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Mixed layer depth and sea ice concentration variability in the Greenland Sea.

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Content

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Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is a complex system of deep and superficial waters transporting heat from the equator to the poles. This system is made up of several components, including overflow waters from the Nordic Seas that contribute to the formation of the Descending limb, with the Greenland Sea being the largest provider of the densest water for the system. The Greenland Sea is one of the few places in the ocean where open-water convection occurs.

Interest in the production of dense waters through the mixed layer depth (MLD) in the Greenland Sea has increased in recent years, due to changes being observed in this system. The sea ice concentration (SIC) decrease in the region and the shallowing of the MLD has generated interest in understanding the possible relationship between these two variables and the potential repercussions of their variability on global climate. Furthermore, it is important to understand salinity and temperature's role in these complex processes.

This study aims to observe the behaviour of the MLD and SIC during the period from 1991 to 2021, and how they relate to variability. To conduct this study, reanalysis data has been used. Therefore, the results will need to be supported by observational data to discuss the validity of the findings.

The results demonstrate a retreat of the SIC and a shallowing of the MLD during the studied period. This is related to an increase in temperature in the uppermost waters. However, no substantial changes in salinity were observed in our findings.

Despite the ice retreat and convection weakening, these factors do not seem to affect the formation of overflow waters in this region. However, it is important to continue studying the variability of this area and its potential implications for the AMOC and, consequently, the global climate system.

Keywords: Atlantic Meridional Overturning Circulation, Mixed Layer Depth, Sea Ice Concentration, Convection, Late Winter, Greenland Sea.

1. Introduction

The Atlantic Meridional Overturning Circulation (AMOC) is an important component of the climate system, especially relevant for the European continental climate (Trenberth & Caron, 2001). The AMOC is a two-branch system: an upper branch transporting warm and salty water from the equator to the poles, and a lower branch returning south at depth as cold and dense water (Rahmstorf et al., 2015).

Several studies using global climate model projections suggest the weakening of the AMOC due to climate change (Cheng et al., 2013), which would have global consequences. It is crucial to study AMOC's variability and possible future scenarios to implement policies that mitigate or enable us to adapt to potential climate impacts, such as rising sea levels, changes in marine ecosystems, and the cessation of dense water formation (Sévellec & Fedorov, 2015).

The Nordic Seas contribute 40% of the dense water masses in the AMOC, in the downwelling limb, thus playing a crucial role in the functioning of this system (J. Hansen et al., 2016). This region provides cold and dense water and transports a significant amount of freshwater from the Arctic to the North Atlantic, which can influence salinity and oceanic circulation (Huang et al., 2020).

The Nordic Seas are located between Greenland and Norway, encompassing the Norwegian Sea, Iceland Sea, Greenland Sea, and the Lofoten Basin, as depicted in Figure 1. They are connected to the Atlantic Ocean by the Greenland-Scotland Range (GSR), while the Fram Strait is the gateway to the Arctic Ocean to the north. To the east is the Barents Sea.

Different currents enter and exit through the GSR. A fundamental part of the ridge is the Denmark Strait, with a maximum depth of 650m (Østerhus et al., 2019). The East Greenland Current (EGC) carries 2/3 of the overflow waters leaving the Danish Strait (DSWO) (Mauritzen, 1996). On the other hand, it is the North Iceland Jet (NIJ, Semper et al., 2019) that contributes to the remaining portion of these dense waters. A third of the remaining overflow water flowing from the Nordic seas to the AMOC is carried through the Bank of the Faroe Islands Channel (Brakstad et al., 2023).

Within the Nordic seas, there are two different physical processes that lead to the formation of dense waters. On the one hand, the boundary current system carries water from the North Atlantic, approximately 5 Sv ($1Sv=10^6 m^3$, B. Hansen & Østerhus, 2000) northward through the Nordic Seas through the Fram Strait. During this trip, the current loses heat and decreases salinity, gradually becoming denser. Finally, some of this densified water descends through the EGC and contributes to the lower limb of the MOC (Spall et al., 2021). The Nordic Seas have two important cyclonic gyres: the Greenland Sea Gyre and the Norwegian Sea Gyre (Huang et al., 2020). The Greenland Sea Gyre is particularly significant because it is the main source of the densest overflow waters in the Nordic Seas (Huang et al., 2020; Brakstad et al., 2023). During winter, the Greenland Sea Gyre fills with cold and dense water, which then moves southward along ridge systems towards the Greenland-Scotland Ridge (Semper et al., 2020). This process is crucial for ventilating the deeper layers of the North Atlantic and has significant implications for heat and nutrient transport in the oceans and global climate (Oschlies et al., 2018). In summary, cyclonic gyres in the Nordic Seas are important patterns of oceanic circulation that play a crucial role in ventilating the deeper layers of the North Atlantic and in the transport of heat and nutrients in the oceans (Bashmachnikov et al., 2021).

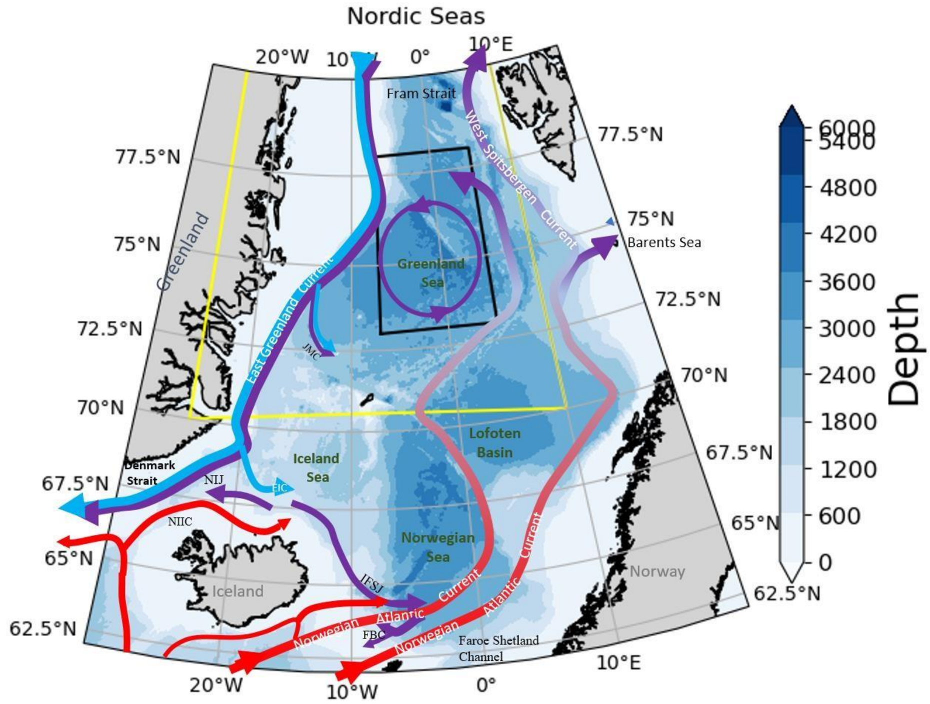

Figure 1: Scheme of the currents and basins of the Nordic Seas. In black, the coordinates of the Greenland Gyre are highlighted, and in yellow, the Greenland Sea is indicated. The acronyms NIC, North Iceland Current, NIIC, North Icelandic Irminger Current, IFSJ, Iceland-Faroe Slope Jet, NIJ, North Icelandic Jet, FBC, Faroe Bank Channel.

1.1 Convection of the Greenland Sea

The Greenland Sea (GS) is one of the few places where deep convection occurs. As a result, intermediate and deep-water masses form (Lauvset et al., 2018). Various processes control the variability of the GS mixed layer depth (MLD. During the summer, when the MLD is very shallow, it is mainly controlled by wind patterns (Rudels et al., 1999). In contrast, the winter season shows a significant deepening of the MLD, driven mainly by changes in upper water salinity and temperature. This deepening reaches its peak in April (Bashmachnikov et al., 2021). The variables that control the formation of MLD (salinity, temperature, and wind primarily) exhibit significant interannual variability (Brakstad et al., 2019). As a result, the characteristics of GS experience substantial interannual variability, which affects the MLD.

Convective depth in the Greenland Sea has changed in recent decades (Horrach Pou et al., in preparation). During the 1970s, layers reaching depths of 3500m were observed in the region (Malmberg & Jó Nsson, 1997). However, since the late 1980s, convection is limited to intermediate depths (Jeansson et al., 2017; Brakstad et al., 2019;).

Therefore, since the late 1980s, the deep-water mass in the Greenland Sea has not been ventilated. However, Lauvset et al. (2018) show in their results that after the 2000s, the MLD increased in depth due to an increase in surface salinity (Latarius & Quadfase, 2016).

On the other hand, the variability of the Greenland ice sheet may be contributing freshwater to the surface of the region (Böning et al., 2016), thereby limiting the increase in salinity described by Lauvset et al. (2018).

In addition to not having a clear understanding of what is happening with the MLD, the pathways that connect the formation of these waters to their contribution to the AMOC are also not well-known. The two channels through which dense waters exit, as mentioned earlier, are located at the ends of Iceland (Figure 1). Within the Iceland Sea, the following currents are found, responsible for crossing the GSR: the North Icelandic Jet (NIJ) and the Iceland-Faroe Slope Jet (IFSJ) (Semper et al., 2020). The hydrographic characteristics of these water masses indicate that they originate in the Greenland Sea, but how they are connected is still unknown (Huang et al., 2020; Brakstad et al., 2023).

As mentioned earlier, understanding the variability of the AMOC is of great importance. Changes in the MLD and SIC in the Greenland Sea could have a significant impact on the downstream conditions and transport by the AMOC. Therefore, it is crucial to study the variability of the MLD, including the impact of SIC and its interactions with salinity and temperature. Through this, we believe that we can gain a better understanding of the processes and dynamics that contribute to changes in the AMOC.

1.2 Objectives

In this project, our primary objectives are to investigate MLD inter-annual variability, and long-term patterns of change in the GS, and to explore potential relationships with sea-ice cover, salinity, and temperature within the period of 1991 to 2021. However, as the data utilized in this study is derived from a reanalysis, it is crucial to ensure that our findings align with the results of recently published studies in the field. By incorporating existing research, we aim to validate and enhance the reliability of our results.

2. Data and Methods

2.1 Dataset

2.1.1 Description and Source of the Dataset

For this project, I will use TOPAZ, specifically its latest version TOPAZ4b, which is a product of the Physical Ocean Analysis from the Nansen Center for Remote Sensing. The data is freely available through the Copernicus Marine Service (CMEMS).

Topaz is a reanalysis product, meaning that it combines models and observations. In this case, it combines the Hybrid Coordinate Ocean (HYCOM) coupled to a sea ice model where temperature and salinity observations are assimilated using the Ensemble Kalman filter (EnKF, Sakov et al., 2008).

2.1.2 What is a Reanalysis?

Reanalysis products play an important role as a scientific tool, offering a continuous stream of information regarding the state of the atmosphere, ocean, and other climate system components, spanning both historical and current periods. These invaluable resources enable us to reconstruct and simulate past conditions by integrating observational data with numerical models.

The significance of reanalyses in physical oceanography stems from various factors:

1. Data complementarity: Reanalyses combine numerical models with observations from various systems, improving the quality and spatial-temporal coverage of the data.

2. Past reconstruction: Reanalyses enable us to replicate historical conditions even without direct observations. This is necessary for understanding past changes and analyzing current trends.

3. Model validation: Reanalyses provide substantial data sources to validate the mathematical models used for future climate projections.

4. Scientific research: Reanalyses are vital tools for studying the environment and climate. They allow for the analysis of interactions between different climate components, investigation of atmospheric and oceanic dynamics, and development of future projections.

5. Real-world applications: Reanalyses are used not only for forecasting future climate and analyzing current climate conditions but also for water resource planning and natural disaster management. Furthermore, they provide detailed data on key variables such as sea water temperature, salinity, ocean currents, and wave height, enabling a better understanding of the state and evolution of the ocean in different regions. These data are essential for several marine-maritime applications, such as navigation and maritime safety.

In conclusion, reanalyses are a crucial source of information for conducting comprehensive studies of the climate, including examination of the past, present, and future.

Tabla 1: Dataset Information

	Arctic Ocean					
	Spatial extent	**Spatial resolution**	**Temporal extent**	**Temporal resolution**	**Depths (levels)**	**Processing level**
Topaz4b data	Lat: 53º/90º Lon:−180º/180º	12,5x 12,5 km	1/Jan/1991 to 31/Dec/2021	Daily, Monthly and Yearly	40	4

The spatial extent for this project, as I have previously mentioned, will encompass the Greenland Gyre region where the MLD exists, apart from results specifically related to ice concentration that will cover the entire Greenland Sea region. Additionally, I will be working with both monthly averages and daily data, spanning the period from January 1, 1991, to December 31, 2021.

2.2 Methods

In this study, the focus is on two key variables, MLD and SIC, essential to understanding the dynamics of the Greenland Sea. MLD provides valuable information about heat exchange, ocean circulation, biological production within the region, and dense water production. By analyzing its variability over the study period, we can gain insights into how it responds to different atmospheric and oceanic conditions and its impact on various processes in the Greenland Sea.

1. Sea Ice Cover Concentration (SIC):

The SIC represents the extent of oceanic ice cover. It is obtained and reprocessed from OSI-SAF, which uses the ARTIST algorithm based on passive microwave data from the SMMR, SSM/I, and SSMIS satellites. The SIC represents the percentage of ice coverage in each grid of the model domain (Lavergne et al., 2019).

2. Mixed Layer Depth (MLD):

The MLD variable represents the depth of the mixed layer in the ocean. Its estimation involves the integration of observational data and numerical models. In-situ measurements of ocean temperature and salinity profiles serve as observational data, which are then assimilated into the numerical ocean model. This assimilation process allows for a more precise prediction of the MLD. In the reanalysis product, the MLD is calculated for each grid point for each timestep and offers a good representation of the observed MLD from the observations.

To summarize, the MLD is derived by combining observational data and numerical models through data assimilation, while the SIC variable is obtained by merging satellite data with numerical models. These variables provide crucial information for investigating the thickness of the MLD, and the extent of SIC, respectively.

3. Practical Salinity Unit (PSU).

The PSU was introduced to represent water salinity through conductivity measurements (M Dauphinee et al., 1980) in the reanalysis. Currently, the most common way to measure salinity in oceanography is as absolute salinity, which is generally expressed in units of mass of salts per unit mass of water. In this study, we will be working with units of absolute salinity, which is a quantitative measure of the total amount of salts present in seawater, including ions such as chloride, sodium, magnesium, and calcium, among others (Gordon et al., 1993).

4. Potential Temperature (ºC):

It is defined as the temperature a seawater sample would have if adiabatically moved to a standard reference pressure (Fofonoff, 1985).

In this study, we will be using TEOS-10 (Thermodynamic Equation of Seawater 2010), which is a set of thermodynamic equations that describe the physical properties of seawater, including salinity, density, temperature, and pressure. It was developed by the Physical Oceanography Committee of the International Association for the Physical Sciences of the Oceans (IAPSO) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

In addition to MLD and SIC, we will also use practical salinity and the potential temperature. By examining the relationship between MLD and these additional variables, we can further enhance the understanding of the processes influencing the variability of the MLD in the Greenland Sea. Together, these variables contribute to a comprehensive analysis of the interactions and dynamics within the study area, shedding light on the intricate relationships and their implications for the marine environment.

2.2.1 Analysis and Filtering of Dataset

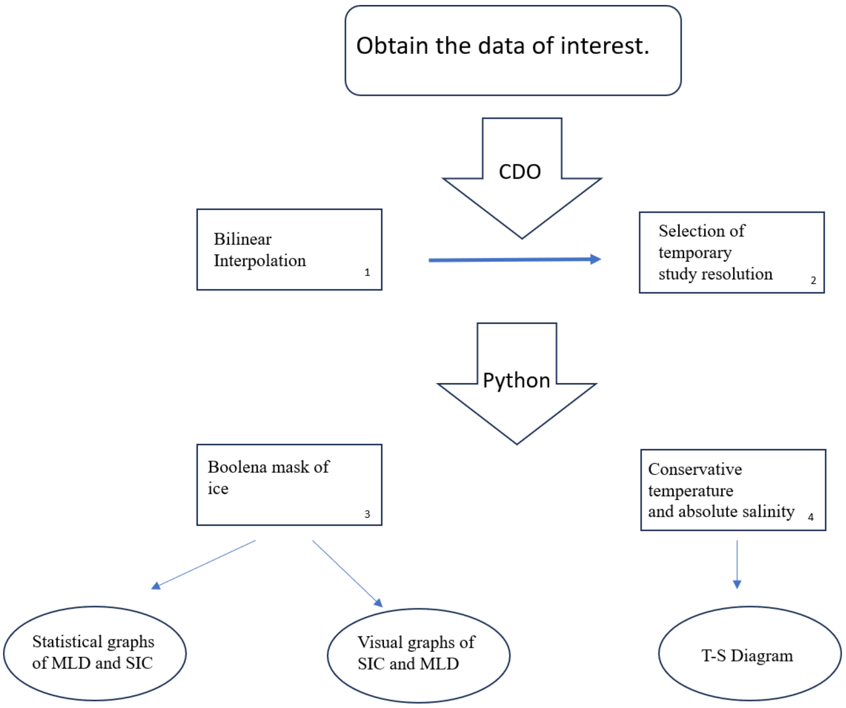

Figure 2: Flow diagram summary of the methodology followed in the work.

First, we perform preliminary data filtering using the CDO (Climate Data Operators) software. We use interpolation to ensure a homogeneous spatial resolution and calculate monthly averages to account for any daily variations. We select the months of December, January, February, March, and April for the variables SIC and MLD. We choose these months because the deepening of the MLD starts in December when the Heat fluxes from the Ocean to the atmosphere enhance and reaches its maximum depth in April. By choosing these months, the important stages of the MLD's seasonal variations in the Greenland Sea can be captured. For temperature and salinity, we also perform data interpolation, but we don't select specific months of interest because we are interested in observing the annual change over the entire period.

Data interpolation plays an important role. We use the "remapbil" option in the CDO command to perform bilinear interpolation, which remaps the data to a regular grid. Bilinear interpolation estimates unknown values of a new point by combining the linear values of the nearest four known points. It's important to note that if the data variation between known points is not smooth and gradual, bilinear interpolation may yield inaccurate results.

After making these modifications to the data, we began working with Python. First and foremost, it is implemented an additional filter specifically for the SIC variable. We set a threshold to consider only SIC data with less than 15% coverage. Values exceeding this limit are converted to empty points, and the corresponding MLD data is also converted to empty points. The presence of sea ice affects the surface salinity found beneath it, and therefore it impacts the MLD. The presence of SIC leads to a fresher and saltier surface layer, which inhibits the convection process. Discarding SIC data exceeding 15% is necessary to ensure that MLD conditions are not affected by this salinity factor, thus obtaining more accurate estimates of the MLD value.

Another essential modification is the conversion of potential temperature (ºC) and salinity (PSU) provided by the dataset to conservative temperature (ºC) and absolute salinity (g/kg). We perform these modifications in Python using the GSW library, which contains the equations of state for seawater (TEOS-10). Python serves as the primary tool for most of the analysis, providing essential features for data filtering and processing according to predetermined criteria.

Next, we calculate the qualitative and quantitative results of interest for the project:

- Initial and final state of the study region.

- Variation of SIC specifying quantitative values in the study area. Decadal variation is analyzed to enable comparison with other studies and better observe the gradual nature of the process.

- Daily and late winter statistical values of MLD, including mean and standard deviation, as well as a figure that provides additional information such as anomalous values, median, or interquartile range.

- TS diagram in the study region, examining changes every 5 years and considering the most relevant isopycnals for our study.

Overall, these analyses provide a comprehensive understanding of the variations in the SIC and the MLD in the GS gyre. The combination of quantitative and visual approaches captures both the numerical and spatial aspects of these variations.

For data processing and analysis, we utilize tools such as CDO and Python, along with libraries like NumPy, Pandas, Xarray, Matplotlib, and Cartopy. These tools and languages facilitate comprehensive statistical analysis and visualization of the downloaded data, enhancing the study of climatic factors and the understanding of marine circulation variability. Moreover, all the tools and data used in this study are open source and all our code follows the FAIR data processing principles. It is Findable (anyone can access it), Accessible (all software is freely available), Interoperable, and Replicable (anyone with the data set can replicate the figures we have made in this study).

2.3 Additional Considerations

The analysis of the dataset reveals biases or inaccuracies in the variables. Reanalysis yields a warm bias in the summertime upper sea temperature and a saline bias in the deeper waters in terms of temperature and salinity. It is also noted that the MLD is too superficial in the summer and too deep in the winter and that there is a tendency for frostbite to occur too quickly in the winter and the summer thaw (Ali et al., 2019).

3. Results and Discussion

As can be seen in Figure 3, the study data show a considerable change in the conditions between 1991 and 2021. Firstly, there is a clear decrease in the percentage of ice in the GS region, particularly noticeable for the 15% of SIC. Regarding the MLD, if we focus on the Greenland Gyre area, it can be observed that the values in 1991 were higher compared to 2021, where there is barely a noticeable difference in depth compared to the surrounding regions. These initial results sparked our great interest in understanding what had happened in the study region, as the changes in our main variables are evident.

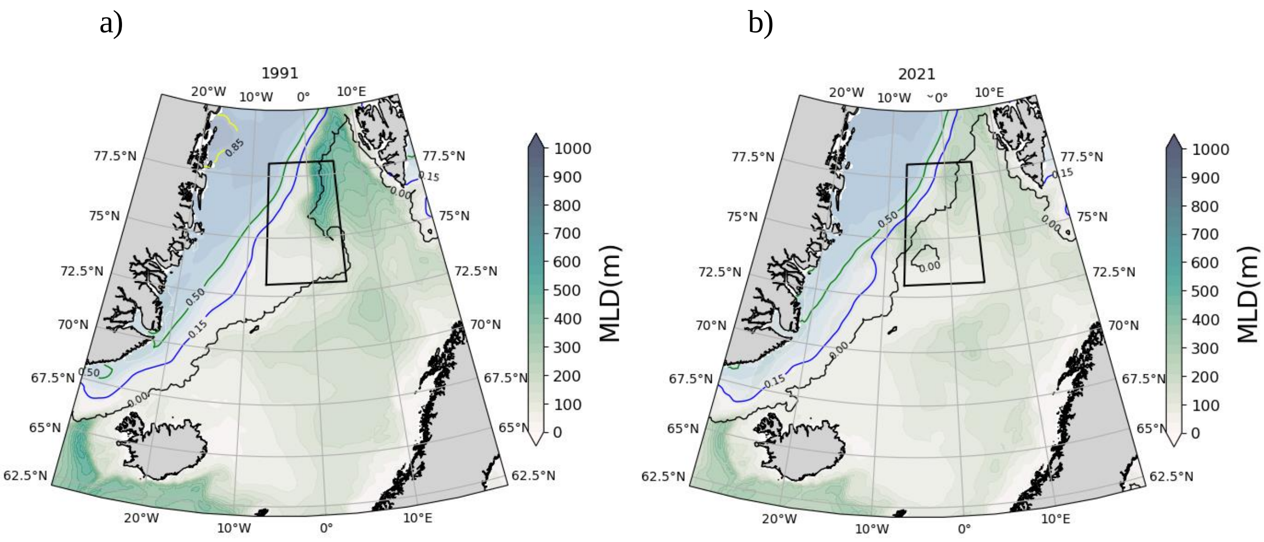

Figure 3: Mean ice concentration and mixed layer depth in the study period: (a) initial year (1991) and (b) final year (2021).

3.1 Variation of the Sea-Ice Concentration in the Greenland Sea

The variability of ice coverage impacts both the depth and location variability of the MLD.

The results obtained from analyzing the SIC data in the reanalysis indicate an apparent decline in this variable during the study period (1991-2021). By dividing the results into decades Figure 4 (a), (b), and (c), we can observe the gradual nature of this process in more detail. If we focus on the black trapezoid, which represents the area of interest in this study, we can see that in the early years, it was mostly covered by ice, primarily within the 0-15% concentration range, which represents the Marginal Ice Zona and the

Sea Ice Edge. However, in recent years, this specific ice-covered portion has significantly decreased.

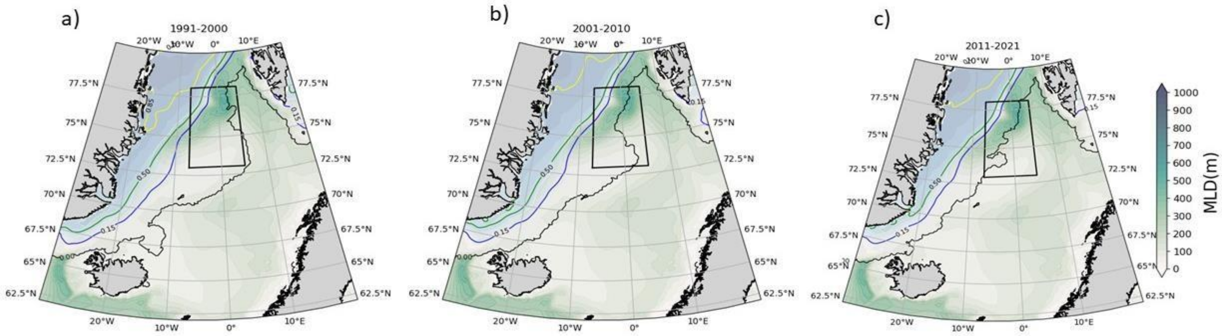

Figure 4: Ice coverage percentage for the three decades of the study: (a) 1991-2000; (b) 2001-2010; (c) 2011-202.. The black, blue, green, and yellow lines represent the boundaries of ice coverage for 0%, 15%, 50%, and 85%, respectively.

If we compare these results with those from other studies, such as the one conducted by Moore et al., (2015), we can observe that their Figure 1d depicts a period very similar to our period in Figure 4b**.** This allows us to make comparisons, and although the results are not identical, they show significant similarities.

If we observe the results of Velicogna et al., (2014), they also conclude that ice coverage has been undergoing a significant decrease since 1990. However, since their data only goes up to 2007, we cannot compare it to the latter half of this study. Nevertheless, they do conclude that they did not observe a deceleration in the ice decline.

The sea ice edge retreat is evident when observing Figures 3 and 4, but now our focus is on quantifying this retreat. To do so, we have calculated the variability in our time series, in square kilometres, for the study area (black trapezoid in Figures 1, 3, and 4).

The results in Figure 5 demonstrate the significant variability in ice coverage in the region, with a maximum value of 7,123*10^4 km^2 in 1997 and a minimum value of 1,225*10^4 km^2 in 2018.

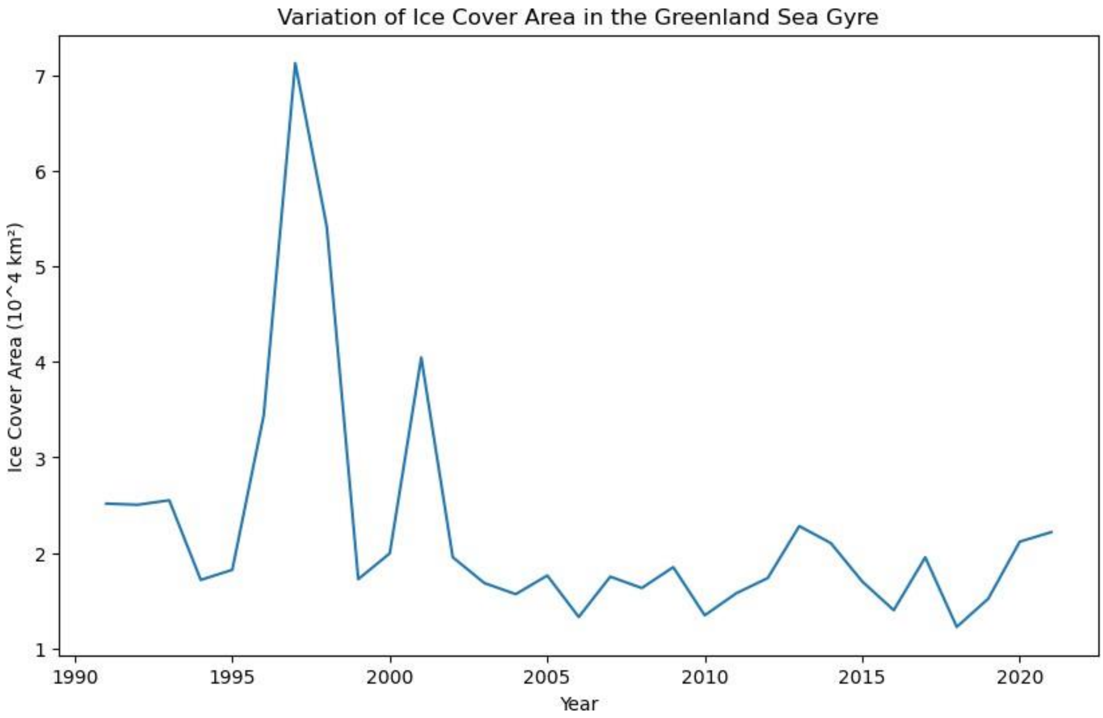

Figure 5: Time series of the late winter for the boundaries of the black box in Figure 3.

The variations in the SIC can have a dual impact on the MLD. Firstly, it can influence the atmosphere-ocean interaction, and secondly, it can affect the freshwater balance in the region. These variations in the ice coverage can potentially influence the depth and dynamics of the MLD (Sha et al., 2016).

The reduction in the SIC can be attributed to various factors, including increasing air and water temperatures, and changing ocean circulation patterns. These factors can work together to accelerate sea ice melting and limit the formation of new ice (Moore et al., 2015).

It is important to note that the decline in SIC in the GS can have significant consequences for ocean circulation and regional climate patterns, which, in turn, can have implications on a global scale.

Our findings underscore the importance of closely monitoring the evolution of SIC in the GS and highlight the need to take measures to mitigate climate change and its associated impacts. Future studies should further investigate the underlying mechanisms of SIC loss and its impact on the ecosystem and regional climate.

3.2 Interannual and Decadal MLD Variability

The annual and interannual variations observed in the MLD are evident, as shown in Figure 6. For instance, in 1997, we observe the maximum value of MLD with a mean of 1265m and a standard deviation of 647m. In contrast, in 2005, we find the minimum value of MLD for our time series, with a mean of 247m and a standard deviation of 74m. These results allow us to see how the daily series represents the changes occurring in the MLD each year. Moreover, it is crucial to understand how the MLD varies during the study period from 1991 to 2021.

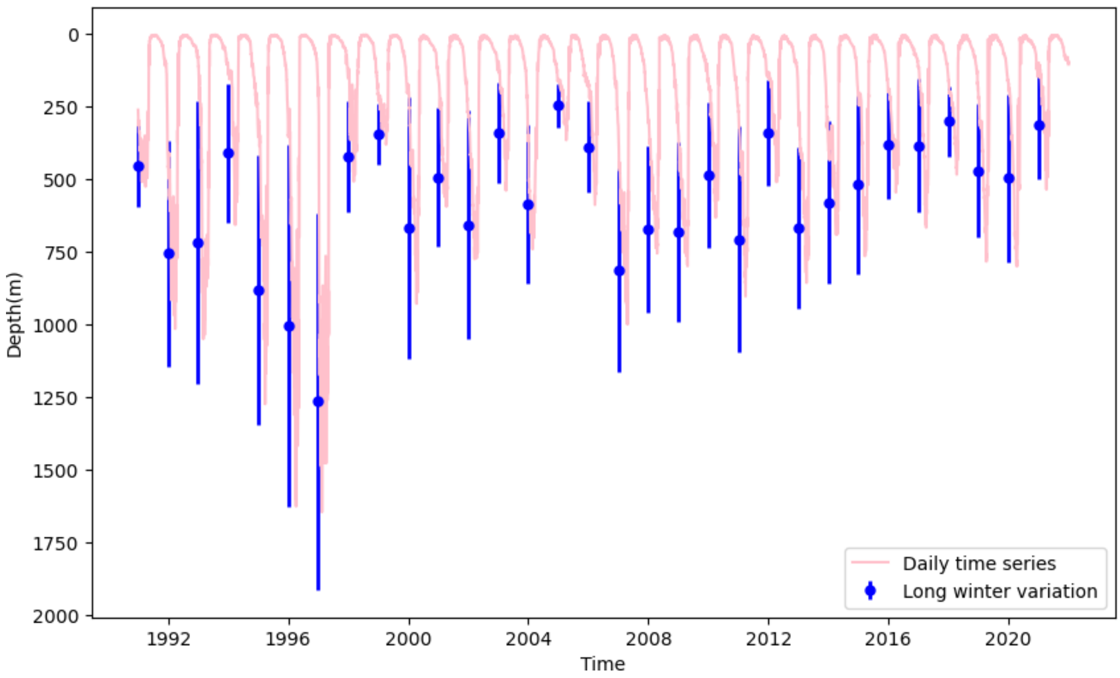

Figure 6: Variation of the MLD, with daily data and for the months of the extended winter.

The valour of MLD can be attributed to various factors, such as changes in wind patterns, sea surface temperature, and salinity (Huang et al., 2021). Rysgaard et al. (2012) highlights the significance of meteorological variations on the MLD.

Lauvset et al. (2018) demonstrated, using observational data in their Figure 5b, that the maximum depth of the MLD did not exceed 1000 meters in the years prior to 2000. However, in the subsequent decade, they observed MLD values surpassing this depth. In contrast, my findings do not align with those results. Instead, they indicate that MLD can exceed 1000 meters in the years preceding 2000, but after this period, such depths are no longer reached.

On the other hand, if we look at the results obtained from the reanalysis, the maximum value achieved in the first decade of the study period (1991-2000) is 1265m, in the second decade (2001-2010) it is 812m, and in the third period (2011-2021) we have 707m. We can observe that the maximum value has decreased over time. Furthermore, the mean value has also decreased, as we would have an average depth of 1004m, 812m, and 707m for the same respective time periods.

In summary, the interplay between climate variability, oceanic processes, and MLD dynamics is a complex and multifaceted field of study. Further research and collaboration among scientists are necessary to gain a comprehensive understanding of these relationships and their implications for climate change and ecosystem dynamics.

The statistical study of MLD for the period of interest reveals clear interannual variability and decadal variation as shown in Figure 6. Consistent with the findings in Figure 6, Figure 7 reveals the maximum median value in 1997, reaching 1526m, while the minimum median occurs in 2005, with a value of 206m. Furthermore, both the mean and median values exhibit a negative trend over the entire time series.

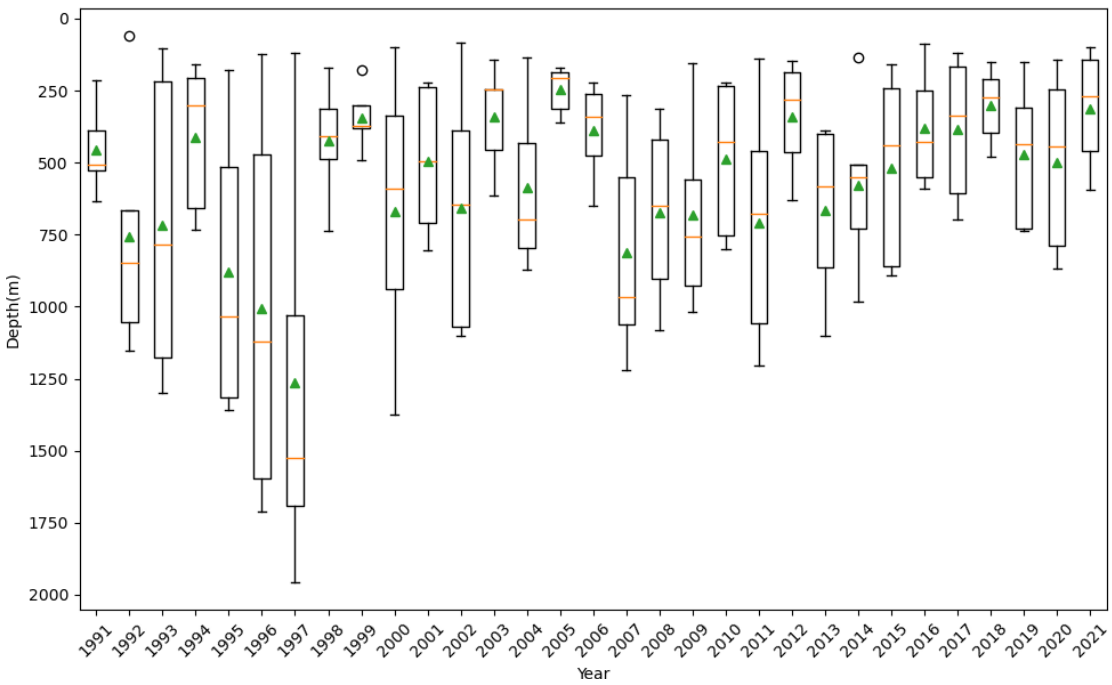

Figure 7: Statistical values of the variation in MLD for the months of the extended winter are of interest. The boxes represent the interquartile range (IQR) that encompasses 50% of the data. The lower part of the box indicates the first quartile (Q1), and the upper part indicates the third quartile (Q3). The horizontal line inside the box represents the median. The green triangle represents the mean. The whiskers extending from the box represent the variability outside the IQR. The individual points represent outliers.

The maximum values found in this MLD study show positive trends in the first two described time periods (1991-2000/2001-2010) and a negative trend in the last period (2011-2021), which is consistent with the results reported by Bashmachnikov et al. (2021) (Figure 4).

Something important that can be observed and needs further analysis is what happens in 1997. In that year, we reach the maximum MLD and have the highest ice concentration in the region. This indicates a clear relationship between these two variables.

The years 1999 and 2005 show values of 491m and 358m, respectively, which are the years with the lowest maximum values. However, when comparing these results with the findings in Table 1 Bashmachnikov et al. (2021), we observe that Somavilla, (2019) reports a maximum depth of 500m for 1999, which is consistent with our results. However, for 2005, Somavilla et al. (2019) obtain a value of 1350m, indicating a considerable difference in the results obtained for that year, but the same study

Bashmachnikov et al. (2021) clarifies in its discussion that these discrepancies may be attributed to anomalies in their measurements.

The obtained results are like those of Strehl et al. (in review), who conducted a detailed study on the MLD from 1950 to 2020. They found that since 1985, the maximum stratification has kept the intermediate and deep water masses separated.

These observations emphasize the complexity of studying MLD and the need for further investigation to understand the factors contributing to its variability. Additionally, it suggests the importance of using multiple data sources and models to validate and improve our understanding of MLD dynamics in the GS.

In this study, we have constructed a TS diagram to analyze the water properties around the interest, which covers the Greenland Sea Gyre.

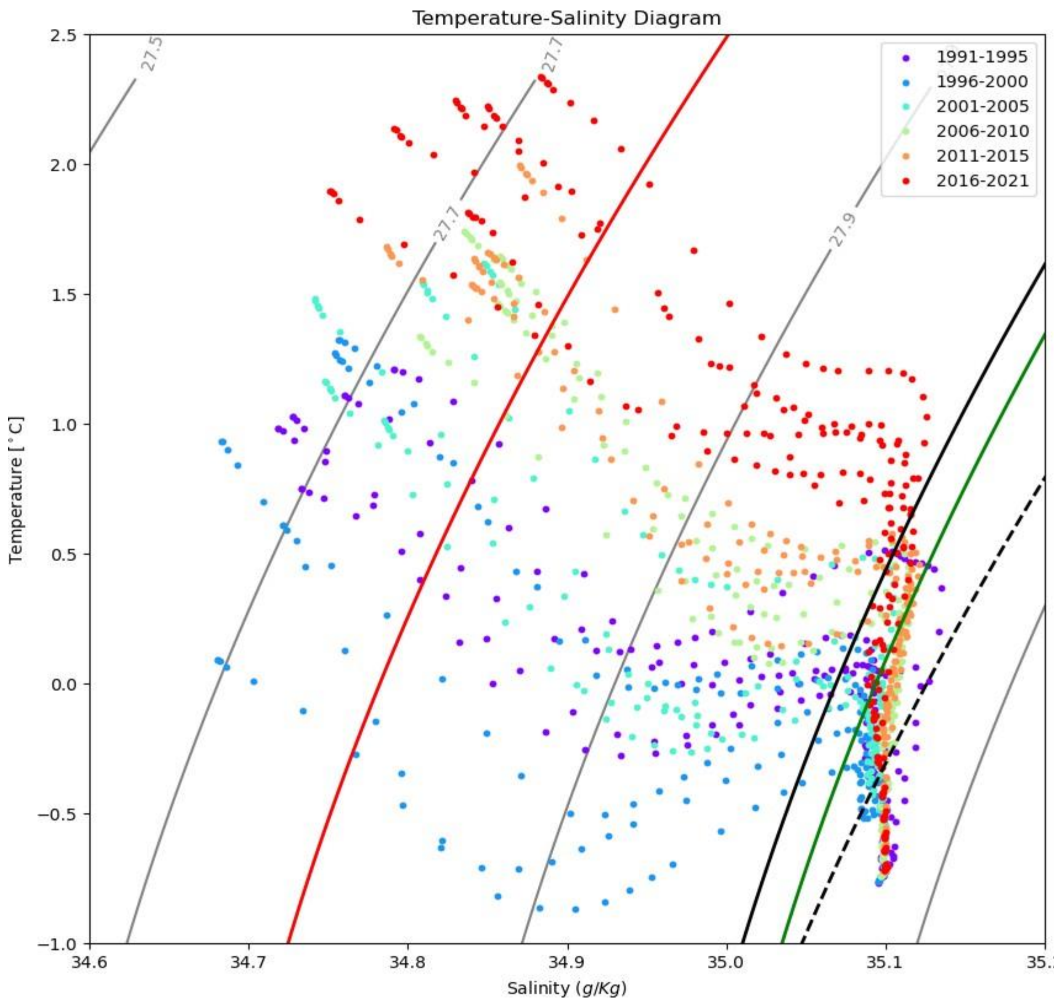

Figure 6: T-S Diagram calculated in the Greenland Gyre, representing the entire water column. It displays the values of conservative temperature (TEOS-10) and absolute salinity. The gray lines indicate potential density (σ_θ Kg m^{-3}). The dashed black line represents the isopycnal $\sigma_{0.5}$ of 30.444 while the continuous marks in red, black and green denote the values of σ_θ27.8, 28.03 and 28.05 respectively.

The graph clearly shows a warming trend in the uppermost waters over time, with a discrepancy in the 1990s, where the early years are warmer than the later ones. However, starting from the 2000s, there is a noticeable increase in temperature, while salinity values remain relatively constant. At the beginning of the study period, the maximum and minimum values of temperature were 0.98°C and -0.67°C, while the maximum and minimum values of salinity were 35.14 g/kg and 34.72 g/kg, respectively. However, in the last year of the study period, the maximum and minimum values of temperature increased to 1.89°C and -0.72°C, respectively, while the maximum and minimum values of salinity changed slightly to 35.10 g/kg and 34.75 g/kg, respectively.

The isopycnal of σ_θ 27.8 kg/m^3 represents the lowest density threshold for water overflow (Brakstad et al., 2023, Figure 5), and denser overflow waters should exceed 28.03 kg/m^3 (Semper et al., 2020). The isopycnal σ_θ 28.05 marks the boundary where the water mass becomes more stable, and minimal variability is observed during the studied period.

Therefore, the values found below this isopycnal are of great relevance as they will contribute to the potential changes experienced by the AMOC. On the other hand, the isopycnal of $\sigma_{0.5}$ 30.444 indicates the boundary between intermediate and deep waters (Brakstad et al., 2023). In this diagram, we can observe that beyond this isopycnal, the water has undergone minimal renewal, which is consistent with the findings of Brakstad et al. (2019).

Considering the information, we have discussed, the reduction of SIC and the weakening of the MLD play significant roles in the TS diagram. When SIC retreats, it leads to more heat being absorbed by the ocean, causing an increase in temperature. At the same time, the melting of SIC introduces fresh water into the ocean, which affects the salinity. These changes in temperature and salinity can have an impact on the MLD, which represents the depth at which the water column is well-mixed. The TS diagram provides a visual representation of these relationships and helps us understand how they shape the ocean dynamics in the Greenland Sea Gyre.

In summary, the TS diagram is a valuable tool for understanding the complex interactions among temperature, salinity, SIC dynamics, and the MLD in the Greenland Sea. It reveals the warming trend in surface waters, the stable behaviour of salinity, and the importance of isopycnals in identifying key water properties and their connection to broader oceanographic processes.

In summary, although we have conducted our study using reanalysis data, it is important to consider that the lack of previously published studies with results obtained from this reanalysis may affect the reliability and accuracy of our findings. Cross-validation and comparison with other studies are critical steps to support and strengthen the interpretation of our findings.

4. Conclusions

The main conclusions are:

.- The results obtained reveal a negative trend in the MLD during the study period from 1991 to 2021. This trend aligns with the observed trend in SIC, indicating a consistent pattern.

.- An evident indication of the relationship between MLD and SIC is observed in the year 1997, where we find values above the average for both variables.

.- The gradual warming of water in the surface layers has a direct relationship with MLD and SIC. The most stable salinity data we have found, compared to other studies such as Lauvset et al. (2018) and Bashmachnikov et al. (2021), which report increases in seawater salinity during summer-autumn, indicate that this salinity increase during warmer periods is compensated during colder periods.

.- The TS diagram obtained shows us that the dense water masses that join the AMOC are still being formed, but their characteristics are changing. Therefore, it is necessary to continue studying them to better understand the possible implications of this fact.

.- Finally, the reanalysis data has generally shown results consistent with findings from other studies (Moore et al., 2015; Brakstad et al., 2019, 2023, Strehl et al., in review). However, discrepancies in the results have also been observed when compared to studies such as Lauvset et al. (2018). Although these results need to be validated and complemented with observational data, reanalyses are approaching becoming a reliable method for oceanographic research.

<u>Possible future studies in relation to the obtained results could include:</u>

- Examining in detail the physical and dynamic processes that contribute to the relationship between MLD and SIC.

- Investigating the implications of the changing characteristics of the water mass. It would be interesting to study the consequences of this change on regional oceanic circulation and local and global climate patterns.

- Validating the results of data reanalysis: It is important to validate and complement the results using observational data, which would enhance the reliability of the findings.

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