European MSc in Marine Environment and Resources
UPV/EHU–SOTON–UB-ULg

Erasmus Mundus
REF: 2013-0237

Drivers of the 2019 Marine Heatwaves in the Mediterranean Sea

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Sciences

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September 2021

PLENTZIA (UPV/EHU), SEPTEMBER 2021

université de BORDEAUX · UNIVERSITY OF Southampton · Universidad del País Vasco / Euskal Herriko Unibertsitatea · LIÈGE université

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CERTIFIES:

That the research work entitled "*Drivers of the 2019 Marine Heatwaves in the Mediterranean Sea*" has been carried out by Manal Hamdeno Abdelkader Elsayed Elawady at the University of Liege, Belgium under the supervision of Dr. Aida Alvera Azcárate from the University of Liege, to achieve 30 ECTS as a part of the MER+ Master program.

In………………………..……………, September …. 2021

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Sign.	Sign.

Acknowledgment

First of all, I would like to express my sincere gratitude to the coordinators of the MER+ program Ionan Marigomez, Manu Soto, Jorg Schafer. Also, I would like to thank Maria Pilar, Maria, Jimenez, and Feli Olivares at the MER Secretariat, and Isabelle Noirot at Uliege international office for their support. Further, I would like to thank my master's thesis supervisor Dr. Aida Alvera Azcárate for her invaluable supervision, support, and tutelage. My gratitude extends to the members of the GHER Research group at the University of Liège including Dr. Alexander Barth, Prof. Jean-Marie Beckers, Charles Troupin, and Bekti. Additionally, I would like to acknowledge my colleagues from Alexandria University, Dr. Hazem Nagy, Dr. Omnia Azaz, Dr. Bayoumy Mohamed, and Dr. Ahmed Magdy Khedr for their patient explanations and key suggestions at different times and other numerous kindnesses. Special thanks goes to my friends and classmates especially Kenechukwu Uba, Cecile Pujol, Marwa Samir, Mervat Mohamed, Kshanika Piyumi, Prabodha Lakrani, Gency Guirhem, Andrea Osorio, Priyanka Soni, and Akinyemi Makanjuola for their advice, encouragement, kindness, and support.

Finally, I would like to express my gratitude to my family, especially my father for his endless love and support, my mother for all of her prayers, care, and love, also my sister and dearest friend Esraa Hamdeno.

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List of Abbreviations

WMED	The Western Mediterranean Basin
EMED	The Eastern Mediterranean Basin
MHW/MHWs	Marine Heatwave / Marine Heatwaves
SST	Sea Surface Temperature
SSTa	Sea Surface Temperature Anomaly
imean	The Mean Intensity of an MHW Event
imax	The Maximum Intensity of an MHW Event
Qi anomaly	The Total Heat Flux Anomaly
MSLP	Mean Sea Level Pressure
MLD	Mixed Layer Depth

Abstract:

Marine heatwaves (MHWs) are prolonged discrete anomalously warm water events that last for more than five successive days and can be described by their duration, intensity, rate of evolution, and spatial coverage. These Episodes of large-scale anomalously high ocean temperatures can have many impacts on marine ecology and ecosystems and major implications for fisheries as well. As a result of the anthropogenic climate change, MHWs have been observed in many parts of the world's oceans and their intensity and frequency are expected to increase in the future. This thesis investigates the 2019 MHWs that have occurred in the Mediterranean Sea, their possible drivers, and their mechanism of formation. The MHWs that occurred in the Mediterranean Sea between June and December 2019 were defined and categorized using the daily NOAA OISST data set and based on a 30-years climatology (1982–2011) baseline. The eastern and western basins of the Mediterranean Sea have shown dissimilarities in the SST and SST anomaly distributions as well as in the characteristics of the MHW events that occurred in them during the study period. The MHWs occurred more often in the WMED than in the EMED with higher intensities while the EMED marine heatwaves were observed to have a longer duration than the WMED ones. In both basins, the MHWs characteristics were linked to the changes in the heat flux anomaly, mixed layer depth, air temperature, mean sea level pressure, and winds. The high anomalous sea surface temperature of the marine heatwaves was associated with high heat flux anomaly, shallow mixed layer, high air temperature, high-pressure system, and low wind speed.

Keywords: marine heatwaves; sea surface temperature; Western Mediterranean Sea; Eastern Mediterranean Sea; maximum intensity; heat flux anomaly; mixed layer depth; atmospheric variables.

Arabic Abstract:

الأمواج البحرية الحارة (MHWs) هي عباره عن موجات منفصله من ارتفاع درجه حرارة مياه البحار و المحيطات و اللتى تحدث بشكل شاذ في دورات لأكثر من خمسة أيام متتالية، ويمكن وصفها من خلال مدتها وشدتها ومعدل تطورها، وتغطيتها المكانية .هذه الموجات الحاره لها تأثيرات عديدة على البيئة البحرية والنظم الإيكولوجية البحرية، كما أن لها آثارا كبيرةً على مصايد الأسماك العالمية .نتيجة لتغير المناخ و ارتفاع معدلات درجات الحرارة، تم ملاحظة وجود هذه الأمواج الحارة في العديد من المناطق بمحيطات العالم ومن المتوقع أن تزداد شدتها وتكرار حدوثها في المستقبل.

تهتم هذه الرسالة بدراسة الأمواج البحرية الحارة التي حدثت في البحر المتوسط عام 2019 ، وبدراسة عوامل نشأتها المحتملة، وآلية تكوينها. وتم تعريف وتصنيف تلك الأمواج البحرية الحارة التي حدثت في البحر المتوسط في الفترة ما بين شهر يونيو وشهر ديسمبر من عام 2019 باستخدام مجموعة البيانات اليومية للقمر الصناعي NOAA وهي بيانات يومية لدرجة حرارة سطح البحر (Optimum Interpolation Sea Surface Temperature (OISST، حيث تم هذا التحليل بناءا على مقارنة درجات الحرارة خلال فتره الدراسه بمتوسط درجات الحرارة المحسوب لمدة 30 سنة فى الفترة من 1982 إلى 2011.

وتخلص الدراسة إلى أن الحوضين الشرقي والغربي للبحر المتوسط أظهرا اختلافات في توزيعات درجة حرارة المياه السطحية الشاذة وكذلك اختلاف في خصائص الأمواج البحرية الحارة التي حدثت وتم رصدها خلال فترة الدراسة. كما أظهرت الدراسة أن الموجات البحرية الحارة تحدث بكثافة أعلى في الحوض الغربي من البحر المتوسط بالمقارنة بحوضه الشرقي، بينما لوحظ أن فتره حدوث الموجة الحاره في الحوض الشرقي للبحر المتوسط أطول من زمن حدوث مثيلتها في الحوض الغربي .وفي كلا الحوضين الشرقي والغربي للبحر المتوسط، تم ربط خصائص الأمواج البحرية الحارة بالتغيرات الشاذة في تدفق الحرارة ما بين الطبقه السطحيه من مياه البحر و الطبقه الملامسة لها من الهواء ، و عمق الطبقة المختلطة، و درجة حرارة الهواء، و متوسط الضغط عند مستوى سطح البحر، و كذلك بالرياح .وتبين أن الارتفاعات الغير معتاده في درجات حرارة مياه سطح البحر المرصوده خلال حدوث الأمواج البحرية الحارة ترتبط بشكل كبير بتدفق حرارى عال ما بين سطح البحر و الطبقه السفليه من الجو، انخفاض في سمك الطبقه السطحيه لسطح البحر، ارتفاع درجة حرارة الهواء، ارتفاع في الضغط الجوي، و كذلك رياح منخفضة السرعة.

1. Introduction:

Episodes of large-scale anomalously high ocean temperatures can have many impacts on marine ecology and ecosystems and major implications for fisheries as well (Hobday et al., 2016). Known as marine heatwaves (MHWs), these extreme events which can take place in summer and also in winter, describe abrupt but prolonged periods of high sea surface temperatures (SST) that can occur anywhere, at any time, with a potential to propagate deeper to the water column (Darmaraki, Somot, Sevault, Nabat, et al., 2019). Despite a growing interest in the extreme weather and climate events study, in particular the marine heatwaves (MHWs), there is limited understanding of the physical processes that drive the MHWs, and how large-scale climate variability modulates the likelihood and severity of these events (Holbrook et al., 2019). Many factors can cause MHW and not all factors are important for each event. The most common drivers of the documented MHWs are air-sea interactions in particular the heat and wind fluxes, climate modes, and ocean currents (Sparnocchia et al., 2006; Olita et al., 2007; Bond et al., 2015; Di Lorenzo & Mantua, 2016; Mavrakis & Tsiros, 2019; Smale et al., 2019; Benthuysen et al., 2020; Ibrahim et al., 2021; Miyama et al., 2021).

1.1 The main MHW events, their drivers, and ecological impacts:

The global average temperature has warmed by 0.89 °C since 1900 under global warming which is mainly caused by the increase of anthropogenic activity (Perkins, 2015). As a result of the anthropogenic climate change, MHWs have been observed in many parts of the world's oceans and according to recent studies, their intensity and frequency are expected to increase (Field et al., 2012). Marine heatwave (MHW), according to Hobday et al., (2016), is “a prolonged discrete anomalously warm water event that lasts for more than five successive days and can be described by its duration, intensity, rate of evolution, and spatial coverage”.

The Mediterranean Sea is considered a hot spot region for climate change (Criado-Aldeanueva & Soto-Navarro, 2020). According to SST present-day levels and depending on the greenhouse gas (GHG) emission scenarios, the annual mean basin SST is expected to rise from 1.5 to 3 °C by the end of the 21st century and this significant rise in SST is expected to accelerate future MHW occurrence in the region (Darmaraki et al., 2019). So far, the knowledge on past MHWs in the Mediterranean Sea is mostly based on reported mass mortalities of benthic species linked to thermal anomalies, which have been observed to increase since the early 1990s (Coma et al., 2009;

Rivetti et al., 2014). One of the first documented strong MHWs worldwide occurred in the western Mediterranean in the summer of 2003, with SST anomalies of 2–3 °C above the climatological mean. This MHW lasted for over a month due to a significant rise in air temperature and a decline in the wind stress and air-sea exchanges (Sparnocchia et al., 2006; Olita et al., 2007). These factors seem to be also the drivers of anomalous SST warming in the eastern Mediterranean area during the heatwave of 2007, with an order of intensity 5 °C above climatology (Mavrakis & Tsiros, 2019). Ibrahim et al., (2021) have studied the spatial variability and trends of marine heatwaves in the eastern Mediterranean from 1982 to 2020. They observed that over the last two decades, the mean MHWs frequency and duration increased in the eastern Mediterranean Sea by 40% and 15%, respectively, and the maximum significant MHW event occurred in the past two decades was 6.35 °C above the climatology threshold with a duration of 7 days and it took place in the summer of 2020. Moreover, they found that the 2020 MHW event was linked to a decrease in the wind stress and an increase in air temperature as well as mean sea level pressure.

The Mediterranean Sea is not only a hot spot for climate change but also is considered as a true hot spot of biodiversity (Mannino et al., 2017), although it represents a small part of the world's oceans, it is inhabited by an unusually rich and diverse biota. It hosts approximately 17,000 species, representing 4–18% of the world's marine biodiversity, and includes temperate, cosmopolitan, subtropical, Atlantic, and indo-pacific taxa. Moreover, an estimated 20–30% of marine species in the Mediterranean are considered endemic to the Basin (Mannino et al., 2017). Under the effect of climate change and the rapid increase of the temperature, the Mediterranean is amongst the most impacted regional sea areas. As a consequence, different coastal and marine ecosystems within the basin suffer from habitat modification and loss, climate change (e.g., warming, acidification, and sea-level rise), and the intentional or indirect introduction of alien species (Katsanevakis et al., 2014). Many recent studies investigated the impacts of the extreme prolonged increase of the sea surface temperature on the *Posidonia oceanica* meadows, the most important endemic seagrass species of the Mediterranean Sea. *Posidonia oceanica* meadows are facing global threats mainly due to episodic heat waves (Traboni et al., 2018). It was reported that *P. oceanica* tolerates short-term temperature increases up to 30 °C. However, at 35 °C, the plant loses functionality as indicated by a decrease in photosynthetic performance, inhibition of plant growth, and an increase of the necrosis incidence in leaves (Ontoria et al., 2019). Other studies found that temperatures above 27 °C can cause a limitation in the growth of the plant by inhibiting its photosynthetic system, a reduction in leaf growth and faster leaf senescence, and the worst cases mortality (Guerrero-Meseguer et al., 2017; Traboni et al., 2018; Guerrero-Meseguer et al., 2020). Moreover, under the worst-case scenarios, *Posidonia oceanica* might lose 75% of suitable habitat by 2050 and is at risk of functional extinction by 2100 (Chefaoui et al., 2018). In the Mediterranean region, the MHWs are not only impacting the seagrass species but also impacting the rocky benthic macro-invertebrate species (Garrabou et al., 2009). As a consequence of the summer 2003 MHW, an extensive mass mortality event of at least 25 rocky benthic macro-invertebrate species (mainly gorgonians and sponges) was observed in the entire North-western (NW) Mediterranean region, affecting several thousand kilometers of coastline (Garrabou et al., 2009).

Globally, numerous studies have explored the modulating factors behind individual MHW events around the world. For instance, a combination of local oceanic and large-scale atmospheric forcing was suggested to be the drivers of the marine heatwave that occurred at the Western Australian coast in 2010/2011 which caused catastrophic damage to local seaweed populations, and the first-ever coral bleaching event on the local reefs (Smale et al., 2019; Benthuysen et al., 2020). In the Northeastern Pacific Ocean, a prime example of marine heatwaves is "the blob" which occurred in 2014–2016 (Bond et al., 2015; Di Lorenzo & Mantua, 2016; Miyama et al., 2021), and is characterized by anomalous SST at more than 3 °C than normal, exceeding four standard deviations which are categorized as an extreme marine heatwave according to Hobday et al., (2018) categorizing scale. Such an extreme MHW can have a catastrophic impact on marine life: the blob caused substantial damage to marine ecosystems, including an anomalous decline in chlorophyll biomass (Whitney, 2015), and massive deaths of sea lions, whales, and seabirds (Welch, 2016). On the other hand, animals favoring warm water temperatures, such as warm-water thresher sharks and ocean sunfish, appeared as far north as the Alaska coast (Welch, 2016). In recent years, MHWs were not limited to the eastern sector of the North Pacific basin but have also occurred in the western side of the basin and caused changes in the marine ecosystem there. For example, it has been reported by mass media and official fisheries statistics in Japan that warm water fishes such as Japanese amberjack or yellowtail (Seriola quinqueradiata) are more frequently caught in the coastal region in northern Japan in the 2010s than before (Makino & Sakurai, 2012). Conversely, cold fishes such as saury (Cololabis Saira) decreased drastically after 2010 (Kuroda

& Yokouchi, 2017). In 2012 there is a reported MHW occurred in the northwest Atlantic, which seriously impacted the local fish species (Mills et al., 2013).

1.2 Defining extreme temperatures in marine systems:

Several metrics have been proposed to assess the effect of extreme thermal stress in the marine environment (Table 1). For instance, to study the impacts of heatwaves on the composition of a marine community Sorte et al., (2010) used an approach in which the MHWs were defined as a period of at least three to five days during which mean or maximum temperature anomalies were at least 3–5 °C above normal, while Selig et al., (2010) used thermal stress anomalies to study the impacts of the temperature anomalies on the coral reef health and management. Moreover, the Degree Heating Weeks (DHWs) metric has been used to study the effect of thermal stress on the Caribbean Sea corals (Eakin et al., 2010), and for evaluating the effect of the temperature variability on the coral bleaching events (Donner, 2011). Maynard et al., (2008) used the degree heating days (DHD) and the heating rate (HR) to investigate the effect of sea surface temperature increase on the coral bleaching events. The previously mentioned metrics generally include the effect of extreme event duration and magnitude of temperature anomalies and beyond coral reef research there is limited consistency regarding how MHW metrics are applied or how useful they are in ecological applications. Recently, Hobday et al., (2016) used a hierarchical approach to define an MHW which considers an anomalously warm event to be an MHW if it lasts for five or more days, with temperatures warmer than the 90^{th} percentile based on a 30-year historical baseline period. This definition has been used frequently to study marine heatwaves by many researchers. For example, Hobday et al., (2016) used their approach to study the 2011 marine heatwave event that occurred in West Australia, the 2003 event that occurred in the Western Mediterranean Sea, and the 2012 event which took place in the Northwest Atlantic ocean. Also, Darmaraki et al., (2019) used the same approach to study the past variability and future evolution of Mediterranean Sea MHWs. Ibrahim et al., (2021) also used the hierarchical approach of defining marine heatwaves to study the spatial variability and trends of marine heatwaves in the Eastern Mediterranean Sea.

1.3 The Aim of work:

It’s obvious that MHWs, which may dramatically increase under the effect of anthropogenic climate change (IPCC, 2012), are important events to be studied, especially as they are causing rapid changes in biodiversity patterns and ecosystem structure and functioning. In 2019, two extreme heatwaves occurred in Western Europe, with historical records broken by more than a degree in many locations, and significant societal impacts, including excess mortality of several thousand people (Vautard et al., 2020). It’s believed that these heatwaves caused the SST of the Northwestern Mediterranean to increase. As a consequence, the Northwestern Mediterranean Sea has suffered from strong MHWs during summer 2019. Therefore, this work aims to:

1- Define the MHWs which took place in the Western Mediterranean Sea (WMED) during summer 2019 and compare it with the MHWs occurred in the Eastern Mediterranean (EMED) during the same period.
2- Calculate the heat fluxes anomaly associated with these MHW events, at the different places in the Mediterranean Sea.
3- Investigate the physical drivers of these marine heatwaves.

Table 1. Examples of metrics commonly used to describe marine heatwaves and warming events in ecological studies.

Metric	Description	Example
Periods of temperature maximum (°C)	The proportion of the daily means that were greater than the upper range of temperatures recorded in a particular region over a period of time.	**(Berkelmans et al., 2004; D. Smale & Wernberg, 2009)**
Temperature anomaly (°C)	The deviation of ocean temperature from the long-term average (long-term climatology).	**(Sorte et al., 2010; Wernberg et al., 2013)**
Thermal stress anomaly (e.g., weeks)	Temperature deviation above a threshold value (rather than the mean value), summed over a period of time.	**(Selig et al., 2010)**
Degree Heating Weeks (°C weeks)	Degree Heating Weeks (DHWs) providing a measure of sustained thermal stress over weeks by integrating SST anomalies above a threshold over the period.	**(Eakin et al., 2010; Donner, 2011)**
Degree heating days (°C days)	The degree heating days (DHD) value is the summed positive deviations of daily mean sea surface temperatures from the climatology of long-term mean summer temperatures (LMST), for a specified period.	**(Maynard et al., 2008)**
Heating rate (°C/day)	Heating rate (HR) is defined as (DHD/ND) where DHD is degree heating days as defined above, and ND is the number of days in which daily mean sea surface temperatures have exceeded the long-term mean summer temperatures. That is, HR is the mean rate at which DHD has accumulated throughout a period of time.	**(Maynard et al., 2008)**
(Hobday et al., 2016) the hierarchical approach of defining an MHW	This approach considers an anomalously warm event to be an MHW if it lasts for five or more days, with temperatures warmer than the 90th percentile based on a 30-year historical baseline period. And then define each marine heatwave event depending on its intensity, duration, frequency, and spatial extent.	**(Hobday et al., 2016; Darmaraki et al., 2019; Darmaraki, Somot, Sevault, & Nabat, 2019; Ibrahim et al., 2021)**

2. Material and Methods:

2.1 The Study Area:

The Mediterranean Sea as shown in (Figure 1), is lying between latitudes 30° and 46° N and longitudes 5°50′ W and 36° E. It is a semi-enclosed basin situated along the border that separates the European and North African climatic regions. It has a total surface of 2.5 million km^2 with an average depth of 1,460 m and a maximum depth of 5,267 m placed on the Matapan trench, in Greece. The Mediterranean Sea comprises two deep basins, the Western and Eastern Mediterranean, which are separated by the Strait of Sicily and it is connected with the Atlantic Ocean through the Strait of Gibraltar and with the Black Sea through the Dardanelles Strait (Longhurst, 2007).

The Mediterranean Sea plays a fundamental regulatory role in the regional climate (Pastor et al., 2020). This semi-enclosed basin acts as a natural laboratory since, despite its reduced dimensions, most of the processes typical of global ocean circulation, such as deep-water formation or thermohaline circulation, take place in the basin. Moreover, semi-enclosed basins such as the Mediterranean are appropriate for characterizing heat and water flux since it makes possible a basin budget closure. The Mediterranean climate is characterized by hot dry summers and humid, cool winters (Criado-Aldeanueva & Soto-Navarro, 2020). In addition, it is known for its particular regional characteristics: large seasonal contrast for temperature and rainfall, strong wind systems, intense precipitation, and Mediterranean cyclones (Allam et al., 2020; Lionello et al., 2006; Nadia et al., 2006).

Knowledge of sea surface temperature (SST) behavior is vital for long-term climate scenarios. The annual average zonal SST gradient over most of the Mediterranean Sea increases from north to south, except over the northern Tyrrhenian and the Levantine sub-basins (meridional gradient), where it increases from west to east, partly due to the Mediterranean surface circulation (Shaltout & Omstedt, 2014). Mediterranean SST variability is affected by a combination of oceanic processes and displays significant regional and seasonal behavior. The upper 400 m in the Mediterranean Sea is characterized by temperatures varying between 15.0 °C and 17.0 °C in the winter season. In summer, the warming effect increases the Mediterranean SST (30–50 m) up to 28.0 °C and a strong thermocline is developed (El-Geziry, 2021).

Besides this oceanographic component, 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 (Pastor et al., 2018). The Mistral winds are cold, dry, and strong north or north-west winds affecting the western Mediterranean coast of south-eastern France (Jiang et al., 2003). In summer, the Mistral winds can rapidly lower the SST. Whereas the Etesian winds that are cold and dry, moderate the western Mediterranean SST in summer (Pastor et al., 2018).

Figure 1. The Mediterranean Sea and its main geographic features.

2.2 The Used Data:

2.2.1 Sea Surface Temperature (SST) data:

The daily SST data used were obtained from the National Oceanic and Atmospheric Administration Optimum Interpolation Sea Surface Temperature NOAA OISST from January 1982 to December 2019 (Reynolds et al., 2007). Which are freely available on the NOAA website (https://www.ncei.noaa.gov/data/sea-surface-temperature-optimum-interpolation/v2.1/access/avhrr/). This data set is an interpolation of remotely sensed SSTs from the Advanced Very High-Resolution Radiometer (AVHRR) imagery into a regular grid of 0.25° and daily temporal resolution. AVHRR OI data for the Mediterranean Sea were extracted from the global data, providing a 11008-point regularly gridded dataset spanning 13,879 days from 1 January 1982 to 31 December 2019.

2.2.2 Atmospheric variables data and heat fluxes:

Atmospheric variables and heat flux components were obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 (Hersbach et al., 2020). For the atmospheric variable, winds at 10 m elevation (U10 and V10), air temperature at 2 m elevation, pressure at mean sea level were used. For the heat flux components, surface net shortwave radiation, surface net longwave radiation, surface latent heat flux, surface sensible heat flux, and forecast albedo were used to calculate the total net flux at the sea surface. The dataset has 0.25° spatial resolution with hourly temporal step. The data are freely available on the EMCWF website (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview).

2.2.3 Mixed Layer Depth (MLD):

The daily MLD data were obtained from Copernicus Marine (CMEMS) Ocean Data product (Escudier et al., 2020). The used data are physical reanalysis product which is generated by a numerical system composed of a hydrodynamic model, supplied by the Nucleous for European Modelling of the Ocean (NEMO) and a variational data assimilation scheme (OceanVAR) for temperature vertical profiles. The model horizontal grid resolution is 1/24° and the unevenly spaced vertical levels are 141. The data are freely available on the CMEMS website (https://resources.marine.copernicus.eu/?option=com_csw&view=details&product_id=MEDSEA_MULTIYEAR_PHY_006_004).

2.3 The Methods of Analysis:

2.3.1 The sea surface temperature anomaly (SSTa) calculations:

A 30-year climatology from 1982 to 2011 was used as a baseline in determining the threshold that was used to detect the MHWs. The same climatology period was also used to calculate the sea surface temperature anomaly and heat flux anomaly. This specific period of climatology was selected according to Hobday et al., (2018) in which they suggested using a 30-year baseline period based on the first availability of global satellite sea surface temperature in the NOAA Optimum Interpolation Sea Surface Temperature (OISST) data set (Reynolds et al., 2007). They also recommended that the baseline period for determining these thresholds should be fixed since updating it as the world warms will change the categories for past events. Furthermore, this baseline was selected to enable me to compare my results with the previous studies on MHWS which used the same baseline.

To have a historical perspective of the strength of the 2019 warming event, the SST anomalies were calculated as described in (Arafeh-Dalmau et al., 2019), by subtracting the climatological daily mean values (1982-2011) at each grid point from the 2019 SST daily values at the same location.

2.3.2 Marine Heat Waves (MHWs) calculations:

To define the 2019 MHWs in the Mediterranean Sea Hobday et al., (2016) definition has been used. According to Hobday et al., (2016), the MHWs are defined as a prolonged discrete anomalously warm water event that can be described by its duration, intensity, rate of evolution, and spatial extent. Specifically, that approach considers an anomalously warm event to be an MHW if it lasts for five or more days, with temperatures warmer than the 90th percentile based on a 30-year historical baseline period. The MATLAB toolbox developed by Zhao & Marin, (2019), has been used to identify the periods where temperatures were above the 90th percentile threshold relative to the climatology, and for a duration of at least 5 days, using the same daily SST database for the 1982–2019 period. The climatological mean has been calculated from the daily Sea Surface Temperature (SST) data from 1 January 1982 to 31 December 2011, by following the Hobday et al., (2016) formula,

$$T_m(j) = \sum_{y=y_s}^{y_e} \sum_{d=j-5}^{j+5} \frac{T\,(y, d)}{11(y_e - y_s + 1)} \qquad (1)$$

where, T_m is the climatological SST mean in ˚C calculated over a period from 1 January 1982 to 31 December 2011, to which all values are relative, j is the day of the year, y_s and y_e are the start and end of the climatological base period respectively, and T is the daily SST on day d of year y. Then the 90th percentile threshold based on the SST climatology period, T_{90} (j) in ˚C were calculated according to Hobday et al., (2016) based on climatological SST mean (X) in ˚C over a period from 1 January 2019 to 31 December 2019 as follows:

$$T_{90}\ (j) = P_{90}\ (X) \quad (2)$$

According to Hobday et al., (2016) definition, MHWs occur when SST at any time (T(t)) exceeds the threshold, defined as the 90th percentile of SST variations (T_{90}(j)) based on a 30-year climatological period (1982–2011), for at least five consecutive days. During the MHW event,

$$t_s \text{ is time, t, where } T(t) > T_{90}\ (j) \text{ and } T(t-1) < T_{90}\ (j) \quad (3)$$

$$t_e \text{ is time, t, where } t_e > t_s \text{ and } T(t) < T_{90}\ (j) \text{ and } T(t-1) > T_{90}\ (j) \quad (4)$$

where, t_s and t_e are the dates on which an MHW begins and ends, respectively.

At each location and for each MHW, the event duration (time between start and end dates), mean, and maximum intensity were calculated. Associated annual statistics were then calculated, including the frequency of events (i.e., the number of discrete events that occurred per the year of 2019),

$$D = t_e - t_s \geq 5 \quad (5)$$

Where D is the MHW duration in days that temperature exceeds the threshold. Then, the MHWs main characteristics (i_{max}) in ˚C and mean intensity (i_{mean}) in ˚C were also calculated using the following formulas,

$$i_{max} = (T(t) - T_m(j)) \quad (6)$$

$$i_{mean} = \overline{T(t) - T_m(j)} \quad \text{for } t_s \leq j \leq t_e \text{ (during the MHW event)} \quad (7)$$

2.3.3 Marine Heat Waves (MHWs) categorization:

As more regional studies have been completed regarding MHWs, scientists have recognized that biological impacts can vary dramatically and appear to be context-dependent. These differences in the apparent biological and socioeconomic impacts of MHWs suggested that the metrics proposed by Hobday et al., (2016) may be extended to further understand the apparent differences. So that, Hobday et al., (2018) proposed an MHW categorization scheme based on intensity (I), which is the sea surface temperature anomaly (SSTa) based on the long-term climatology for a location. After an event has concluded, the maximum intensity (i_{max}) can be used to categorize the overall event, they proposed to base categories of MHWs, identified as described above, on multiples of the value represented by the local difference between the climatological mean and the climatological 90th percentile, which is the threshold used to identify MHWs (Figure 2). Multiples of this local difference will describe different categories of MHWs. The magnitude of scale descriptors, defined as moderate (1×, Category I), strong (2×, Category II), severe (3×, Category III), and extreme (4×, Category IV), can be allocated at each point in space and time of an MHW event, based on the intensity (I) measure (Figure 2).

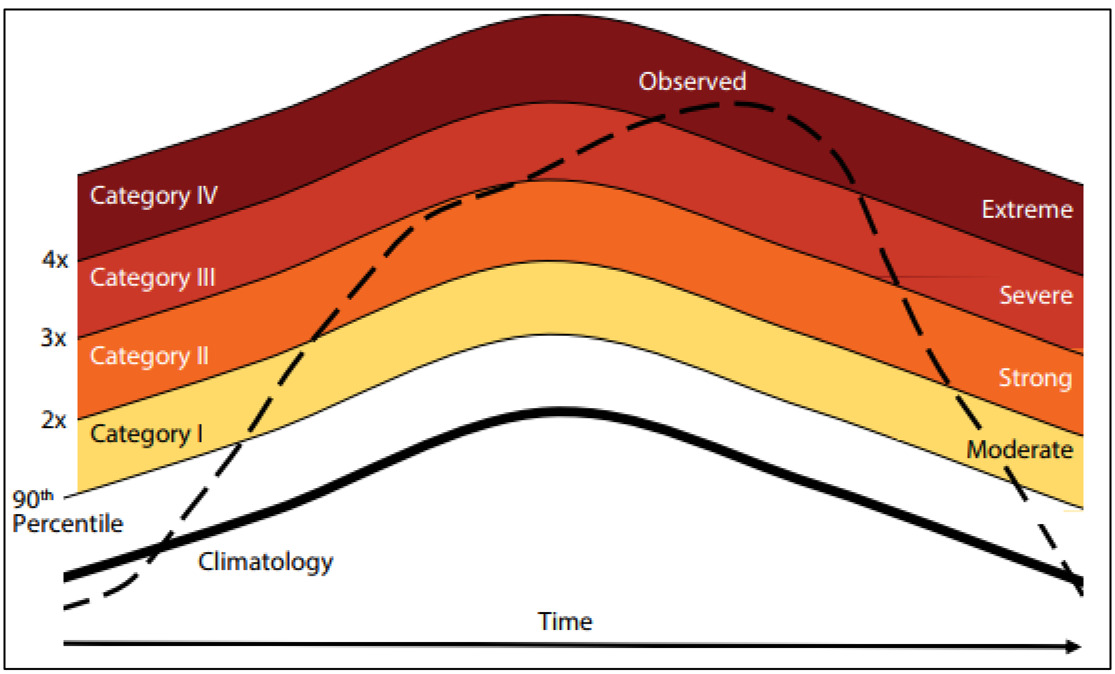

Figure 2. Categorization schematic for marine heatwaves (MHWs) showing the observed temperature time series (dashed line), the long-term regional climatology (bold line), and the 90th percentile climatology (thin line). Multiples of the 90th percentile difference (2× twice, 3× three times, etc.) from the mean climatology value define each of the categories I–IV, with corresponding descriptors from moderate to extreme.

Source: (Hobday et al., 2018).

2.3.4 Total heat flux calculations:

The general principle of heat transfer in a given area at the ocean surface is represented in (Figure 3). The rate of heat gain or loss at the ocean surface can be expressed as the difference between the total heat coming from the Sun and the total thermal energy loss from the given area at the ocean surface. The total heat flux (Q_i) were calculated as described in Simpson & Sharples, (2012), using the following formula:

$$Q_i = Q_s * (1 - A) - (Q_b + Q_c + Q_e) \quad (8)$$

where Q_i is the total heat flux gain or loss in a given area at the ocean surface (watt/m^2), Q_s is the rate of heat absorbed by the ocean from incoming solar radiation (watt/m^2), A is the Albedo, Q_b is the rate of heat loss by back radiation (watt/m^2), Q_c is the sensible heat loss by convection and conduction (watt/m^2), and Q_e is the rate of heat loss (latent heat) by evaporation from the ocean surface (watt/m^2).

After calculating the total heat flux, the heat flux anomaly at each grid point was also calculated over the study period using the same method that was used to calculate the sea surface temperature anomaly.

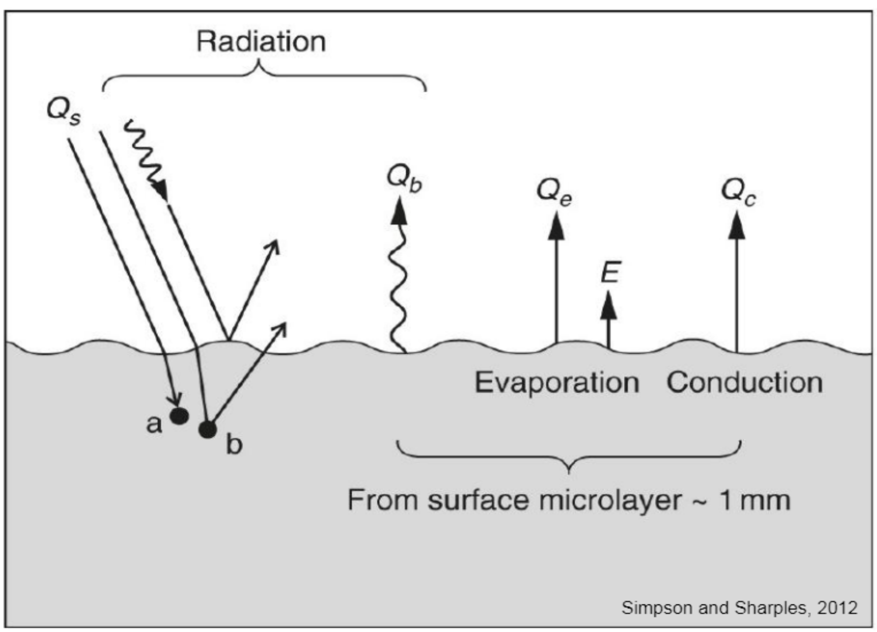

Figure 3. The general principle of heat transfer in a given area at the ocean surface. Qs is the rate of heat absorbed by the ocean from incoming solar radiation, Qb is the rate of heat loss by back radiation, Qc is the sensible heat loss by convection and conduction, and Qe is the rate of heat loss (latent heat) by evaporation from the ocean surface (watt/m2).

Source: (Simpson & Sharples, 2012).

3. Results:

3.1 Sea Surface Temperature (SST) description:

To study the spatial variability of the SST in the Mediterranean Sea, the SST average was calculated at each grid point for the 2019 summer months (from June to December), and the anomaly over the same period was also calculated based on the SST climatology (1982-2011) from NOAA OISST, (Figure 4). Figure (4-a) shows the spatial distribution of the SST in the Mediterranean Sea from July to December 2019, it is clear that the SST varies from 18 ^{o}C to 26 ^{o}C and it is increasing towards the east, so over the study period, the higher values of SST were found in the eastern part while the lower ones were observed in the western basin of the Mediterranean Sea. Moreover, from the climatological anomaly map of summer 2019, Figure (4-c), there is a noticeable spatial variability of SSTa, the highest values were recorded in the eastern Mediterranean, the northern half of the western Mediterranean, and the Ionian Sea. A lowest, but also positive, SSTa were observed to the south of Italy and the Alboran Sea.

Figure (5 a-b) shows a comparison between the temporal variability of the 2019 SST and the SST climatology at the western and eastern Mediterranean basins of the Mediterranean Sea. This series shows that, in the Mediterranean Sea, for both western and eastern basins, the 2019 SST was higher than the climatology from June to December. In addition, the basic statistics for both data series at both sites were calculated (Table 2). In the western basin, the average SST is higher than the SST climatology by 1.39 ^{o}C, the maximum SST is higher by 2.89 ^{o}C, and the minimum SST is also higher by 0.97 ^{o}C. While in the eastern basin the average SST is higher than the SST climatology by 1.22 ^{o}C, the maximum SST is higher by 1.4 ^{o}C, and the minimum SST is higher by 0.59 ^{o}C. By comparing the 2019 SST in the western and eastern Mediterranean, the eastern basin mean, maximum, and minimum SST is higher than its corresponding values in the western basin.

Table 2. The western and eastern Mediterranean Sea mean, maximum, minimum, and standard deviation of the SST in (°C) over the study period and climatology periods.

Region	Period	Mean (°C)	Maximum (°C)	Minimum (°C)	S.D
Western Mediterranean	June – December (2019)	21.41	27.02	14.91	3.50
	June – December (1982-2011)	20.02	24.13	13.94	3.05
Eastern Mediterranean	June – December (2019)	25.44	28.40	19.19	2.5
	June – December (1982-2011)	24.22	27.00	18.6	2.4

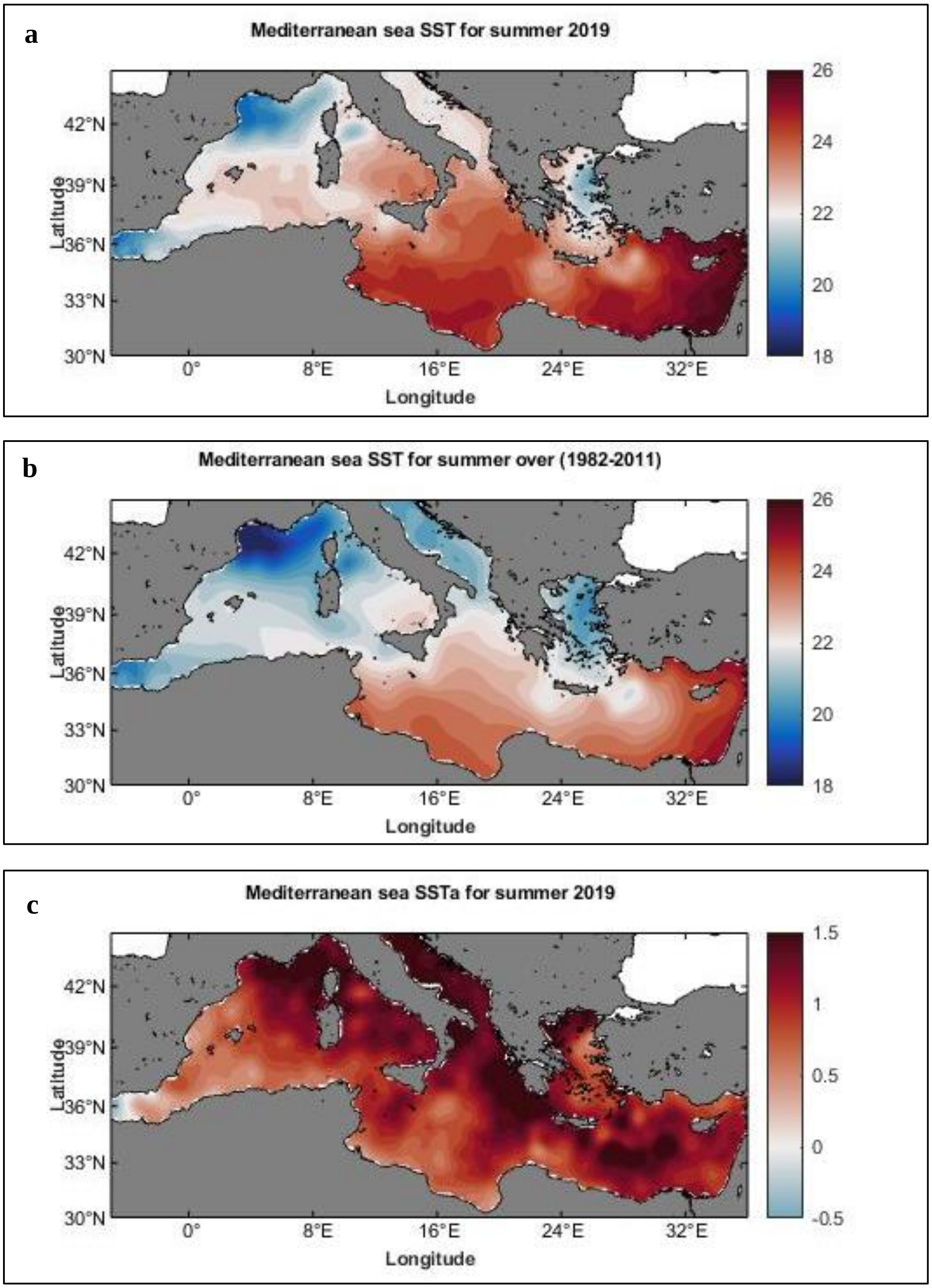

Figure 4. SST spatial distribution in the Mediterranean Sea. a) SST for summer 2019, b) SST over the climatology period (1982-2011) for the summer month, and c) the climatological anomaly map for summer 2019.

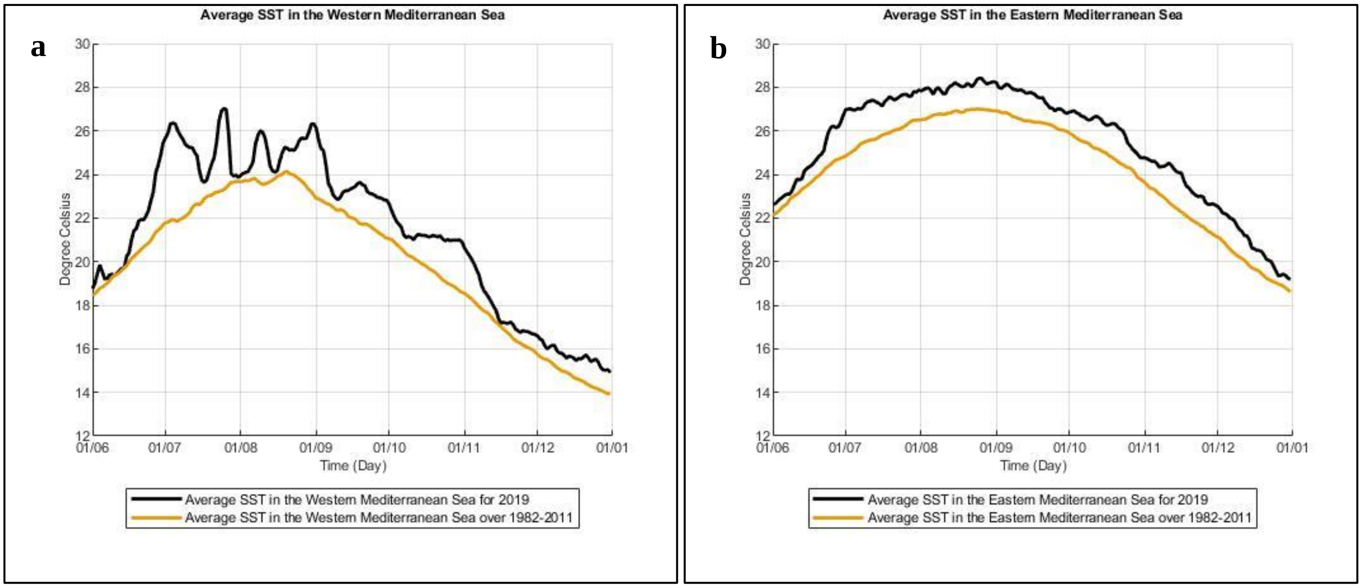

Figure 5. Temporal evolution of the averaged SST in (◦C), the black line represents SST in summer 2019 and the yellow one represents the SST over the climatology period (1982-2011) over the summer months, a) in the Western Med. Sea and b) in the Western Med. Sea.

3.2 Spatial description of the MHWs main characteristics in the Mediterranean Sea:

Marine heatwaves in the Mediterranean Sea over the study period were identified from daily SST time series and a set of metrics were calculated to characterize them, following Hobday et al., (2016). Figure (6 a–d) depicts the spatial distribution of the 2019 Mediterranean Sea MHWs main characteristics, the number of events (count), mean intensity (i_{mean}), maximum intensity (i_{max}), and duration (days), which are overlaid with no significant values ($p > 0.05$) for the entire study period. In the whole Mediterranean the number of the MHW events that occurred during the study period ranged between 1 to 8 events, the average i_{mean} fluctuated between 1 to 2.5 ^{o}C, the average i_{max} varied from 1 to 3.5 ^{o}C, and the MHWs duration was between 5 to more than 50 days. More so, there is a very clear contrast between the Eastern Mediterranean (EMED) and Western Mediterranean (WMED) marine heatwaves. For instance, the 2019 WMED marine heatwaves were more likely to occur and more intense than the EMED marine heatwaves, while the marine heatwaves that occurred in the EMED were longer in terms of the duration than the ones that occurred in the WMED.

To get a better understanding of the relation between the MHW characteristics, the correlation between them was calculated, following Oliver et al., (2018). A strong relationship between the MHWs mean frequency and mean duration at each location over the study period was found. The spatial pattern of mean MHW frequency and duration was highly negatively correlated ($r = -0.747$), which means that the frequency was low where duration was long, and vice versa.

While there was no correlation between the MHWs mean frequency and mean intensity or the MHWs mean duration and mean intensity.

In order to study the MHW events that occurred in the western and eastern basins of the Mediterranean Sea, two different sites were selected, represented by the green solid dots, as shown in Figure (6). The first site is located in the northwestern Mediterranean (in the Ligurian Sea) and the second site is located in the southeastern part of the Mediterranean (in the Levantine basin).

3.3 Extreme MHW events in the Mediterranean Sea at the different locations and their category

The MHW events at each location were plotted as shown in Figure (7), and each event was classified as being a Moderate (category I), Strong (II), Severe (III), or Extreme (IV) MHW according to the Hobday et al., (2018) categorizing scheme. Table (3) shows the significant extreme MHW events characteristics (count, i_{mean}, i_{max}, and duration) that occurred at each location in the Mediterranean Sea over the study period (June to December 2019) with the corresponding MHW_{onset}, MHW_{peak}, MHW_{end}, MHW category, total heat flux anomaly (Qi_anom), longitude, and latitude.

In the WMED which is represented by location 1, six MHW events took place during the study period. The i_{mean} varied between 1.81 ^oC and 5.27 ^oC, the i_{max} ranged from 2.25 ^oC to 6.42 ^oC, and the duration of the MHW events fluctuated between 5 and 20 days. In terms of the MHW events severity, the WMED experienced three significant strong MHW events, the SST exceeded twice the 90th percentile difference, and the other events were classified as moderate events. The first strong event that occurred in the WMED basin lasted for 15 days (26/06 to 10/07), and the i_{mean} and i_{max} associated with this event were the maximum intensity recorded in the WMED basin during the study period. While the second strong event in the WMED lasted for 6 days (22/07 to 27/07) with i_{mean} and i_{max} 4.14 ^oC and 4.8 ^oC, respectively. Finally, the third strong MHW event that took place in the WMED lasted for 11 days (24/08 to 3/09) with i_{mean} and i_{max} 4.18 ^oC and 5.38 ^oC, respectively.

For the EMED basin, location 2, only two MHW events occurred during the study period. These two events were characterized by low intensity and long duration (21 days for the first event and 159 days for the second one) compared with the WMED MHW events, and both events were categorized as strong events, Table (3).

3.4 The heat fluxes anomaly in the Mediterranean Sea at the different locations:

One of the possible causes of the increase in SST is the increase in downward net air-sea heat flux (Miyama et al., 2021). The heat fluxes anomaly between June and December 2019 has been calculated based on a 30-years climatology average (1982 – 2011), and the time series at each location was plotted in Figure (8). In addition, the total heat flux (Qi) anomaly associated with each of the MHW events at the different locations is presented in Table (3). Generally, from Figure (8 a-b), it is obvious that the total heat flux anomaly distribution in the Mediterranean Sea at both locations is mostly affected by the latent heat followed by the sensible heat. In the WMED, the anomaly of the heat flux ranged between -120 Watt/m^2 and 120 Watt/m^2 with maximum values observed in September and minimum values recorded in late October. Whereas, in the EMED the total heat flux ranged between -30 Watt/m^2 and 70 Watt/m^2. From Table (3), in the WMED basin, the anomaly of the total heat flux was positive (inward to the ocean) during the first five MHW events which means that the surface ocean was gaining heat from the atmosphere. While the total heat flux anomaly was negative (upward to the atmosphere) during the last MHW event that occurred in the WMED which indicates that the atmosphere was receiving the heat that was lost by the surface of the ocean. On other hand, in the EMED the total heat flux anomaly was negative during the first event and positive during the last event.

Table 3. The main characteristics of each MHW event at each location.

Loc.	Event no.	Onset_Day	Peak_Day	End_Day	Duration (days)	Max. Intensity (ºC)	Mean Intensity (ºC)	Intensity Variance	MHW Category	Qi_anom (W/m^2)
Loc. 1 (6.3 ^{0}E , 42.5 ^{0}N)	1	26-06-2019	03-07-2019	10-07-2019	15	6.42	5.27	1.04	II Strong	15.77
	2	22-07-2019	25-07-2019	27-07-2019	6	4.80	4.14	0.83	II Strong	13.63
	3	08-08-2019	10-08-2019	12-08-2019	5	3.29	2.85	0.35	I Moderate	45.2
	4	24-08-2019	31-08-2019	03-09-2019	11	5.38	4.18	1.02	II Strong	78.32
	5	15-09-2019	19-09-2019	02-10-2019	18	3.26	2.64	0.38	I Moderate	6.98
	6	19-10-2019	31-10-2019	07-11-2019	20	2.25	1.81	0.25	I Moderate	-102.58
Loc. 2 (30.87 ^{0}E , 33.37 ^{0}N)	1	23-06-2019	30-06-2019	13-07-2019	21	2.68	1.96	0.32	II Strong	-7.33
	2	22-07-2019	23-10-2019	27-12-2019	159	2.69	1.91	0.37	II Strong	36.99

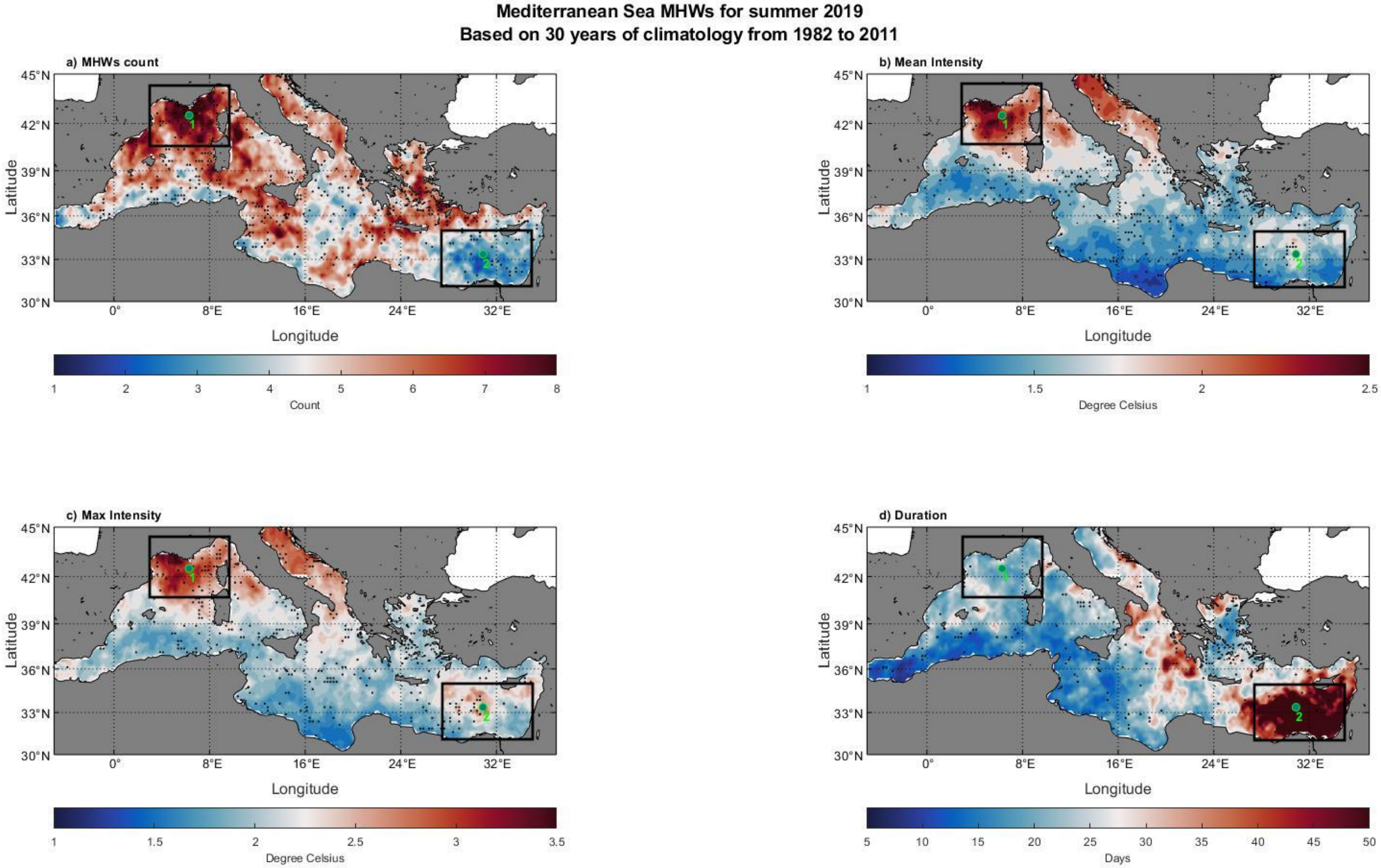

Figure 6. The Marine heatwave properties in the Mediterranean Sea for 2019 , averaged time series of a) MHW frequency (Count), b) mean MHW mean intensity (imean) (◦C), c) mean MHW maximum intensity (imax) (◦C), d) mean MHW duration (days). The black dots indicate the change is not significantly different ($p > 0.05$). Where, the solid green dots present the different locations selected in the Mediterranean basin to study the MHW events at these locations.

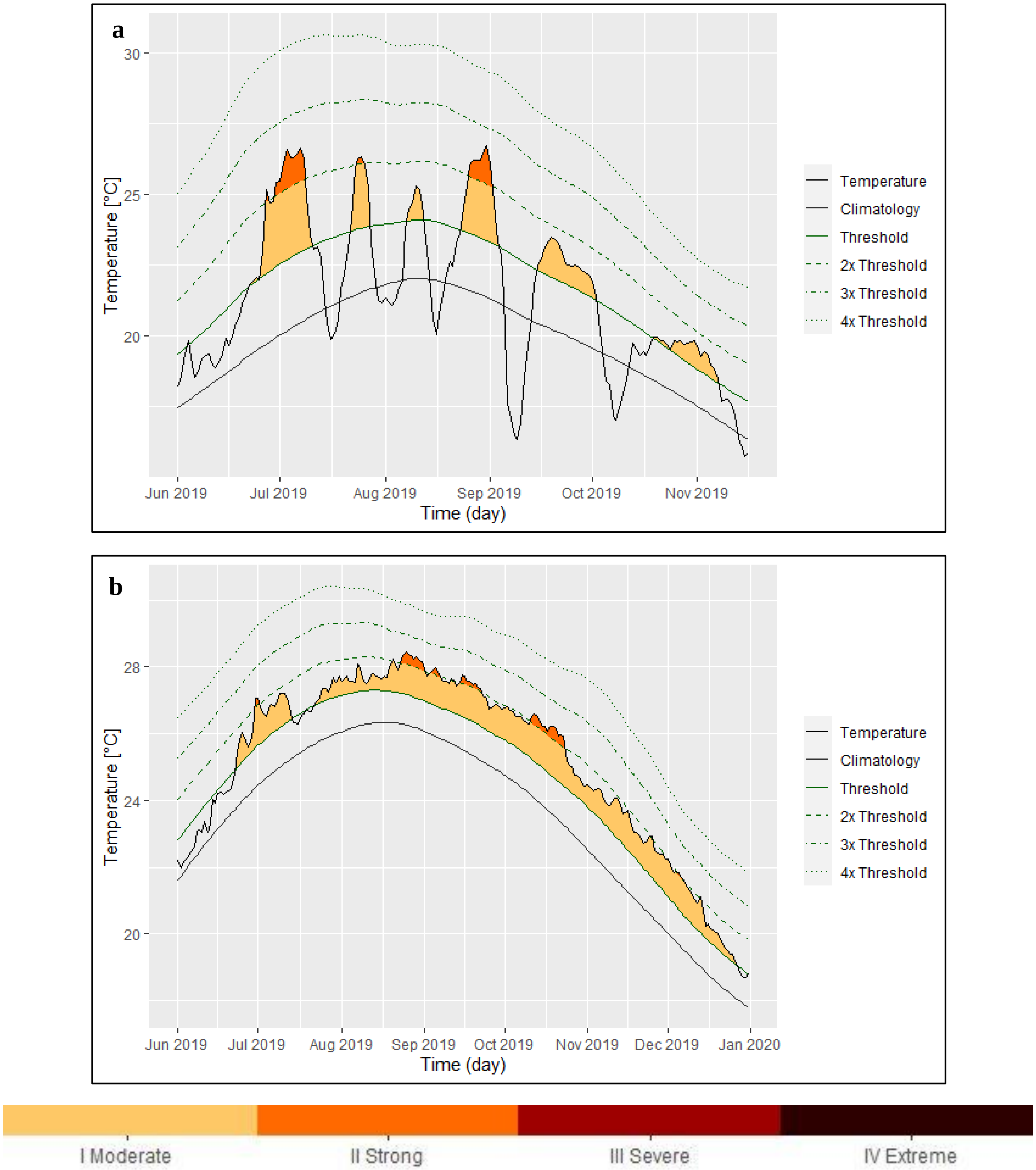

Figure 7. The extreme MHW significant events over the study period. The filled area indicates the period associated with the identified MHW, Multiples of the 90th percentile difference (2× twice, 3× three times, etc.) from the mean climatology value define each of the categories I–IV, with corresponding descriptors from moderate to extreme. a) The extreme MHW significant events at location one, and b) The extreme MHW significant events at location two.

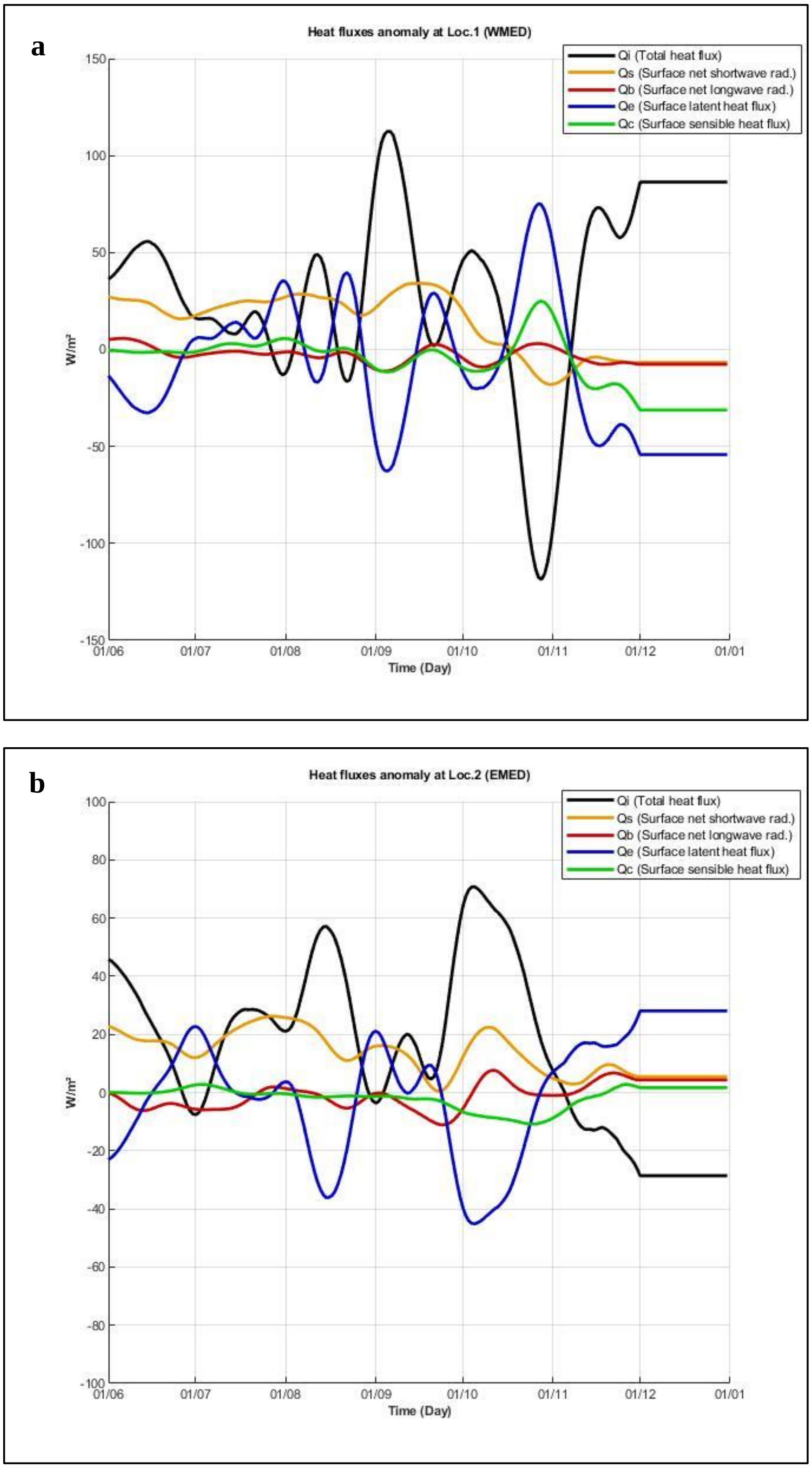

Figure 8. The Heat Fluxes anomaly at the different locations in the Mediterranean Sea over the period of study, the total heat flux (Qi) in watt/m2 is represented by the black line, the surface net solar radiation (Qs) in watt/m2 is represented by the yellow line, the surface net long wave radiation (Qb) in watt/m2 is represented by the red line, the surface latent heat flux (Qe) in watt/m2 is represented by the blue line, and the surface sensible heat flux (Qc) in watt/m2 is represented by the green line. Where, a) the average heat fluxes anomaly at location one , and b) the average heat fluxes anomaly at location two.

3.5 The relation between the MHWs magnitude and the Mixed Layer Depth (MLD) at the different locations:

In the Mediterranean Sea at different locations, the MLD and SST time series were compared with each other over the study period and plotted in Figure (9). The cross-correlation between them was also calculated at the different locations and the result was plotted in Figure (10). From Figure (9), it was noticed that there is an inverse relationship between the MLD and the SST in both western and eastern Mediterranean basins which were confirmed by the result of the cross-correlation analysis. In the WMED the highest correlation between the SST and MLD (r = - 0.806) was at time lag -2 days which means that the MLD decreased (became shallower) 2 days before the SST increases, and vice versa. In the EMED the highest correlation between the SST and MLD (r = - 0.813) was at time lag -1 day which means that the changes in the MLD occur one day before the changes in the SST.

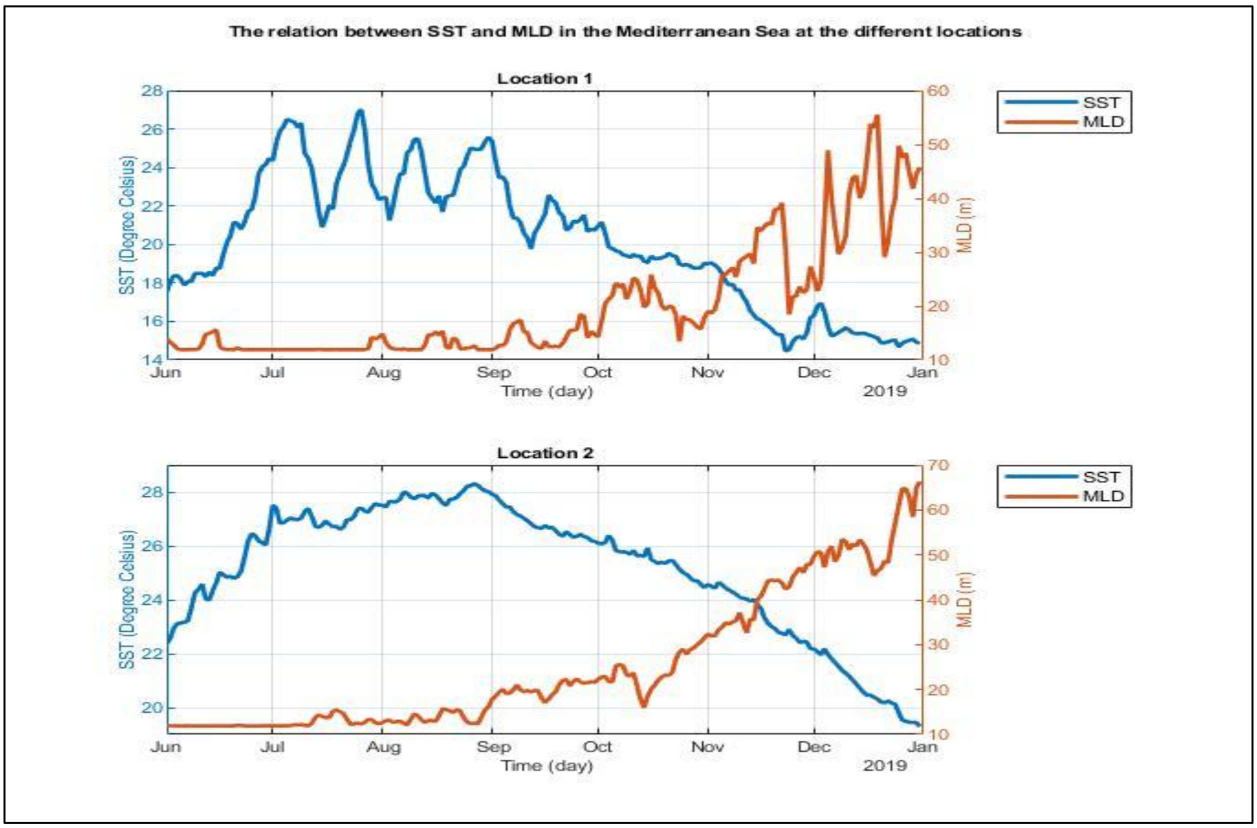

Figure 9. Temporal evolution of the SST in (◦C) on the left y-axis and the MLD in (m) on the right y-axis, over the study period at the different locations.

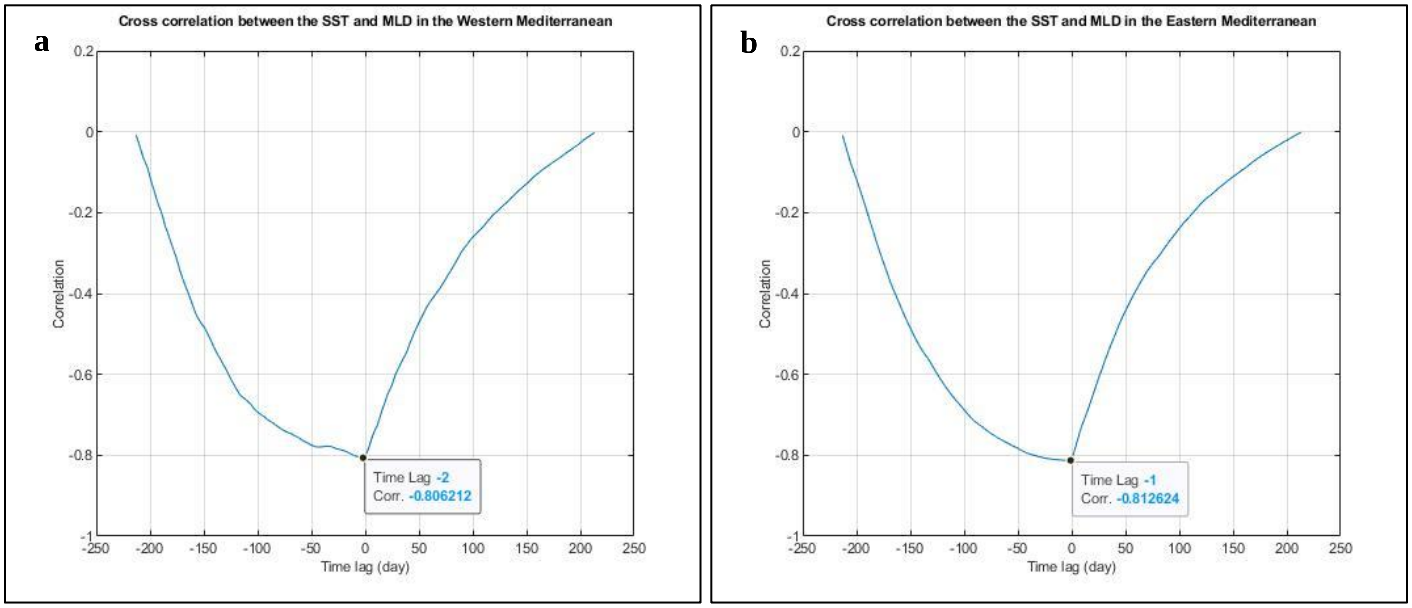

Figure 10. The cross correlation between the SST and the MLD during the study period for a) the western Mediterranean and b) the eastern Mediterranean. The data labels are showing the time lag (in day) associated with the highest correlation.

3.6 The relation between the sea surface temperature anomaly and the atmospheric variables associated with the strong MHW events:

To understand how the atmospheric variables can contribute to the MHWs formation, the relation between the SSTa, 2m air temperature, mean sea level pressure (MSLP), and wind speed vectors were investigated during the strongest MHW events that occurred at each location. For the WMED, the average of each variable was calculated over the period of the strong MHW events at each grid point and plotted in Figures (12-14), while for the WMED that was suffering from a very long MHWs, the average of each variable was calculated for 10 days around the peak day of the event at each grid point and plotted in Figure (15). The cross-correlation between the SSTa and the atmospheric variables was also calculated, and the results were plotted in Figure (11).

In the WMED during the strong MHW events, the SSTa was associated with high air temperature (> 25 ^{0}C), high MSLP (> 1014 hPa), and low to no wind speed. Moreover, the cross-correlation results show a very interesting relationship between the atmospheric variables and the SSTa, Figure (11 a-c). A strong direct correlation (r = 0.675) was found between the SSTa and the air temperature with a time lag of -2 days, which means that the air temperature increases 2 days before the SST, in other words, the increment in the air temperature leads the SST to increase. Furthermore, there is a high direct correlation between the SSTa and the mean sea level pressure (r = 0.607) with time lag -1 day, which means that the MSLP is leading the SSTa by one day. Finally, a moderate inverse correlation was found between the SSTa and the wind speed (r = -

0.534) with a time lag of -6 days, which implies that the wind speed is leading the SSTa by six days.

On the other hand, in the EMED basin, the MHW sea surface temperature anomaly was also associated with high air temperature (> 25 ^{0}C), high MSLP (> 1015 hPa), and low wind speed. Figure (11 d-f) shows the cross-correlation between the SSTa and the atmospheric variables in the EMED basin. A strong direct correlation was obtained between the SSTa and both air temperature and MSLP with time lag -13 and 0 days, respectively, while a high inverse correlation between the SSTa and wind speed was found with time lag -9 days. This indicates that the air temperature is leading the SSTa by 13 days, the changes in the SSTa and MSLP are occurring simultaneously, and the wind speed is leading the SSTa by 9 days.

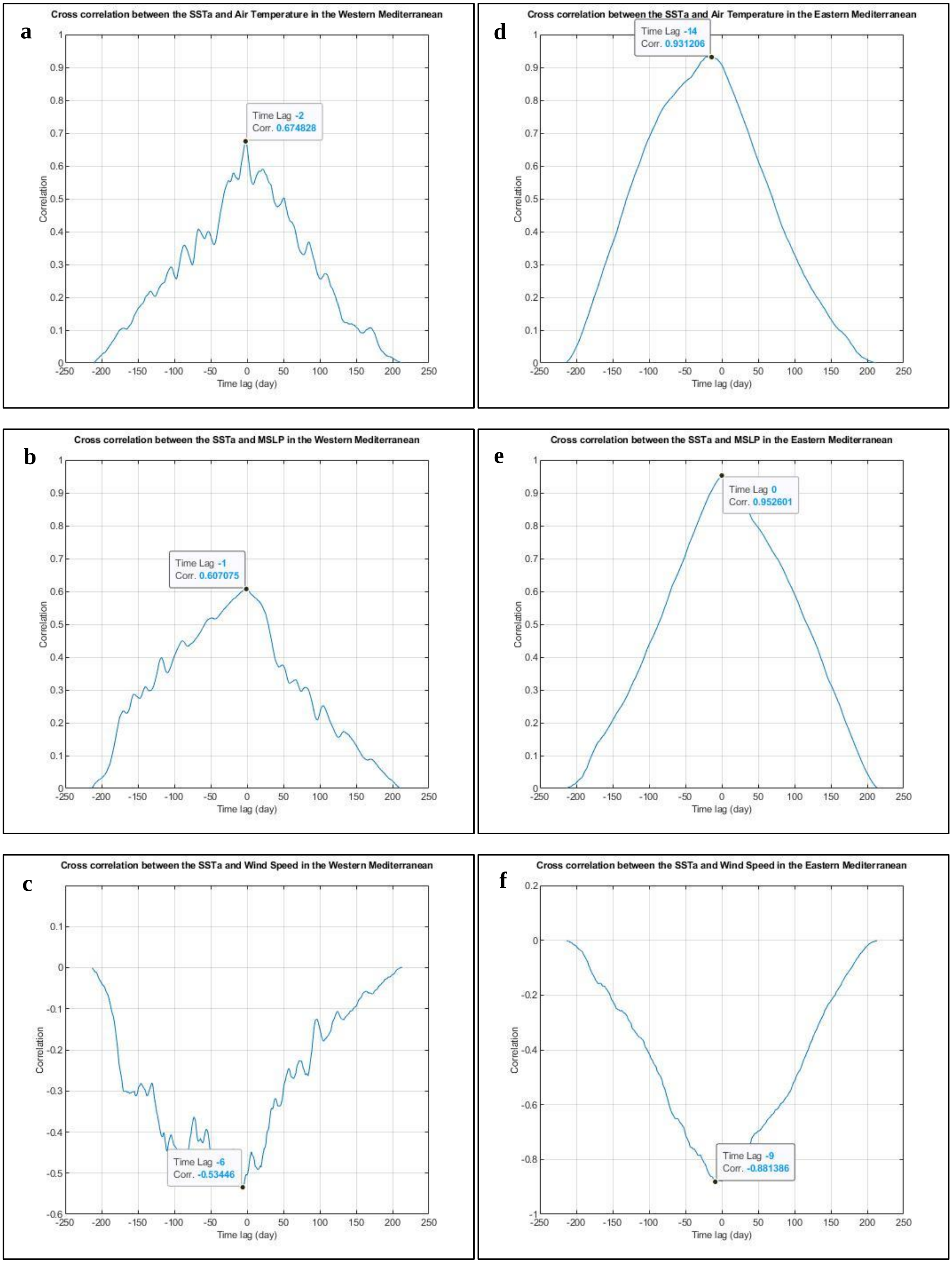

Figure 11. The cross correlation between the SSTa and the atmospheric variables during the study period for the western Mediterranean and eastern Mediterranean. The data labels are showing the time lag (in day) between the variables associated with the highest correlation.

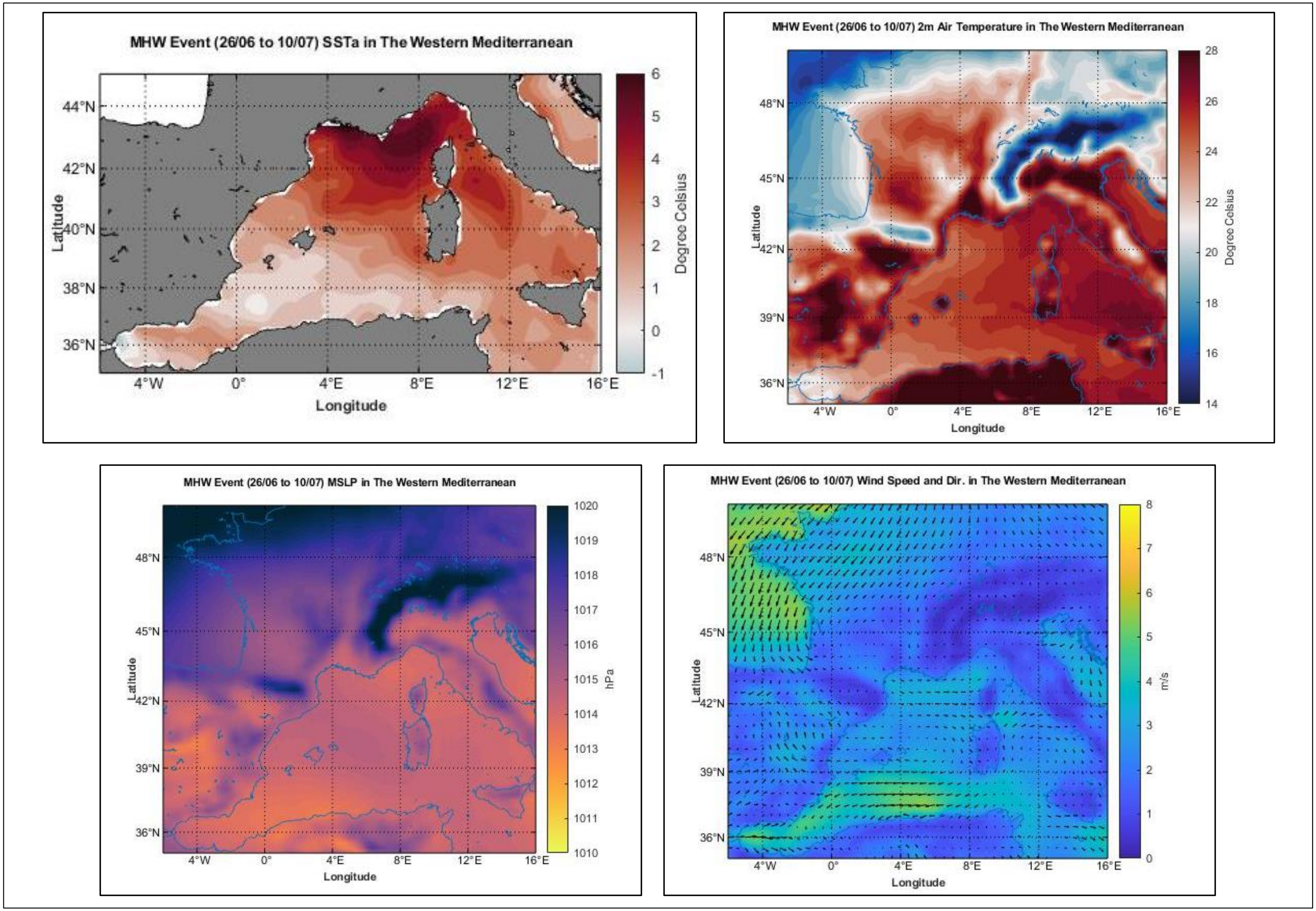

Figure 12. The Western Mediterranean strong MHW event (26/06 to 10/07) where, a) MHW mean SST anomaly °C, b) 2 m mean air temperature °C, c) mean sea level pressure in hPa, and d) wind speed and direction in m/s, based on ERA5 hourly data.

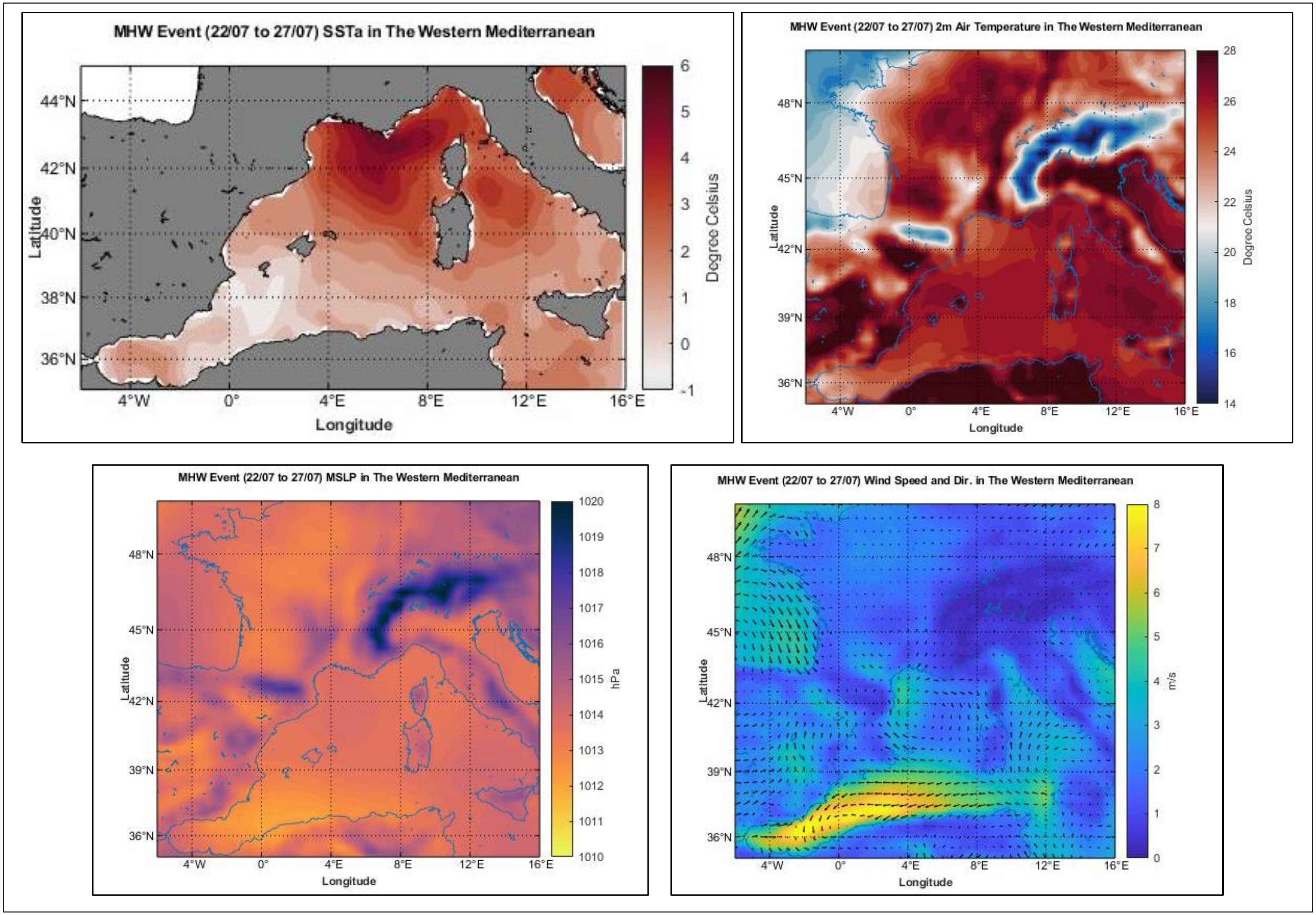

Figure 13. The Western Mediterranean strong MHW event (22/07 to 27/07) where, a) MHW mean SST anomaly °C, b) 2 m mean air temperature °C, c) mean sea level pressure in hPa, and d) wind speed and direction in m/s, based on ERA5 hourly data.

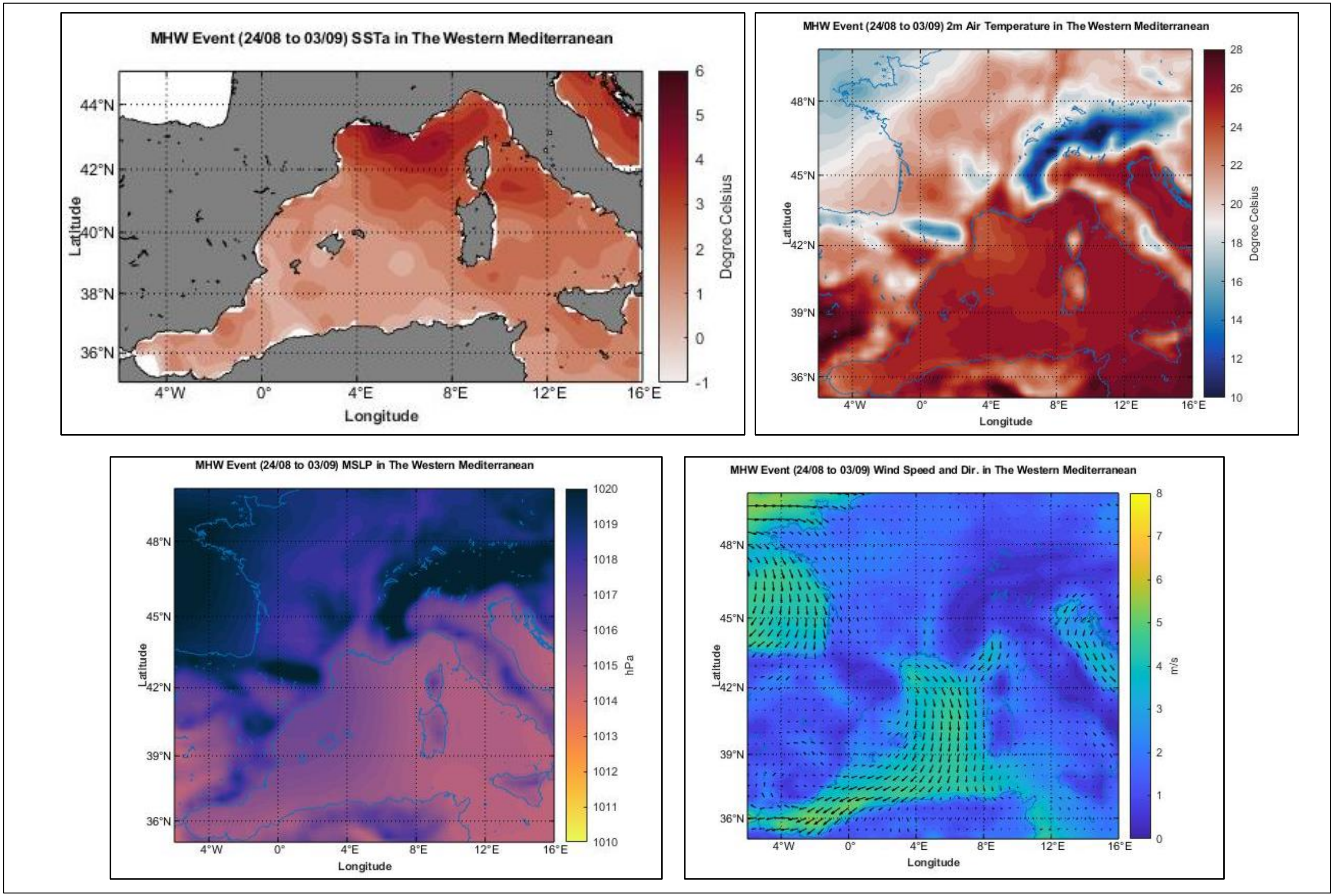

Figure 14. The Western Mediterranean strong MHW event (24/08 to 03/09) where, a) MHW mean SST anomaly °C, b) 2 m mean air temperature °C, c) mean sea level pressure in hPa, and d) wind speed and direction in m/s, based on ERA5 hourly data.

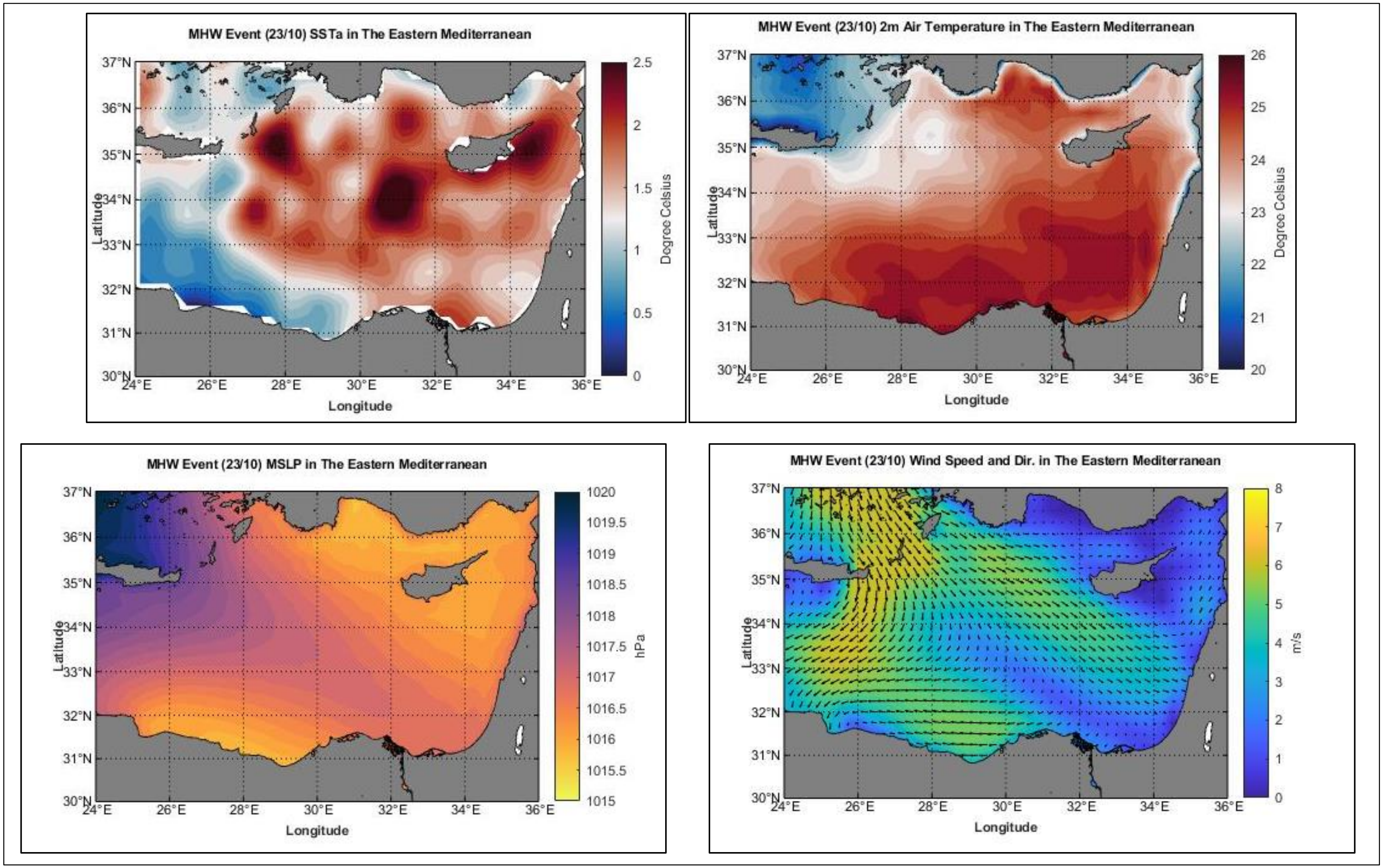

Figure 15. The Eastern Mediterranean strong MHW event (event peak day 23/10) where, a) MHW mean SST anomaly °C, b) 2 m mean air temperature °C, c) mean sea level pressure in hPa, and d) wind speed and direction in m/s, based on ERA5 hourly data.

4. Discussion

The Mediterranean Sea presents a typical behavior of a mid-latitude sea (Pastor et al., 2020; Pastor et al., 2018). The spatial variability of the SST in the Mediterranean Sea from June to December 2019, (Figure 4a), is showing that the recorded SST in the WMED is lower than its corresponding values in the EMED. In addition, by comparing the 2019 SST with the average SST over the climatology period (1982-2011), (Figure 4b), in the whole Mediterranean the 2019 SST is exceeding the climatological average during the study period. As a result, the sea surface temperature anomaly values for the period of study are positive over the whole Mediterranean Sea except in the Alboran Sea near to Gibraltar strait, the SSTa values were negative. The highest SSTa values were recorded in the eastern Mediterranean basin, the northern half of the western Mediterranean, and the Ionian Sea. While a low SSTa values, but also positive, were observed to the south of Italy and the Alboran Sea, (Figure 4c).

The hierarchical approach of defining an MHW, recently developed by Hobday et al., (2016), was used to detect the MHWs that occurred during summer 2019 in the Mediterranean Sea. The spatial distribution of the MHW characteristics over the study period has shown a dissimilarity between the MHWs in the eastern and western Mediterranean Sea, (Figure 6 a-d). More especially, the MHWs occurred more often in the WMED than in the EMED with higher intensities while the EMED marine heatwaves were observed to have a longer duration than the WMED marine heatwaves. These observations tally with the correlation test that was performed between the different metrics of the MHWs since a high inverse relation (r = -0.747) was found between the mean MHW count and duration.

After defining the marine heatwaves in the whole Mediterranean Sea, the MHW events that occurred at specific locations in the eastern and western basins during the study period were categorized in terms of their severity using Hobday et al., (2018) MHWs categorizing scheme, Figure (7 a-b). Six MHW events took place in the WMED basin between June and December 2019, three of those events were categorized as strong events, the SST exceeded twice the 90th percentile difference, while the rest of the events were categorized as moderate events. The first two strong MHW events which took place between 26/06 and 27/07, were synchronizing with the heatwaves that hit the central and western European regions between 24/06/2019 and 28/07/2019.

These European heatwaves were categorized as strong events and the air temperature observed during these events exceeded the record of the historical maximum daily mean temperature (Vautard et al., 2020). Furthermore, in the EMED basin, only two events were detected during the study period and both of them were categorized as strong events.

The total heat flux (Qi) anomaly was calculated in the western and eastern Mediterranean basin over the study period based on 30-years of climatology (1982 - 2011), Figure (8 a-b). Generally, the anomaly of the heat flux in the WMED ranged between -120 and 120 Watt/m^2, while its corresponding values in the EMED ranged between -30 and 70 Watt/m^2. This dissimilarity in the heat flux anomaly values between the eastern and western basins of the Mediterranean Sea could have resulted from the contrast in the SST between the two basins since it is known that the sea surface temperature in EMED is higher than the WMED, (Table 2). This assumption agrees with Song & Yu, (2017) who stated that the turbulent heat fluxes (latent heat and sensible heat) differ with the change of the physical parameters (e.g. SST, surface air temperature, humidity, and cloud fraction) which will certainly affect the total heat flux magnitude. In addition, Papadopoulos et al., (2012) reported that the difference in the heat fluxes in the western and eastern Mediterranean basins is mainly linked to the intra-basins SLP (the anomaly of sea level pressure (SLP) difference between South France (5E, 45N) and Levantine Sea (30E, 35N)).

Moreover, the total heat flux (Qi) anomaly associated with each MHW event at each location was calculated, (Table 3). In the WMED, during the first five recorded MHW events, the values of the calculated Qi anomaly were positive while it was negative during the last recorded MHW event. Furthermore, in the EMED the Qi anomaly associated with the first recorded event was negative while it was positive during the second recorded event. The positive heat flux anomaly indicates that the heat flux is downward towards the ocean and its magnitude is higher than the climatology average. In this case, it is believed that the high heat flux from the atmosphere to the ocean will lead to an increase in the SST to the limit which may cause an MHW which tallies with Schlegel et al., (2021) and Sen Gupta et al., (2020). On the other hand, the negative Qi anomaly indicates that is upward towards the atmosphere and the heat loss from the ocean is higher than the climatology average. Therefore, the air-sea flux could not cause the SST increase but the increase in SST induced the anomalous upward net-heat flux which agrees with Miyama et al., (2021).

In the WMED, during the normal situations, the MLD is fluctuating between 10m to 60m depth while in the EMED basin the MLD is deeper and ranges between 15m to 70m (D'Ortenzio et al., 2005). During the study period, the relation between the MLD and SST was investigated. A strong inverse correlation was found between the MLD and the SST during the MHW events. Moreover, it is observed that during the period of investigation the MLD in the WMED fluctuated between 12m and 55m while in the WMED it ranged from 11m to 65m which is shallower than the average in both sites. It is also noticed that during the strong events the MLD is not only shallower than the average but also steady, (Figure 9). In addition, at both WMED and EMED basins, the cross-correlation test revealed that the changes in the MLD are leading the changes in the SST by 2-days and 1-day, respectively, (Figure 10). In other words, the shoaling of the mixed layer is likely driving the SST to increase which may cause an MHW. This result tallies with Schlegel et al., (2021), who stated that the mixed layer depth (MLD) has a strong negative correlation with the onset of the MHWs, which means that the MLD could be used to predict the MHWs.

It is well known that, increasing of both air temperature and MSLP and decreasing of the wind variability and speed especially the strong and persistent winds like Mistral on the north-western Mediterranean and the Etesian winds in the Levantine basin which moderate the sea surface temperature in summer, will lead the SST to increase (Jiang et al., 2003; Shaltout & Omstedt, 2014; Pastor et al., 2018; El-Geziry, 2021). To understand how the atmospheric variables (air temperature, MSLP, and wind) can contribute to the occurrence of the extreme sea surface temperature anomaly in the Mediterranean Sea, the relation between the SSTa associated with the strong MHW events and the atmospheric variables were investigated, (Figures 12-15). An interesting relationship was found between them, generally, during the MHW events, the high SSTa was associated with high air temperature (> 25 ^{0}C), high MSLP (> 1014 hPa), and low to no wind shear at both sites. The high air temperature will lead to an increase in the SST. In addition, at both western and eastern Mediterranean basins, the cross-correlation (CC) was calculated between the SSTa and the atmospheric variables, (Figures 11). The result of the CC test showed that the changes in the atmospheric variables were leading the SSTa. Generally, it was observed that the correlation between the atmospheric variables and the SSTa is higher in the EMED than in the WMED. In the WMED basin, an inverse relationship was found between the wind and SSTa with a correlation equals to -0.534 with a time lag of 6-days. While there was a positive correlation between the MSLP and SSTa (r = 0.607) at time lag 1-day. At last, a direct correlation between the air temperature and the SSTa was observed (r = 0.674) with a time lag of 2-days. At the same time, in the EMED basin, the correlation between the wind and SSTa was negative (r = -0.88) with a time lag of 9-days, while a strong direct relationship has been found between both MSLP and air temperature with the SSTa at 0- and 13-days lag, respectively.

The dissimilarity in the correlation and time lag results between the western and eastern Mediterranean basins could be a result of the different nature of both basins moreover, it indicates the formation mechanism of the MHWs is also not the same at both sites. In conclusion, it is believed that the combination of high air temperature, high MSLP, and calm winds can lead to a high sea surface temperature anomaly and cause an MHW. This result matches with (Holbrook et al., 2019; Sen Gupta et al., 2020; Ibrahim et al., 2021).

From the foregoing results, the proposed scenario of the formation of the 2019 MHWs in the Mediterranean Sea is:

1- The weakening of the winds starts first over the area, several days before the MHW event starts, leading to the formation of a high-pressure system over the area.
2- The atmospheric high-pressure and low winds mean that the area under them will experience the same weather for a longer period during which the mixed layer gets shallower.
3- This raises the air temperature causing the SST to also increase and depending on the magnitude of this increment the SSTa will rise as well.
4- This can be seen in the air-sea heat flux anomaly. During some events, the anomaly is positive, the common case during the period of study, which means that the ocean surface is receiving heat from the atmosphere. At some other MHW events, the heat flux anomaly can be negative. This occurred only once at each basin during the study period, which means that the increase in SST induced an anomalous upward net-heat flux.

5. Conclusion

Using a consistent framework to identify and categorize the 2019 MHWs (Hobday et al., 2016; Hobday et al., 2018), the MHWs that occurred in the Mediterranean Sea between June and December 2019 were defined and categorized using the daily NOAA OISST data set and based on 30-year climatology (1982–2011) baseline. The Mediterranean Sea eastern and western basins have shown dissimilarities in the SST and SST anomaly distributions as well as in the characteristics of the MHW events that occurred in them. In the WMED basin, six events took place between June and December 2019 with maximum intensity fluctuating between 2.25 ^{o}C and 6.42 ^{o}C, and duration ranged from 5 to 20 days. At the same time, two MHW events were defined in the EMED with observed maximum intensities about 2.685 ^{o}C for both events and duration of 21 days and 159 days, respectively.

Different atmospheric and oceanic variables were studied to evaluate the drivers of the defined MHWs at both western and eastern Mediterranean basins. In agreement with Sen Gupta et al., (2020) and Schlegel et al., (2021), the strong MHWs occurrence (high event maximum intensity) was associated with high total heat flux anomaly. In addition, the highest SSTa of the MHW events were associated with high atmospheric temperatures, atmospheric high-pressure systems, weak wind speeds, and shallow mixed layer depth, which agrees with Holbrook et al., (2019) and Ibrahim et al., (2021).

For the future, I propose to study the Mediterranean Sea MHWs on a longer time scale in order to have a good idea about the temporal evolution of the MHWs in the region. Furthermore, I would like to investigate whether using different climatology baselines considering ocean warming will have a significant difference in defining and classifying the MHW events. It will be also interesting to investigate the anthropogenic factors that contribute to global warming and the increasing of the MHWs severity and frequency. Finally, it is very important to study how the extreme anomalous sea surface temperature events affect the Mediterranean ecology and biology.

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THE PRESENT RESEARCH WORK HAS BEEN (PREPARED TO BE) PUBLISHED IN:

This research is being prepared to be published in a peer-review journal (the journal is not yet decided).