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MASTER THESIS:

"A study on the interactions between the climate and the marine wind potential in the Mediterranean Sea"

Σωτηρίου Μαρία-Αλίκη

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Ευχαριστίες

Ολοκληρώνοντας αυτήν την μεταπτυχιακή εργασία, θα ήθελα να ευχαριστήσω την τριμελή επιτοπή μου.

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Table of Contents

List of Figures

Extended Abstract

In the present study, 42 years of data, covering the years from 1979 until 2020, is used in order to analyze the wind speed and the sea surface temperature characteristics in the Mediterranean basin. Their mean values, variability, and trend, as well as the relationship between them are examined in the monthly, annual and interannual time scales. The datasets used are obtained from the ERA5 reanalysis, a dynamical–physical coupled numerical model that produces climatic projections. The ERA5 reanalysis has been compared to alternative models for the accuracy of its results and has been proven to be the optimal to date. The datasets utilized are the vertical and horizontal wind speed at 10 m height from the surface, as well as the sea surface temperature.

Firstly, the Mediterranean Sea is examined for its properties, in order to set the background for the following analysis. The ways in which the Mediterranean basin and the climate interact are discussed, while taking into account the climatic indices (North Atlantic Oscillation, Southern Oscillation, ENSO, Mediterranean Oscillation, East Atlantic – West Russian). In the next chapters, the anthropogenic climate change, and its interaction with the wind potential in the Mediterranean area, is extensively discussed, as well as its roots and its effects on a global scale. Subsequently, the two variables under study, which are the wind speed and the sea surface temperature in the Mediterranean basin, are examined through a bibliographic review, for their seasonality and trends in the decades.

In the final part of this work, the numerical analysis of the variables is produced using Matlab coding. The long-term variability is assessed applying the mean annual and inter-annual variability for the two parameters. The mean annual sea surface temperature is found to increase southwards, while the mean annual wind speed is highest in the Gulf of Lion and the Aegean Sea. The highest mean annual and inter-annual variability are found in the northern part of the basin for both studied parameters. The mean annual correlation is found to be highest offshore Corsica and Sardinia Isl., where the inter-annual variability of both parameters also exhibited highest values. Finally, regarding the 99 quantiles, which indicate the trend for extreme events, the sea surface temperature has positive values in the northern and eastern parts of the basin, while the wind speed exhibits its highest values in the Adriatic, central Aegean and Ionian Seas and the southern Levantine basin.

Keywords: Mediterranean Sea, wind speed, wind potential, sea surface temperature, climate change, climatic indices

Περίληψη

Στην παρούσα μελέτη, χρησιμοποιούνται δεδομένα 42 ετών, που καλύπτουν τα έτη από το 1979 έως το 2020, προκειμένου να αναλυθεί η ταχύτητα του ανέμου και τα χαρακτηριστικά της θερμοκρασίας της επιφάνειας της θάλασσας στη λεκάνη της Μεσογείου. Οι μέσες τιμές, η μεταβλητότητα και η τάση τους, καθώς και η μεταξύ τους σχέση εξετάζονται στη μηνιαία, ετήσια και διαετήσια κλίμακα. Τα δεδομένα που χρησιμοποιούνται προέρχονται από το ERA5, ένα συζευγμένο αριθμητικό μοντέλο που παράγει κλιματικές προβλέψεις. Το ERA5 έχει συγκριθεί με εναλλακτικά μοντέλα για την ακρίβεια των αποτελεσμάτων που παράγει, κι έχει αποδειχθεί ότι είναι το βέλτιστη σήμερα. Τα δεδομένα που χρησιμοποιήθηκαν είναι η κατακόρυφη και οριζόντια ταχύτητα ανέμου σε ύψος 10 m από την επιφάνεια, καθώς κι η θερμοκρασία της επιφάνειας της θάλασσας.

Αρχικά, η Μεσόγειος Θάλασσα εξετάζεται για τις ιδιότητές της, προκειμένου να τεθεί το υπόβαθρο για την ανάλυση που ακολουθεί. Συζητούνται οι τρόποι με τους οποίους αλληλεπιδρούν η λεκάνη της Μεσογείου και το κλίμα, ενώ λαμβάνονται υπόψη και οι κλιματικοί δείκτες (North Atlantic Oscillation, Southern Oscillation, ENSO, Mediterranean Oscillation, East Atlantic – West Russian). Στα επόμενα κεφάλαια, συζητείται εκτενώς η ανθρωπογενής κλιματική αλλαγή και η αλληλεπίδρασή της με το αιολικό δυναμικό στην περιοχή της Μεσογείου, καθώς και οι ρίζες και οι επιπτώσεις της σε παγκόσμια κλίμακα. Στη συνέχεια, οι δύο υπό μελέτη μεταβλητές, που είναι η ταχύτητα του ανέμου και η θερμοκρασία της επιφάνειας της θάλασσας στη λεκάνη της Μεσογείου, εξετάζονται μέσω βιβλιογραφικής ανασκόπησης, για την εποχικότητα και τις τάσεις τους ανά τις δεκαετίες.

Στο τελευταίο μέρος αυτής της εργασίας, παράγεται η αριθμητική ανάλυση των μεταβλητών με χρήση κωδικοποίησης Matlab. Η μακροπρόθεσμη μεταβλητότητα αξιολογείται με την εφαρμογή της μέσης ετήσιας και διαχρονικής μεταβλητότητας για τις δύο παραμέτρους. Η μέση ετήσια θερμοκρασία της επιφάνειας της θάλασσας βρέθηκε να αυξάνεται προς τα νότια, ενώ η μέση ετήσια ταχύτητα ανέμου είναι υψηλότερη στον Κόλπο του Λέοντα και στο Αιγαίο Πέλαγος. Η υψηλότερη μέση ετήσια και διαχρονική μεταβλητότητα εντοπίζεται στο βόρειο τμήμα της λεκάνης και για τις δύο παραμέτρους που μελετήθηκαν. Η μέση ετήσια συσχέτιση βρέθηκε να είναι η υψηλότερη στην υπεράκτια περιοχή έξω από την Κορσική και τη Σαρδηνία, όπου η διαχρονική μεταβλητότητα και των δύο παραμέτρων παρουσίασε επίσης τις υψηλότερες

τιμές. Τέλος, όσον αφορά τα ποσοστά 99%, που σχετίζονται με την τάση για ακραία φαινόμενα, η θερμοκρασία της επιφάνειας της θάλασσας έχει θετικές τιμές στα βόρεια κι ανατολικά τμήματα της λεκάνης, ενώ η ταχύτητα του ανέμου παρουσιάζει τις υψηλότερες τιμές στην Αδριατική, στο κεντρικό Αιγαίο, στο Ιόνιο Πέλαγος και στη νότια Λεβαντίνη.

Λέξεις κλειδιά: Μεσόγειος Θάλασσα, ταχύτητα ανέμου, αιολικό δυναμικό, θερμοκρασία επιφάνειας της θάλασσας, κλιματική αλλαγή, κλιματικοί δείκτες

Thesis Scope & Delimitation

The objective of the present work is to study the wind potential and the sea surface temperature in the Mediterranean basin, as well as their interaction with the climate and its changes over time. The Mediterranean Sea is chosen as it constitutes an optimal location for climatology studies, since it is a climate change "hot-spot", where all potential changes are accumulated and therefore manifested in an intense way.

First purpose of the thesis is to review past and recent knowledge on the subjects of climate change, wind potential and sea surface temperature in the Mediterranean basin, in order to provide a clear image of the area under study and its wind potential, as well as of the parameters that will be investigated. The next objective is to statistically analyze and examine the variables over the 42-years of available data, using Matlab, and then to depict the results on the map of the area, in a comprehensive and clear manner, so that the findings are easy to understand. The explanation of the figures is also part of the thesis scope. The statistical analysis of the variables includes their mean annual and monthly values, their annual mean values, their correlation, mean annual variability, inter-annual variability, the annual mean values trends, as well as the mean annual trends for the 99 percentiles, which are related to the extreme phenomena of the area.

Thesis structure

The thesis is organized in five Chapters:

Chapter 1 contains the Introduction, which is in turn arranged into sections on the various fields of interest. Firstly, there is a description of the Mediterranean basin and its interactions, then there is a description of the climate of the area, and its variability and trends, and finally, the introduction is concluded with a review on the climate change, generally and in the studied area, its effects, and mitigation options. Chapter 2 contains the theoretical background, were a bibliographic review of the characteristics and behavior of the two studied parameters, namely the wind speed and the sea surface temperature, is presented. Chapter 3 contains the data and the methodology used for the analysis that follows. Chapter 4 contains the results, in the form of figures with the appropriate explanation. Chapter 5 contains the conclusion of the thesis.

1. Introduction

1.1. The Mediterranean Sea

The Mediterranean Sea stretches from west to east over about 4000 km from 6 W to 36 E, and from south to north, over 1500km between 30 and 46 N (*State of the Environment and Development in the Mediterranean (SoED) 2020*, 2021). With a surface of approximately 2.500.000km^2, and a length of 46.000 km it represents 0.8% of the total ocean surface and 0.3% of their volume (Azov, 1991). The natural borders separating the basin are the Strait of Gibraltar for the Atlantic Ocean, and the Dardanelles Strait with the Black Sea, while it can be mentally separated in eastern and western sub-basins by the Strait of Sicily.

Figure 1 The Mediterranean Sea and sub-basins (https://en.wikipedia.org/wiki/Mediterranean_Sea)

Though not an ocean, it holds an important role in climate and oceanographic studies. Historically, since the Mediterranean Sea has hosted many civilizations and was frequented by men since tens of millennia, its various phenomena and its circulation have been studied since antiquity. This scientific study has economic, social, environmental, and political attachments for most countries which face the Mediterranean. The Mediterranean Sea constitutes one of the first areas studied by oceanographers and one of the best sampled, because of its easy access. The first description was that of the Strait of Gibraltar, and how it functions, by J.S. Von Waitz in 1755 (Deacon, 1985).

The Mediterranean Sea is described to be a miniature ocean (Lacombe, 1971) (Bethoux and Gentili, 1999) and one can study there many phenomena present as well in the oceans of the globe, where it is significantly more difficult to study, such as deep convection (Leaman and Schott, 1990; Schott *et al.*, 1996; Mertens and Schott, 1998), convection on continuous plateaus (Bethoux *et al.*, 2002), passage of water masses in shallow straits (Vignudelli *et al.*, 2000; Stratford and Haines, 2002; Beranger, 2004), jet current and baroclinic instability (Millot, 1987, 2005), thermohaline circulation and interactions of water masses (Wüst, 1961), quasi-permanent eddies (Francisco Criado-Aldeanueva and Soto-Navarro, 2020; Estournel, Marsaleix and Ulses, 2021). The Mediterranean also presents different scales for the various interactions to take place, the basin, the sub-basins and the mesoscale (Robinson *et al.*, 2001).

Terrain and Winds

On a regional level, the surrounding relief influences the wind and the climate. Specifically, the mountains around the basin, block and constrain the wind, thus leading to the creation of local and regional wind systems Figure 2. Such wind systems are the Mistral and the Tramontane in France, the Bora in Italy, the Etesians in the Aegean Sea, and the Sirocco and they are important in their influence on the climate of the Mediterranean basin as well as the circulation of the Mediterranean Sea. The Mistral is a strong wind that originates in France and influences its Mediterranean coasts. It is severe and persistent, potentially dangerous, and it contributes in the development of high sea states in the region, while it cools the sea surface (Schott *et al.*, 1996; Jiang, Smith and Doyle, 2003). On Mistral days, the wind speed in the Gulf of Lion reaches 8-12 m/s (Obermann *et al.*, 2018). The Etesians are cool and dry winds, that blow intensely during July and August in the Aegean Sea (Metaxas and Bartzokas, 1994; Soukissian *et al.*, 2018). Under their influence, in the Aegean Strait, the wind speed can exceed 15 m/s, and the wind gusts may surpass the speed of 20–25 m/s (Kotroni, Lagouvardos and Lalas, 2001), even though it has been shown that both the frequency of the Etesians, and their speed decreases over time. Especially the wind speed has been shown to present a negative trend, and a study on a dataset of 31 years calculated a 1 m/s decrease (Poupkou *et al.*, 2011).

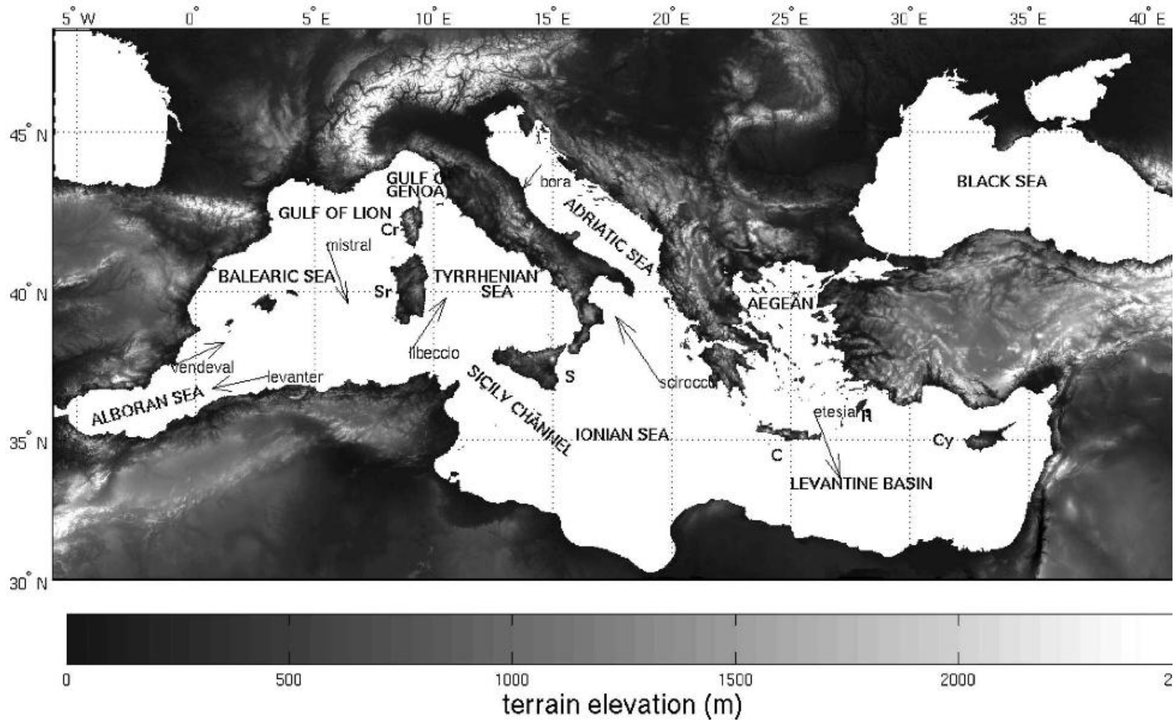


Figure 2 The Mediterranean Basin and its main winds. In Uppercase letters are the names of the main sub-basins (Zecchetto and De Biasio, 2007)

Rivers

The rivers that pour out in the Mediterranean Sea, especially the Nile, the Rhone, and Evros, impact the salinity of the basin, which accordingly affects the exchanges that occur with the climate. Their flow rate varies but is not negligible. Evros adds 200m^2/s of water which is distributed over the surface of the Aegean Sea, changing its salinity (https://el.wikipedia.org). The rate of the annual mean discharge, of the rivers combined, into the Mediterranean is 8.1 x 10^3 m^3/s (Struglia, Mariotti and Filograsso, 2003). What has generally impacted the inflow of the river water, is the construction of immense dams, over the years, such as the Egyptian Assouan dam. Skliris and Lascaratos in their work, indicate that the overall flows of rivers pouring into the Mediterranean have been reduced by 50%

over the last 150 years of the study, because of the commissioning of many dams (Skliris and Lascaratos, 2004).

It has been indicated by studies that there is a seasonal freshwater cycle, which leads to a deficit. The cycle fluctuates at around 600 mm/year, with a minimum during the month of May and a maximum in early autumn. The deficit has been calculated to be 680 ± 70 mm/year, over a long period, however in this case there appears a significant difference between the eastern and the western sub-basins, with the Eastern Mediterranean having 70% higher deficit due to less precipitation accompanied by higher evaporation (Criado-Aldeanueva, Soto-Navarro and García-Lafuente, 2012).

Figure 3 Schematic map of the Mediterranean showing different basins and main rivers flowing to the Mediterranean (Martinez-Ruiz et al., 2015)

Black Sea

The exchanges happening between the Black Sea and the Aegean Sea occur on two layers, with slightly saline waters entering the Aegean at the surface and more saline -thus heavier- waters leaving at the sub-surface (Yüce, 1996), therefore their results are often counted in with that of the rivers. It has been estimated for the Aegean Sea, that there is a supply of fresh water in the order of 6000 m^3/s (Tomczak and Godfrey, 1994). On a regional scale standpoint, the water that enters the Mediterranean from the Black Sea, which holds salinity between 24 and 28 psu, represents the equivalent of 1.7 m/year of fresh water deposited on the surface of the Aegean Sea (Zervakis, Drakopoulos and Georgakopoulos, 2000), which later gets divided on the Mediterranean surface. The flow from the rivers together with the Black Sea, is equivalent to 0.22 m/year (Tomczak and Godfrey, 1994) or 0.27 m/year (Bethoux, 1979) distributed over the surface of the Mediterranean.

Thermohline circulation

The Mediterranean Sea functions as a thermodynamic machine exchanging salt, water and heat with the Atlantic Ocean through the Strait of Gibraltar, which is 20 km wide at the narrowest point and 380 m depth at the shallowest point. Regardless its size, it allows the exchange between the two oceans by a current that runs in both directions. Thus, almost 1 Sv of warm (15.5°C) and salty (36.2 psu) water moves on the sea surface from the Atlantic to the Mediterranean, while colder (13°C) and saltier (38.4 psu), so heavier water, leaves the Mediterranean from the deeper layers. These exchanges lead to the Mediterranean gaining water and heat via Gibraltar Strait, from the Atlantic (Theocharis *et al.*, 1999; Curry, Dickson and Yashayaev, 2003; Potter and Lozier, 2004; F. Criado-Aldeanueva and Soto-Navarro, 2020).

The Mediterranean Sea is a concentration basin, since the thermodynamic exchanges described above transform the low-salinity water from the Atlantic into saline water in the Mediterranean basin, as water enters the basin from the surface and exits from the bottom. This function is possible when a flow of water equal or larger to the flow in Gibraltar, passes from the surface layer, through the thermocline, and enters the deep layer. Since the average precipitation and river runoff do not balance the average evaporation over the basin, this difference in salinity and temperature, produces a vertical circulation, the thermohaline circulation, which is an inflow of water from the Atlantic through the Strait of Gibraltar, in order to compensate for the deficit (Theocharis *et al.*, 1999).

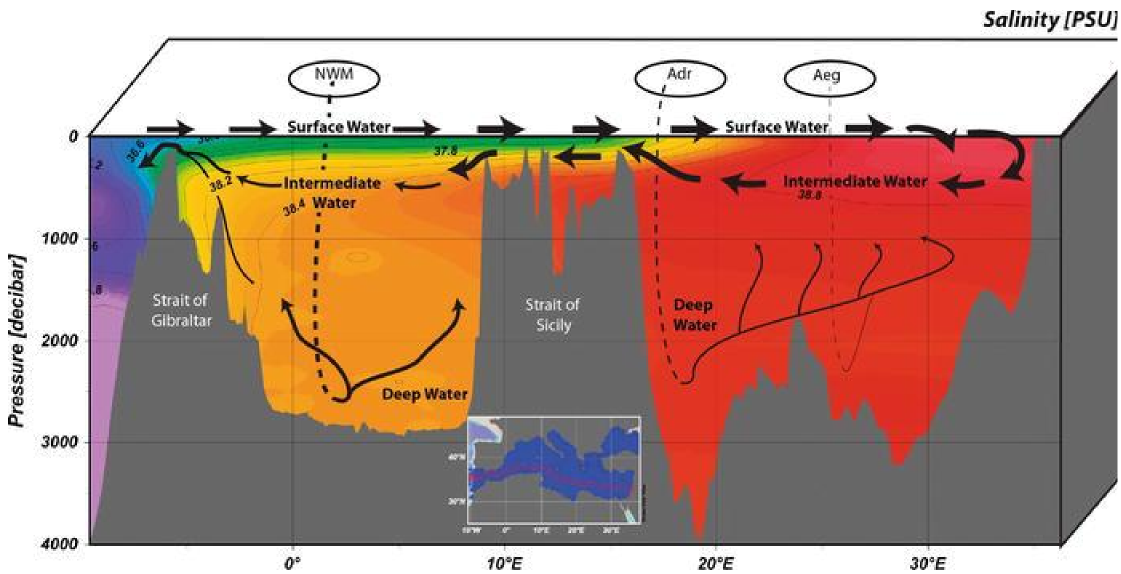


Figure 4 Mediterranean thermohaline circulation (MEDAR Group, 2022)

The way the Mediterranean Sea influences the basin environment can be properly understood by also considering the thermodynamic exchanges of water and heat. Accordingly, this information is important in any climatic studies in the area since the atmosphere and the ocean constitute a system.

1.2. The Mediterranean Sea's climate

The Mediterranean has been shown to have an influence on the global thermohaline circulation, due to its being a source of salt (Reid, 1979). Consequently, there is a repercussion on the climate through this process. The time during which water masses remain in the Mediterranean basin, is between 10 and 100 years depending on the mass, which is much lower than the equivalent time in the global ocean. This leads to the conclusion that the Mediterranean Sea can prove to be an indicator, and thus provide a quick way to locate climate anomalies that will later pass to the Atlantic, and the rest of the ocean (Bethoux, 1979).

Moreover, the Mediterranean surface is a source of heat and water for the atmosphere. It has been shown that the Mediterranean Sea influences the climate locally (Lebeaupin, Ducrocq and Giordani, 2006), and regionally, with its impact on Mediterranean cyclogenesis (Alpert, Neeman and Shay-El, 1990) (Barlan and Caillaud, 2004) but also over the entire northern hemisphere (Li, 2006), and can even influence the African monsoon (Fontaine *et al.*, 2002; Rowell, 2003). Any climate changes caused by the Mediterranean Sea surface temperature seem to propagate either by advection in low layers (export of heat and humidity), or by a modification of the Asian jet-stream which starts in northern Africa (Li, 2006).

Climatic Indices

On the subject of the impact of the major variability modes on the ocean variables in the Mediterranean, quite a few studies have been carried out. The atmospheric circulation does not follow a specific linearity, but is a chaotic system, in the sense that not two identical starting points can lead to the same state, after the same period. The atmospheric circulation has been found to be unpredictable over a two-week time frame (LORENZ, 1969). However, the study of the climatology takes place on longer timescales, and therefore can produce certain behaviors that lead to predictions. Using statistical methods, large scale atmospheric modes can be defined and quantified, in order to study any deviations from the characteristic spatial patterns they present over time. These modes influence the climate and weather of their respective regions of impact and can give information on the connection between the local climate and the general variability, using their indices as a numerical representation.

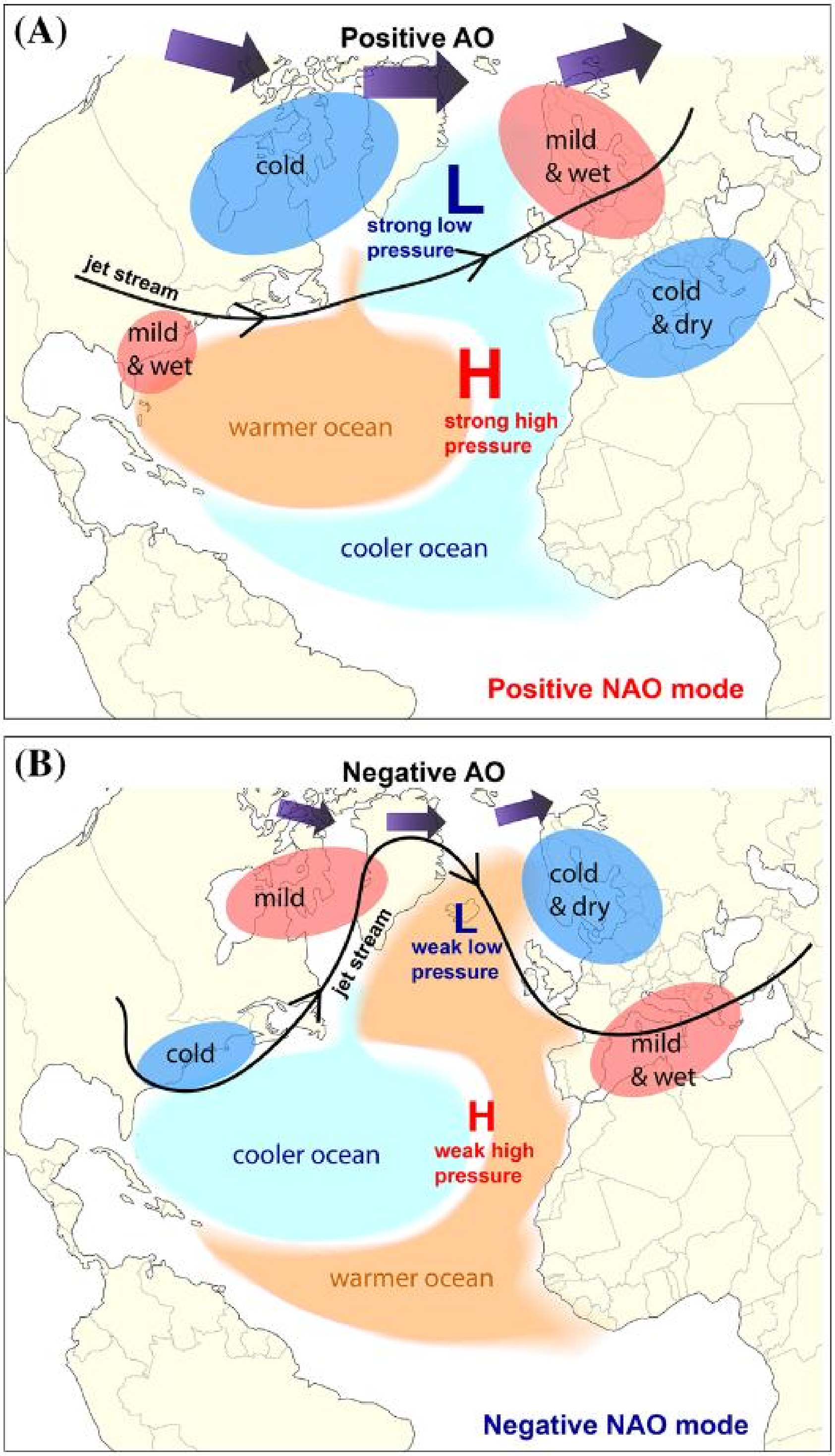


Figure 5 The North Atlantic Oscillation (Báez, Gimeno and Real, 2021)

The North Atlantic Oscillation is generally an important variability mode on a global scale and is the oldest known pattern to have been studied. Its influence expands from the eastern US coasts to Siberia, and from the subtropical Atlantic to the Arctic, with important atmospheric mass movements between the last two. The change between the two North Atlantic Oscillation phases, the positive and the negative, has serious impacts on the global climate, and consequently on society (Hurrel *et al.*, 2003; Martínez-Asensio *et al.*, 2014a). As for the climate of the Mediterranean basin, the indices can be utilized to examine and monitor the climatic variables on the long-term, and the modes that mostly influence this region are the North Atlantic Oscillation, the East Atlantic pattern, the East Atlantic– West Russian pattern, the Scandinavian pattern, and the Mediterranean Oscillation. Among these, the North Atlantic Oscillation, and the Mediterranean Oscillation, seem to have the most important impact. On the other hand, the Southern Oscillation seems to have little influence on the Mediterranean region, by itself, while the El Nino – Southern Oscillation pattern, has a more marked impact on the region, although not in a homogeneous way, since there are spatial differences in the impact exerted by La Nina. The areas that are mostly affected are found to be the Balkans, Eastern Spain and Turkey. The more extreme El Nino – Southern Oscillation phases impact a larger part of the basin, producing both humid and dry conditions, however, there still is a seasonal diversity. The conditions of drought are related to La Nina events, while El Nino creates humid conditions over the region (Xoplaki *et al*., 2021).

In contrast, the North Atlantic Oscillation, can explain and overlap with parts of the variability in Mediterranean Sea, especially during winter. When the positive North Atlantic Oscillation phase is in process, warmer conditions over the western sub-basin have been observed, with colder conditions over the eastern sub-basin. The opposite has been found to happen during negative NAO phases (Skliris *et al.*, 2011). The influence of the North Atlantic Oscillation has been studied widely: influence of the North Atlantic Oscillation on the Mediterranean depressions trajectory in winter and leading on wintertime rainfall (Ulbrich *et al.*, 1999) (Xoplaki *et al*., 2000, 2004), on atmospheric temperature and SST during winter (Trigo, Bigg and Davies, 2002), its influence on precipitation in autumn on the west (Valero *et al.*, 2004), on summer temperatures (Xoplaki *et al.*, 2003), on ocean-atmosphere fluxes over the Aegean Sea (Josey, 2003; Zervakis *et al.*, 2004), and on ocean-atmosphere fluxes in the west (Vignudelli *et al.*, 2000; Tsimplis and Josey, 2001; Rixen *et al.*, 2005). Other teleconnections have been found between the Mediterranean climate and the NAWA (North Africa - West Asia) (Paz, Tourre and Planton, 2003) and between the climate in the Mediterranean and the Indian monsoon (Raicich, Pinardi and Navarra, 2003).

The climate experienced a positive phase in the period from the 1960s to the 1990s, which was followed by a decrease in the Mediterranean Sea level. That was a period when the North Atlantic Oscillation also experienced a gradual increase through the decades 1970 and 1980, reaching a maximum during the late 1980s, and consequently decreasing to a low and negative phase (Skliris *et al.*, 2011). The positive phase is considered to have triggered a change in the flow of water from the Mediterranean basin. Effectively, more evaporation was measured, due to fewer depressions, and drier air. That led to less precipitation and smaller river flow, and in turn to a raise in surface salinity in the eastern basin. Generally, the positive North Atlantic Oscillation phase has been found to trigger negative anomalies in the Mediterranean evaporation, therefore reducing the latent heat losses (Francisco Criado-Aldeanueva and Soto-Navarro, 2020).

In a study on heat fluxes in the Mediterranean, it was found that the North Atlantic Oscillation had minimum impact, on both the entire basin, as well as on the sub-basins, with only 5 Wm^{-2}, which is relatively small, considering that the contribution of the East Atlantic pattern to the mode related heat anomalies, was of the order of 25 Wm^{-2}. The East Atlantic – West Russian pattern was shown to cancel out itself with opposite influences on the eastern and western sub-basins, which concluded to an exchange between the two, and a small overall budget. The climate modes have a strong influence on the Mediterranean Sea level, especially during winter, when the sea level fluctuation is three times larger, compared to summer. The way the North Atlantic Oscillation affects the sea level is twofold: firstly, by influencing the evaporation and the precipitation anomalies through the freshwater flux, and secondly by affecting the surface pressure. The result is a negative correlation between the North Atlantic Oscillation and the sea level, and as the pressure increases, the sea level decreases (Tsimplis and Josey, 2001). The Scandinavian pattern has been found to be positively correlated with the sea level changes (Martínez-Asensio *et al.*, 2014a).

The climatic modes also affect the thermosteric sea level, whose variance is smaller than the sea level’s but is still an important parameter. The thermosteric sea level changes as a result of the alterations in the ocean temperature, and its variability is larger during winter. The North Atlantic Oscillation has been shown to affect the thermosteric sea level mostly in the eastern sub-basin, while the Scandinavian pattern influences only 9% of the measured variability, there. The East Atlantic pattern affects strongly the western sub-basin by 17%, and the entire basin as well, by 49%. Finally, significant correlation with the East Atlantic – West Russian has been measured too (Martínez-Asensio *et al.*, 2014a).

Depression systems

The depressions originating in the Atlantic, influence the Mediterranean climate, either directly or due to their reactivation when passing over the Mediterranean Sea. The depression systems created in the Mediterranean or reaching the basin afterwards, are propagated through vorticity anomalies originating from the Atlantic depressions, while they are also influenced by the relief when they reach the coasts and the surface, which contributes to their route (Maheras *et al.*, 2001; Trigo, Bigg and Davies, 2002). These depressions passing over the Mediterranean, whether initially from the Atlantic or from the Mediterranean, are responsible for a significant part of the precipitation in the basin during fall, spring, and winter. Their variability during the course of a year is influenced by the North Atlantic Oscillation index, and it affects significantly the Mediterranean climate. Generally, on Mediterranean cyclone tracks, it has been found that the frequency of the cyclone tracks, decreases after the month of May, and tends to increase after October. Most eastern Mediterranean cyclones are created offshore Cyprus and in southeastern Aegean (Flocas *et al.*, 2010).

1.3. Variability and trends in the Mediterranean

Extreme events

The different forcings described in the Mediterranean basin lead to various extreme events. Episodes of drought, floods, extreme cold or hot, wildfires, landslides, and other destructive events, are increasingly common phenomena. Most studies indicate and remark that the extreme heat that has already been witnessed, is expected to increase. A study conducted in Greece, that focused on extreme climatic indices showed that there is a tendency for the Mediterranean climate to migrate towards a tropical future state. Every Greek city under study was found to have a positive temperature trend, a fact that is expected to lead towards a general environment that is warmer. The study also indicated the areas in Greece that are more vulnerable to climate change, as being Crete and western Greece. Crete is expected to have drier and also hotter conditions, while western Greece is already known to be prone to desertification conditions, with a rapid decrease of precipitation. The last 40 years, that gave data for these results, also indicated that the extreme events measured occur increasingly often and are more severe than before. The study concluded in a positive correlation between human activities and the emerging conditions (Καραβούλιας, 2020). However, a different study using extreme climate indices, showed that in the eastern Mediterranean basin the annual frost days also have an increasing trend (Kostopoulou and Jones, 2004).

More studies that have been completed on the issue of extreme events, come to similar conclusions for the entire Mediterranean basin. One such work, indicates that the area is expected to have "*extremely hot temperature events*", and the study remarks that during the past years there has been an increase in heat waves, both in frequency and in severity of results, as well as an increase in the temperature variability during summer. These events are expected to increase more intensely in the future (Diffenbaugh *et al.*, 2007). Similar results come from a different study, where the days of heat wave, are those when the 90% percentile of the maximum temperature of a particular area, is exceeded six days consecutively. The frequency of their occurrence is expected to increase to approximately to 40 days per summer, in the years 2071-2100, when in the period 1961-1990 it was 2 days per summer, in the Mediterranean basin (Fischer and Schär, 2010). The heat waves are therefore projected to happen more often, but also to be more intense (Giorgi, 2006; Fischer and Schär, 2010; Xoplaki *et al.*, 2021).

Studies present the summer of 2003 as an example to the dire results of the Mediterranean heat waves, since it was until recently the hottest recorded. The heat wave that occurred then, resulted in 40.000 deaths mostly from the western Mediterranean and Europe, with women aged 75 and more the most vulnerable target group (Garcia-Herrera *et al.*, 2010). In Portugal 5% of the country was burnt (Trigo, 2006), and since the majority of the European countries was heavily impacted, the total production was decreased by 30%. The losses from the agriculture due to the extremely dry and warm conditions that ensued, rose to billions of euros (Ciais *et al.*, 2005; Garcia-Herrera *et al.*, 2010).

Trends

The trends of different climatic parameters have been studied in the Mediterranean basin, in the decadal and multi-decadal scale, as they provide a link with the global warming and with any internal variability of the earth system that may contribute to the general climatic trends observed.

Concerning the droughts, a trend towards less precipitation is observed over the last decades, as a decrease in rainfall during the previous two decades over the Eastern Mediterranean, and especially Greece has been observed (Xoplaki *et al.*, 2000), while the precipitation trend has been linked to a cyclogenetic weakening in the Mediterranean (Trigo Isabel, Davies Trevor and Bigg Grant, 2000). Similar results have been obtained for the precipitation concerning the western basin (Valero *et al.*, 2004). A study has also observed a decrease in rainfall for Spain, Italy, Turkey, Israel and Cyprus, in the time span between 1951 and 1995. However, the observed decrease was accompanied by an increase in the number of heavier rainfalls over that period. The reason for this is that the decrease in the number of rainy days is followed by an increase in frequency and persistence of sub-tropical anticyclones over the Mediterranean (Alpert, Neeman and Shay-El, 1990).

A significant decrease in precipitation has been measured over the French Mediterranean coasts, for the end of the 20th century (Moisselin *et al.*, 2002). ERA15 reanalysis datasets have been utilized for the period from 1979 to 1993 in order to show a downward trend in rainfall over sea (Boukthir and Barnier, 2000). The coasts of Spain in the Mediterranean basin have been examined as well, and in the study the researchers concluded that there is a upwards, warming trend (Quereda Sala *et al.*, 2000). The provided explanation included the urbanization effect, which impacts the local climate heavily. However, the warming that was measured all over the basin and its coastal areas cannot only be attributed to the results of urbanization, since the anthropogenic climate has many effects. An issue that should be taken into account is the overlap with natural variability, that makes it harder to discern the signal of the anthropogenic change.

Concerning the deeper layers under the Mediterranean Sea surface, one study has shown the warming and salinization of the deep waters (>800m) in the West basin (Bethoux *et al.*, 1990). The respective average trends were found to be $3.47x10^{-3}$°C/year and $1.07x10^{-3}$ psu/year over the period of 1959-1997. Additionally, concerning the intermediate layer, the trends have been found to be between 6.8 and $9.1x10^{-3}$°C/year and between 1.8 and $1.9x10^{-3}$ psu/year (Bethoux and Gentili, 1999). The observed trends were attributed by the writers to climate change, while it was believed that they correspond to a heat loss lessening of the order of 1.74 W/m^2, together with an observed increase of 0.1 m in water deficit.

More studies have reported long-term warming and salinization in the Mediterranean waters. For the period between 1950 and 2000, there have been indications that there are long-term trends for deep water temperature and salinity increase, in the layers below 600 m. In the Western Mediterranean especially, it was calculated that there are trends for warming and salinization of the deep waters, of approximately $2.0x10^{-3}$°C/year and $1.0x10^{-3}$ psu/year, respectively. These trends were reported to be more marked in the last 15 years of the study. Conversely, the surface, and the intermediate layer (150-600 m) waters in the Eastern Mediterranean, were found to have a downward, cooling trend, after comparison between the years 1990-2000 and the years 1960-1970. Generally, for the 50 years of the study and for the entire basin, the authors noted an increase in heat content between 1.3 and $1.5x10^{21}$ J and in saline content between 1.4 and $1.6x10^{14}$ psu/m^3, which corresponds to anomalies of average temperature and salinity from 0.09 to 0.10°C and 0.035 to 0.04 psu (Rixen *et al.*, 2005).

The general sea surface temperature has also been studied. Relative research concluded that there appears to be a daily warming trend, that ranges from 0.009ºC/year to 0.06ºC/year. The measured increasing trend is also found to have spatial differences all over the basin. The highest warming, which was over 1.5°C occurred in the western basin, and more specifically in the Ligurian sea, as well as in the eastern basin, in the Levantine sub-basin (Pastor, Valiente and Khodayar, 2020). A different study concluded that there appears to be an increasing sea surface temperature trend during summer, of 0.056°C/year, and a decreasing trend in winter, of 0.029°C/year (Rayner *et al.*, 2006). The sea surface temperature is reviewed more extensively in Chapter 2.1.

A study on the sea surface temperature variability and trend in the Mediterranean produced the following graph for the Mediterranean and its sub-basins:

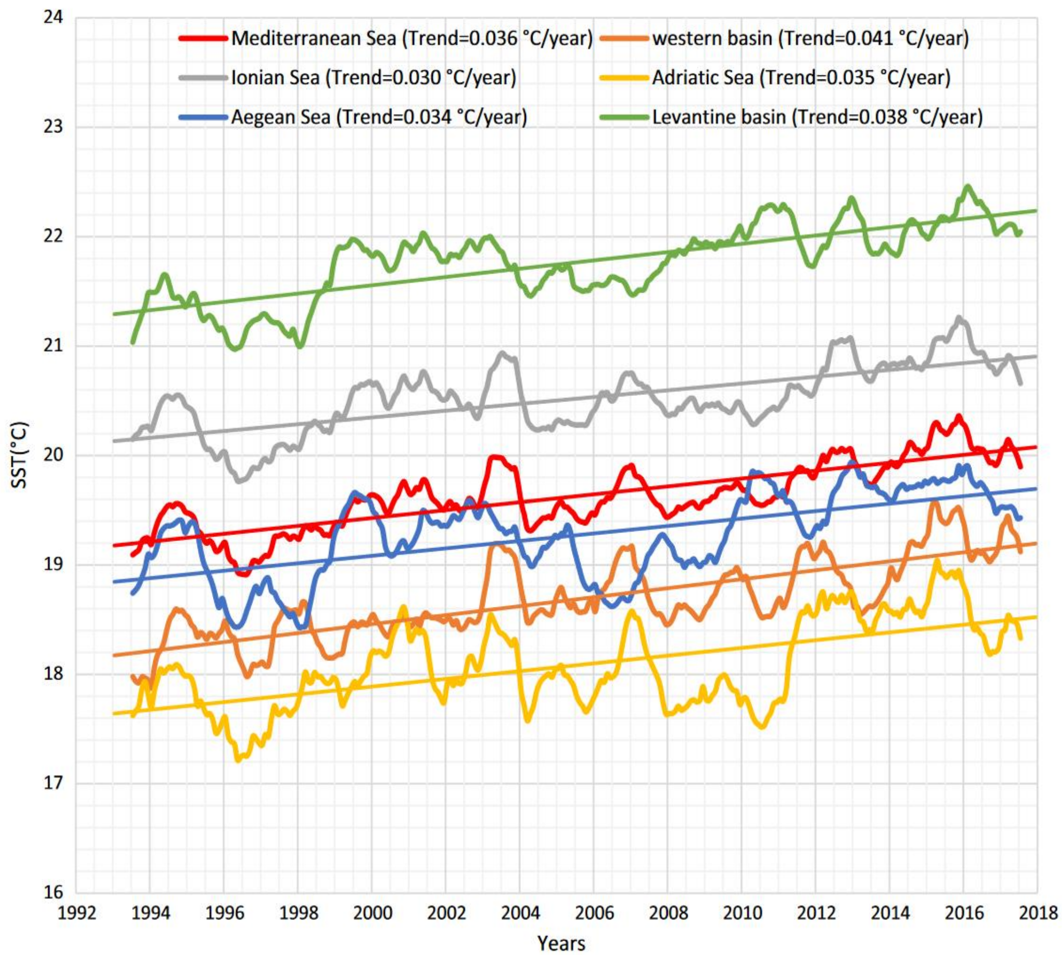


Figure 6 The deseasoned sea surface temperature time-series and linear trends for Mediterranean Sea and its sub-basins (Mohamed et al., 2019)

Among the different sub-basins, the highest trend is encountered in the western basin, in this study, while the highest mean in the Levantine sub-basin (Mohamed *et al.*, 2019).

Seasonal cycle

The seasonal cycle observed under the surface is the result of external forcings, atmosphere-water interactions, and the river and Atlantic runoff. Under this influence, the Mediterranean has a visible seasonality both on the surface, for the sea surface temperature and the water density, but also due to the transport straits (Vignudelli *et al.*, 2000; Beranger, 2004), the currents (Alhammoud *et al.*, 2005), and the phenomenon of deep convection. On the subject of vorticity fields, there has been a recorded seasonality in the Tyrrhenian Sea and the Levantine sub-basin, due to the surrounding orography. The wind interacts with the islands and exhibits high stress and vorticity values, as high as the values of the cyclones and anti-cyclones of the areas. The wind stress and vorticity is always increased there, however there is a seasonality related to the wind patterns of the Mistral and Etesian winds respectively, that affect with their seasonality the mean values of the wind fields (Zecchetto and De Biasio, 2007).

The sea surface temperature's seasonality has been extensively researched. The warming rate of autumn and winter has been found to be less than 0.02°C/year, while the highest warming rate has been measured during spring, with a rate of 0.065±0.012°C/year (Holbrook *et al.*, 2019). This is a result that coincides with the temperature seasonality, with cold winters, warmer springs, hot summers, and cooler autumns, as in the graph the follows:

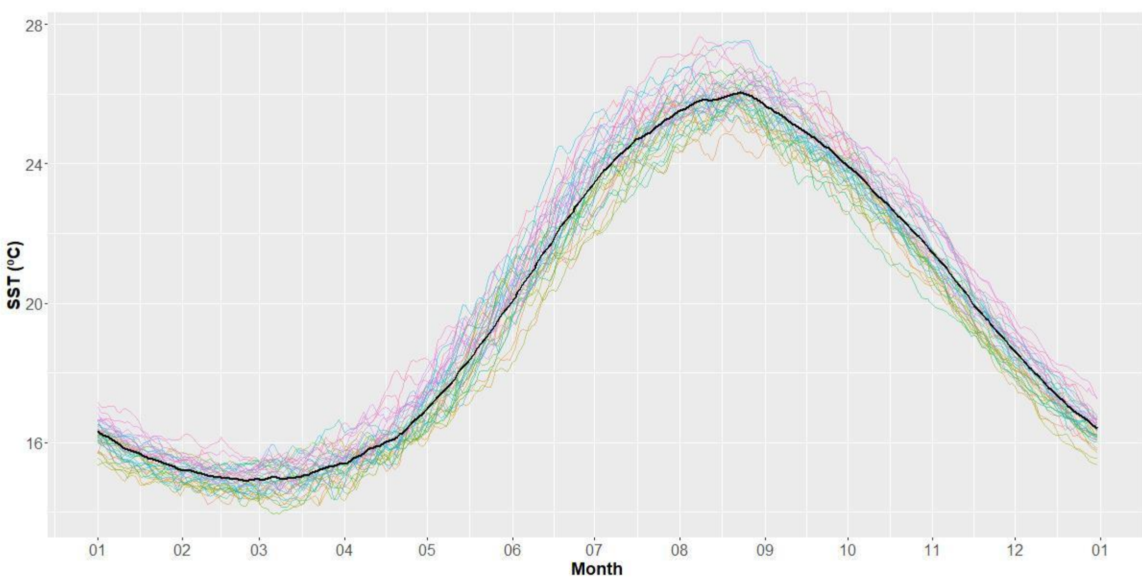


Figure 7 Annual cycle for the mean Mediterranean SST from 1982 to 2019. Each line represents a year in the study period, and the black solid line indicates the climatic mean (Pastor, Valiente and Khodayar, 2020)

A warming trend that is higher during spring and summer, than during autumn and winter was indicated in a study for the years between 1985 and 2008 (Pastor, Valiente and Palau, 2018). For the same period, the authors also found that the mean annual trend of the sea surface temperature had a seasonal variability in the entire basin, which ranged from 0.054°C/year in spring (MAM) and 0.044°C/year in summer (JJA), to 0.027°C/year in autumn (SON) and 0.023°C/year in winter (DJF). The seasonality appears to have trends as well, decreasing during the summer months and an increasing trend during winter, while no trend was observed during the rest of the year (Pisano *et al.*, 2020).

However, lately this established seasonality seems to present certain alterations in its cycle. On a global level, results of a different study show that the seasonal temperatures have shifted towards higher and more varied values. Especially over the northern hemisphere, during the decade 2005-2015 it was found that 80% of summers are warmer than average, and that the summer temperatures' distribution has shifted one standard deviation and more, since the period 1951-1980 (Hansen *et al.*, 2016). An analysis that was completed recently for the Mediterranean, presented a shift of the winter months to January, February and March, instead of the DJF season of December, January and February. At the same time, the summer months seem to be July, August, September, instead of JJA, which was June, July and August (Pastor, Valiente and Khodayar, 2020). Another study also indicated the existence of "ocean" seasons, with winter happening from January until April, spring from May to June, summer from July to October, and autumn from November to December. These seasons were defined after calculations of the heat storage in the Adriatic (Artegiani *et al.*, 1997).

1.4. Climate Change

Recent decades have seen an increase in the scientific world's engagement with climate change and its repercussions on life on Earth. The climate system consists of the atmosphere, the hydrosphere, the lithosphere, the cryosphere, and the biosphere, as well as the interactions between them, whose source is the solar radiation received by the system. The energy balance and any changes in the climate, is regulated by the amount of radiation it receives, absorbs, and reflects.

Solar energy is received by the climate system, and in order to retain the energy equilibrium, energy flows leave the system. The solar energy, after entering the system, is partly reflected by the atmosphere and the surface of the earth, and the rest gets absorbed by the system. Then, the surface and the atmosphere emit infrared radiation. However, the atmosphere absorbs and then re-emits back towards the earth's surface part of the infrared radiation emitted by it. Additionally to the emitted infrared radiation, the system has two heat fluxes, the sensible and the latent, from the surface to the atmosphere (Lindsey, 2009).

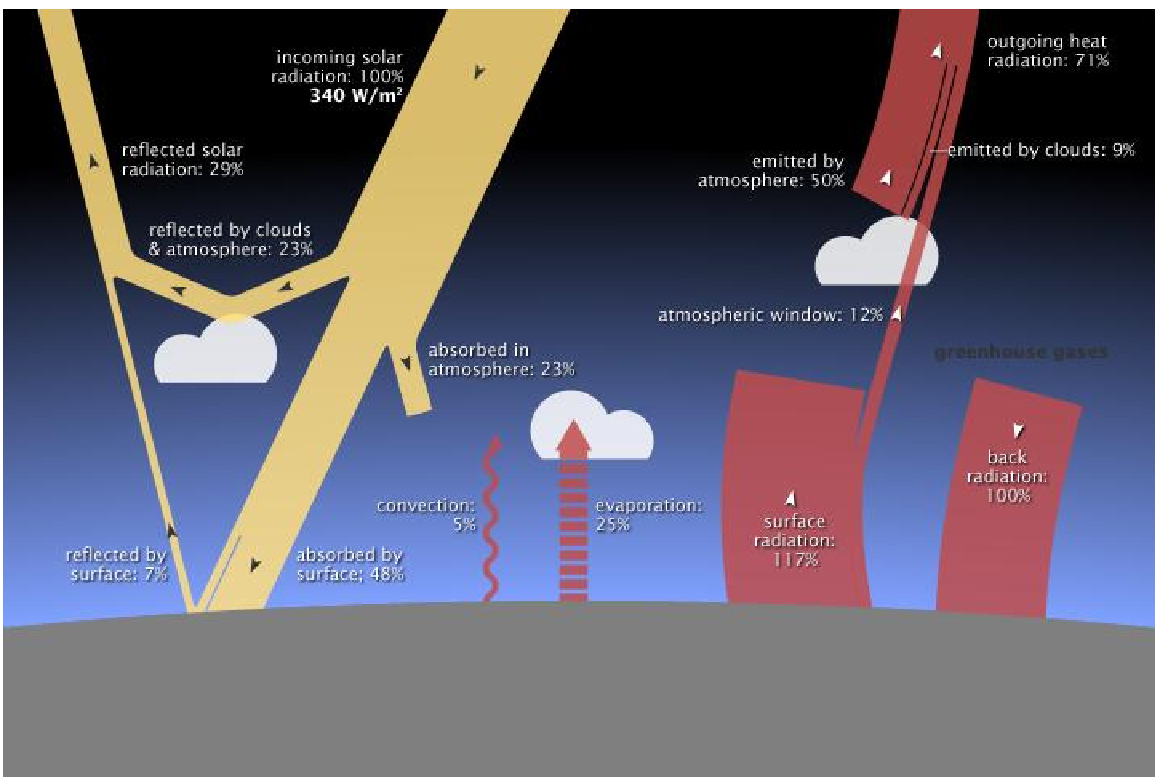


Figure 8 The Earth's energy budget (Lindsey, 2009)

The greenhouse effect, in its original form, is the natural phenomenon steadying earth's surface temperature at approximately 15°C, through the processes of solar radiation absorption, surface radiative forcing, and the properties of the atmosphere.

However, since the industrial revolution, the energy balance between the Sun, the Earth, and its atmosphere, has sustained a dramatic yearly change. From the middle of the 19th century, the new technologies that were developed gave the means to humanity to develop at an unprecedented speed, transforming the planet and the societies. Historically the economies evolved gradually towards mass production, in a process that took decades, but recent technological developments and the invention of the Internet have radically transformed this process. The fast growth has altered the economic and social structure with important consequences. A vital effect for the climate is the emissions of greenhouse gases into the atmosphere, significantly varying its composition and forcing it to store energy, due to human activities which therefore bring about the anthropogenic greenhouse effect and consequent climate change (Jain, 1993; Mikhaylov *et al.*, 2020).

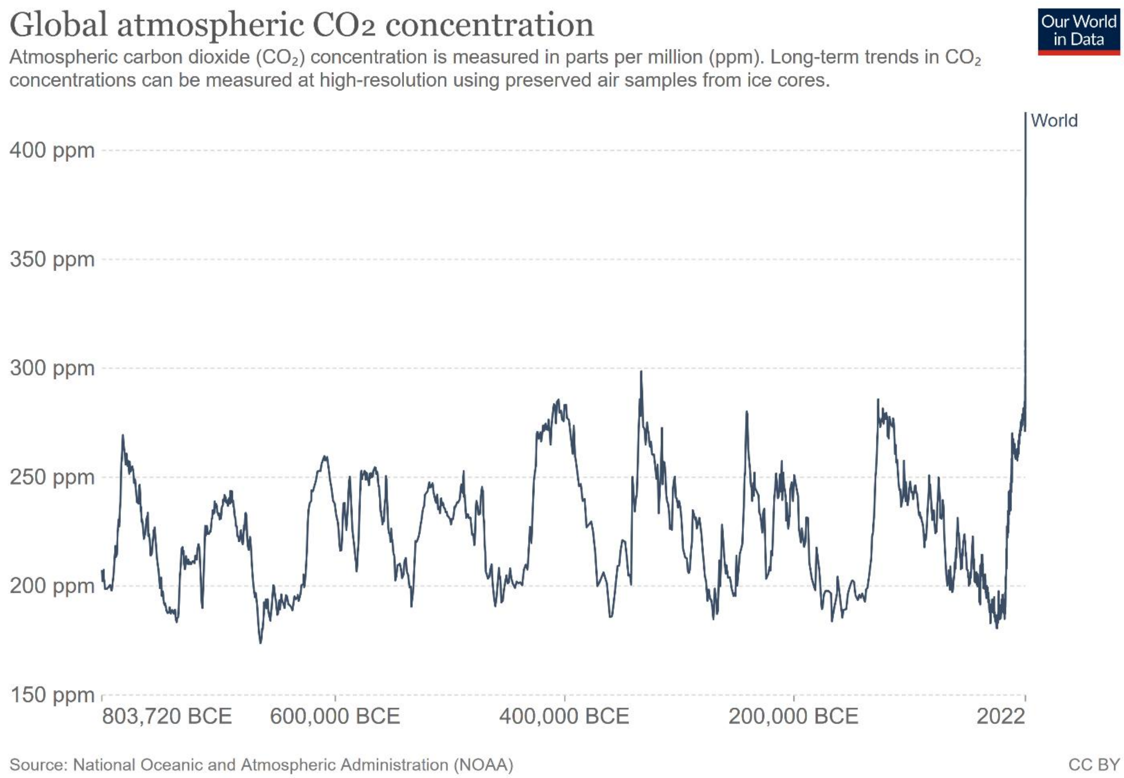


Figure 9 Global average concentrations of CO2 in the atmosphere over the past 800,000 years, source: https://ourworldindata.org

The imbalance produced by the increased greenhouses gases in the atmosphere causes the climate system to react, in order to restore the previous balance. One direct effect is the increase in the planet's temperature overall. The warming observed since the beginning of the 19th century is undoubtedly due to the increase in greenhouse gas emissions, as it is an unprecedented phenomenon for at least 1,400 years (Marcott *et al.*, 2013)(Masson-Delmotte *et al.*, 2013). The changed composition of the atmosphere, as part of the climatic system, leads to alterations in the atmospheric and oceanic circulations, the acidity level of the oceans, the hydrological cycle, the precipitation amount, and the sea level, and many more parameters. All these phenomena, which are directly related to human activities make up the anthropogenic climate change and are presented with further detail in the following chapters.

Greenhouse gases

As already mentioned, the greenhouse effect, is a natural phenomenon, where various atmospheric gases, the greenhouse gases, stabilize earth's temperature. The most important greenhouse gases are water vapor, carbon dioxide (CO_2) and methane (CH_4). An atmospheric component that has gained much attention lately are the aerosols, that have several effects. The direct parasol effect is the solar radiation scattering into the atmosphere, which cools the system. However, they also have indirect effects, which are mostly related to their interactions with the clouds, in more than one way. The aerosols accelerate the formation of clouds, when at the same time they reduce the drop size, thus increasing their reflective ability (Prather, Hatch and Grassian, 2008; France *et al.*, 2013).

The climate system feedbacks

The energy balance of the system gets destabilized by various factors, creating a radiative forcing (Hansen *et al.*, 1981), in which energy is added or subtracted from the system, which then tries to compensate the difference. When a radiative forcing takes place, there are multiple interactions between the system's components and different feedback mechanisms are used (Stocker and Schmittner, 1997; Forster and Rmaswamy, 2007). One response of the system is to modify its temperature, by managing the intensity of the infrared radiation emissions towards the space.

A negative feedback that the climate system has, is the increase of the infrared radiation from the surface to the atmosphere, when its temperature increases. On the other hand, a positive feedback is related to water vapor, during which the temperature increase leads to a rise in water vapor concentration, which as mentioned before is a main natural greenhouse gas, therefore reinforcing the original greenhouse effect. The ozone is another doubly affecting gas, since tropospheric ozone increases the forcing, while stratospheric ozone decreases it. However, even with the uncertainty from the aerosols, these interactions induce a negative radiative forcing. Different feedbacks take place over different time scales (Prather, Hatch and Grassian, 2008; Lohou and Patton, 2014).

Climate systems destabilizers

Natural factors

The imbalance created in the system originates also in the solar radiation fluctuations and the Earth's orbit. The intensity of the received radiation varies temporally due to the motion and orientation of the Earth in terms of the Sun position. The radiation emitted from the Sun also fluctuates, because of the appearance of sunspots, and other natural cycles of variability. The radiative forcing that has been measured since the middle of the 18th century because of solar cycles, is 0.05±0.05 W/m^2 (Myhre *et al.*, 2013).

Natural factors that disrupt the balance in the climate, exist also within the system, for example the volcanic eruptions which release sulfur dioxide changing the atmosphere's chemical composition. Volcanic eruptions occur in the system unpredictably and the response time is long and faceted (Jungclaus *et al.*, 2010; Miller *et al.*, 2012). Together with the sulfur dioxide, the eruption releases also carbon dioxide, but the amount is less important to the one released through anthropogenic activities, by 100 times (Gerlach, 2011). Contrarily, the particles of the sulfuric acid generate a negative radiative forcing because they reflect partly the solar radiation back into space. The released ash particles also have the same result, and together they can cool the system rapidly, as has been witnessed during recent eruptions like Mount Pinatubo (Philippines, 1991) which produced an approximately -5 W/m^2 radiative forcing (Minnis *et al.*, 1993; Stenchikov *et al.*, 1998).

The human factor

Today, the most important factor affecting the Earth's energy budget is humanity, especially since the industrial revolution. After the 1850, humanity's activities modified the composition of the atmosphere and intensified the greenhouse effect by emitting aerosols and greenhouses gases, in order to sustain the technological process. The carbon dioxide concentration in the atmosphere today, has been increased by 40% compared to 1750 levels (Hartmann *et al.*, 2013). The human influence on the climate however extends to the rest of the system, especially through land use, which alters the surface albedo and its reflective ability, and the presence of vegetation. Especially when it comes to the vegetation the effects are vital, since there are changes in the carbon storage and the evaporation process (Douville *et al.*, 2002; Zampieri *et al.*, 2009)(Shukla and Mintz, 1982).

Therefore, the human induced radiative forcing is very complex. It has been calculated that the radiative forcing of the anthropogenic greenhouse gases was 2.3 W/m^2 until 2011. Figure 10 illustrates the increase of the greenhouse gases since the middle of the 20th century. The planet's radiative ability depends on its temperature which rose 0.85°C between 1880 and 2012, with almost all the earth exhibiting warming, as there has been an increase in the number of hot days and nights and a decrease in the number of cold days and nights is very likely (Hartmann *et al.*, 2013).

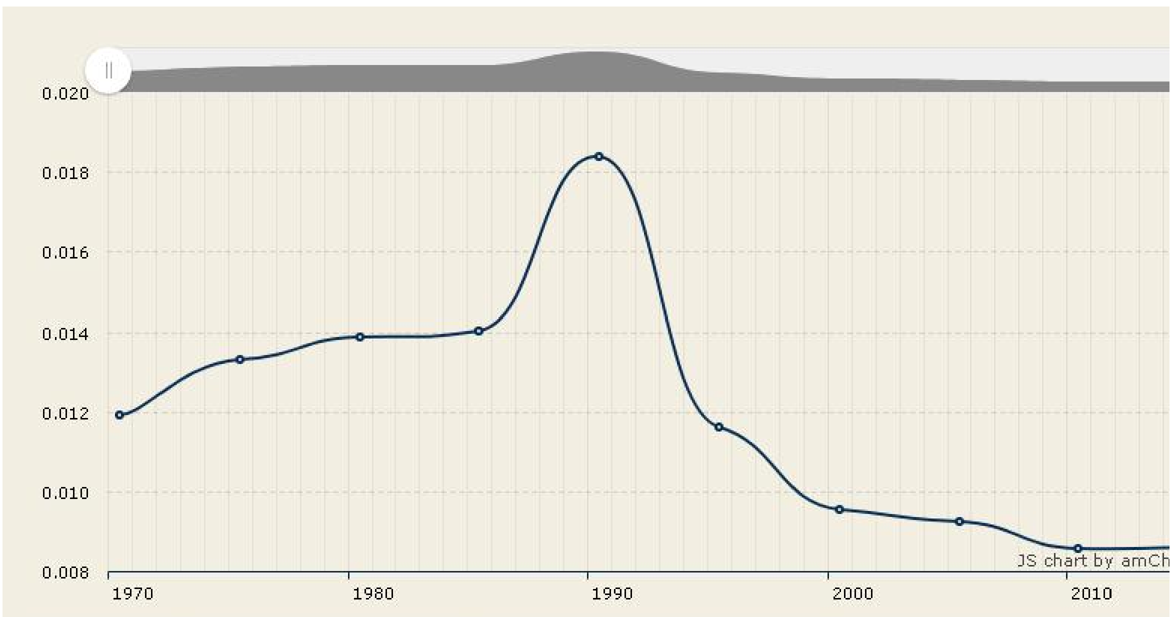


Figure 10 Total greenhouse gas emissions (European Environment Agency, https://www.eea.europa.eu/data-and-maps/data/greenhouse-gas-emission-projections-for-6)

The Mediterranean Sea as a climate change "hot-spot"

The Mediterranean Sea is considered to be a climate change "hot spot", due to the reported variations in atmospheric temperature, sea surface temperature, but mostly precipitation. According to a study that calculated a Regional Climate Change Index (RCCI), and applied it to 26 regions, comparing their climate change responsiveness, the Mediterranean Sea emerged as the region most indicative of climate change, along with northeastern Europe (Giorgi, 2006; Tuel and Eltahir, 2020). Consequently, in the context of climate change, the Mediterranean Sea is expected to have increased temperatures, especially during the daytime hours and summertime, with an increased rate compared to the global rates, of 20% and 50% respectively (Lionello and Scarascia, 2018). This result is considered robust enough, for the more intense rise of temperature to be expected (Kirtman *et al.*, 2013).

Climate change results

In the previous chapters some of the possible results that we expect in the future from the anthropogenic climate change have been analyzed, like the extreme events frequency, the alterations in the seasonality and water circulation, the sea temperature increase, and the sea level rise. These are the better-known climate change outcomes, but more negative effects have been mentioned in the various projections about future outcomes. In the event that no measure for emission mitigation is undertaken throughout the 21st century, it is shown that the global temperature will continue to increase, although not in a uniform fashion throughout the globe, and an increasing contrast between regions and seasons is expected. In any case, the continental ice will continue to melt which will lead to a continuation of the ocean warming and the sea level increase, that may have destructive results for the island and coastal populations (Collins and Knutti, 2013). The rise of the sea level is not only a direct result of the melting ocean and continental ice, but also of the thermal expansion of the oceans, and while during the 20^{th} century the rate of the increase was 1.7 cm / decade, during the period between 1990 and 2010 the rate increased to 3.2 cm / decade (Asutosh *et al.*, 2020). The sea level is expected to rise between 30 and 80 centimeters, from the level it held during the period 1986-2005 (Church and Clark, 2013).

An eminent issue that will alter the greenhouse gases' quantities is the ice sheets melting at the polar areas, after which there can be no return to the previous state, and the impacts will be uncontrollable, since apart from the sea level rise the melting would release carbon dioxide and methane, two greenhouse gases that were captured in the ice and sealed for centuries (Raynaud *et al.*, 1993). Another addition to the greenhouse gases, may occur as well from the permafrost melting, which was mentioned before, and which also holds significant amounts of gases (Van Gameren, Weikmans and Zaccai, 2014).

More such disruptive effects than can be expected are the extensive loss of the ozone layer, the increased wildfires, the salinization of aquifers, the permafrost melting, the frequency increase of tropical hurricanes and cyclones, which are expected to become commonplace, the floodings and the modification of the distribution areas of diseases, and many more that are will not be mentioned in this work, as they are not as relevant. A complete catalogue of the adverse effects would not be possible (Quratulann *et al.*, 2021).

Ocean acidification

The ocean acidification is another eminent issue that humanity should address. The global ocean acts as a carbon sink and therefore has a major impact on stabilizing the planet's climate system and on minimising the changes that occur. This fact is known since the 1950's from various sources of evidence. There have been observations for the increase in the dissolved inorganic carbon in the ocean (Gruber, Landschutzer and Lovenduski, 2019), and the uptake of anthropogenic carbon dioxide emissions has also been measured and found to be approximately one quarter of the total amount emitted. The problem that this process creates is that the additional carbon that is incorporated by the ocean leads to its acidification. The sea water has lately turned towards a more acidic nature with lower pH, which affects the marine organisms promoting damage to coral reefs and algae, and alters the sea water properties (Hönisch *et al.*, 2012; Doney *et al.*, 2020).

Climatic zones displacement & biodiversity threat

The way to analyze and examine the climate system is more than one. The most common approach is to assess any climate change from a fixed time in the past and quantify the differentiations thereafter. A different approach would be to spatially analyze it. That would require to set some areas of the planet that have similar climatic conditions, and consequently to track how these areas change as they move (the conditions move) across the planet, following the new conditions that the anthropogenic climate change creates. Also, one would need to track not only the direction but also the velocity of the movement, and correlate those to the known anthropogenic climate forcings.

The ecosystems are known to move according to conditions in order to adapt and survive. This ecosystem spatial velocity is tracked for a specified area and includes the speed and orientation that an ecosystem acquires in order to advance towards similar climatic conditions as before, since these are necessary for its survival. More than a decade ago, a study succeeded in showcasing the fact that in the last decades the ecosystems move, following the anthropogenic climate change, by examining 1.700 species whose movements were correlated to the local climates (Parmesan and Yohe, 2003). The resulting conclusion was that the ecosystems indeed progress in order to adapt to change and survive, but what was not yet certain was whether they move fast enough to succeed. What has been the case lately, is that humanity has witnessed the extinction of many species of flora and fauna, which easily leads to the reasoning that climate change does endanger biodiversity and ecosystems, as they cannot adapt as fast as the climate transforms. Studies have proven the above reasoning, also claiming that the climate change's ecological consequences have to be minimized to preserve as much as possible the global environment. Otherwise the new conditions might have dramatic effects on all aspects of society, which relies on ecosystems (Chapin *et al.*, 2000; Dawson *et al.*, 2011; Dobrowski *et al.*, 2013).

Moreover, one study on the same subject proved that the ecosystem movements occur because of temperature changes and not because of precipitation (Mahlstein *et al.*, 2011). The climate zone movement that has been tracked, consists of a vertical movement towards higher altitudes and a horizontal movement towards the poles, and since antiquity this movements happened at maximum rate of approximately 17 kilometers/decade (Chen *et al.*, 2011). The directions of climatic zone movements lead to the conclusion that some climate zones will eventually disappear, as they move towards the poles.

In the case of climatic zone disappearance, the ecosystems that live in them will disappear as well, since they cannot survive in different conditions, and there is a direct link between the disappearing ecosystems, and the threats to biodiversity and species. The polar and the mountainous ecosystems are the ones that are affected firstly (Nogués-Bravo *et al.*, 2007). Adding to the ecosystem threat by the climate, is the threat by the land use alterations, which endangers biodiversity even more, as crops and pastures become more extensive (Ordonez *et al*., 2014). It has been estimated that a percentage between 10 to 48% of climatic zones will disappear before 2100, and new climatic zones will appear starting from the tropical areas (Williams *et al*., 2007). The oceans suffer less warming than the continental areas, mostly due to higher thermal content potential, but even so the movement of the climatic zones seems to be faster over the ocean in some latitudes, and the areas with the fastest climatic zone movements coincide with the areas that are richer in biodiversity (Burrows *et al*., 2011).

Speed of change

What the modeling data and results seem to indicate, is that while the natural climate change has been a progressive phenomenon, the anthropogenic climate change may happen in ruptures, rather than in a smooth fashion (O'Neill and Oppenheimer, 2004; Klein *et al*., 2015), while the warming during the last millennium has never been as rapid as it is nowadays (Smith *et al*., 2015).

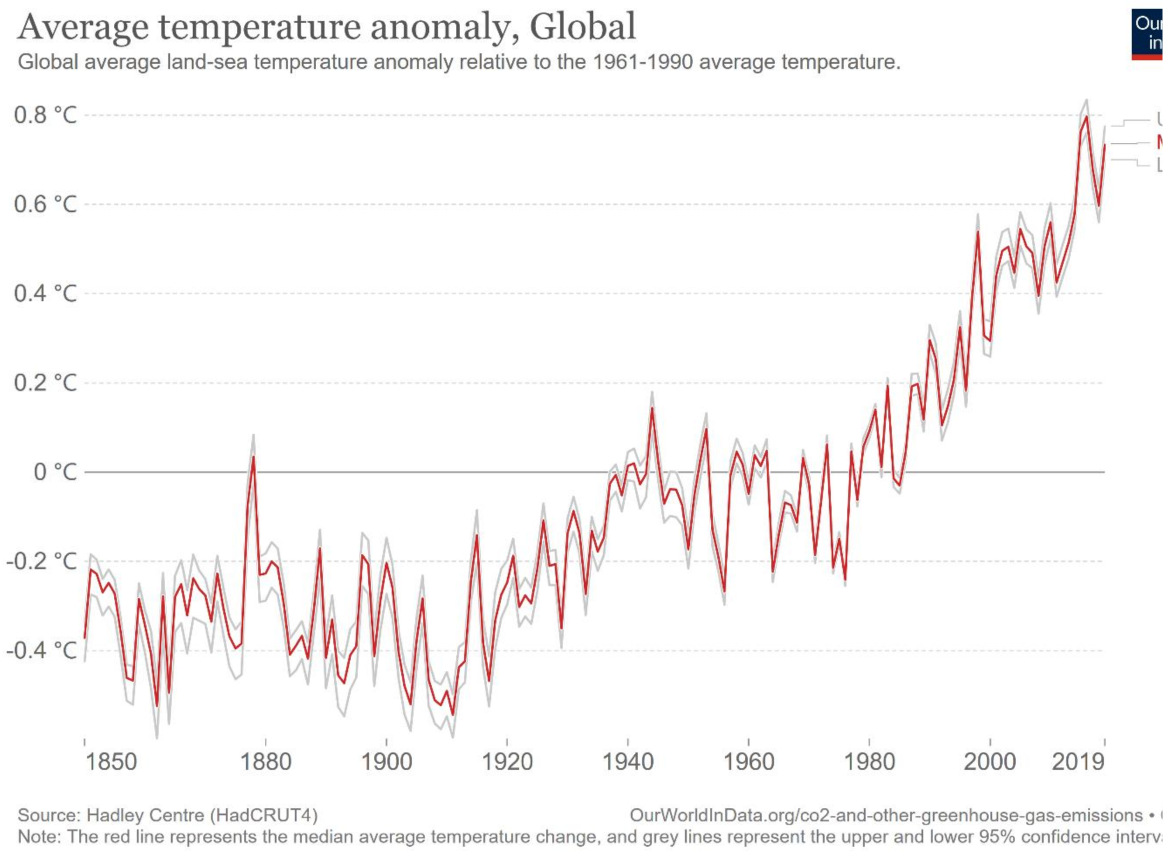


Figure 11 Average annual temperature trend through time, with upper and lower confidence intervals shown in light grey, source: https://ourworldindata.org

This difference is obvious from the previous Figure 11 where the temperature anomaly since the second phase of the industrial revolution begun is shown. Considering the temperature as a climate change indicator, one can see from the figure that the last decades have altered the climate more drastically than before, indicating the climate change acceleration.

1.5. Mitigation & Adaptation

In the context of policies and political and societal discussions on the climate change issue, what is usually encountered are the mitigation measures, and mostly the reduction of greenhouse gas emissions per country, as the way to combat the eminent threats. The term adaptation is not as usual in contrast, and it is more vague than mitigation, which has in fact specific goals and plans of action. One difference between the two, is that while mitigation includes every emitting country in its measures - regardless of the lack of homogeneity on technological progress, economies, populations and more – adaptation is more targeted, both on the issue to be solved, and on the subject that creates the issue. Additionally, mitigation requires action and effort, when adaptation happens intuitively, as it occurs for the ecosystems, albeit on various levels at the same time, through synergies and trade-offs ('IPCC Synthesis Report', 2014).

Both mitigation and adaptation, exist as part of a strategic plan to avert the climate change consequences. Any plan and course of action, however, relies on the results of the climate models, which hold a level of inaccuracy in their projections of the future outcomes, and this averts major investments in adaptation and mitigation measures, since there is real possibility of failure. Moreover, the climatic conditions, on which most efforts seem to be focused, are but one aspect of the general problem of the societies' vulnerability to climate change, with other dimensions being economy, culture, and the globalization. Adaptation implementation, together with mitigation actions, will prove critical in order to reduce the risk from climate change until any mitigation measure affects positively the conditions.

In Europe, adaptation measures have been deemed as "no regret", meaning that no matter the final climatic conditions, there can be no harm in implementing adaptation measures. The current European goal set by the European Parliament, several Member States, and 300 cities, is to be climate neutral by 2050, and reduce emissions by at least 55% by 2030, compared to 1990. European decision-makers take into consideration the adaptation process, and the European Green Deal, which is the strategy for sustainability and adaptation. The Climate-ADAPT platform is another tool for information and knowledge on the concept of adaptation, that can help the localized actions, since adaptation is a more local issue, as already mentioned. Investments and policies are expected to be "*climate-informed*" with efforts being made towards more data on losses from climate disasters. The Member States will need to report on their adaptation actions and policies to the Governance of the Energy Union and Climate Action, in an effort to confirm Europe-wide participation in the adaptation strategies in place (European Commission, 2021).

IPCC & RCPs

Modeling of the climate system makes it possible to study its evolution from the past, and to project its future conditions given possible behaviors adopted by society, mainly the amount of greenhouse gas and aerosol emissions, and mitigation actions. Most climate projections evaluate any changes by comparison between the estimated future state with a fixed reference at the beginning of the industrial era. That way, it is projected that no mitigation measures can avert the likely increase of the global temperature by at least 1.5°C from the beginning of the 19th century by the end of the 21st century (Collins and Knutti, 2013), while actually, extreme temperature events are very likely to multiply (International Panel on Climate Change, 2012).

The IPCC was founded in 1988 by the United Nations Environmental Program Committee, the United Nations General Assembly, and the World Meteorological Organization (WMO) and constitutes an important international institution for the assessment of climate change. It is an intergovernmental institution in the sense that any member state of the United Nations can participate, and it provides information on the current state of knowledge on climate change, which is scientific based, and its conclusions can potentially impact the environmental policies, the economy, and the society in general. The information provided by the published reports produced from IPCC reach and can affect decision-makers. The target is to both adapt to the new conditions and to mitigate future change. Its reports examine and evaluate the available social, scientific, and technical information on climate change, also considering the economic perspective. Scientists from different countries of the world participate in the reports voluntarily to produce an objective and inclusive report on the issue. The IPCC reports are published every few years and they are separated into Working Groups, with WG1 stating current knowledge on climate change, WG2 reporting the conclusions drawn, and WG3 suggesting possible mitigation measures (https://www.ipcc.ch/).

According to the IPCC and its Sixth Assessment Report (AR6), released in 2018, *it is unequivocal that human influence has warmed the atmosphere, ocean and land.* The IPCC brings together relevant scientists in order to study the aforementioned subject, make projections about future outcomes, and suggest potential solutions. According to their Summary for Policymakers, since 1750 the greenhouse gases have increased disproportionately, and each decade is warmer than the last. In fact 2011–2020 is 1.09ºC higher than 1850–1900, with 1.07ºC of it *likely* caused by human activities (IPCC, 2021).

As mentioned, another vital role of the IPCC is the release of future climate projections, namely the Representative Concentration Pathways (RCP), which are structured after general circulation scenarios that present different possible outcomes, until the final projection year, which is 2100. Those outcomes are a result of different greenhouse gas emissions, forest biomass, and atmospheric circulations, and are presented as different possible trajectories to follow. Any possible climatic development is dependent on all potential socioeconomic changes, the progress in technology, the energy consumption, likely land use alterations, and other factors that participate in the greenhouse gas emissions and climate pollution. These different parameters are used as the input variables in the climate model simulations, so as to examine their developing impacts and explore possible mitigation options.

The scenarios were built through interdisciplinary dialogue and their development required the collaboration of different modeling techniques and scientific domains, such as economic modeling, climate system modeling and anthropogenic emission modelling. The constructing process of IPCC reports, consist of reviewing scientific literature and selecting the relevant climatic, economic, political, and demographic information. The result was different scenarios, from which four were chosen as the most accurate for the depiction of the current state given the existing literature and are related to different changes in greenhouse gas concentration (International Panel on Climate Change, 2012).

The four main RCPs are distinguished by the radiative forcing level that each expects (8.5, 6, 4.5 and 2.6 W/m^2), by the end of the century compared to the pre-industrial levels:

— The RCP8.5 scenario, is the one with the highest greenhouse gases emissions, while it also assumes a relatively high population growth, relatively low-income growth, a mediocre rate of technological progress and intensive energy production. Moreover, this scenario includes no energy-demand decrease, and no mitigation policies from the states. RCP8.5 assumes that no changes towards a more sustainable future are followed by the human population. The result on the sea surface temperature, predicted by this scenario is a rise in global sea surface temperature of 1.5°C by 2050, and 3.2°C by 2100, compared to 1870–1899 temperatures (Genner, Freer and Rutterford, 2017).

— The RCP6.0 scenario takes into account a higher technological process and relative state intervention concerning mitigation policies, with emission limits for countries, and for industries. The greenhouse gas emissions are expected to peak in 2040, after which they begin to decrease, for the radiative forcing to remain below 6 W/m^2.

— The RCP4.5 scenario, expects an anthropogenic radiative forcing of 4.5 W/m^2 by the end of the 21st century, and a stabilization of the anthropogenic emissions earlier in the century. For this radiative forcing to not be exceeded the scenario includes some measures taken towards the application of carbon capture technology, of low-emission energy generation technologies, and also the development of geological carbon storage. In addition to the steps taken in technology progress, the scenario involves alterations in land use, such as forest expansion, with global forests mass becoming more extensive than it is today, in this scenario (Thomson *et al.*, 2010).

— The RCP2.6 scenario, aimed at limiting the global warming below 2°C and it expected a radiative forcing below 2.6 W/m^2 by 2100. It could potentially have been realized only under the condition that humanity lowered its carbon emissions, so that they declined after a peak in 2020. The steps that would need to be taken to reach this goal were overly demanding for our unprepared societies, with rapid advancements in carbon storage technology, increase in the use of renewable energy and intensive reforestation, all steps leading to a 70% reduction in emissions, with the joined effort and participations from all the countries. This pathway predicted a rise in global sea surface temperature of

0.8°C by 2050, and 1.2°C by 2100, compared to 1870–1899 (Genner, Freer and Rutterford, 2017)

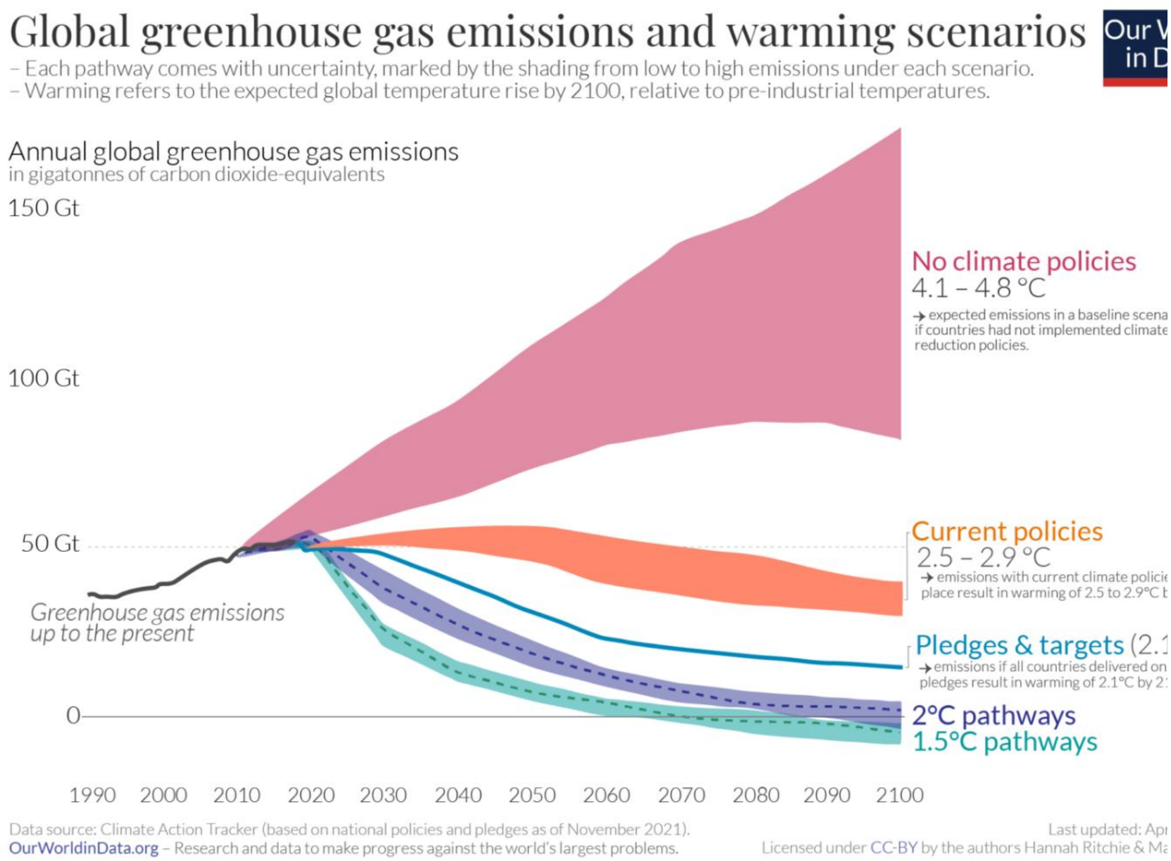


Figure 12 The four main RCPs and the temperature rise until 2100, source: https://ourworldindata.org

Regarding the population growth, the RCP scenarios consider the population growth projections of the United Nations (see Figure 13). The last three RCPs follow the medium UN scenario, concerning the population, by which the population is expected to reach 9.7 billion in 2050 and 10.4 billion in 2100 (*World Population Prospects 2022*, 2022). The RCP8.5 differs in this respect, as it takes into account a higher rate of population growth, together with the lowest income projections for the developing countries.

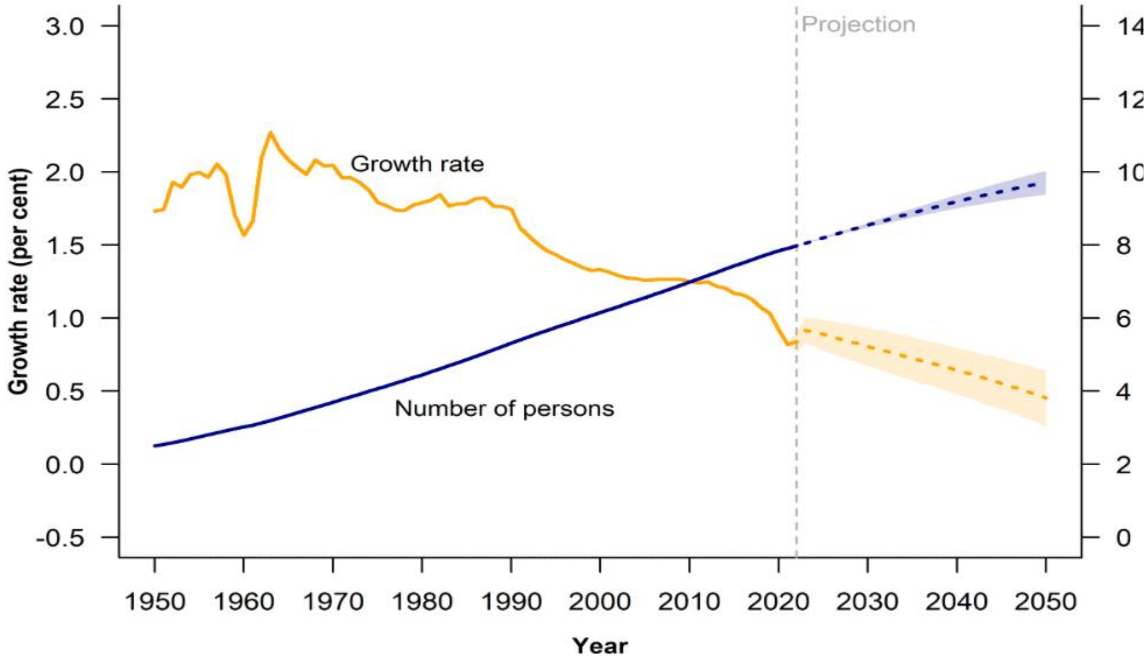


Figure 13 Global population size and annual growth rate: estimates, 1950-2022, and medium scenario with 95 per cent prediction intervals, 2022-2050 (*World Population Prospects 2022*, 2022)

In terms of energy use, the last three scenarios include some form of mitigation measures, while RCP8.5 considers intensive energy consumption, which is attributed mostly to the higher growth of the population. All the scenarios expect increased fossil fuel use for energy production, but the last three also include carbon capture technology, and it is the intensity of carbon capture that allowed in RCP2.6 such a low radiative forcing by 2100. Land use also plays an important part in the trajectories. In RCP8.5, one of the reasons for its high radiative forcing is the fact that the agriculture expands and takes up more space globally, instead of forest mass that can capture more carbon. The crops are shown to increase also in the other scenarios, even in RCP2.6. RCP6.0 depicts a decrease in pastures at the same time with an increase in crops (Moss *et al.*, 2010; Thomson *et al.*, 2010; Riahi *et al.*, 2011; Vuuren *et al.*, 2011).

Sustainable Development Goals

In 2015, the United Nations General Assembly, set up 17 Sustainable Development Goals (SDGs), that are conceived as guidelines to be followed by the UN Member States, in order to become more sustainable and ecology-forward, by 2030 (https://sdgs.un.org/goals). Those otherwise called Global Goals, are "a universal call to action to end poverty, protect the planet and ensure that all people enjoy peace and prosperity" (https://www.undp.org).

The 17 Goals are:

1.No poverty

2.Zero hunger

3.Good health and well being

4.Quality education

5.Gender equality

6.Clean water and sanitation

7.Affordable and clean energy

8.Decent work and economic growth

9.Industry, innovation, and infrastructure

10.Reduced inequalities

11.Sustainable cities and communities

12.Responsible consumption and production

13.Climate action

14.Life below water

15.Life on land

16.Peace, justice, and strong institutions

17.Partnerships for the goals

The goals are interconnected, which means that often the success of one, needs the success of others to be accomplished. The UN provides support to governments for them to integrate the SDGs into their national development plans and policies. Achieving the SDGs requires the partnership of governments, the private sector, civil society, and citizens alike (https://www.undp.org). The SDGs cover all aspects of life on Earth, and number 7 specifically references energy: "*Ensure access to affordable, reliable, sustainable and modern energy for all*". This SDG also calls for renewable energy sources to gain a larger share in the nations' energy mixes, more importantly for the heating and transportation sectors, those being the most vital greenhouse gas emitters.

Following the Paris Agreement which was adopted by 196 Parties, in 2015, the countries involved committed to the binding agreement of reducing their greenhouses gas emissions as soon as possible, in an effort to keep global warming at 1.5ºC (not more than 2ºC), compared to pre-industrial levels (International Renewable Energy Agency, 2018) (https://unfccc.int). This amendment should work complementary with the SDG on energy, but with only 16% of the global energy mix coming from renewable energy sources in 2019 (https://ourworldindata.org/energy-mix), the 2ºC goal seems unattainable.

1.6. Renewable energy

Since the main cause of climate change is the release in the atmosphere of CO_2 and other greenhouses gases, the last decade has seen renewable energy sources emerge as a viable solution for the future, in the sense that they can provide cleaner energy, in terms of greenhouses gas emissions (McGowan, 1991). The effort to keep fossil fuel burning to a minimum would not only help in minimising the extent of anthropogenic climate change, but would also tackle another eminent issue, that is the future lack of fossil fuels due to overuse (Adua, Zhang and Clark, 2021). Current calculations suggest that we have numbered years of fossil fuel burning left, specifically 114 for coal, 53 for natural gas, and 51 for oil Figure 14. Especially for the Mediterranean Sea, and its islands, renewable energy sources can prove invaluable, for multiple reasons: their steadily decreasing prices as the technologies mature, the difficulty of many of the islands to get connected to the national grid on the mainland, and the high energy potential those sources have there (Vara *et al.*, 2020). Particularly for wind energy, with its high yield and technology maturity, more extensive use of this source can prove essential in the effort to improve the energy status of these areas.

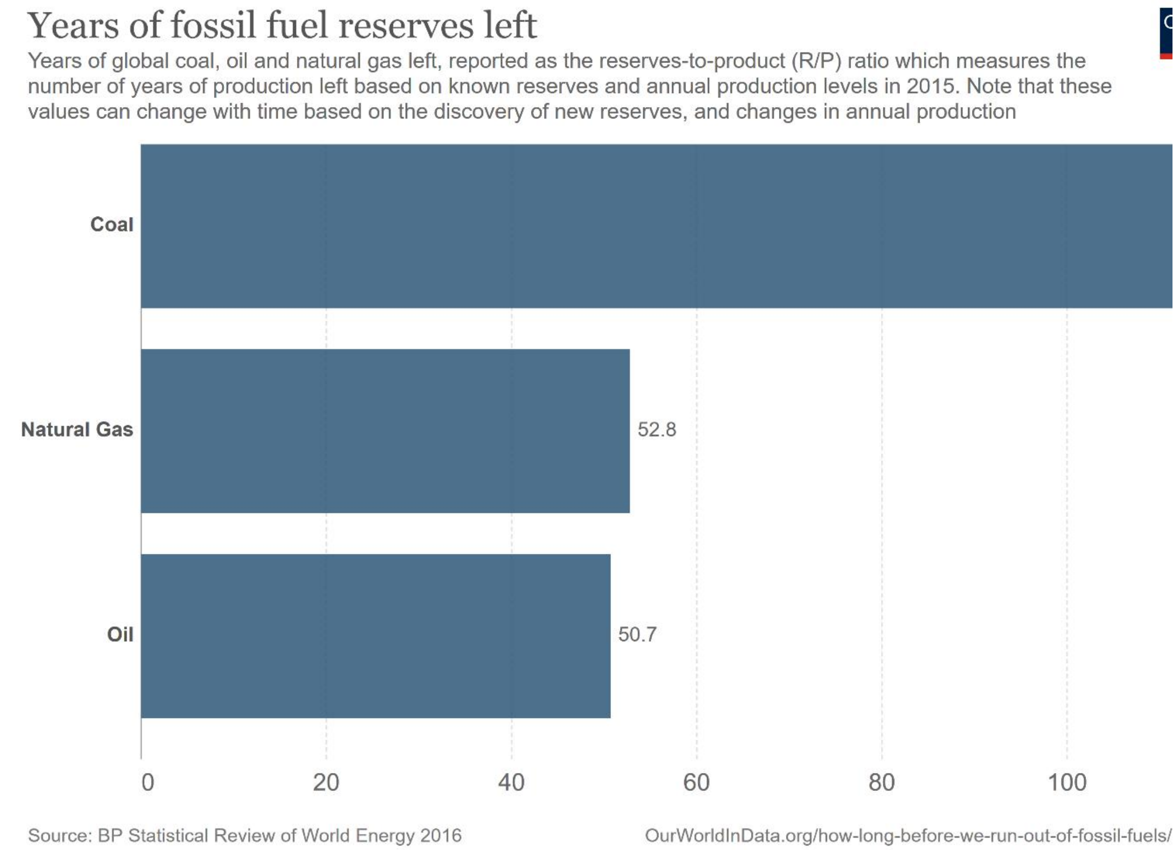


Figure 14 Years of global coal, oil and natural gas left, source: https://ourworldindata.org/

The role that scientists expect that the renewable energy sources can play in the issue of climate change, is the greenhouse gas emission mitigation or stabilisation. It is the reason for the policies on renewable energy from the Kyoto Protocol and the Paris agreement alike. However, this is a potential result that renewable energy use can have. A recent study on this subject conducted in the U.S., seems to suggest that an increase in the renewable energy percentage, and the amelioration of energy efficiency measures, have approximately the same results, regarding the energy-related CO_2 emissions globally. Still, it was statistically proven that 1% increase in renewable energy will lead to 0.70% decrease in CO_2 emissions, while a 1% increase in energy efficiency measures will lead to 0.61% of decrease in energy-related CO_2. Nonetheless, the authors conclude that this slight advantage of the renewable energy over the energy efficiency, is vital in the effort to maintain the temperature increase below 2^{o}C (Adua, Zhang and Clark, 2021).

Renewable Energy & Climate Change

Climate change, impacts in its turn the performance of the renewable energy sources. Regarding wind energy, the increasing temperatures can cause a decline of the air density ρ, thus slightly reducing wind energy, since $E = \frac{1}{2}At\rho v^3$ (Laakso *et al.*, 2010). This potential effect is discussed in more detail in Chapter 2. Moreover, in the context of climate change, extreme events such as storms are expected to increase in frequency, therefore another issue is the damage that may be sustained by wind turbines and their blades by frequent lightnings.

Wind gust appearance on the other hand, is a phenomenon still under research, however it is projected that in the next 50 years, the increase in wind speed variability will bring about an increase in wind gusts (Cheng *et al.*, 2014; Jeong and Sushama, 2019). Accordingly, wind turbines should be manufactured to sustain such a change without being damaged or reducing their energy output. When it comes to offshore energy production, multiple papers indicate a future of increased wave activity in the higher latitudes, as in the North Atlantic (Bromirski *et al.*, 2013; Reguero, Losada and Mendez, 2019; Patra, Min and Seong, 2020), although not so in the Mediterranean region (Lionello and Scarascia, 2018). Consequently, when built in locations with increased wave activity, wind turbines and wave energy converters will again need to be modified to sustain the loads.

2. Theoretical Background

2.1. Sea surface temperature

The sea surface temperature is one important climatic parameter that can be indicative of both the natural climate variability, and of the anthropogenic climate change, while at the same time regulating the heat transfer between the ocean and the atmosphere (Pisano *et al.*, 2020). In terms of annual variability, the sea surface temperature is first and foremost influenced by solar radiation, but other meteorological factors and irregularities in the seasonal variability may also modify the sea surface temperature (Yu and McPhaden, 1999; Pezzulli and Hannachi, 2015). For example, the sea surface temperature has been found to be controlled by the horizontal advection of the heat and the vertical mixing of the heat inflow through the Gibraltar Strait, as well as by the heat flux between the atmosphere and the sea (Skliris *et al.*, 2011).

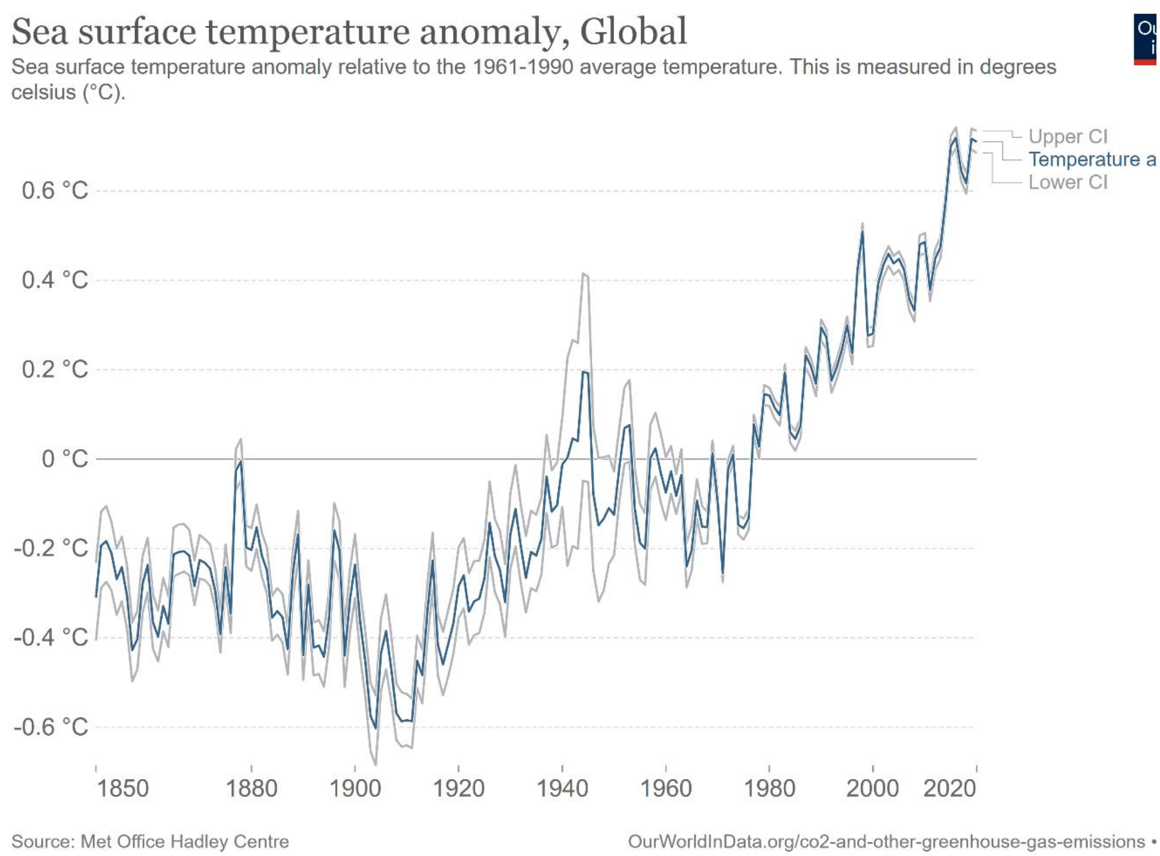


Figure 15 Sea surface temperature anomaly relative to the 1961-1990 average temperature

A comparison between Figure 11 and Figure 15, that show the atmospheric temperature anomaly and the sea surface temperature anomaly, extracts the conclusion that the two parameters have a similar behavior and trend, while their slopes increase abruptly together at the year 1980 and afterwards. As mentioned, the oceans and the atmosphere interact through latent and sensible heat fluxes (Cayan, 1992; Romanski and Hameed, 2015; Leyba, Solman and Saraceno, 2019) and accordingly the changes of one variable, lead to changes in the other.

On an interannual basis, the climatic indices, such as North Atlantic Oscillation and ENSO, play a vital role in the adjustment of the sea surface temperature (Hurrell and Deser, 2009; Deser *et al.*, 2010; Martínez-Asensio *et al.*, 2014b), thus making it difficult to determine the signal of the human-induced change. However said change is indisputable, as during the last decades has transpired an increase in the thermal energy content of the oceans (Trenberth, 2009), which invariably leads to a rise in sea surface temperature ('IPCC Synthesis Report', 2014). This change is evident from model results as well, that showcase the rise in sea surface temperature during the 20th century for most areas of the global ocean, indicating at the same time the rise of the greenhouse gases concentrations in the atmosphere (http://www.epa.gov). Consequently, sea surface temperature can accurately depict climatic changes, and can also be used as an index for showing how anthropogenic climate change affects the oceans and the marine energy yield.

The increase of temperatures in the Mediterranean Sea due to the region's unique response to climate change and its interaction with the atmosphere, may lead to an additional increase in the sea surface temperature, and various researches indicate this through their results: 0.03 ± 0.008ºC/year (Nykjaer, 2009), 0.5–1ºC rise in the mean temperature for the whole basin (López García and Camarasa Belmonte, 2011), 0.035 ± 0.007ºC/year for a period of 31 years (Shaltout and Omstedt, 2014), 0.036 ± 0.003ºC/year, for a period of 27 years, and a period of 36 years, in two different studies (Pastor, Valiente and Palau, 2018; Mohamed *et al.*, 2019). Studies suggest strongly that the increased trend is more pronounced during spring and summer (Kostopoulou and Jones, 2004; Skliris *et* *al.*, 2011), with a warming rate difference of as much as 0.048ºC/year between spring and autumn (Skliris *et al.*, 2011).

Another important finding is that between the western and the eastern basin there is a different trend (Skliris *et al.*, 2011; Criado-Aldeanueva, Soto-Navarro and García-Lafuente, 2012; Pastor, Valiente and Palau, 2018; Pisano *et al.*, 2020), and in every case the eastern basin displays a higher trend, by 0.026ºC/year (Pastor, Valiente and Palau, 2018) (see Figure 16).

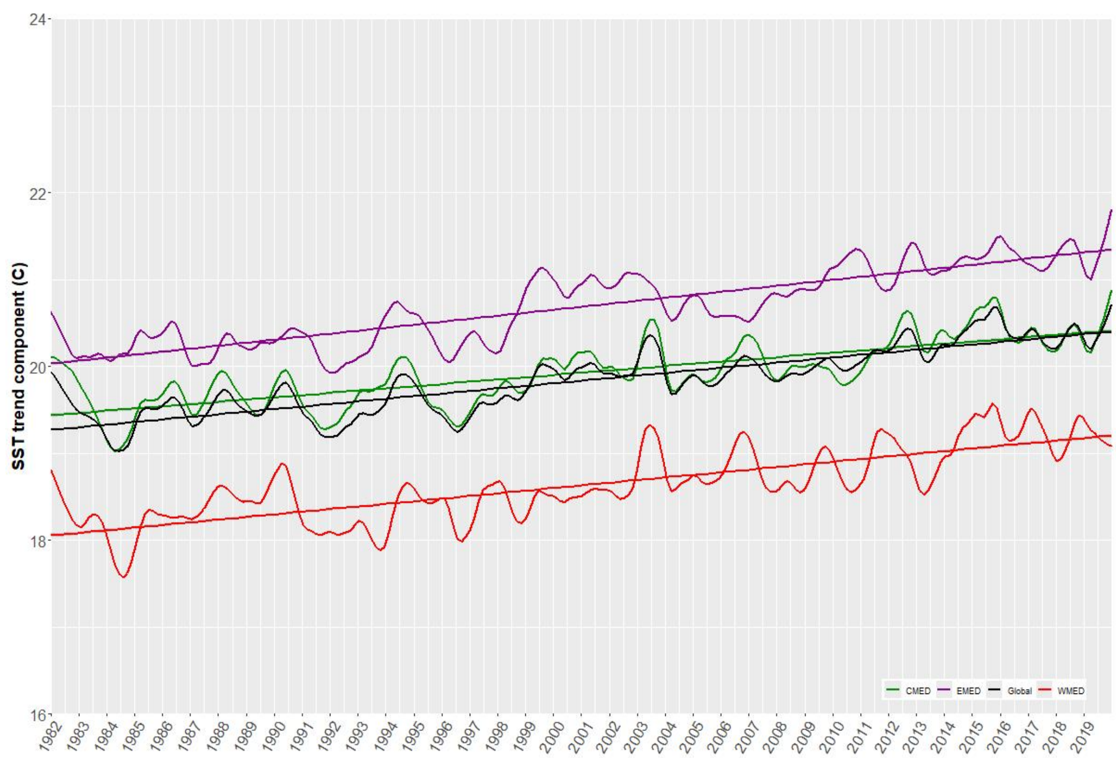


Figure 16 Deseasonalized SST trend component and linear regression (at 99% confidence level) for 1982–2019 for the global Mediterranean basin (black),WMED (red), CMED (green) and EMED (magenta).

The same work produces another interesting finding, which is that the 75 and 90 percentiles were found to have faster increasing warming rates. This result indicates that the warming in the Mediterranean sea is happening mostly because of an increase in the high sea surface temperature mean values, rather than solely due to an increase in the extreme values (Pastor, Valiente and Palau, 2018). Concerning the areas in the basin that are affected by the temperature changes, one study indicates that the areas that display much warmer water than the rest of the basin -with "*much warmer*" temperatures considered those of more than two standard deviations from the mean (>22.4°C)- did not cover more than 0.4% of the Mediterranean Sea, and are found mainly in the east Levantine sub-basin. Conversely, the much colder areas, which were calculated to have sea surface water temperatures less than 17.1°C covered only 2.8% of the Mediterranean Sea and were found in the Gulf of Lion and in the northern Adriatic sea (Shaltout and Omstedt, 2014).

When it comes to climatic indices, there is strong evidence that both phases of the North Atlantic Oscillation influence the climate, especially the temperature and the precipitation of the Mediterranean Sea, all over the basin, and as mentioned before, researchers have concluded that the decreased precipitation registered there during the decades between 1960 and 1990, was due to the North Atlantic Oscillation variability (Pastor, Valiente and Palau, 2018). When it comes to the sea surface temperature, the positive phase of the North Atlantic Oscillation has been associated with cooler conditions over the eastern sub-basin and warmer conditions over the western sub-basin, with the opposite behaviour occurring during its negative phase (Skliris *et al.*, 2011). The East Atlantic index increases the heat losses during wintertime (F. Criado-Aldeanueva and Soto-Navarro, 2020), and its positive phase leads to increased sea surface temperatures (Skliris *et al.*, 2011). Generally, the North Atlantic Oscillation is found to impact the wintertime temperatures (Hurrell and Deser, 2009), while the East Atlantic pattern impacts the various climatic parameters all year long (Josey, Somot and Tsimplis, 2011). The Scandinavian Oscillation index also mildly affects the heat loses by increasing them (Josey, Somot and Tsimplis, 2011). An important index for the Mediterranean variability, explaining the observed trends and changes in the region, is the Mediterranean Oscillation, an index that has been shown to have a high correlation with sea surface temperature in the Mediterranean region (Skliris *et al.*, 2011). An issue that has yet to be determined, is the ability to separate the natural climate variability that is due to atmospheric circulations (North Atlantic Oscillation, ENSO and more), from the results of anthropogenic climate change. It has been shown that the effects of actual climate change will be concealed by the North Atlantic Oscillation variability over Europe (Ravestein *et al.*, 2018), since it can produce a 20-30% variation in wind energy yield, in high wind potential areas (Ravestein *et al.*, 2018), as an indication of North Atlantic Oscillation's influence on the climate.

2.2. Wind Speed

The wind speed and consequently the wind potential, is not negligible in the Mediterranean area, although the anthropogenic climate change influences both. The wind speed of an area is important when determining the potential wind energy that can be extracted there, as wind energy is given by the formula:

$$E = \frac{1}{2} At\rho v^3 \quad \mathbf{(1)}$$

where, E the wind energy, A the area through which the wind blows, t the time, ρ the air density and v the wind speed. Therefore, its study is vital for the future of the wind energy in the area and the establishment of wind energy projects.

In a report on the wind speed patterns of Italy, the north coasts of Sicily are shown to have wind speed potential that ranges from 6-8m/s (Majidi Nezhad *et al.*, 2019). A different study, which utilized the ERA5 reanalysis dataset for the span of 35 years and examined the whole Mediterranean Sea, revealed three regions, the Gulf of Lion, the Alboran Sea, and the Aegean Sea, as having the highest wind potential (Soukissian, Karathanasi and Zaragkas, 2021). Similar observations regarding wind speed, emerged from a study conducted in Greece, which used the ERA-Interim dataset, and showed wind speed potential of 5-9 m/s in the Mediterranean Sea, lessening closer to the shores. Regarding the wind speed, the Gulf of Lion presented the highest value, with a wind speed of 7.4 m/s and the central Aegean Sea the second highest at 7.2 m/s (Soukissian *et al.*, 2018).

The same study also proved that there are different values for the wind speed trend slope in each sub-basin, illustrating the fact that no uniform behavior can be determined for the wider region. Specifically, the Ionian Sea, the north Tyrrhenian and north Adriatic Seas, the eastern part of the Algerian basin up to the Balearic Sea, and the western part of the south Levantine basin had positive slopes, where the wind speed appeared to increase yearly in the mean. Conversely, the north Levantine basin, the Ligurian, the central Aegean, and the east Alboran Seas, presented negative slopes, and the wind speed decreased on an annual basis (Soukissian *et al.*, 2018). Studies also indicate that the Mediterranean Sea overall will show a decrease in wind potential until the end of the century, when following the RCP8.5 approach (Tobin *et al.*, 2016).

In the Mediterranean Sea, researches examining favourable positions for offshore wind farm development, indicate that areas of interest are the Adriatic Sea and the Gulfs of Lion and Gabes, as well as parts of the Aegean Sea, the Mediterranean coasts of Spain, and the north African coasts. The most important criteria taken into account in the study revealing these areas of interest, were a mean annual wind speed value exceeding 4.1 m/s at 10 m height, and the bottom depth suitability (shallow, intermediate, and deep depths analysis) (Soukissian *et al.*, 2017). Another study indicated as best areas for offshore wind farm development in the Mediterranean Sea the South-West part of Sicily and Sardinia, the Aegean and Ionian Seas, the Gulf of Tripoli, the whole Adriatic Sea, and the Gulfs of Tunisia, Hammamet, and Gabes (Pantusa and Tomasicchio, 2019).

2.3. Sea surface temperature & Wind Speed in the Mediterranean Sea

Few studies have been executed in the Mediterranean Sea, combining wind speed and sea surface temperature data, to determine their relationship. However, one such examination reports that there is in fact an important impact between the two variables, since higher sea surface temperature values promote the blending of atmospheric air and marine boundary layer air, a process which leads to increased wind speed values (Meroni *et al.*, 2020). Additionally, it has also been indicated that at large scales (10^3-10^4 km) the sea surface temperature anomalies have a negative correlation with wind speed, a behaviour which gets reversed at mesoscales (10-100 km) (Okumura *et al.*, 2001). A different approach to the subject, is the relationship between sea surface temperature and cyclogenesis in the Mediterranean Sea. It has been proven that when the sea surface temperature increases, so does the cyclone track intensity, and therefore positive trends of cyclone frequency have been registered during the months of increasing sea surface temperature trends (Flocas *et al.*, 2010).

Moreover, if we take into account formula **(1)** above, and the Ideal gas law:

$$PM = \rho RT \quad \textbf{(2)}$$

where P is the pressure measured in atmospheres (atm), T is temperature measured in kelvin (K), R is the ideal gas law constant 0.0821 atm(L)/mol(K), M is the molar mass (gmol) and ρ is the density (gL),

we understand that the energy produced by the wind, does not only depend on the wind speed, but also on the wind density, in a proportional way, where as the air density increases, so does the energy yielded, as was briefly mentioned before. The air density, however, is depended (inversely proportional) to the air temperature, which in turn interacts with the sea surface temperature and its value changes accordingly (see chapter 2.1). As a consequence of the described relationships between the parameters involved, the sea surface temperature can alter the wind speed, and the wind energy.

3. Data-Methodology

3.1. Data Sources

In this work, the ERA5 reanalysis dataset was utilized. It has been implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF), and it is a dynamical–physical coupled numerical model that uses historical records and 4D-Var data assimilation in order to produce estimations on the climate and its various parameters, on a global scale (Hersbach *et al.*, 2020). The metocean data, include more than 200 indicators and indices, comprising of time series and trends for the physical and chemical characteristics of the global ocean and the particular basins, such as CO_2, chlorophyll, sea surface temperature, air temperature, salinity and many more. ERA5 is the product dataset of a long line of reanalyses produced by the ECMWF that were initiated in 1979 and are becoming increasingly sophisticated, with higher resolution and more accurate forecasting. Its data is available and can be freely accessed from the Copernicus Climate Data Store (https://marine.copernicus.eu). Compared to the previous ERA-Interim reanalysis, the ERA5 dataset has a more sophisticated resolution, with ~31 km for the horizontal dimension, 137 levels in the vertical dimension, and 1 h for the time scale resolution, making it an adequate source of data for this study.

ERA5 in particular offers plenty of variable datasets: land and sea hourly/monthly temperature, arctic temperatures, pressure levels, wind speed, precipitation, thermal comfort, fire danger, soil erosion, agrometeorological indicators and bioclimatic indicators. For the present study, the "ERA5 hourly data on single levels from 1979 to present" dataset was analyzed towards the production of all results and conclusions. The variables of interest are the 10m v-component of wind -which is the northward component of the 10m wind- the 10m u-component of wind -which is the eastward component of the 10m wind- and the sea surface temperature (sea surface temperature). The sea surface temperature is measured in Kelvin, while both wind components are measured in m/s. The two wind components are consequently combined, to get the speed and direction of the horizontal wind, at 10m. The 10m wind speed was preferred and chosen over the 100m wind speed, because of the proximity to the surface, which can yield more significant results with respect to their interdependency.

The ERA5 dataset has been validated by a number of studies dedicated to this task. In the Mediterranean, a validation focusing on the Tyrrhenian and the Ligurian areas by downscaling the ERA5 atmospheric reanalysis, in order to produce a hindcast for the period 1990-2018, indicated, after comparison with the ERA5 data, that the downscaling improves the hindcast's reliability for wind speed and wind direction results (Vannucchi *et al.*, 2021). In one study, the estimation of the global wind power potential has been performed using ERA5 (Ulazia *et al.*, 2019), while in a different one, ERA5 wind speeds have been compared against LIDAR measurements at different heights (Aniskevich *et al.*, 2017). It was therefore concluded that the ERA5 wind speed data deviates up to 20% from LIDAR measurements. ERA5 wind and wave data have also been validated for the Caspian Sea, after comparison with the ERA-Interim data, and advanced scatterometer and offshore platforms measurements. It was concluded that there is a good agreement for wind speed values of 2 m/s or more.

Wind speed results over the South Brazil coasts from ERA5 and two different reanalysis datasets were compared to in-situ measurements, and ERA5 emerged as the most accurate reanalysis (de Assis Tavares *et al.*, 2020). In a study analyzing global data for 37 years, different reanalysis models hindcasts (ERA5, MERRA2, ERA-I, CFSR, and WAVEWATCH III) have been compared to satellite and buoy measurements, thus proving again that the ERA5 reanalysis is the most accurate (Olauson, 2018; Sharmar and Markina, 2020). Finally, in a research that took place in Greece, an evaluation of ERA5 wave and wind parameters against in-situ buoy measurements in the Greek Seas concluded that the ERA5 reanalysis dataset might give an underestimation of the actual values of the examined parameters (Kardakaris, Boufidi and Soukissian, 2021).

3.2. Statistical Methods

For the statistical analysis that follows in the next chapter of results, the terms used in the results, follow the terminology of previous work (Soukissian *et al.*, 2018). The annual mean wind speed is the mean wind speed for a particular year, and the mean annual wind speed, the mean wind speed from the annual means. Similarly, the mean monthly wind speed is the mean wind speed for a particular year and month, and the mean monthly wind speed for a particular month is estimated as the mean of the mean monthly wind speeds. For time, the index t is used, with $u(t_i) = u_i$ being the time series of wind speed. The monthly scale is indicated with the letter m, and the decadal with the letter j.

Following the above, the annual mean wind speed is:

$$m_{u,j} = \frac{1}{N}\sum_{i=1}^{N} u_i \qquad \textbf{(3)}$$

with N the number of hours in a year

and the mean annual wind speed $m_{u,Y}$ is:

$$m_{u,Y} = \frac{1}{J}\sum_{j=1}^{J} m_{u,j} \qquad \textbf{(4)}$$

with J the total number of years

The monthly mean wind speed for year j and month m, is accordingly:

$$m_{u,j,m} = \frac{1}{K}\sum_{i=1}^{K} u_i \qquad \textbf{(5)}$$

with K the total number of hours for the month and year that are analyzed, hence $m = 1,2, \cdots, 12$.

and the mean monthly wind speed for month m is:

$$m_{u,m} = \frac{1}{J}\sum_{j=1}^{J} m_{u,j,m} \tag{6}$$

The mean annual variability (MAV), indicates the variability of a parameter within each year, and is the mean annual coefficient of variation. The variability of a parameter from year to year is the inter-annual variability (IAV), which is the ratio of the standard deviation of the annual mean wind speed to the overall mean wind speed.

For the correlation and the slopes of the variables examined, we utilize the following two methods:

Kendal Tau Correlation

The datasets for the two variables – sea surface temperature and wind speed – are tested for correlation on the different time scales examined. In order to get accurate results, the Kendall's tau correlation method is utilized. Tau, is a correlation coefficient, first introduced by Kendall in 1938 (Kendall, 1938), that is non-parametric, and computes a rank correlation. A rank correlation tests the similarity between the rankings of different variables (en.wikipedia.org). It is bound between the values -1 and 1, thus quantifying the correlation between the variables examined.

The tau correlation coefficient, examines each pair of the joint variables x_i and y_i, and determines the existence of potential correlation through the equation:

$$\tau = \frac{No\ of\ concordant\ pairs - No\ of\ discordant\ pairs}{\binom{n}{2}}$$

Firstly, the x_i values are placed in increasing order, and consequently the number of corresponding values of y_i that remain in the same order (concordant pairs) or not (discordant pairs) are counted. In that sense, concordant pairs are the ones whose indices and values are in order, with the opposite being true for discordant pairs. The advantage of the Kendall tau correlation, in contrast to other correlation methods, is the fact that the original data can be independent of a distribution, a characteristic imperative for continuous random variables, as are wind speed and sea surface temperature.

In order to estimate the mean annual and mean monthly correlation coefficient between the variables, we used the following method: the annual sea surface temperature values of year 1979 were correlated against the annual wind speed temperature of the same year, for each gridpoint (11115 in total number). The mean 42 correlation values computed at each grid point give the mean annual correlation for this year. Accordingly, the monthly mean sea surface values for January 1979 were correlated against the monthly mean values of wind speed for the same month and year at each grid point. The mean of the 42 correlation values that were calculated for January was then visualized for the figures.

Slopes - Theil Sen Estimator

In this study the Theil-Sen estimator was used to acquire the trends for both studied variables, in all the examined time scales, as a measure of how much the variable changes in that particular time scale. It was introduced by Theil (Theil, 1950), and extended by Sen (Sen, 1968), and estimates a value for the slope so that Kendall's correlation tau, between $y_i - b_1 t_i$ and t_i equals to zero . The estimation of the Theil-Sen slope uses the following formula:

$$b_{ij} = \frac{y_i - y_j}{t_i - t_j}, \text{ for all } i > j, j = 1,2,\cdots,\mathrm{n}-1, i = 2,3,\cdots,\mathrm{n}, \quad \textbf{(7)}$$

where all possible combinations of pairs of points y, t, are estimated, with t_i, t_j being the time points corresponding to y_i, y_j. The median of the estimated slopes b_{ij}, is the Theil-Sen estimator, where the slopes are $n(n-1)/2$, with n the sample size (Wilcox, 2017; Soukissian *et al.*, 2018).

This method was preferred in comparison to the ordinary least squares approach, for a variety of reasons. Firstly, it is a non-parametric test that allows some measure of absence of normalcy in the data, a useful characteristic for the datasets used here (Karathanasi, 2020). It is also resistant to outliers, and the robustness of the estimation has been verified by calculating its break down point. That is the point after which the estimator becomes redundant, and for the Theil-Sen it is 0.293, indicating a robust estimator (Geyer, 2006; Peng, Wang and Wang, 2007). Moreover, it has a high asymptotic efficiency and proven unbiasedness for continuous error distributions, while it is considered a good estimator for mean squares error, in comparison to other slope estimators. Finally, the Theil-Sen estimator has been found to be efficient (*"super-efficient"*) for discontinuous error distributions as well (Peng, Wang and Wang, 2007).

In order to estimate the sea surface temperature and wind speed trends, the mean monthly values of each variable were used to create a matrix. For example, the January matrix would contain columns of January 1979, January 1980, January 1981 … January 2020 and the slope was estimated for each grid point using the method described. The same happened for the annual timescale.

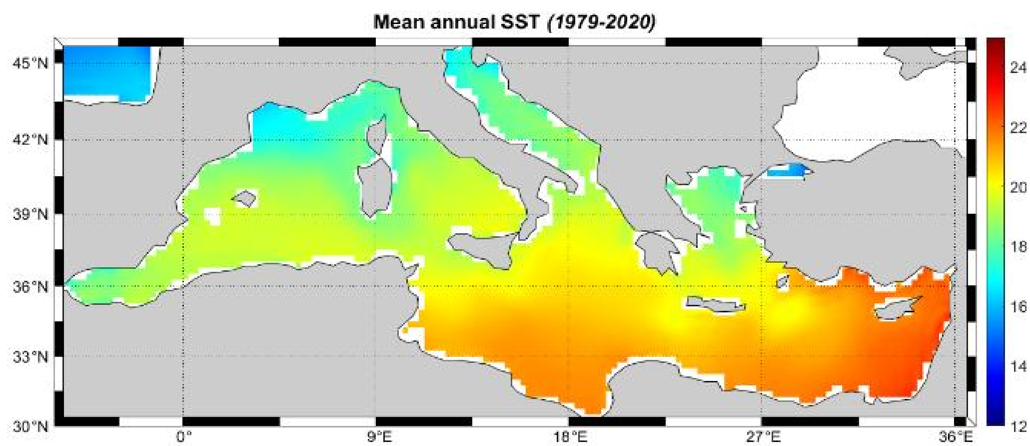
4. Results

In the following chapter, the results on the annual, interannual and monthly time scales, are presented and explained using the methodology that was previously analyzed.

4.1 Annual & inter-annual time scales

Mean annual sea surface temperature and wind speed

The following two graphs, represent the mean annual values of the studied variables:



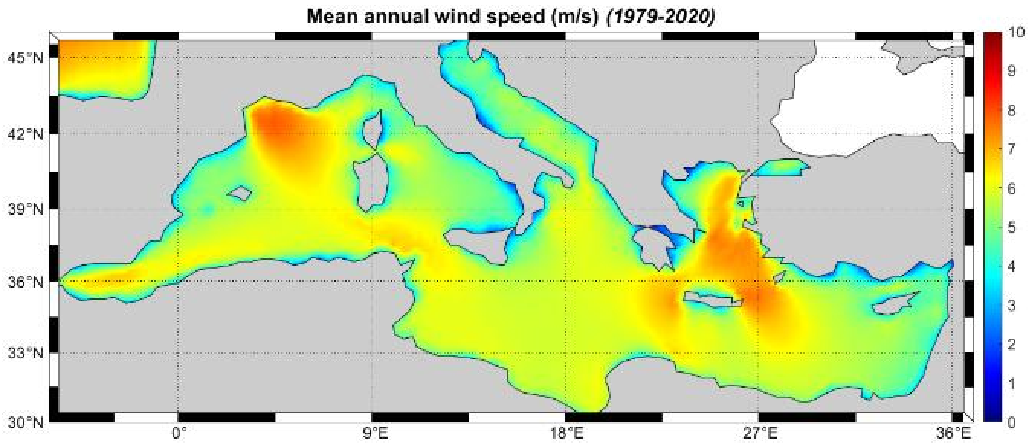


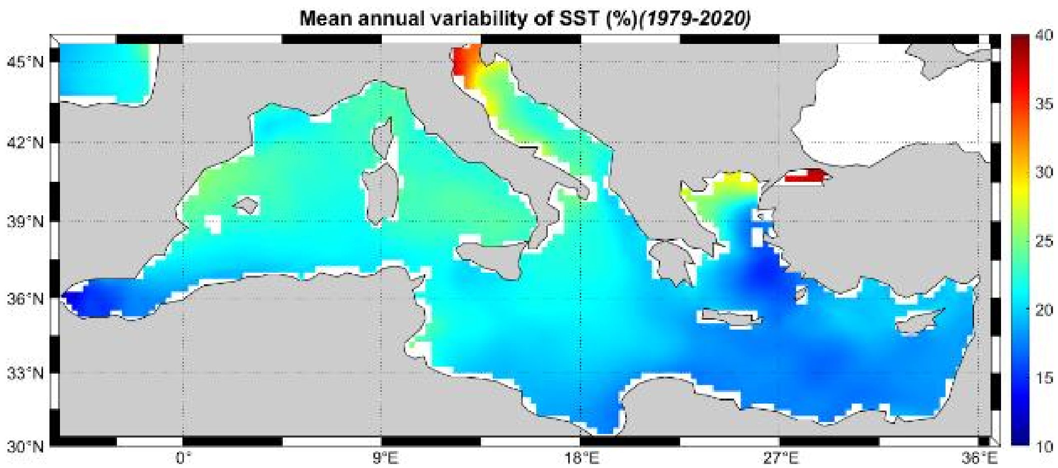
Figure 17 Mean annual sea surface temperature (up) and wind speed (down)

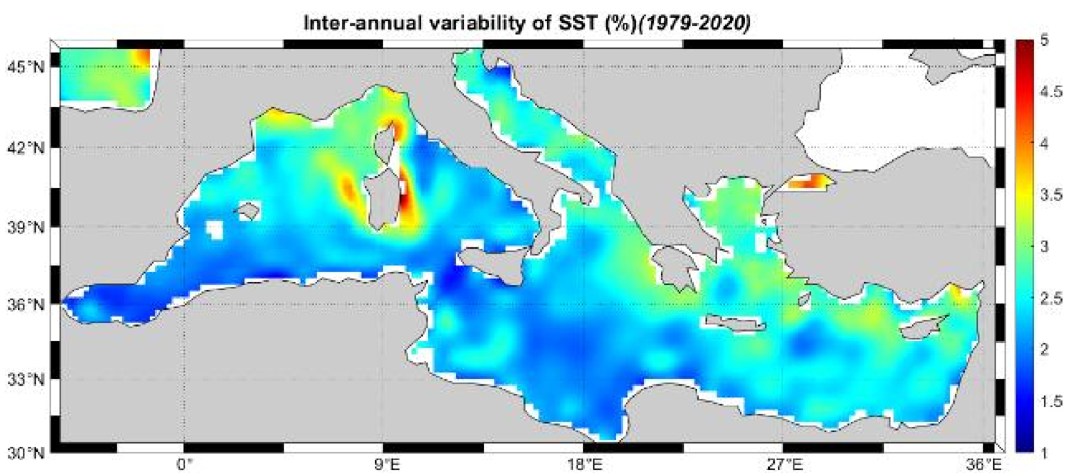
The sea surface temperature in the upper plot of Figure 17 is decreasing northwards and has its highest mean annual values in the southeastern part of the basin. This spatial distribution was expected since the sea surface temperature is inversely proportional to latitude (http://ferret.wrc.noaa.gov/las). The highest sea surface temperature value (27°C) can be found in the south of Cyprus, and the lowest (12.76°C) in the Sea of Marmara, in the northern coasts of Turkey.

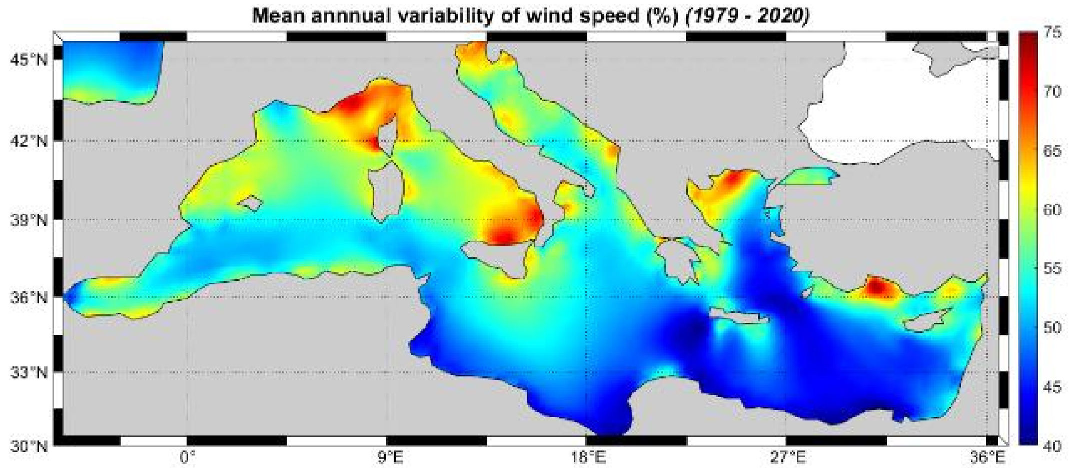
For the wind speed, on the plot below, the areas with the highest mean values appear to be the Gulf of Lion, the Aegean Sea, and the sea surrounding the west and east coasts of Crete Isl., as well as the Alboran Sea. The highest mean wind speed values overall, occur in the Gulf of Lion (7.80 m/s), and in the offshore area west of Crete Isl. (7.62 m/s). The Gulf of Lion and the Aegean Sea are the areas that present specified wind patterns, the Mistral, and the Etesians accordingly, therefore this result is not unexpected, since both patterns are created by strong winds, with high speeds (see Chapter 1.1.). The Gulf of Lion and the central Aegean Sea, while they present the highest mean annual wind speed values, they have low sea surface temperature values.

Mean annual & inter-annual variability

The mean annual and inter-annual variability of both variables, are presented in the following graphs:







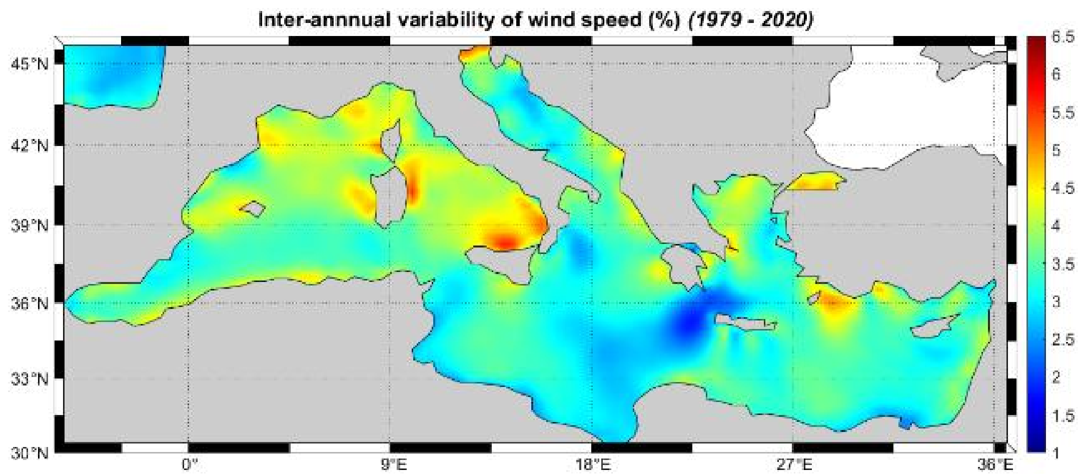


Figure 18 Mean annual and inter-annual variability for sea surface temperature (upper two) and wind speed (two below)

The upper pair of plots in Figure 18 show the mean annual variability (MAV) and the inter-annual variability (IAV) of sea surface temperature. The MAV, depicted on the uppermost plot, has a value of around 20-25% for the majority of the basin, while the areas with the lowest values are the Alboran Sea (12%), the Gulf of Lion, the Aegean Sea, and all southeastern basins. The highest values are found in the northern part of the basin, specifically in the north Adriatic Sea, and in the Sea of Marmara (46%). On the other hand, the inter-annual variability of sea surface temperature has a spatial pattern of decreasing values from west to east, with the exception of the areas off Corsica and Sardinia Isls. where the highest values occur (2%). The Sea of Marmara and the northeastern coasts of Cyprus are also exhibiting high IAV values (~4.5%).

The pair of plots below illustrate the MAV and the IAV for wind speed. The third plot indicates that the general spatial pattern of the MAV has values declining from north to south. The highest values appear in the Ligurian Sea, the southeastern Tyrrhenian Sea, the north Levantine basin, where the overall maximum (75%) appears, and the north Aegean Sea, while there are also relatively high MAV values in the coasts of the Adriatic Sea. Parts of the Adriatic coasts also indicate high MAV values (>60%). The final plot illustrates the IAV, which exhibits lower values at the southern part of the basin (except from the coasts of Algeria), and the highest in the Balearic, the Ligurian and the Tyrrhenian Seas, as well as the north Aegean and the southern coasts of Turkey. Its overall largest values (6%) appear in the east Tyrrhenian sub-basin, while the lowest value appears off the west coast of Crete Isl. and spread in a zone over to the African coasts.

The sea surrounding Sardinia and Corsica Isls. is the area exhibiting the highest IAV for both variables, as well as high wind speed MAV. This particular region is known for the strong sea breezes (Furberg, Steyn and Baldi, 2002) and the important wind fluctuations (Proverbio and Quesada, 1989), therefore high wind speed variability was anticipated for this region. Further comparisons between the figures, can showcase the fact that the areas with the lowest MAV values, are the same for both variables, namely the west Alboran Sea, the Gulf of Lion, the Aegean and generally the southern part of the basin. Higher IAV values appear also in the northern basin for both variables.

Mean annual correlation

The following Figure 19 depicts the linear correlation between the mean annual sea surface temperature and the mean annual wind speed. The correlation is estimated using Kendall's Tau correlation coefficient (see Chapter 3.2).

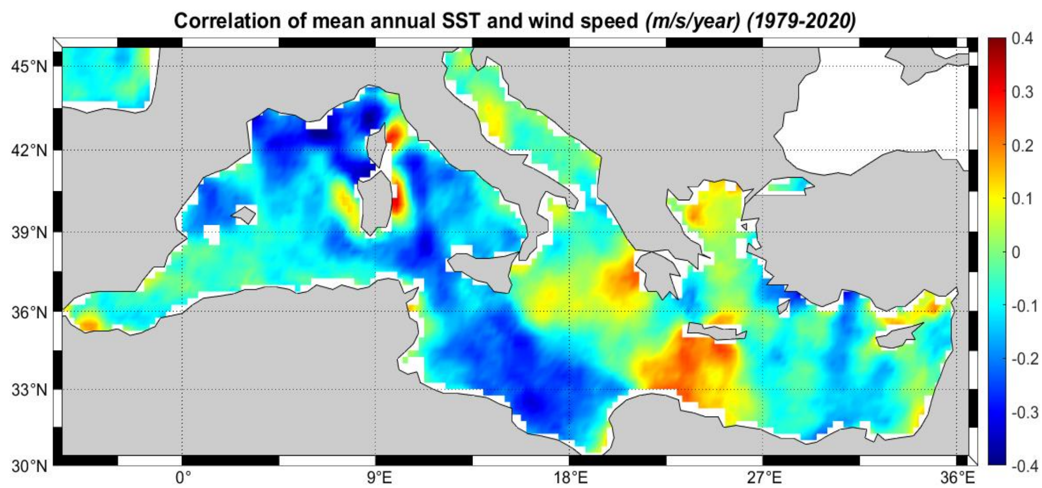


Figure 19 Correlation between mean annual sea surface temperature and wind speed

There appears no uniform spatial distribution, rather the negative correlation coefficient values (-0.4) follow a strip that covers the Balearic, Ligurian, Tyrrhenian and southern central Mediterranean Seas. Also, negative slopes appear in the central Levantine basin, again seemingly in a line that connects the north and the south point in the basin. For those regions, when the rank of one variable increases the rank of the other decreases, having a negative relation between them. In the areas covered by the strip, however, appear the highest overall values (0.32) off the east coasts of Sardinia and Corsica. Other regions with high correlation coefficient values are the central and east Ionian Sea and the southwestern Levantine basin off the south coasts of Crete Isl. Relatively high correlation coefficient areas appear in the east Levantine basin, and in the north Aegean Sea. In these cases, as the rank of the one variable increases, so does the rank of the other one. The rest of the Mediterranean Sea has correlation coefficient values around 0, indicating no particular correlation between the two variables.

Mean annual trends

In Figure 20 the linear slopes for the annual mean sea surface temperature and wind speed are presented. The slopes are indicative of the variable's trend, i.e., of its tendency to increase, decrease or remain constant, over the time span under analysis.

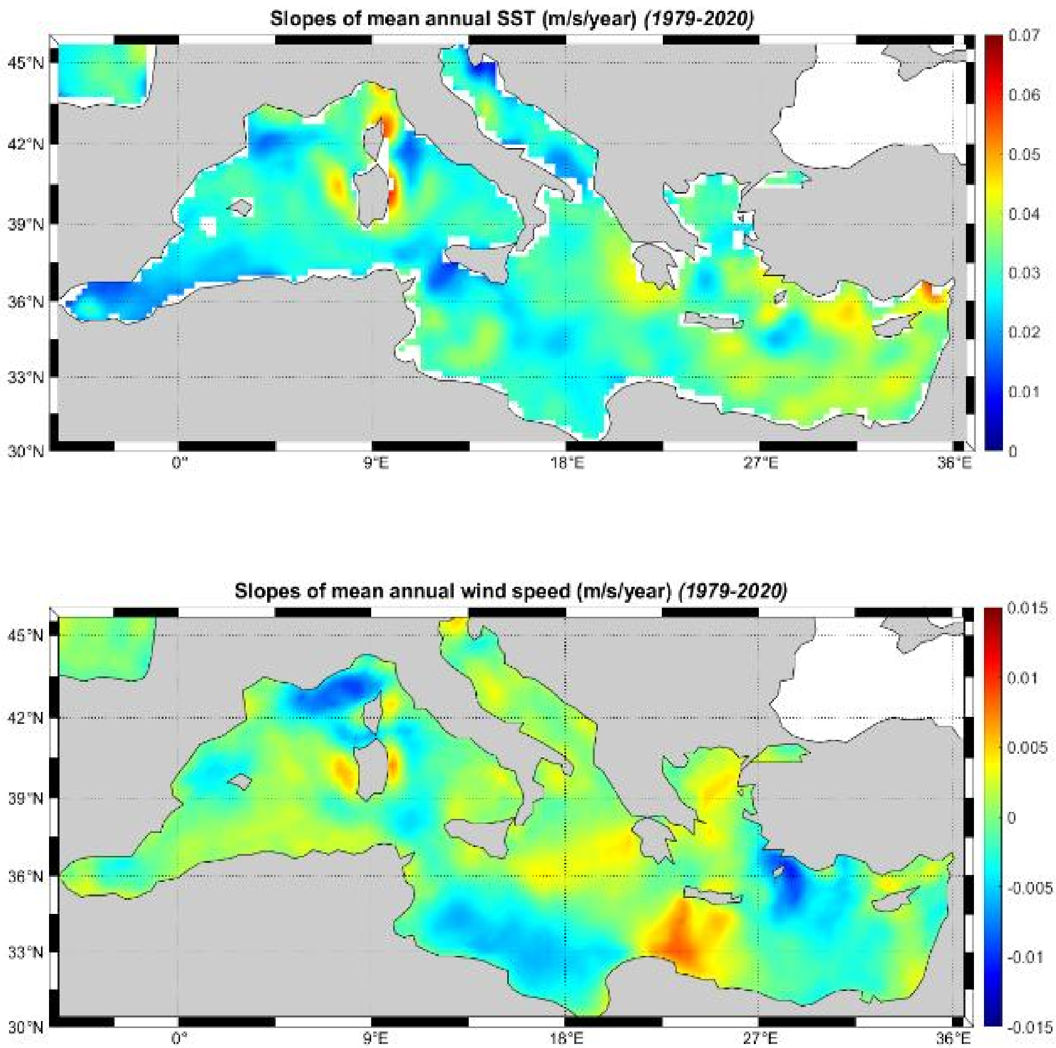


Figure 20 Slopes of mean annual sea surface temperature (upper) and wind speed (below)

For the sea surface temperature, there are no negative slopes present. The highest values (0.074 m/s/year) appear off the west and east coasts of Corsica and Sardinia. The sea off the northern coasts of Cyprus also exhibits high slope values. Zero slopes appear mostly in the Alboran sea, the Gulf of Lion, the north Tyrrhenian, the southern coast of Sicily and in parts of the Adriatic. The general spatial distribution indicates decreasing values westwards.

For the wind speed, there are negative slope values, which indicate a decreasing trend for the mean annual wind speed. The highest positive slopes appear in the area between Crete Isl. and the African coasts (0.048 m/s/year), and then in the central Aegean, the Ionian, the east Levantine basin and offshore the western and eastern coasts of Sardinia Isl. On the other hand, the Ligurian Sea, the south central Mediterranean sub-basin, and the rest of the Levantine basin, exhibit negative slopes. The minimum slope (-0.011 m/s/year) appears in the Aegean Sea, offshore the island of Rodos, an expected result, given previous work (Soukissian *et al.*, 2018).

The areas off the east coasts of Sardinia and Corsica, off the west coasts of Sardinia, and off the northeastern coasts of Cyprus have the highest slopes for both variables. On the other hand, for the sea space between the west coast of Cyprus and Rodos Isl., while it presents increased sea surface temperature slope values, the mean annual wind speed slope values are negative.

The following two figures show the trend for the sea surface temperature, and the wind speed, for the entire basin, over the 42-year period. The trendlines which indicate the behavior of the variables are also shown, together with a calculation of the slope value.

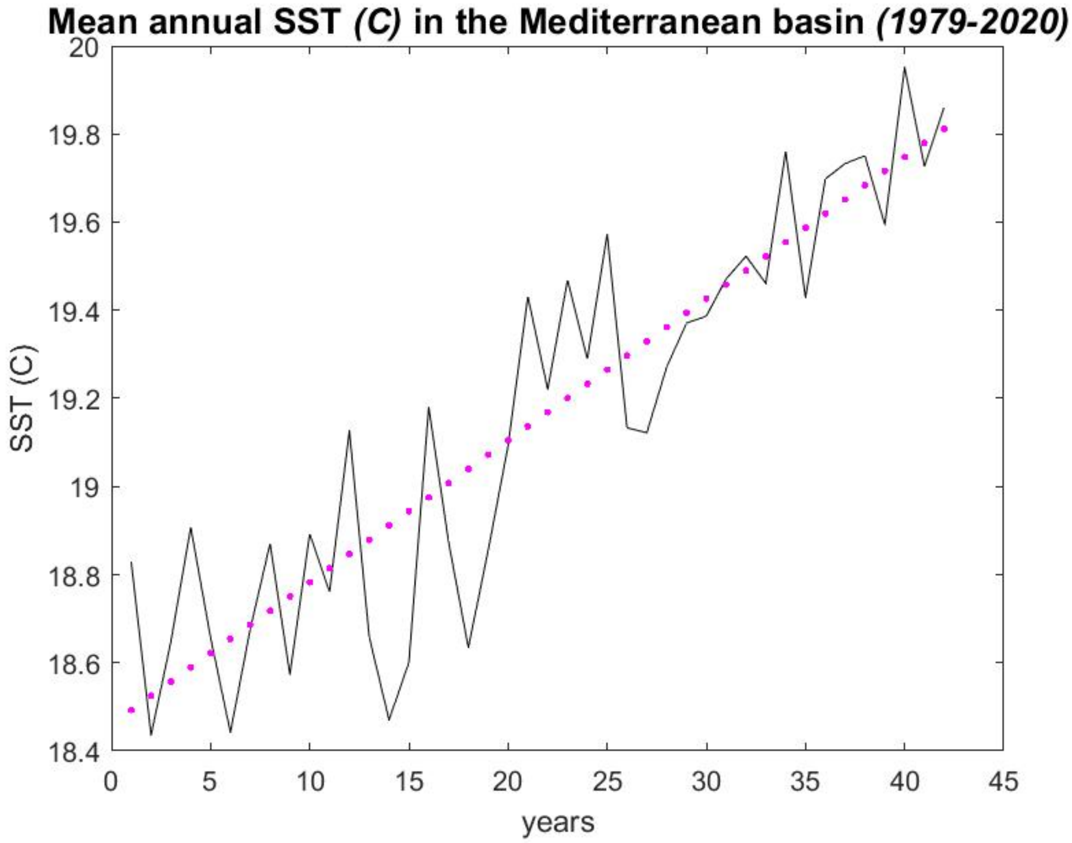


Figure 21 Mean annual sea surface temperature trendline

In Figure 21, the mean annual sea surface temperature with trendline: sst=0.0322t+18.4609

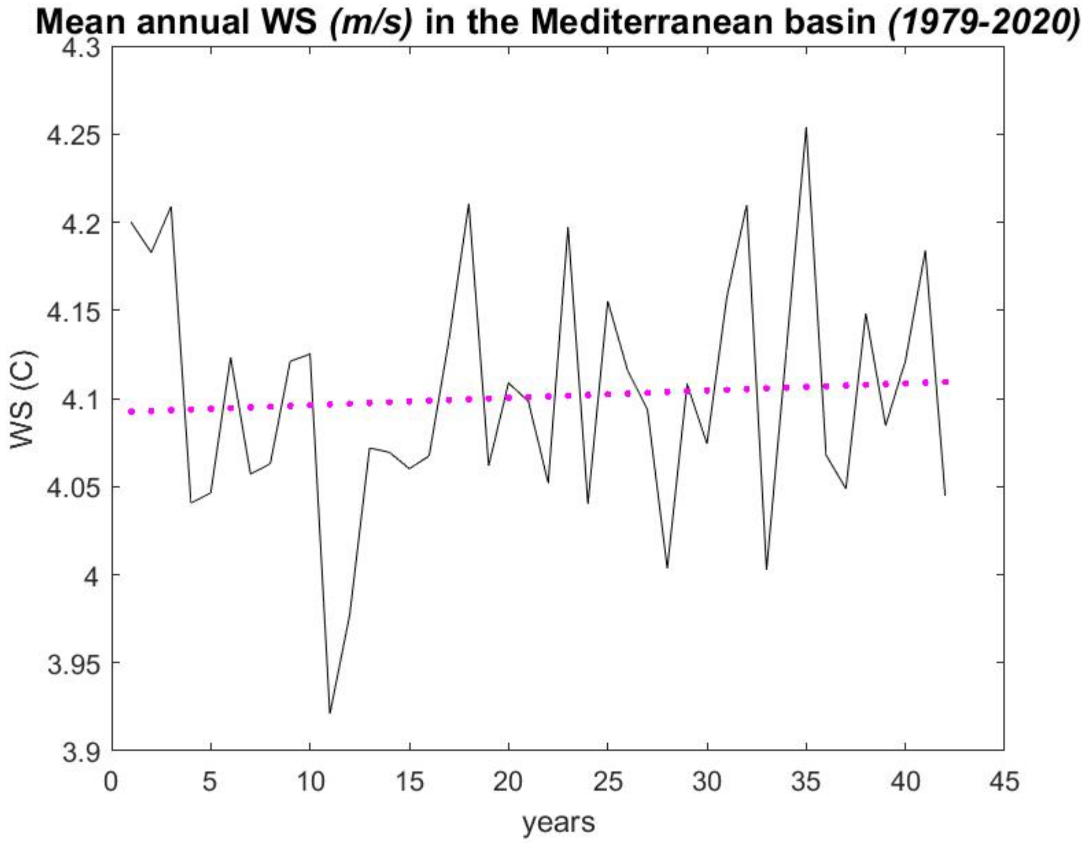


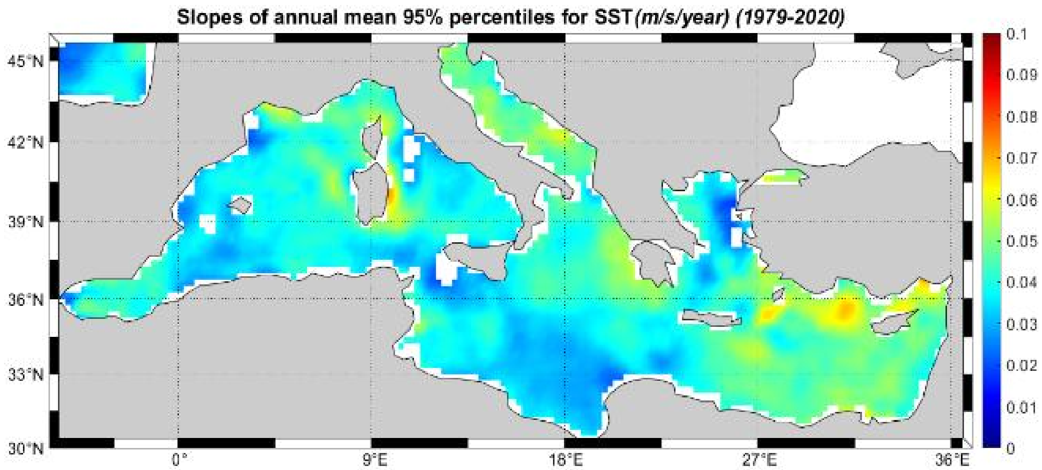
Figure 22 Mean annual wind speed trendline

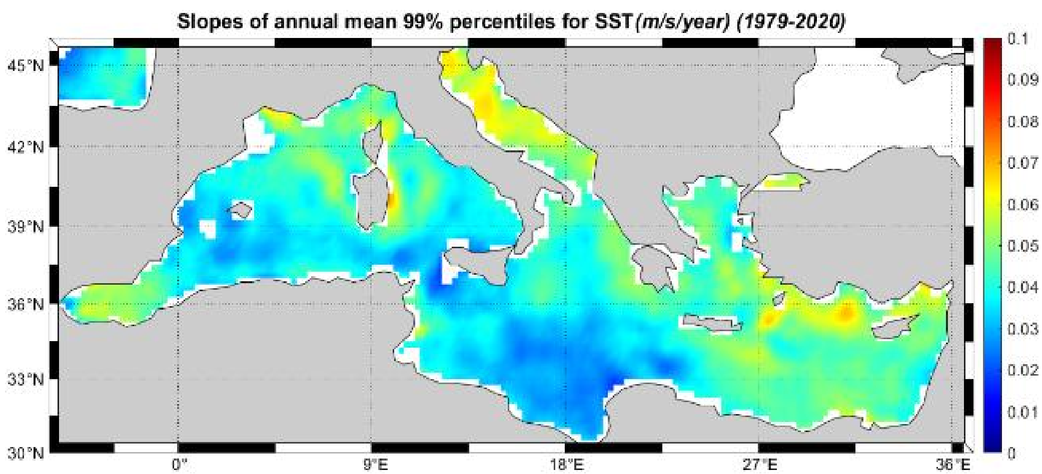
In Figure 22, the mean annual wind speed with trendline: ws=0.0004t+4.0920

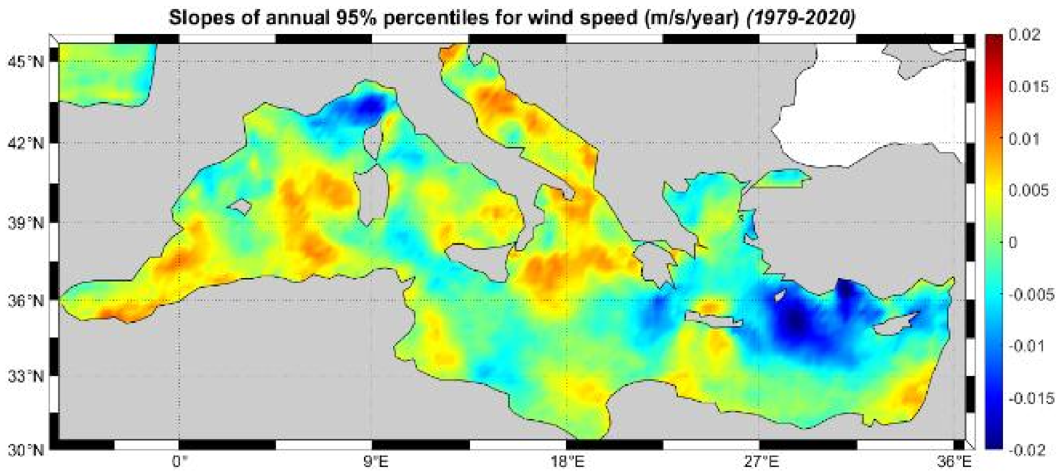
From Figure 21 & Figure 22 we can conclude that the sea surface temperature and the wind speed have positive slopes, 0.0322 and 0.0004 respectively, for the entire basin, in the span of the 42 years. On the behavior of the sea surface temperature for the Aegean and its trend, we can use the results presented here to make projections about the future of the area. If we consider that the mean slope value of 0.03°C/year continues, and no actions are initialized, while no other climatic changes affect this observed trend, by 2050 we can expect a sea surface temperature increase of almost 0.84°C, and by 2100 an increase of 2.34°C, from today's values. This projection, although it holds potentially dramatic consequences, is in accordance with the projections mentioned in the Introduction, and similar results should be expected.

Mean annual trends for 95% & 99% percentiles

In Figure 23 the spatial distributions of the 99% and the 95% percentiles for each variable are shown:







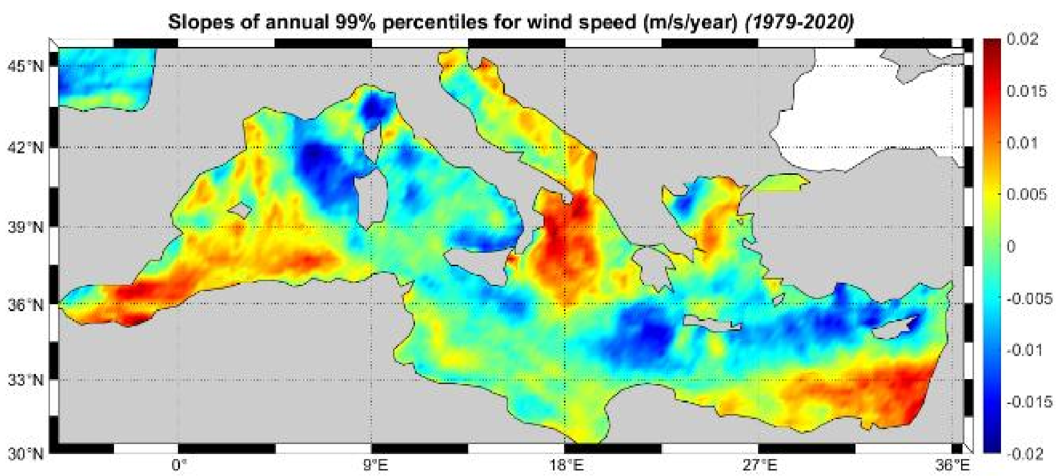


Figure 23 Trends for the 99% & 95% percentiles for annual mean sea surface temperature (upper) and wind speed (down)

For the sea surface temperature, the plots of the 95% and 99% percentiles present a similar behavior. The lowest values appear in the central Mediterranean basin, the east Aegean, the south Tyrrhenian and the Algerian and Balearic basins. Highest values occur in the Adriatic and east Ionian basins, the Alboran, the Ligurian, the west Tyrrhenian, and the north and south Levantine basins. The east coasts off Sardinia and Corsica, as well as the northern part of the Levantine basin have the highest percentile values for both plots. The areas that present different behaviors are the Tyrrhenian and the Aegean Seas. Especially, the Aegean Sea, has 95% percentile slopes close to 0, but 99%

percentile slopes around 0.04 m/s/year. Moreover, another difference is observed in the Adriatic Sea, which has much higher 99% percentile values.

For the wind speed, the west part of the basin, the Adriatic and Ionian Seas, the central Aegean, and the south Levantine basin, have the highest slope values in both plots, even as the 99% slopes reach to higher values than the 95% slopes. Additionally, the west coasts of Crete, the northernmost Aegean and the central and north Levantine basins, have the lowest (negative) slopes, in both cases. The major differences occur on the west coasts (positive 95% slopes – negative 99% slopes), the northwestern coasts (negative 95% slopes – positive 99% slopes) and eastern coasts (lower values for the 99% slopes) of Sardinia. Moreover, the north coasts of Sicily have positive 95% slopes and negative 99% slopes, and its south coasts, have 95% slopes close to 0, but negative 99% slopes. The area between the east coasts of Crete Isl., and the west coasts of Cyprus, has in both cases negative slopes. However, in the 95% plot, the negative values expand towards Rodos Isl. leaving only a small area north of the island with slopes of 0, while in the 99% slopes plot, the negative values appear as a strip between the islands, and northwards the slopes are around 0, with the north of Rodos even exhibiting positive slopes.

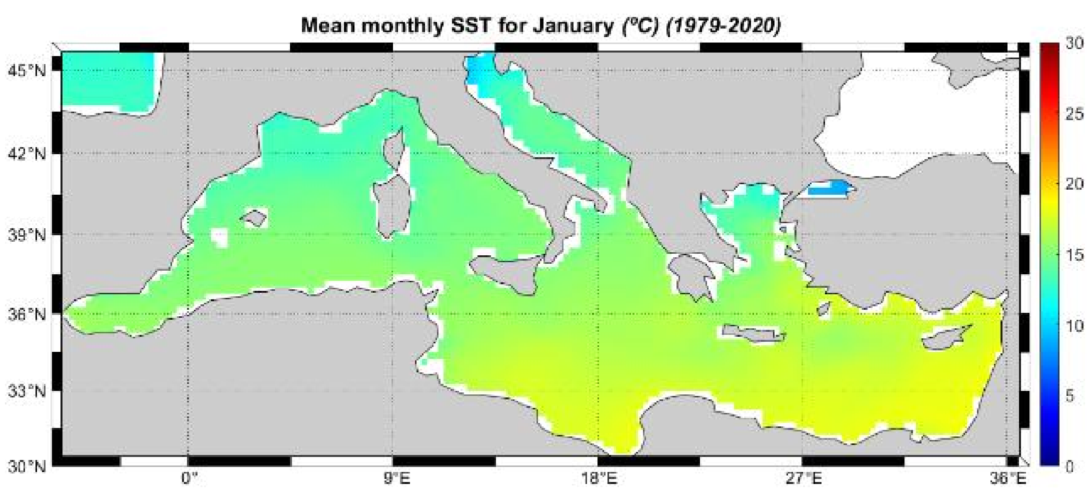
For the 95% slopes plots, the west basin has low sea surface temperature slopes, but high wind speed slopes, apart from the northwestern coasts of Corsica, where the sea surface temperature slopes are close to 0 and slightly positive, but the wind speed slopes are negative. In the central basin, the Adriatic and the Ionian have positive slopes for both variables, but the south region has sea surface temperature slopes of 0, and positive wind speed slopes. In the east basin, the Aegean has negative sea surface temperature slopes, but positive wind speed ones, and the north Levantine basin has positive sea surface temperature slopes but negative wind speed slopes. For the 99% slopes the Alboran, south Balearic, Algerian, and Central Mediterranean basins have low sea surface temperature slopes and high wind speed slopes. The north Balearic, Ligurian and Tyrrhenian basins have positive sea surface temperature slopes, but negative wind speed slopes. The Adriatic has positive values in both cases, although the wind speed slopes have higher values. The east basin has sea surface temperature slope values around 0.06 m/s/year, apart from the north Levantine, where they exceed 0.07 m/s/year. On the other hand, that area has negative wind speed slopes.

An important aspect of the above analysis is the fact that the slopes of the 95% and 99% percentiles reach higher values compared to the slopes of the mean sea surface temperature and mean wind speed. That leads to the conclusion that extreme sea surface temperature and wind speed events are increasing faster than the actual mean sea surface temperature and wind speed respectively. Accordingly, in the future, we can expect the extreme events that we already witness, to occur more frequently than before, for the Adriatic Sea in particular, where all the percentiles seem to increase faster.

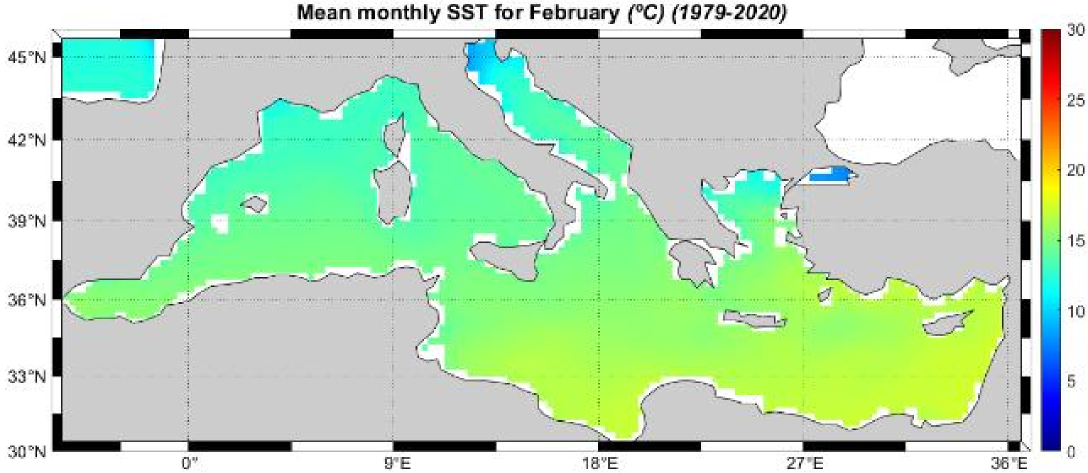
4.2. Monthly scale

Mean monthly sea surface temperature & wind speed

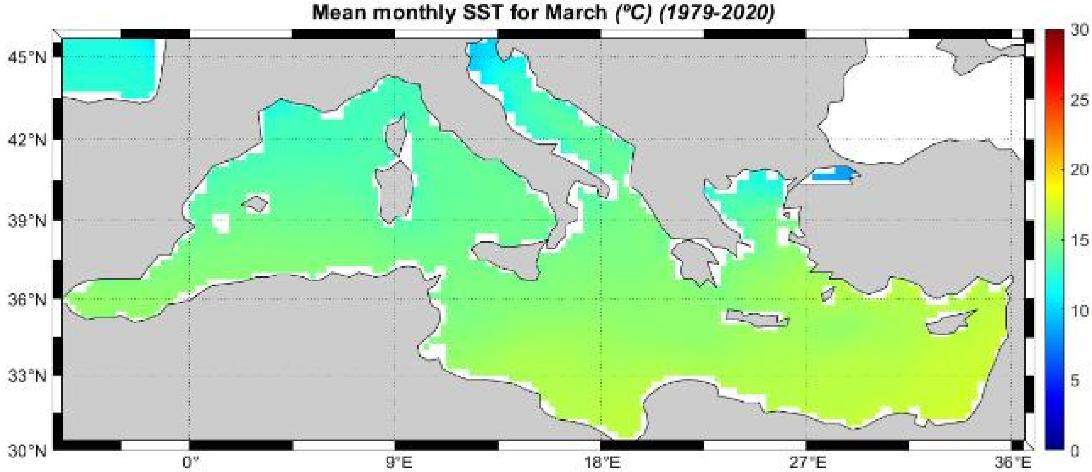
The next two figures, Figure 24 and Figure 25 represent the mean monthly distribution for sea surface temperature and wind speed.



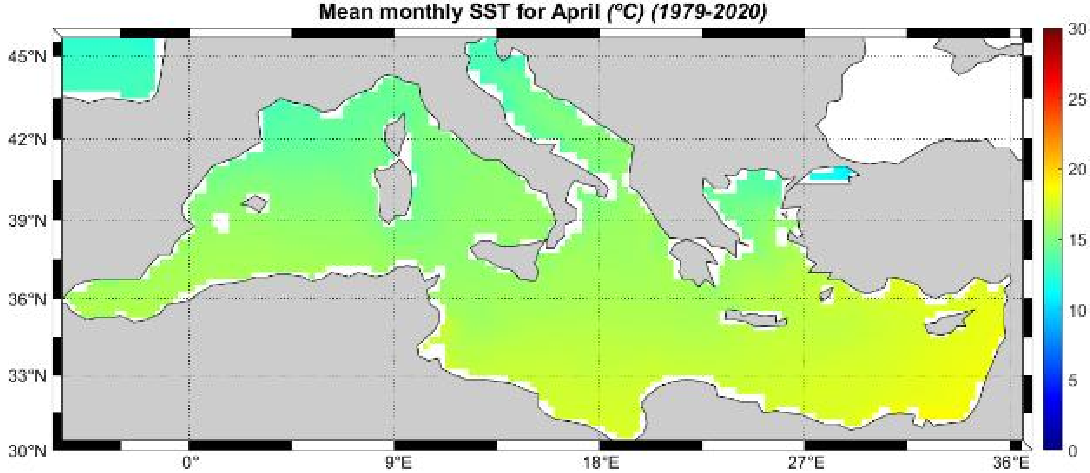
Mean monthly SST for February (ºC) (1979-2020)

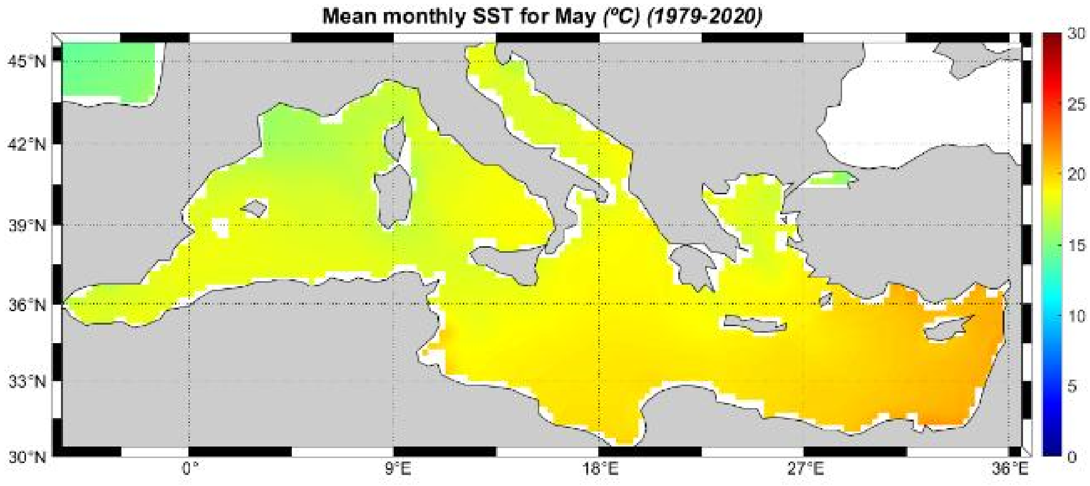


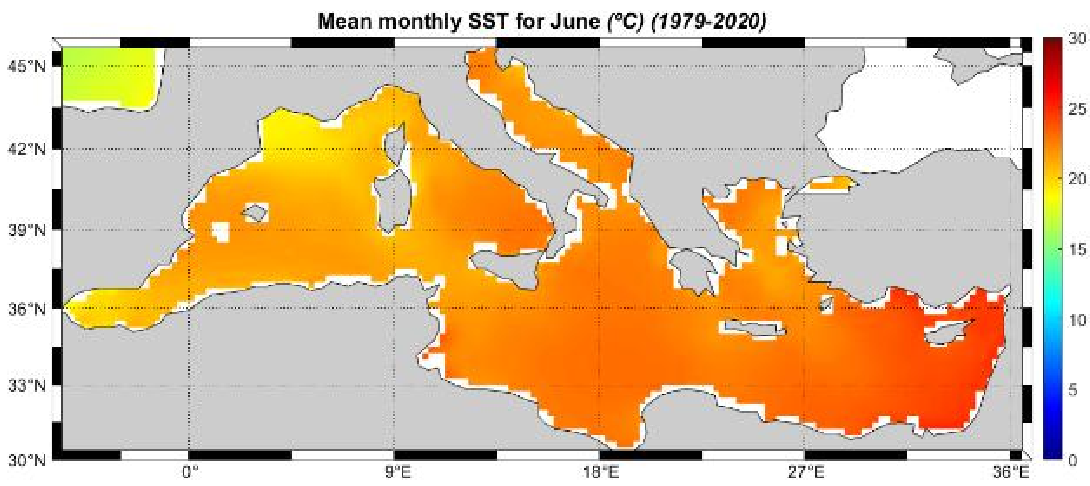
Mean monthly SST for March (ºC) (1979-2020)

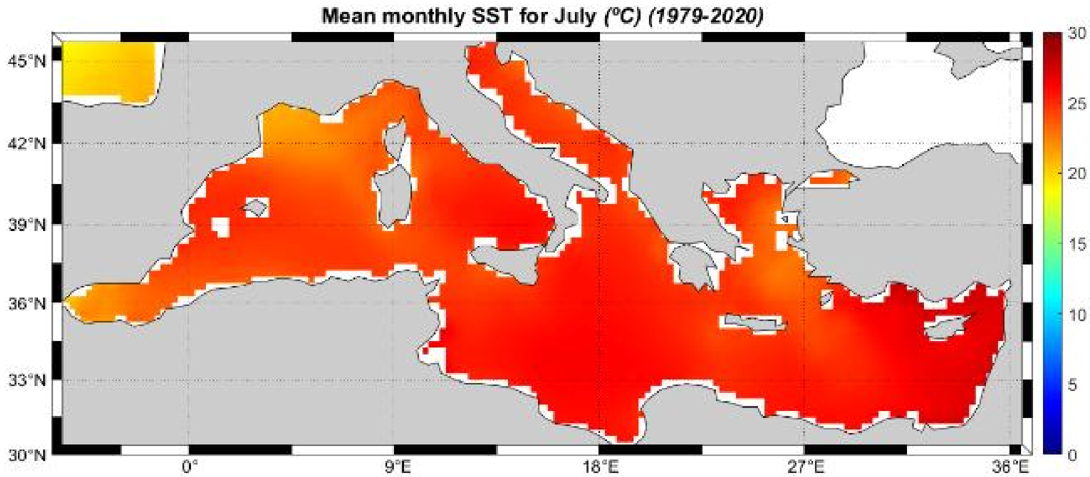


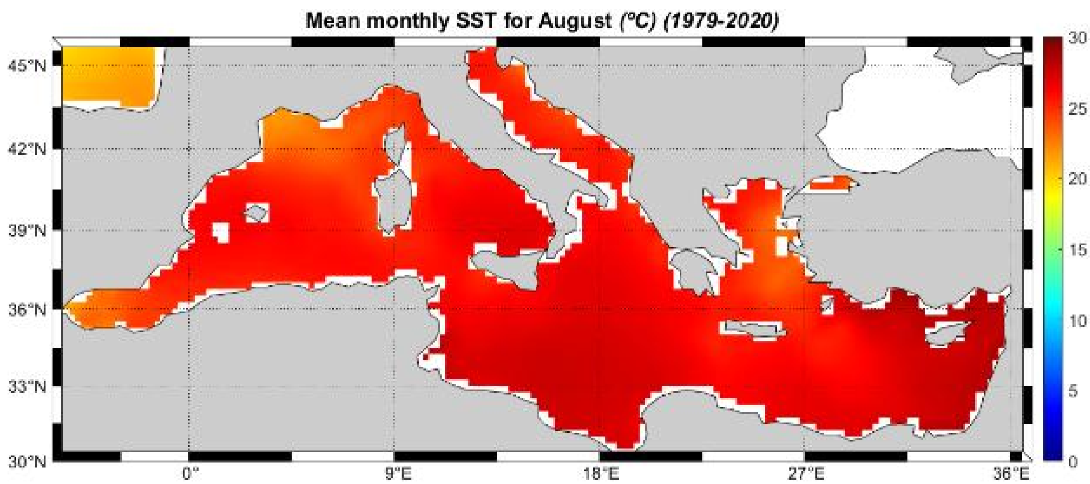
Mean monthly SST for April (ºC) (1979-2020)

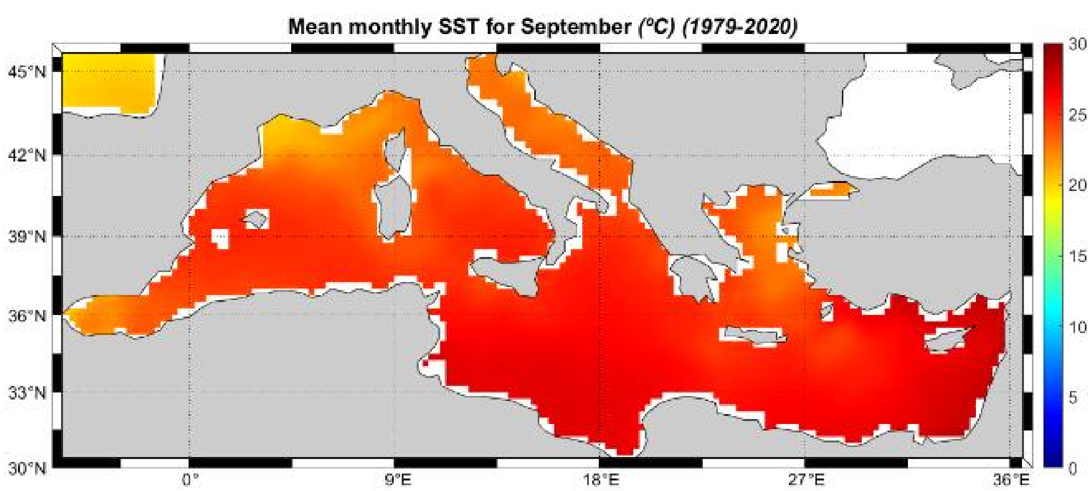


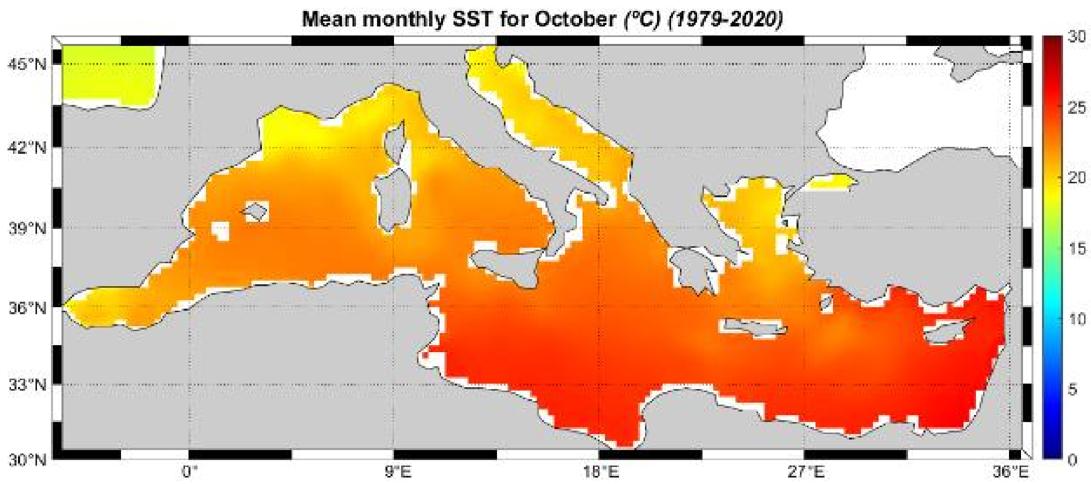

Mean monthly SST for May (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0

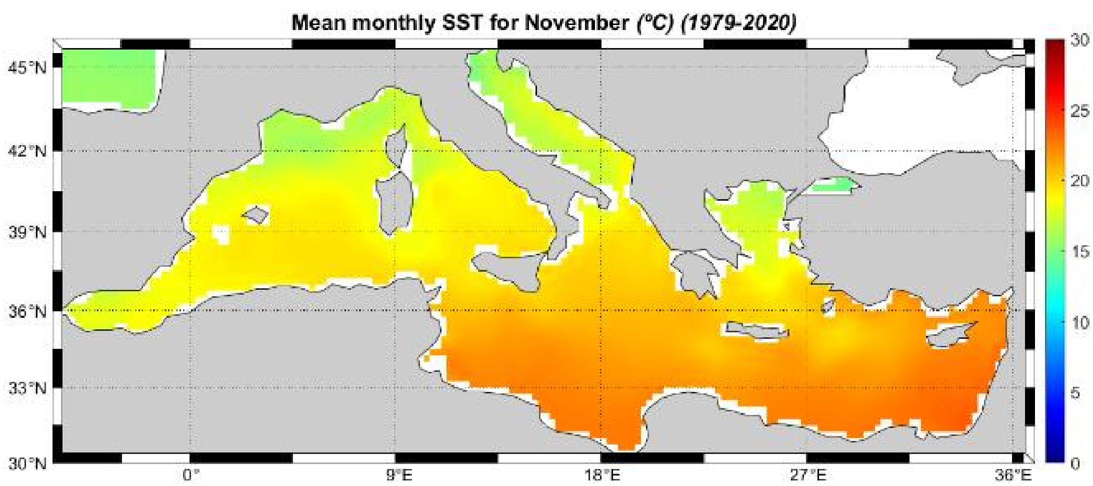

Mean monthly SST for June (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0


Mean monthly SST for July (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0


Mean monthly SST for August (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0


Mean monthly SST for September (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0


Mean monthly SST for October (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0


Mean monthly SST for November (ºC) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
30
25
20
15
10
5
0

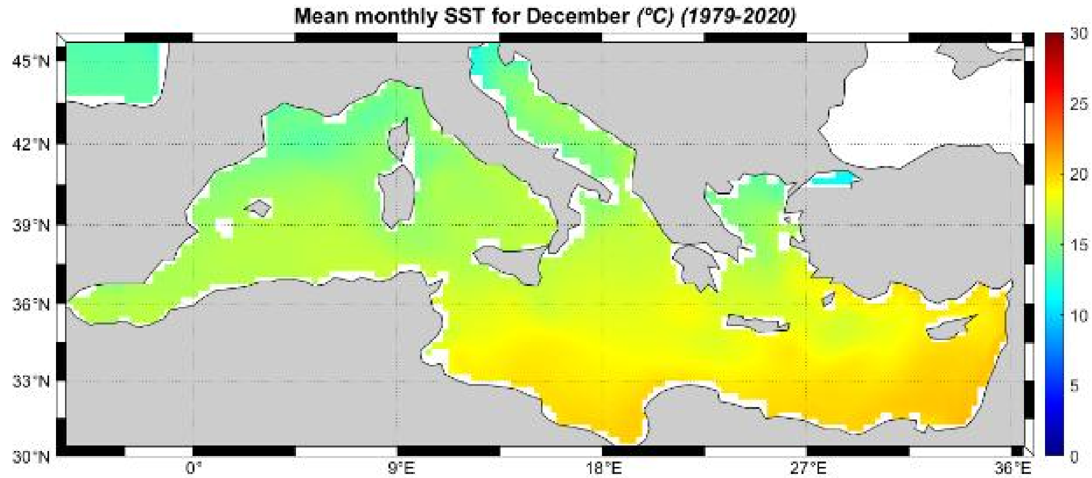
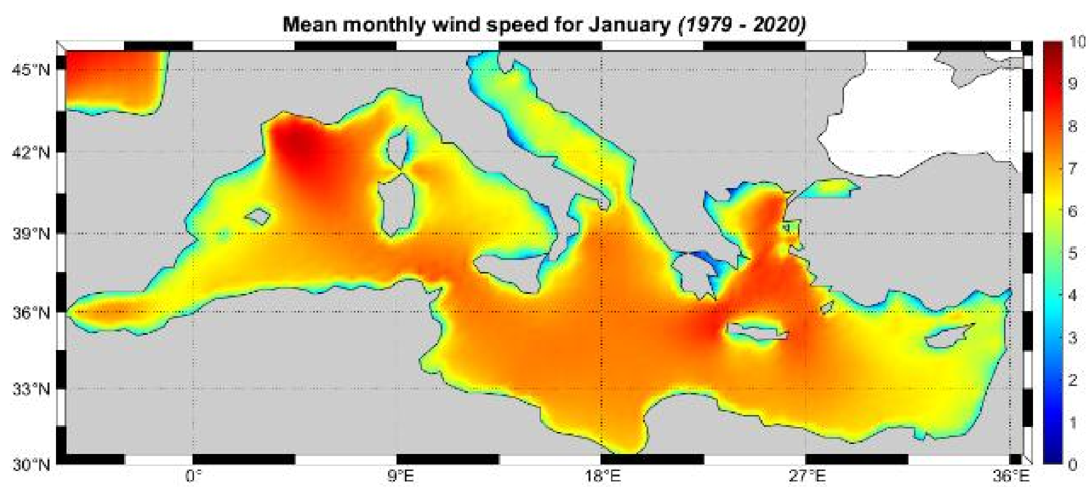
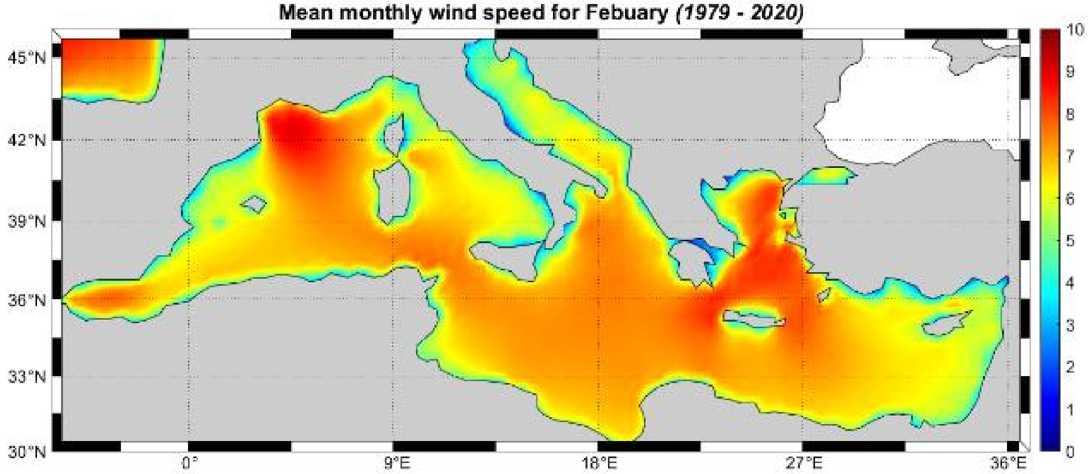


Figure 24 Mean monthly sea surface temperature

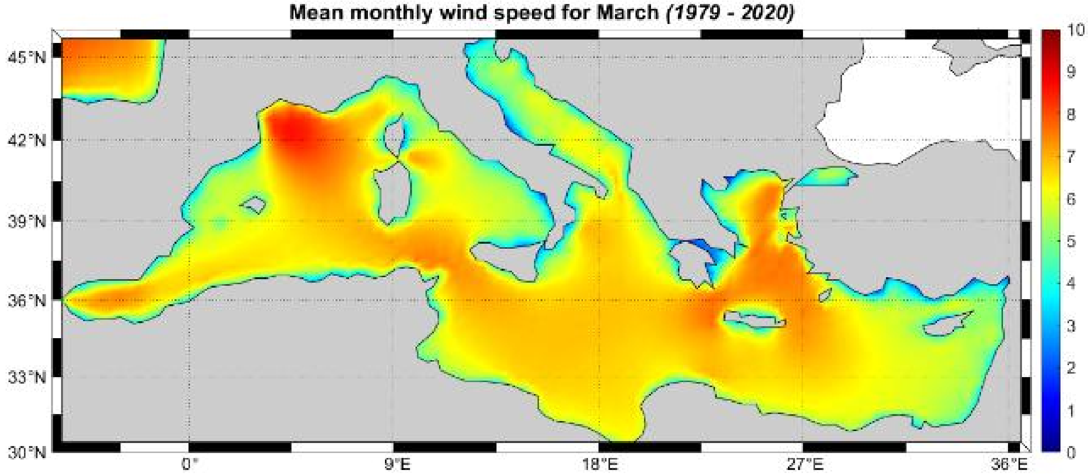
In Figure 24 the sea surface temperature for all the months has the same behavior of increasing values southwards. The mean sea surface temperature values increase from January and February, when they have their minimum (2.58ºC) until August, where they have their highest values (30.67ºC), and consequently they decrease until December.



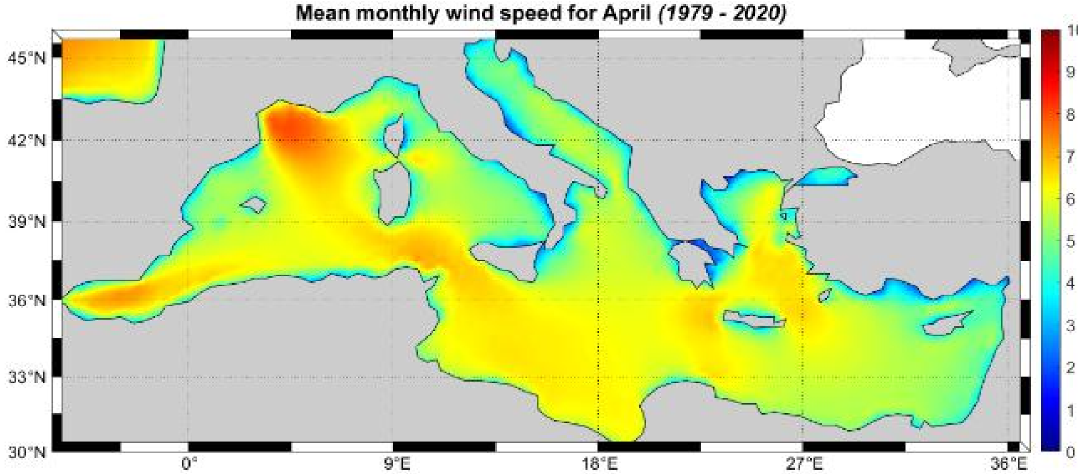
Mean monthly wind speed for Febuary *(1979 - 2020)*

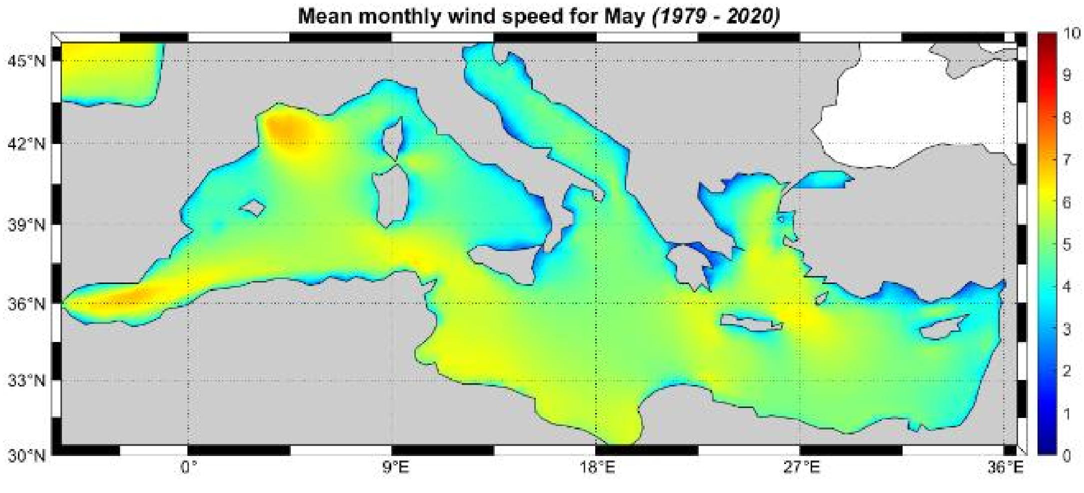


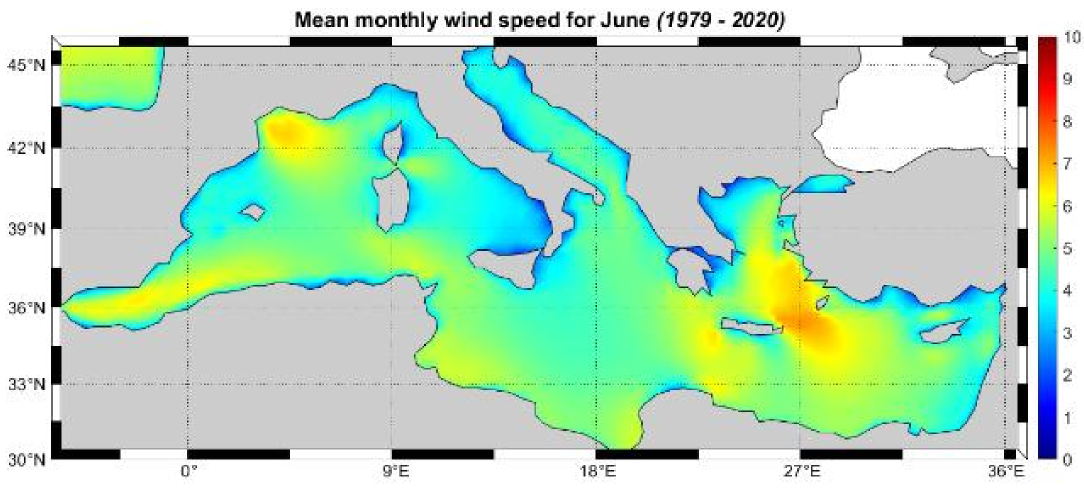
Mean monthly wind speed for March *(1979 - 2020)*

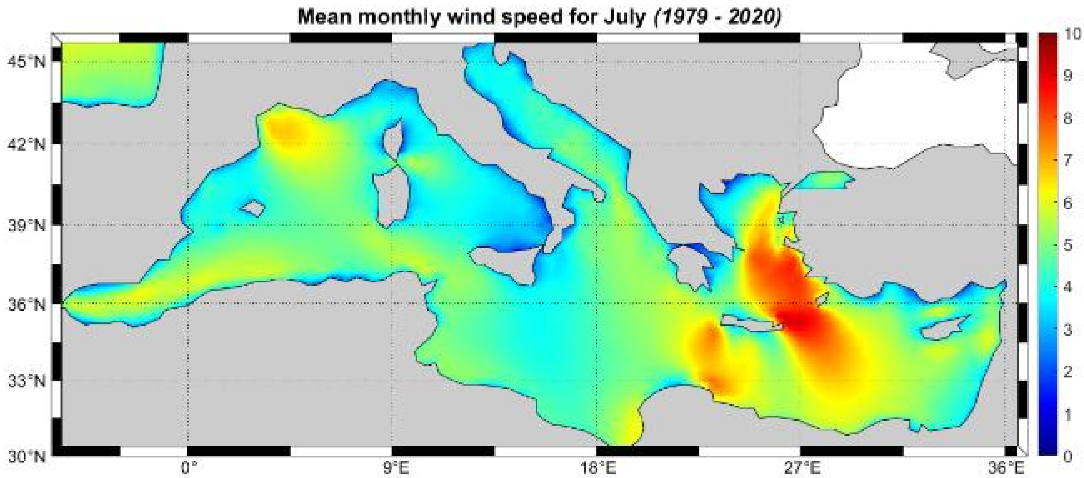


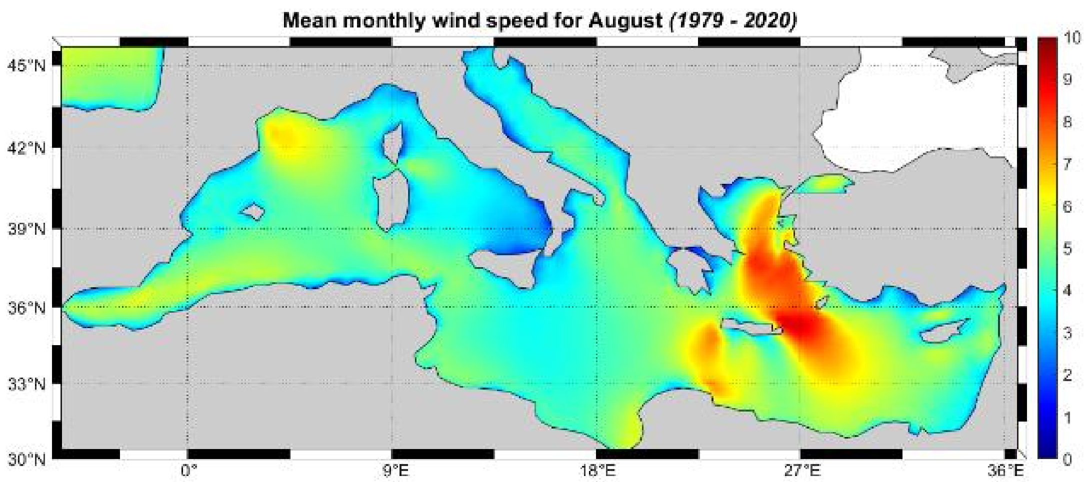
Mean monthly wind speed for April *(1979 - 2020)*

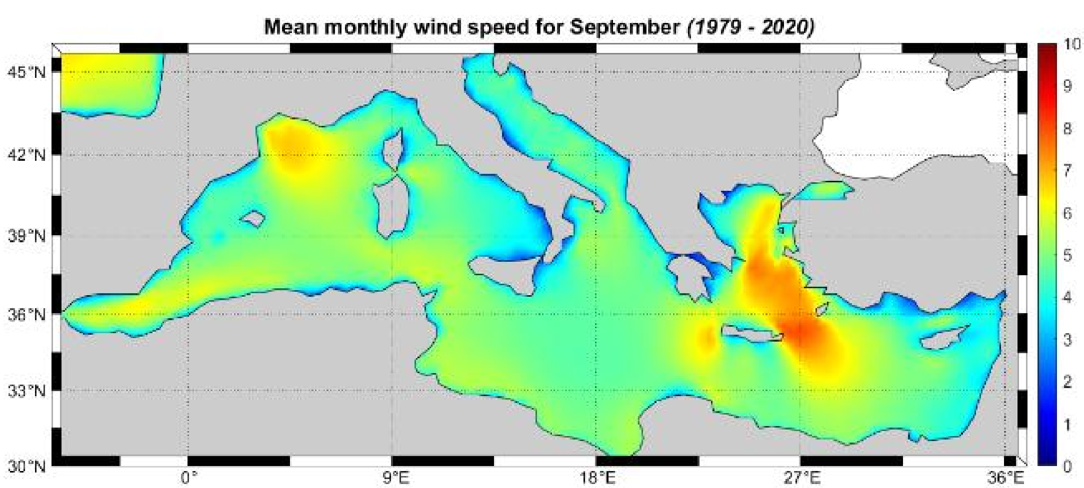


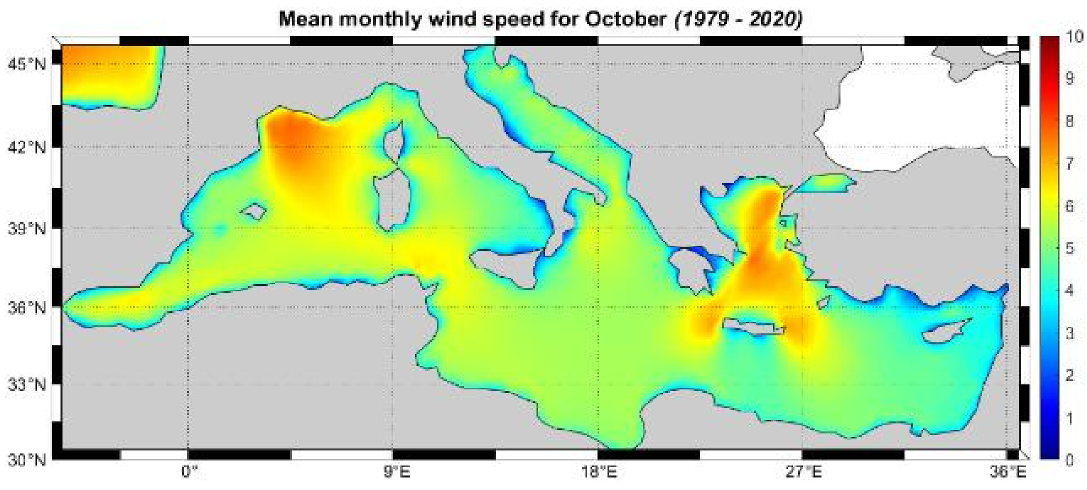

Mean monthly wind speed for May (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
10
9
8
7
6
5
4
3
2
1
0

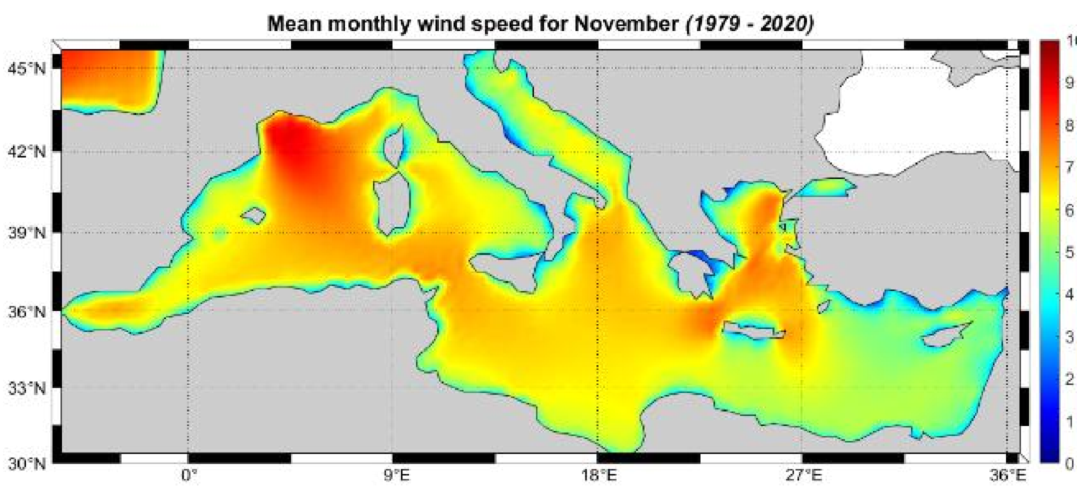

Mean monthly wind speed for June (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
10
9
8
7
6
5
4
3
2
1
0


Mean monthly wind speed for July (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0
1
2
3
4
5
6
7
8
9
10


Mean monthly wind speed for August (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0
1
2
3
4
5
6
7
8
9
10


Mean monthly wind speed for September (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0
1
2
3
4
5
6
7
8
9
10


Mean monthly wind speed for October (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
10
9
8
7
6
5
4
3
2
1
0


Mean monthly wind speed for November (1979 - 2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
10
9
8
7
6
5
4
3
2
1
0

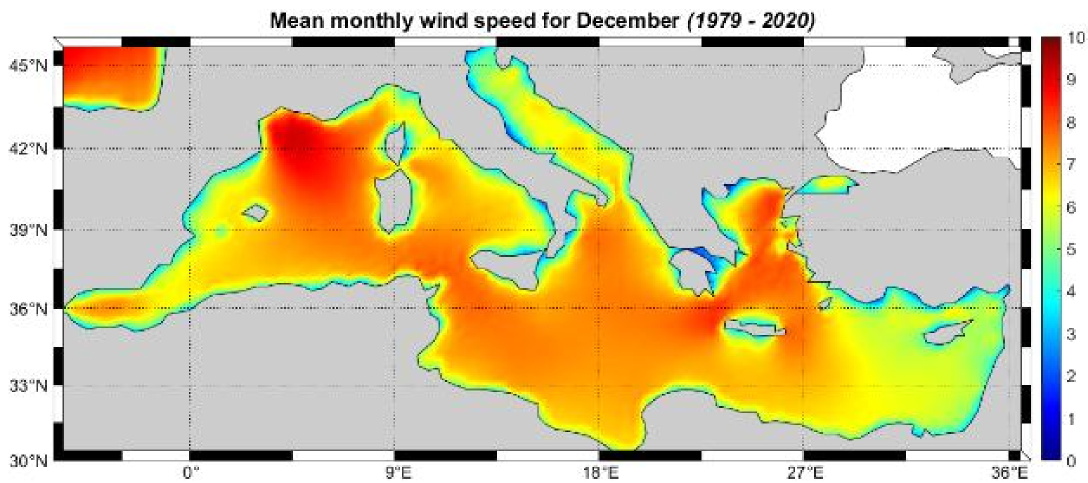


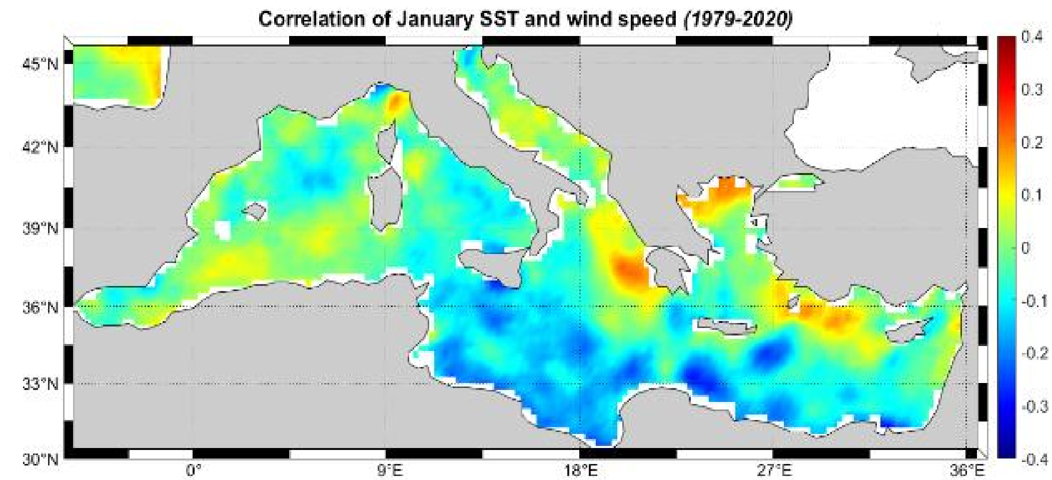
Figure 25 Mean monthly wind speed

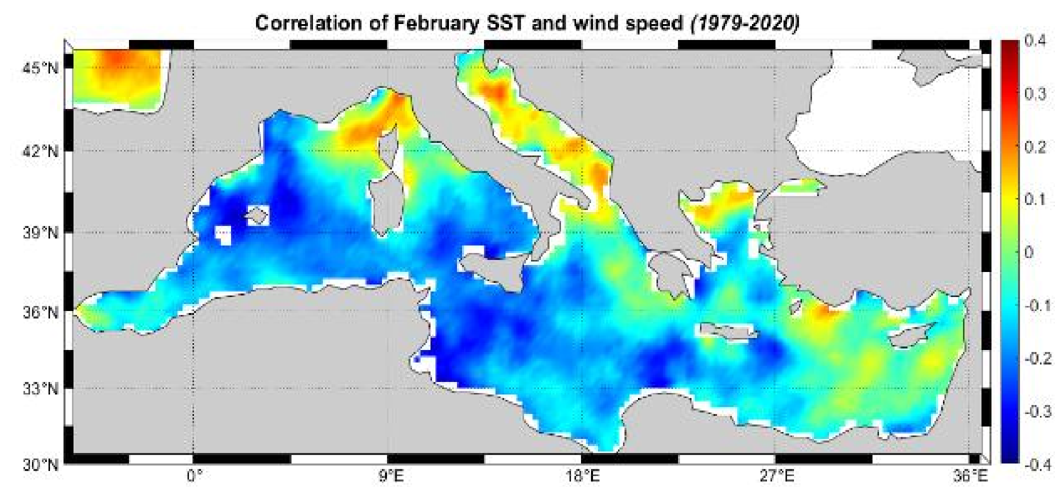
In Figure 25, some months are characterized by distinct features. From November to April, there are high wind speed values all over the basin, with highest values in the Aegean and the Balearic Seas. Wind speed starts to increase during November, and continues so until February, when it peaks. Then it decreases until April when it reaches values close to November's. For most of the basin, the wind speed values are around 7 m/s. From May until September, there are lower wind speed values all over the basin, compared to the previous period, however the Gulf of Lion and the Aegean Sea still have the highest values. The wind speed in the Aegean Sea increases from May to August, and then drops until September. For most of the basin, the wind speed values are around 4.5 m/s. During October, wind speed starts to increase all over the basin, and especially in the Aegean Sea and the Gulf of Lion. The month with the highest wind speed overall, is February and the overall highest mean wind speeds are encountered in the Gulf of Lions and the central Aegean Sea. The overall lowest wind speeds occur in August, notwithstanding the existence of the Etesians, as it is a localized phenomenon, and does not affect the entire basin.

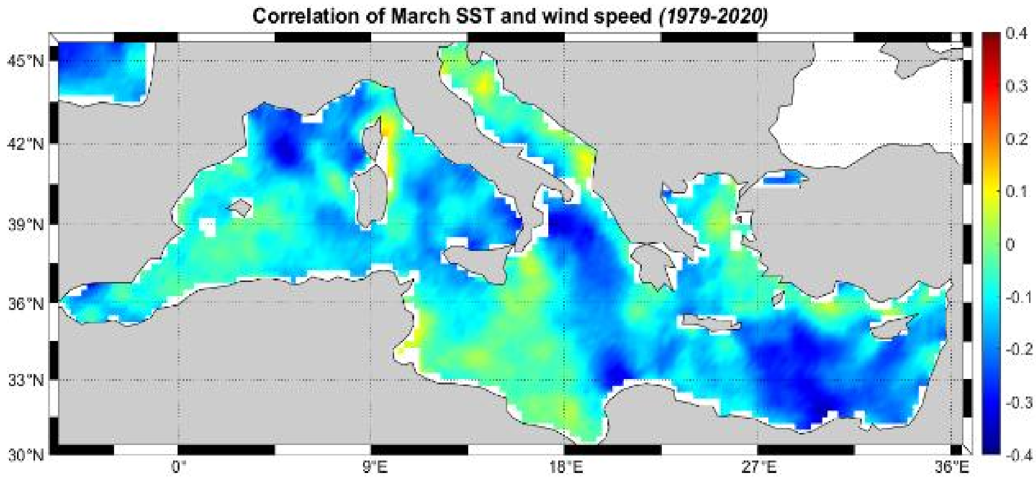
The general behavior between the two variables is opposite, with the sea surface temperature increasing from January until August, and the wind speed decreasing during the same period. An exception to this behavior is the existence of the Etesians, that have high values during August. The wind speed then goes on to increase again until December, while the sea surface temperature decreases.

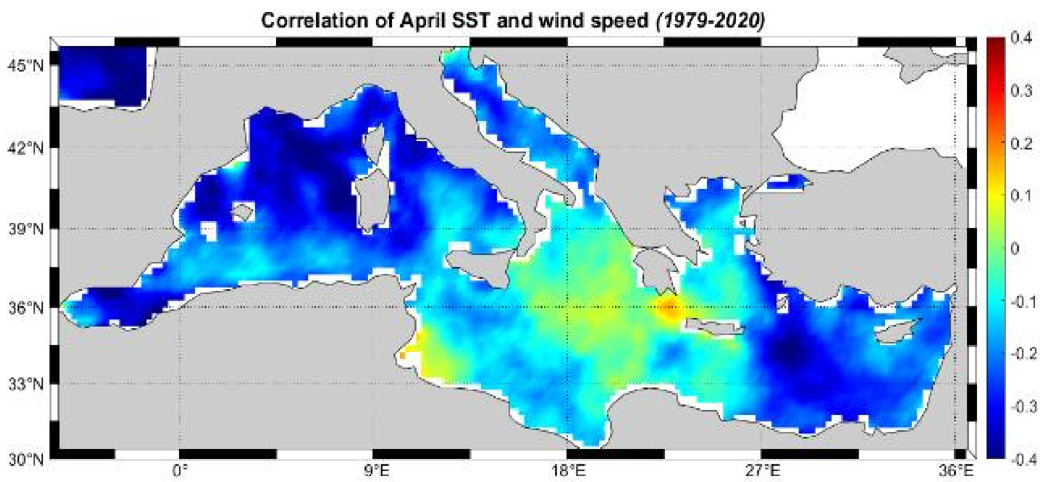
Mean monthly correlation

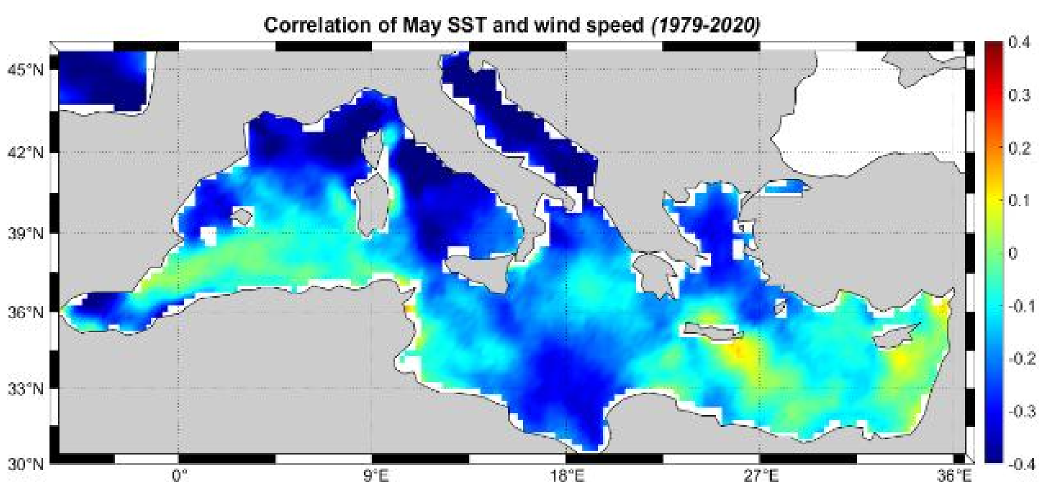
The correlation between the mean monthly sea surface temperature and the mean monthly wind speed is given for the different months:

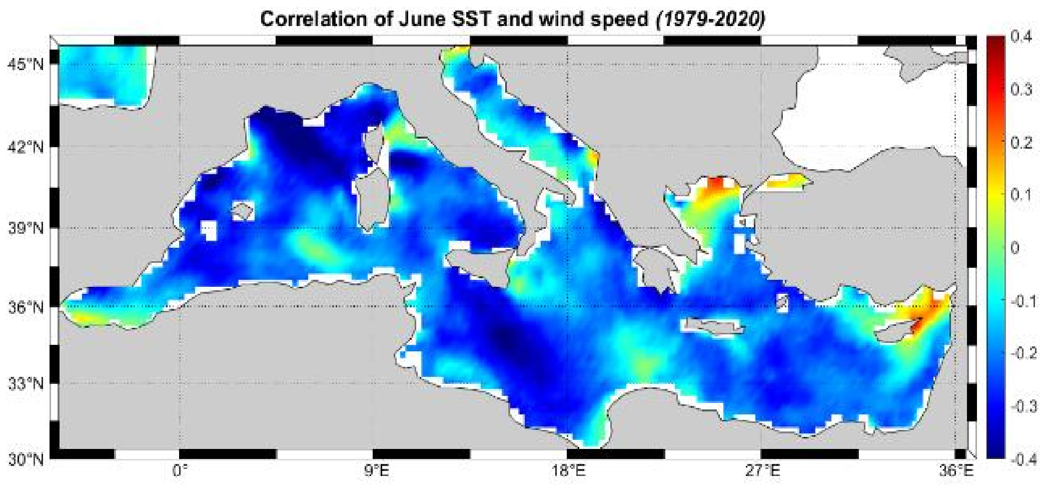


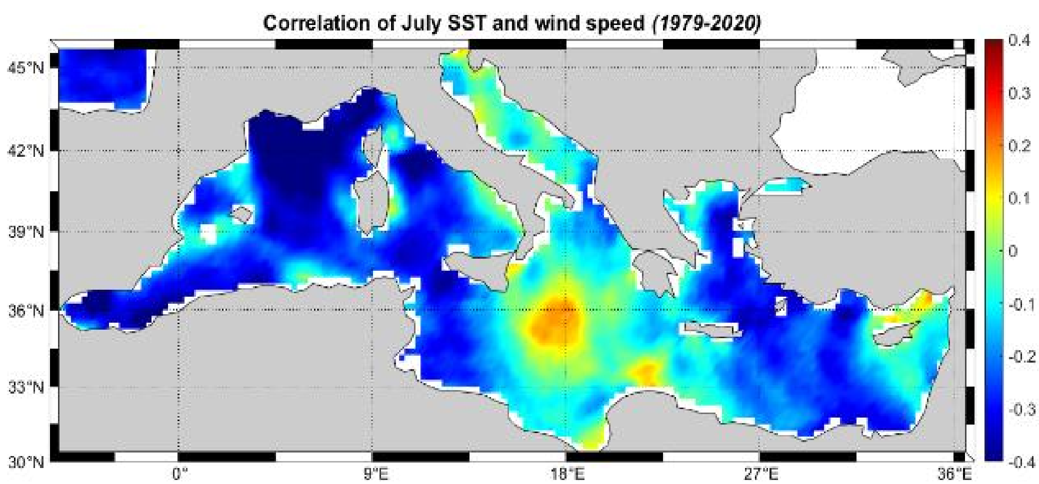


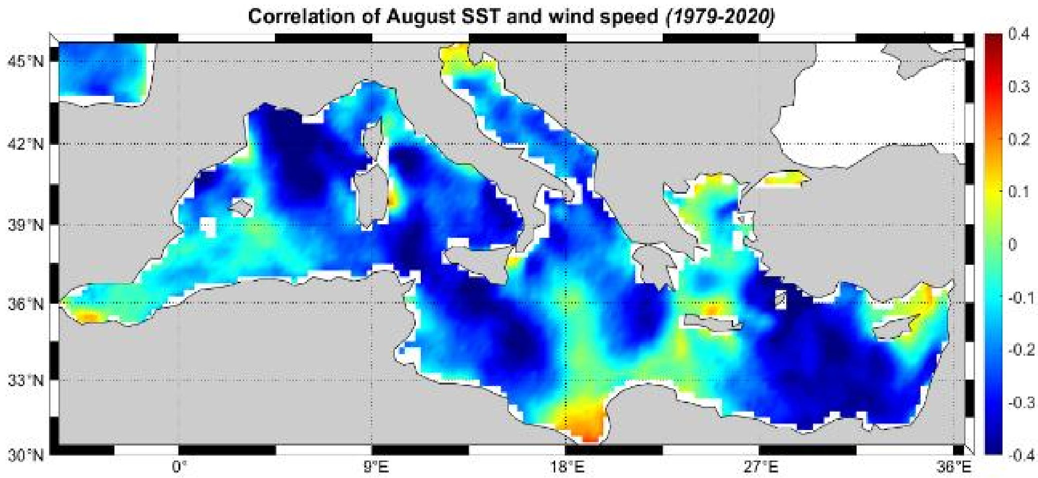

Correlation of March SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4

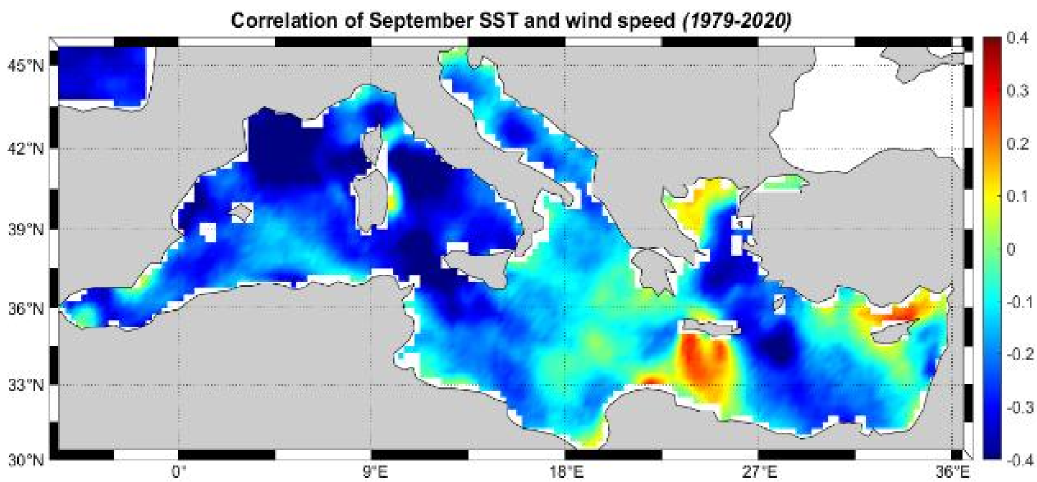

Correlation of April SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4

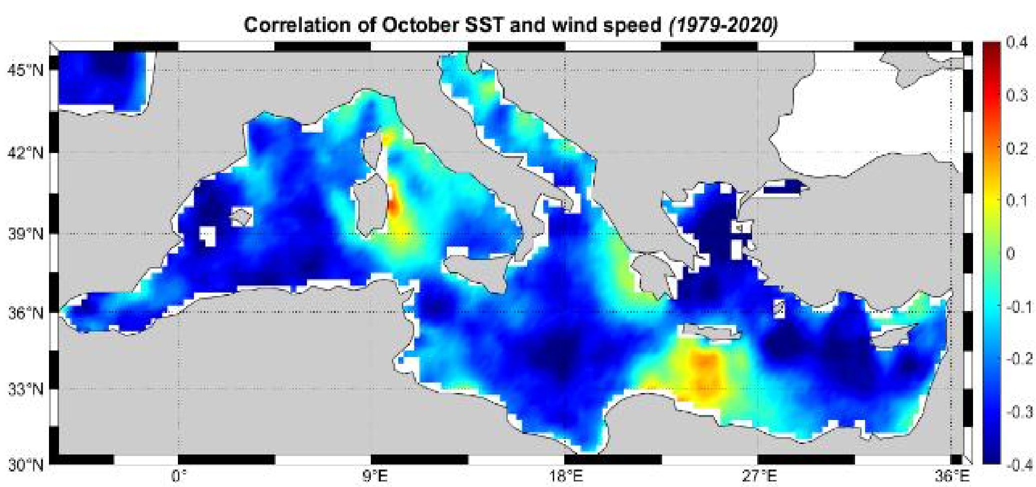

Correlation of May SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4


Correlation of June SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4


Correlation of July SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4


Correlation of August SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4


Correlation of September SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4


Correlation of October SST and wind speed (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4

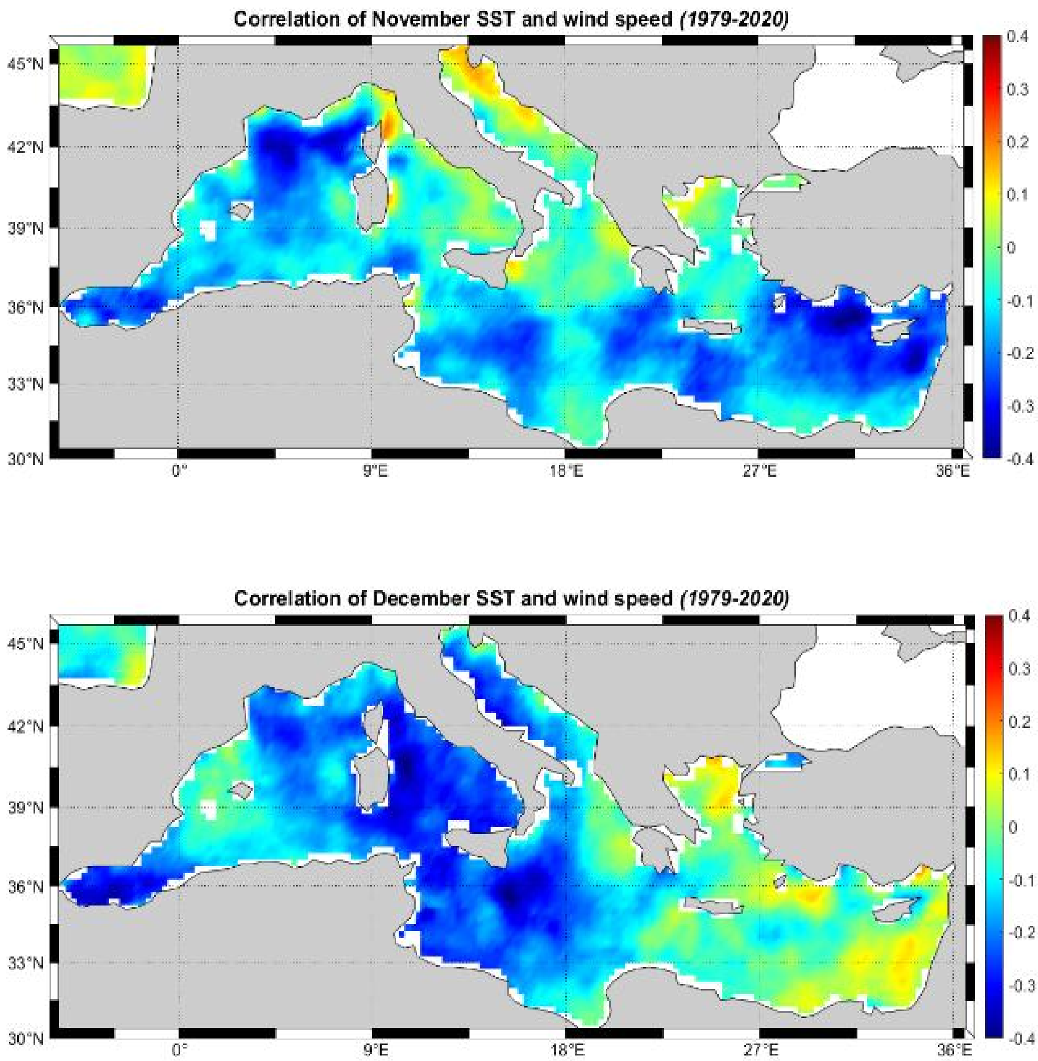


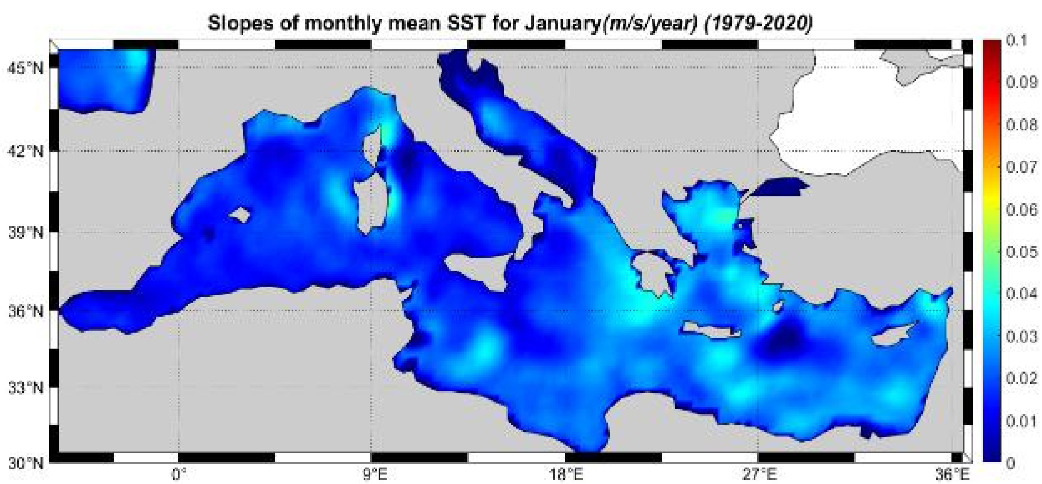
Figure 26 Correlation of mean monthly sea surface temperature and wind speed

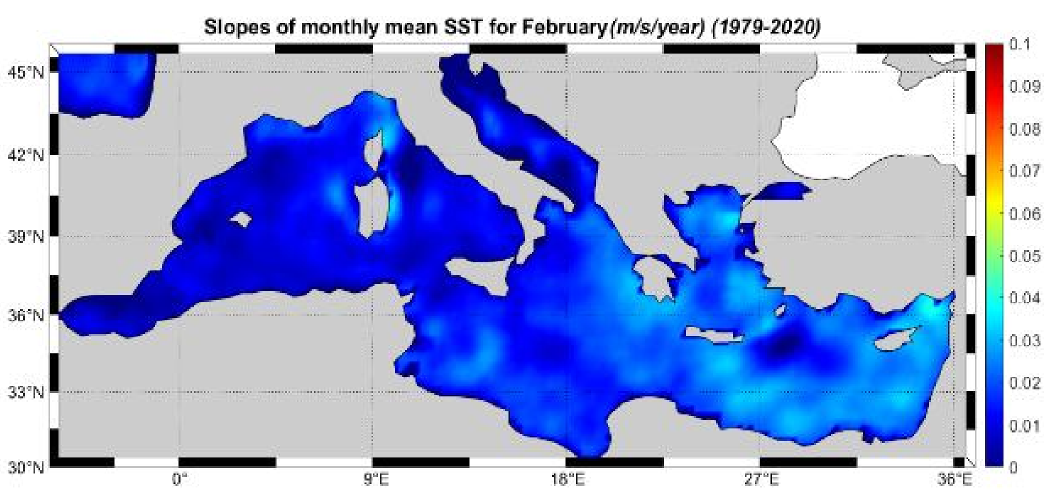
Figure 26 shows the correlation coefficient on the monthly scale, between the mean monthly values of sea surface temperature and wind speed. The west part of the basin has negative correlation coefficient values for most months, apart from January and March, when the majority of the slope values are close to 0. The east part of the basin also has negative values, apart from the months of January, February, May and December where the correlation coefficient assumes slightly positive values in certain areas. The central basin on the other hand, has positive values for more months in the year, and especially January, July and September, that present correlation coefficient values of over 0.3. The overall highest values appear in the north Aegean Sea, during June, and in the south

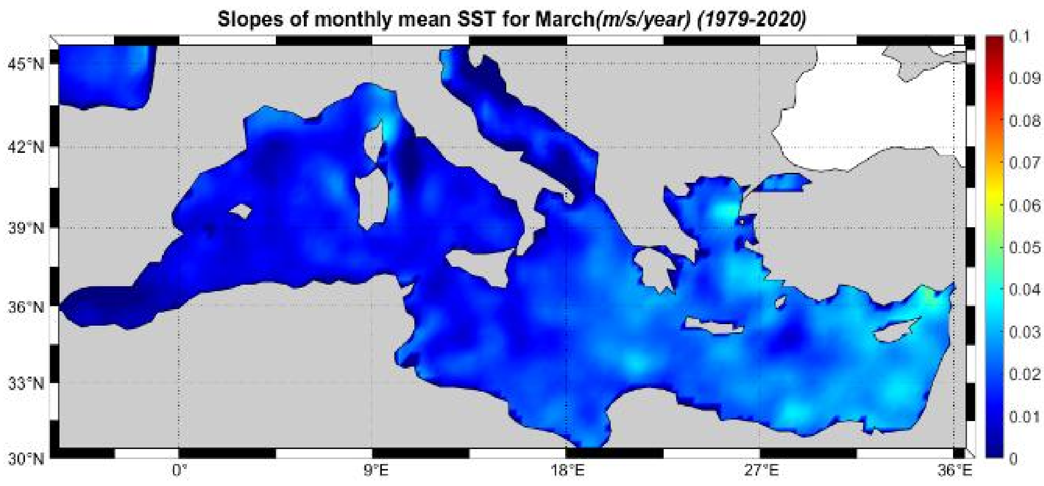
Levantine basin, off the south coasts of Crete Isl., during September. The month with the highest values all over the basin, however, is January, and therefore is the month that affects the general correlation between the two variables the most. During August, the Aegean is the region with the highest correlation, which could be attributed to the Etesian winds.

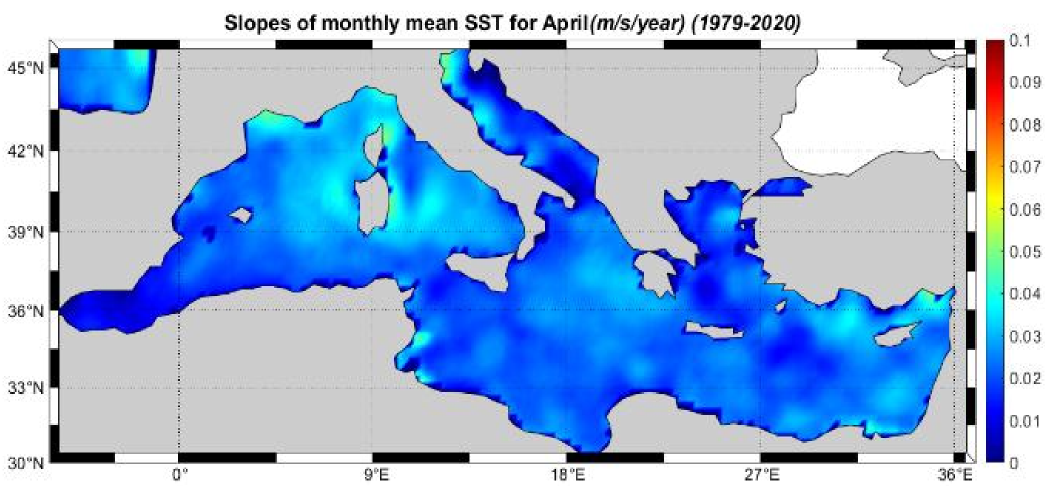
Mean monthly trends

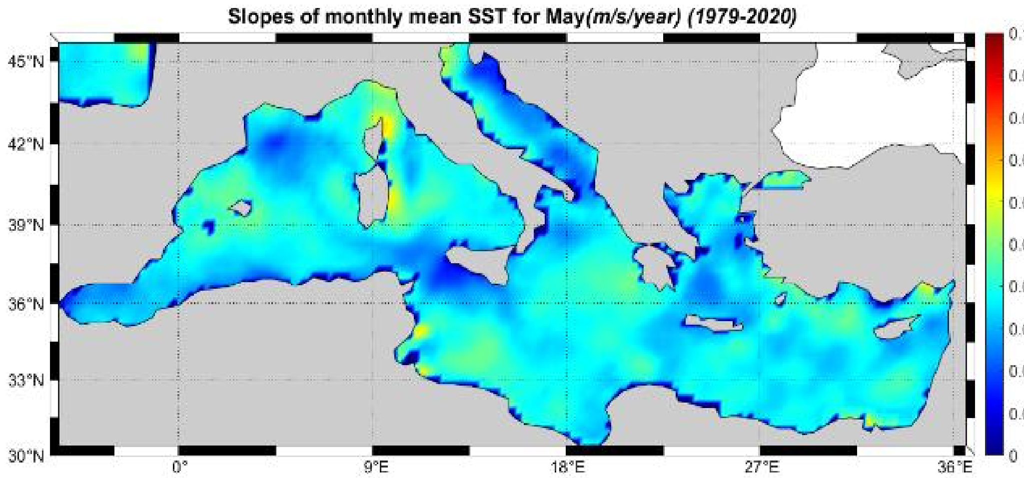
The following Figure 27 depicts the trends for the mean monthly sea surface temperature values.

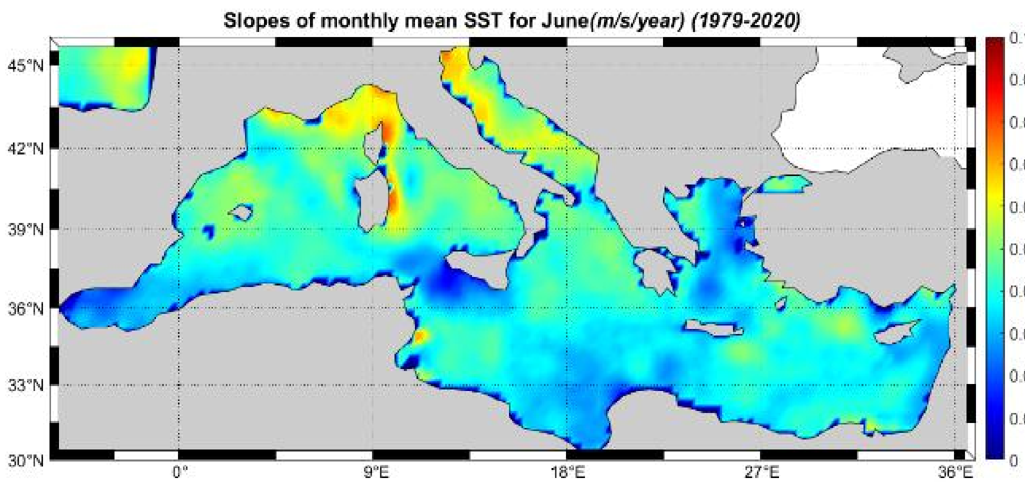


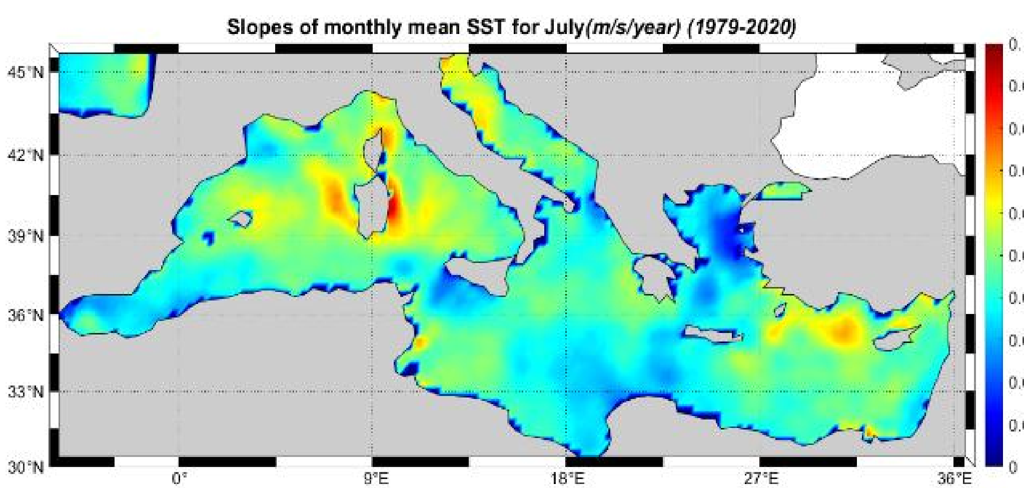


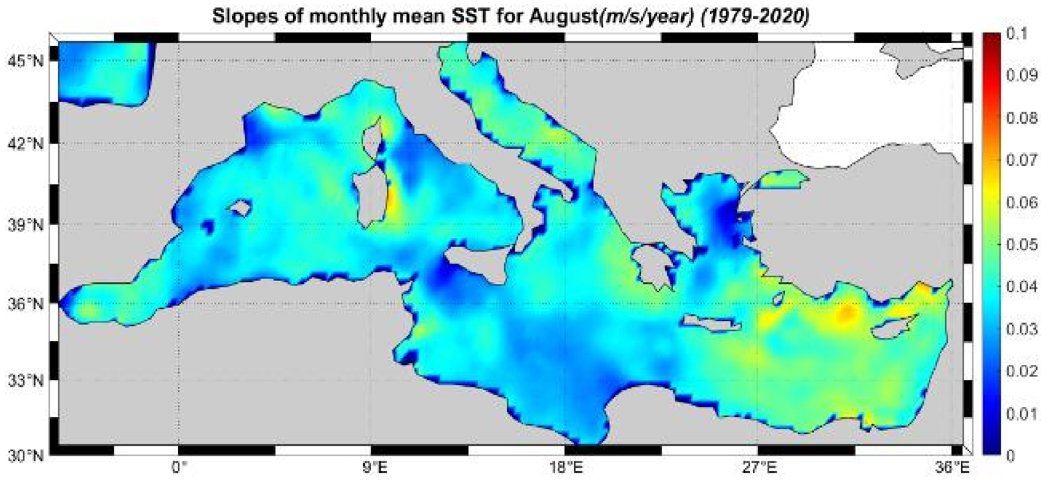

Slopes of monthly mean SST for March(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0


Slopes of monthly mean SST for April(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

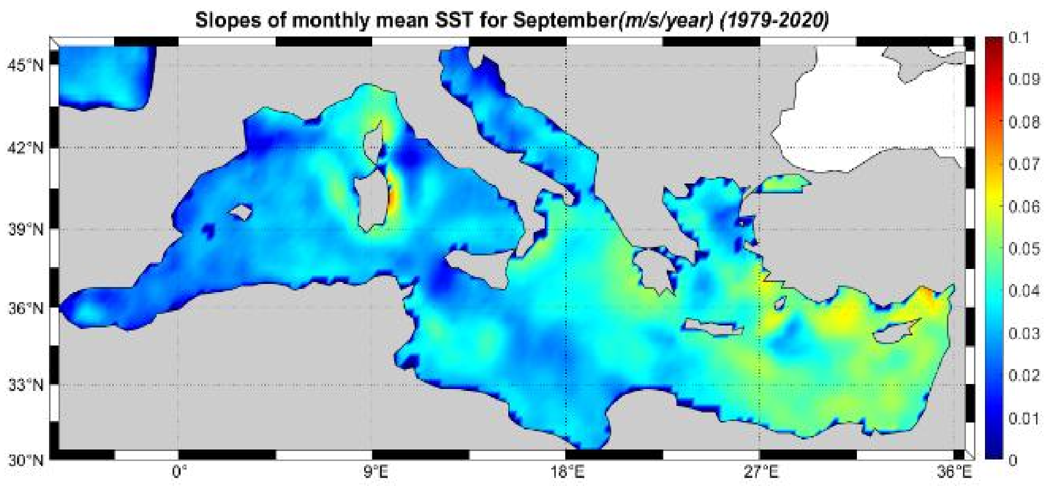

Slopes of monthly mean SST for May(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0


Slopes of monthly mean SST for June(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

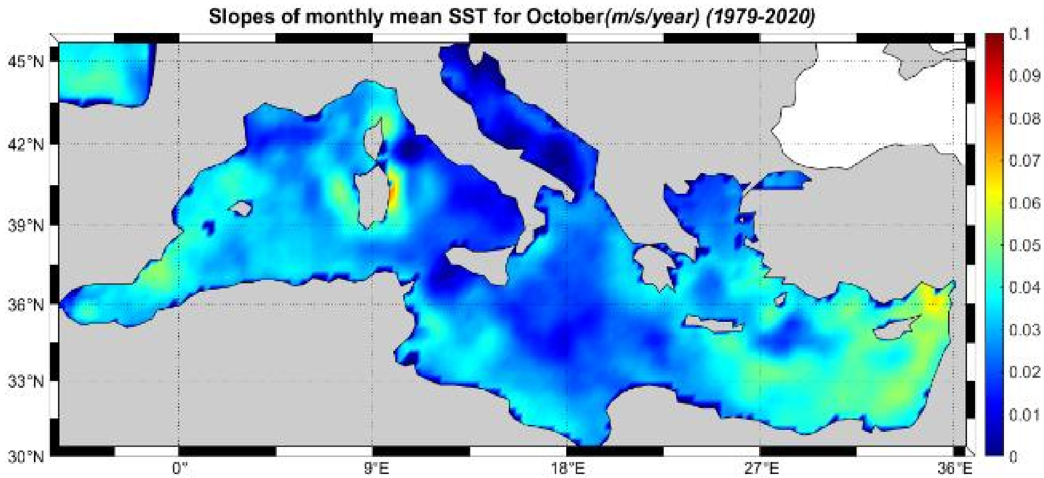

Slopes of monthly mean SST for July(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0



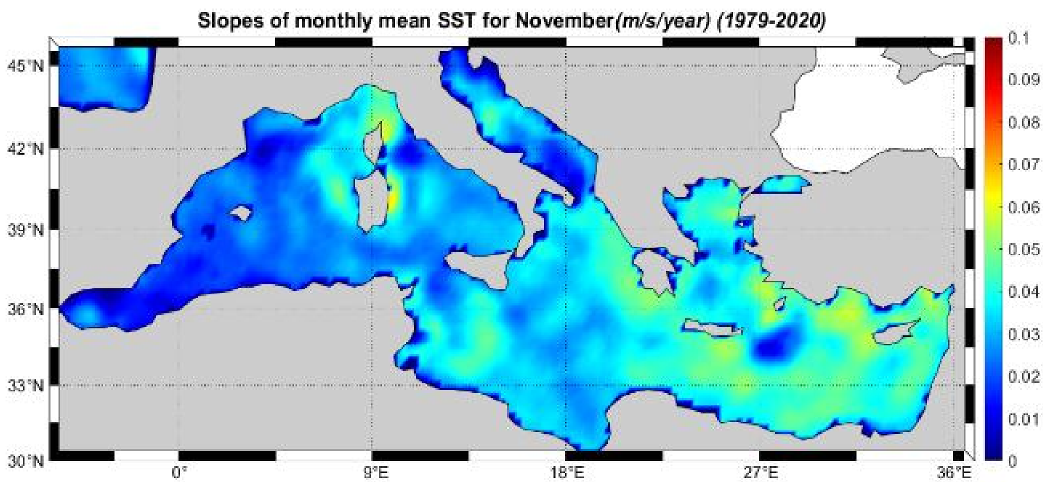
Slopes of monthly mean SST for August(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0



Slopes of monthly mean SST for September(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0



Slopes of monthly mean SST for October(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0



Slopes of monthly mean SST for November(m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

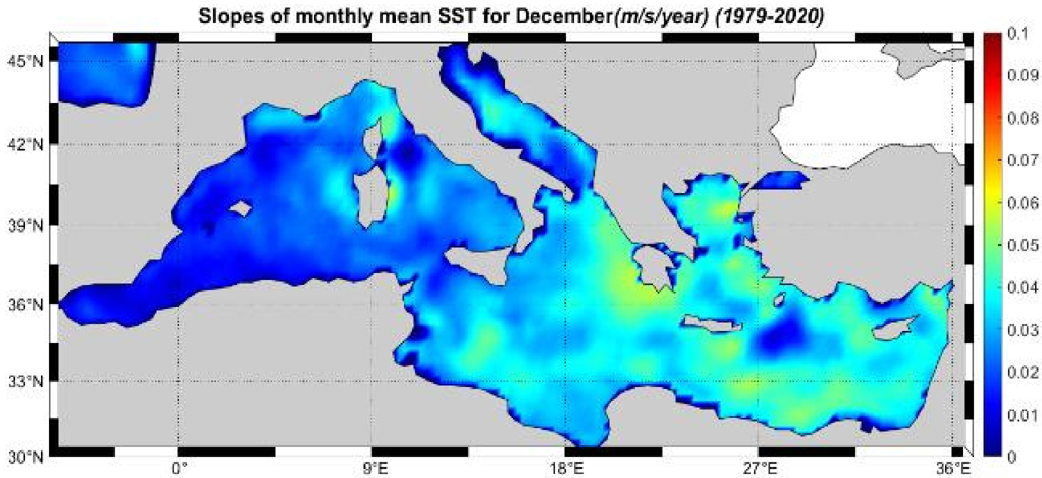
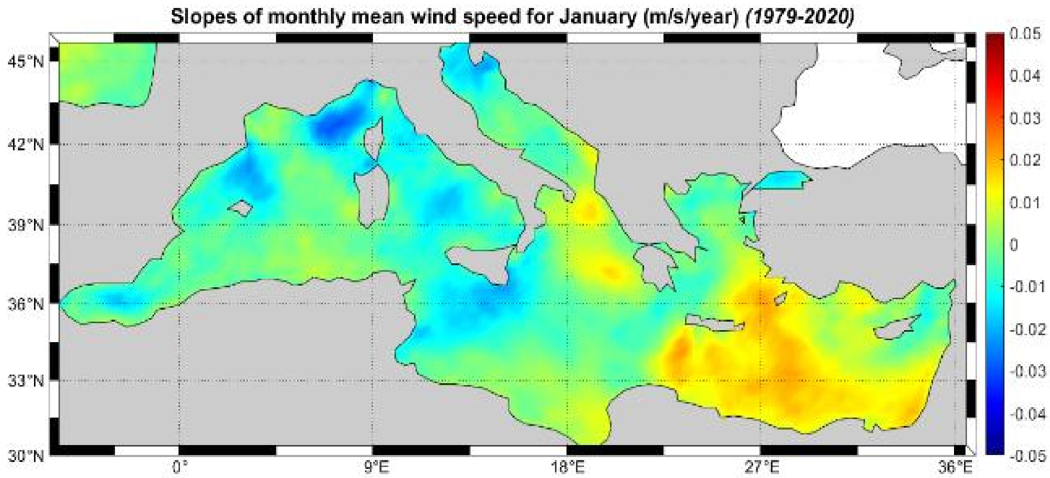
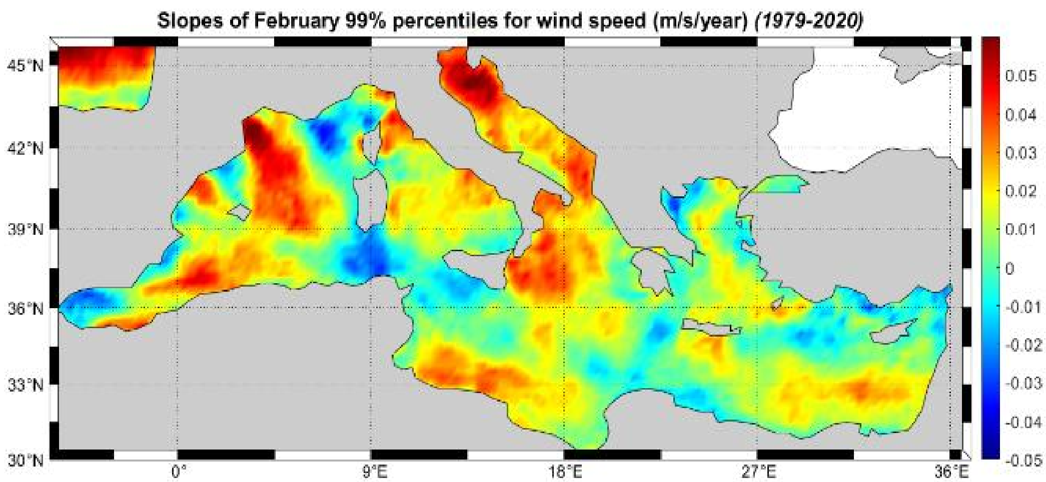
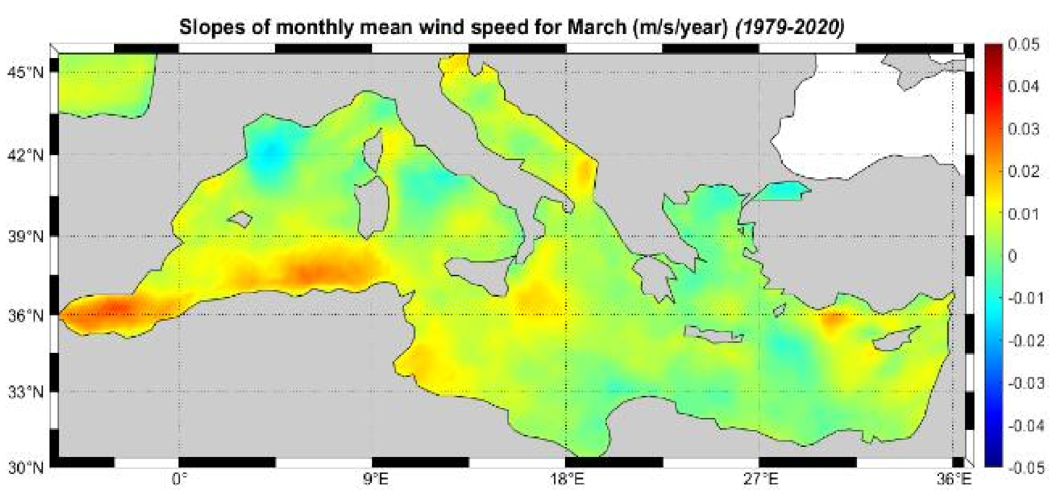


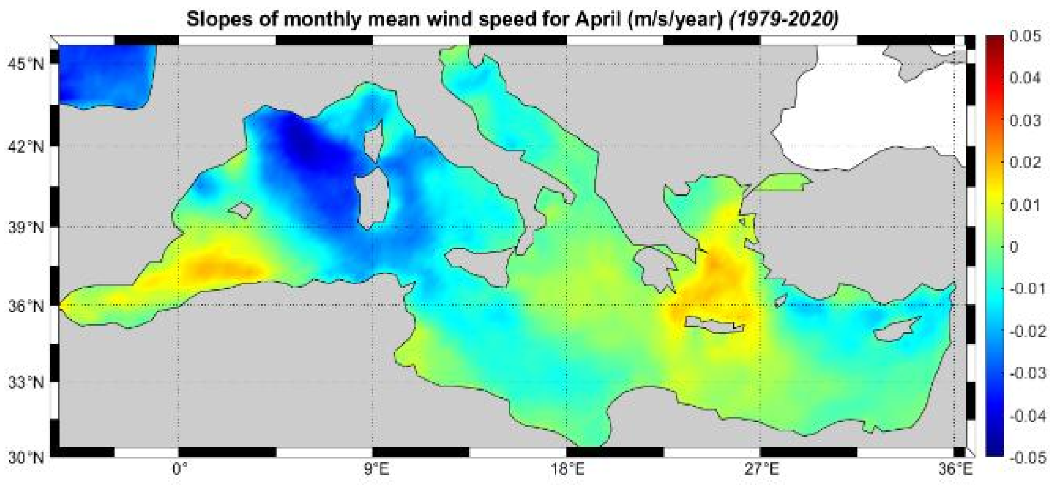
Figure 27 Mean monthly trends for sea surface temperature

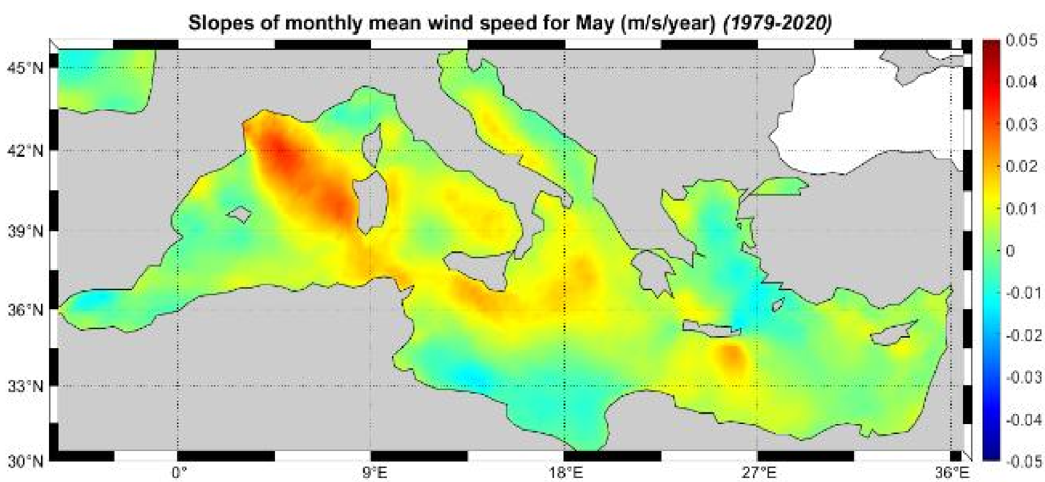
From January until June the slope values increase, and then from July until December they decrease. For most months, the eastern basin has higher values compared to the western part, apart from June and July, when it is the opposite. For all of the months, even in the period from January until April, when almost all of the basin has slope values around 0 m/s/year, the west and east coasts of Corsica and Sardinia, have the maximum slopes. The overall maximum (0.091 m/s/year) appears on the east coasts of Sardinia, during July, and the overall minimum (negative) slope (-0.092 m/s/year), appears in the north Adriatic Sea, during January. The west basin has negative or almost 0 slope values from January until March. In April the mean values start to increase especially in the Balearic, Ligurian and Tyrrhenian Seas, until July, when the whole western basin has values over 0.04 m/s/year. The mean values then decrease, with the sea space off the west coasts of Sardinia and Corsica always exceeding 0.06 m/s/year. The east basin presents the same behavior from January until April. Then, from May until September, the majority of the region has values around 0.05 m/s/year, with the north and northwestern parts exceeding 0.06 m/s/year. From September until December, an area off the east coasts of Crete Isl., in the central Levantine basin has increasingly negative slopes, while the rest of the east basin continuously has higher slope values. A distinct feature that can been noticed in the previous figures, is that across the coastal areas, the sea surface temperature slope values are 0.

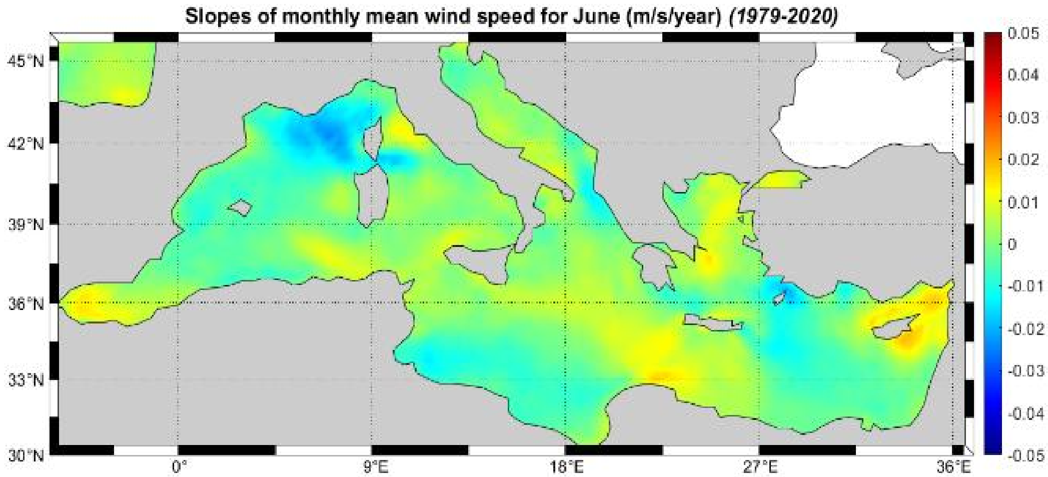

Slopes of monthly mean wind speed for January (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05

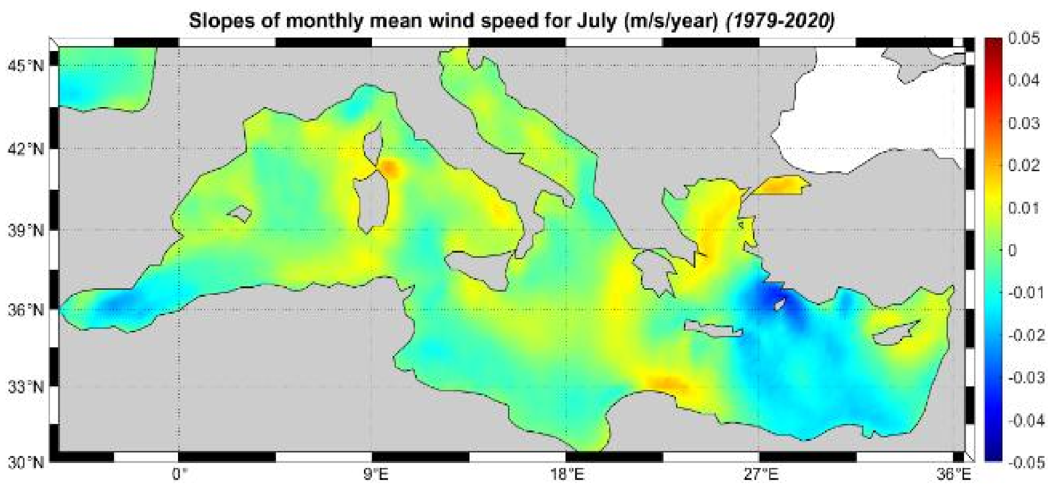

Slopes of February 99% percentiles for wind speed (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05

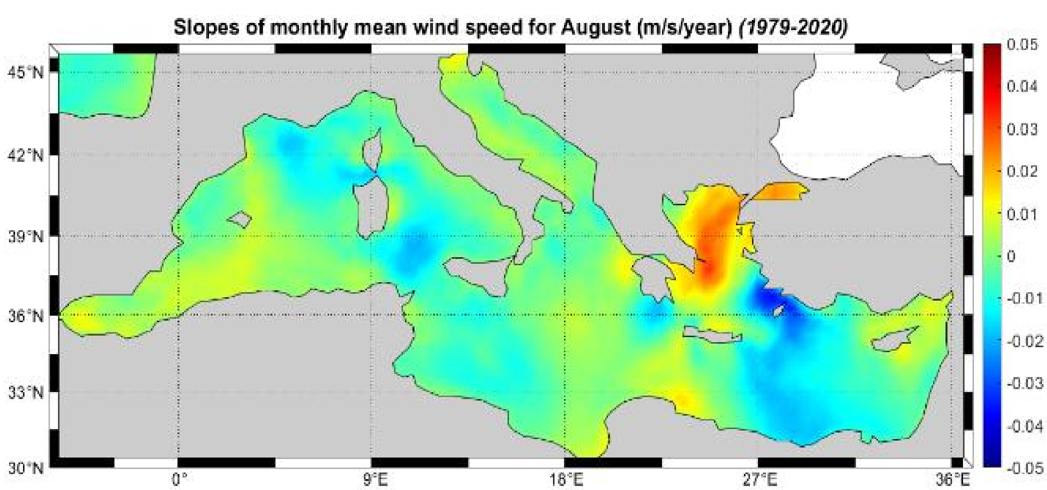

Slopes of monthly mean wind speed for March (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05

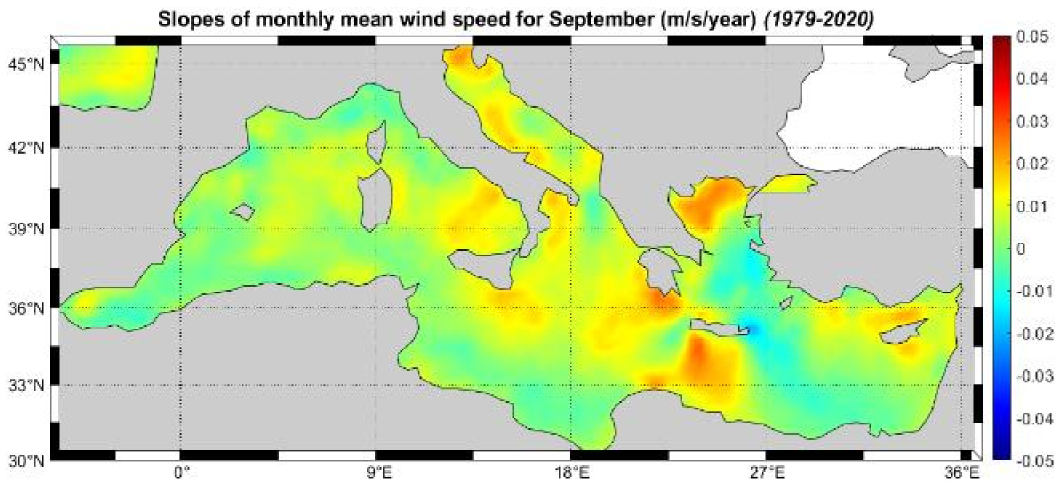

Slopes of monthly mean wind speed for April (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05

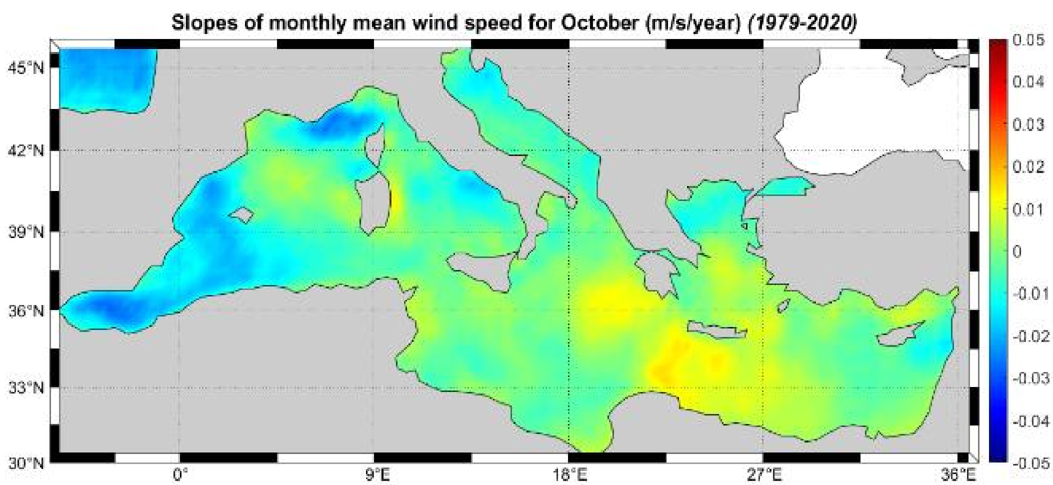

Slopes of monthly mean wind speed for May (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05

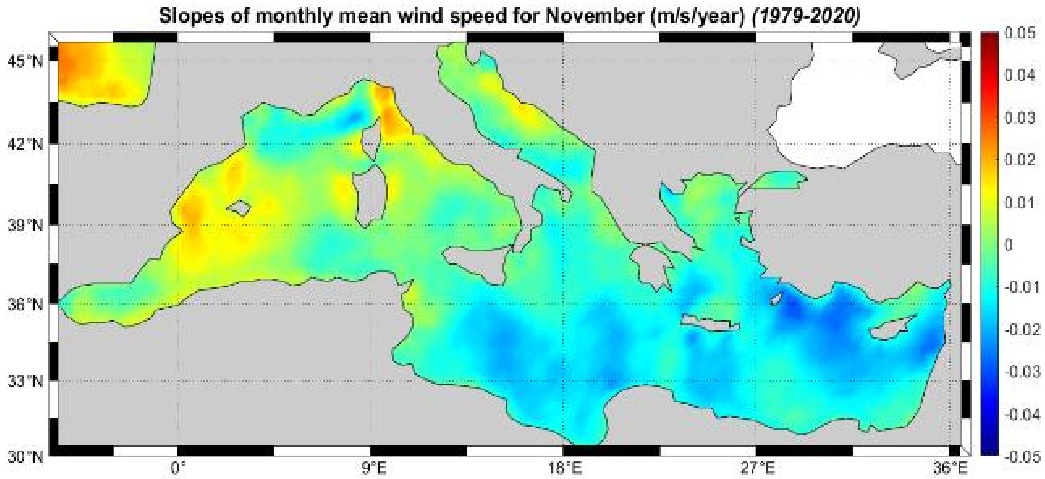

Slopes of monthly mean wind speed for June (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05


Slopes of monthly mean wind speed for July (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05


Slopes of monthly mean wind speed for August (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05


Slopes of monthly mean wind speed for September (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05


Slopes of monthly mean wind speed for October (m/s/year) (1979-2020)
45°N
42°N
39°N
36°N
33°N
30°N
0°
9°E
18°E
27°E
36°E
0.05
0.04
0.03
0.02
0.01
0
-0.01
-0.02
-0.03
-0.04
-0.05



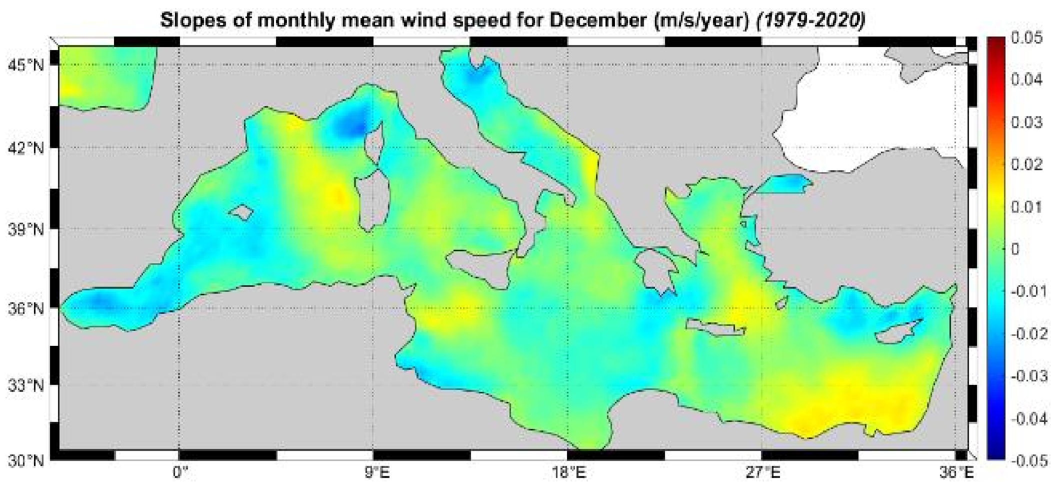


Figure 28 Mean monthly trends for wind speed

In Figure 28 the linear trends are depicted for the monthly mean wind speed. The overall maximum (0.035 m/s/year) and minimum (-0.045 m/s/year) slopes are encountered during May and April accordingly, both in the Gulf of Lion. In January the east basin has higher slope values than the west basin, while the opposite happens in February. In March, the Alboran Sea has the highest slope values, extending across the African coasts. In April, the area extending from the Gulf of Lion to the east coasts off Sardinia have the lowest slopes, while the Alboran and the Aegean Seas have the highest. In May, that is reversed, and the majority of the basin is characterized by positive slopes, with the Gulf of Lion having the highest values. During June, July, and August the slope spatial distribution is similar, with very low absolute slopes (close to 0 m/s/year) in the western Mediterranean and increasingly positive slopes in the Aegean Sea (reaching values up to 0.034 m/s/month during August), due to the Etesian winds. There are also increasingly negative slopes in the Levantine basin. October, November and December are characterized by rather mild slopes.

Comparing the slopes of sea surface temperature and wind speed, what is easily discernible is the fact that in February there are very low (and negative) sea surface temperature slopes all over the basin, and very high wind speed slopes. In April, when the sea surface temperature slopes in the Gulf of Lion tend to increase, they wind speed slopes at the same area decrease to negative values abruptly. The opposite happens in May, with decreased sea surface temperature slopes and increased wind speed slopes in the area. During July and August, the Levantine basin has higher sea surface temperature slopes than most of the basin, but the wind speed slopes are lower there than the rest of the basin.

5. Conclusions

The core of this study contained the joint analysis of the wind speed and the sea surface temperature in the Mediterranean Sea, as well as the relationship between the two linear variables. The Mediterranean was selected as it is an area especially indicative of global climatic changes. At the same time, the study of the variability of metocean characteristics is important, since the variability of these parameters, like the ones studied here, can be modified extensively due to climate change, demonstrating its existence and effects. Therefore, the study of the variability of the wind speed and the sea surface temperature in the Mediterranean, can be a good indicator of any alteration to the global climate, due to human activities. The provided results were produced after statistical analysis of the datasets from the ERA5 reanalysis.

The sea surface temperature examination indicated that the mean annual values increase southwards, as expected, while the mean annual and inter-annual variabilities decrease southwards. The trend for the mean annual values is highest in the eastern basin, and the 95 and 99 percentile trends are highest in the Adriatic, Ionian, and Levantine basins. The wind speed examination revealed mean annual values highest in the Gulf of Lion and the Aegean Sea. The mean annual variability decreases southwards, while the inter-annual variability is highest in the Tyrrhenian Sea. The trend for the mean annual values is highest in the West Levantine, the Aegean, and the Ionian Seas. The 95 percentile trend is highest in the Alboran, the Algerian, and the Adriatic basins, while the 99 percentile trend is highest in the Alboran, Algerian, Adriatic, and southern Levantine basins. The mean annual correlation between the two variables appears to be the highest off the east coasts of Corsica and Sardinia Isls., two areas that also appeared to have high inter-annual variability for both parameters. In general, the correlation results on both time scales examined -the annual and the monthly- did not provide robust enough conclusions on the interrelations of the two variables.

Considering the trends for the studied variables, in the case where these slopes remain constant in the coming decades, in 2100 the mean temperature for the whole basin is expected to increase by 2.34ºC, and the overall mean wind speed by 0.031m/s, although not in an even fashion throughout the basin. This overall increase for wind speed is very slight to be considered a significant result. On the other hand, the sea surface temperature projection lays between the RDP2.6 and the RCP8.5 projections for the increase in the global sea surface temperature (see Chapter 1.5).

In order to produce a more detailed analysis of the wind climatology and the sea surface conditions of the Mediterranean basin, future research would require a higher spatial resolution with a larger number of gridpoints in the area. Previous work has indicated that one way of achieving this would be downscaling the ERA5 datasets. It should however be considered, that an expected improvement in the multi-decadal analysis results should be achieved when the expected addition of the data for the decades 1950 - 1978 in the ERA5 datasets is complete. Trend examination results may differ significantly since the added data can provide an expanded view on the behavior of both variables, their mean and extreme values. Moreover, wind direction is an important parameter in the wind energy yield, and potential future studies could combine sea surface temperature, wind speed and wind direction, for a more complete overview of the Mediterranean wind energy regime.

According results of long-term metocean variability for the annual, seasonal, and decadal timescales should be quantified and should be taken into consideration to produce realistic and trust-worthy projection results, needed for the future anthropogenic climate change mitigation actions and operating conditions of marine renewable energy projects. Recently, the climate change mitigation action plan, has been paused on a political level, due to the pandemic, the wars, and the global energy crisis that ensued. However, these are all interconnected with the athropogenic climate change and the vast alterations that are increasingly encountered everywhere in the world and should not be confronted as an entirely different issue. The generations that grow up with the notion of the anthropogenic climate change and the adverse impacts it will have on their future shape a different understanding. Their experience will significantly influence their way of making decisions in relation to mitigation and adaptation in the coming years.

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