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Master Thesis

Study of the impact of the Mediterranean Sea on the physical and geochemical response of the North Atlantic Sea by numerical simulation methods

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Abstract

The interaction between different oceanic regions plays a crucial role in shaping global climate patterns and the distribution of heat, salinity, and nutrients. One such significant interaction occurs between the Mediterranean Sea and the North Atlantic Ocean through the Strait of Gibraltar. The present study considers the complex interaction between these two regions and addresses the impact of the Mediterranean Sea on the North Atlantic Ocean's dynamics and biogeochemical processes. By examining a coupled sea-ice configuration based on the global hydrodynamic numerical model, NEMO, in combination with the PISCES model for biogeochemistry activity, the study highlights how the absence of the Mediterranean Outflow (MOW) affects the thermohaline properties and investigates the influence of these interactions on the marine biogeochemistry in the North Atlantic region. To achieve this objective, two simulations were performed for a period of 100 years. The first one considers the actual global conditions that occur in the ocean and atmosphere, referred to as the Reference, while the second one consists of a hypothetical scenario assuming the absence of the Mediterranean Sea that is achieved by closing the Strait of Gibraltar, referred to as the Experiment. The obtained results are focused on the last year of the Experiment and examine the variations in nutrients and thermohaline properties on the surface and the upper – ocean. They show an increase in the upper cell of the AMOC north of the Strait of Gibraltar and a decrease towards the South. Following these variations, the Subpolar Gyres' eastern region has expanded slightly to the north while surface nutrients and phytoplankton concentrations have increased in this region.

Keywords: Twin Experiment; NEMO ORCA-2; PISCES; North Atlantic; Biogeochemistry; AMOC

Περίληψη

Η αλληλεπίδραση μεταξύ διαφορετικών ωκεάνιων περιοχών διαδραματίζει κρίσιμο ρόλο στη διαμόρφωση των παγκόσμιων κλιματικών προτύπων και στην κατανομή της θερμοκρασίας, της αλατότητας και των θρεπτικών συστατικών. Μια τέτοια σημαντική αλληλεπίδραση λαμβάνει χώρα μεταξύ της Μεσογείου και του Βόρειου Ατλαντικού Ωκεανού μέσω του Στενού του Γιβραλτάρ. Η παρούσα μελέτη αναφέρεται στην πολύπλοκη σχέση μεταξύ αυτών των δύο περιοχών και εστιάζει στην επίδραση της Μεσογείου στη δυναμική και τις βιογεωχημικές διεργασίες του Βόρειου Ατλαντικού Ωκεανού. Εξετάζοντας ένα συζευγμένο αριθμητικό μοντέλο που περιλαμβάνει το παγκόσμιο υδροδυναμικό αριθμητικό μοντέλο NEMO σε συνδυασμό με το μοντέλο PISCES για τη βιογεωχημική δραστηριότητα, η μελέτη αναδεικνύει τον τρόπο με τον οποίο η απουσία του νερού εκροής της Μεσογείου (MOW) επηρεάζει τις θερμοαλατικές ιδιότητες και διερευνά την επίδραση αυτών των αλληλεπιδράσεων στη θαλάσσια βιογεωχημεία στην περιοχή του Βόρειου Ατλαντικού. Για να επιτευχθεί αυτός ο σκοπός, εκτελέσθηκαν δύο προσομοιώσεις για μια περίοδο 100 ετών. Η πρώτη περιλαμβάνει τις πραγματικές παγκόσμιες συνθήκες που επικρατούν στον ωκεανό και την ατμόσφαιρα, και αναφέρεται ως Μοντέλο Αναφοράς (Ref), ενώ η δεύτερη αποτελείται από ένα υποθετικό σενάριο απουσίας της Μεσογείου Θάλασσας που επιτυγχάνεται με το κλείσιμο του στενού του Γιβραλτάρ και αναφέρεται ως Πειραματικό (Exp). Τα αποτελέσματα επικεντρώνονται στο τελευταίο έτος του Πειράματος και εξετάζουν τις μεταβολές των θρεπτικών ουσιών και των θερμοαλατικών ιδιοτήτων στην επιφάνεια και στα ανώτερα στρώματα του ωκεανού. Δείχνουν αύξηση της Μεσημβρινής Μεταφοράς Όγκου (AMOC) στα πρώτα 800 μέτρα από την επιφάνεια βόρεια του Στενού του Γιβραλτάρ και μείωση προς το Νότο. Ως αποτέλεσμα των συγκεκριμένων μεταβολών, το ανατολικό όριο του θαλάσσιου υποπολικού Στρόβιλου (Subpolar Gyre) επεκτάθηκε ελαφρώς προς τα βόρεια, και τα επιφανειακά θρεπτικά συστατικά καθώς και οι συγκεντρώσεις στο φυτοπλαγκτόν και ζωοπλαγκτόν αυξήθηκαν στην περιοχή αυτή.

Λέξεις-Κλειδιά : Συζευγμένο αριθμητικό μοντέλο, Βόρειος Ατλαντικός, Βιογεωχημεία

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Abbreviations Table

Atlantic Meridional Overturning Circulation	AMOC
Mediterranean Sea	MED
Black Sea	BLS
Levantine Intermediate Water	LIW
Atlantic Water	AW
West Mediterranean Deep Water (Gulf of Lion)	WMDW
North Atlantic Central Water	NACW
Mediterranean Overflow Water	MOW
Strait of Gibraltar	SoG
Subpolar Gyre	SPG

Chapter 1. Theoretical Overview

The semi-enclosed Mediterranean Sea plays a significant role on the surrounding regions' climate and oceanography. The Strait of Gibraltar is the primary channel for the sea's interaction with the North Atlantic Ocean, which has a substantial impact on the physical and biogeochemical properties of both areas. This work investigates the effects of the Mediterranean Sea on the North Atlantic, with a particular emphasis on numerical simulation experiments. High rates of evaporation in the Mediterranean cause a water deficit that must be made up for by the entrance of fresher Atlantic water. The equilibrium of temperature and salinity in the Mediterranean is preserved in large part by this mechanism.

Depending on time and referring to seasonal variability, water volume as well as associated properties are known to change, with peak exchanges normally happening around winter when there is increased deep convection activities taking place. The North Atlantic's thermohaline circulation is influenced by the mixing of the Mediterranean outflow, composed mainly of Levantine Intermediate Water (LIW) and West Mediterranean Deep Water (Gulf of Lion – WMDW), with the Atlantic waters.

The dense Mediterranean outflow sinks at intermediate depths in the North Atlantic and spreads there, thereby contributing significantly towards global thermohaline circulation. This process is crucial for modulating global climate patterns. The outflow is associated with unique geochemical signatures such as higher salinity and nutrient concentrations which impacts biogeochemical cycles in the north Atlantic. This has significant implications for productivity and carbon sequestration potential of the North Atlantic, affecting global carbon cycling.

The North Atlantic's water mass distribution and circulation are greatly influenced by the Mediterranean outflow. Warm, salty water influences the density structure and thermohaline circulation. This contribution is essential to the AMOC's deep limb's operation. The AMOC is weakened when the Mediterranean Sea is closed because there is less availability of the region's dense, salty waters. There are notable geochemical reactions to modifications in the Mediterranean outflow. The North Atlantic's biogeochemical cycles and nutrient distributions are influenced by the nutrient-rich waters of the Mediterranean. Reduced nutrient input from the closure of the Mediterranean would result in decreased primary productivity and changed nutrient dynamics in the area. This may influence marine ecosystems as well as the general properties of the ocean.

This kind of situation makes it necessary to use numerical simulations to understand how other climatic conditions affect each other between these areas. Numerical simulations have been essential to this understanding, particularly when high-resolution models are used.

A global ocean model used for climate research, the NEMO-ORCA2 model has an approximate 2° horizontal resolution. To replicate realistic ocean conditions, it integrates a variety of physical parameterizations and forcing mechanisms to study ocean dynamics, sea ice processes, and biogeochemistry. Technical Specifications and Setup the OPA (Ocean Parallelise) general circulation model, which is optimized for both vector and scalar systems, is implemented by the ORCA2 configuration. To power ocean circulation models, it incorporates a wide range of atmospheric forcings and comprehensive physical parameterizations. LIM2 and LIM3, two advanced sea ice components, are recent additions to the model. With its multi-category thickness distributions and enhanced depiction of ice deformation and thermodynamic processes, LIM3 improves sea ice physics. Sea ice extent and ocean characteristics in polar regions are simulated more realistically thanks to these updates. By optimizing boundary conditions through a 4D-Var data assimilation technique, NEMO ORCA2 increases the model's accuracy in representing dynamic features such as jet streams. Better simulations of ocean currents like the Gulf Stream and Kuroshio are a result of this.

Two scenarios are simulated by the NEMO ORCA2 model set up for this study. One in which the Mediterranean Sea is open and one in which, it is closed. Understanding the variations in climatic and oceanographic conditions under these two configurations is made easier by these simulations. The model enables a thorough examination of the physical and biogeochemical alterations brought about by the Mediterranean outflow's presence or absence. The North Atlantic's thermohaline structure is impacted by the Mediterranean outflow. Lack of it may cause stratification in the water column to shift, which may affect the formation of deep water and the general circulation patterns of the ocean. The distribution of heat and salt, as well as vertical mixing, are all impacted by these variations in the density and stratification of the water column. These processes are essential to preserving the thermohaline circulation.

It would be interesting to watch how the following variables change as a result of the closure of the Mediterranean Sea. The Mediterranean outflow has a direct impact on temperature and salinity profiles, which will alter significantly if it closes. Vertical mixing and circulation will be impacted by these modifications, which will also have an effect on the water column's density structure and stratification. Tracking nutrient concentrations is crucial to comprehending the effects on biogeochemical cycles and primary productivity. Important markers of the total effect on large-scale ocean circulation are the AMOC's stability and strength. Furthermore, variations in sea surface height (SSH) may signal modifications in the distribution and circulation patterns of water mass.

1.1. Mediterranean Sea Circulation and Characteristics

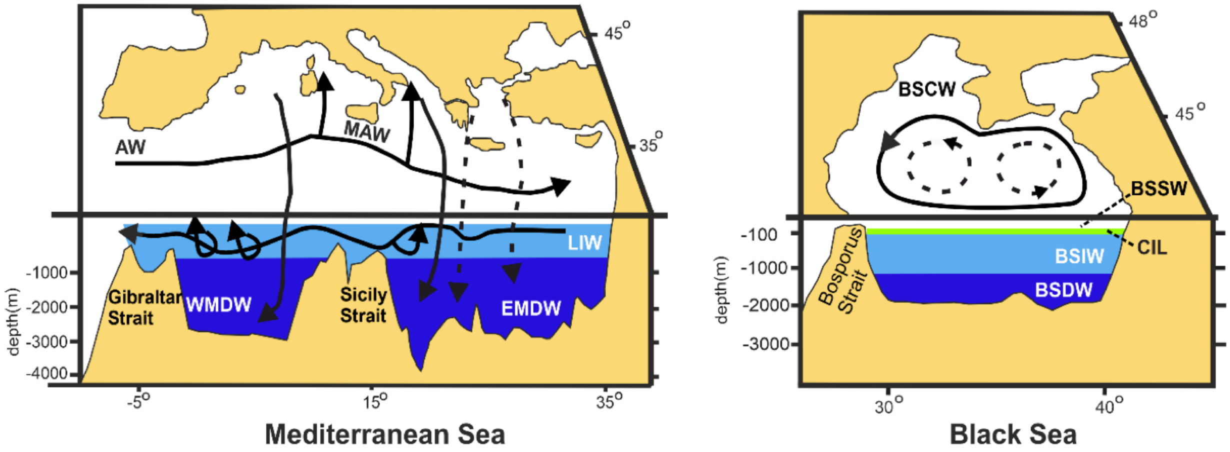


Figure 1. Principal water masses and generalized patterns of circulation in the BLS (right scheme) and MED (left scheme) basins (1)

The Mediterranean Sea functions as a complicated system that converts Atlantic Water (AW) into Mediterranean Waters (MWs). It is distinguished by high evaporation rates that surpass precipitation and river runoff. Complex circulation patterns and mechanisms like thick water production are responsible for this transition. Because of the Coriolis effect, the waters in the Mediterranean often follow counterclockwise gyres. Unstable currents in the southern regions, particularly the Algerian and Libyo-Egyptian Currents, exacerbate the quasi-permanent gyres that each of the Western and Eastern Basins have along the continental slope.

The inflow of AW across the Strait of Gibraltar initiates the circulation of surface waters in the Western Basin.This influx moves eastward along the Algerian coast, first forming clockwise gyres in the Alboran Sea. Water distribution is greatly impacted by anticyclonic eddies produced by instability in the Algerian Current. As AW passes through the Channel of Sicily in the Eastern Basin, it splits into several veins and produces mesoscale eddies. Complex circulation patterns are produced when topographical characteristics interact with these eddies and currents.

Levantine Intermediate Water (LIW) is mostly created south-southeast of Rhodes. The creation of deeper waters, such the Adriatic and Aegean deep waterways (AdDW), is largely dependent on LIW. As they cascade over sills and mingle with resident waters, these deep waters overflow into the basins' deeper regions. They move along the sides of the basin and finally add to the outflow that passes through the Strait of Gibraltar.

Mesoscale characteristics, wind patterns, and topography all have an impact on the circulation of the Mediterranean, which in turn affects biological activities, heat and salt distribution, and water mixing. The study analyses circulation patterns using in situ measures like CTD profiles and remotely detected data like sea surface temperature. The circulation of the Mediterranean Sea is a result of intricate interactions between topographical characteristics, intermediate and deep waters, and surface currents. Although the overall functioning and key mechanisms are known, there is still controversy about local patterns of circulation, especially in the Eastern Basin. (2)

Low biological productivity in the Mediterranean Sea (MS) is a result of large nitrogen loadings from nearby areas. Phosphorus (P) and nitrogen (N), the two primary nutrients that the MS receives, come from the Atlantic Ocean through the Strait of Gibraltar rather than from sources on land. Deeper Mediterranean water that is richer in bioavailable forms of P and N, such as phosphate and nitrate, balances the input of surface water from the Atlantic. There are notable distinctions in the nutrient inputs to the Eastern Mediterranean Sea (EMS) and the Western Mediterranean Sea (WMS). The WMS has almost three times better primary production than the EMS because it gets four to five times more marine inputs. With yearly values of 148 g C m^2 yr^1 in the WMS and 56 g C m^2 yr^1 in the EMS, the primary productivity in the WMS is projected to be 2.5 times that in the EMS. The two basins' different thermohaline circulation patterns preserve the disparities in nutrient imports and primary output. A biogeochemical model of nitrogen (N) and phosphorus (P) explains the trophic conditions and distribution of nutrients in the Mediterranean Sea. Similar to subtropical gyres, the model suggests that considerable proportions of new production in the WMS and EMS are supported by lateral inputs of inorganic and organic P supplied from the ocean. With dissolved organic P and N entering the WMS and EMS mainly through the Straits of Gibraltar and Sicily, being mineralized to PO4 and NO3, and then being exported out of the basin by the dominant anti-estuarine circulation, the mass balance calculations indicate that the Mediterranean Sea is net heterotrophic. The WMS goes through phases of both N and P limitation, whereas the EMS is clearly P restricted. Deep water (DW) molar NO3 ratios in the EMS are larger than in the WMS, which is indicative of low denitrification rates and the varying reactive N ratios of inputs into the two basins.

Almost half of the lead and nitrogen and one-third of the total phosphorus in the MS are delivered by atmospheric deposition, which plays a major role in the nutrient dynamics of the region. In surface waters with low nutrient levels, this deposition promotes sporadic phytoplankton blooms and new growth. While turbulent mixing and the influx of WMS surface water support new production in the EMS, it is primarily sustained by the inflow of Atlantic surface water and upwelling from intermediate water in the WMS. (3)

There are unique carbonate system features and biogeochemical characteristics in the Intermediate Water (IW) of the Western Mediterranean. Due to internal biogeochemical processes and interaction with other water bodies, IW experiences considerable changes as it travels from the Eastern Mediterranean to the Western Mediterranean. Variations in salinity, temperature, dissolved oxygen, and nutrient concentrations are among the key characteristics of IW. The salinity of IW is about 38.9 PSU. The Western Mediterranean's salinity drops to around 38.6 PSU as it flows westward as a result of interaction with less saline waters. IW in the Eastern Mediterranean has a temperature of about 14.8°C. In the Western Mediterranean, this drops to about 13.5°C, indicating the cooling impact of mixing with nearby waters. IW in the Eastern

Mediterranean normally contains dissolved oxygen values of 200 µmol/kg, which are greater. Dissolved oxygen levels, however, drop to around 150 µmol/kg as it moves westward, suggesting more respiration and slower oxygen renewal rates. Levels of nutrients also differ greatly. Levels of nutrients also differ greatly. The concentration of nitrate in the Eastern Mediterranean IW is roughly 4.7 µmol/kg, but in the Western Mediterranean it rises to about 8.2 µmol/kg. Remineralization processes also cause silicate to increase from 4.9 µmol/kg to 6.2 µmol/kg and phosphate levels to climb from 0.21 µmol/kg to 0.37 µmol/kg. The carbonate system is also impacted because calcifying organisms are impacted by processes like ocean acidification, which alter the concentration of carbonate ions. The total alkalinity drops from 2622 µmol/kg to 2592 µmol/kg and the pH values drop from 8.079 to 8.049 as IW flows westward, suggesting further acidification. Because of this pH change, the concentration of carbonate ions decreases, which makes the water less suited for calcifying organisms like corals and shellfish. (4)

1.2. North Atlantic Circulation

The North Atlantic circulation, particularly the North Atlantic Meridional Overturning Circulation (AMOC), is a cornerstone of the global climate system. It begins with the Gulf Stream, a powerful western boundary current transporting warm, salty water from the Gulf of Mexico northwards along the eastern United States. Initially carrying about 30 Sverdrups (Sv) of water, the Gulf Stream's volume increases to approximately 100 Sv downstream of the Straits of Florida due to the integration of recirculating gyres.

As the Gulf Stream progresses northward, it cools and becomes denser, eventually sinking in the Nordic Seas and the Labrador Sea. This process, known as thermohaline circulation, results in the formation of North Atlantic Deep Water (NADW), which then flows southward along deep ocean currents, crossing the equator and contributing to the global conveyor belt. NADW formation is crucial as it involves significant cross-equatorial transport and deep-water formation, impacting global climate patterns.

The interaction between various water masses, such as the South Atlantic Central Water (SACW) and the Antarctic Bottom Water (AABW), significantly influences the deep circulation of the North Atlantic. SACW affects the upper layers, while AABW, formed in the Weddell Sea, contributes to the deep western boundary current (DWBC). The DWBC, carrying NADW, is enhanced by counterclockwise recirculating gyres and the addition of modified bottom or intermediate water, increasing its transport to about 40 Sv.

The North Atlantic Current (NAC), a continuation of the Gulf Stream, plays a crucial role in recirculating waters within the North Atlantic. It merges with recirculating gyres, contributing to a transport of 12 Sv, and resolves the "northern gyre" dilemma by incorporating flow from both the Gulf Stream and recirculating gyres. This complex interaction of currents and gyres enhances the overall transport and mixing of waters in the North Atlantic.

In the low-latitude North Atlantic, water originating from the South Atlantic significantly influences circulation. Approximately 13 Sv of water flows into the Caribbean and exits through the Straits of Florida at temperatures of 7°C or higher, representing the coldest temperature for the Florida Current. This water mass, a critical replacement for NADW, is essential in maintaining the balance of the thermohaline circulation.

At mid-latitudes, the circulation features significant transformations. The NAC, for instance, carries about 37 Sv of water, with 25 Sv attributed to recirculations and 12 Sv linked to NADW formation. The interaction between the Gulf Stream and NAC systems is vital for the overall transport and heat exchange processes in these regions.

In high-latitude regions, the circulation is dominated by the sinking of cold, dense water in the Nordic Seas and Labrador Sea, contributing to NADW formation. Dense water production in these areas is estimated at about 6 Sv, which flows southward, integrating into the global thermohaline circulation system.

Deep water formation in the North Atlantic primarily occurs in the Nordic Seas and the Labrador Sea. These regions are crucial for the creation of NADW, a significant component of the global thermohaline circulation. In the Nordic Seas, the process begins with the cooling of warm, salty water transported northward by the Gulf Stream and its extension, the North Atlantic Current. As the water loses heat to the atmosphere, it becomes denser and sinks, contributing to the formation of NADW. This dense water overflows from the Nordic Seas into the North Atlantic, significantly contributing to the southward flow of deep water. The dense cold water production rate in these regions is estimated at around 6 Sv, which subsequently flows southward, integrating into the DWBC system.

In the Labrador Sea, a similar process occurs. Warm, salty water is cooled by the frigid Arctic air, increasing its density and causing it to sink. This process is a crucial part of the thermohaline circulation, as it helps drive the deep southward currents that form part of the NADW. The water formed here is also integrated into the DWBC, contributing to the overall deep-water flow in the North Atlantic.

Temperature analysis and deep-water formations are integral to understanding the North Atlantic circulation. The thermocline layer, characterized by a sharp vertical temperature gradient, separates the warm surface waters from the cold abyssal waters. Potential temperatures decrease with depth, and at great depths, these temperatures are always less than measured temperatures due to compression. The formation of NADW involves cooling of surface waters, leading to their sinking and subsequent equatorward return in strong, narrow currents known as deep western boundary currents.

The interaction of mesoscale eddies and recirculating gyres adds complexity to the circulation patterns, often obscuring the general circulation's intensity but playing a crucial role in shaping deep circulation and thermohaline flow. For instance, the Florida Current's northward transport through the Straits of Florida is well-constrained by observations, underscoring the importance of inter-ocean exchanges in the global circulation system.

Seasonal variations in phytoplankton biomass and nutrient concentrations are seen in the North Atlantic Ocean. Physical oceanographic processes like mixing and stratification as well as biological activities like phytoplankton growth and nutrient absorption are the main drivers of these cycles. An important yearly occurrence in the North Atlantic is the spring bloom, which usually begins in late winter and peaks in April. As temperatures rise, more light becomes available and the water column begins to stratify, causing this bloom. Deeper waters replenish the quantities of nutrients over the winter, keeping the surface water well-mixed. Stratification results from the surface being warmed by the rising sunshine as spring draws near. In the euphotic zone, where photosynthesis may occur with adequate light, this mechanism traps nutrients. Consequently, available nutrients are quickly consumed by phytoplankton, which causes a significant rise in biomass. In this process, silicate, phosphate, and nitrate are essential nutrients. The concentrations of these nutrients in the surface waters drop as a result of phytoplankton consuming them.

Peacock-hued swirls of blue and green arrived in the North Atlantic in late May 2010. The shimmering waves stretched from the west of Ireland to the Bay of Biscay, forming a massive arc hundreds of kilometres broad. This natural-color picture was taken on May 22, 2010, by NASA's Terra satellite using the Moderate Resolution Imaging Spectroradiometer (MODIS). The vivid hues originate from phytoplankton, little creatures that proliferate rapidly in the spring and summer months over the North Atlantic, extending from Iceland to the French coast.

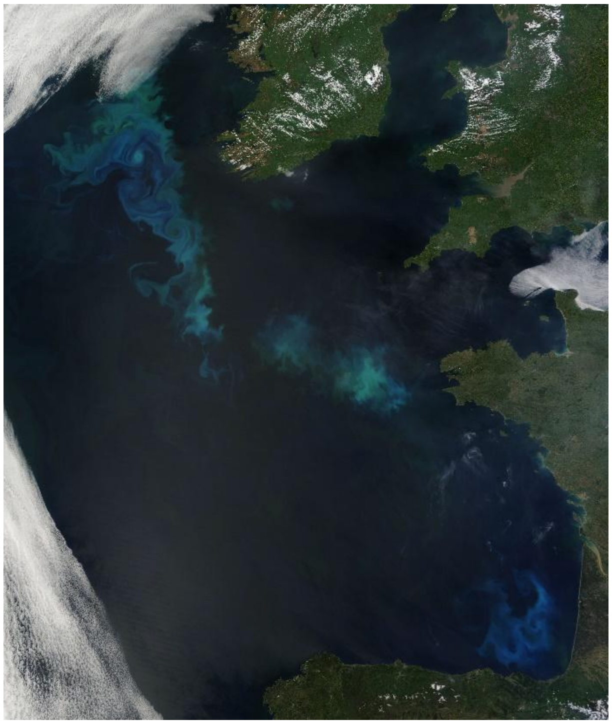


Figure 2.NASA image by Jeff Schmaltz, MODIS Rapid Response Team. Caption by Holli Riebeek and Michon Scott.

Due to sun heating in the summer, the water column becomes significantly stratified after the spring bloom. The euphotic zone experiences nutrient depletion as a result of this stratification, which restricts nutrient replenishment from deeper waters. During this time, the availability of essential nutrients —particularly nitrogen and phosphorus— limits the development of phytoplankton. On the other hand, localized upwelling or nutrient recycling mechanisms could allow for continuing production in some locations. Surface waters are nutrient-poor due to the severe stratification, yet phytoplankton can still flourish in areas with adequate nutrients.

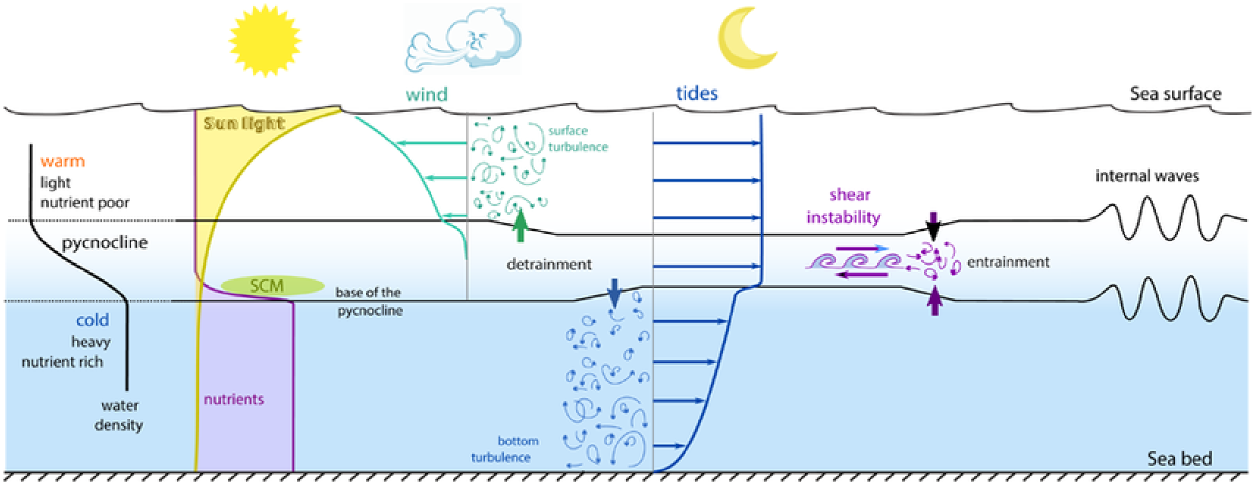


Figure 3. Conceptual illustration of the water column in seasonally stratified shelf seas, where a pycnocline—a habitat for the subsurface chlorophyll maximum (SCM)—separates the warm, nutrient-poor top layer from the cold, nutrient-rich bottom layer. (5)

As mixing increases and stratification diminishes in the fall, a secondary, lesser bloom frequently happens. By bringing nutrients back to the surface, this mechanism encourages the development of phytoplankton in another pulse. Because there is less light available and less nutrients left over than in the spring, the fall bloom is often less intense than the spring bloom. It still contributes to the North Atlantic's total production, making it an important yearly cycle occurrence.

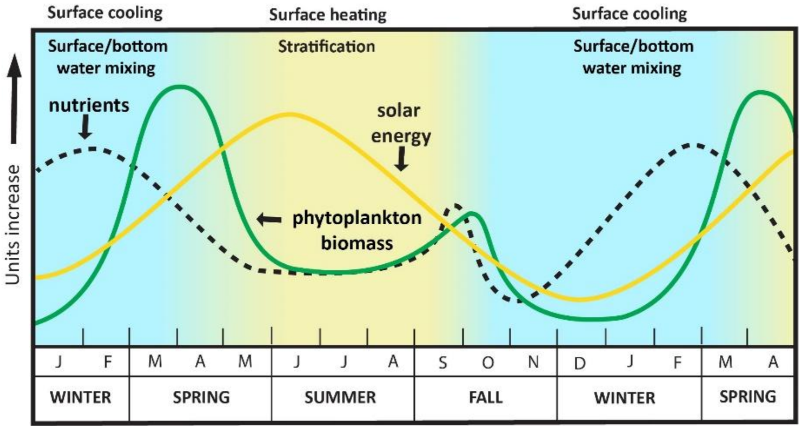


Figure 4. Nutrients and phytoplankton seasonal variability

Wintertime brings about a well-mixed water column as a result of increased wind and cooling, dissolving stratification. The nutrients that were lost over the summer and fall are replenished by this process, which takes nutrients from deeper waters to the surface. Surface waters with high nitrogen concentrations prepare the ground for the ensuing spring bloom. During this time, silicate, phosphate, and nitrate levels rise dramatically, which creates the ideal environment for phytoplankton development when light levels rise once more in the spring.

Because of the vigorous mixing and abundant food availability, the subpolar gyre exhibits significant seasonal cycles, with noticeable blooms in the spring and autumn. Deep water masses that carry nutrients from the Nordic Seas and Labrador Sea, such the Labrador Sea Water, are very beneficial to this region. High levels of primary production are supported year-round by the constant supply of nutrients brought to the surface by these deep waters. As opposed to the subpolar gyre, the subtropical gyre has weaker seasonal cycles and lower overall output. The subtropical gyre has more permanent stratification, which restricts the amount of nutrients that may reach the surface waters. Consequently, nutrient concentrations are often lower, which causes phytoplankton blooms to be less noticeable. In some cases, when events of up-welling occur, they can bring nutrient – rich waters to the surface which increase for a short period of time the primary productivity. (6), (7)

In summary, the North Atlantic circulation is a complex and dynamic system driven by the interplay of various currents and water masses. It plays a crucial role in regulating global climate by facilitating the exchange of heat and water between the equator and the poles. Understanding this system requires integrating observations from multiple regions and employing advanced modelling techniques to capture the intricate details of oceanic flows. The deep water formations in the North Atlantic, primarily occurring in the Nordic Seas and the Labrador Sea, are vital for the creation of NADW, which drives significant heat exchange and influences global climate patterns.

1.3. Significance of Mediterranean – North Atlantic interactions

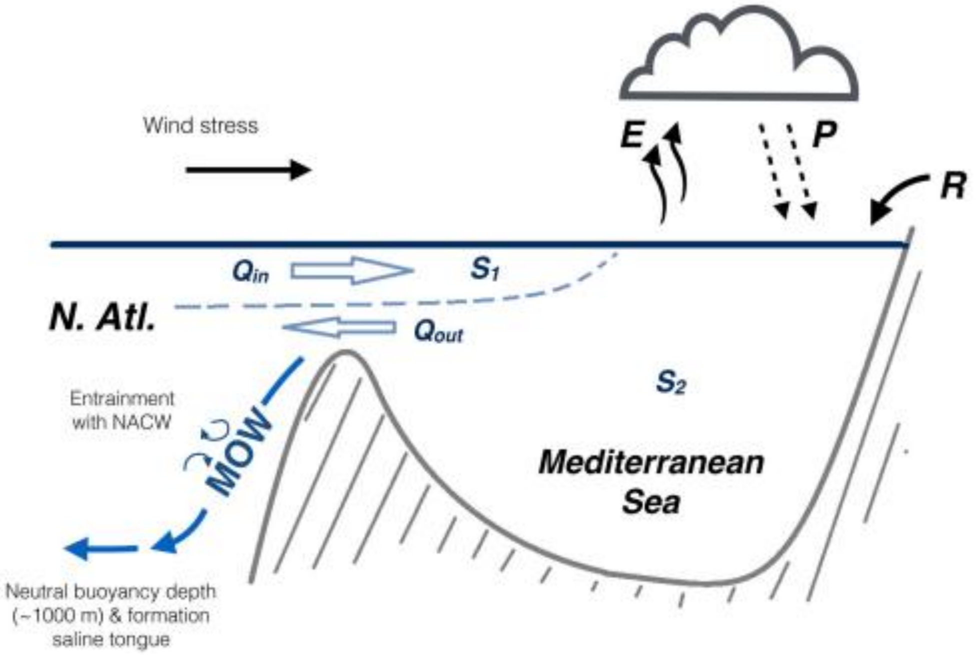


Figure 5. Mechanism of water exchange in the Strait of Gibraltar

There are two main regions where deep-water masses are formed and merge to become the MOW. The first is the Western Mediterranean Deep Water (WMDW), which is formed south of the Gulf of Lion in the northern part of the Western Mediterranean basin. It has a characteristic salinity of 38.44 g kg1 and a temperature of 12.9 C. The second is the Levantine Intermediate Water (LIW), which is formed in the Eastern Mediterranean basin in the region between Rhodes and Cyprus. The net evaporation (E–P–R) is primarily positive throughout the Mediterranean basin, with the exception of the vicinity of the main river estuaries, where R is dominant.

Formation of MOW

Dense water masses play a crucial role in the ocean's thermohaline circulation. These waters, formed over continental shelves or in marginal seas under dry and cold conditions, drive significant climatic impacts. In the Mediterranean Sea, dense waters are formed through a reverse estuarine circulation process. Fresh Atlantic waters enter the Mediterranean through the SoG, where high evaporation rates surpass precipitation and river runoff, leading to the formation of dense, saline waters. These waters exit the Mediterranean as deep currents, forming a saline tongue in the North Atlantic at mid-depths. This saline pool is known as the Mediterranean Overflow Water (MOW).

Atmospheric Influences

Atmospheric fluctuations, particularly the North Atlantic Oscillation (NAO), play a vital role in controlling net evaporation and wind patterns in the SoG region. The NAO's positive and negative phases significantly impact the salt and volume transport through the SoG, influencing the variability of the MOW. Additionally, the Scandinavian Blocking pattern affects the Mediterranean region's precipitation and wind patterns, further impacting MOW properties.

Both the integrated freshwater flux (E–P–R) over the Mediterranean basin and the net volume transport through the SoG exhibit notable variability. Though the volume alterations within the Mediterranean are minor on longer periods, the yearly mean netflow fluctuates substantially. With alternating stages of salt import from the Atlantic and export to the Atlantic, the salt transport through the SoG likewise shows variance. This pattern suggests that salt is periodically released and stored in the Mediterranean Sea, depending on atmospheric circumstances.

The impact of the NAO on MOW is significant, as its low phase is linked to stronger westerly winds, which in turn improve inflow and outflow at the SoG. This has an impact on the development and variability of dense water masses in the Mediterranean.

Depths and Onset of Changes

The most significant variations in temperature and salinity occur at the boundary where the incoming and outgoing water masses meet. Below depths of around 100 meters, the incoming Atlantic water begins to blend with the existing Mediterranean waters, resulting in progressive alterations in temperature and salinity patterns. The Mediterranean Water tongue, a salinity maximum, is formed when the outflowing Mediterranean water at depths of 200-500 meters modifies the properties of the intermediate and deep layers of the Atlantic.
The exchange of water masses also affects the dynamics of nutrients and biological productivity. The Atlantic water that enters the Mediterranean Sea usually contains a high concentration of nutrients, which helps to sustain the growth of primary producers in the region. In contrast, the Mediterranean water that flows out, albeit having fewer nutrients because of the huge amount of nutrients absorbed by organisms within the Mediterranean, still plays a role in distributing nutrients in the North Atlantic. The interactions between these exchanges have a direct influence on the biological productivity, resulting in noticeable effects on both the phytoplankton and zooplankton populations. The passage over the Strait of Gibraltar also impacts the vertical mixing and upwelling processes. The influx of Atlantic water can trigger upwelling along the Mediterranean coastline, resulting in the upward movement of nutrient-rich deep waters to the surface, which promotes primary productivity. The Mediterranean outflow in the Atlantic Ocean plays a role in vertical mixing, impacting the movement of nutrients and the productivity of marine life at intermediate depths.

The study determined that the formation of MOW is a result of the combination of Levantine Intermediate Waters (LIW) and Western Mediterranean Deep Waters (WMDW). The current flows from a narrow passage and moves in a northwest direction along the middle slope at depths between 400 and 1400 meters. The upper shelf, ranging from 500 to 730 meters in depth, is characterized by the presence of sandy drifts, strong currents and waves. The lower part appears to have greater depth (ranging from 585 to 750 meters) and displays more prominent and well-defined characteristics of erosion. These features suggest a more concentrated and swifter movement of MOW in past cold climates. The emergence of present-day paths commenced around 3.8-3.9 million years ago, marked by notable transformations during the late Pliocene-early Pleistocene era as a result of worldwide cooling, a decline in sea levels, and and increase of the thermohaline circulation.

The five detected water masses are (SAW), (ENACW), (AAIW), MOW, and (NADW). The MOW is comprised of two distinct sections: the upper permanent core and the lower permanent core, each with its own unique characteristics.

Through various studies, scientists concluded that MOW enhance AMOC and plays a crucial role to the climate variability of the northern hemisphere and the planet. The interaction of MOW with the seabed creates significant characteristics of the profile that reflect changes in density, volume, and flow velocity over time. The two distinctive parts along the middle slope indicate different processes and flow characteristics at various depths. The MOW, finally, is shaping sedimentary processes and influencing global ocean circulation and climate. (8)

Chapter 2. Study Purpose and Methodology

The purpose of this study is to assess how the presence or absence of the Mediterranean Sea affects the physical and biogeochemical changes in the North Atlantic Sea and to comprehend how these modifications may affect ocean circulation regionally over the years. Thus, we used a twin coupled simulation model that consists of the physical model NEMO and biogeochemical model PISCES.

NEMO model

The Nucleus for European Modelling of the Ocean (NEMO) is a popular Global Circulation Model (GCM) used for studying interactions between the ocean and sea-ice. It utilizes the Boussinesq and hydrostatic approach. The OPA (Océan PArallélisé) model and the LIM (Louvain-la-Neuve Ice Model) are employed to solve the fundamental equations of ocean dynamics and thermodynamics, specifically for sea-ice dynamics. The basic equations are a collection of non-linear differential equations employed for the calculation of atmospheric and oceanic fluxes. The NEMO model utilizes a Cartesian coordinate system with unit vectors i, j, and k to solve equations for momentum conservation, hydrostatic balance, ocean incompressibility, heat and salt conservation, and the equation of state. Gravitational force is the main factor in large-scale circulation, causing k to be the upward vector (directed towards the sea surface), and i and j to be tangent vectors on geodynamic surfaces. Let U represent the velocity vector, where U=Uh+ωk (with h being the horizontal field). T represents potential temperature, S represents salinity, and ρ represents in situ density.

The Boussinesq approximation employs a fixed reference density for the ocean, presuming that fluctuations in density may be considered insignificant. Density disparities are solely considered when computing in situ buoyancy using the equation of state, as the force of gravity is sufficiently potent to provide a noticeable impact on weight. Buoyancy effects encompass the influence of baroclinic pressure, vertical density stratification, and the establishment of neutral surfaces for mixing along isopycnals, while the transfer of momentum is parameterized. Incompressibility refers to the property of a fluid where its density remains constant while it is in motion. This is equal to the velocity vector having zero divergence in three dimensions. Multiple techniques exist for vertical grid modelling. Certain models employ depth (z-grid) or density (isopycnic coordinates) as the vertical coordinate, whilst others adhere to the seabed topography (s-grid). The NEMO model employs a z-coordinate system that is segmented into layers of different thicknesses. These layers are arranged in such a way that the distance between them increases as one moves from the top to the deep ocean. Specifically, the layers are around 5m thick near the surface, around 1000m thick in intermediate regions, and about 200m thick on the bottom. This configuration allows for a more comprehensive examination of the surface layers in comparison to the deeper parts of the ocean. This decreases the amount of computing work, resulting in a more efficient model. The ocean is defined by the boundaries of coasts, the topography of the bottom, and the contact between the air and water at the surface. The sea surface height (SSH) is regarded a free surface at this interface.

NEMO utilizes a tripolar horizontal grid that includes two poles located in the Northern Hemisphere (Canada and Siberia) to eliminate curvature in the maritime area. Additionally, a third pole is positioned in the Southern Hemisphere at the Geographical South Pole. It utilizes, also, an Arakawa C-grid, where each box is precisely positioned in the centre of the (i,j,k) space. Scalar variables, such as temperature, salinity, ice thickness, free surface height, and surface fluxes, are located at the geometric centre of each cell, known as the T-point. On the other hand, vector values, such velocity, are positioned at the centre of each cell's surface. The first experiment (Exp I) mimicked global ocean circulation by applying a consistent yearly force based on the climatology stated in the section. The ERP restoring factor was also activated, as specified in the section. The experiments were conducted for a duration of 100 years in order to achieve a condition of equilibrium.

In the second experiment (Exp II), the domzgr.F90 module was modified to compute ocean bathymetry at each position by reading bathymetric data from the bathy_meter.nc database. The alteration transformed the whole Mediterranean Sea region into land.

The main equations from NEMO model are derived from the primitive equations.

Momentum Equations:

Horizontal

$$\frac{\partial Uh}{\partial t} = -\left[(\nabla\times U)\times U + \frac{1}{2}\nabla\left(U^2\right)\right]_h - fk\times U_h - \frac{1}{\rho_o}\nabla_h p + D_U + F_U \quad (2.1)$$

Where: U_h is the horizontal velocity, f is the Coriolis parameter, ρ_0 is the reference density, p is pressure, and D_U and F_U are small-scale parameterizations and surface forcing terms, respectively

Vertical (Hydrostatic)

$$\frac{\partial p}{\partial z} = -\rho g \quad (2.2)$$

Tracer Equations (Heat and Salt Conservation):

$$\frac{\partial T}{\partial t} = -\nabla\cdot(TU) + D_T + F_T \quad (2.3)$$

$$\frac{\partial S}{\partial t} = -\nabla\cdot(SU) + D_S + F_S \quad (2.4)$$

Where: T is temperature, S is salinity, D_T, D_S are diffusive terms, and F_T, F_S represent surface forcings

Continuity Equation:

$$\nabla\cdot U = 0 \quad (2.5)$$

Equation of State:

$\rho=\rho\ (T, S, p)$ (2.6)

PISCES model

An essential component of the NEMO simulation platform is PISCES v2, a complex biogeochemical model created by Aumont et al. (2015). It aims to study and simulate biogeochemical processes and ocean productivity. These processes can be thoroughly analyzed and simulated thanks to the model's 24 variables.

It focuses on the fluxes of carbon, nitrogen, phosphorus, silicon and iron in the oceans, taking into account physical and biological processes, and considers the influence of the atmosphere and human activities. In addition, it simulates the photosynthetic activity of phytoplankton, the basis of the food web, and examines the production of organic matter based on nutrient availability and solar radiation. It also includes transport mechanisms (advection and diffusion) and interactions with ocean currents and the dynamics of transport of gases such as CO_2.

In the context of zooplankton, PISCES represents their functional groups and studies critical biological processes, including phytoplankton grazing, respiration and death. It accounts for the conversion of organic matter from phytoplankton to higher trophic levels by monitoring particle production and their contribution to the biological carbon pump. Furthermore, it incorporates the influence of environmental factors, such as temperature, and considers the transport mechanisms that determine zooplankton dispersal.

Chapter 3. Results and Analysis

Our focus will be on examining the results from the last year of our data to ensure a more robust and rigorous analysis, as the model has reached a more stable state and the differences or variations in the results can be more clearly distinguished. The model run 2 times for 100 years period, which the first run will refer to as Reference (Ref) and the second run, in which we exclude the Mediterranean Sea will refer to as Experiment (Exp).

3.1 Atlantic Meridional Transport

The vertical cross sections of the mean annual stream function of the meridional volume transport (AMOC) for the two experiments is shown in Figure 6 and the AMOC anomaly (Exp – Ref) in Figure 7.

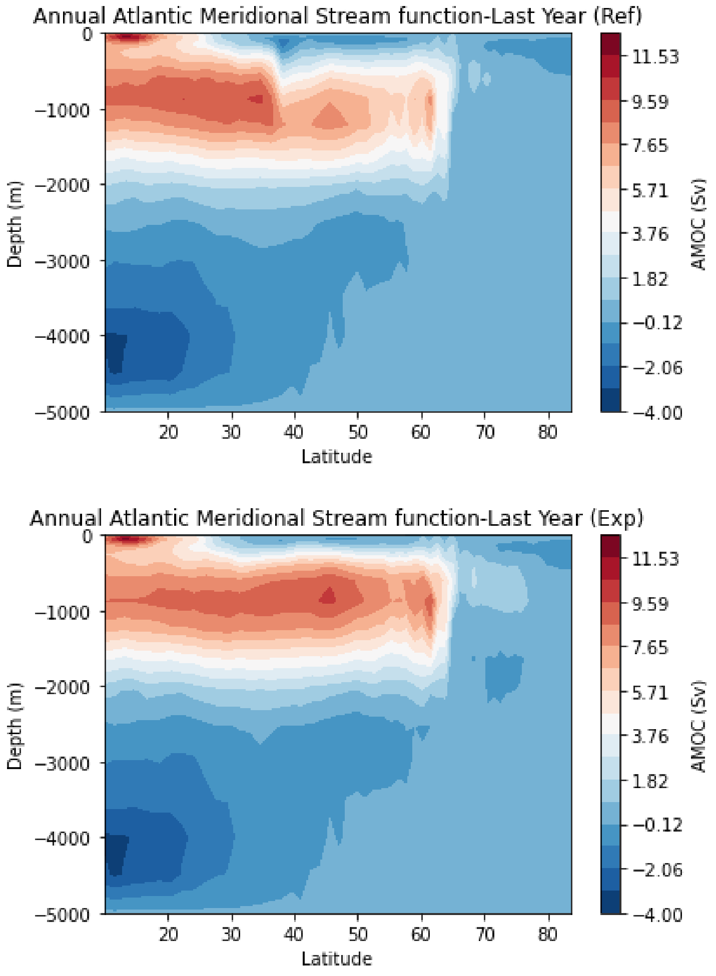


Figure 6. Annual mean of the AMOC index for the North Atlantic. Top: Ref, Bottom: Exp.

In the Experiment model in Figure 6 (bottom), AMOC is observed to be increasing and moving to Northern latitudes with more strength. In reference map, we observe two maximums in 35°N and 45°N and in experiment map, only the maximum in 45°N. The absence of the 35°N maximum is due to the closure of the Mediterranean Sea. The underestimation of the maximum value of the Atlantic Meridional Overturning Circulation (AMOC) in the NEMO ORCA-2 model is related to several physical and numerical factors that affect the accurate simulation of ocean processes.

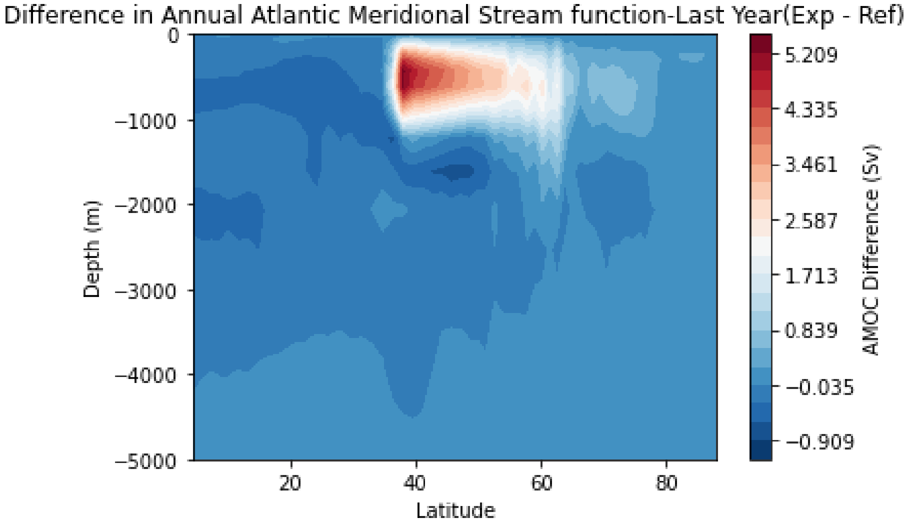


Figure 7. Differences in the annual mean AMOC index for the North Atlantic (Exp - Ref).

In Figure 7 we observe with more details and clearly that the AMOC strengthens in the upper 1000 meters as we move toward higher latitudes, with the first noticeable increase occurring around 37°N. Before this, the region between 20°N and 37°N experiences a freshwater deficit due to a negative mass balance, which causes freshwater from neighbouring regions, like the equatorial and subpolar areas, to converge. The Mediterranean Sea contributes to this imbalance by balance the freshwater deficit. In the experiment without the Mediterranean, the AMOC increases north of the Strait of Gibraltar, but decreases south of it.

The strengthening of the AMOC north of the Strait of Gibraltar (SoG) is due to a change in the density gradients across the Atlantic. Mediterranean Outflow Water (MOW) is typically dense and saline, helping to create a density-driven flow that supports the AMOC. When the Strait is closed, the lack of MOW disrupts this process, causing the northern Atlantic to compensate by increasing the circulation in the upper layers. This strengthens the AMOC by enhancing the density contrast and buoyancy-driven circulation in the region north of Gibraltar, increasing the thermohaline circulation from lower to higher latitudes, as it is shown in previous study by Ivanovich et al. (9)

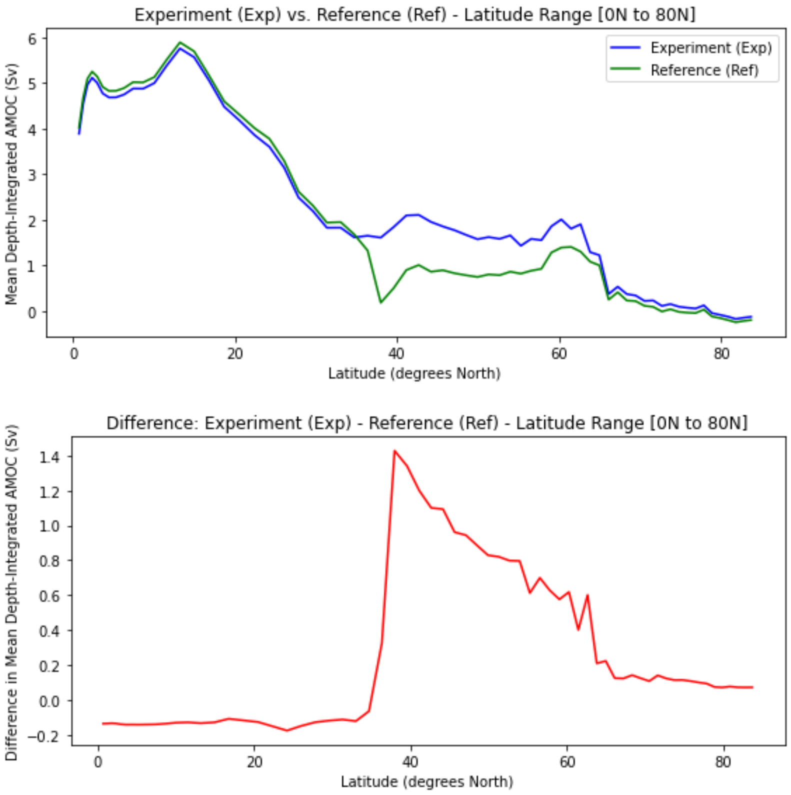


Figure 8. Line graph of the variability of average AMOC depending on latitude (upper diagram) and the difference of the 2 experiments (bottom diagram)

To have a better view of the behaviour of AMOC at each latitude, Figure 8 shows the average transport throughout the water column, integrating the AMOC transport for the entire depth. The results are similar to Figure 7, showing in the bottom graph the increase of AMOC approximately up to 1.4 Sv after 37 °N and a decrease of -0.15 Sv to -0.2 Sv South of it.

3.2 Thermohaline properties

In the final year of the experiment, we calculated the North Atlantic mean of all the variables.

Temperature and Oxygen Comparison

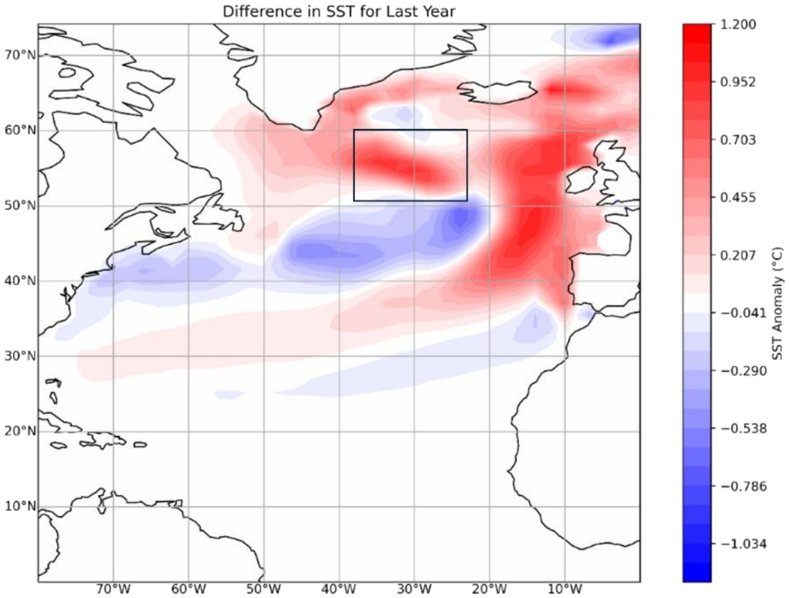


Figure 9. Sea Surface Temperature Anomaly for the last year of the data, Exp – Ref

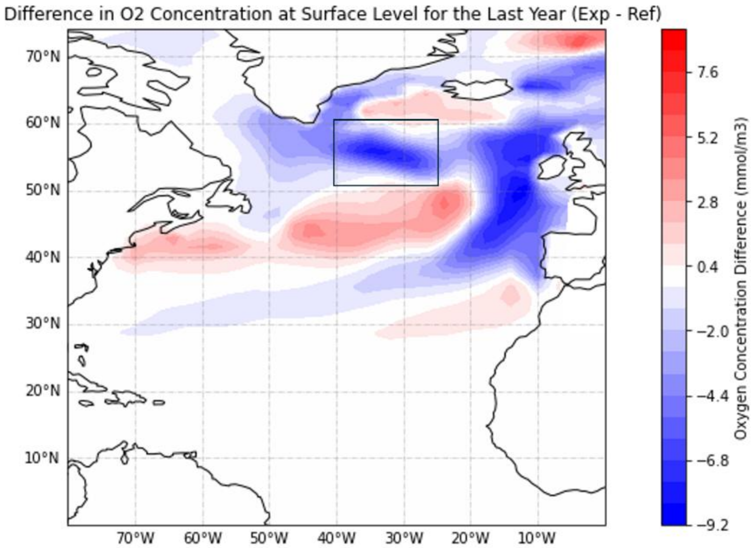


Figure 10. Difference in Oxygen Surface Concentration (mmol/m3)

In the final year of the experiment, we calculated the North Atlantic mean of all the variables.

Previous studies have shown that there is a negative correlation between Oxygen and Temperature. (10) In Figure 9 and 10, we observe this exact negative correlation as is expected. In the subpolar gyre (40ºW - 20ºW and 50ºN - 60ºN), there is a significant increase of sea surface temperature in the experiment model as we observe, approximately from 0.95 to 1.18 °C (Figure 9). In the same area, a decrease of Oxygen concentration is apparent in Figure 10 from -4.7 to 7mmol/m^3. As the temperature of water rises, the amount of oxygen that can dissolve decreases, following the gas solubility rules established by Henry's Law. Warmer waters contain lower levels of dissolved oxygen as oxygen molecules escape easier into the atmosphere, resulting in oxygen deficiency in the upper layers of the ocean. (11)

The AMOC is a conveyor system that uses the North Atlantic Current (NAC) to move warm, salty water from subtropical to subpolar areas. This process changes the density structure in the area by rising the subpolar gyre's temperature and salinity. The density gradients that regulate gyre circulation are reinforced by increased salinity and heat flux from subtropical waters. As the water mass becomes less dense and more stratified, these gradients cause the subpolar gyre to expand north-eastward.

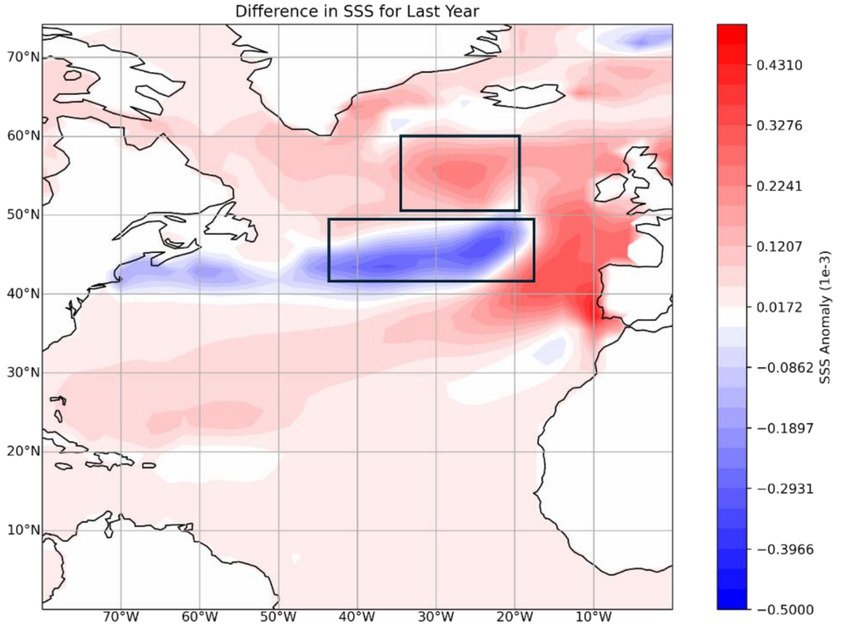


Figure 11. Sea Surface Salinity Anomaly for the last year of the data, Exp – Ref

Results in Figure 11 shows that the mean sea surface salinity of the last year of the data in experiment model, has been increased by 0.23‰ in the subpolar gyre as a result of the intensification of the AMOC north to the strait of Gibraltar. This enhances the formation of Atlantic Deep Waters; thus, we see the increase of the thermohaline properties. Below the boundaries of SPG, the NAC (North Atlantic Current) brings less dense surface waters to the higher latitudes as the surface salinity is decreasing, approximately -0.4‰.

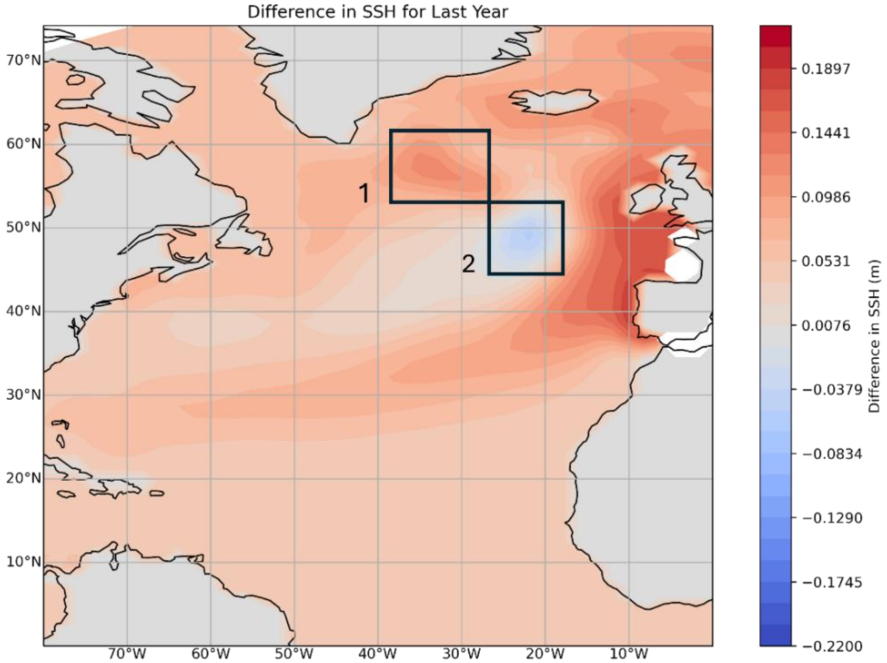


Figure 12. Sea Surface Height Anomaly for the last year of the data, Exp – Ref

In line with the SST Anomaly, the mean sea surface height (SSH) (Figure 12) has increased in the areas where the temperature increased and specifically by 0.14m in the highlighted area 1, caused by the thermal expansion and decreased near the boundaries of the North Atlantic Current (highlighted area 2).

Zonal cross-sections at 35ºN Latitude (Strait of Gibraltar)

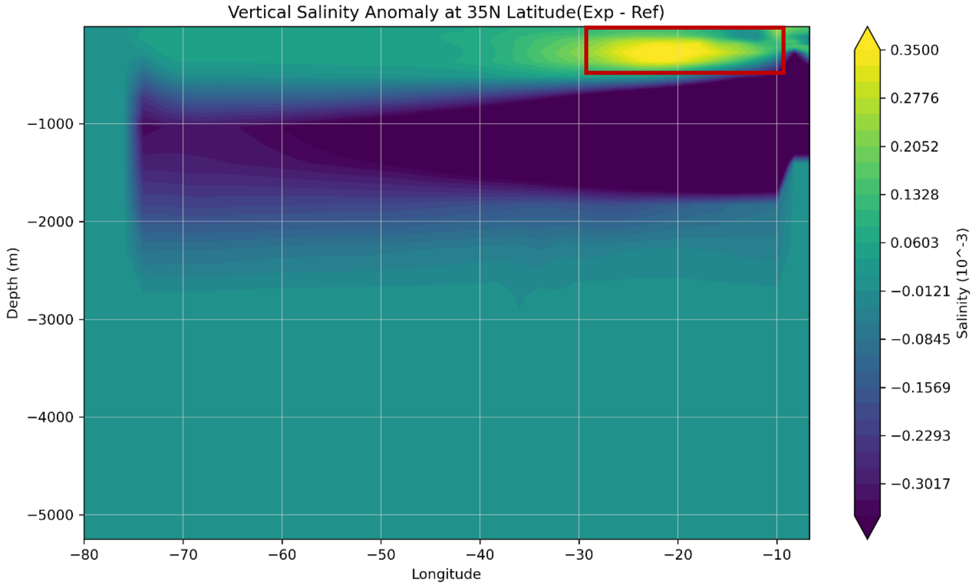

Vertical Salinity Anomaly at 35N Latitude(Exp - Ref)

Figure 13. Vertical Salinity Anomaly on North Atlantic at 35N Latitude (Strait of Gibraltar), Exp - Ref

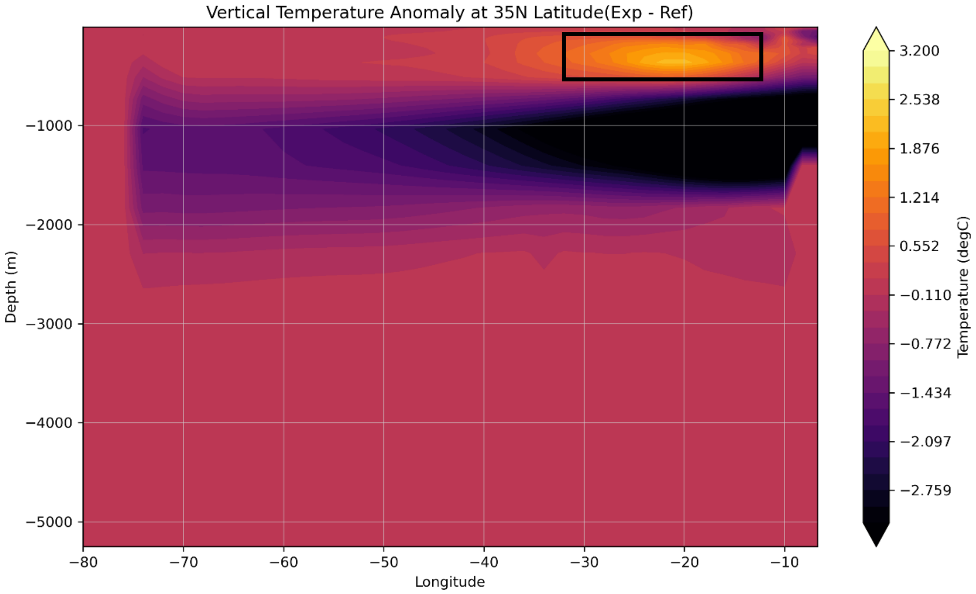

Vertical Temperature Anomaly at 35N Latitude(Exp - Ref)

Figure 14. Vertical Temperature Anomaly on North Atlantic at 35N Latitude (Strait of Gibraltar), Exp - Ref

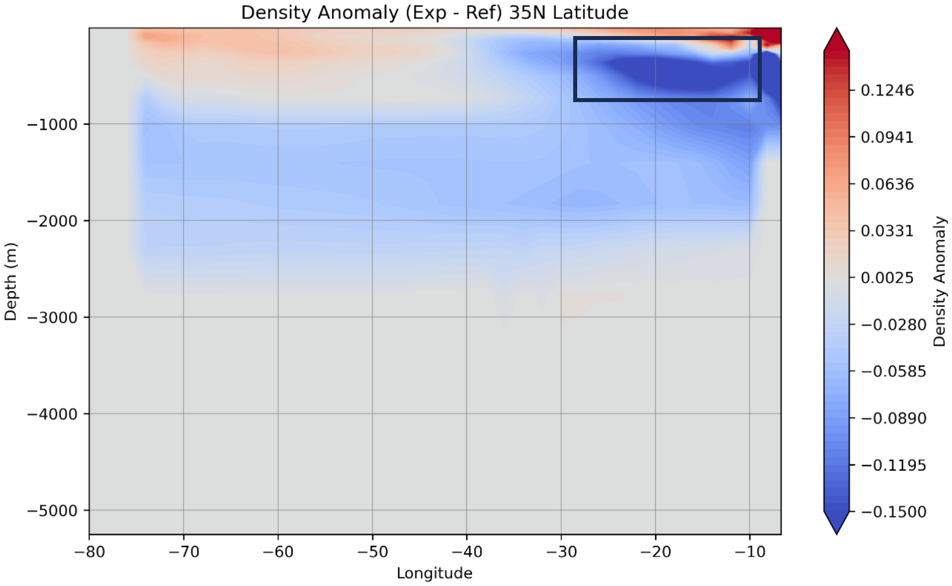


Figure 15. Vertical Density Anomaly on North Atlantic at 35N Latitude (Strait of Gibraltar), Exp – Ref

In Figure 13,14,15 we observe the zonal sections at 35N Latitude, of salinity, temperature and density anomaly accordingly. In the highlighted box, that indicates a depth range from 217m to 730m although the Salinity and Temperature in the experiment model increase, the density anomaly in Figure 15 shows an extreme decrease of around 0.15 Kg/m^3. Below 730m we observe a smaller, but noticeable decrease of density that is caused by the absence of MOW, that as we mentioned before, which balances at around 1000m depth when enters the Atlantic Ocean.

3.3 Biogeochemical properties

Delta Carbon Dioxide (ΔCO_2), Alkalinity, Dissolved Inorganic Carbon (DIC) and pH

ΔCO_2 represents the difference or change in the partial pressure of carbon dioxide (pCO_2) between two different areas or systems. In the context of the ocean, ΔCO_2 is used to assess the exchange of CO_2 between the ocean and the atmosphere. A positive ΔCO_2 suggests that the ocean is releasing CO2 to the atmosphere, while a negative ΔCO_2 indicates that the ocean is absorbing CO_2 from the atmosphere.

Alkalinity refers to the ocean's capacity to neutralize acids regulating pH and the ocean carbon cycle and is largely controlled by the concentration of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) ions. Higher alkalinity means that more of the dissolved CO_2 is stored in the ocean as bicarbonate and carbonate ions rather than as free CO_2, reducing the concentration of CO_2 in the water.

When alkalinity increases, it shifts the carbonate equilibrium in the ocean. This equilibrium is described by the chemical reactions:

1. CO_2 (gas) $\rightleftharpoons$ CO_2 (dissolved)
2. CO_2 (dissolved) + $H_2O \rightleftharpoons H_2CO_3$ (carbonic acid)
3. $H_2CO_3 \rightleftharpoons H^+ + HCO_3^-$ (bicarbonate)
4. $HCO_3^- \rightleftharpoons H^+ + CO_3^{2-}$ (carbonate)

With higher alkalinity, the system favours the conversion of CO_2 into bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}), reducing the concentration of free CO_2 in the water.

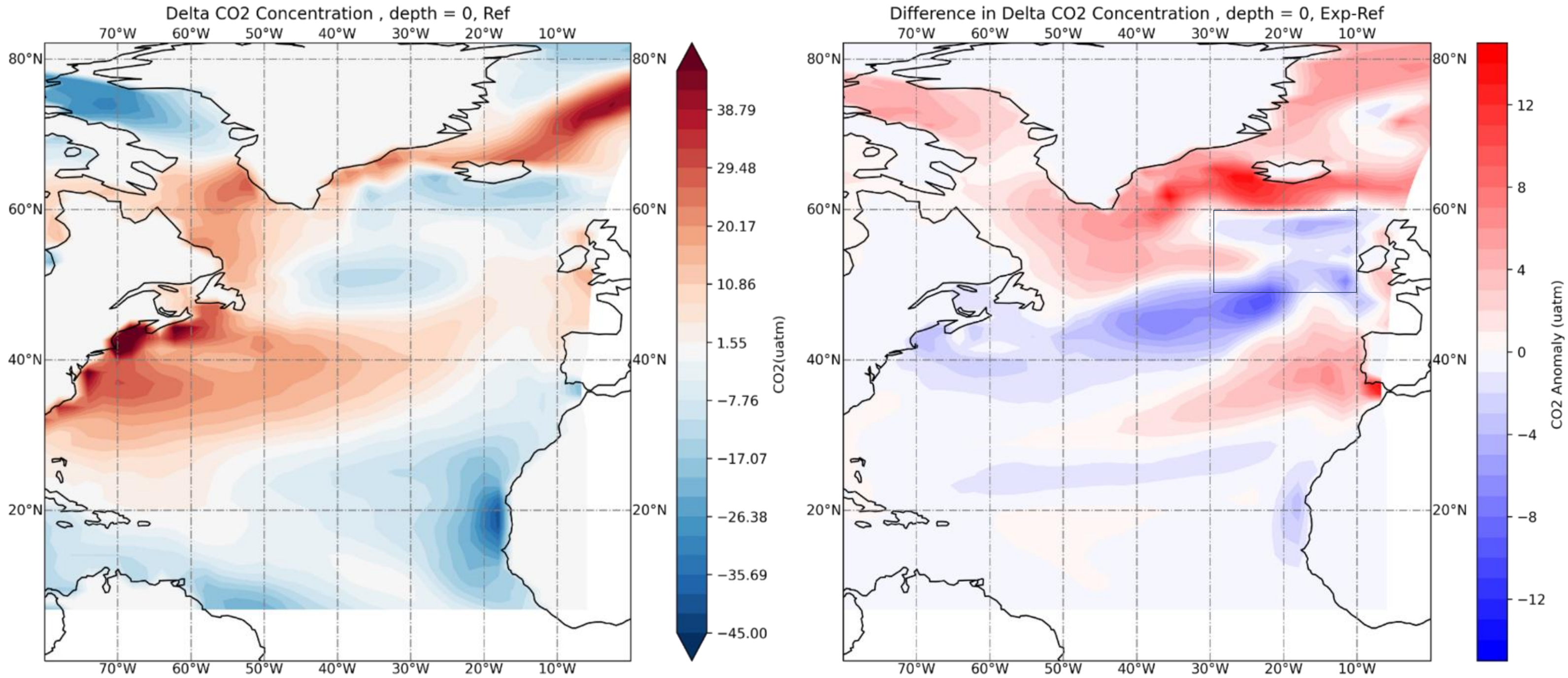


Figure 16. Delta Carbon Dioxide (ΔCO2) Surface Concentration in Reference model (Left) and Delta Carbon Dioxide (ΔCO2) Surface Concentration Anomaly, Exp – Ref (Right)

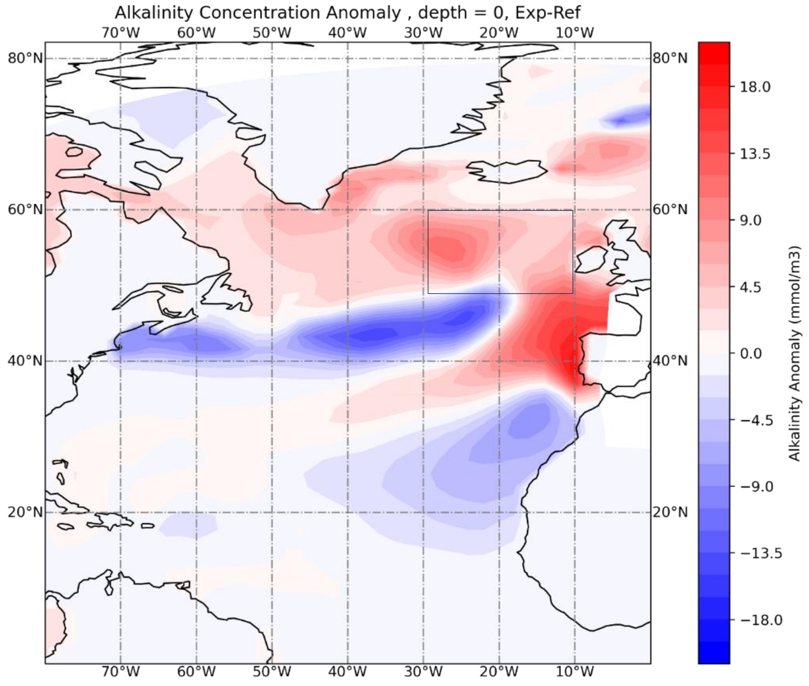


Figure 17. Difference in Surface Alkalinity, Exp – Ref

The results that are shown in Figure 16 (right map) and Figure 17 above are in line with this theory. In the area that we observe a small north – eastward expansion of the subpolar gyre in the highlighted box (30°W - 10°W / 50°N - 60 °N), the surface Delta Carbon Dioxide is more negative indicating that the ocean in the experiment model absorb more CO_2 from the atmosphere. In accordance with this behaviour, the alkalinity in this specific area increases.

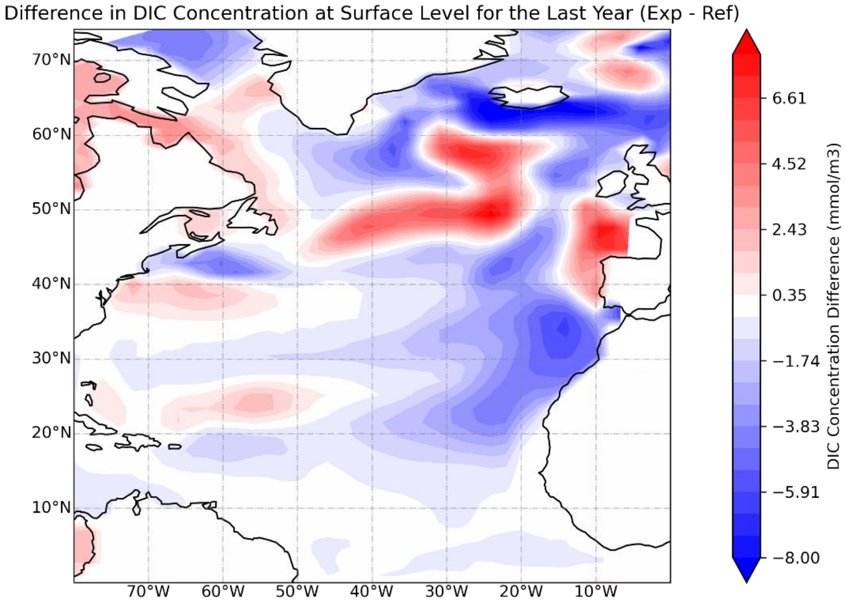


Figure 18. DIC (Dissolved Inorganic Carbon) Concentration anomaly, Exp – Ref

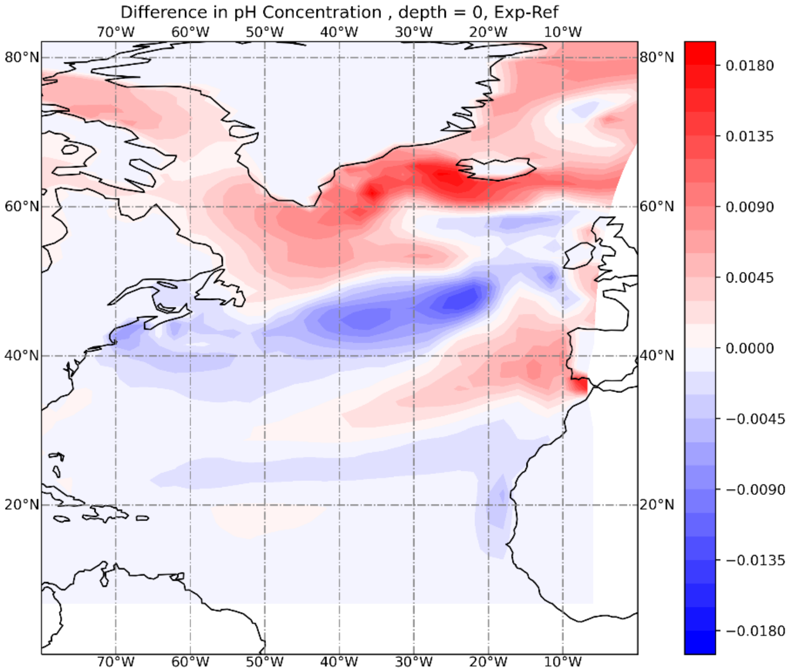


Figure 19. pH Anomaly, Exp - Ref

Dissolved Inorganic Carbon (DIC) in the ocean is a key element of the Earth's carbon cycle and ocean chemistry and consists of the total amount of carbon dioxide (CO_2) and its associated chemical compounds dissolved in seawater. It significantly impacts pH regulation, marine ecosystems, and global climate. Several factors influence the levels and distribution of DIC in the ocean. Temperature affects DIC because warmer water holds less CO_2, leading to a reduction in DIC levels. Salinity also plays a role by impacting the solubility of CO_2 in seawater.

The ocean's carbonate system controls the relationship between pH and dissolved inorganic carbon (DIC) in the surface ocean. The main interaction is that variations in DIC concentrations affect the concentration of hydrogen ions (H^+), which directly affect pH, and the balance of carbonate species (CO_2, HCO_3^-, and CO_3^{2-}). By distributing DIC among its many components, the carbonate system serves as a buffer against pH variations in seawater. More DIC is found as bicarbonate (HCO_3^-) and dissolved CO_2 at lower pH values, and more is found as carbonate ions (CO_3^{2-}) at higher pH values.

Focusing on North Atlantic on the higher latitudes, results in Figures 18 and 19 are shown the negative correlation between these two components. On the Eastward Subpolar Gyre, DIC concentration are increased drastically on the Experimental run, leading to a drop of pH in the same region by -0.007.

Nutrients (NH_4, NO_3^-, $CaCO_3$, PO_4^{3-}, SiO_4^{4-}, Fe)

The process of nutrient enrichment, which frequently occurs during the spring season, often results in the occurrence of intense phytoplankton blooms. These blooms play a crucial role in modifying the thermal characteristics of the ocean surface. The increased density of phytoplankton enhances the absorption of solar radiation due to their pigmentation, which can result in an increase in surface water temperature. This process creates a feedback loop, whereby warmer surface waters encourage further stratification, resulting in the separation of the surface layer from cooler, deeper waters and a reduction in vertical mixing. Consequently, warmer temperatures persist in the upper layers. The blooms also intensify the stratification of the water column, a pivotal physical process in the region. Stratification restricts the upward movement of cooler waters and the downward penetration of heat, establishing a temperature gradient that traps heat in the surface layers. This phenomenon has been demonstrated to play a pivotal role in the North Atlantic Spring bloom and its seasonal dynamics.

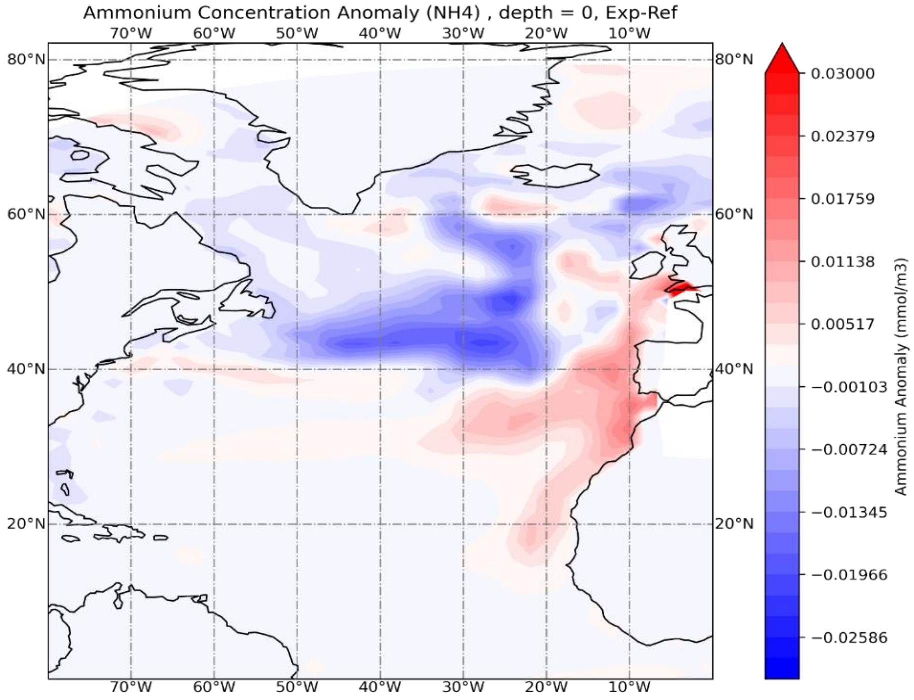


Figure 20. Difference in Ammonium Surface Concentration in North Atlantic, Exp – Ref

The results that are shown in Figure 20, indicate that an overall Ammonium decrease occurs into the region of the Subpolar gyre. The Mediterranean Outflow Water (MOW) exerts an indirect influence on surface nutrients through its contribution to the formation of intermediate water masses, which eventually mix upward to replenish surface nutrients. In the absence of MOW, there is a probable reduction in the upward flux of ammonium and nitrate to the surface, which could result in potential nutrient limitation for phytoplankton.

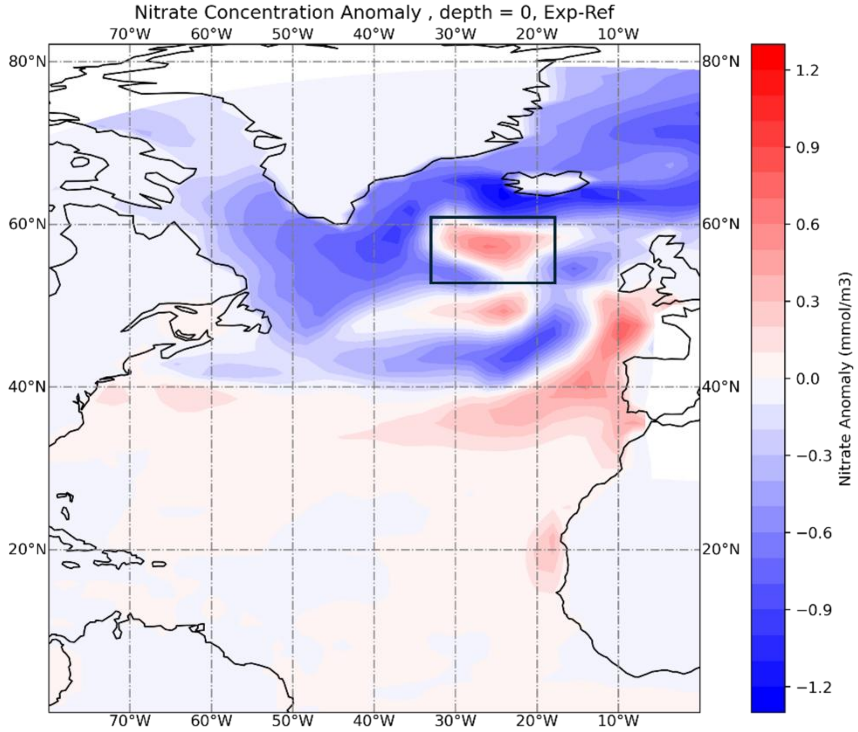
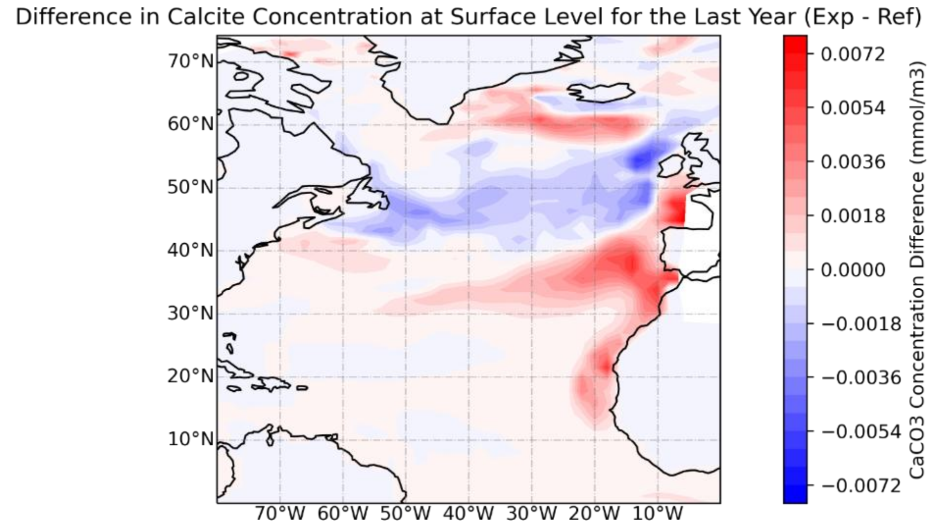
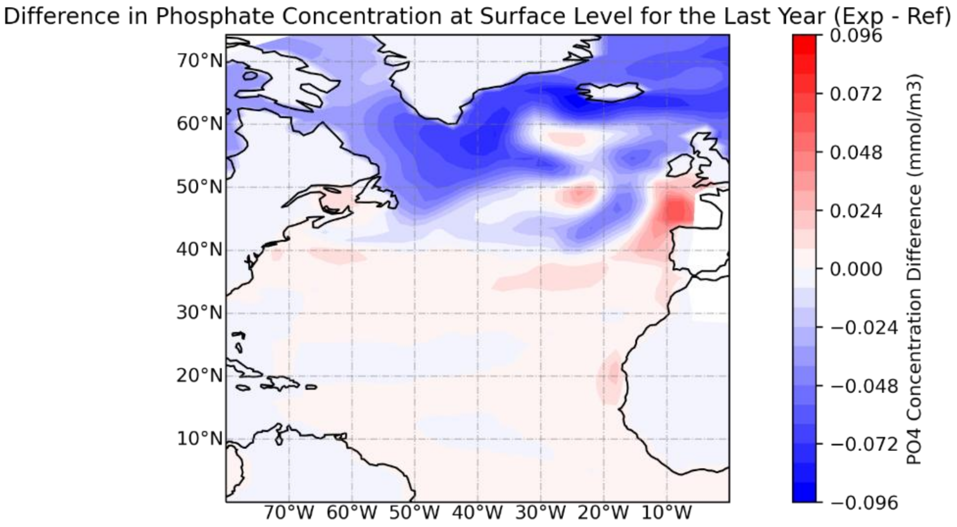


Figure 21. Difference in Nitrate (NO_3^-) Surface Concentration in North Atlantic, Exp – Ref

In Figure 21, Nitrate concentration shows an overall surface decrease except the area of the eastern subpolar gyre that it is expanded as we mentioned above. The increase on the surface close to the Strait of Gibraltar and moving northward is probably due to the water accumulation of the remaining waters that couldn't move to the mediterranean sea due to its closure. In the east region of the subpolar gyre, we notice an increase with maximum value of 0.63 mmol/m^3.



Difference in Calcite Concentration at Surface Level for the Last Year (Exp - Ref)



Difference in Phosphate Concentration at Surface Level for the Last Year (Exp - Ref)

Figure 22. Surface Calcite Concentration Anomaly in North Atlantic (top map) and Surface Phosphate Concentration Anomaly in North Atlantic (bottom map), Exp – Ref

Calcite concentrations as they are shown of the top map on Figure 22, aren't affected into the subpolar gyre, but we observe a surface decrease with minimum value of -0.0039 mmol/m^3 along of the North Atlantic Current and an increase in higher latitudes, below Iceland, with a maximum value of 0.0036 mmol/m^3. On the other hand, Phosphate surface concentration exhibits an overall decrease in North Atlantic subpolar and polar regions with minimum value at -0.092 mmol/m^3 in between Iceland and Greenland.

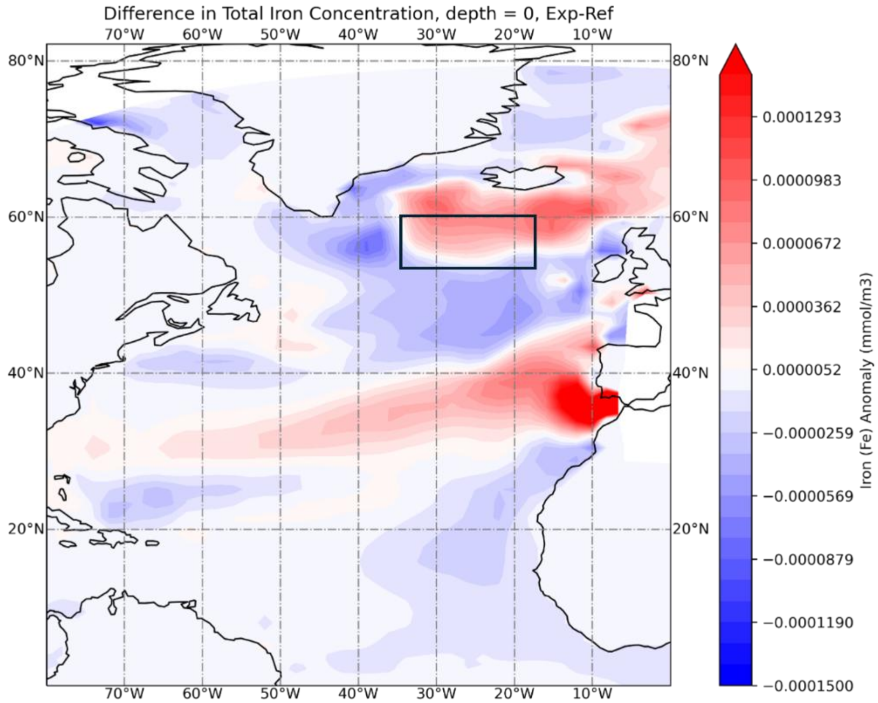


Figure 23. Total Iron Concentration Surface Anomaly, Exp - Ref

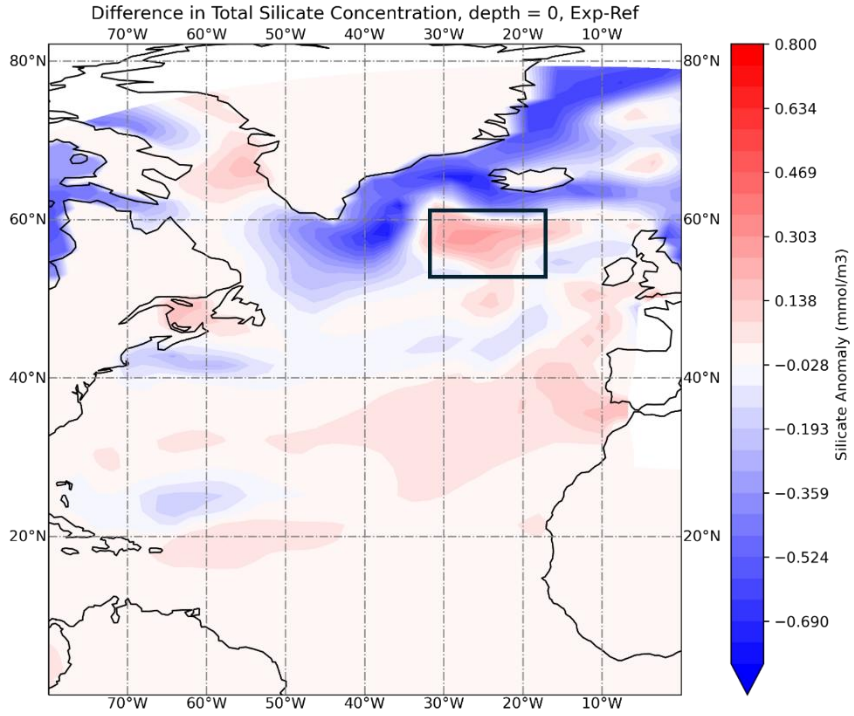


Figure 24. Total Silicate Concentration Surface Anomaly, Exp – Ref

The increase of the AMOC that acts as a conveyor belt and transports warm saline waters from the tropical Atlantic to the Arctic region, caused a melting of ice in the polar area, bringing nutrient – enriched waters southward into the subpolar gyre. The East Greenland Current receives freshwater and nutrients (such as iron and silicate) from the melting of Greenland's ice sheet. This current enters the subpolar gyre and primarily affects the eastern boundary. Mixing processes have the ability to vertically redistribute nutrients, bringing them closer to the surface where the East Greenland Current meets the gyre boundary. The highlighted area of both Figures 23 and 24 that shows the Iron and Silicate concentrations, accordingly, shows an increase in the Experiment run of the model with no MOW, with the top peak of 1.22×10^{-4} mmol/m^3 for iron and 0.322 mmol/m^3 for silicate. The increase of these two nutrient compounds is explained thoroughly in accordance with studies that shown the relationship between ice melting from the polar region conducted by several scientific groups (Debyser et al. (2022), Nguyen et al. (2024), Foukal et al. (2024))

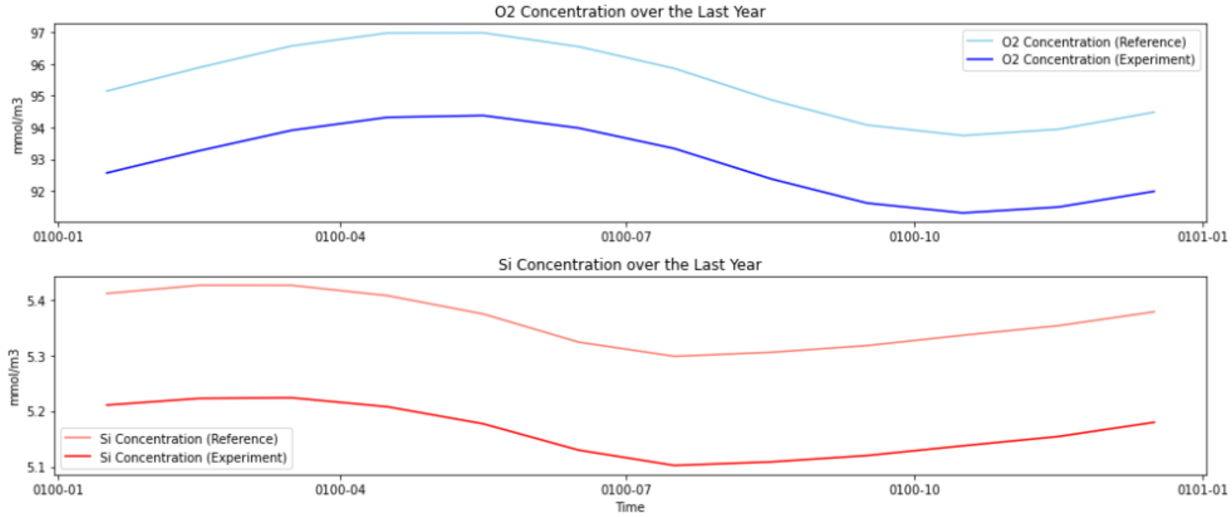


Figure 25. Mean Seasonal Variability of Oxygen and Silicate concentrations for both models

It is important to mention that although we notice an increase, in the experiment model with No Mediterranean Sea, of silicate concentration in eastward part of the Subpolar gyre, the overall mean seasonal variability of silicate is less in the experiment than in reference model as it is depicted in Figure 25 along with the seasonal variability of O_2.

Phytoplankton and Zooplankton Concentration

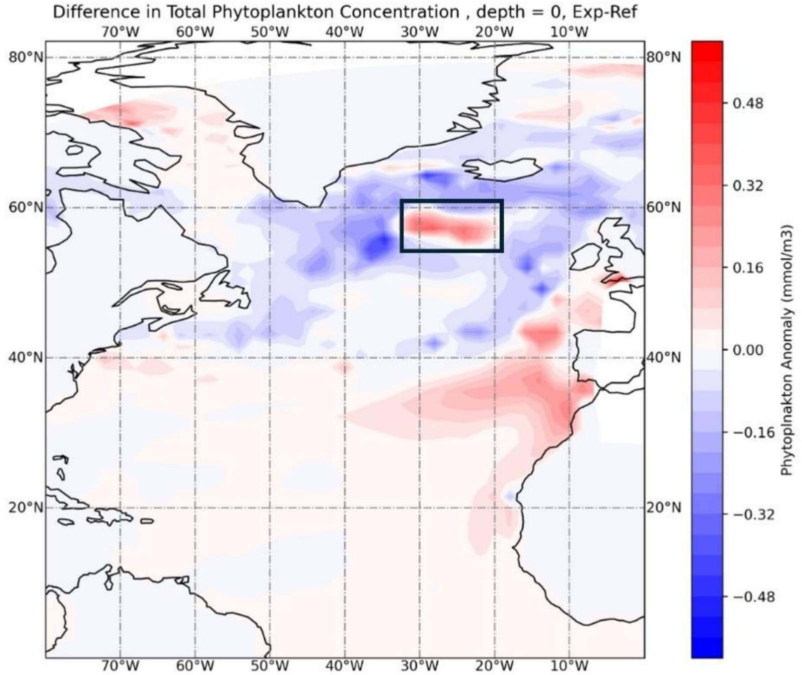


Figure 26. Difference in total Phytoplankton Concentration in North Atlantic, Exp - Ref

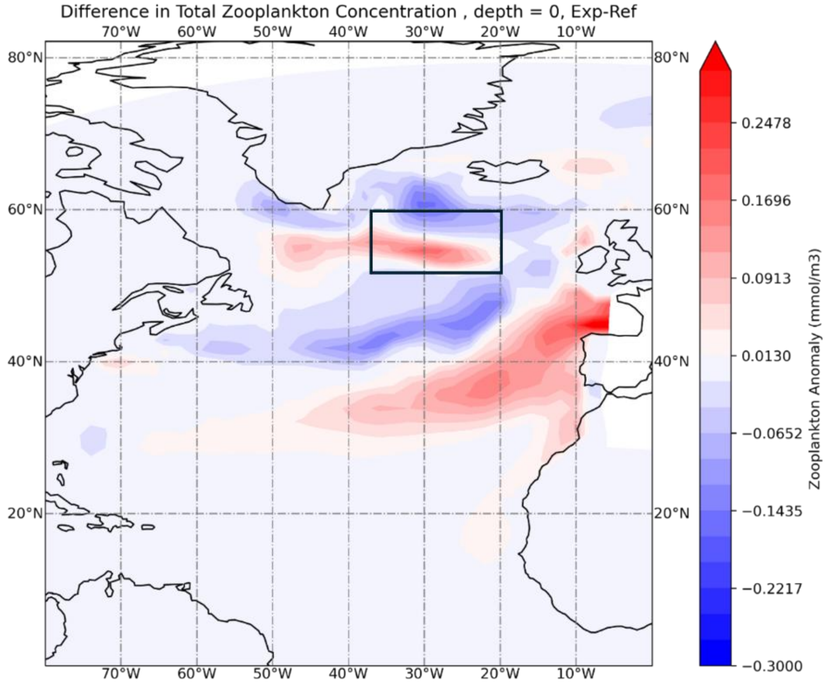


Figure 27. Difference in total Zooplankton Concentration in North Atlantic, Exp - Ref

As a result of the changes in nutrients on the surface of the North Atlantic, we reach certain conclusions about the activity of phytoplankton and, by extension, zooplankton in this region. Phytoplankton growth is limited by light and nutrients. However, at high latitudes, because light is limited, the primary mechanism for phytoplankton growth is derived from nutrients. In the eastward expansion of the subpolar gyre, we noticed an increase in phytoplankton concentration with peak of 0.34 mmol/m^3. (Figure 26)

This is explained by the increase of Silicate concentration in the same area, as already shown above (Figure 24). The main reason for this, is the diatom dominance of this area. Phytoplankton blooms are mainly caused by the increase of diatoms concentration which the shells that built them require silicate.

Diatoms are the main food source of many zooplankton species, including copepods, for example, which are the dominant zooplankton group in the subpolar gyre. Thus, zooplankton increases in the highlighted area depicted in Figure 27 with maximum value of 0.1683 mmol/m^3. These results are aligned with previous studies made by Martinez et al. (2011) and Henson et al. (2012) investigating the relationship between zooplankton productivity and diatom blooms fuelled by nutrient availability.

Chapter 4. Summary of Results and Conclusions

The findings indicate that the Atlantic Meridional Overturning Circulation (AMOC) is significantly impacted by the Mediterranean outflow. According to the experimental model, AMOC strengthened in the top layers north of the Strait of Gibraltar when the Mediterranean Sea was closed. This resulted from changes in the density gradient, which caused buoyancy-driven circulation to increase at high latitudes. In contrast, AMOC declined south of the Strait due to the disruption of regular thermohaline circulation caused by the lack of thick, salty water from the Mediterranean. As a result of that, we observed a north- eastward expansion of the subpolar gyre that has significant impact on nutrient and carbon cycles in this region. The model that run without the Mediterranean Sea showed higher nutrients concentrations in the east boundary of the subpolar gyre but an overall decrease in the remaining subpolar region and a higher dissolved inorganic carbon (DIC) concentration, resulting in a slight reduction in pH levels. Surface alkalinity increased in regions with enhanced CO_2 uptake, reflecting the ocean's diminished role as a net carbon sink. The alterations facilitated increased phytoplankton concentrations, especially diatom-dominated blooms within the subpolar gyre, specifically in the area that the north–eastward expansions occur.

Chapter 6. Future Research

The findings of this research explain the dynamic and influence of the Mediterranean Sea on the physical and biogeochemical properties of North Atlantic Ocean. However, the complexity of these processes gives space on numerous opportunities for further investigation. Future research can show how fine-scale changes in temperature and salinity might spread through the North Atlantic and impact global climate systems under various scenarios by using advanced coupled models that resolve both local and global interactions. Another study area might be to analyse how persistent changes in nutrient dynamics might reshape subpolar gyre ecosystems and their role in the global carbon cycle.

Furthermore, using examples such as the Messinian Salinity Crisis or the mid-Pliocene Warm Period, simulating historical periods can be used to gain knowledge on the evolution of the Mediterranean-Atlantic interactions. These events expose major variations in the MOW characteristics and their impacts on the general circulation and climate of the world oceans. Nevertheless, many aspects of these transitions are still ambiguous, especially the factors controlling the variations during the crucial stages including the transitions between the glacial and interglacial periods. High resolution studies of sediment cores and isotopic analyses would help to enhance the current knowledge of these historical interactions. This will enable us to determine the environmental conditions that existed during these times and hence, to know how such processes may occur in the future given different climate change conditions. In addition, the increasing global anthropogenic activities such as desalination, pollution, and resource extraction are becoming a major concern. Although the current research is mainly based on natural causes of MOW variability and its implications on AMOC, the collective effect of these anthropogenic activities on outflow characteristics, nutrients balance and salinity gradient has not been well understood. In addition, the potential geoengineering interventions, for instance, controlling the flow at the Strait of Gibraltar is an interesting yet debatable area of study. Such actions raise several environmental and geopolitical concerns, and the analysis of these may help in developing measures that can ensure the sustainable management of these systems.

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