend is 0.06 °C/yr. When comparing this trend to Pastor et al. (2018) studies, which compute a 0.110 °C/yr trend using data derived from the AVHRR sensor, thus the MODIS trend results are smaller than the ones given by AVHRR data. SST trends have also been computed by ten-year periods, from years 2003 to 2019, in the entire Mediterranean Sea and by sub-basins, revealing the existence of different SST patterns not only in space, but also referring to time. In the first case, from the year 2004 onwards, the warming trend has stabilized around a mean value of 0.055 °C/yr. The highest trend is retrieved for periods 2007–2016 and 2009–2018, 0.056 °C/yr. When focusing on the different sub-basins SST behavior, we can establish four groups: the Ligurian and Tyrrhenian Sea, which increase their trend progressively until the last period, 2010–2019; the Balearic

Sea, the Mediterranean Western Basin and the Alboran Sea, which reach their maximum during the period 2008–2017; the Aegean and Adriatic Sea, which are the earliest to reach their SST trend maximum; the Mediterranean Eastern Basin, which behaves differently, by gradually decreasing its trend during the periods analyzed. The highest trend during 2010–2019 is associated to the Ligurian Sea, with a 0.122 °C/yr value, which is also the highest trend reached overall.

Correlation coefficients between NAO index and SST are higher in every case (Mediterranean Sea, Eastern basins and Western Basins) than the ones estimated by Skliris et al. (2012). For the Mediterranean Sea and the Eastern basins, they showed low negative (Spearman) correlations whereas our study, has estimated positive correlations of 0.50 and 0.15, respectively. Kendall correlation coefficients are positive but lower than the ones estimated with Spearman's method. A possible hypothesis that could explain these inversions on the correlation is the increase of the warming trend in the last ten years, which could have influenced the interrelation between the NAO index and SST. However, this is out of the scope of this paper, although further research for this area is required.

Our validations show high correlations between the *in situ* data used (Puertos del Estado's REDEXT buoy system) and the MODIS SST estimated. Correlations range between 0.97 and 0.99 after applying the MN-11 bulk-in situ transformation model, meaning a high accuracy of the satellite observations and, therefore, their applicability to climatic studies.

As trends have been confirmed to be positive lately, it is crucial to monitor SST behavior through time, in order to know the evolution of the parameter in real time and enable scientists to provide estimates of the Mediterranean Sea surface's warming rate and counsel policy makers in their decisions. With this aim, we pretend to extend this study in the future, as new data become available.

CRediT authorship contribution statement

S. García-Monteiro: Data curation, Formal analysis, Funding acquisition, Investigation, Validation, Visualization, Writing - original draft, Writing - review & editing. **J.A. Sobrino:** Conceptualization, Formal analysis, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing - review & editing. **Y. Julien:** Data curation, Formal analysis, Investigation, Methodology, Software, Writing - review & editing. **G. Sòria:** Methodology, Software. **D. Skokovic:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Acuña, V., Muñoz, I., Giorgi, A., Omella, M., Sabater, F., Sabater, S., 2005. Drought and postdrought recovery cycles in an intermittent Mediterranean stream: structural and functional aspects. J. North Am. Benthol. Soc. 4, 919–933.

Alappattu, D.P., Wang, Q., Yamaguchi, R., Lind, R.J., Reynolds, M., Christman, A.J., 2017. Warm layer and cool skin corrections for bulk water temperature measurements for air-sea interaction studies. J. Geophys. Res. 122 (8), 6470–6481.

Almarza, C., Rodríguez, C. y, Peraza, B., 2004. El largo y cálido verano de 2003. In: Meteorological Calendar 2004. Environmental Minister.

Androulakis, D.N., Banks, A.C., Dounas, C., Margaris, D.P., 2020. An evaluation of autonomous in situ temperature loggers in a coastal region of the eastern mediterranean sea for use in the validation of near-shore satellite sea surface temperature measurements. Remote Sens. 12 (1140), http://dx.doi.org/10.3390/rs12071140.

Androulidakis, Y.S., Krestenitis, Y.N., Kourafalou, V.H., 2012. Connectivity of North Aegean circulation to the Black Sea water budget. Cont. Shelf Res. 48, 8–26.

Artale, V., Calmanti, S., Malanotte-Rizzoli, P., Pisacane, G., Rupolo, V., Tsimplis, M., 2006. Chapter 5 The Atlantic and Mediterranean Sea as Connected Systems. In: Development in Earth and Environmental Sciences, vol. 4, pp. 283–323.

Astraldi, B.C., Gasparini, M.C., 1995. Climatic fluctuations, current variability and marine species distribution - a case-study in the Ligurian sea (northwest Mediterranean). Oceanol. Acta 18 (2), 139–149, Open Access version: https://archimer.ifremer.fr/doc/00096/20768/.

Axaopoulos, P., Sofianos, S., 2010. Lon term variability of sea surface temperature in Mediterranean Seea. AIP Conf. Proc. 1203, 899.

Bakun, A., Agostini, V.N., 2001. Seasonal patterns of wind-induced upwelling/downwelling in the Mediterranean Sea. Sci. Mar. 65 (3), 243–257.

Bernardello, R., Serrano, E., Coma, R., Ribes, M., Bahamon, N., 2016. A comparison of remote-sensing SST and in situ seawater temperature in near-shore habitats in the western Mediterranean Sea. Mar. Ecol. Prog. Ser. 559, 21–34. http://dx.doi.org/10.3354/meps11896.

Brown, B., Minnett, P.J., 1999. MODIS Infrared Sea Surface Temperature Algorithm. Algorithm Theoretical Basis Document. Version 2.0. University of Miami, Miami, United States of America.

Carbonell, A., García, T., González, M., Álvarez-Berasategui, D., Mallol, S., Miguel de la Serna, J., Bultó, C., Bellido, J.M., Barcala, E., Baro, J., 2018. Modelling trawlings discards of the Alboran fisheries in the Mediterranean Sea. Reg. Stud. Mar. Sci. 23, 73–86.

Climatic Research Unit, 2020. (Accessed 08 january 2020).

Coll, M., Puigserver, M., Navarro, J., Palomera, I., Dambacher, J., 2018. Plausible pressures on small pelagic fish population changes in the NW Mediterranean Sea. Forum on Fisheries Science in the Mediterranean and The Black Sea (FishForum 2018), 10-14, Rome, Italy.

ECV inventory. Global Climate Observation System, 2010. Available in https://gcos.wmo.int/en/essential-climate-variables/ecv-factsheets.

Fenoglio-Marc, L., 2002. Long-term sea level change in the Mediterranean Sea from multi-satellite altimetry and tide gauges. Phys. Chem. Earth A/B/C 27 (32), 1419–1431.

Feudale, L., Shukla, J., 2010. Influence of sea Surface temperature on the European heat wave of 2003 summer. Part I: an observational study. Clim. Dynam. 36 (9–10), 1691–1703.

Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L., 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Ed. Cambridge University Press, Cambridge, United Kingdom and New York, USA, p. 1132.

Flanders Marine Institute, 2018. IHO Sea Areas, Version 3. http://dx.doi.org/10.14284/323, Available online at http://www.marineregions.org/.

Gacic, M., Marullo, S., Santoleri, R., Bargamasco, A., 1997. Analysis of the seasonal and interannual variability of the sea surface temperature field in the Adriatic Sea from AVHRR data (1984–1992). J. Geophys. Res. 102 (c10), 22937–22946.

Ghanea, M., Moradi, M., Kabiri, K., Mehdinia, A., 2016. Investigation and validation of MODIS SST in the northern Persian Gulf. Adv. Space Res. 57, 127–136. http://dx.doi.org/10.1016/j.asr.2015.10.040.

Hao, Y., Cui, T., Singh, V.P., Zhang, J.R., Yu, R., Zhang, Z., 2017. Validation of MODIS sea surface temperature product in the coastal waters of the yellow sea. IEEE J. Sel. Top. Appl. Earth Obs. Remote Sens. 10 (5), 1667–1680. http://dx.doi.org/10.1109/JSTARS.2017.2651951.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X., Zhang, T., Pegion, P., 2012. On the increased frequency of mediterranean drought. J. Clim. 25, 2146–2161.

Jones, P.D., Jonsson, T., Wheeler, D., 1997. Extension to the North Altlantic Oscillation using early instrumental pressure observations from Gibraltar and South-West Iceland. Int. J. Climatol. 17, 1433–1450. http://dx.doi.org/10.1002/(SICI)1097-0088(19971115)17:13<1433::AID-JOC203>3.0.CO;2-P.

Lionello, P., Galati, M.B., 2008. Links of the significant wave height distribution in the Mediterranean Sea with the Northern Hemisphere teleconnection pattern. Adv. Geosci. 17, 13–18.
Lionello, P., Sanna, A., 2005. Mediterranean wave climate variability and its links with NAO and Indian Monsoon. Clim. Dyn. 25, 611–623. http://dx.doi.org/10.1007/s00382-005-0025-4.
Manabe, S., Stouffer, R.J., 1988. Two stable equilibria of a coupled ocean-atmosphere model. J. Clim. 1 (9), 841–866.
Mao, K.B., Ma, Y., Tan, X.L., Shen, X.Y., Liu, G., Li, Z.L., Chen, J.M., Xia, L., 2017. Global surface temperature change analysis based on MODIS data in recent twelve years. Adv. Space Res. 59, 503–551.
Met Office, 2019. North atlantic oscillation. Available in https://www.metoffice.gov.uk/weather/learn-about/weather/atmosphere/north-atlantic-oscillation.
Minnett, P.J., Smith, M., Ward, B., 2011. Measurements of the oceanic thermal skin effect. Deep Sea Res. II 58, 861–868. http://dx.doi.org/10.1016/j.dsr2.2010.10.024.
MITECO (Environmental Spanish Ministry), 2011. Impacts of Europe's Changing Climate – 2008 Indicator-Based Assessment. Ed. Ministerio de Medio Ambiente y Medio Rural y Marino. Centro de publicaciones, Madrid, Spain, ISBN: 978-84-491-1125-9, p. 246.
Mohamed, B., Abdalahh, A.M., El-Din, K.A., Nag, H., Shaltout, M., 2019. Interannual variability and trends of sea level and sea surface temperature in the Mediterranean Sea over the last 25 years. Pure Appl. Geophys. 176, 3787–3810. http://dx.doi.org/10.1007/s00024-019-02156-w.
2019. North Atlantic Oscillation. University of East Anglia, https://crudata.uea.ac.uk/cru/data/nao/nao_3dp.dat. Accessed on the 5th of July of 2020.
Nykjaer, L., 2009. Mediterranean sea surface warming 1985–2006. Clim. Res. 39 (11), 11–17. http://dx.doi.org/10.3354/cr00794.
Pastor, F., Valiente, J.A., Palau, J.L., 2018. Sea surface temperature in the mediterranean: Trends and spatial patterns. Pure Appl. Geophys. 175, 4017–4029. http://dx.doi.org/10.1007/s00024-017-1739-z.
Physical Oceanography Distributed Active Archive Center (PO.DAAC), 2018. Firefox ESR v38.4.0 Web Page. Available online [https://podaac.jpl.nasa.gov/] from NASA EOSDIS PO.DAAC, Pasadena, CA, Accessed November 5, 2018.
Puertos del Estado, 2015. Conjunto de Datos: REDEXT. Ministry of Development, 25th of June of 2015.
Puertos del Estado, 2020. Redext buoy system. Historical sea temperature data series. Downloaded the 21 of July of 2020.
Qin, H., Chen, G., Wang, W., Wang, D., Zeng, L., 2014. Validation and application or MODIS-derived SST in the South China Sea. Int. J. Remote Sens. 35 (11–12), 4315–4328.
Rafferty, J.P., 2019. North Atlantic Oscillation. Encyclopedia Britannica. Available in Osborn TJ (2011) Winter 2009/2010 temperatures and a record-breaking North Atlantic Oscillation index. Weather 66, 19–21, Accessed on the 8th of July of 2020.
Rhoads, Y.S., Zodiatis, G., Hayes, D., Konnaris, G., Georgiou, G., 2013. Proceedings Volume 8795, First International Conference on Remote Sensing and Geoinformation of the Environment (RSCy2013). p. 87950N. http://dx.doi.org/10.1117/12.2028329.
Sakalli, A., 2017. Sea Surface temperature change in the Mediterranean Sea under climate change: a linear model for simulation of the sea Surface temperature up to 2100. Appl. Ecol. Environ. Res. 15 (1), 707–716. http://dx.doi.org/10.15666/aeer/1501_707716.
Schluessel, P., Emery, W.J., Grassi, H., Mammen, T., 1990. On the bulk-skin temperature difference and its impact on satellite remote sensing of sea surface temperature. J. Geophys. Res. 95 (C8), 133341-13356.
Karina von Schuckmann, et al., 2019. Copernicus marine service ocean state report, issue 3, 2019. Oper. Oceanogr. 12 (sup1), S1–S123. http://dx.doi.org/10.1080/1755876X.2019.1633075.
Shaltout, M., Omstedt, A., 2014. Recent sea surface temperature trends and future scenarios for the Mediterranean Sea. Oceanología 56 (3), 413–443.
Skliris, N., Sofianos, S., Gkanasos, A., Mantziafou, A., Vervatis, V., Axaopoulos, P., Lascaratos, A., 2012. Decadal scale variability of sea surface temperatura in the Mediterranean Sea in relation to atmospheric variability. Ocean Dyn. 62 (13), 13–30.
Sobrino, J.A., García-Monteiro, S., Julien, Y., 2020a. Surface temperature of the planet earth from satellite data over the period 2003–2019. Remote Sens. 12 (12), 2036. http://dx.doi.org/10.3390/rs12122036.
Sobrino, J.A., Julien, Y., García-Monteiro, S., 2020b. Surface temperature of the planet earth from satellite data. Remote Sens. 12, 218.
Sousa, P.M., Trigo, R.M., Aizpurua, P., Nieto, R., Gimeno, L., García-Herrera, R., 2011. Trends and extremes of drought indices throughout the 20th century in the Mediterranean. Nat. Hazards Earth Syst. Sci. 11, 33–51. http://dx.doi.org/10.5194/nhess-11-33-2011.
Vigo, M.I., Sánchez-Reales, J.M., Trottini, M., Chao, B.F., 2011. Mediterranean Sea level variations: Analysis of the satellite altimetric data, 1992–2008. J. Geodyn. 52 (3), 271–278.