





Sea Surface Temperature in the Mediterranean: Trends and Spatial Patterns (1982–2016)

FRANCISCO PASTOR,¹  JOSE ANTONIO VALIENTE,¹ and JOSÉ LUIS PALAU¹ 

Abstract—Oceans play a key role in energy storage in the global Earth–Ocean–Atmosphere system. Within this framework, the knowledge of past evolution and future trends of sea surface temperature is crucial for the future climate scenarios. Previous studies have highlighted the role of sea surface temperature as an important ingredient for the development and/or intensification of heavy precipitation events in the Western Mediterranean basin but have also highlighted its role in heat waves in Europe. In this study, a consistent warming trend has been found for daily sea surface temperature data series derived from satellites (1982–2016) for the whole Mediterranean region and for different temporal scales, from daily to monthly, seasonal and decadal estimates. Additionally, spatial clustering analysis has been run to look for its spatial structure. Two main distribution modes have been found for sea surface temperature in winter and summer, while spring and fall show transitional regimes. Winter mode shows a north-to-south increasing gradient banded structure while summer regime presents a set of well-differentiated areas.

Key words: Sea surface temperature, warming, trend, spatial patterns.

1. Introduction

According to the Fifth Assessment Report of the IPCC (2013) most of the global energy change inventory is stored in the oceans; about 93% of the increase in Earth's energy inventory in the period from 1971 to 2010 has induced warming of the oceans, while its upper layer (0–700 m deep) accounts for 64% of the total. This huge storage of energy has led to an increase in global sea surface temperature (SST hereafter) and a rise in global sea level. Additionally, in the near-term projection chapter of the IPCC report, (Kirtman et al. 2013) say

that it is very likely that global averaged SST will increase in the near term. An increase that will likely keep going in the longer term ocean warming for centuries in all scenarios, even if greenhouse gases emissions are decreased or concentrations kept constant (Collins et al. 2013).

Hartman et al. (2013) state that the number of heavy precipitation events over land has increased in more regions than it has decreased since 1950, while (Kirtman et al. 2013) say that frequency and intensity of heavy precipitation events over land will likely increase on average in the near term, but with regional differences. For longer term projections (Collins et al. 2013) more intense individual storms are expected as temperatures increase.

In the Mediterranean, SST has been shown as an important ingredient for the onset and/or intensification of heavy precipitation events (HPE), especially in its western basin. During the last years a number of research papers have investigated the relationship between SST and precipitation in the area, mainly by means of numerical modelling with mesoscale models for HPE (Pastor et al. 2001; Lebeaupin et al. 2006; Katsafados et al. 2011; Miglietta et al. 2011; Pastor et al. 2015) or with regional models for global precipitation (Bozkurt and Sen 2011). There have also been studies looking for statistical correlation between Mediterranean SST and precipitation; Turuncoglu (2015) found that precipitation over the Anatolian Peninsula is very sensitive to the SST of the surrounding seas. But Mediterranean SST does not only affect (is correlated to) precipitation in the Mediterranean basin but also to precipitation and flooding in Central Europe (Volosciuk et al. 2016) and the Sahel (Rowell 2003). Other authors have also found that Mediterranean SST played a role in the persistence and intensification of the summer 2003 heatwave in Central Europe (Feudale and Shukla 2007, 2011a, b). It is

¹ Meteorology and Pollutant Dynamics Department, Fundación Centro de Estudios Ambientales del Mediterráneo, Parque Tecnológico C/Charles R. Darwin, Paterna, 14 46980 Valencia, Spain. E-mail: paco@ceam.es

therefore clear that a good knowledge of SST climatology, spatial patterns and trends is a main concern regarding Mediterranean and European climate trends and projections, especially in the case of HPE events.

Standardised sea surface temperature *in situ* observations, mainly from trading ships, started on the second half of the nineteenth century according to the rules agreed in the Brussels Maritime Conferences on 1853 (Rayner et al. 2006). The collections of such historical data and its integration with recent observations have provided a very useful tool to monitor global change. Since the middle of the twentieth century data from ocean profilers and drifting buoys were incorporated to the global observation of SST. From the 1970s, the onset of the satellite era, SST data collection experienced a great improvement both in terms of spatial and temporal coverage. Gridded SST datasets can be used to analyse spatial patterns and trends globally or in regional basins, like the Mediterranean.

In the last years, some authors have investigated SST warming for the Mediterranean basin or sub-basins. Rixen et al. (2005) found, from *in situ* observations, an increase in the average temperature of the upper layer (0–150 m) of the Mediterranean of 0.5 °C from 1980 to 2000, while Belkin (2009) calculated a higher increase of 1.4 °C from 1978 to 2003. From AVHRR sensors on board on satellites, longer SST data series have been studied; Criado-Aldeanueva et al. (2008) found a trend for SST of 0.06 °C/year for the global Mediterranean basin (1992–2005), while Nykjaer (2009) separated the Mediterranean in its western and eastern basins and found different trends for both in a longer period from 1985 to 2006. In the case of the Western basin he found a 0.03 °C/year and a higher 0.05 °C/year for the Eastern basin. Skliris et al. (2012) used two different data bases to investigate decadal variability of SST in the Mediterranean. They found different total increases in SST for the 1985–2008 period for the whole Mediterranean (0.89 °C), the Western (0.62 °C) and Eastern (1.01 °C) basins. For the 1982–2012 period, Shaltout and Omstedt (2014) found a warming trend of 0.36 °C/decade for the Mediterranean basin and a higher 0.51 °C/decade for the Black Sea. These latest studies indicate the need of understanding spatial patterns in the Mediterranean

SST field. In his doctoral thesis, Pastor (2012) used clustering techniques to look for differentiated SST areas in the Mediterranean, finding two main regimes for SST distribution in winter and summer for the 1985–2009 period. Another aspect that has also been investigated recently is the role of SST in the global water cycle. At a global level, Durack et al. (2012) described the intensification of the global water cycle from 1950 to 2000 following the “rich get richer” mechanism with fresh sea regions becoming fresher and salty regions becoming saltier in response to observed warming and also showing a close relationship between evaporation/precipitation rate and sea surface salinity. Skliris et al. (2016) also stated an intensification of the water cycle for both observational data and climate projections. Mariotti (2010) studied the relationship between evaporation/precipitation and SST in the Mediterranean finding a significant increase in evaporation since the mid-1970s, preceded by a descent during 1965–1975. In her work, Mariotti states that the evaporation increase was primarily driven by SST increase and remarks the importance of evaporation in observed salinity changes in the Mediterranean. The timing of evaporation cycles found by Mariotti roughly coincides with the SST long-term cycle found by Marullo et al. (2011), whose study describes a 70-year cycle for a reconstructed SST time series (1854–2008) in the Mediterranean that shows a decrease in SST from the mid-1960s to the late 1970s and then changes to an increase until the end of the series in 2008.

Recently, the Group for High Resolution Sea Surface Temperature¹ (GHRSSST) has established a framework and set of best practices for processing and sharing SST data in a coordinated and standard way convenient for scientists and data users. This has allowed having new databases, reprocessed to meet the quality standards of the group, for the study of SST. In this paper, the authors have used one of these data bases to extend the above-mentioned studies across a longer time period and to investigate spatial behaviour of SST in the Mediterranean. The next section of this paper describes the SST data used and statistical methodologies applied; Sect. 3 presents the

¹ GHRSSST website: <https://www.ghrsst.org/>.

results for both spatial and temporal SST analyses, while conclusions are shown in Sect. 4.

2. Data and Methods

GHRSSST is an open international science group that promotes the use for monitoring SST. A group of satellite data providers involved in the group deliver their data to the GHRSSST Data Assembly Centre (GDAC, online at <http://ghrsst.jpl.nasa.gov>) that distributes data to users in near-real time. Later (30 days) data are stored at the Long Term Stewardship and Reanalysis Facility (LTSRF, online at <http://ghrsst.nodc.noaa.gov>) for long-term archive. For our study we have used the GHRSSST Level 4 AVHRR_OI Global Blended Sea Surface Temperature Analysis, (GDS version 2)² from the National Centers for Environmental Information (NCEI), available at the Physical Oceanography Distributed Active Archive Center (PODAAC) of the Jet Propulsion Laboratory from NASA.

This dataset is obtained by optimal interpolation from different data sources such as AVHRR satellite sensors and in situ platforms, yielding a smoothed and complete global SST field with a 0.25 degree spatial resolution. Daily SST data are available from September 1, 1981 to the present and are updated in near-real time in a preliminary version that is processed and revised to the final version after 2 weeks. Detailed information about this dataset can be found at Banzon et al. (2016). For our study we have extracted a subset of the data for the Mediterranean region, yielding a 4248 points regularly gridded dataset over the Mediterranean Sea for a total of 12,784 days for the period 1982–2016. From this subset, a climatology was built for the whole data period for both SST monthly mean and anomaly values.

For the study of spatial patterns of SST, clustering techniques have been applied to the averaged monthly data to look for areas with similar behaviour. The cluster analysis has been performed with the “clustering large applications” technique (CLARA) developed by Kaufman and Rousseeuw (1990),

specially designed to deal with large data objects and implemented in the R Project for Statistical Computing (R Core Team 2017). The CLARA approach to clustering big datasets relies on a sampling approach. Instead of analysing the whole dataset, CLARA considers a sample of the data with a fixed size and applies partition around medoids (PAM) clustering algorithm to generate an optimal set of medoids for that sample. Then, the quality of the medoids found is evaluated by measuring the average dissimilarity between every object in the complete dataset and the medoid of its corresponding cluster, defined as a cost function. To minimize sampling bias, this process is repeated a predefined number of times; then, the final clustering selected is the one which minimizes the cost function. The optimal number of clusters is found with the silhouette method by choosing the cluster set that maximised the average silhouette width. For a proper evaluation of linear SST trends, daily data time series were analysed to identify seasonal, trend and remainder components. To perform this analysis, methods and functions from the R forecast package were used. At first, *ts* and *stl* functions were used to build the time series and split them into their components (trend, seasonal and remainder). Once the data were decomposed, the *tslm* function from the R forecast package (Hyndman and Khandakar 2008) was used to fit a linear model for the trend component of the time series, giving both the model slope and its error, and to extract global, decadal and monthly SST trends.

3. SST Analysis

In this section we show the results of the different analyses run on SST data. Our first step was to calculate the monthly averaged SST for each point on the data grid for every month over the whole time span of the data series. Figure 1 shows monthly averaged SST maps for 1982–2016. These maps reflect the typical annual SST cycle in mid-latitude seas with the lowest values in winter (typically February in the Mediterranean), a steep increase in spring towards the maximum values at summer (August); autumn presents a progressive decrease towards winter values.

² Last accessed on March 2017: https://podaac.jpl.nasa.gov/dataset/AVHRR_OI-NCEI-L4-GLOB-v2.0.

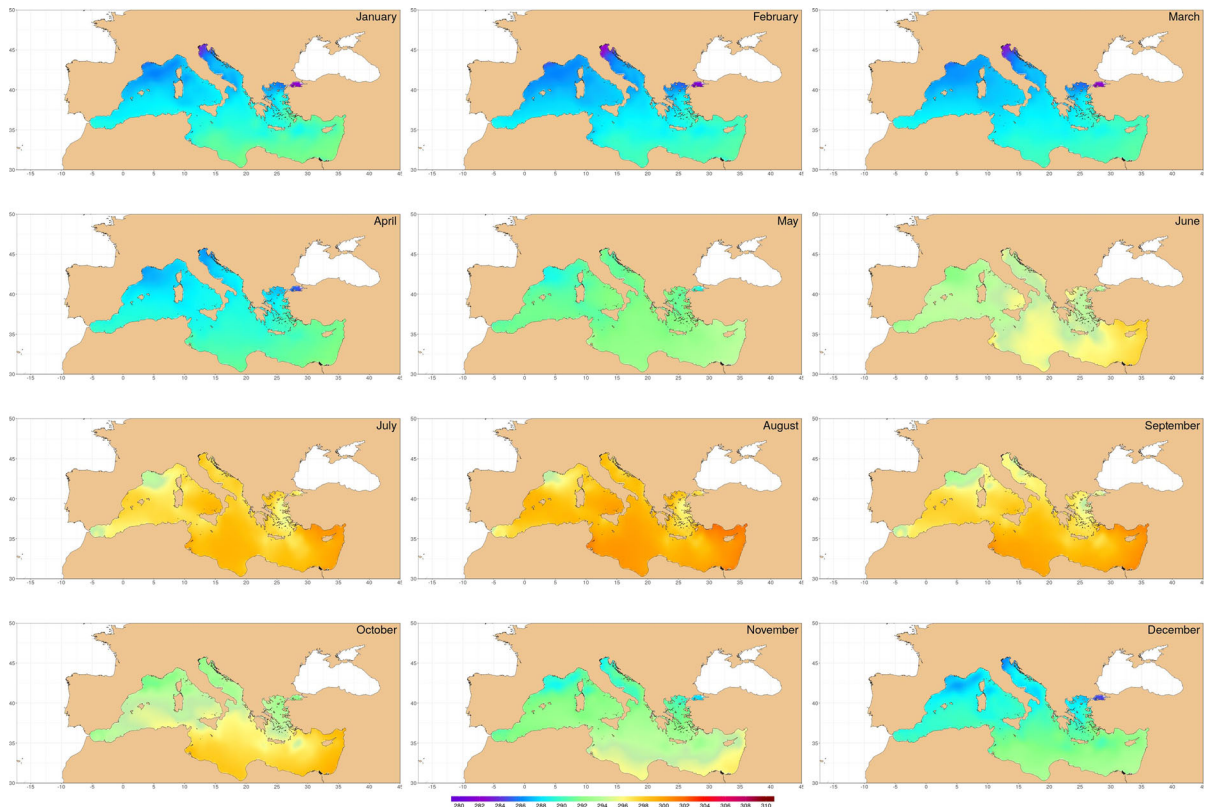


Figure 1
Mean monthly SST climatology 1982–2016

3.1. Spatial Distribution

In Pastor et al. (2015) the influence of different SSTs from different Mediterranean areas, defined in Pastor (2012) for 1982–2009, on torrential rains in the Valencia region is investigated. In this work, we have extended the spatial analysis of Mediterranean SST to the longer data series available from 1982 to 2016. Clustering techniques have been applied to the monthly averaged SST for every month in the data series.

Although cluster analysis for any year and month leads to slightly different clusters, both in shape and extension, a series of repetitive patterns appear throughout the data series. From the study of the clustered areas, two main regimes for spatial distribution of SST in the Mediterranean have been found for winter and summer months. Winter regime usually runs from December to March, showing a clear north-to-south increasing gradient (Fig. 2,

upper) with a latitudinal banded structure. Highest temperatures in winter mode are found in south-eastern Mediterranean, while the lowest are located at the northern end of the Adriatic Sea. After 1–2 months' transitional regime in spring, the summer regime (Fig. 2, lower) is established between June and September. In this summer mode, the simple banded winter structure is substituted by the appearance of a number of differentiated areas that do not follow any simple or linear temperature spatial gradient. Although the highest SST values are found, like in the winter case, at the south-eastern Mediterranean region, there are also some areas where very close temperatures are recorded like the Libyan coast or, in some years, the southern half of the Tyrrhenian Sea. The lowest SST values for summer are always found on two distant areas located in the Gulf of Lyons and the Alboran Sea, Strait of Gibraltar area. It is worth mentioning that the eastern part of the

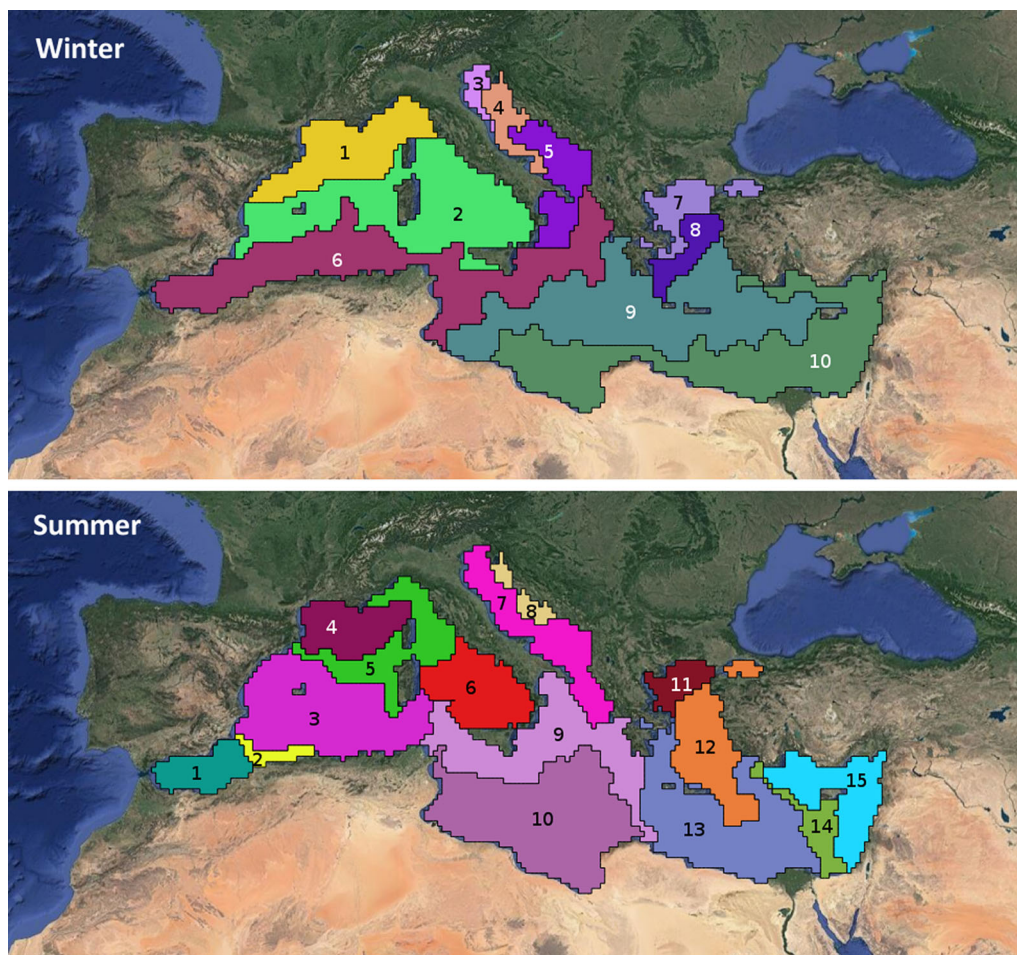


Figure 2

Spatial clustering for monthly averaged SST data (1982–2016) for winter (upper) and summer (lower) regimes

Aegean Sea presents lower values in the framework of a globally warmer eastern Mediterranean.

Despite the air–sea interaction, the oceanographic component plays a major role in the spatial distribution of SST, especially on medium or long temporal scales. Consequently, some of the spatial patterns obtained through cluster analysis correspond or show some known patterns of the Mediterranean thermohaline circulation (THC). In all of the monthly cluster maps (not shown) the dense water formation and upwelling areas in the Gulf of Lyons and Ligurian Sea are clearly shown, more persistently in the Gulf of Lyons case. Other persistent features in the clustering analysis linked to THC are the Atlantic water inflow through the Gibraltar Strait into the

Alboran Sea, the Black Sea water inflow into the Northern Aegean or the summer cluster in the Tyrrhenian Sea. At a smaller scale, transient or smaller structures like the Ierapetra gyre, located at the south-east of Crete, are present on the monthly analysis. Besides this oceanographic component, and at least in part, SST spatial distribution can also be meteorologically conditioned by the presence of strong and persistent winds like Tramontane and Mistral on the north-western Mediterranean and the Etesian winds in the Levantine basin, to a lesser degree in this case (Béranger et al. 2010). These strong and persistent winds favour the upwelling of colder water mass by surface water entrainment. On the Western Mediterranean (WMED), thermally

driven breeze regimes dominate on summer across the whole basin (Millán et al. 2005; Palau and Rovira 2015) as in the Gulf of Libya and Middle East coast (Kallos et al. 1998, 2013). These relatively light winds could favour stagnation, or weak displacement, of surface waters and enhance warming of the surface shallow layers. In autumn, a 1–2 months progressive transition takes place until winter mode is well established on late November or December.

3.2. Trends

The analysis of temporal trends has been run for the whole Mediterranean basin from daily data. Time series have been built from daily data for all grid points in the dataset belonging to the Mediterranean Sea. To study SST trend, time series for each grid point have been analysed in order to investigate the spatial distribution of trends across the Mediterranean. Additionally to the daily linear trends, decadal trends have been investigated to check if the trends are equally shaped across the whole data series. Globally averaged and seasonal trends have been calculated to assess if the observed warming is uniform for the whole basin or if differences arise from the study.

The results of the linear trend analysis for SST from 1982 to 2016 show an overall warming trend across the basin. The globally averaged trend for the Mediterranean has a value of $(9.92 \pm 0.95) \times 10^{-5} \text{ }^\circ\text{C/day}$ (Fig. 3). This warming trend ranges from a minimum value of $2.47 \times 10^{-5} \text{ }^\circ\text{C/day}$ to a maximum of $1.58 \times 10^{-4} \text{ }^\circ\text{C/day}$. These trends account for total SST increases (Fig. 4, upper) in the range 0.32–2.01 $^\circ\text{C}$ across the basin during the 35 year study period, with a mean value of 1.27 $^\circ$. This trend, and all those shown in this study if not indicated otherwise, is statistically significant at 99% confidence level. To check the consistency of these results with SST trends previously found by other authors, we have run the trend analysis for different periods inside our database temporal span. The total SST increase derived from our analysis for the 1985–2008 period, trend of $(1.06 \pm 0.17) \times 10^{-4} \text{ }^\circ\text{C/day}$, for the whole Mediterranean basin gives a value of 0.93 $^\circ\text{C}$, which is in good agreement with the 0.89 $^\circ\text{C}$ value found in Skliris et al. (2012), although this latter value was calculated for monthly

SST versus our daily data. There is also good agreement with the trend calculated by Shaltout and Omstedt (2014) for the 1982–2012 period yielding a value of 0.35 $^\circ\text{C/decade}$ while in our case it would be of 0.36 $^\circ\text{C/decade}$. Lower panel in Fig. 4 shows the SST trend clustering, from this map it can be seen that the warming is not uniform across the basin; two main regions appear with different warming intensity. The lower, but still positive, warming trend is found in the central Mediterranean around Italy (most of Tyrrhenian and Ionian basins) and parts of Algerian and Morocco coast, being higher in the centre and north of the Western Mediterranean while the highest warming is located in the Levantine basin, in agreement with the studies of Nykjaer (2009), Skliris et al. (2012) and Shaltout and Omstedt (2014) that found higher values for SST trend in the eastern Mediterranean basin.

Although warming trend is positive for the whole series, warming rates are not constant neither spatially nor across the study period. To study these different temporal trends, the thirty-five years long SST time series has been divided in three time periods to check for decadal trends. From this analysis it can be seen that the warming trend was not uniform across the studied time period. A weaker but still warming trend is found for the first decade in the data series while warming clearly accelerated for the last two decades, with very similar values for both of them. For the first decadal trend (1982–1992) we have found a value of $(1.67 \pm 0.53) \times 10^{-4} \text{ }^\circ\text{C/day}$ while the other two almost double this trend with values of $(2.82 \pm 0.47) \times 10^{-4} \text{ }^\circ\text{C/day}$ and $(3.08 \pm 0.47) \times 10^{-4} \text{ }^\circ\text{C/day}$ for the 1993–2004 and 2005–2016 decades. All these trends were found to be statistically significant at a 99% confidence level. These trends account for total SST increases of 0.67, 1.24 and 1.35 $^\circ\text{C}$ respectively for the three decadal periods. If we compare the global linear trend with the sum of the decadal trends different accumulated SST increases appear. This can be consequence of the acceleration of the warming trends across time. Probably a simple linear trend does not properly explain the actual behaviour of Mediterranean SST in the recent decades.

In addition to the daily and decadal trend analysis, seasonal and monthly analysis have also been

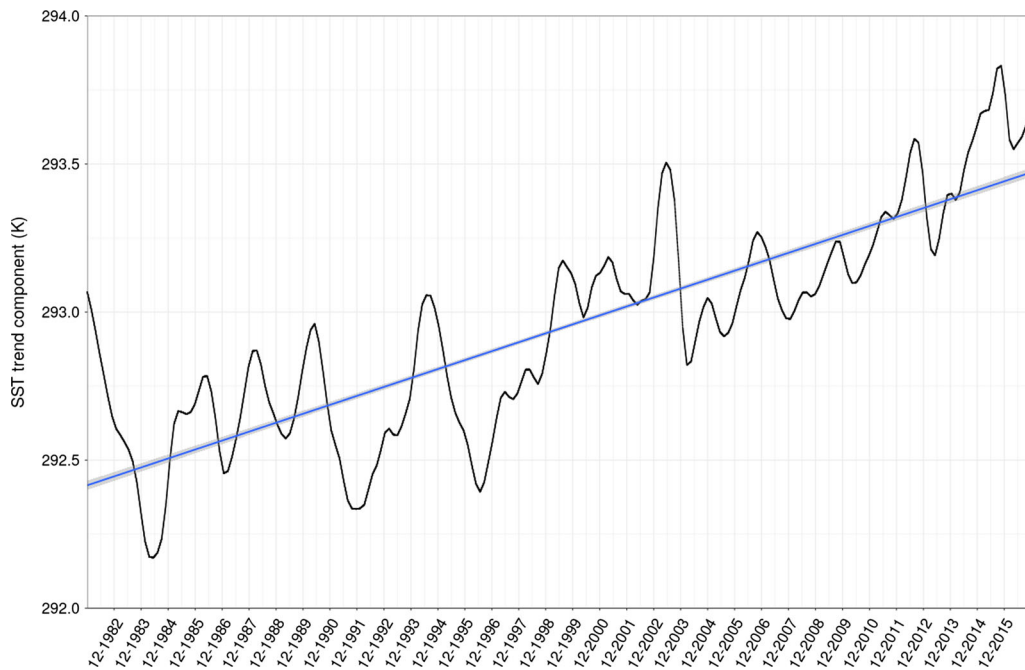


Figure 3
SST linear trend for 1982–2016 (grey shaded area shows 99% confidence interval)

performed to check the warming trend consistency across the year. Seasonal time series were built by grouping the corresponding months throughout the whole time series and averaging SST values; from these data series, maps of seasonal linear trends were found, shown in Fig. 5. Similar averaged warming trends were found for summer (JJA), autumn (SON) and winter (DJF) being respectively $(3.6 \pm 0.7) \times 10^{-2}$, $(3.3 \pm 0.6) \times 10^{-2}$ and $(3.4 \pm 0.6) \times 10^{-2}$ °C/year, with a highest total increase of 1.24 °C in summer for the 1982–2016 period, while spring (MAM) shows a slightly lower warming rate of $(2.8 \pm 0.4) \times 10^{-2}$ °C/year. Summer trend coincides with that found by Shaltout and Omstedt (2014) but trends differs for the rest of the seasons, especially in winter when we have found a much higher warming rate. As two clear SST spatial distribution modes were found from clustering analysis, seasonal trends were studied for the different clusters shown in Fig. 2 but only for winter and summer (Table 1). From this analysis, it stands out that the warming trend in winter is clearly higher in the Eastern Mediterranean basin (clusters 7–10 from

Fig. 2 upper map) while the Western basin (clusters 1, 2 and 6) and the Adriatic Sea (clusters 3, 4 and 5) present similar trend values. In summer, similar values are found between Eastern (clusters 11–15 in Fig. 2, lower) and Western (clusters 1–6) basins while the Mediterranean central area (Ionian sea and Gulf of Libya, clusters 9 and 10) show the lowest warming trend for summer. The highest seasonal values for summer correspond to the Adriatic Sea (clusters 7 and 8). Although if we look to individual clusters, the highest trend values both correspond to northern Aegean Sea, cluster 7 in winter and cluster 11 in summer.

If we look to the monthly trends for the whole data series (Fig. 6), we can see that the lowest SST total increase is found from January to March, with values clearly about 0.7 °C, far below the 1.06 °C global monthly averaged value, while the highest warming appears from May to July with an average SST increase of 1.38 °C. From then on, August to December, monthly SST trends remains very close to the monthly mean averaged trend. Figure 7 shows the spatial distribution of monthly SST trends; in these

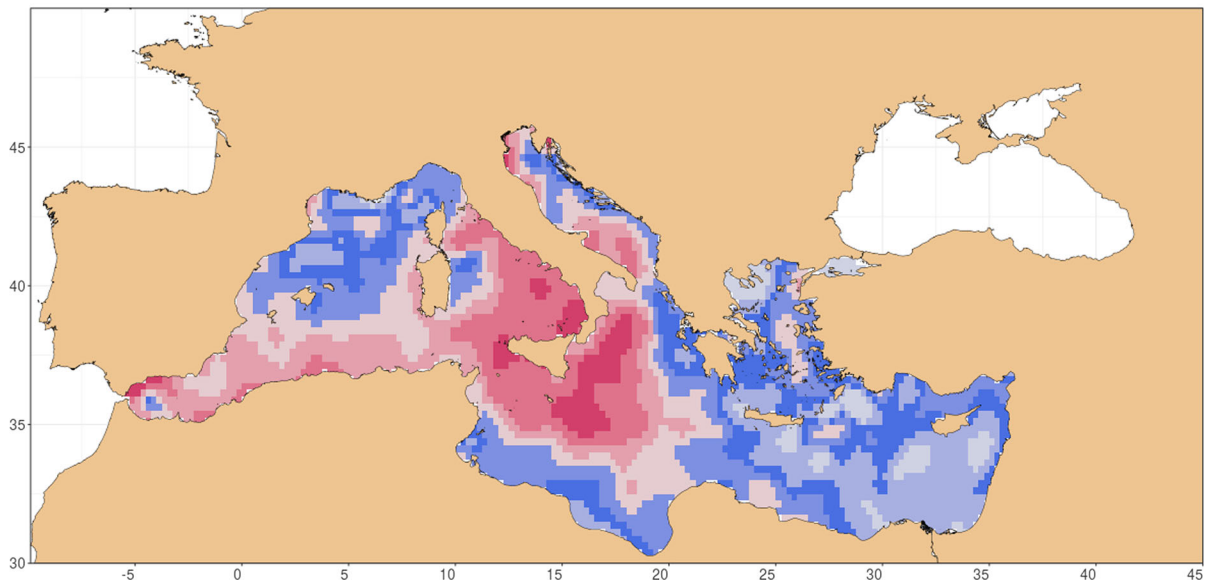
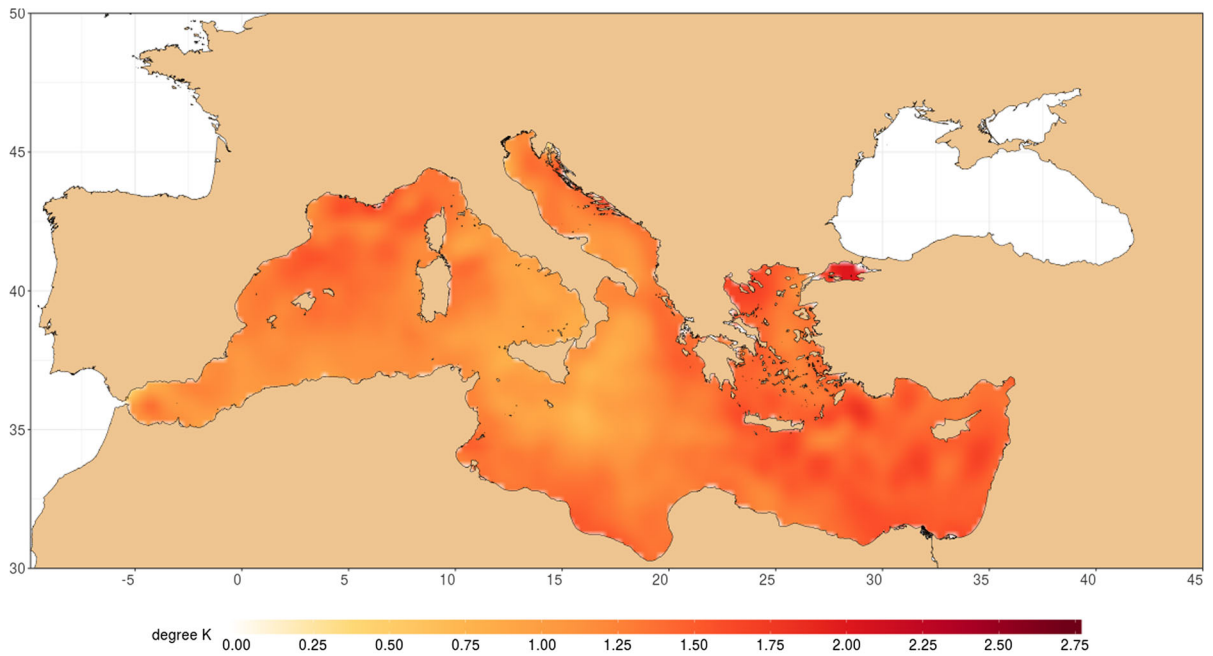


Figure 4
Map of global SST increase (upper) and spatial trend clustering (lower) for the Mediterranean sea (1982–2016)

maps it can be also seen that the highest warming rates run from May to July but it is also important to note that the warming distribution is not uniform across the basin. The highest warming rate is found for the northern part of the Western Mediterranean region in June.

4. Conclusions

In recent studies, sea surface temperature in the Mediterranean has been shown to play a relevant role in the genesis and/or intensification of torrential rains across the whole basin, especially in the Western

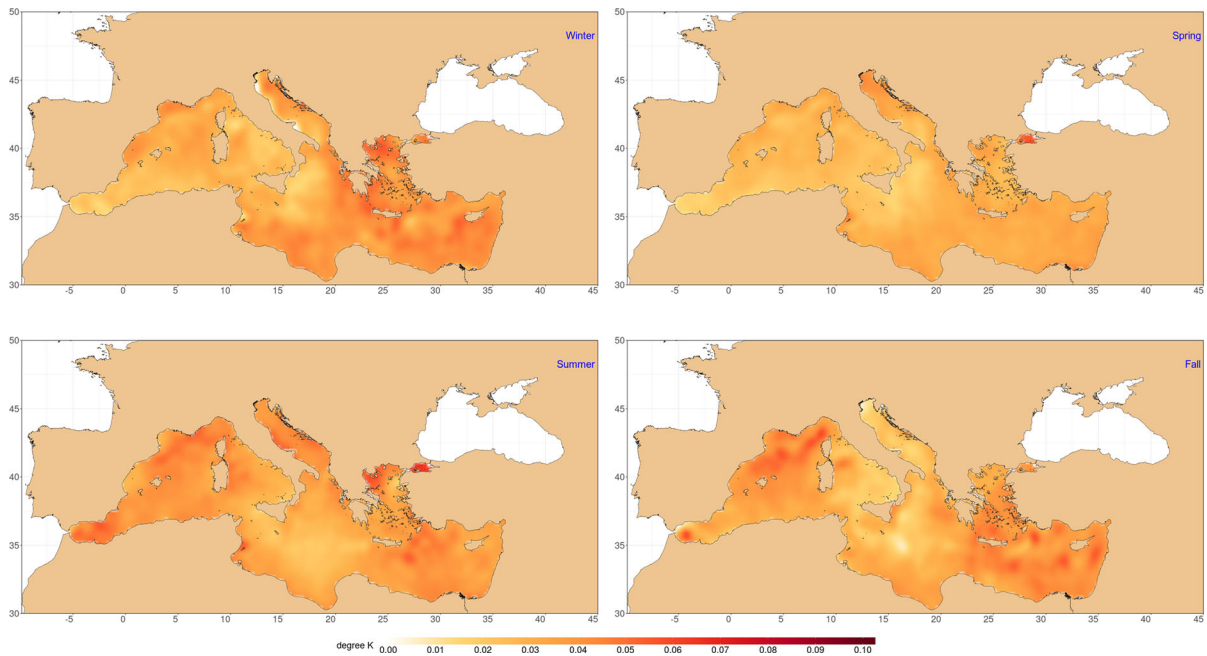


Figure 5
Map of seasonal SST trend for 1982–2016 (all trends significant at the 99% confidence level)

Table 1

Seasonal clustered SST yearly trend ($^{\circ}\text{C}/\text{year}$)

Cluster averaged trend ($^{\circ}\text{C}/\text{year}$)		
Cluster	Winter	Summer
1	3.28E−02	4.54E−02
2	2.87E−02	3.65E−02
3	2.27E−02	3.76E−02
4	3.18E−02	4.30E−02
5	2.97E−02	3.85E−02
6	2.59E−02	3.16E−02
7	4.53E−02	4.07E−02
8	4.25E−02	4.12E−02
9	3.79E−02	2.95E−02
10	4.02E−02	2.83E−02
11	–	4.67E−02
12	–	3.84E−02
13	–	3.77E−02
14	–	3.73E−02
15	–	3.47E−02

Mediterranean basin. Thus, a good knowledge of SST spatio-temporal climatology and trends could be a helpful tool to understand climate change in the basin. With this purpose in mind, we have analysed the longest SST satellite data time series available,

running from 1982 to 2016. In a first approach, a monthly averaged SST climatology was built and used for spatial pattern analysis. Then, both daily and monthly time series were used to look for daily, monthly and seasonal trends of SST.

Regarding the SST monthly climatology, the expected behaviour for a mid-latitude sea is observed. Lowest SST values are found in February while the highest ones are present in summer between July and August. From these monthly values a spatial clustering analysis showed recurrent patterns across the whole time span of the data series. Although SST presents a great spatial variability, and hence clustered areas do not always present same size or shape or are centered on the same SST values, a set of common shapes are found for every season/month in all studied years. This recurrence has allowed us to identify two main regimes of SST spatial distribution for winter and summer (Fig. 2). Winter regime is characterized by a north-to-south increasing temperature gradient, organized in latitudinal bands, while summer present a highly complex structure with a set of distinct well-defined areas not following any simple gradient structure, although in general SST is

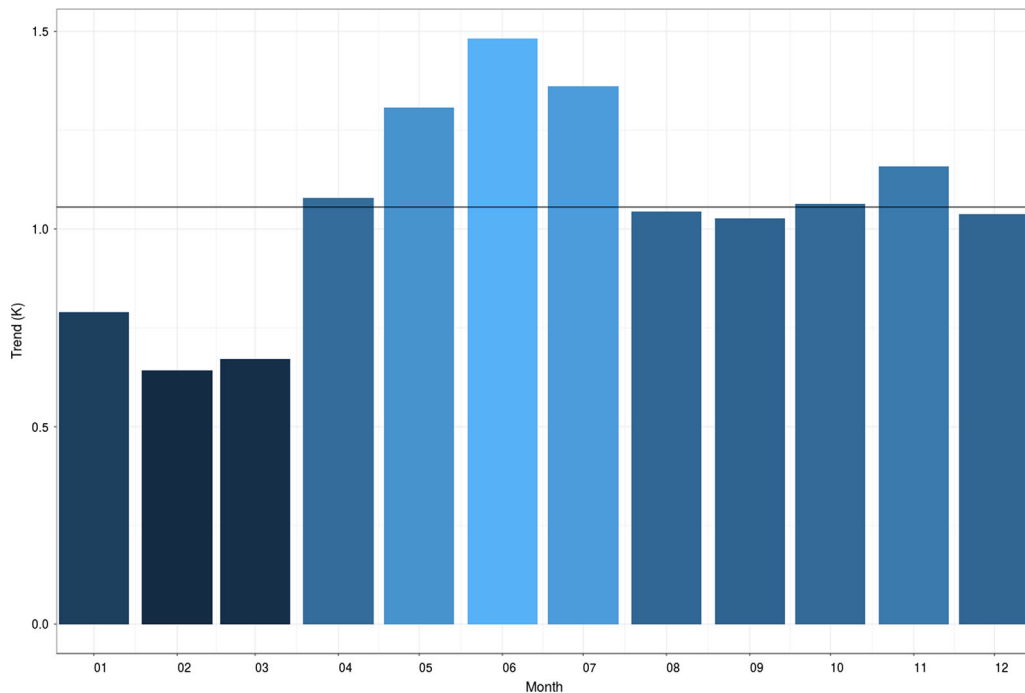


Figure 6
SST monthly total increase for the 1982–2016 period

higher to the south-eastern Mediterranean basin. Both, spring and fall show transitional regimes between the two main modes.

A consistent warming trend has been found for Mediterranean SST in the 1982–2016 period. For the daily data, an averaged linear trend of $(9.92 \pm 0.95) \times 10^{-5} \text{ }^\circ\text{C/day}$ giving a $(1.27 \pm 0.12) \text{ }^\circ\text{C}$ value for the mean total increase. This warming rate is not constant throughout the whole time series but shows differences with a much steeper trend for the last two decades. Analysis of decadal trends has shown a clear increase of the warming trend from 1993 to the day. The 35 year data series was divided in three “almost decadal” periods, yielding a trend of $(1.67 \pm 0.53) \times 10^{-4} \text{ }^\circ\text{C/day}$ for the first decade (1982–1992) and higher values of $(2.82 \pm 0.47) \times 10^{-4} \text{ }^\circ\text{C/day}$ and $(3.08 \pm 0.47) \times 10^{-4} \text{ }^\circ\text{C/day}$ for the 1993–2004 and 2005–2016 decades. The warming rate in the last decade accelerated in a 1.8 ratio respect to the 1982–1992 trend. Besides not being homogeneous on an interannual scheme, SST trend is neither homogeneous also on an intra-annual basis. Looking at

seasonal and monthly averaged SST, different linear trends were found for seasons and months. On a seasonal scale, the lowest warming rate of $(2.8 \pm 0.4) \times 10^{-2}$ corresponds to spring (March–April–May) while the other three seasons show similar trends in the range from $(3.3 \pm 0.6) \times 10^{-2}$ to $(3.6 \pm 0.7) \times 10^{-2} \text{ }^\circ\text{C/year}$. On a monthly basis, lowest warming is found from January to March, followed by the highest rate period from May to July. From August to December warming rate is on average value and almost constant throughout this period. Additionally, monthly warming trends are not spatially uniform across the basin for any month.

These results demonstrate that the Mediterranean SST should not be treated, despite being a relatively small and semi-closed basin, as a uniform field since it presents an important spatial variability, depending on the time of year. Summer SST presents not only higher values but especially its own marked spatial patterns which are very different from that on winter. This should be taken into account when studying relationship between SST and extreme meteorological events, especially torrential rains, in the

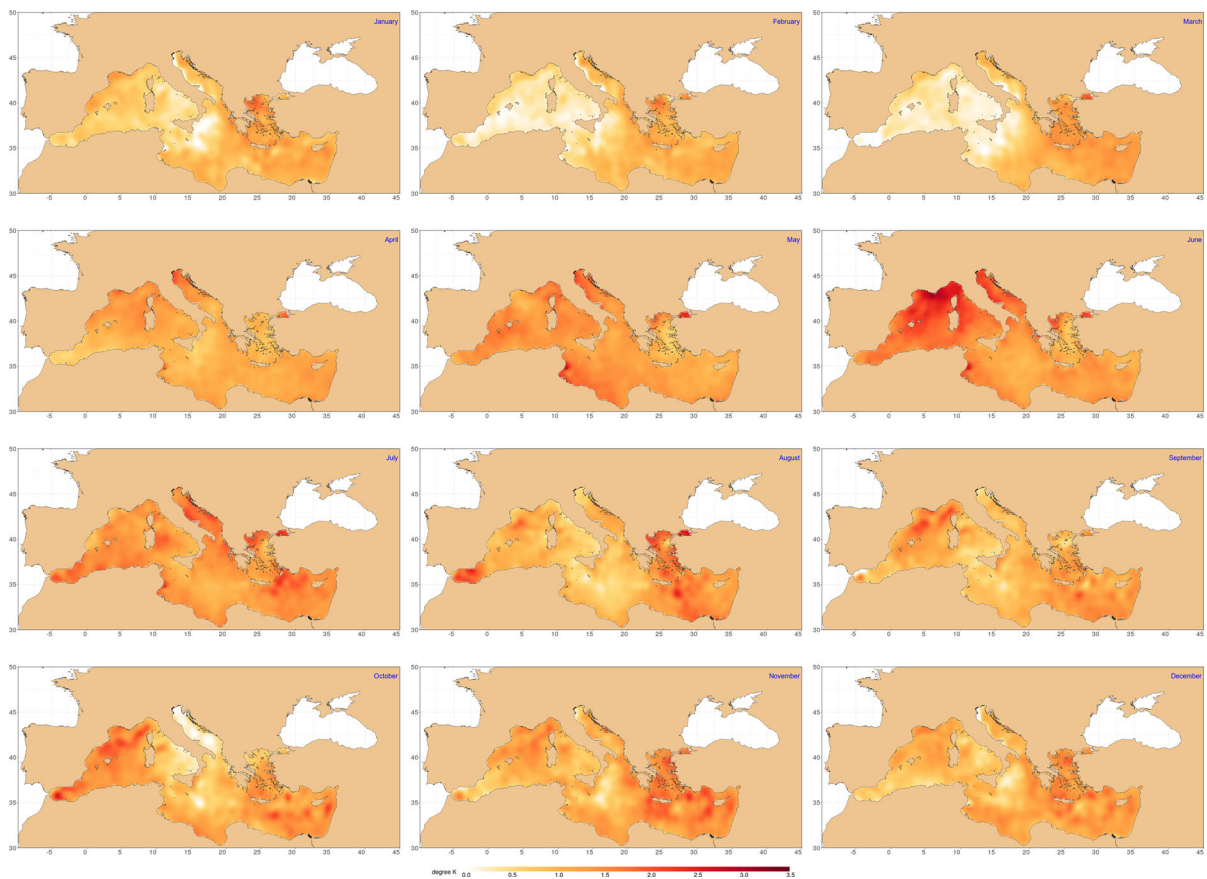


Figure 7

Maps of monthly averaged SST increase for the 1982–2016 period (all trends significant at the 99% confidence level)

Mediterranean basin. Numerical modelling sensitivity experiments and statistical correlation analysis of such relationship should take into account the actual spatial patterns rather than simply making linear uniform changes to the SST field.

Another important conclusion from the results confirms the definition of the Mediterranean basin as a hot-spot for climate change. SST warming rates are not only consistent but have accelerated throughout the study period, in a context of accelerated global warming observed during this century. It is also noticeable the difference from the closer Black Sea, where Miladinova et al. (2017) did not find any SST significant trend for the 1960–2015 period while Shapiro et al. (2010) found a warming in the 1985–2000 period embedded in an overall downward trend for the twentieth century. Shaltout and Omstedt

(2014) found a $0.51\text{ }^{\circ}\text{C}/\text{decade}$ increase for the Black Sea from 1982 to 2012 that is higher than the global $0.36\text{ }^{\circ}\text{C}/\text{decade}$ we have found in the Mediterranean for 1982–2016 but lower than the decadal trends from 1993 to 2016. Nevertheless, the warming trend found in our study should be framed within a broader framework of SST natural variability on longer, multidecadal scales. In the work of Marullo et al. (2011), a 70-year oscillation was detected in a reconstructed SST time series for the 1850–2008 period (Fig. 3 from Marullo et al. (2011)). In this context, our time series, and derived trends, are part of this oscillation starting from a minimum SST value around 1980–1983 and increasing until a maximum for SST around 2015–2020. As neither SST trends nor projections are supplied in the work of Marullo, we can neither accurately assess if the warming trend

found in our study completely falls in such decadal oscillation nor if some decrease should have been detected in the last years of our satellite SST series. In addition to natural variability, Millán (2014) defines, from meteorological field campaigns, an accumulation process of water vapour and air pollutants stacked in layers up to 4000 m over the Western Mediterranean basin that could produce a greenhouse effect which would provoke additional SST warming not linked with natural variability and summing to the “rich get richer” mechanism proposed by Durack et al. (2012). Moreover, spatial distribution of warming trends is not uniform through the year nor spatially across the basin. These increased SST warming and its differences across the basin could have strong implications for Mediterranean environment in many directions; further work is to be conducted in the investigation of the possible correlation between SST and precipitation trends in the Mediterranean basin, with special emphasis in heavy precipitation events with a great societal impact.

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REFERENCES

- Béranger, K., Drillet, Y., Houssais, M.-N., Testor, P., Bourdallé-Badie, R., Alhammoud, B., et al. (2010). Impact of the spatial distribution of the atmospheric forcing on water mass formation in the Mediterranean Sea. *Journal of Geophysical Research*, *115*, C12041. <https://doi.org/10.1029/2009JC005648>.
- Banzon, V., Smith, T. M., Chin, T. M., Liu, C., & Hankins, W. (2016). A long-term record of blended satellite and in situ sea-surface temperature for climate monitoring, modeling and environmental studies. *Earth System Science Data*, *8*, 165–176. <https://doi.org/10.5194/essd-8-165-2016>.
- Belkin, M. (2009). Rapid warming of large marine ecosystems. *Progress in Oceanography*, *81*, 207–213.
- Bozkurt, D., & Sen, O. (2011). Precipitation in the Anatolian Peninsula: Sensitivity to increased SSTs in the surrounding seas. *Climate Dynamics*, *36*, 711–726. <https://doi.org/10.1007/s00382-009-0651-3>.
- Collins, M., Knutti, R., Arblaster, J., Dufresne, J.-L., Fichefet, T. et al. (2013). Long-term climate change: Projections, commitments and irreversibility. In: Stocker, T.F., et al. (Eds.). *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.
- Criado-Aldeanueva, F., Del Río, J., & García-Lafuente, J. (2008). Steric and mass-induced Mediterranean sea level trends from 14 years of altimetry data. *Global and Planetary Change*, *60*(3–4), 563–575.
- Durack, P. J., Wijffels, S. E., & Matear, R. J. (2012). Ocean salinities reveal strong global water cycle intensification during 1950 to 2000. *Science*, *336*, 455–458.
- Feudale, L., & Shukla, J. (2007). Role of Mediterranean SST in enhancing the European heat wave of summer 2003. *Geophysical Research Letters*, *34*, L03811.
- Feudale, L., & Shukla, J. (2011a). Influence of sea surface temperature on the European heat wave of 2003 summer. Part I: An observational study. *Climate Dynamics*. <https://doi.org/10.1007/s00382-010-0788-0>.
- Feudale, L., & Shukla, J. (2011b). Influence of sea surface temperature on the European heat wave of 2003 summer. Part II: A modeling study. *Climate Dynamics*. <https://doi.org/10.1007/s00382-010-0789-z>.
- Hartmann, D.L. et al. (2013). Observations: Atmosphere and surface. In: Stocker, T.F. et al. (Eds.). *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge and New York: Cambridge University Press.
- Hyndman, R. J., & Khandakar, Y. (2008). Automatic time series forecasting: the forecast package for R. *Journal of Statistical Software*, *26*(3), 1–22.

- IPCC. (2013). *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 1535. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J. et al. (Eds.). Cambridge: Cambridge University Press, New York, <https://doi.org/doi:10.1017/CBO9781107415324>.
- Kallos, G., Kotroni, V., Lagouvardos, K., & Papadopoulos, A. (1998). On the long-range transport of air pollutants from Europe to Africa. *Geophysical Research Letters*, 25, 619–622.
- Kallos, G., Mitsakou, C., Alastuey, A., van Aardenne, J., Astitha, M., et al. (2013). Mechanisms of climate variability, air quality and impacts of atmospheric constituents in the Mediterranean Region. In: Regional Assessment of Climate Change in the Mediterranean (pp. 119–156). Dordrecht: Springer.
- Katsafados, P., Mavromatidis, E., Papadopoulos, A., & Pytharoulis, I. (2011). Numerical simulation of a deep Mediterranean storm and its sensitivity on sea surface temperature. *Natural Hazards and Earth System Sciences*. <https://doi.org/10.5194/nhess-11-1233-2011>.
- Kaufman, L., & Rousseeuw, P. J. (1990). *Finding groups in data: An introduction to Cluster analysis*. Hoboken: Wiley.
- Kirtman, B., Power, S.B., Adedoyin, J.A., Boer, G.J., Bojariu, R. et al. (2013). Near-term climate change: Projections and Predictability. In: Stocker, T.F., et al. (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge and New York.
- Lebeauupin, C., Ducrocq, V., & Giordani, H. (2006). Sensitivity of torrential rain events to the sea surface temperature based on high-resolution numerical forecasts. *Journal of Geophysical Research*, 111, D12110. <https://doi.org/10.1029/2005JD006541>.
- Mariotti, A. (2010). Recent changes in the Mediterranean water cycle: A pathway toward long-term regional hydroclimatic change? *Journal of Climate*, 23, 1513–1525.
- Marullo, S., Artale, V., & Santoleri, R. (2011). The SST multi-decadal variability in the Atlantic-Mediterranean region and its relation to AMO. *Journal of Climate*, 24, 4385–4401. <https://doi.org/10.1175/2011JCLI3884.1>.
- Miglietta, M., Moscatello, A., Conte, D., Mannarini, G., Lacorata, G., & Rotunno, R. (2011). Numerical analysis of a Mediterranean ‘hurricane’ over south-eastern Italy: Sensitivity experiments to sea surface temperature. *Atmospheric Research*, 101, 412–426.
- Miladinova, S., Stips, A., Garcia-Gorriaz, E., & Macias Moy, D. (2017). Black Sea thermohaline properties: Long-term trends and variations. *Journal of Geophysical Research: Oceans*, 122, 5624–5644. <https://doi.org/10.1002/2016JC012644>.
- Millán, M. (2014). Extreme hydrometeorological events and climate change predictions in Europe. *Journal of Hydrology*, 518(Part B), 206–224. <https://doi.org/10.1016/j.jhydrol.2013.12.041>.
- Millán, M., Estrela, M., Sanz, M., Mantilla, E., Martín, M., Pastor, F., et al. (2005). Climatic feedbacks and desertification: The Mediterranean model. *Journal of Climate*, 18, 684–701.
- Nykjaer, L. (2009). Mediterranean sea surface warming 1985–2006. *Climate Research*, 39, 11–17.
- Palau, J., & Rovira, F. (2015). Meso-alpha scale tropospheric interactions within the Western Mediterranean Basin: Statistical results using 15-year NCEP/NCAR reanalysis dataset. *Advances in Meteorology*. <https://doi.org/10.1155/2015/302746>.
- Pastor, F. (2012). Ciclogénesis intensas en la cuenca occidental del Mediterráneo y temperatura superficial del mar: Modelización y evaluación de las áreas de recarga. Doctoral thesis Retrieved from <http://hdl.handle.net/2445/35282>
- Pastor, F., Estrela, M., Peñarrocha, D., & Millán, M. (2001). Torrential rains on the Spanish Mediterranean coast: Modeling the effects of the sea surface temperature. *Journal of Applied Meteorology*, 40, 1180–1195.
- Pastor, F., Valiente, J. A., & Estrela, M. J. (2015). Sea surface temperature and torrential rains in the Valencia region: Modeling the role of recharge areas. *Natural Hazards and Earth System Sciences*. <https://doi.org/10.5194/nhess-15-1677-2015>.
- R Core Team. (2017). *R: A language and environment for statistical computing*. Vienna: R Foundation for Statistical Computing.
- Rayner, N. A., et al. (2006). Improved analyses of changes and uncertainties in sea surface temperature measured in situ since the mid-nineteenth century: The HadSST2 dataset. *Journal of Climate*. <https://doi.org/10.1175/JCLI3637.1>.
- Rixen, M., Beckers, J. M., Levitus, S., Antonov, J., et al. (2005). The Western Mediterranean deep water: A proxy for climate change. *Geophysical Research Letters*. <https://doi.org/10.1029/2005GL022702>.
- Rowell, D. P. (2003). The impact of Mediterranean SSTs on the Sahelian rainfall season. *Journal of Climate*, 16, 849–862. <https://doi.org/10.1175/1520-0442>.
- Shaltout, M., & Omstedt, A. (2014). Recent sea surface temperature trends and future scenarios for the Mediterranean Sea. *Oceanologia*, 56(3), 411–443.
- Shapiro, G. I., Aleynik, D. L., & Mee, L. D. (2010). Long term trends in the sea surface temperature of the Black Sea. *Ocean Science*, 6, 491–501. <https://doi.org/10.5194/os-6-491-2010>.
- Skliris, N., Sofianos, S., Gkanasos, A., et al. (2012). Decadal scale variability of sea surface temperature in the Mediterranean Sea in relation to atmospheric variability. *Ocean Dynamics*. <https://doi.org/10.1007/s10236-011-0493-5>.
- Skliris, N., Zika, J. D., Nurser, G., Josey, A. S., & Marsh, R. (2016). Global water cycle amplifying at less than the Clausius-Clapeyron rate. *Nature Scientific Reports*, 6, 38752. <https://doi.org/10.1038/srep38752>.
- Turuncoglu, U. U. (2015). Identifying the sensitivity of precipitation of Anatolian peninsula to Mediterranean and Black Sea surface temperature. *Climate Dynamics*. <https://doi.org/10.1007/s00382-014-2346-7>.
- Volosciuk, C., et al. (2016). Rising Mediterranean sea surface temperatures amplify extreme summer precipitation in Central Europe. *Scientific Reports*. <https://doi.org/10.1038/srep32450>.