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THE IMPACT OF THE ATLANTIC MERIDIONAL OVERTURNING CIRCULATION (AMOC) VARIABILITY ON THE MEDITERRANEAN CLIMATE FOR THE LAST SIX DECADES

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SUMMARY

The Atlantic Meridional Overturning Circulation (AMOC) is a major ocean circulation system in the Atlantic Ocean. The AMOC transports heat to the poles and cold saline waters to the tropics. This mechanism is responsible for many climate and weather systems, firstly by keeping the temperatures mild even in high latitudes and secondly by providing heat and moisture to the air. This mechanism is naturally unstable and changes in time, depending on sea-ice melt, wind patterns, sun radiation variation etc. Anthropogenic climate change and global warming has altered the balance in the global system accelerating change. As models evolve and improve their outcomes, recent research has indicated that the AMOC is in a weaker state than previously thought with impacts more severe than expected. As AMOC is a global circulation system, the impacts can reach remote systems many kilometers away. Given that the Mediterranean is a hot spot for climate change and the risks it faces can get severe, we focus on the relationship between the two remote systems, the AMOC slowing down and the Mediterranean climate. We use the ECMWF ERA5 Reanalysis datasets, which are the newest reanalysis datasets, to get our monthly datasets (sea surface temperature, surface air temperature and precipitation) from 1959 to 2021, and correlate them with an AMOC fingerprint. We found that there is indeed a relationship although it is not homogenous and there is no evident, strict pattern. More specifically there is a connection between the AMOC and the Mediterranean Sea surface and air temperatures up to a two-year time lag, and a strong winter correlation with the precipitation in the Mediterranean up to three years ahead. The results are encouraging. They suggest a possibility for improved forecasts in the region as well as predicting several months in advance any extreme events.

ΠΕΡΙΛΗΨΗ

Το AMOC είναι από τα κυριότερα συστήματα ωκεάνιας κυκλοφορίας στον Ατλαντικό. Μεταφέρει θερμότητα από τις ζεστές τροπικές περιοχές, στους πόλους και, αντίστροφα, ψυχρά αλμυρά νερά από τους πόλους σε νοτιότερα πλάτη. Ο μηχανισμός αυτός έχει σημαντικό ενεργό ρόλο για πολλά κλιματικά και καιρικά φαινόμενα. Ο τρόπος με τον οποίο συμβαίνει αυτό, είναι αρχικά διατηρώντας τις θερμοκρασίες σχετικά ήπιες ακόμα και σε υψηλά γεωγραφικά πλάτη, λόγω των θερμών νερών. Κατά δεύτερο, τα θερμά νερά αποτελούν πηγή θερμότητας και υγρασίας για την τροπόσφαιρα, ελέγχοντας έτσι καιρικά φαινόμενα όπως καταιγίδες. Ο μηχανισμός κυκλοφορίας είναι εκ φύσεως ασταθής και μεταβλητός στον χρόνο. Επηρεάζεται από πολλούς παράγοντες που ελέγχουν την ωκεάνια κυκλοφορία, κυρίως από την παροχή γλυκού νερού πάγων, από τα συστήματα ανέμων, από την ηλιακή ακτινοβολία κ.ά.. Η ανθρωπογενής κλιματική αλλαγή και παγκόσμια θέρμανση έχει αλλάξει τις ισορροπίες στο γήινο παγκόσμιο σύστημα, μεταξύ άλλων, ενισχύοντας και επιταχύνοντας φυσικές διεργασίες. Καθώς τα κλιματικά και ωκεάνια μοντέλα βελτιώνονται και εξελίσσονται, πρόσφατες έρευνες υποδεικνύουν ότι το ρεύμα του Ατλαντικού έχει μια τάση καθυστέρησης τα τελευταία χρόνια, αρκετά πιο σημαντική συγκρινόμενη με προηγούμενες προσομοιώσεις, με αρκετά πιο έντονες επιπτώσεις σε παγκόσμια κλίμακα. Δεδομένης της κρισιμότητας των φαινομένων που αντιμετωπίζει η Μεσόγειος εν όψει της κλιματικής αλλαγής και των δυσμενών συνθηκών που θα πρέπει να αντιμετωπίσει στα επόμενα χρόνια, επικεντρωνόμαστε στη σχέση που μπορεί να έχουν τα δύο απομακρυσμένα συστήματα, το AMOC και το κλίμα της Μεσογείου. Στην έρευνά μας χρησιμοποιούμε δεδομένα από τη βάση ECMWF ERA5 reanalysis που είναι από τις πιο πρόσφατες και έμπιστες χρονοσειρές σήμερα. Συγκεκριμένα χρησιμοποιούμε μηνιαίες τιμές για την επιφανειακή θαλάσσια θερμοκρασία, την επιφανειακή θερμοκρασία του αέρα και το συνολικό ύψος κατακρημνισμάτων, για το χρονικό διάστημα από το 1959 ως και το 2021, και τις συσχετίζουμε με κατάλληλα επιλεγμένο δείκτη του AMOC. Από τα αποτελέσματά μας προκύπτει πως πράγματι υπάρχει μια σχέση μεταξύ των δύο συστημάτων, η οποία όμως δεν είναι ομοιογενής και δεν παρουσιάζει κάποια σταθερή τάση, κοινή για τις παραμέτρους. Συγκεκριμένα, προκύπτει πως υπάρχει αξιοσημείωτη σχέση μεταξύ του AMOC και των δύο θερμοκρασιών (θαλάσσια και αέρα) με χρονική καθυστέρηση ως και δύο χρόνια, ενώ βρέθηκε ισχυρή συσχέτιση με τα κατακρημνίσματα του χειμώνα με επίδραση έως και τρία χρόνια μετά. Τα αποτελέσματα είναι σίγουρα ενθαρρυντικά. Εξακρίβωση της σχέσης μεταξύ του AMOC και της Μεσογείου σε επόμενες έρευνες, μπορεί δυνητικά να βελτιώσει σημαντικά τις προγνώσεις στην περιοχή και να προειδοποιηθούν με αυτό τον τρόπο οι τοπικές κοινωνίες για ακραία καιρικά φαινόμενα, μήνες πριν συμβούν.

Preface

This study would be impossible without the precious help of Ms Iliana Polychroni. With her skills, experience and patience, she guided me through all the code lines needed to get our results. Her efficiency made a long on hold passion of mine come to life, pushing me to take the next steps in research and get from a huge amount of data to a tangible result.

Special thanks to my supervisor Maria Hatzaki that showed me trust and gave me motivation to develop my thoughts and my past inspirations into new ones. After our collaboration I feel more than ready to take my next step in my career.

Contents

1 INTRODUCTION

Human induced climate change has caused widespread impacts and damages to nature as we know it today and, consequently, to humans. It is projected with high confidence, according to the IPCC Sixth Assessment Report (AR6), that during this century, temperatures and severe marine heat waves will increase, there will be stronger upper-ocean stratification, a rise in global mean sea level, increased ocean acidification and oxygen decline. Acting as Earth's inertia to climate change are the oceans absorbing both the excessive Carbon Dioxide humans released to the atmosphere causing the Earth to warm, as well as excessive heat. It is believed that by absorbing heat and CO_2, oceans have masked part of the climate change. Of course, all this heat does not go unnoticed. The oceans chemical composition has been altering to the detriment of ocean life and ecosystems. Another thing happening is altering the ocean circulation system. According to the IPCC AR6, global warming has increased global sea surface temperatures on average by 0.88°C, in a range from 0.68 to 1.01°C since 1850, with 0.60°C of this warming having occurred since 1980. Increased heat and increased fresh-water input from the melting of ice-sheets, cause a weaker circulation. Many ocean currents will decline with high confidence due to anthropogenic climate change (IPCC AR6 WG1, 2021), including the Atlantic Meridional Overturning Circulation which is very likely to decline in this century. Although AMOC's decline is very likely, there is low confidence in the timing and magnitude of the decline.

The Atlantic Meridional Overturning Circulation or AMOC is the main overturning system of the Atlantic and it transports warm surface water northwards and cold deep-water southwards, as part of the global ocean circulation system. The AMOC influences global ocean heat content and transportation, global anthropogenic carbon uptake, climate sensitivity and sea level change. It's relationship with climate is close, since it can cause surface air temperature change, and rainfall pattern change. The AMOC regulates precipitation patterns and moisture transports and can also cause shifts in the ITCZ, Hadley Cell and the Northern Hemisphere westerly jet (Liu et al, 2020). Besides that, it plays an important role in the energy flux between the top of the atmosphere and the Earth's surface. With this many impacts, changes in the AMOC are of concern.

At the same time the Mediterranean has exhibited some spectacular changes as a result of climate change. According to the Mediterranean Action Plan for the United Nations Environment Programme (Climate Change in the Mediterranean factsheet), the Mediterranean is warming faster than the global trend. The air temperature is expected to warm by 20% faster than the global average and by 1.54 degrees higher. Already the sea surface temperatures have risen by 0.4 degrees. Rainfall is to decrease by 30% in an already dry area. The risk for fire, heatwaves, erosion and other environmental issues is escalating.

Most of the natural systems on Earth are connected. Climate is definitely something binding the world together since important climatical phenomena such as the Asian monsoons, the el Niño and la Niña cycles, global wind routes and atmospheric jets, can be caused by forces far away and be felt kilometers further. Global and regional feedbacks, positive and negative, are transferring these forcings and effects to different subsystems and regions. With this thought, there might be a connection between the AMOC and most specifically AMOC' variability with the climate in more southern areas than its position, like the Mediterranean.

The Mediterranean being an already distressed place due to climate change with a worrying future (MedECC, MAR1, 2020), is at high risk and need for better future projections to adapt and resist to the expected conditions. In the following paragraphs, we try to find how the weakening AMOC affects Mediterranean Sea surface temperature, surface air temperature and total precipitation.

In this study, first some theoretical background will be given, explaining how the ocean circulation works and how it affects the climate through some observed examples in historical times. Moreover, an introduction will be given regarding the weakening of the circulation, based on previous research and the possible impacts such a progressive decline might have. Before giving some basic information about the Mediterranean region, observational and measuring systems and techniques for the AMOC system investigation will be explained, including models and how they work. Some future scenarios will be reported, and the section will be concluded with insight into the statistical methods necessary for this study. In the next section we will explain the methodology followed and the data that we used, as well as how we analyzed them in order to present our results and remarks in the third section. This study will end with our final conclusions on the matter and with the references list.

2 THEORETICAL BACKGROUND

The oceans, covering about 70% of the Earth's surface, are not only abundant but are vital for life and climate on the blue planet (NOAA, Ocean facts, 2023). Under the ocean surface, more than 500000 species form complicated ecosystems that either depend on each other (like in coral reefs) or are completely different and even almost isolated (deep sea ecosystems) (UN ocean factsheet 2017). Humans depend on the ocean as well. Almost 40% of the world's population lives near the coast. Marine resources such as fishing, touristic evolvement, energy and material exploitation, transportation are of global importance, and drive not only economic growth and engineering development but also political decisions (UN ocean factsheet 2017). For Earth, the oceans are the means to transport energy and heat throughout the globe. The sun provides the oceans with energy which gets absorbed and stored, due to the high heat capacity the oceans have. This way, they keep global (and local) climate relatively steady. They are also a global storage for carbon dioxide and isotopic information, reflecting past global climate and/or other major natural phenomena. By transporting heat and humidity, it can create weather and climate systems extending for many kilometers inland. In fact, looking back in paleoclimate records, changes in climate are associated with changes in ocean circulations (Meccia 2022). Moreover, they absorb excessive carbon dioxide and release oxygen. Since the oceans are in direct connection with the atmosphere, in a non-stop dynamical exchange of energy, humidity and molecules, they are vital for climate research.

This energy and matter circulation is all part of Earth's energy budget. The sun provides energy in the form of radiation (total solar irradiance). Part of that energy reached the earth's surface and part of that is reflected back to space. The fraction of the energy that gets reflected is called albedo or planetary albedo (Trenberth, 2022). To be in an energetic balance, means to have an equal energy outflow with the inflow. When achieving energetic balance, the climate is relatively stable, since there is no warming or cooling. So, the incoming shortwave solar radiation should be equal to the outcoming longwave Earth's radiation. However, the Earth is a special place and is surrounded by the atmosphere. The atmosphere in turn, absorbs not only part of the solar incoming radiation but also part of the emitted outgoing radiation that gets either re-emitted or absorbed. The absorption and re-emission of energy by the atmosphere of mostly the longwave radiation is increasing Earth's temperature, that would otherwise be shockingly low. This phenomenon is called the greenhouse effect, which is known to be intensified due to human activities, raising temperatures globally (Trenberth, 2022).

Earth's Energy Imbalance (EEI) is the net effect after all the feedbacks interacted. It is hard to measure the EEI but it is estimated to be about 0.9 W/m^2. To compare, the average energy flow in the climate system is about 240 W/m$^{2\,(}$Trenberth, 2022). This is the net energy flow resulting from mostly human activities, that have changed the atmosphere's chemical composition, the albedo of the Earth and much more. The EEI is pretty small, and this is not how climate change is experienced. Instead, the net excess energy has to accumulate. And this is where it gets complicated. This energy accumulates in ice, causing it to melt and in oceans, increasing their heat content. Consequently, the oceans are expanding and in combination with melting glaciers and sea-ice, sea levels are rising (Trenberth, 2022). The oceans are stratified. The surface layer is the mixed layer where the ocean is in direct contact with radiation and wind forces. Below that, there is a layer where the temperature decreases with depth and is referred to as thermocline. Then the deeper layers are found (noaa, https://oceanservice.noaa.gov/facts/thermocline.html).

Oceans, through their fluid motions and heat capacity are shaping Earth's climate and climate variability. Ocean circulation happens through wind patterns and heat and moisture exchanges. Currents are basically fast tracks for transporting energy. They are continuous vectoral movements of seawater both in horizontal directions (currents) and in vertical directions (upwellings or downwellings) and are driven mostly by wind stress, density and heat differences as well as gravity and forces associated with the rotation of the Earth (Goosse, 2015). This allows water-masses with different water properties and characteristics to mix and move around the globe. For example, an important and popular current of interest is the Gulf Stream. In the middle and high latitudes, the westerly winds drive the ocean eastwards. At the same time, at lower latitudes, the easterly trade winds drive the ocean westwards (Goosse, 2015). Following the wind pattern, results in a circular movement that is completed with a strong western boundary current (the Gulf Stream in the Atlantic). These currents and wind patterns are also responsible for upwellings and sea level differences. Interestingly, the gulf stream has a sea level difference up to 1 meter between the eastern and the western side of the current, that can constitute risk for coastal flooding in case of a weakening of the Gulf Stream (Goosse, 2015). The Gulf Stream is part of a much larger ocean movement, that is the Atlantic Meridional Overturning Circulation or AMOC for short. The AMOC is also called a thermohaline circulation because it is caused by heat and density gradients, although a big component of it, is wind driven. It is part of the global conveyor belt. In principle, warm water masses from the equator and the tropics in general, travel via the Gulf Stream along the north-western Atlantic boundary to the north pole where they cool down and become denser and saltier (due to the formation of sea-ice). There they sink, forming the Atlantic deep waters and travel south, meeting the Antarctic deep waters. Upwellings bring these water masses back near the surface where they warm up again and meet other water masses entering the system from the conveyor belt. It is a very slow circulation in comparison with others. It can take a water parcel more than a thousand years to find its way back to the surface, storing heat and chemical information (https://oceanservice.noaa.gov/facts/amoc.html). There are only a few places in the world that can produce deep waters. Today, the AMOC's two main convection sites are the Labrador Sea and in the Nordic Seas. In fact, it is estimated the 2/3 of the waters are fed from the Nordic Seas, which consist of waters from the Greenland, Iceland and Scotland ridges and cascades (GIS). The other 1/3 are fed from the Labrador Sea. (*Mohamed Ayache et al. 2018*).

2.1 Breaking down the movement – Ekman theorems

In general, large scale ocean circulations are driven by wind, by fluxes of heat and freshwater across the surface and the interior (thermohaline circulation currents), and by tidal movement (Rahmstorf 2002). Wind currents mix the surface via upwellings and downwellings, mostly close to the equator and the coasts, as a result of the Ekman pumping. Ekman pumping is a mechanism that refers to the vertical velocity at the base of the Ekman layer. Wind moves the surface of the sea creating friction. This friction is passed on from layer to layer increasing in depth, but of course, losing energy on the way down. At a certain point of depth, water will no longer be affected by the wind. The overlaying water layer that is moving because of the wind's friction is called the Ekman layer (The Ekman layer – Physics Across Oceanography: Fluid Mechanics and Waves (pressbooks.pub))Ra. The original surface water movement should be in the same direction of the wind. But the Earth is constantly rotating so the Coriolis force creates a divergence of a few degrees (20° to 40°), that increases with depth, until some water moves with a 180° divergence, in the opposite direction of the wind (Ekman spiral). After all, all these different water directions are combined and the final movement is at an angle of 90° from the wind direction, either to the right in the Northern Hemisphere or to the left in the Southern Hemisphere. This is called the Ekman transport. So, if the Ekman transport creates an up- or downwelling, the term is Ekman pumping. This happens mostly, as mentioned, close to the coasts or the equator, as these are natural boundaries. It can also happen in the middle of the ocean but then the wind stress would have to be suitable. For example, near the equator, strong westerly winds blow from east to west. In the Northern Hemisphere, the ocean moves vertical to the wind direction and to the right, so to the North. In the Southern Hemisphere, the ocean moves vertical to the wind direction but this time to the left, so towards the South. In this case a north-south divergence is created, pumping water from the deeper layers. This is a typical upwelling. Upwellings bring fresh nutrients from depth to the surface making these waters highly productive. On the other hand, further away from the tropics, in the mid-latitudes, Ekman transport usually piles water up making downwellings or creating gyres. Gyres, are circular motioned ocean currents, created by wind patterns. Gyres can vary in scale. The subtropical gyre is located in mid-latitudes in the Atlantic, while the subpolar gyre, is located in the polar and subpolar regions, beneath an atmospheric low.

To understand the importance of wind driven currents in climate, they play a big part in the southern oscillation cycle or better known as el Niño and la Niña cycles. At the same time, they mix and move the ocean, mixing water masses and contributing to the global conveyor belt. On the other hand, tidal currents affect the climate since they are also a great way to mix water and a main source for turbulent energy. How thermohaline circulations affect climate is not well documented and researched, there is still lack in good observational data-series and little is known about the natural variations. Wind driven currents can also mask some of the thermohaline convection variations, which makes research even harder.

It is known, that in Earth's evolution, climate has been through the whole spectrum. It is only natural that climate has been changing and will continue to do so in the future. Consequently, since energy is constantly flowing, the oceans follow and change their patterns as well. More specifically the AMOC, has not been stable. There have been many conversations about AMOC's variability. Of course, AMOC's movement is affected directly by climate, just as much the AMOC is affecting the climate itself. Time series show that it has a decadal and centennial natural variability. Meccia et al. in their paper from last year (Meccia et al. 2022) look into the internal natural variability of the overturning circulation, giving great insight in the mechanisms that might drive it. The observed fluctuations of the AMOC vary depending on the timescale. On seasonal and inter-annual timescales, the variations are caused by wind changes. A delayed response to the North Atlantic Oscillation gives decadal variability. The multi-centennial variability or low-frequency variability is a topic of research with many possible explanations. By analyzing time series, there is a strong connection found between the stratification variability and, more specifically, between the mixed layer depth and AMOC variability. Moreover, salinity is an important indicator for low-frequency variability with a time lag from 5 up to 50 years depending on the geographical region (time between the maximum salinity and the maximum AMOC strength).

In this study, both the terms thermohaline circulation and meridional overturning circulation are being used. Although the terms are pretty close, they are not the same. It is important to make the distinction before moving on. The thermohaline circulation (THC) is driven by fluxes of heat and freshwater and the interior mixing of heat and salt (Rahmstorf 2006). The meridional overturning circulation or MOC refers to the north-south flow as a function of latitude and depth. Wind driven currents are included in the MOC. The THC is larger than the MOC and not specified in meridional directions. The THC is a forcing mechanism, a concept that cannot be measured, whereas the MOC is a stream function (Rahmstorf 2006).

2.2 Ocean and climate for the last 120,000 years

In order to understand what is happening today, one must first look in the past. Sediment cores and corals are an excellent source of information about past ocean circulation conditions. Using multiple proxies, temperature and salinity reconstructions can be provided. Rahmstorf in 2002 collected these proxies in an attempt to reconstruct the ocean circulation and climate for the past 120,000 years. The first thing he distinguishes when looking at the data are three different circulation models, different in temperature range and geographic convection site, namely the stadial, interstadial and Heinrich models. These models are connected with the glacial and interglacial periods. In the interstadial phase, the North Atlantic Deep Waters (NADW) formed in the Nordic Seas, during the stadial phase they formed a little southern, south of Iceland in the subpolar Atlantic, while in the Heinrich period, the convection wasn’t significant.

For more than 2 million years, planetary forces control climate. By planetary forces, the Milankovich cycles are meant, that come from the Earth’s orbit around the sun. These forces are responsible for changes in Earth’s insolation. So, an abrupt climate shift happened from the Eemian interglacial period to the next glacial period between 120 and 115 thousand years ago, reaching ice age in only a few thousand years. In Rahmstorf’s research, there was no evidence of a NADW being affected by the cold climate. Another important climatic event are the Dansgaard-Oeschger events (D/O events). They happen very quick, in less than 30 years and are high in amplitude. They start with a rapid warming of 5-10 degrees Celsius in a few decades, followed by a relatively steady period where the climate slowly cools in a duration of a few centuries, ending with a rapid drop in temperature. In these events, there is a hemispheric discrepancy with the north warming in a higher amplitude than the rest of the world and the south cooling. An explanation for the D/O events lies in the thermohaline Atlantic Circulation, the AMOC, and more specifically in changes in the volume that the circulation transports. Another explanation is the latitude shifts of the NADW convection site from the Nordic seas to mid-latitudes. This explanation fits well with the observations and the timesteps of the D/O events and is also supported by models and sediment data. The third important climatic events Rahmstorf analyses are the Heinrich events. They are characterized by major iceberg export into the ocean. During these periods, the NADW formation ceased or was very weak. What is also worth mentioning regarding past climate was the last glacial maximum or LGM, about 20 thousand years ago. Increased ice sheets with a higher albedo in combination with low CO_2 values, lead to global cooling and regarding the ocean circulation, a southward shift of the NADW formation site. The recovery from the glacial period started in the northern hemisphere with increased insolation and synchronous increase in CO_2. This initiated global warming and ice melt followed by a sea level rise by 130 meters, which obviously affected the AMOC. 8200 years ago, there was another cooling observed, associated with a weakening of the AMOC due to meltwater input.

2.3 AMOC: A declining mechanism

As mentioned, past reconstructions show with no doubt that the AMOC has a natural variability and is not stable during geological time (Ayache et al. 2018, Latif et al. 2022). For short time periods, the variability is small in magnitude. In fact, many researchers (such as Caesar et al. (2021)) agree that since about 400 A.D., the AMOC has been relatively stable. But today and since the 1980s, the AMOC is in a declining state. This is in agreement with Dima and Lohmann (2010), who found that the conveyor has been weakening since the 1930s. Thompson et al. (2010) found that there was a sudden decline since the 1970s in the SST difference between Northern and Southern Hemisphere (Rahmstorf 2015). Another study also supports this, with findings confirming that the AMOC reached a minimum state around 1990, recovered to a peak value in the early 2000s, and then declined again, with the decline starting at the end of the 1950s until today (Caesar et al 2018). They also confirmed that the decline is within the range predicted as a response to anthropogenic climate change. When comparing observational data, it is clear that the North Atlantic is cooling, with a maximum in the Gulf Stream, and the South Atlantic is warming with the maximum in the Benguela Current of South Africa (Rahmstorf et al. 2015). Freshwater "hosing experiments", which are models simulating freshwater input in the North Atlantic, also show a decline and often a collapse of the AMOC. These experiments try to simulate Earth when Greenland's sea-ice melts. But according to the IPCC (AR6, WG1, FAQ 9.3), a complete shutdown is unlikely. In the IPCC's AR6 of the first working group "The physical science basics", chapter 9, they present a graph showing clearly where and what the AMOC is and what a weakening looks like. In this graph, the importance of the gulf stream is also noted, and how it's also part of the subtropical gyre.

AMOC's strength is mostly influenced by its natural variability or the so-called internal forcings. At the same time, anthropogenic climate change has caused a significant external forcing as well which is not properly represented in all models (Latif et al. 2022). It is, thus, hard to measure how much each forcing contributes to the modern observations. In fact, Kostov et al. in their paper of 2021, find that wind stress and surface anomalies (which both count for natural forcings) each explain a fraction of the total modern variability in the subpolar circulation on interannual to decadal timescales, leaving space for anthropogenic forcings. In their study, Rahmstorf et al.(2015) find that the observed decline in the late 20th century is a clear result of anthropogenic climate change, since the probability of the AMOC reaching a similarly weak state just with its natural variability is <0.005. This is supported by paleo-proxies, that indicate that this decline is unprecedented in several centuries (since 500a.d.).

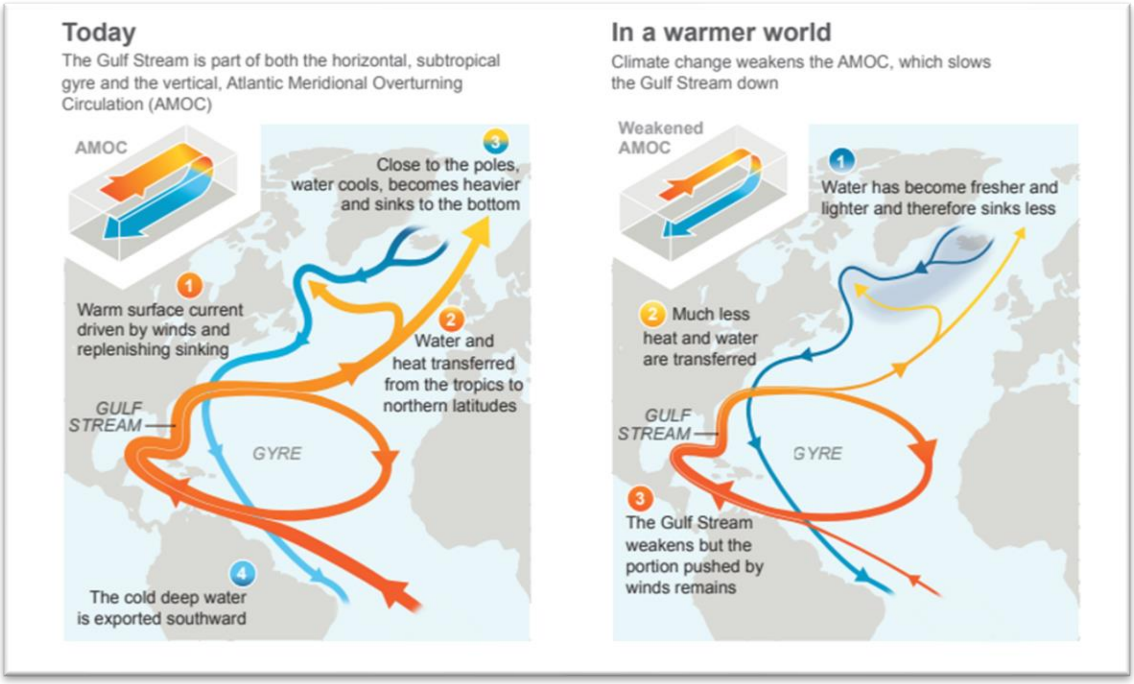


Figure 2.1. Graph showing the impact of a warmer climate on the Gulf Stream as part of the AMOC (Source: Graph taken from the IPCC AR6 WG1, Chapter 9 FAQ3)

Caesar et al., in their paper of 2021, collected various proxy data in an attempt to reconstruct the AMOC's evolution. Their result show that the AMOC is progressively declining and is now in its weaker state for the past thousand years. Their work is a completement to their previous research of 2018, where Caesar et al validate the slowing down of the AMOC by comparing observed data with modeled results in a climate with rising CO_2 values. One thing necessary was to establish a fingerprint that would indicate the AMOC's behavior. In all datasets and models, when the AMOC is weakening and climate has higher CO_2 levels, a cold patch around the subpolar gyre is observed, due to excessive sea-ice melting and less northward heat transport from the tropics. So, when combining the sea-surface-temperature in the subpolar gyre with the global mean temperature, a useful AMOC index is created, for larger scale variations. An important thing to note is that during the summer months, a surface mixed layer emerges that is most vulnerable to surface forcings and hides the cold patch. So, the index is defined from November to May, for a better signal to noise ratio. They define the cold patch large enough so it can conclude all cold patches found in all the models, since the geographic region can vary from model to model. Furthermore, models with a realistic AMOC, correlate to the above defined AMOC index at R=0.95, which is proof that the AMOC variations mostly control the SST (sea-surface-temperature) anomalies in the North Atlantic. Also, when reconstructing the time evolution of the AMOC from observed data from 1870 to 2016, they noticed that the AMOC reached a minimum in the 1990s, followed by a recovery in the early 2000s to then continuing declining. The decline is approximately of a total of 2,6 Sv until today.

However, the scientific community is not homogenous in agreement with the Caesar index. Swingedouw et al. (2022) note that the sub-polar warming hole, to which the index is based, can also be caused by other forces such as cloud coverage and wind stress heat fluxes. Their argument is that although many different arguments support the decline of the AMOC (sea surface salinity, Florida current strength, proxies), the certainty of those results is moderate, especially for long-term trends. The next question Swingedouw et al. (2022) set, is the origin and cause of the weakening. On one hand, Bonnet et al. (2021), based on CMIP6 model ensembles justify the weakening on centennial, natural internal variability. On the other hand, Caesar et al. (2018) emphasize the weakening on the Greenland Ice Sheets melting (a result of climate change).

2.4 Impacts of a weak AMOC

A slowing down of the AMOC is certainly something to be alert about. A slowing down means less heat is transported from the tropics to the poles, causing a heat surplus in the tropics and a cooling in the poles. Wei Liu et al. in their paper published in June 2020, give a satisfactory explanation of all the impacts a weaker AMOC would have, using the National Center for Atmospheric Research (NCAR) Community Climate System Model version 4 (CCSM4). The first thing that changes is ocean surface temperatures, higher in the tropics and subtropics and lower in the polar and subpolar regions. Additionally, when there is less heat transported to the poles, sea-ice loss is also slowed down. Especially in the Arctic, the cooling of the ocean contradicts the warming of the atmosphere, eventually resulting to a rapid loss of sea-ice because of the so-called Arctic Amplification (AA). AA is a term used to describe the faster rate in which the arctic is warming in comparison with lower latitudes, as is evident from not only observations, but also models and paleoclimate proxies. It is a result of many local feedbacks and changes in the poleward energy flux and has major implications for the advance of climate change and thus humanity (Rantanen et al. 2022, Previdi et al. 2021). Projections show that before the end of this century the Arctic will be ice-free in the summer. But lucky or not, a weak AMOC delays the complete melting by approximately 6 years. Still enough sea-ice is lost that, in combination with the expanded (from the heat) oceans, sea levels will rise, especially in places that already have a natural sea level imbalance, such as North America. Basically, with global warming, interestingly, while the atmosphere is getting unstable, the effect on the ocean is stability. Global warming makes the ocean more stable, preventing efficient mixing, a risk for marine life (oxygen depletion) and heat transportation. Positive feedbacks will in turn increase the temperature of the air as well, intensifying global warming impacts.

Extending to the troposphere, temperature gradients become larger, but would potentially grow in scale if it wasn't for the AMOC. Storms would increase in frequency and intensity, since warm air can hold more moisture. In the tropics and subtropics, the Inter-Tropical Convergence Zone (ITCZ) would shift, which is a low-pressure band around the globe, where the trade winds of both hemispheres come together, creating heavy storms and rainfalls. It is part of the atmospheric Hadley cell that circulates air from this low-pressure point to high pressure points in the subtropics (https://www.metoffice.gov.uk/weather/learn-about/weather/atmosphere/intertropical-convergence-zone). Precipitation is to increase in the tropics and decrease in the subtropics.

Jackson et al, in their research of 2015, also support the impacts mentioned above, further highlighting that the impacts would be severe for mankind and need to be understood and well documented, in order to assist present and future policy making. Furthermore, extreme colds are to be expected in North America, while climate projections suggest that the weakening might strongly affect the survival of a number of amphibians, which is usually considered as a key indicator of environmental health (Swingedouw et al. 2022).

2.5 Oceanic Observation Systems

Now more than ever, with a rapidly changing climate that alters all the components that control the ocean's movement and specifically the AMOC, the oceans need to be closely observed. Unfortunately, systematic observations only began since 2004 (Caesar et al. 2021). One of the first measurements taken in the Atlantic, were done by *Bryden et al. (2005)*, in 1957 and later continued in 1981, 1992, 1998 and 2004. The data collected showed a decline in the AMOC. As measurements became necessary, mooring systems were deployed. The RAPID mooring array, at 26°N continuously observes strength and structure. The OSNAP program, since 2014, has an observing system across the subpolar North Atlantic and it consists of two sections, the OSNAP west and the OSNAP east. The first full data recovery was in the summer of 2016 (*Frajka-Williams et al. 2019*). OSNAP's results show that the majority of the overturning occurs north of the OSNAP east section, which is north of southeastern Greenland at 60°, up to the Scottish shelf at 57° N (Frajka-*Williams et al. 2019*). Other observation systems and arrays consist of the RAPID/MOCHA arrays in the subtropical North Atlantic (fully deployed in 2004) that provide data every 18 months, and give results associated with seasonal and interannual variations (*Frajka-Williams et al. 2019*). More data are collected with the MOVE array at 16°N and the SAMBA array at 34.5°S. Satellite methods can also be used to estimate ocean circulation.

2.6 Measuring the AMOC – Proxies

All these observational systems provide time series with information about sea surface temperature, salinity, velocity etc. The AMOC is a complicated system combining multiple subsystems and environments, affected by forces from both small and regional, as well as global and planetary forces. But as mentioned, it is a thermohaline circulation, meaning it is mostly driven by temperature and salinity differences. Sea Surface Temperature or SST is in most cases used as an indicator for AMOC's variability, since its behavior is usually tracked by changes in heat transport and thus temperature (Rahmstorf et al. 2015). This is why, in modes, the AMOC is represented as temperature (and sometimes salinity) differences between low and high latitude ocean cells (Kim *et al. 2022*). The values are statistically processed to fill any data gaps. The data is then being used in physical equations that describe the AMOC's behavior. The overturning of the Overturning Circulations happens in the northern Atlantic and more specifically, in the Labrador and Nordic Seas. The Nordic Seas consist of waters from Greenland, Iceland and Scotland ridges and cascades (GIS) (Ayache et al. 2018). So, theoretically, any change in the strength of the AMOC would be observable in these sights. The velocity and intensity of the AMOC is measured in Sverdrups, Sv for short, after the Norwegian oceanographer Harold Sverdrup, and is a unit for volume transport. It is equivalent to 1 million cubic meters per second and is almost exclusively used in oceanography, to describe ocean currents. In climate science and in marine science, common physical indicators for ocean and climate conditions are proxies. A proxy is an indirect indicator for physical parameters such as temperature, salinity, velocity, depth, CO2 content etc. They are derived via chemical analysis and mathematical equations from observable information, such as the skeleton, shell, shape, abundance of specific marine species, chemistry in ice-cores, information hidden in pollen or tree rings, from grain-size, shapes, chemistry and form of sediments and many more. Basically, any useful data that is not directly measured is considered a proxy, with the basic requirement that the relationship between the proxy parameter and the quantity of interest is known (transfer functions). These proxy data can then also be used as input in models, to measure the AMOC's and climate variability. Proxies can be categorized as microfossil assemblages, stable isotopes, radiogenic isotopes, biogenic compounds, elements and lastly sedimentology (Meissner et al. 2009). Common proxies, that are also used in this study, are Nitrogen and Oxygen isotopes, marine productivity indexes, foraminifera specific species abundance that can be an indicator for temperature and productivity and grain size.

Regarding proxies, the basic most important indicator is the d18O isotope. It is reflecting past glacial and interglacial periods, important climatical changes affecting ocean circulation and global climate. The isotopic records are taken from foraminifera that are preserved within sediments. Foraminifera are single celled protists marine benthos and zooplankton organisms, that commonly make their shell skeleton out of Calcium Carbonate (CaCO3), which is preserved only in depths smaller than the Carbonate Compensation Depth, the depth were Carbonate molecules are dissolved. With that, they make valuable fossil records (Wade 2001). Oxygen isotopes are measured from the ratio between the stable oxygen isotopes ^{16}O and ^{18}O of the sample minus the standard sea water ratio of today, divided by the same standard ratio. It is calculated as $\delta^{18}O$ ‰, the deviation in parts per thousand or per million. The fractionation is dependent of temperature, so that at higher temperatures there is less fractionation, meaning the species will be depleted in ^{18}O, while in colder temperatures there is more fractionation, and the species will be enriched in ^{18}O (Wade 2001). This is due to evaporation. Evaporation transports mostly the lighter isotope into the atmosphere and, when it later rains again, the heavier isotopes fall-down in drops, leaving the lighter in the clouds (Gornitz 2009). After many cycles of evaporation and precipitation, there is a notable difference in the isotopic ratios between oceans and atmosphere. When eventually it snows in the higher latitudes, and temperatures are cold, the light isotopes in the rain form sea-ice and glaciers, locking the lighter isotopes in the ice. During these cold periods, the ocean is enriched in the heavier isotope and this composition is retraceable in the foraminifera shells. In warmer climates, precipitation returns the lighter isotopes back to the ocean, depleting the composition of the higher isotope, ^{18}O. But besides evaporation mechanisms, temperature alone also causes some fractionation. This is how glacial and inter-glacial periods are documented.

For oceanography and AMOC research, Caesar et al. (2021), made another distinction, categorizing ocean proxies into three groups: proxies that reconstruct temperature and heat patterns on the surface and subsurface, proxies that reconstruct subsurface water mass properties and finally proxies that reflect deep-sea currents. Of course, using one proxy is insufficient for any research. To increase reliability many proxies should be used combined, in order to also limit errors and uncertainties coming from the preservation mechanisms of the fossils, geographical limitations and local special conditions. Combining proxy data with numerical models can give insight into past conditions.

2.7 Earth System Modeling and AMOC

Many different approaches have been tried out in order to understand the AMOC better. A crucial detail that potentially can change the results, is the model being used. Every model is different and has limitations. For example, some models from the Coupled Model Intercomparison Project phase 6 (CMIP6), have a larger climate sensibility and might exhibit larger warming (Bonet et al. 2021). In this case, a comparison with other model ensembles helps understand the model outputs better.

But what is a model? Models are a representation of our physical world. They are based on well-documented physical processes and mathematical equations to simulate the energy and material transport throughout the natural systems. Climate models are also known as General Circulation Models or GCMs and use very complex mathematical equations to virtually project past, present and future conditions. They have an initial input which is used to solve the equations multiple times in supercomputers, progressing in the future or the past. Basically, a GCM splits Earth in three-dimensional cells with information that gets passed on and transformed to the next cell, modelling the exchange of matter and energy in specific time-steps. How small or big these cells are, defines the model resolution and the time step defines the detail in the results. Of course, if either the cell size or the time-step are too small, it will take a lot of computational power. To test a model, scientists use a method called “hindcasting” where they compare model outputs with observations from the past. And for predictions and future assessments, they define a future scenario, conditions that might be true in the future, in order to discover how the natural elements will respond. Using different scenarios help to understand the feedbacks between the elements better (climate.gov, Climate Models). The physical principles of climate dynamics that a climate model must contain, include the conservation of air and water mass, the conservation of energy, conservation of air momentum in three directions and the ideal gas law for air. Consequently, the variables they must contain include air temperature, pressure, density, water vapor content and wind magnitude. Climate models can be divided into global or regional (MIT Climate Portal, Climate Models). In the same spirit, ocean models focus on the physical parameters of the ocean. The mathematical equations describe the motion of fluids, biochemical processes as well as sea-ice mechanics. Parameters originating outside the ocean basin, are in this case the inputs and are called “boundary conditions”. These include surface air temperature, wind, pressure, sea surface height, ice concentration but also geographical actual boundaries of the basins and ridges. They also incorporate real observational data that can originate either from actual in situ platforms or from satellites. Ocean model results can be regarding the past (reanalysis) the present (analysis) or the future (predictions). Ocean simulations are very important for climate change research since they project how the oceans will affect climate and life. In modelling a very useful practice is to use ensembles. Ensembles are experiments with slightly different settings, resulting to slightly different outcomes. These outcomes could then be averaged and in this way avoid big uncertainties while estimating an error (Copernicus Marine Service, Ocean Monitoring and Forecasting Models). To better understand the earth system as a whole, distinct ocean or climate models are combined and put to interact with one-another making the so called “coupled models”.

2.8 Future projections of AMOC

So having understood that the AMOC is connected with climate and that any change would have serious consequences for humans, it is wise to look deeper into what the model scenarios predict future climate and future AMOC would be. Bellomo et al. (2021) tried thirty ensemble scenarios finally reaching a CO_2 concentration four times of what it is today, using the coupled model intercomparison project phase 5 and phase 6 (CMIP5-CMIP6). The first thing they confirmed, is again, a decline of the AMOC. The amount of the decline varies between the ensembles with a range for CMIP5 from -4 to -10 Sv and in CMIP6 from -1.5 to -17.5 Sv. To assess future scenarios for AMOC's evolution, they divided the model ensembles to a group with small AMOC decline and a group with large decline. To isolate the AMOC's response to climate change from other factors, Bellomo et al. (2021) normalized the model outputs by dividing the changes in the variables by the change in Global mean Surface Air Temperature, showing this way the expected change by degree of global warming. The parameters investigated are the surface temperature change, precipitation change and atmospheric circulation change, all in comparison with AMOC change. With a weaker heat transport to the poles, the northern Atlantic suffers from minimum temperatures (North Atlantic Warming Hole – NAWH). The larger AMOC's reduction is, the larger the NAWH. This also happens when the AMOC decline is small but to a lesser extent. At the same time, a large weakening is followed by a cooling in Europe but not so much in North America and a reduced Arctic Amplification. Regarding precipitation, in the model group with the small decline, it is predicted that precipitation will follow the wet-get-wetter and the dry-get-drier pattern. The large decline group does not follow the same pattern, having even completely opposite predictions. In the last group, it appears that precipitation changes are driven by dynamic changes in atmospheric circulation rather than the thermodynamic changes due to global warming. That includes a stronger El Niño response in the Pacific Ocean, a precipitation peak in the Tropics in the Atlantic Ocean, an ITCZ shift with a large temperature gradient between the equator and the pole. In the mid latitudes, the two AMOC decline groups act in an opposite manner, meaning that when in one group there is a precipitation increase, in the other there is a decrease. This climate behavior is probably happening because of the different warming observed in the North Atlantic between the two groups. The Indian monsoon is also affected by the AMOC, a connection long established (Cherchi 2019), with the AMOC balancing and moderating the monsoon's response to climate change. In this case, a small AMOC decline increases Indian precipitation significantly and a large one brings less change. In the wind and atmospheric circulation, the westerly winds are expected to increase speed poleward and decrease southward in both scenarios and in both hemispheres. A clash or a competition is also expected between the Arctic Amplification Jet and the tropical upper troposphere warming, with the arctic amplification pushing the mid-latitude jet towards the equator and the tropical warming (in combination with the expansion of the Hadley Cell), are pushing the mid-latitude jet poleward. Generally, the intensity of the AMOC decline will drive the jet's shift. A large AMOC decline pushes the jet towards the North.

In the paper written by Swingedouw et al. (2022), the future scenarios highly depend on the amplitude of the weakening, accounting for high uncertainty. Another issue when projecting the AMOC is the detail needed or in other word the right resolution for models. Higher resolution models can depict some key smaller scale processes in the climate system but at the same time fail to properly represent the first order AMOC drivers that are in a much larger (global) scale such as atmospheric heat flux and ocean stratification. Hirschi et al. (2020) looked deeper into the resolution problem in ocean models. They found that eddy-rich models that have high resolution at about 2-3 km, show a stronger AMOC. Low-resolution models (about 100km horizontal resolution) and eddy resolving models (10-25 km resolution) show about 20-25% of the AMOC strength in the high-resolution models. As a result, future projections in high resolution models, show a much more intense weakening of the AMOC compared to low resolution models. Swingedouw et al. (2022) believe the high-resolution eddy-rich models are an improvement in ocean research, providing more detailed information regarding ocean processes, and more specific, regarding the Greenland Ice sheet melt, that might be underestimated in coarser models. In their paper they present new high-resolution eddy-rich models with and without the updated estimate of the Greenland Ice-sheet melt (GrIs) over the past few decades, comparing their results with CMIP6 member models. In contrast to the simulations of the CMIP6 models, Swingedouw et al. (2022) suggest that the GrIs has already impacted the Labrador Sea Convection and the AMOC in the recent past quite strongly, leading to great uncertainty worldwide regarding future climate projections.

2.9 The Mediterranean- A hot spot for climate change

Just like the AMOC, the Mediterranean Sea is known to be very vulnerable to climatic changes. A basin of almost 2.6 million km^2, surrounded by 23 countries and home to 480 million people, is a cultural, environmental, and socio-economic treasure. It is well documented that the Mediterranean region is a so called “hot spot” for climate change, with temperatures rising all year round, with a higher rate than globally, and precipitation being overall reduced (Lionello et al. 2018). Although the region has seen worse climate conditions than today (for example the mean temperature was about 8 degrees lower than today during the last ice age and 3 degrees higher during the mid-Holocene), current conditions develop over 100-150 years, accelerating fast, while past climate change took thousands of years. This means natural systems are forced into change and do not have the appropriate time to adapt, bringing higher risks to modern life (Lange 2020). Thus, more extreme events and serious impacts are expected. Assessing the impact of global warming and of a weaker AMOC (see above), the Mediterranean region will with no doubt be highly affected. Of course, with higher air temperatures, evaporation will increase. As a result of a weak AMOC precipitation is expected to weaken as well, leaving the Mediterranean hot and dry. And since all these changes result from regional and global feedback loops, it is crucial to gain a holistic view of all the systems and how they are interconnected. With this thought, we try to understand the amount to which the Mediterranean and the Atlantic are connected.

The morphology of the region is very diverse, both land and underwater. Islands of all sizes, underwater mountain ridges and trenches, shallow and deep subbasins and sub-seas, creates great heterogeneity in Mediterranean climate. The biggest difference is observed between northwest Mediterranean and the southeast. The northwest is mostly affected by the north Atlantic oscillation and other northern hemisphere teleconnections such as the Scandinavian or the Russian pattern, while the south is impacted by the midlatitude Hadley cell and the Asian monsoons, as well as subtropical patterns (in Lionello 2012). This constitutes the simulation problem of the Mediterranean. In order to get correctly all the local differences, the various subsystems and their complicated interactions need to be represented in a high-resolution model. Such a model, combining all the morphological anomalies and all the atmosphere – sea – land interaction around the Mediterranean and perhaps up to the origin of those systems, is yet not available. For the best simulation, a resolution of less than 0.2° is needed, although most global models use a resolution around 2.5° (in Lionello 2012). Luckily there is constant improvement in this domain. The data we used in this study is of the latest reanalysis ERA5 dataset that has a resolution of 0.25 – 0.5 degrees.

The Mediterranean is connected with the Atlantic Ocean through the Gibraltar straits, where warm salty waters outflow in the ocean. Because the Mediterranean is shallow (salty) and in a sense isolated from the oceans, in combination with the warm temperatures and sunshine that dominate the region, the water masses that outflow the straits, are very distinct from the Atlantic masses. Although tectonics are mainly responsible for changes in the volume that flows out the straits, dry and warm conditions can also result to variations in the outflow to the Atlantic. It is believed that the Mediterranean Outflow Water (MOW for short) is connected to the AMOC (Ivanovic et al. 2014). Most studies support the *shallow source* hypothesis, according to which, the MOW flows westwards and joins the north-eastwards flowing north Atlantic current, contributing with warm saline waters to the NADW formation in the northernmost North Atlantic. Indeed, the MOW waters are very well documented, and they do contribute to the AMOC but for a relatively small percentage, mostly with salinity and not so much with heat (Ivanovic et al. 2014). But is the opposite also true? How does the AMOC slowing down affect the Mediterranean?

2.10 Insight to the statistical methods

Raw data, either observed data or reanalysis data, or proxy data, have zero meaning. In order to tell their story, they have to be analyzed and compared with each other or to some established truth. Most importantly, with any data, time and space must be well defined and known throughout the research. Mean values are very commonly used to get a wider picture of your data and your data behavior. A mean value is defined as the sum of all values divided by the total number of those values. So, you can calculate monthly values from daily data, yearly from monthly and so on.

Another very useful tool in statistics is the correlation coefficient. In climate science, we often want to compare two (or more) variables to get a sense of how strong or weak their relationship is, whether they are depended on each other. There are different correlation coefficients, that suit every dataset. The covariance correlation coefficient is used when a normal distributed relationship exists between the variables. When this normal distributed relationship lacks, Spearman's correlation might come in hand. Kendall's correlation is another type of correlation that measures the strength of dependance between the variables. But the most widely used correlation coefficient is the Pearson's correlation. To calculate Pearson's correlation, the variables have to be normally distributed with a linear relationship. The coefficient is a number between 1 and -1. The closest it is to 1 the stronger the positive correlation is, meaning that they have a strong relationship and when one variable increases, the other follows. The closest the number is to -1, the stronger the negative correlation is, meaning that they have a strong relationship and when one variable increases, the other goes the exact opposite way and decreases. The closest it is to 0, the weaker the correlation is, meaning that they have a non-existing linear relationship. The Pearson's correlation is also what we use in this study. By calculating the correlation coefficient, we were able to see how much the AMOC and the AMOC slowing down affect Mediterranean's sea surface temperatures, air temperatures and total precipitation. When applying the correlation function, a so-called p-value is also calculated. The p-value indicates what the probability is for the correlation to not be trustworthy. To be precise, it is generated after a process called the "hypothesis testing". With the hypothesis testing you check whether your results are statistically important. In other words, it is the test to see if the results are valid and what the odds are for them to happen by chance.

3 DATA and METHODS

3.1 Data

In this study, we used ERA5 reanalysis datasets created by the ECMWF, the European Centre of Medium-range Weather Forecasts, and provided by the Copernicus Climate Change Service (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview). The ERA5 reanalysis provides global climate and weather datasets from 1959 onwards. Reanalysis data are the most useful and widely used kind of data that consist of a combination of model data with observations covering the whole globe in a complete and consistent dataset. A funny way to understand reanalysis better is to consider that they are sometimes referred to as “maps without gaps”. The dataset is completed with a principle called data assimilation where every few hours a previous forecast is compared and combined with new observations, constantly updating and improving the product, going back several decades. When computing a reanalysis, the starting point are usually present conditions of the Earth’s system, slowly blending short range forecasts and past data. However, reanalysis is at a lower resolution than current (weather) forecasts but are constantly improving by reprocessing previous reanalysis, implementing satellite information and comparing the results with other institutes around the globe.

ERA5 reanalysis dataset is the fifth generation of atmospheric reanalysis produced by the ECWMF, following the FGGE project, the ERA-15, ERA-40, ERA-interim, from 1979 to 2019. It is updated every day with a small time period afterwards for any errors to be corrected and the final release being available at a maximum three months later. The variety of data provided in the ERA5 reanalysis is huge, including a large number of atmospheric, ocean-wave and land-surface parameters, with improved homogeneity. The data is estimated hourly or to pre-calculated mean values. It is gridded with a standard latitude-longitude grid of 0,25x0,25 degrees and an uncertainty of 0,5 degrees, except for the ocean-wave data that have a grid of 0,5x0,5 and an uncertainty of 1 degree.

Although the ERA5 reanalysis is a significant and improved tool for research, there are some known issues. ERA5 presents a larger cold bias in the lower stratosphere and a larger warm bias near the stratopause in comparison with other reanalysis and with previous editions, which can lead to some discontinuities in the higher atmosphere. Another known flaw is the so called “rain bombs”, geographic regions that show unrealistically higher precipitation than normal. These episodes luckily do not occur often and are restricted to mostly isolated grid-points in orographic areas. Same happens with snow depth, that can be unrealistically high in regions with an altitude higher than 1500 meters. Discontinuities can also occur in root soil moisture (Hersbach et al. 2020). But these flaws do not occur in the data used in this study, and our research is not affected by them.

Reanalysis data is of great significance for the scientific community. Without them there would be serious gaps in our understanding of Earth’s systems, climate and climate change. Having complete datasets from past conditions gives better insight to the relations that exist between the systems. Going further and further back in time, reanalysis data improve future projections making them more reliable. Observations alone are also problematic since they are measured in specific places of interest, leaving the rest of the grid un-measured and un-observed. And although it would be necessary, it would be physical impossible to measure hourly every grid on Earth. Reanalysis solves this problem, again, by filling the gaps, giving scientists everything they need to reconstruct the past, present and future. Today they are widely used, not only for scientific research but also for policy making and businesses, education, renewable energy, agriculture and so much more. Important organizations dealing with climate change are leader clients for reanalysis climate-earth-ocean datasets, including the WMO (World Meteorological Organization).

For this study, we chose monthly data from the ERA5 reanalysis timeseries, provided by Copernicus Climate Change Service platform. To look into Mediterranean's climate, we choose to analyze three variables from 1959 to 2021. The referred variables are the sea surface temperature, the surface air temperature at 2 meters height and the total precipitation. The air temperature is calculated both above sea and land by interpolating between the lowest model level and the Earth's surface. It is calculated in Kelvin units but for our analysis and plotting we transformed the data into degrees Celsius. Total precipitation is a parameter representing both rain and snow falling to the earth's surface. It does not include fog or precipitation that is evaporated into the atmosphere. Depending on the dataset, it is accumulated either daily or hourly or every 3 hours. It is measured in meters which represents the depth of water if it were spread out evenly over the grid cell. The Sea Surface Temperature or SST is the surface temperature of the sea and because it is a foundation parameter, it is unaffected by the daily cycle of the sun. It is measured in Kelvin units, but during our work we compiled it to Celsius Degrees.

Besides that, we visualized the proxies and indicators collected by Caesar et al. in 2021. We made the visualization in a much simpler way that is easy to understand and draw conclusions (Figure 4.2). Every indicator was plotted against time. The time period chosen was the same time period as the AMOC index as defined in Caesar et al. (2018), from 1870 to 2016. Their definition of the index is as follows: the difference between the mean SST of the geographic region that is most sensitive to a reduction in the AMOC (the subpolar gyre region) and that of the whole globe. Important enough, the mean SST does not include all the twelve months of the year, but only from November to May. That is because, according to Caesar, the AMOC's signals are more intense during that time, in comparison with the boreal summer months. So, in full clarity, the AMOC index for a certain year is defined as the mean SST in the subpolar gyre region for the following November–May season, minus the global mean SST for that season. Rahmstorf et al. (2015) defined an AMOC index just like Caesar's with the only difference that except of the global mean, they used the mean temperature of the Northern Hemisphere. Rahmstorf's index has a very similar behavior as Caesar's, as is notable from the graph. The other proxies visualized, are subsurface temperature data from the subpolar gyre region at 400 meters depth, the mean Ocean Heat Content difference between the Atlantic Ocean and the Southern Oceans, d15N isotopical data variations as well as d18O isotopes, a marine productivity indicator (methane-sulfonic acid concentration, namely MAS) and proxy data from the species T. Quinqueloba that is known to prefer cold waters. We verify, just like Caesar that all proxies show a decline throughout time. In order for the comparison to make physical sense, the proxies have to be taken from the same region of interest, the region the AMOC index is measured. Indeed, al sample sights are taken from the North Atlantic subpolar region, as shown in the map (Figure 3.1).

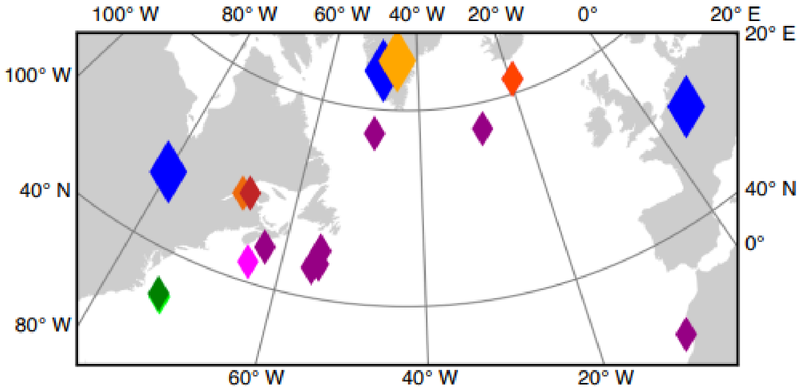


Figure 3.1: Map showing the sample sights of the proxies provided by Caesar et al. (2021)

Table 1: The table below is an explanation of the Map above. The colors on the left, are found in the map and represent the proxies on the right column of the table. Caesar et al. (2021)

Color	**Proxy**
Blue	SST proxies
Purple	Subsurface Ocean Temperature
Pink	$\delta^{15}N$ data of deep sea gorgonian corals
Orange	Relative abundance of T.Quinqueloba
Dark Green and light Green	Mean Grain size of sortable silt
Brown	$\delta^{18}O$ in benthic foraminifera
Light Orange- Yellow	Subpolar Gyre Marine Productivity

3.2 Methods

Establishing that the AMOC is in a weak state and declining in a faster rate than normal due to rising global temperatures and rising CO_2, we want to see whether this decline affects the climate in the Mediterranean Sea. As mentioned, the Mediterranean region is a hot-spot for climate change, which means temperatures are rising in faster rate than the rest of the globe while at the same time precipitation rates are falling. This could be linked to a weak AMOC. We will assess the correlation between Caesar's AMOC index and climate parameters in the Mediterranean region.

For the Mediterranean, we used monthly data from the ERA5 reanalysis dataset. The parameters that were downloaded are the sea surface temperature, surface air temperature in 2 meters height and total precipitation. Data ranges from 1959 up to 2021. Firstly, we organized our data into yearly values (to also match the annual AMOC index), by calculating the mean value every 12 months, and after that we calculated seasonal values, both for summer and for winter. The summer season consists of June, July and August while the winter season of December, January and February. Having the data organized, we plotted annual maps and correlation maps, showing how strong or weak the parameters relate to the AMOC. In the correlation section a very important detail is the calculated Lag between the parameters.

Usually, the calculation of the correlation of two variables, happens one-by-one. To explain this better, if the data is organized in a matrix with two columns, one for each variable, both columns must be of same length, and they correlate by row. Row one of the first variable is compared with row one of the second variable and so on for all rows. In practice this can be done by the following equation, that calculates the correlation coefficient r for n sets of values over variables x and y:

$$r = \frac{n \sum xy - (\sum x)(\sum y)}{\sqrt{\{n \sum x^2 - (\sum x)^2\}\{n \sum y^2 - (\sum y)^2\}}}$$

Where Σ stands for sum. This is equation for the Pearson Correlation that, as said, will be used in this study. The r value gives the strength of a relationship while to test for the significance of the correlation, the t-value is calculated. The t-value is expressed by the following equation:

$$t = \frac{r\sqrt{n-2}}{1-r^2}$$

Where r is the correlation coefficient and n is the sets of values. The value of n – 2 stands for the degrees of freedom for the dataset. By calculating the t-value and the degree of freedom, the null hypothesis from the hypothesis testing, can be rejected and the p-value can be found, all via the appropriate statistical t table.

To explain the hypothesis testing, one starts with a null hypothesis versus the real one, saying that the results have zero significance, or basically accepting as true any opposite statement than the one that needs to be proven. The goal then is to reject this null hypothesis and accept the other. When checking the statistical significance of a correlation coefficient, the t-function does the trick. The t-function describes the variability of the distances between sample means and the population mean when the population standard deviation is unknown, and the data approximately follow the normal distribution (https://statisticsbyjim.com/probability/t-distribution/). Basically, in our case, only the correlation coefficient needs to be known and the sample population. The function has a numeric output (t statistic value) that then need to be compared with the critical t values, from known and established statistical tables. In a t-distribution table, the rows represent the freedom degrees of the t-function, and the columns represent the statistical significance level (https://statisticsbyjim.com/hypothesis-testing/t-distribution-table/). Finding the right column (so the right significance level) is the result of the hypothesis testing. To find the right column, one has simply to find the maximum number from the row with the correct freedom degrees, from which the result of the t-function is larger. If there is no such number and the t-function result is low, then the research results are statistically unsignificant and the null hypothesis remains true. If, however, there is such a number, then the null hypothesis is declined and the other one is true with the significance derived from the table. The most common accepted significance is 0,05 which means the results are trusted at about 95%, with a chance of 5% to be wrong. The number 0,05 or in other words the column names, coincide with the p value generated while calculating the correlation coefficient. P-values show how unlikely it is for the correlation to happen if there is no relationship between the variables. In other words, it shows how trustworthy the results are. For example, If the results are to be trusted at a level of 95%, the probability to be wrong would be 0.05%. In this case, the p value is 0.05. In this study, we consider statistically significant all values that have a p value lower than 0.05.

But sometimes the variables have a physical sense and a time gap before the effect of the first variable reaches the second one. This is definitely the case with the ocean. Oceans, although they are sensitive and move constantly, they are also slow. A warm water layer might need days, weeks, months, or years to get from point A to point B and transport its characteristics. A weather system or cold front also needs time to travel. This creates a time lag in order to notice the result of a change. It is possible to find this time lag or at least look for it when working with correlations. If our data is organized by year (which in our case is), we can compare the AMOC index to the Mediterranean SST starting one or two years later. This is simple done by moving down the timeseries of the second variable while keeping the first one stable.

Calculating the lagged correlation needs some care and awareness of what exactly is correlated. As said, we correlated the AMOC index with three parameters, SST, SAT and total precipitation. There is one important detail though. AMOC's signal is not as strong in every month of the year. It is stronger from November to May, when changes from the previous months are reflected. This is why Caesar et al in 2018 stated their definition for the index as "the AMOC index for a certain year is defined as the mean SST in the subpolar gyre region for the following November–May season, minus the global mean SST for that season". So, when we talk about the AMOC index of the year 1959, we are actually talking about the mean SST from November 1959 to May 1960. Notice how the majority of the monthly values lie in the next year. So, in principle there would be no point correlating the index with the Mediterranean parameters for the same year, one-by-one. The parameters have mean annual values meaning from January to December 1959, when the index only begins in November 1959, and it would be impossible to affect the Mediterranean. Of course, there would be physical sense if we wanted to investigate how the Mediterranean affected the AMOC, and not how the AMOC affects the Mediterranean which is our main question. But the Mediterranean outflow waters are not strong enough to actually correlate significantly with the AMOC. It does contribute to it but it is almost a negligible force to its variability. So, when in this study we refer to lag 0 (no lag) we are actually correlating the index with the referred parameter beginning one calendar year later, lag 1 would be a comparison with the parameter two years later etc.

For all the data analysis, graphs, and statistical computations we used the R software. R is a very popular language and has a free open-source software environment for statistical computing and graphics.

4 RESULTS and DISCUSSION

4.1 *Temporal variations of different AMOC indicators*

In this section, we present and discuss the results of our research. In Figure 4.1, the time evolution of Caesar's AMOC index is plotted, and in Figure 4.2, the rest of the proxies Caesar et al. used in 2021 to evaluate AMOC's regression. For all the plots, the same time period is used (1870 to 2016). Every variable has its own plot for a clear representation. Note how every variable is declining following a linear trend.

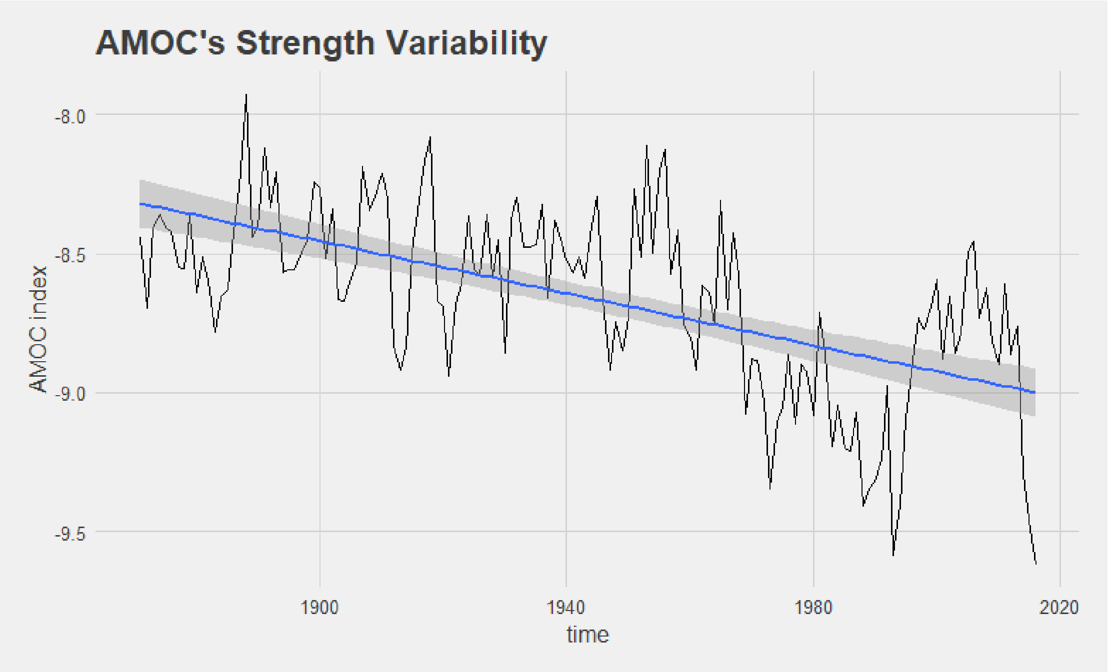


Figure 4.1: AMOC index from 1870 to 2016 as defined in Caesar et al 2018.

This linear declining trend shows the evolving behavior of the AMOC. Recalling the AMOC definition, it is the mean SST in the subpolar gyre region (SPG) minus the global mean SST. According to this expression, there are two ways the index is to decline. It could either mean the global SST is warming or the SPG SST is declining. It is known for a fact that the past years, global sea surface temperature is rising. So, if only the global mean was to rise and thus there was nothing special happening in the subpolar gyre, temperature wise, the SST of the region would follow the global warming trend, heat up, and the trend line would be relatively stable. This is not the case. There is a clear decline in the AMOC index, indicating that perhaps the first parameter of the equation is changing as well, in an opposite direction of the global warming, meaning the SPG SST is cooling. An SPG SST cooling indicates two things, there is less heat transported to the north Atlantic region and there is more cool water input (ice melt). Both explanations show a weaker overturning mechanism, thus, a weaker AMOC. Feedback mechanisms make it possible that this is caused by warmer surface

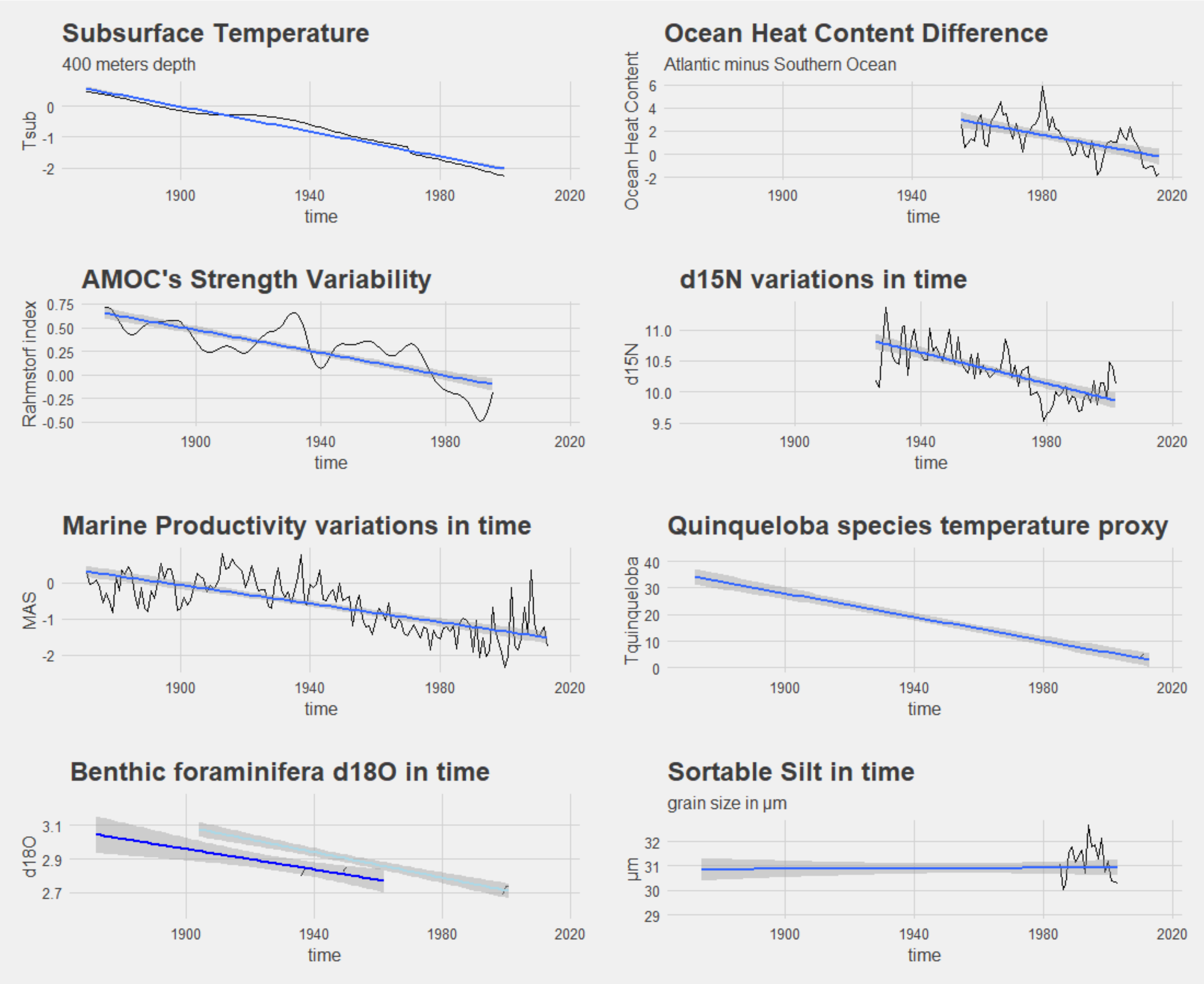


Figure 4.2: AMOC proxies against time. Smooth trend line is added. Data from Caesar et al. (2021)

air temperatures in the north (Arctic Amplification) that cause more ice to melt. The cold water from the melted icesheets pushes back the warm water stream from the tropics. Looking at the proxies, they show a decline as well. The Rahmstorf AMOC index, just like Caesar's, shows the further SPG temperature decline in contrast with the North Hemisphere mean temperature rise, as part of the global warming trend, indicating once more an overturning decline.

Clearly enough, the subsurface temperature and the Ocean Heat Content are declining, proving cooling in the region. The other proxies need an extra thought to be understood and to find the connection with the AMOC. The T. Quinqueloba species are known to prefer cold and nutritious waters. Their abundance is not only controlled by temperature but also by nutrients. A logical argument would argue that a cooling in the area should increase their abundance. However, their decline in this case is justified by a strong barrier in the nutrient and particle transportation towards the upper ocean, leaving the bottom water rich in nutrients and the surface depleted (Spooner et al. 2020). In other words, this is explained by a vertical frontal system caused by increased stratification. When stratification is enhanced, less water masses are mixing, leading to a weaker overturning circulation. The same argument is reinforced by the marine productivity proxy (measured by methane-sulfonic acid concentration) and the δ15N variation. Nitrogen is also associated with primary productivity. A decline in productivity follows a decline in the isotopic fractionation. The $\delta^{18}O$ ratio is an indicator for freshwater input and stratification as well. Decreased Oxygen stable isotopes ratio suggest less ice cover, more freshwater and less mixing with sea bottom water masses. Plotted on the graph are two different datasets from different sites that are however, as seen on the map, close to each other, and show similar trend. This again shows a weak overturning circulation. The sortable silt mean grain size has no impressive trend. The data is limited, and it would be risky to draw any conclusions from that. However, we can note that there is a slight positive trend, that would mean that the bottom currents are weaker (bigger grain size means less transport and small current velocity).

4.2 The Mediterranean climate from ERA5

In this section we approach the Mediterranean Climate in terms of Sea Surface Temperature, Surface Air Temperature and Total Precipitation, as calculated from the ERA5 reanalysis dataset using R. The maps below are depicting the climatology of the region, meaning they are a mean state, concluded from all the available values. To be more precise, the maps were made by finding the mean value from every year in our dataset, from 1959 up to 2021. This is very useful to understand the average conditions in the area. In Figure 4.3, the Sea Surface Temperature is increasing towards the south, with its peak in the southeast Levantine basin. There the temperatures can reach the maximum of about 23-24 degrees, while in the Black Sea, minimum values can be found of about 13-14 degrees.

The surface air temperature map shows a differentiation between land and sea (figure 4.4). This is expected since the sea has a milder temperature variation than land, due to is high heat capacity. Temperatures are again increasing towards the south and south-east since warm fronts and warm weather systems are coming from the tropics and subtropics (north Africa), impacting south Mediterranean. Over land, temperatures have a range from 8 to 18 degrees, with the exception of the high mountain regions where air temperatures can naturally reach below 5 degrees. It is expected that annual mean temperatures will be increasing.

Annual precipitation values, as shown in figure 4.5, are low, about 2mm of rain (and other forms of precipitation), except for the major mountain ranges, west of the Pindus range, central and south of the Alps, the Pyrenees and west-northwest of the Cantabrian Mountain range. While observing the data it was noticed that there is little variation in the last 60 years, which is normal for the region. Again, projections show that mean precipitation values will get lower in the coming decades.

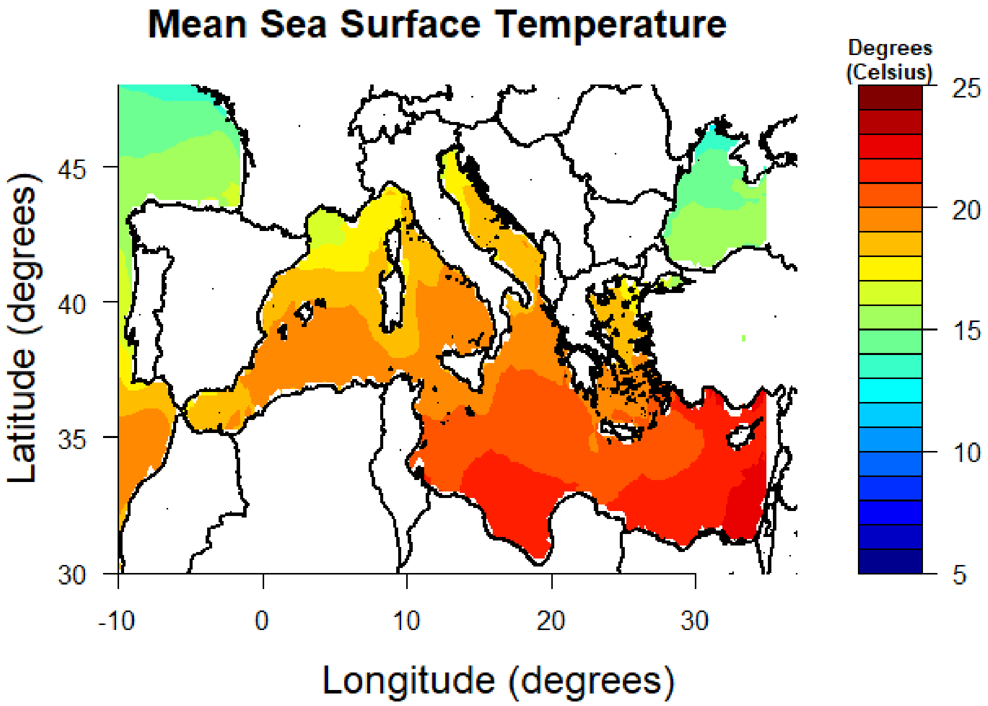


Figure 4.3: Mediterranean Mean SST from 1959 until 2021.

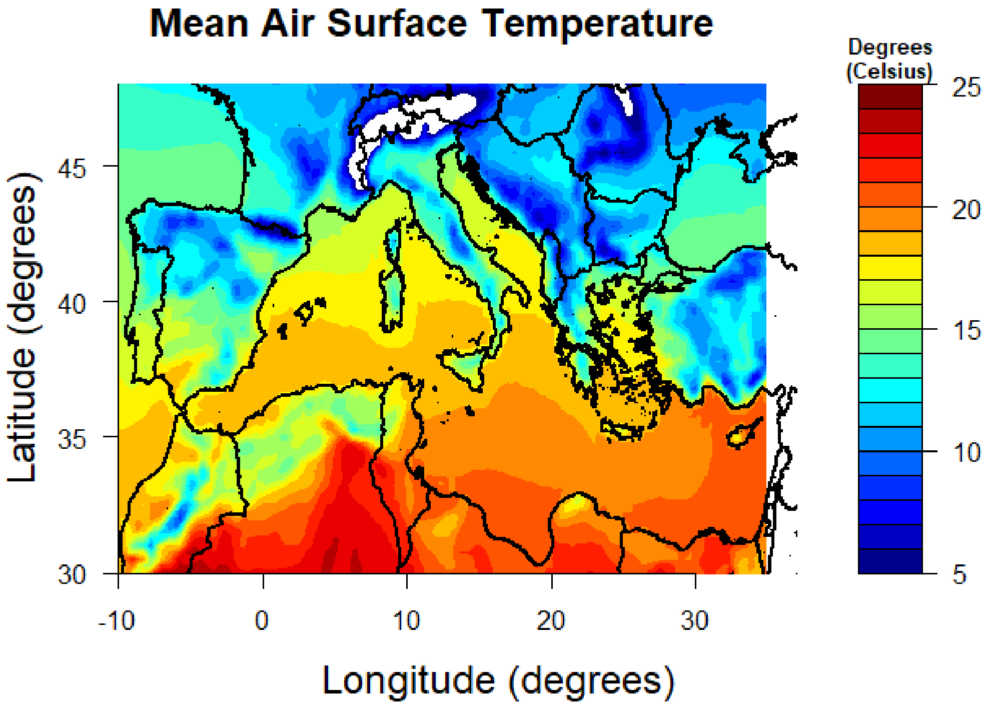


Figure 4.4: Mediterranean Mean Surface air Temperature at 2 meters height, from 1959 to 2021

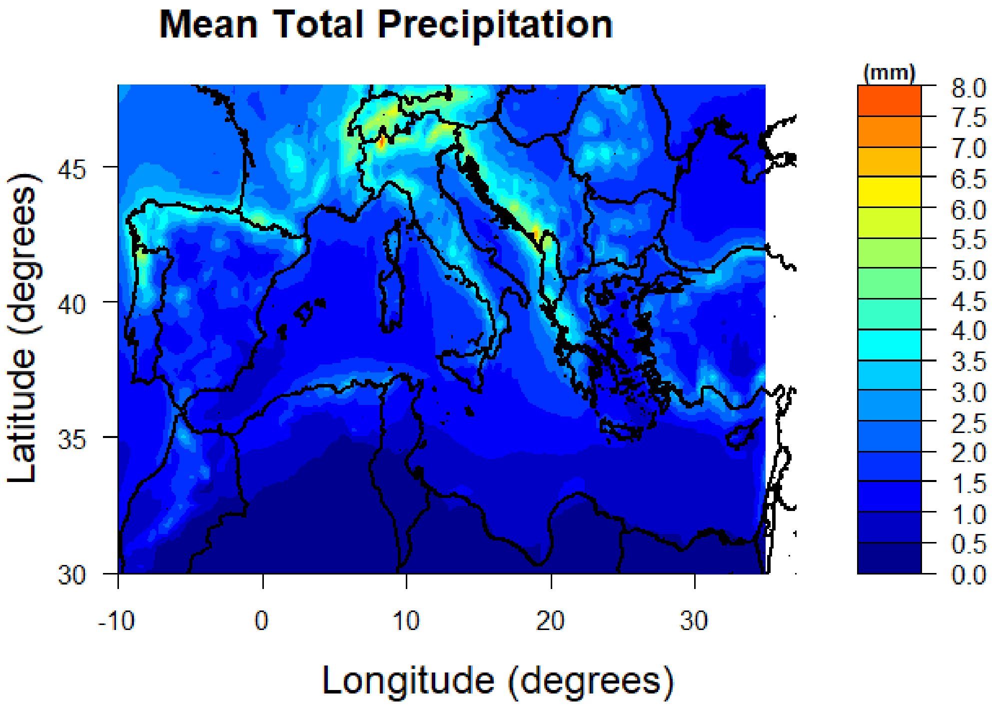
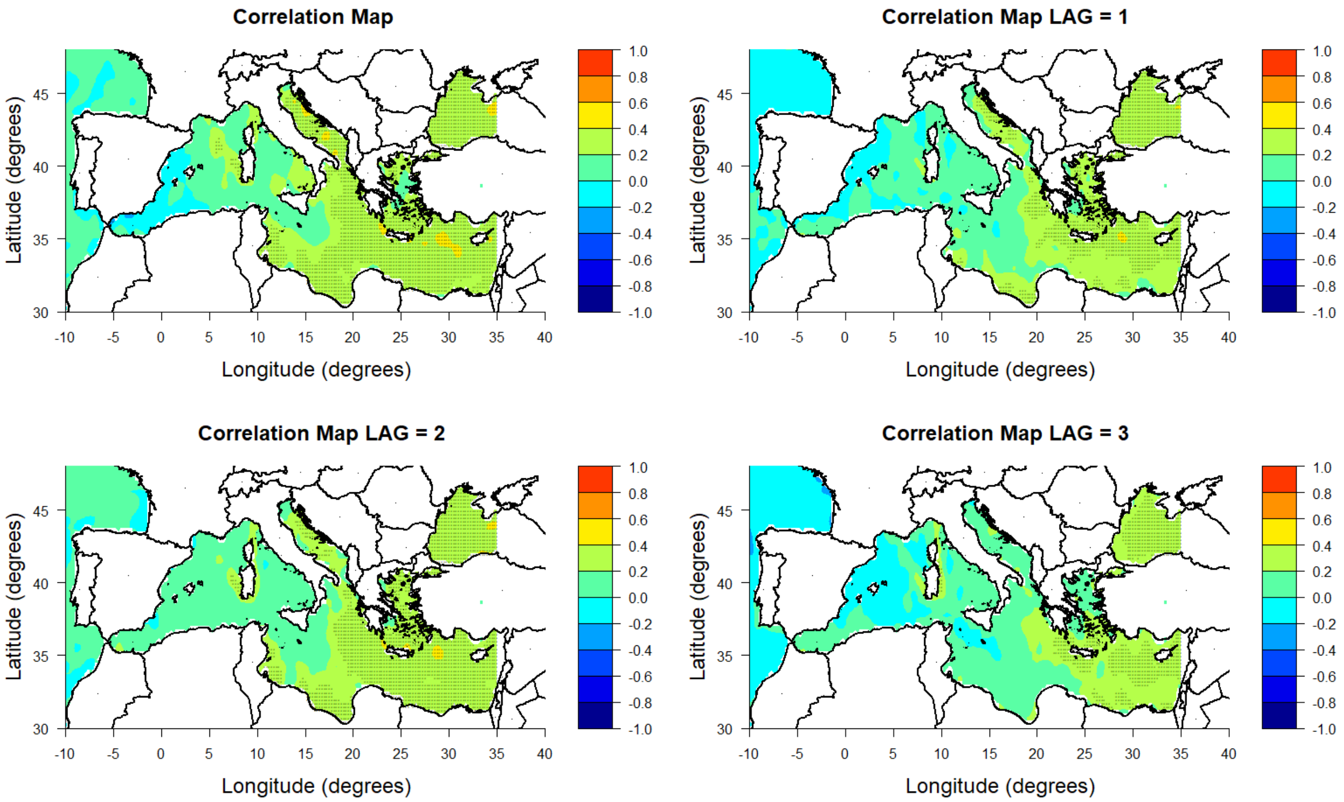


Figure 4.5: Mediterranean Mean Total Precipitation from 1959 to 2021

4.3 The AMOC impact on Mediterranean climate

In this paragraph, we analyze the correlations between the AMOC index and the Mediterranean Climate. By correlating these two parameters, we aim to recognize any relations between the two, resulting after multiple feedbacks. To be precise below we will correlate the Caesar AMOC index that refers to the subpolar Gyre and the Mediterranean SST, SAT and Total Precipitation. In Figure 4.6, we correlate the index with the annual SST values of the Mediterranean up to 3 years lag. In all maps following, the points with a p-value lower than 0.05 or the points with the best statistical significance are annotated with an asterisk ("*"). It seems there is some significant positive correlation between the AMOC and the central-eastern Mediterranean Region, for all lag years but mostly for the same year and two years after, with a correlation coefficient ranging from 0.1 up to even 0.5. On the contrary, central and west Mediterranean has a unsignificant correlation, with coefficients values close to zero, so not high enough to indicate an important relationship.

As mentioned before, a positive correlation means positive linear relationship between the variables compared. When the independent variable increases the dependent increases as well and when the independent decreases, the dependent follows and decreases as well. In this case, the AMOC index, as showed in Figure 4.1, is decreasing in time. According to the correlation maps, the eastern Mediterranean, and every positive correlated area in the following maps is decreasing it's measured variable as well. For example, when positive correlations are observed in the SST maps, it means that as the subpolar gyre is cooling and the AMOC is slowing down, the eastern Mediterranean is cooling as well, deprived of the heat that would circulate back in the east Atlantic. The same goes for surface air temperatures cooling and for rain patterns decreasing. When a negative correlation is observed, given the AMOC index is decreasing, in the Mediterranean there would be a warming in SST, a warming in Surface Air Temperature (SAT) and an increase in rainfall.


Correlation Map

Correlation Map LAG = 1

Correlation Map LAG = 2

Correlation Map LAG = 3

Figure 4.6: AMOC-Mediterranean Annual SST Correlation

In Figures 4.7 through 4.10, the summer seasonal correlations for Sea Surface Temperatures are visualized. For the summer season, extending from June to August, the direct comparison in figure 4.7 seems to have the best positive correlation and most statistical importance in comparison with the rest. Figure 4.8 has values closer to zero while Figures 4.9 and 4.10 have a smaller surface of meaningful correlation coefficients. Again, the statistically significant correlation is limited in the eastern Mediterranean.

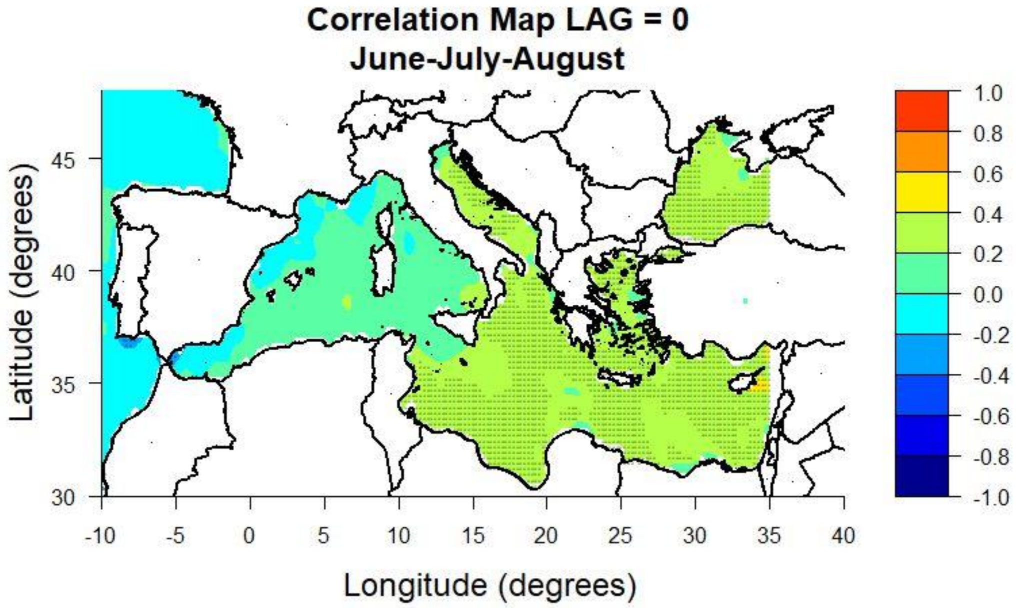


Figure 4.7: SST Summer Correlation with no lag

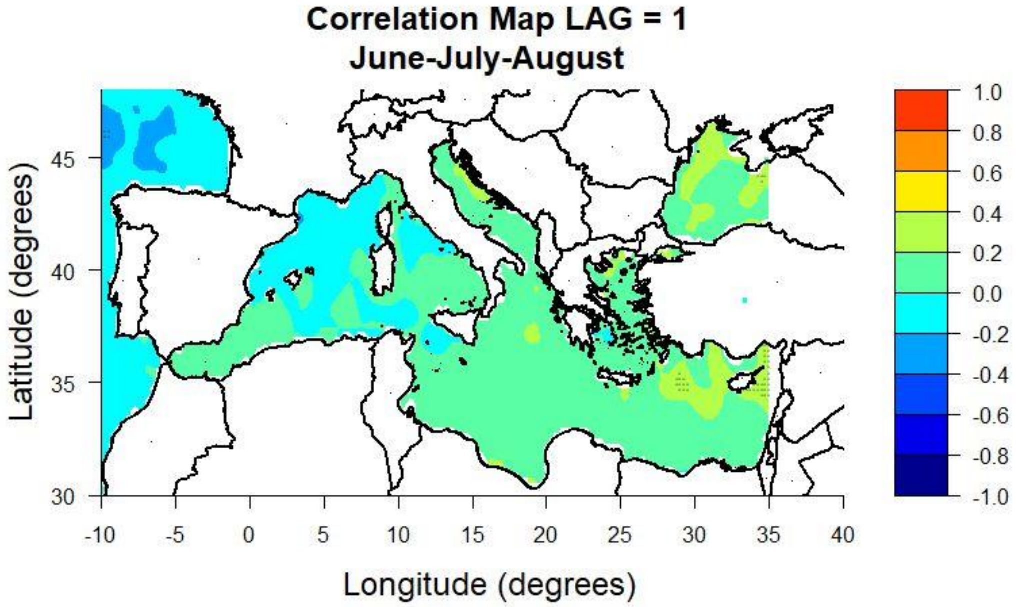


Figure 4.8: SST Summer Correlation with Lag 1

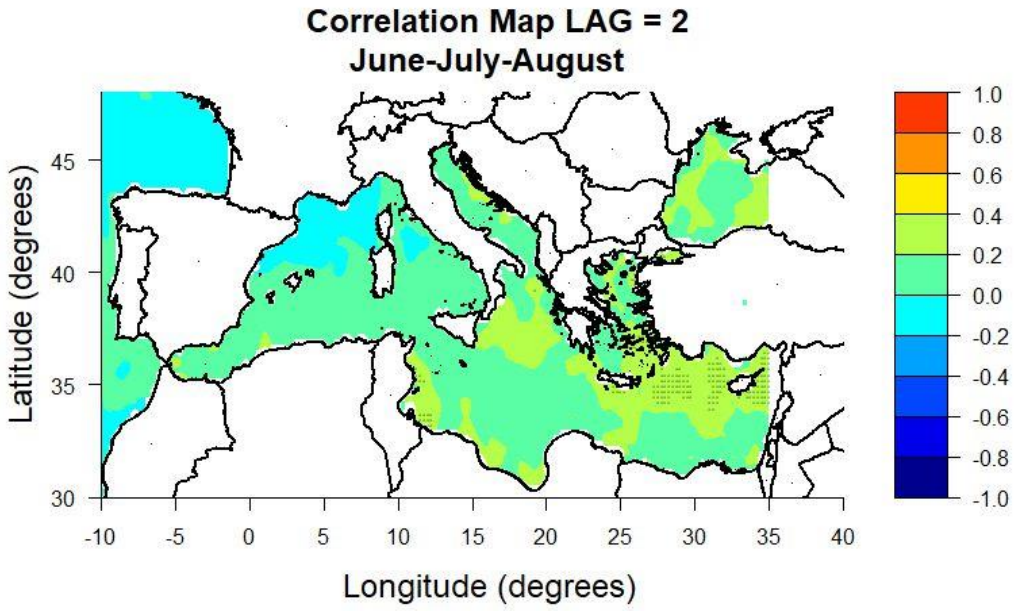


Figure 4.9: SST Summer Correlation with Lag 2

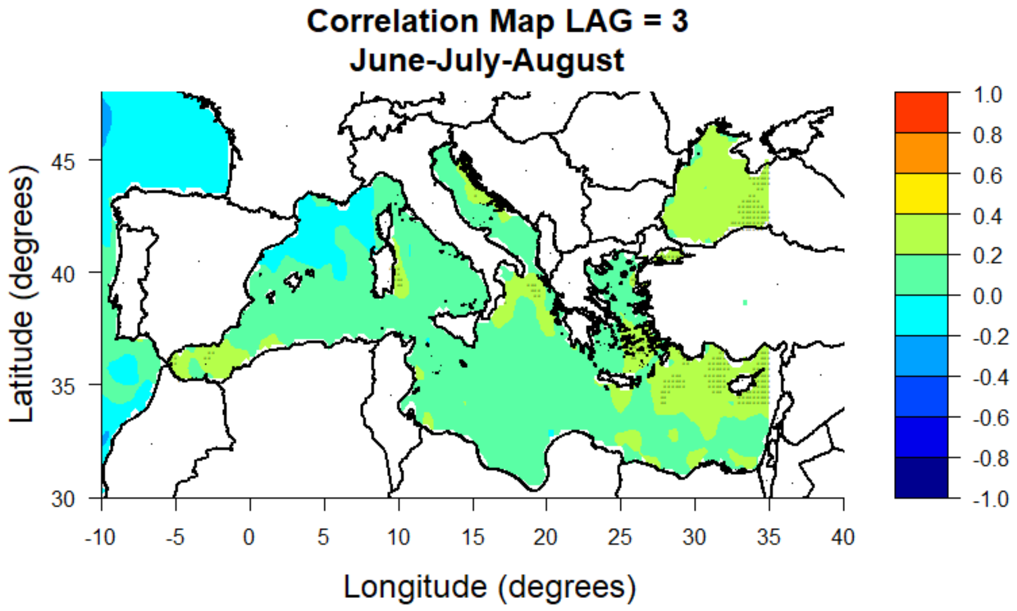


Figure 4.10: SST Summer Correlation with Lag 3

From Figures 4.11 through 4.14, the winter season correlation is mapped. Here, the maps are slightly different than the summer season. In Figure 4.12, a significant negative correlation is found in the western Mediterranean region, indicating warming as the gyre is cooling. The same negative correlation is found in Figure 4.11 too, but in a much smaller surface. Important positive correlation is found in all maps of the winter season in the eastern side, with most pronounced the two-year lag map in Figure 4.13. There, correlation coefficient values reach up to 0.5 and are all statistically significant. It is interesting how in the same map there is no significant negative correlation observed, indicating possibly different causes.

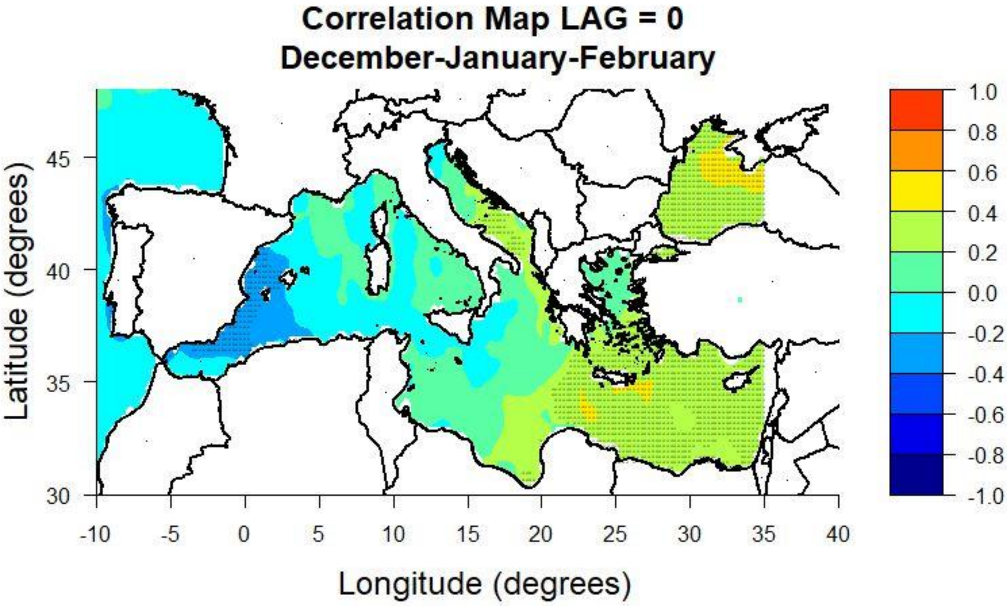


Figure 4.11: SST Winter Correlation with no Lag

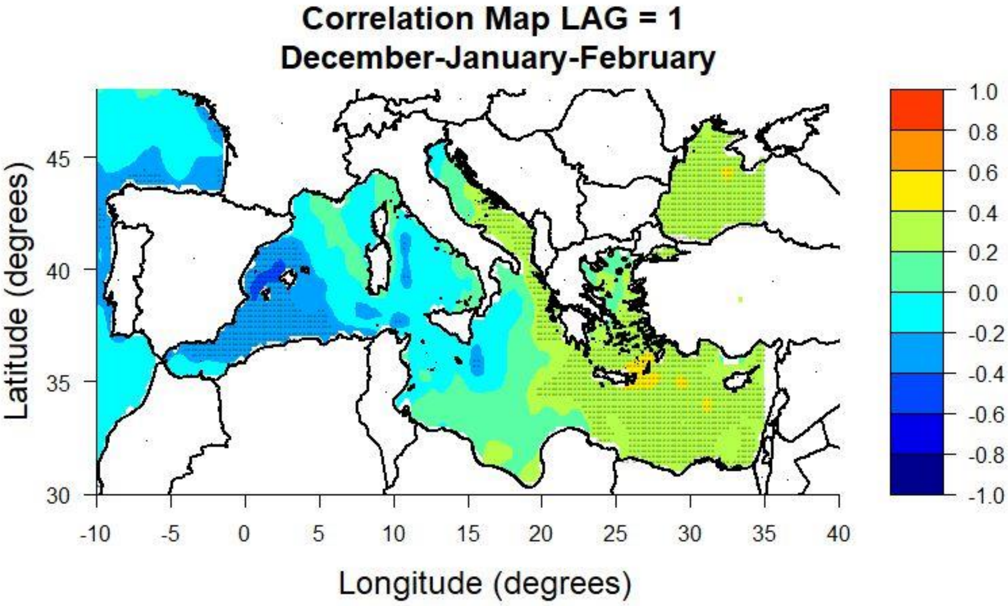


Figure 4.12: SST Winter Correlation Lag 1

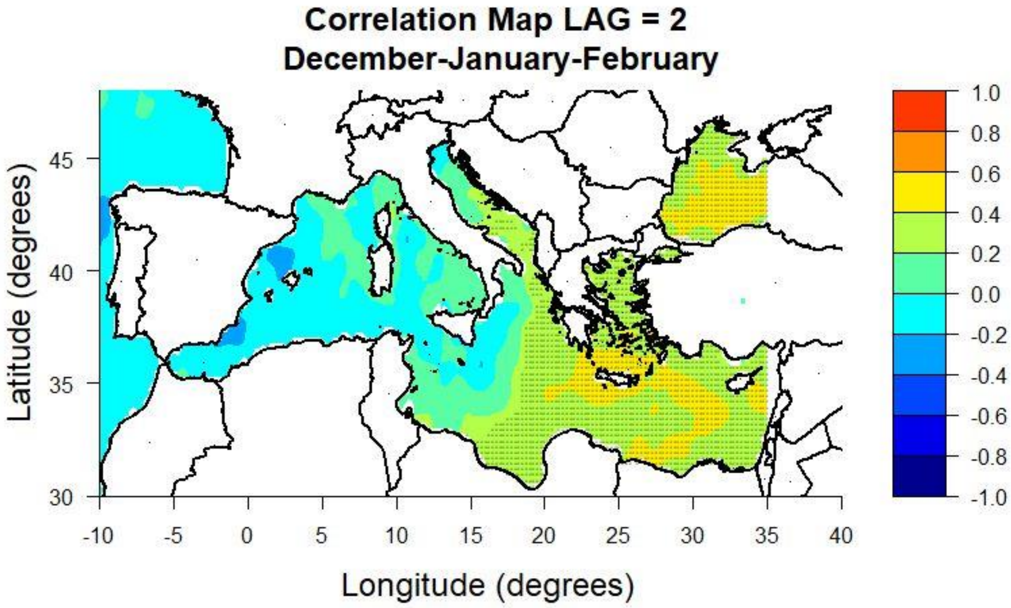


Figure 4.13: SST Winter Correlation with Lag 2

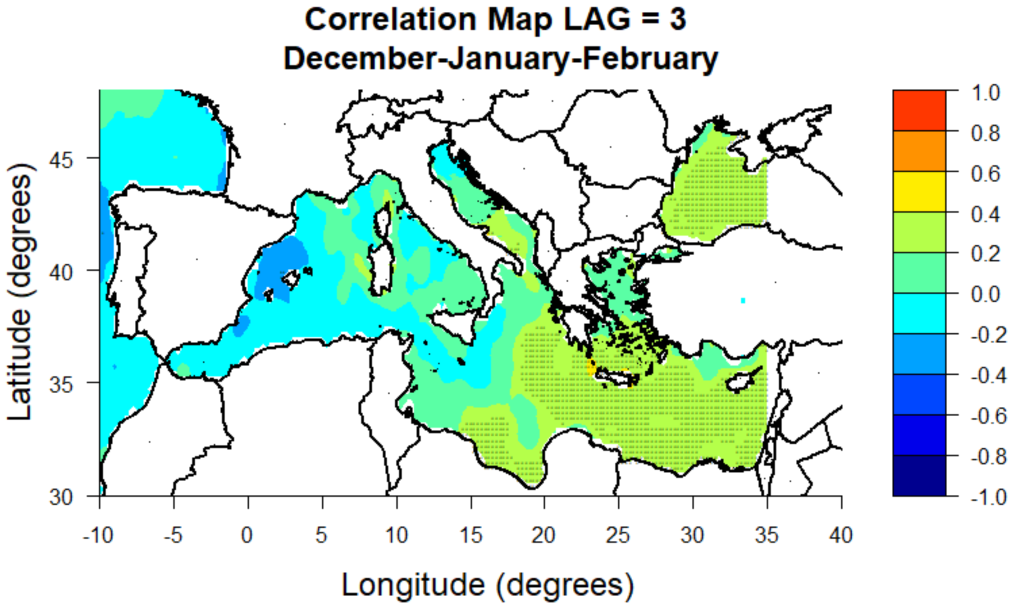


Figure 4.14: SST Winter Correlation with Lag 3

Following the SST, the next parameter to correlate with the AMOC and see for any relationships is the surface air temperature at 2 meters height. The correlation between the annual mean surface air temperature values and the AMOC index is in Figure 4.15. The strongest correlation is found within the first year, again, just like the SST maps, with positive correlation in the eastern Mediterranean and zero to slightly negative in the western Mediterranean. It is interesting to note the negative correlation in the last graph with lag 3.

The negative correlation of value around 0.3 has more statistical significance (low p-values) in contrast with the rest of the map.

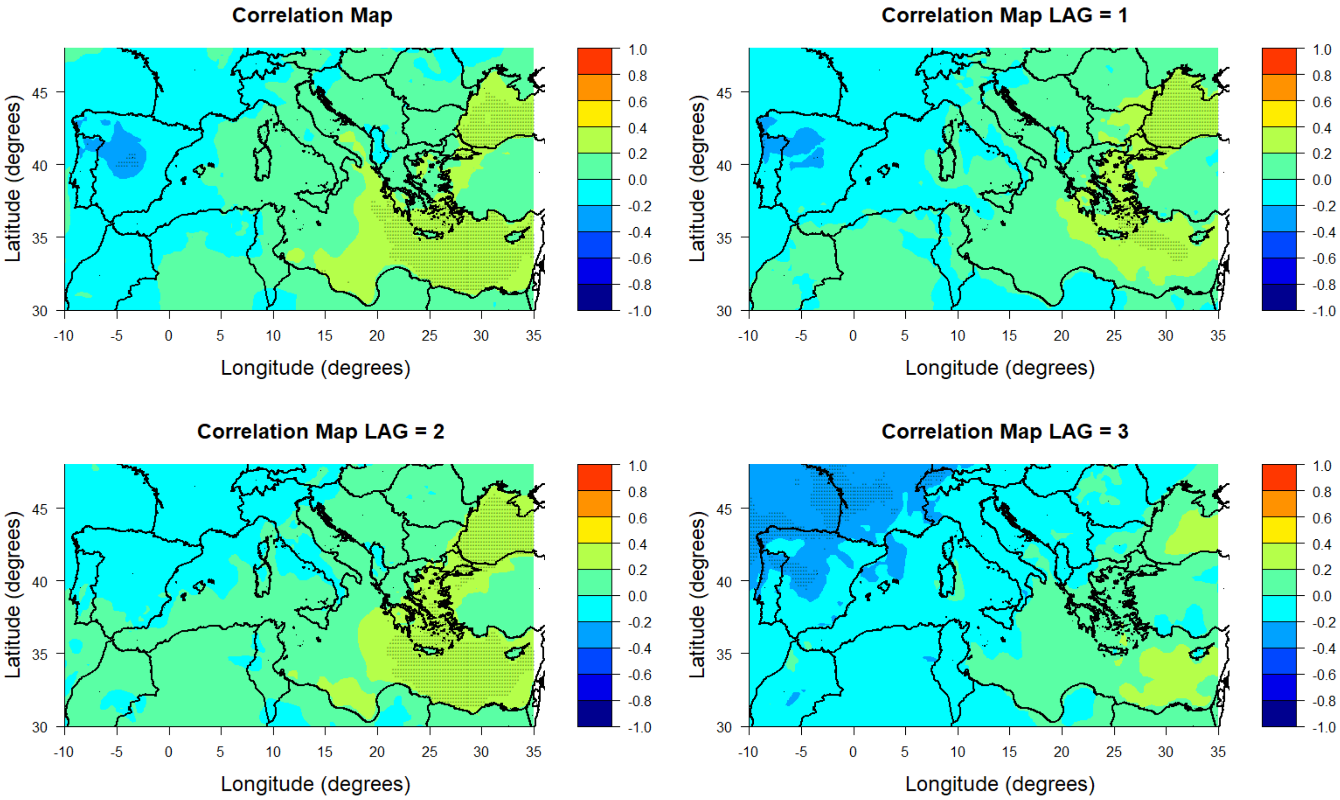


Figure 4.15: Surface Air Temperature Mean Annual Values Correlated with AMOC Index. Up to three years lag

On the seasonal correlations, depicted in the following graphs, the summer season resembles the annual values, with the stronger positive correlation appearing in Figure 4.16. By implementing a time lag, the correlation coefficient becomes less significant. Figures 4.17, 4.18 and 4.19 do not show any outstanding relationships, perhaps with a local increase in the south-east in Figure 4.18. There is no significant negative correlation observed in the summer season.

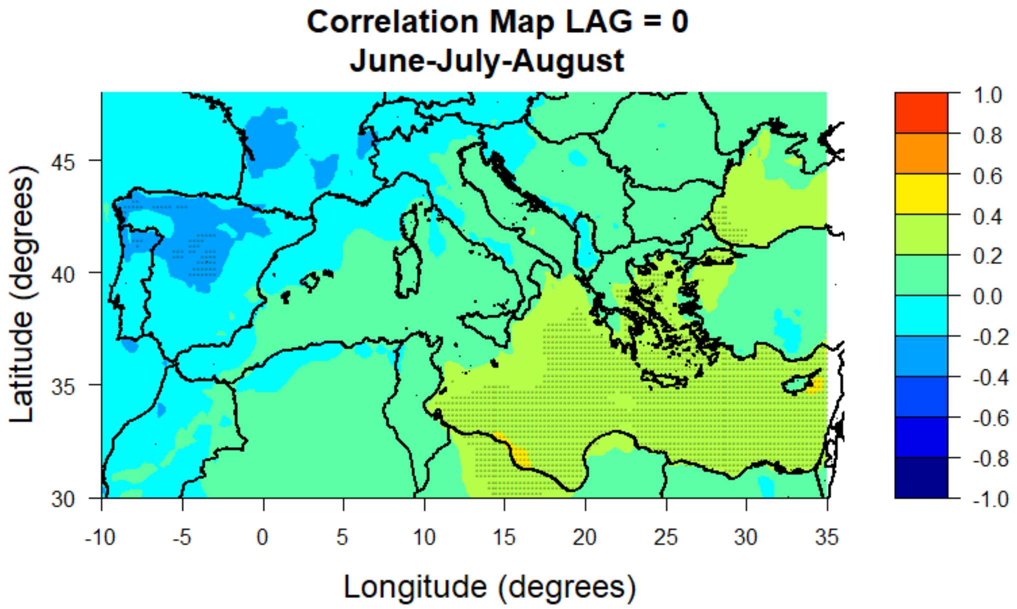


Figure 4.16: Surface Air Temperature Summer Correlation with no Lag

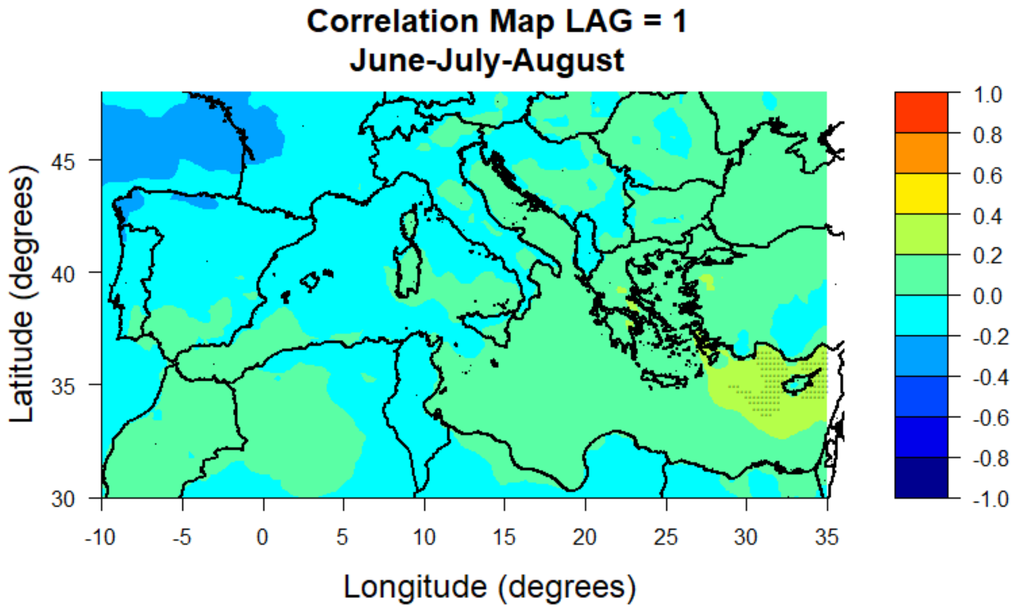


Figure 4.17: Surface Air Temperature Summer Correlation with Lag 1

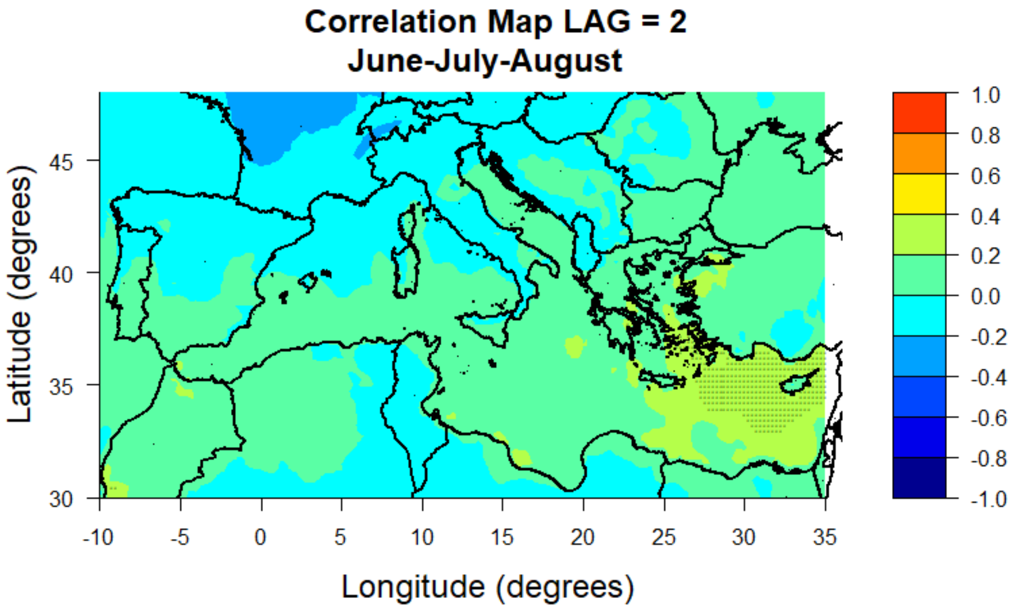


Figure 4.18: Surface Air Temperature Summer Correlation with Lag 2

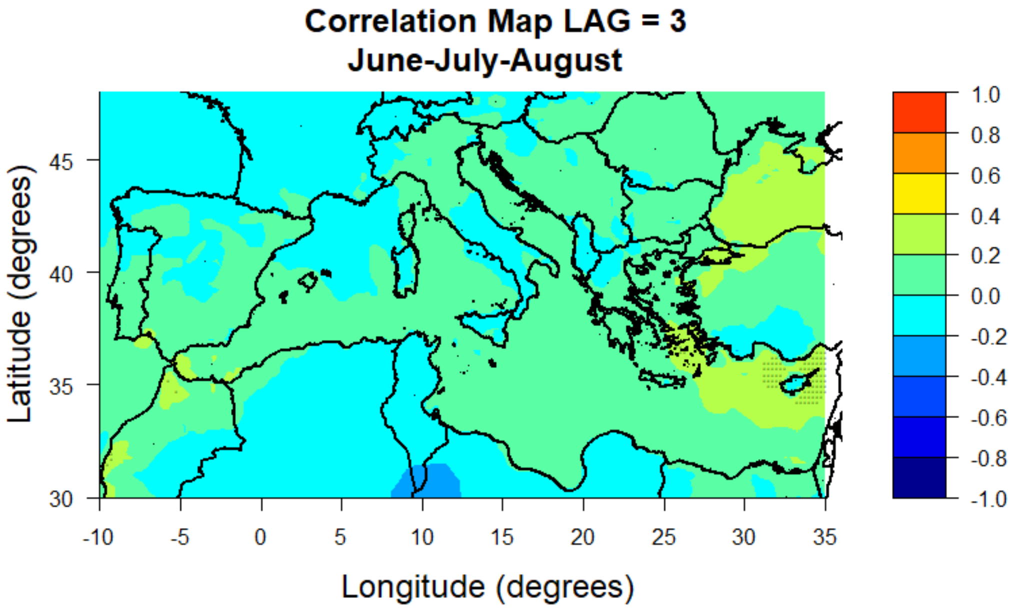


Figure 4.19: Surface Air Temperature Summer Correlation with Lag 3

Regarding the winter season for the Surface Air Temperatures, depicted in figures 4.20 through 4.23, something interesting happens. In contrast with the summer season, in winter there is a strong positive correlation lagging two years, in the map in Figure 4.22, again in the eastern Mediterranean. A reminder that this means it follows the trend of the index, so as the index decreases, surface air temperatures in the east also decrease. On the other hand, with a three-year lag in Figure 4.23, the surface air temperature in the west shows a very strong negative correlation with surprisingly high statistical significance. This means that as the index decreases, surface air temperatures in the west increase, lagging three years. This is very interesting and shows how different atmospheric systems have completely different effects on different time scales. Figure 4.21 has also some negative correlations, but nothing like in Figure 4.23. To understand the connection between the AMOC and the Mediterranean surface air temperature further research is required.

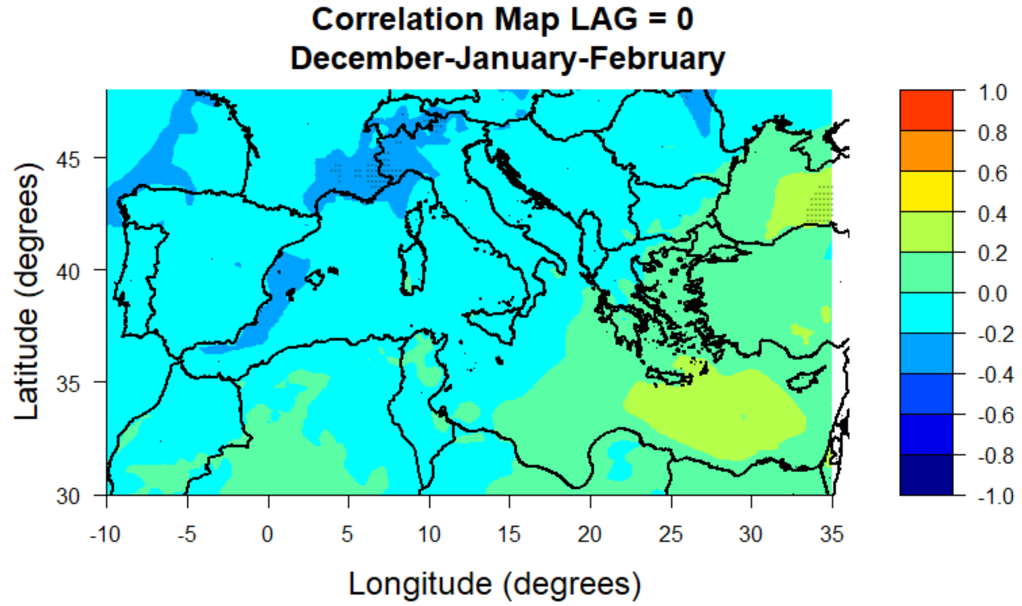


Figure 4.20: Surface Air Temperature Winter Correlation with no Lag

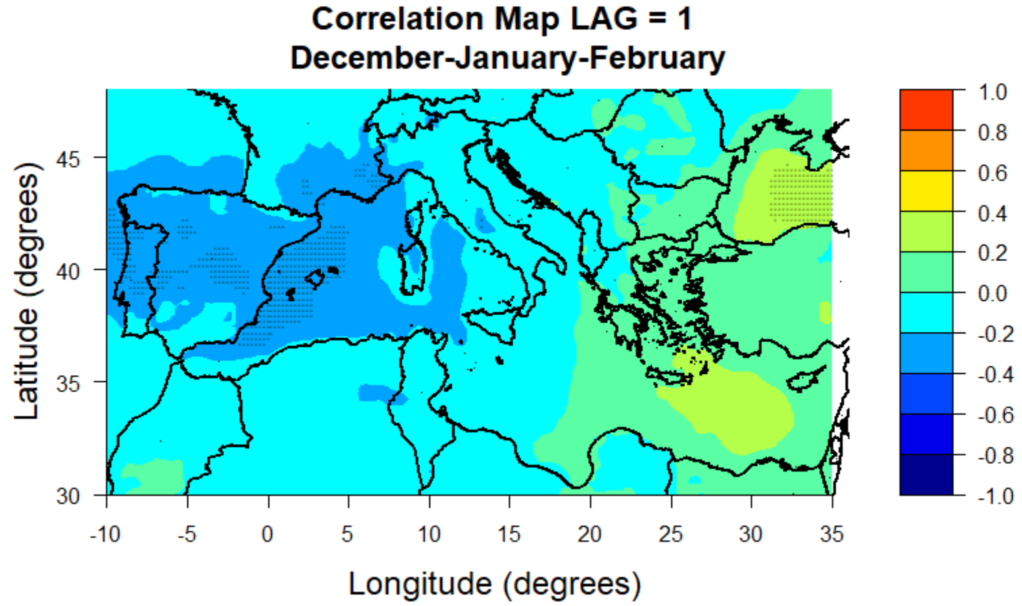


Figure 4.21: Surface Air Temperature Winter Correlation with Lag 1

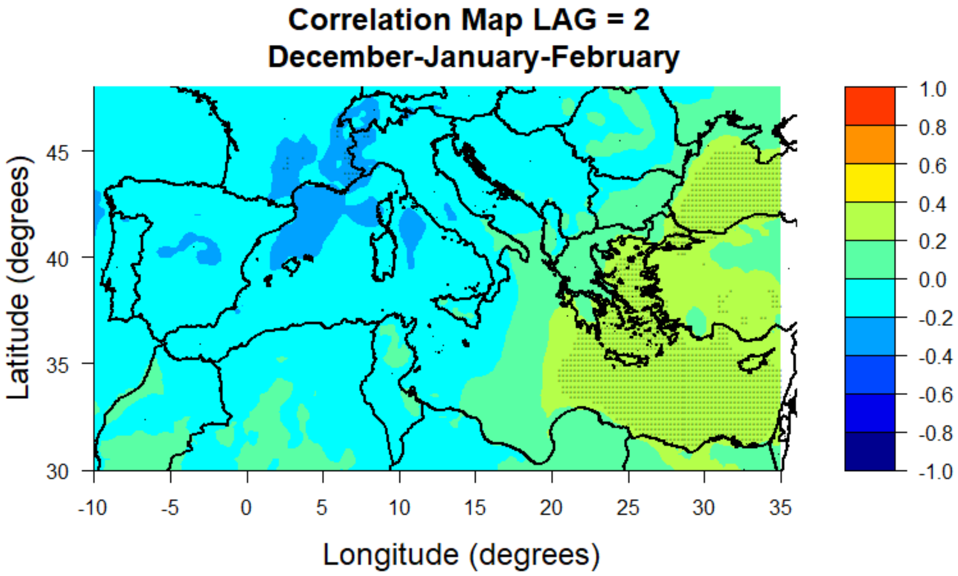


Figure 4.22: Surface Air Temperature Winter Correlation with Lag 2

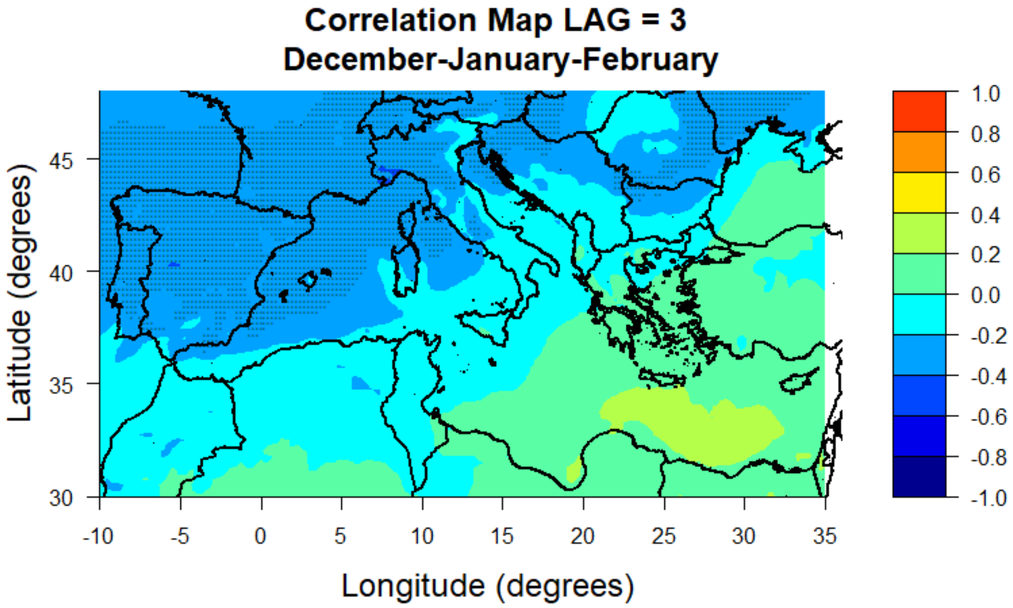


Figure 4.23: Surface Air Temperature Winter Correlation with Lag 3

Lastly, we investigate the total precipitation observed in the Mediterranean region. In Figure 4.24, the correlation maps between the mean annual total precipitation values and the AMOC index are depicted.

It is clear, that when comparing the mean annual total precipitation with the AMOC index in figure 4.24, there is a notable positive correlation at a three-year lag, with also great statistical significance. This time the positive correlation is not restricted in the east, but extends to the west as well, covering most of the Mediterranean region. Positive correlation means dry conditions as the total precipitation decreases along with the decrease of the AMOC index.

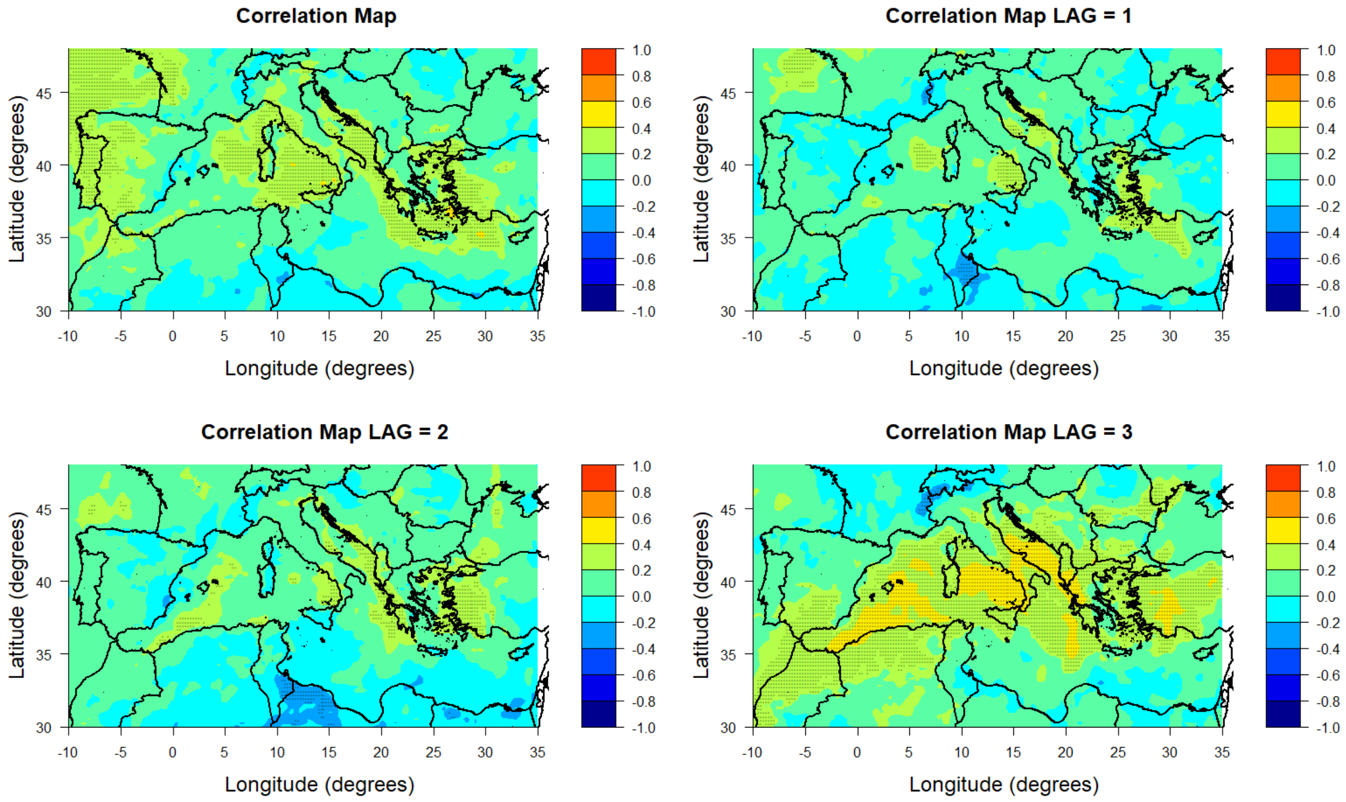


Figure 4.24: Total Precipitation Mean Annual Correlation Map

Following, the summer season correlations are showed, from Figure 4.25 through 4.28. In this case the correlations are spread out throughout the Mediterranean and are not restricted to the east or the west. Positive and negative correlation coexist as spots on the map. Most positive correlations are found in Figure 4.25 and Figure 4.28, while negative correlations can be found in the maps with lag 1 and 2, in Figures 4.26 and 4.27. It is unclear if there is a pattern from this information.

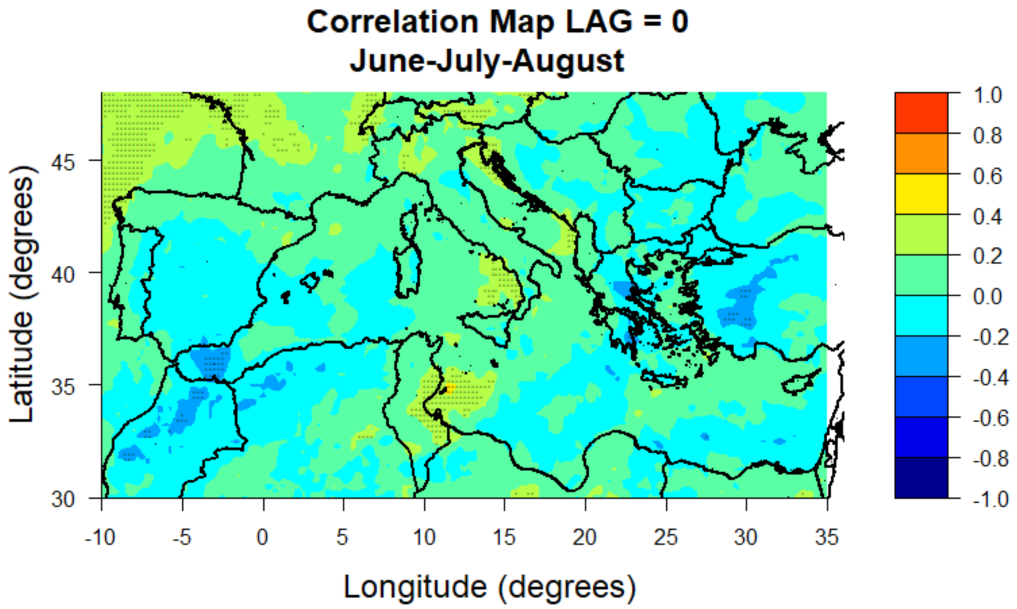


Figure 4.25: Total Precipitation Summer Correlation with no Lag

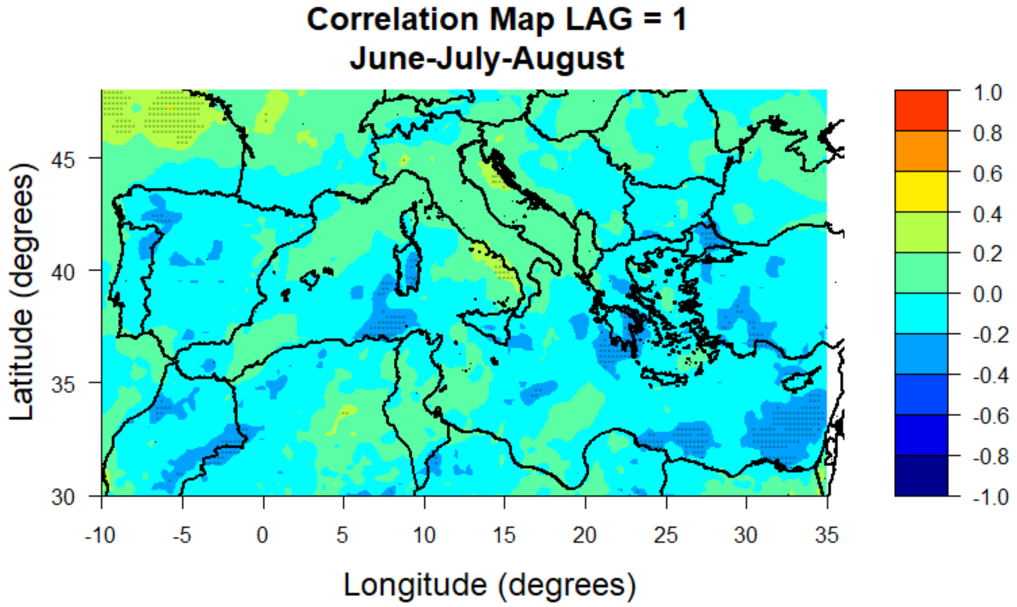


Figure 4.26: Total Precipitation Summer Correlation Lag 1

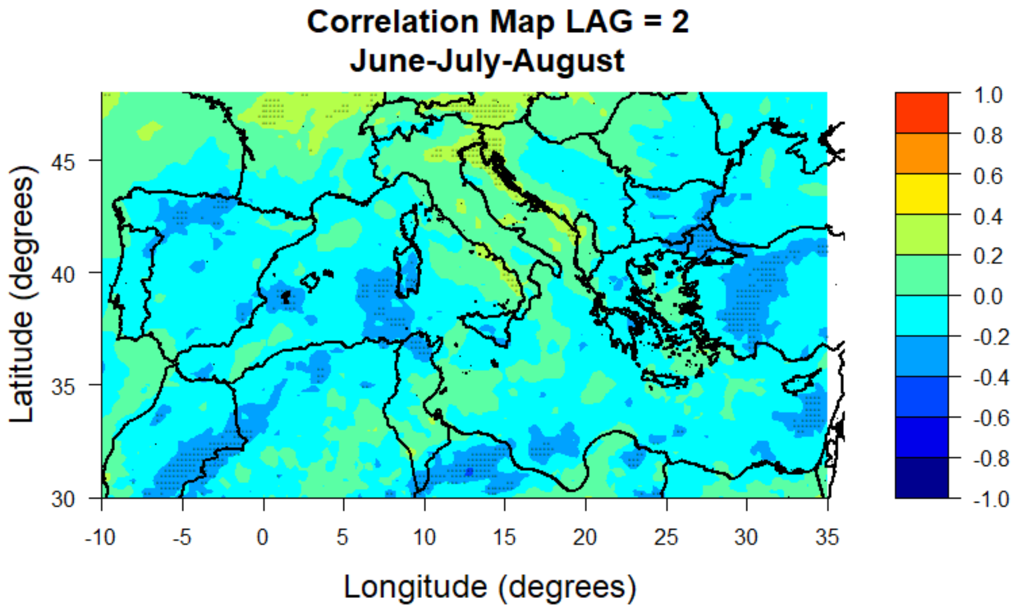


Figure 4.27: Total Precipitation Summer Correlation Lag 2

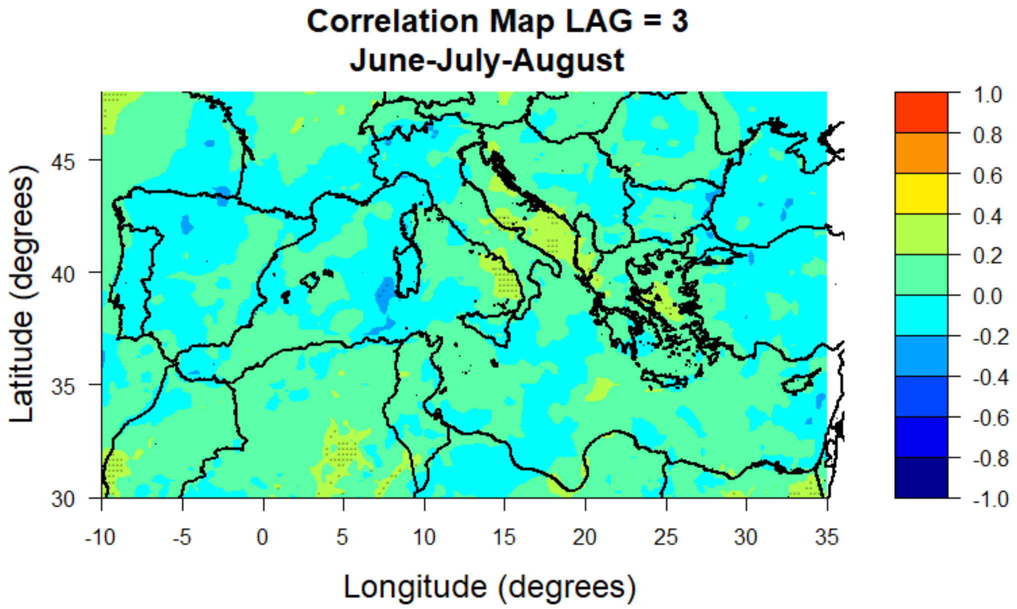


Figure 4.28: Total Precipitation Summer Correlation Lag 3

From Figure 4.29 to 4.32, the winter season for the total precipitation correlation values are shown. Here, from December through February, mostly positive correlation values are observed. The highlight of these maps is the correlation with a three-year time lag in figure 4.32. High values, close to 0.6 with high statistical significance prevail over the Mediterranean region. Figures 4.29, 4.30 and 4.31 also show satisfactory positive correlation, mostly in the Balkan and Italian region, but Figure 4.32 still stands out. This indicates that winters are going to be drier as the AMOC weakens.

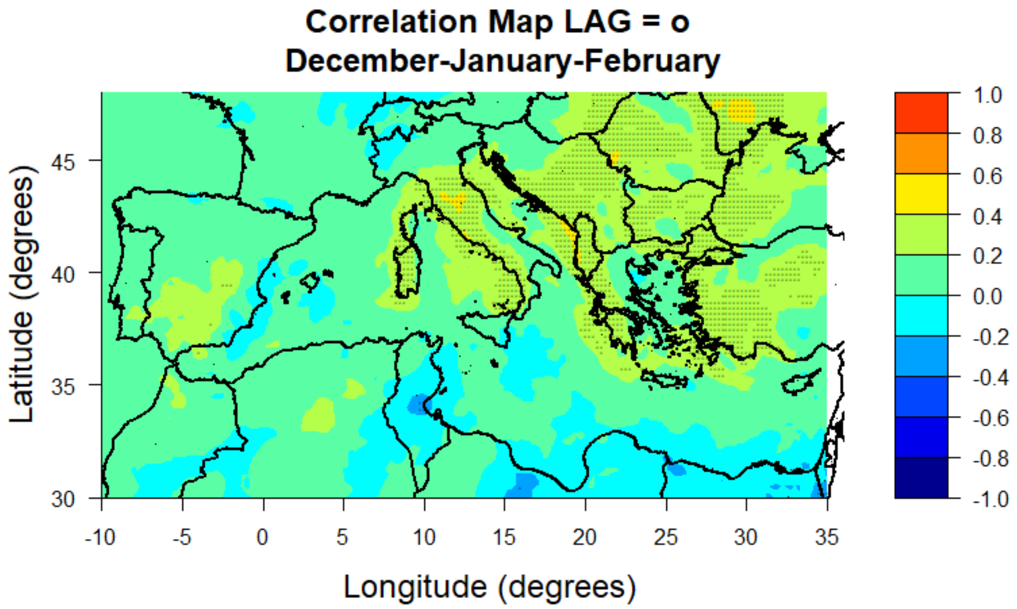


Figure 4.29: Total Precipitation Winter Correlation with no lag

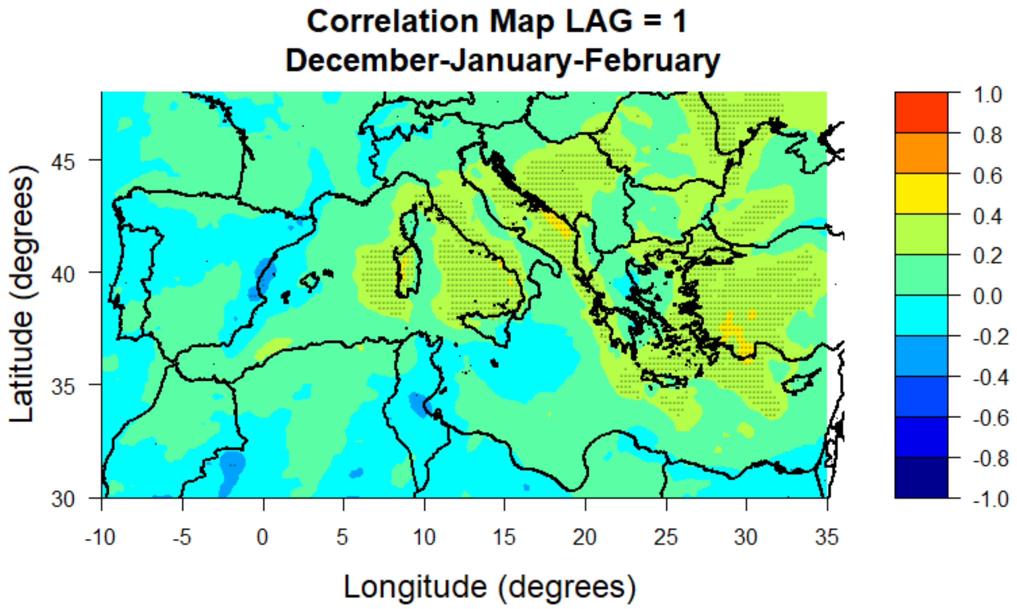


Figure 4.30: Total Precipitation Winter Correlation with Lag 1

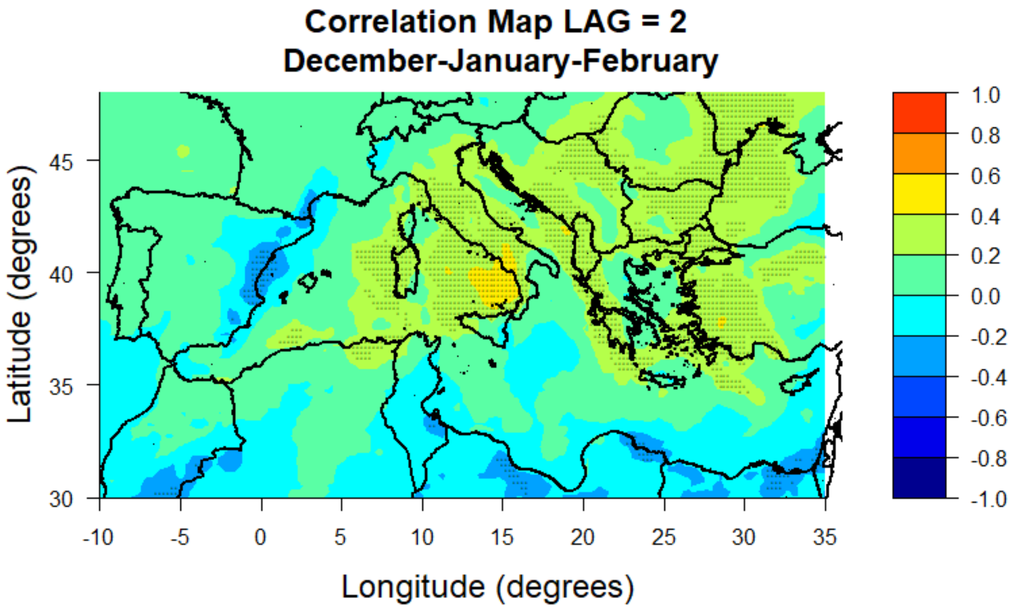


Figure 4.31: Total Precipitation Winter Correlation with Lag 2

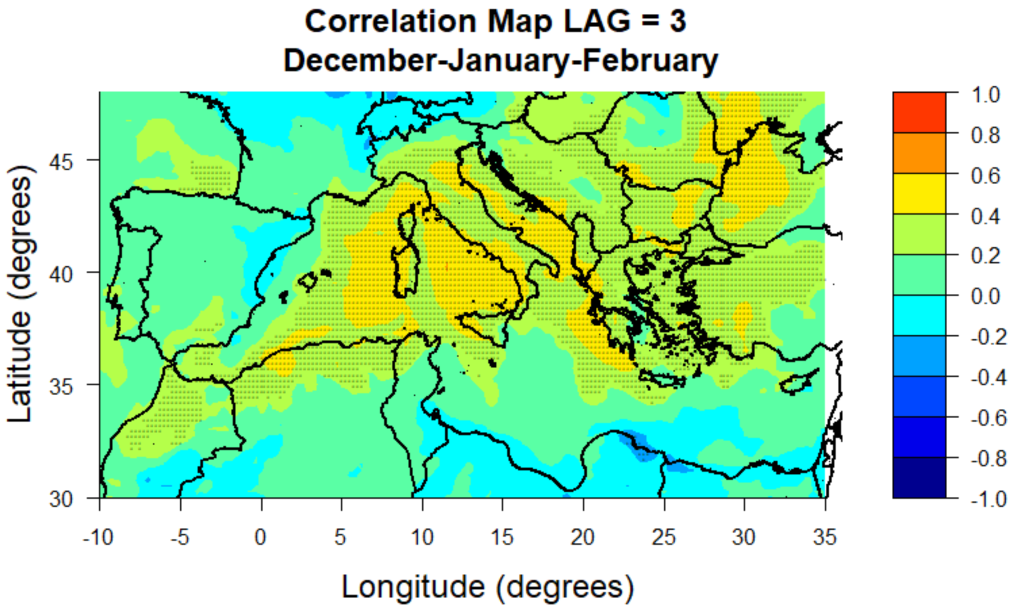


Figure 4.32: Total Precipitation Winter Correlation with Lag 3

In conclusion, all three parameters share a relationship with the AMOC. Of course, not all correlations were of equal importance. The positive correlation with the total precipitation variable at a three-year lag stood out, as well as the negative correlation regarding the surface air temperature at lag 3 as well, both in the winter season. Again, in the winter season, the sea surface temperature showed good correlation with the AMOC, at lag 2. Summer correlations in all variables seemed to be milder than the winter ones. Some notable correlation appeared at zero lag, both on the SST and the surface air temperature for the summer season. In general, the AMOC impacts the Mediterranean the most after a three-year time gap.

The results we got are encouraging. The three Mediterranean climate variables researched seem to have a relationship with the AMOC. However, this relationship is not as clear as hoped and is not homogenous throughout the region. One thing that stood out is that in most maps, the correlations seemed to be divided between east and west Mediterranean, with sometimes even complete opposite correlation coefficients. The only exception to this rule was the precipitation which had a more complicated spread. This clue, along with the variety of values found suggest that Mediterranean climate is driven by more complicated atmospheric and/or ocean systems. The AMOC, although not the only forcing affecting Mediterranean climate, it is a major contributor with correlation values reaching 0.5 both positive and negative. With AMOC's future being still an issue of debate, depended on so many factors and at the same time so devastating for humanity impacts, this relationship demands more detailed research. Additionally, the Mediterranean region is so sensitive to rising temperatures and climatic changes, any lead towards future conditions and evolution of this tremendous issue we are upon, is vital for adaptation policies and measures, ensuring a future a little more sustainable that today.

5 CONCLUSIONS

This study has collected and presented some of the latest material in ocean and climate science in an attempt to highlight the importance of climatic feedbacks for future projections, connecting the AMOC with the Mediterranean basin. And although the evidence is compelling, there are many questions and issues being raised regarding the confidence and the trust in these findings and also in the connection and interrelationship between the components leading to these findings. The limited length of the observational records is definitely a known issue, since systematic observations only began in 2004. Between the models there is strong disagreement as well. In the CMIP5 ensembles there is no observable trend for the AMOC, while in the CMIP6 there is a trend but not in agreement with other reconstructions, adding a recovery period in the mid-late 20th century. For some researchers, the validity of proxy-based reconstructions is in question since many of the proxies (like SST-proxies) are influenced by many other factors beside the AMOC. Another debate is that the variability of the subpolar gyre, used as an indicator for the variability of the AMOC, might not be accurate since the subpolar gyre could be independent and wind driven. But a compelling argument is that observational records, even though they are short, do show a large AMOC variability, that is underestimated in the CMIP models.

Regarding the positive correlations observed in the maps, the concept of cooling might be contrasting the measured and observed trends. It is proven, that the Mediterranean region is going to heat up with climate change and get drier, as a known hot spot for climate change. Especially the eastern Mediterranean is expected to face in the following years, harsh conditions with extreme heat waves and drought. So, the fact that we forecast a cooling behavior might be raising questions. However, this is a good example of the complexity of the global climate system. The AMOC index used is a good indicator of the weakening or the strengthening of the overturning mechanism of the Atlantic, not the ocean circulation altogether. The correlation found is between the cooling in the subpolar gyre and not heat transport in the rest of the ocean, that is and will still continue in a different than previously pattern. At the same time, the Mediterranean is exposed to very warm fronts coming from the tropics and subtropics that might have a higher influence than the ocean. It is also a fact, as mentioned before that the eastern part of the Mediterranean, is mostly influenced by subtropical patterns and Asian monsoons and less by north-west patterns such as the subpolar gyre and the AMOC (in Lionello 2012, I3). Another parameter is the ITCZ, that many papers and previous research have indicated that will shift in a different pattern than normal, leading to drier conditions in the Mediterranean (MedECC, MAR1). So, in order to understand the Mediterranean climate better, and all the components a weak AMOC impacts, it is best to consider all parameters. Although for the Mediterranean, extreme heat is forecasted, the fact that one parameter, the AMOC parameter, might bring cold air in this area, gives hope for a more environment and human-friendly heat equilibrium. There is no doubt further research is needed.

Another interesting finding is the area where the statistically significant correlations were found. The temperature variables (SST and SAT) appeared to have a more east-west pattern, while precipitation had spots and significant correlations all over the Mediterranean region. This could indicate a separation to which variables are mostly affected by the AMOC and which by other circulation patterns. It is possible that precipitation is more influenced by the AMOC, than the air and sea surface temperature.

But when we look purely at the statistically significant correlations, precipitation is mostly correlated with the AMOC in the winter season after a lag of three years while the sea surface temperature has a better relationship without time lag up at a two-year lag, again mostly in winter. The same goes for the surface air temperature where there is additionally a significant negative relationship three years ahead.

A given bias from this study is that we assume the AMOC overturning system is depended on the subpolar gyre. This is the assumption made by Caesar et al. (2018) that provided the AMOC index but also from other researchers. There are indeed strong indications that the overturning is connected with the subpolar gyre and any change is originating there. But there is no complete certainty and the precise percentage to which these two mechanisms are connected is still unknown. So, any relationship resulting from this study between the AMOC and the Mediterranean should be considered with caution.

To conclude, the climate system is a very complicated system and even today there are important uncertainties regarding its proper representation. One of the issues the scientific community has come across is simulating the Atlantic Meridional Overturning Circulation or AMOC and more generally the ocean circulation system. Among other, open questions still are the correct resolution for such a model, how to resolve the lack of observations, and how to represent correctly the many components and parameters that drive it (like winds, cloud cover and ice). The human factor could be the biggest uncertainty since it has a significant effect on climate and the oceans. At the same time, the continuous absorption of heat and Carbon Dioxide from the atmosphere in the oceans, might be masking the scale of the anthropogenic damage in the natural systems, that might be bigger than thought. Of course, there is no equation predicting how humans will act in the next decades. The one thing we know is that the world is warming, and the oceans are changing. There is strong evidence that the AMOC is slowing down, which in turn will affect the amount of heat and salt being transported. This in turn will affect the air temperature and air humidity as well as the wind systems which of course alter weather patterns and climate. The Mediterranean region is a region that already experiences change in terms of heatwaves, extremes and altered rain patterns which according to the global temperature patterns will only get worse. Since it is a very vulnerable place for climate change, with local communities already struggling with drought and extreme heatwaves, policymakers need to put all their efforts to sustaining this cultural treasure and natural beauty that is the Mediterranean and make the right decisions to adapt as well as possible to the new harsh conditions they face today and will face tomorrow. In order to make proper predictions of how Mediterranean climate will evolve, a good understanding of the various parameters that compose the region climate must be gained. We looked into the effect the AMOC has on the Mediterranean Sea and climate, as the AMOC is widely known driver of global (and regional) climate, as it is the source of many weather systems known to affect Europe and south Europe. We found that indeed there is a connection but were unable to generalize the findings or find a consistent trend, due to the multi-variability both of the AMOC as well as the Mediterranean responding to multiple atmospheric/oceanic systems and to a complicated morphology. The findings are, however, promising enough to lead to further investigations and to perhaps lead to a new generation of Mediterranean climate predicting models that integrate the AMOC variability and change in the northern Atlantic Ocean for improved forecasts. Of course, for this to work, it is vital we gain a better understanding of the AMOC. This will not only benefit Mediterranean forecasts but also global and north European forecasts, since changes in the AMOC are strongly connected with global climate changes and north European climate. And since it is well-known that changes in the AMOC have tremendous impacts for the environment and humankind, there is no room for delays.

6 References

Ayache M., Swingedouw D., Yannick M., Frédérique E., Christophe C., Multi-centennial variability of the AMOC over the Holocene: A new reconstruction based on multiple proxy-derived SST records, Global and Planetary Change, Volume 170, Pages 172-189, ISSN 0921-8181 (2018) https://doi.org/10.1016/j.gloplacha.2018.08.016.

Bellomo, K., Angeloni, M., Corti, S. *et al.* Future climate change shaped by inter-model differences in Atlantic meridional overturning circulation response. *Nat Commun* **12**, 3659 (2021).https://doi.org/10.1038/s41467-021-24015-w

Bonnet, R., Swingedouw, D., Gastineau, G. et al. Increased risk of near term global warming due to a recent AMOC weakening. Nat Commun **12**, 6108 (2021). https://doi.org/10.1038/s41467-021-26370-0

Caesar, L., McCarthy, G.D., Thornalley, D.J.R. et al. Current Atlantic Meridional Overturning Circulation weakest in last millennium. Nat. Geosci. **14**, 118–120 (2021). https://doi.org/10.1038/s41561-021-00699-z

Caesar, L., Rahmstorf, S., Robinson, A. *et al.* Observed fingerprint of a weakening Atlantic Ocean overturning circulation. *Nature* **556**, 191–196 (2018). https://doi.org/10.1038/s41586-018-0006-5

Cherchi, A. Connecting AMOC changes. *Nat. Clim. Chang.* **9**, 729–730 (2019). https://doi.org/10.1038/s41558-019-0590-x

Climate.gov: Climate Models, https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-models

Copernicus Climate Change Service (C3S), *Climate Reanalysis*, assessed 28/02/2023, https://climate.copernicus.eu/climate-reanalysis

Copernicus Marine Service, Ocean Monitoring and Forecasting Models https://marine.copernicus.eu/explainers/operational-oceanography/monitoring-forecasting/models

Correlations and Hypothesis testing from https://www.statisticshowto.com/

Drijfhout, S. Competition between global warming and an abrupt collapse of the AMOC in Earth's energy imbalance. *Sci Rep* **5**, 14877 (2015). https://doi.org/10.1038/srep14877

European Centre for Medium-Range Weather Forecasts (ECMWF), Fact sheet: Reanalysis, 9 November 2020, https://www.ecmwf.int/en/about/media-centre/focus/2020/fact-sheet-reanalysis

Frajka-Williams E, Ansorge IJ, Baehr J, Bryden HL, Chidichimo MP, Cunningham SA et al. Atlantic Meridional Overturning Circulation: Observed Transport and Variability. Front. Mar. Sci. 6:260. (2019) https://doi.org/10.3389/fmars.2019.00260

Goosse, H. *Climate System Dynamics and Modelling*. Cambridge: Cambridge University Press (2015). https://doi.org/10.1017/CBO9781316018682

Gornitz, V. Paleoclimate Proxies, An Introduction. In: Gornitz, V. (eds) Encyclopedia of Paleoclimatology and Ancient Environments. Encyclopedia of Earth Sciences Series. Springer, Dordrecht, pp 1049, (2009). https://doi.org/10.1007/978-1-4020-4411-3_171

Hersbach H, Bell B, Berrisford P, et al. The ERA5 global reanalysis. QJR Meteorol Soc. 2020;146:1999–2049, (2020). https://doi.org/10.1002/qj.3803

Hirschi, J. J. -M., Barnier, B., Böning, C., Biastoch, A., Blaker, A. T., Coward, A., et al. The Atlantic meridional overturning circulation in high-resolution models. J. Geophys. Res. Oceans 125, e2019JC015522. (2020) https://doi.org/10.1029/2019JC015522

Hutala S. 2020, Physics Across Oceanography: Fluid Mechanics and Waves, Chapter 35: The Ekman Layer, University of Washington: https://uw.pressbooks.pub/ocean285/chapter/the-ekman-layer/

IPCC Sixth Assessment Report, Working Group 1: The Physical Science Basis, Chapter 9: Ocean, Cryosphere and Sea Level Change, Chapter 9: Ocean, Cryosphere and Sea Level Change | Climate Change 2021: The Physical Science Basis (ipcc.ch)

Ivanovic, R.F., Valdes, P.J., Gregoire, L. et al. Sensitivity of modern climate to the presence, strength and salinity of Mediterranean-Atlantic exchange in a global general circulation model. Clim Dyn **42**, *859–877 (2014). https://doi.org/10.1007/s00382-013-1680-5*

Jackson, L.C., Kahana, R., Graham, T. et al. Global and European climate impacts of a slowdown of the AMOC in a high resolution GCM. Clim Dyn **45**, 3299–3316 (2015). https://doi.org/10.1007/s00382-015-2540-2

JMP Statistical Discovery, Statistics Knowledge Portal: Correlation, https://www.jmp.com/en_us/statistics-knowledge-portal/what-is-correlation.html

Kim, SK., Kim, HJ., Dijkstra, H.A. *et al.* Slow and soft passage through tipping point of the Atlantic Meridional Overturning Circulation in a changing climate. *npj Clim Atmos Sci* **5**, 13 (2022). https://doi.org/10.1038/s41612-022-00236-8

Kostov, Y., Johnson, H.L., Marshall, D.P. et al. Distinct sources of interannual subtropical and subpolar Atlantic overturning variability. Nat. Geosci. **14**, 491–495 (2021). https://doi.org/10.1038/s41561-021-00759-4

Latif, M., Sun, J., Visbeck, M. *et al.* Natural variability has dominated Atlantic Meridional Overturning Circulation since 1900. *Nat. Clim. Chang.* **12**, 455–460 (2022). https://doi.org/10.1038/s41558-022-01342-4

Lionello Pierro (ed.), 2012: The climate of the Mediterranean Region, Elsevier, pp.592

Lionello, P., Scarascia, L. The relation between climate change in the Mediterranean region and global warming. Reg Environ Change **18**, *1481–1493 (2018). https://doi.org/10.1007/s10113-018-1290-1*

Liu W., Fedorov A. V., Xie S.-P., Hu S., Climate impacts of a weakened Atlantic Meridional Overturning Circulation in a warming climate. Sci. Adv.6, eaaz4876 (2020) https://doi.org/10.1126/sciadv.aaz4876

Manfred A. Lange, 2020: Climate Change in the Mediterranean: Environmental Impacts and Extreme Events, The Cyprus Institute, IEMed Mediterranean Yearbook 2020

Manfred A. Lange: https://www.iemed.org/publication/climate-change-in-the-mediterranean-environmental-impacts-and-extreme-events/

Massachusetts Institute of Technology, Climate Portal, Explainer: Climate Models, 8 January 2021 https://climate.mit.edu/explainers/climate-models

Meccia, V.L., Fuentes-Franco, R., Davini, P. *et al.* Internal multi-centennial variability of the Atlantic Meridional Overturning Circulation simulated by EC-Earth3. *Clim Dyn* (2022). https://doi.org/10.1007/s00382-022-06534-4

MedECC (2020) *Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report* [Cramer, W., Guiot, J., Marini, K. (eds.)]. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632 pp., ISBN: 978-2-9577416-0-1, https://doi.org/10.5281/zenodo.4768833.

Meissner KJ, Montenegro A., Avis C.: Paleoceanography. Encyclopedia of Paleoclimatology and Ancient Environments. Encyclopedia of Earth Sciences Series. Springer, Dordrecht, pp 1049 (2009)

Met Office Hadley Center Climate Briefing Note, September 2019 https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/climate/ocean-and-cryosphere-report/srocc_amoc.pdf

Met Office, Intertropical Convergence Zone (ITCZ), https://www.metoffice.gov.uk/weather/learn-about/weather/atmosphere/intertropical-convergence-zone

National Oceanic and Atmospheric Administration (NOAA), What is the Atlantic Meridional Overturning Circulation (AMOC)?, https://oceanservice.noaa.gov/facts/amoc.html 20/01/23

National Oceanic and Atmospheric Administration (NOAA), Why should we care about the ocean? National Ocean Service website https://oceanservice.noaa.gov/facts/why-care-about-ocean.html 20/01/2023

Pinar Ersoy. 2021, Types of Correlation Coefficients, in Towards Data Science, https://towardsdatascience.com/types-of-correlation-coefficients-db5aa9ea8fd2

Rahmstorf, S. Ocean circulation and climate during the past 120,000 years. *Nature* **419**, 207–214 (2002). https://doi.org/10.1038/nature01090

Rahmstorf, S., Box, J., Feulner, G. *et al.* Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. *Nature Clim Change* **5**, 475–480 (2015). https://doi.org/10.1038/nclimate2554

Rahmstorf, S.: Thermohaline Ocean Circulation. In: Encyclopedia of Quaternary Sciences, Edited by S. A. Elias. Elsevier, Amsterdam (2006).

Rantanen, M., Karpechko, A.Y., Lipponen, A. *et al.* The Arctic has warmed nearly four times faster than the globe since 1979. *Commun Earth Environ* **3**, 168 (2022). https://doi.org/10.1038/s43247-022-00498-3

Spooner, P. T., Thornalley, D. J. R.,Oppo, D. W., Fox, A. D.,Radionovskaya, S., Rose, N. L., et al. Exceptional 20th century oceancirculation in the Northeast Atlantic.Geophysical Research Letters, 47, e2020GL087577. (2020) https://doi.org/10.1029/2020GL087577

Statistics How to, The probability and statistics topic index, https://statisticsbyjim.com/probability/t-distribution/

Swingedouw D, Houssais M-N, Herbaut C, Blaizot A-C, Devilliers M and Deshayes J AMOC Recent and Future Trends: A Crucial Role for Oceanic Resolution and Greenland Melting? Front. Clim. 4:838310 (2022). https://doi.org/10.3389/fclim.2022.838310

Thompson, D. W. J., Wallace, J. M., Kennedy, J. J., & Jones, P. D. (2010). *An abrupt drop in Northern Hemisphere sea surface temperature around 1970. Nature, 467(7314), 444–447.* https://doi.org/10.1038/nature09394

Trenberth, K. *The Changing Flow of Energy Through the Climate System*. Cambridge: Cambridge University Press (2022). https://doi.org/10.1017/9781108979030

United Nations Environment Programme, Climate Change in the Mediterranean, https://www.unep.org/unepmap/resources/factsheets/climate-change

United Nations sustainable development, The ocean conference factsheet, https://www.un.org/sustainabledevelopment/wp-content/uploads/2017/05/Ocean-fact-sheet-package.pdf June 2017

Wade Bridget, 2001: High-resolution stable isotope records as indicators of late middle Eocene climate change, University of Edinburgh, PhD thesis via EThOS