Dominant patterns of atmospheric variability and their impact on sea ice concentration in the Labrador Sea

by

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Abstract

The thesis presents results from an Empirical Orthogonal Functions (EOF) analysis of the dominant patterns of atmospheric circulation and their impact on the variability of sea ice in the Labrador Sea. The study uses ERA5 reanalysis of sea level pressure and sea ice from the European Center for Medium-Range Weather Forecasting (ECMWF). The analysis focuses on the relationship between the EOFS of sea ice concentration and three dominant patterns of the North Atlantic atmospheric variability: the North Atlantic Oscillation (NAO), the Greenland Ridge (GR) and the Scandinavia–Greenland pattern (SG). The first EOF of the sea ice concentration determines the interannual variability of the offshore horizontal sea ice extension. The second EOF is related to the variations in the magnitude of ice concentration in the areas covered by ice every year. A significant correlation was found between the NAO and the first sea ice EOF pattern. In particular, the results suggest that the quasi-decadal transition in sea ice concentration observed in the mid-1990s was related to a quasi-decadal transition from a positive to a negative phase of NAO. The results provide a reference for identifying the drivers of ocean variability in the Labrador Sea and their potential impact on the regional marine ecosystem and climate.

Acknowledgements

I would like to express my deepest gratitude to all those who helped me to complete this project.

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Chapter 1

Introduction

Sea ice forms due to surface cooling and consists of ice, seawater and air bubbles. It is observed mainly in the cold polar and subpolar areas where it substantially impacts the air-sea interaction and ocean currents, temperature and salinity.

Sea ice has a significant impact on climate. It reflects a large portion of the sunlight incident to the Earth's surface back into space and thus plays an essential role in the overall energy balance of the planet. As global temperatures rise, the sea ice is melting at a higher rate, leading to an additional reduction of albedo and warming of the Earth's surface. This determines the positive feedback between the sea and climate warming, intensifying the global temperature increase.[1]

Parts of the coastal areas of the northwest Labrador Sea are covered by ice in the winter and are ice-free in the summer. The processes of formation and melting of sea ice affect the salinity and density of the seawater and, in this way, affect ocean water mass characteristics and ocean currents.

In this thesis, I study sea ice variability in the Labrador Sea in connection with

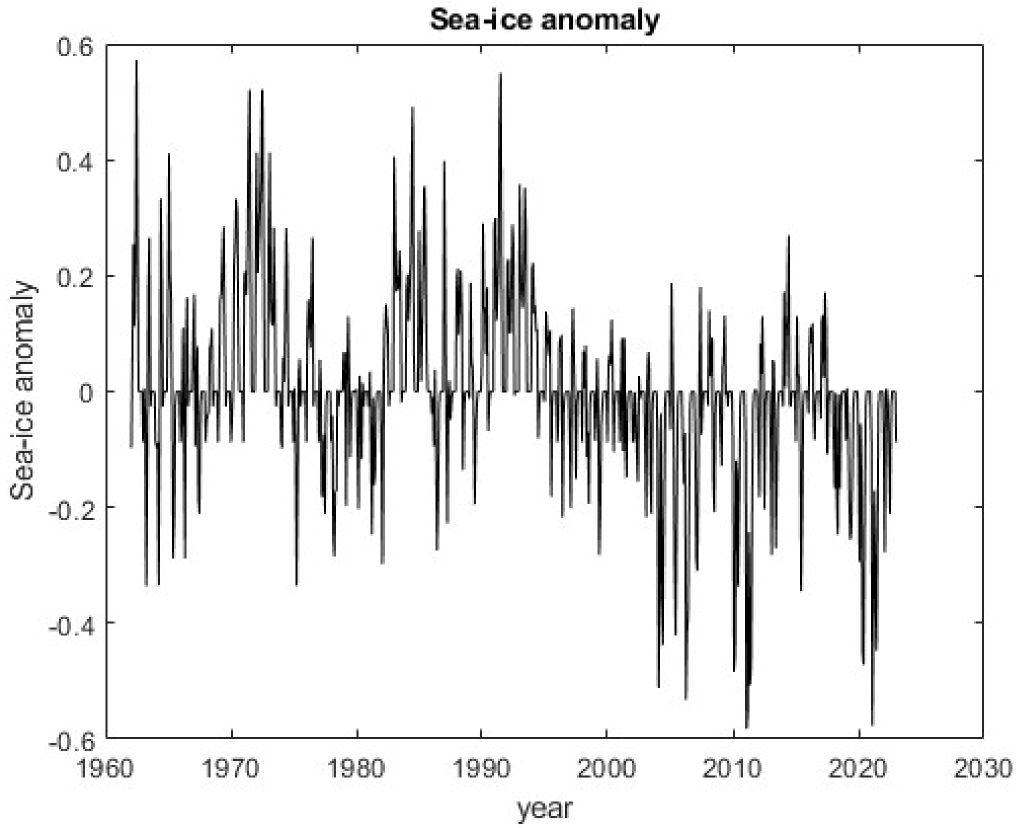


Figure 1.1: sea-ice anomaly from 1962-2022

atmospheric circulation. Figure 1.1 shows the time series of the sea ice anomaly in the western Labrador Sea from 1962 to 2022. The anomaly is calculated as the difference between the sea ice concentration values and their monthly mean. Sea ice concentration is the percentage of the area of sea ice in a unit area of the ocean. It is an indicator and driver of climate change at high latitudes. Sea ice concentration is a very important piece of data in the study of high-latitude climate, as it shows the area and extent of sea ice. There are several different methods for measuring sea ice concentration, including in situ measurements, SAR and visible light, and microwave radiation measurements. The most widely available sea ice data are usually from passive microwave instruments including SMMR, SSMI, SSMIS, AMSR-E, and AMSR-2. This study uses the OSI SAF dataset after 1979, and the results are calculated based on atmospherically-corrected SSMIS brightness temperatures combined with algorithms. Units are usually described in percent. It shows a transition from high sea-ice anomaly in the 1980s and the early 1990s towards anomalously low values in the 2010s. Such a transition was also observed in the water mass characteristics. [4] Hauser et al explained the transition in ocean characteristics with the role of atmospheric regimes in determining the long-term variations in atmospheric circulation.

This study aims to understand if and how sea ice variability is related to the changes in atmospheric circulation determined by the atmospheric regimes. In previous studies, e.g., Hauser et al (2014), the gaze has been mainly focused on the North Atlantic Oscillation (NAO) with respect to net heat fluxes at the sea surface (NHF), sea surface temperature (SST), and sea surface salinity (SSS), but an important component of the polar region, sea ice, has been neglected. The aim of this thesis is to explore the role of sea ice in the overall general circulation research system and its relevance to the atmosphere. The relationship between atmospheric circulation and surface ocean characteristics is quite complex, and the addition of sea ice variability to the overall North Atlantic research system complements some of these studies. Through analysis and observation, it is found that among the various modes of SLP manifestation in the North Atlantic only the positive phase NAO has a high correlation coefficient, and that the expansion and retreat of sea ice is positively correlated with the strength of the positive phase of the NAO. In this paper, the relationship between the North Atlantic Oscillation (NAO) and sea ice will gradually deepen starting from the atmospheric circulation. The results are obtained and comparatively analyzed using the EOF calculation method.

1.1 Interannual modes of atmospheric variability over the Labrador Sea

Earth receives energy from the sun and loses energy by emitting long-wave infrared (IR). The long-time average of the incoming and outgoing radiations balance exactly each other [8]. However, their magnitudes differ depending on the latitude (see Figure 1.2). The Earth receives more solar energy in equatorial areas and less near the poles. At the same time, the IR emissions change little with the latitude. As a result, the energy balance (which is the sum of incoming solar radiation and IR emission) is positive over the tropics areas and negative over the polar areas (see Figure 1.3). Therefore, air at the surface is warmer at the equator and cold at the poles.

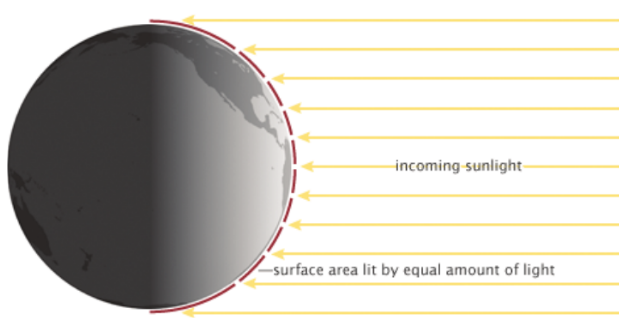


Figure 1.2: Earth's uneven heating by the sun.(after [8])

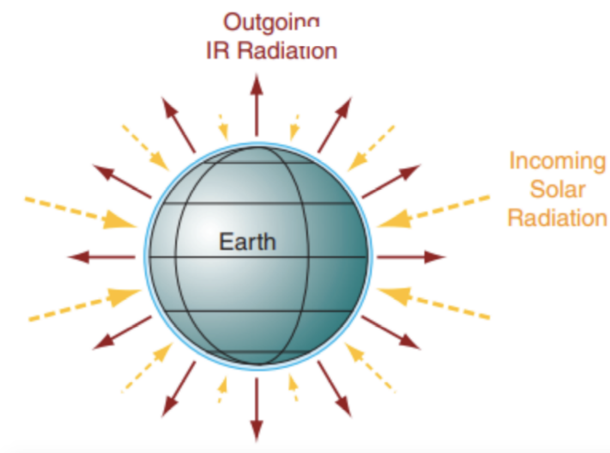


Figure 1.3: Incoming Solar radiation (SR) and Outgoing IR Radiation.(after [8])

The atmosphere (and ocean) must move the surplus of heat (black curve in Figure 1.4) to compensate for the excess of incoming (red curve in Figure 1.4) over outgoing radiation in the tropics (red curve in Figure 1.4) and the deficit at high latitudes (blue curve in Figure 1.4). This heat is transported by meridional components of winds in the atmosphere and current velocities of the oceans, which convey the surplus of energy from the tropics toward the polar areas. This seemingly simple model is complicated in reality by factors like the Earth's rotation, the presence of the continents and interactions between the atmosphere and oceans.[8]

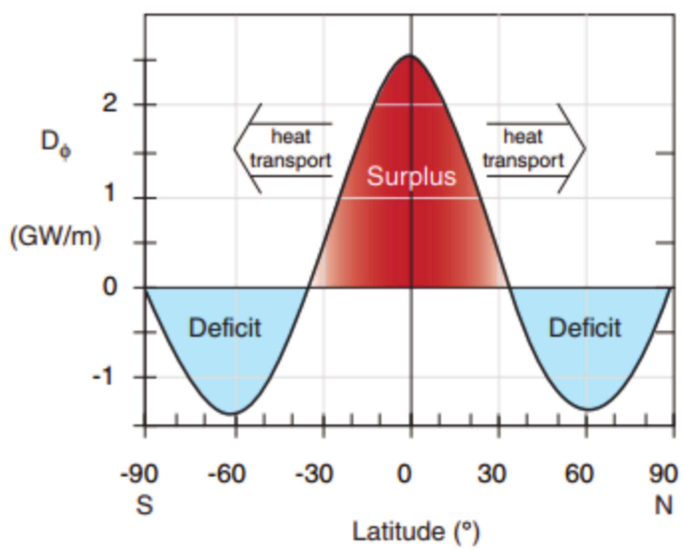
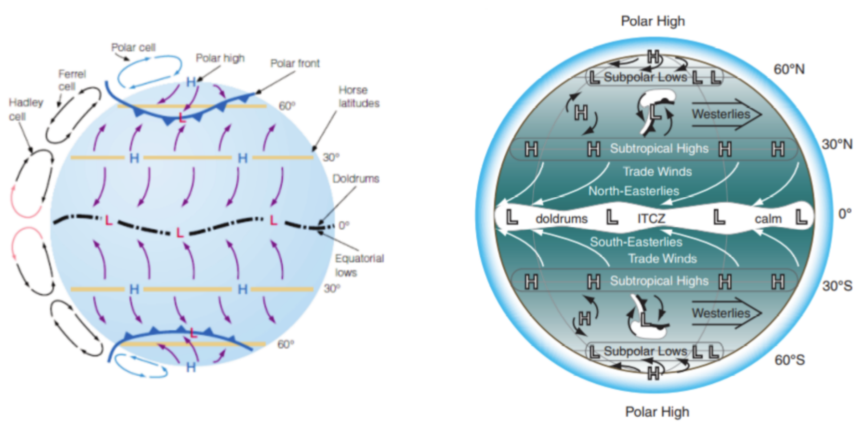


Figure 1.4: The zonal (longitudinal) average of the Incoming Solar radiation (SR) (red curve), Outgoing IR Radiation (blue curve) and the net meridional heat transport in the atmosphere and ocean (black curve). (after [8])

The heat transport in the atmosphere occurs in the so-called overturning cells, they are the Hadley cell, the Ferrel cell and the Polar cell. The Earth's rotation modifies these cells (Figure 1.5a). Due to the effects of rotation, the equatorial thermally driven Hadley cells extend only to latitudes of about 30°. The cold and dense air descends over the poles in the one-cell model, but now the near-surface transport of cold polar air extends equatorward to latitudes of about 60° N. The polar front is the area at about 60° N between the cold air of polar origin and the subtropical air. A third cell, or the Ferrel cell, forms between the polar and Hadley cells. Sometimes this third cell is also called a frictional term because it is not thermally driven as the two other cells. It is driven by descending air at the north edge of the Hadley cell and rising air at the southern edge of the polar cell. [8]



(a)

(b)

Figure 1.5: The three-cells circulation: (a) Overturning circulation; (b) Schematic surface pressure distribution.(after [8])

The general rule is that the areas of upward motion in the vertical cells have low atmospheric pressure, and the areas of descending air have high pressure. The pole's atmosphere has a high-pressure system near the surface, and the equator has a low-pressure belt along it (Figure 1.5b). The surface pressure in the area of the Ferrel cell is high in the subtropic (due to the descending motion at the edge of the Hadley cell) and low pressure in the subpolar region (due to upward motion at the southern edge of the polar cell).

The surface pressure in the real world differs from the simple three-cell model because of the impact of the continents on the air dynamics and circulation. The continents, ice masses, oceans, mountains, and forests change the surface pressure distribution. Due to their impact, the high and low-pressure zonal belts transform into high and low-pressure centers. The most important centers are Bermuda-Azores High, the Pacific High, the Icelandic Low, and the Aleutian Low (see Figure 1.6).

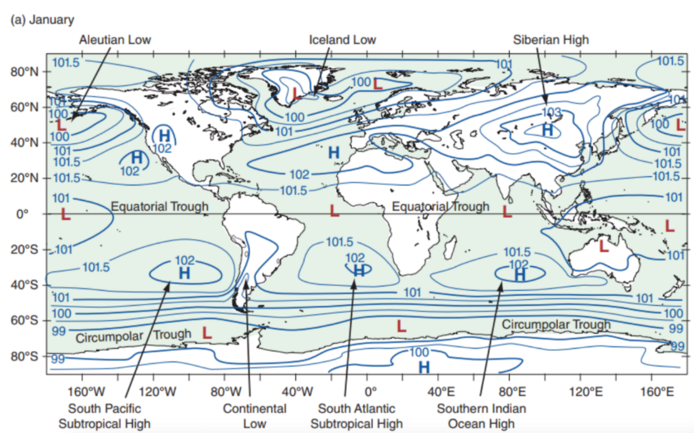


Figure 1.6: Long-term mean of surface pressure in January.(after [8])

The three-cell model also fails to explain the observed meridional heat transport in the atmosphere. More specifically, the estimated transport in the Ferrel cell is lower than the observed [9]. Large-scale eddies and waves generated much of the Ferrel cell's heat transport in middle latitudes.

In 1969, Chester Newton and Eric Palmen introduced an alternative to the three-cell model shown in Figure 1.7. There are two major cells - the Hadley and polar cells. At mid-latitudes, the meridional transport is driven by moving vortices or storms. The subtropical (STJ) and subpolar (SPJ) jets play a major role in these dynamics. These localized areas of strong winds at about 10-12 km altitude meander and determine the predominant directions of storms at mid-latitudes.

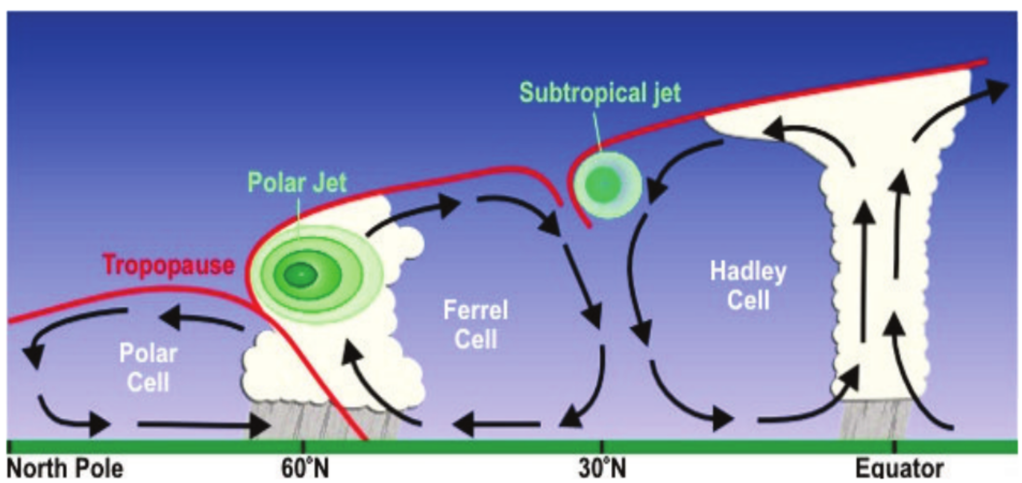


Figure 1.7: Cross-section of the positions of vertical cells and the polar and subtropical jet streams. (after [8])

1.2 The North Atlantic Oscillation

It was found that the variability of the position of the Subpolar Jet Stream (SPJ) and the frequency and strength of the storms along the SPJ over the North Atlantic are correlated to the anomalies of sea-level pressure centers in the subtropical area between the Bermuda-Azores High and the subpolar center of Icelandic Low. The variation of these pressure anomalies is known as the North Atlantic Oscillation.

The North Atlantic Oscillation (NAO) is a major mode of atmospheric variability in the Northern Hemisphere [6]. Its intensity is measured using the time-dependent anomaly of sea-level pressure, calculated as the difference between the observed pressure at any time and the long-term mean pressure. The sign and intensity of NAO are determined by the difference of sea-level pressure anomalies in the Bermuda-Azores High (subtropical high pressure) and the Icelandic low in the North Atlantic (subpolar low pressure)[7] and is called the NAO index. The variations in the NAO index reflect the redistribution of atmospheric mass between mid-latitudes and the Arctic in the Northern Hemisphere. The sign and magnitude of the NAO index also correlate with the westerlies' strength and direction, the jet stream's position and the path of storms across the North Atlantic.

When the NAO index is positive, both sub-polar low pressure and subtropical high pressure are above average. The winter storms are stronger than normal bringing cold air and high winds over the Labrador Sea. [5] When the NAO is in the negative phase, the difference in surface pressure between the Bermuda-Azores High and the Icelandic Low is below average. A negative NAO index is associated with weaker westerly winds, fewer storms, and warmer winters over the Labrador Sea.

1.3 The blocking patterns

Beyond the NAO, the path of the subpolar jet stream and the paths of storms over the Labrador Sea are often affected by another atmospheric pattern called the blocking pattern.

There are two major blocking patterns in the North Atlantic: the Greenland Ridge (GR) and the Scandinavian-Greenland pattern (SG).

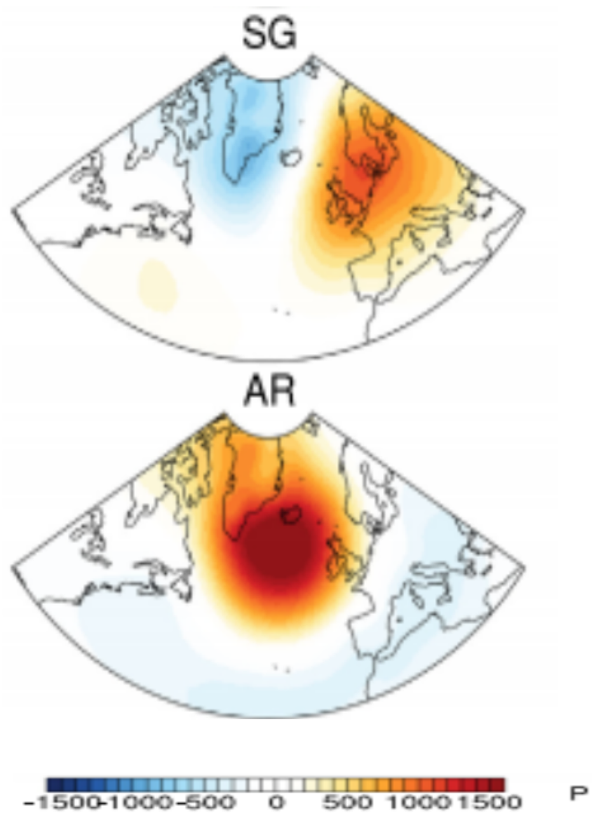


Figure 1.8: Schematic distribution of sea level pressure (P) in the blocking patterns (a) Scandinavian-Greenland Pattern (SG) and (b) Greenland Ridge (GR). (after [4])

Chapter 2

Data and Methodology

2.1 Data

In this study, I used the Fifth-generation European Center for Medium Range Weather Forecasts (ERA5) monthly reanalysis from 1962 to 2022. The ERA5 data set is a product of the European Center for Medium-Range Weather Forecast (ECMWF). It is a combination of simulations with coupled global atmosphere-ocean - sea ice numeric models and observations. The optimal combination of models and observations is achieved through data assimilation. The studied region is between latitudes 10° - 80° N and the longitude range between 70° W and 10° E.

2.2 The method of Empirical Orthogonal Functions

In this study, I used the Empirical Orthogonal Function (EOF) analysis. The EOF analysis is often used to develop climate indices in different areas of the planet. It determines the spatial patterns of atmospheric and oceanic variability coherent over the whole domain [3]. The EOFs are computed by using the anomalies of certain parameters that determine the deviation from the climatological mean which are written in a matrix form.

In the course of Mathematical Physics, we used orthogonal functions to obtain solutions to complex physical problems. We would normally write the solution $y(x,t)$ as a superposition of orthogonal functions $X_n(x)$

$$y(x,t) = \sum_{1}^{N} C_n(t) X_n(x)$$

The original aim of EOFs (Obukhov, 1947; Fukuoka, 1951; Lorenz, 1956) was to achieve an expansion of a space-time field y(x,t), where t and x denote respectively time and spatial position, as

$$y(x,t) = \sum_{1}^{N} C_n(t) P_n(x)$$

x is the spatial position; $C_n(t)$ are the coefficients of expansion called principal components; $P_n(x)$ are empirical orthogonal functions determined by using observations; $X_n(x)$ are the eigenfunctions of Sturm-Lioville problem for the operator of the physical problem L:

$$LX_n(x) = w(x)\lambda_n X_n(x)$$

Depending on the operator L we define the functions $X_n(x)$: - In problems in Cartesian coordinates these are normally the Fourier sin and cos functions. - In problems with cylindrical symmetry X_n are the Bessel's functions. - In problems with spherical symmetry X_n are the spherical harmonics.

The EOFs $P_n(x)$ define a new variable as a solution of the eigenvalue problem for the covariance matrix $R = A^T A$ [2]. In practice, the EOFs $P_n(x)$ aim to find a new set of variables that capture most of the observed variance from the data. As such, they are the eigenfunctions of the covariance function R :

$$RP_n(x) = \lambda_n^2 P_n(x)$$

Chapter 3

Modes of North Atlantic atmospheric variability

3.1 Dominant EOFs of the sea level pressure.

Figure 3.1 shows the percentage of the variance in the original sea level pressure (SLP) data obtained from the dominant 6 EOFs. The variance obtained from the n-th orthogonal function P_n is found by using the following equation:

$$\sigma_i = \frac{\lambda_i^2}{\sum_{k=1}^{n} \lambda_k^2}$$

Based on Figure 3.1, I conclude that the variance of the first three EOF modes account for the major proportion of the variance in the original data. Starting with the fourth mode, the percentage of individual patterns is small, so it is considered that the remaining results with small Percentages, except for the first three patterns, are viewed as noise.

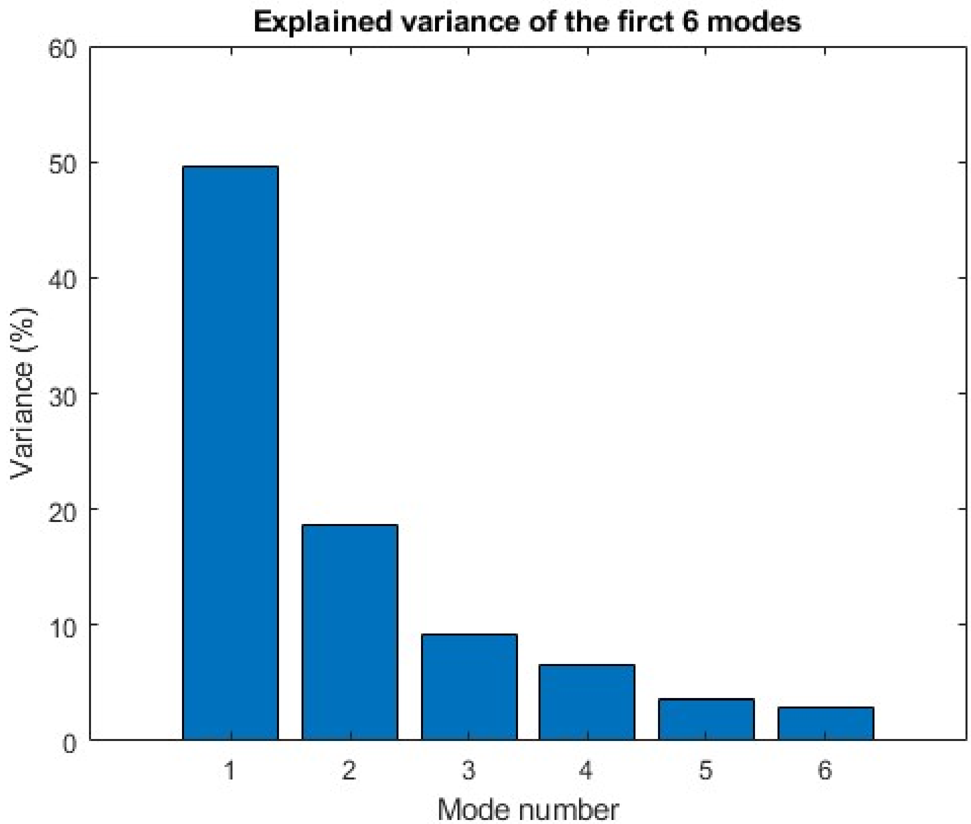
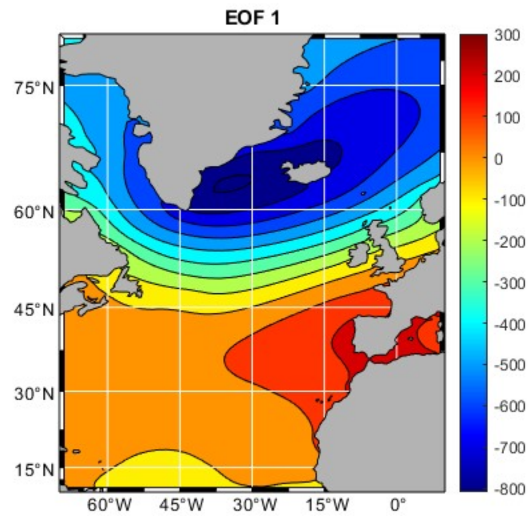


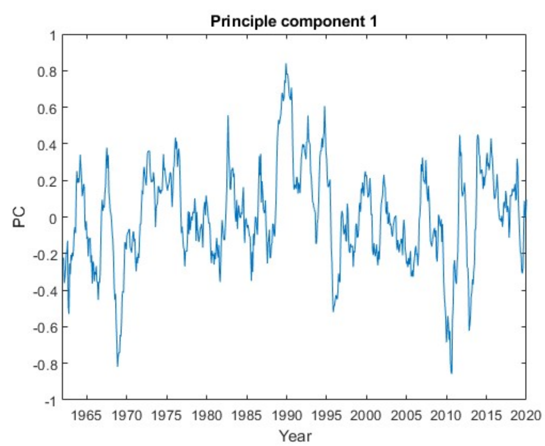
Figure 3.1: The variance explained by the first 6 EOF's of the pressure data.

3.2 The North Atlantic Oscillation

The first dominant mode of atmospheric variability (see Figure 3.1) is the North Atlantic Oscillation. The spatial structure of the EOF shown in Figure 3.2a has a minimum in the sub-polar area near Iceland and a subtropical high pressure located near the coast of Spain. The principal component of EOF1 is shown in Figure 3.2b. The largest positive phase index value was around 1990 and the lowest in 2011.



(a) Spatial structure of the first EOF - the NAO



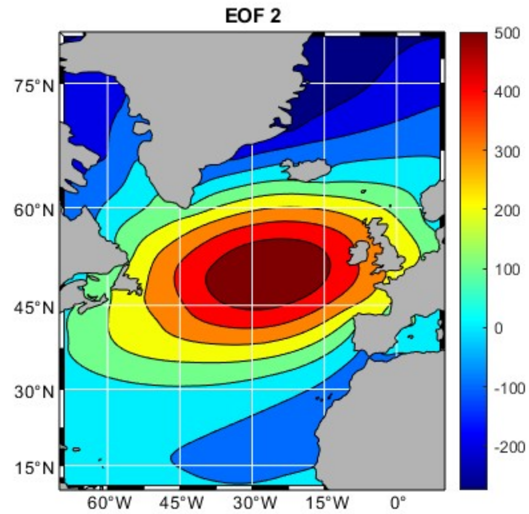
(b) Principle component of EOF1 from 1962 to 2022

Figure 3.2: The first EOF of the SLP - NAO

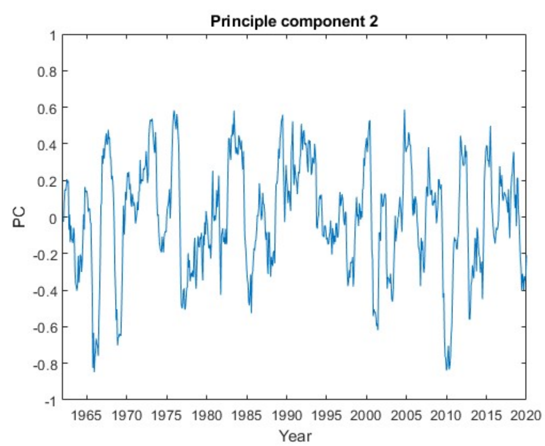
3.3 Blocking Pattern modes

The second and third EOFs of the sea level pressure have spatial structures of blocking patterns. The second EOF has a structure of the Greenland ridge (see Figure 3.3). The third EOF is the Greenland-Scandinavian pattern (see Figure 3.4). They show the distribution of SLP at different modes and the principal component results, respectively. And they are two different blocking patterns on the North Atlantic.

Beyond the NAO, other atmospheric patterns that influence the climate of the North Atlantic are the blockings. A large-scale pattern of an almost stationary atmospheric high-pressure field can prevent the motion or change the direction of storms. The Blocking patterns usually present for days to weeks, resulting in unchanged weather for long periods of time.

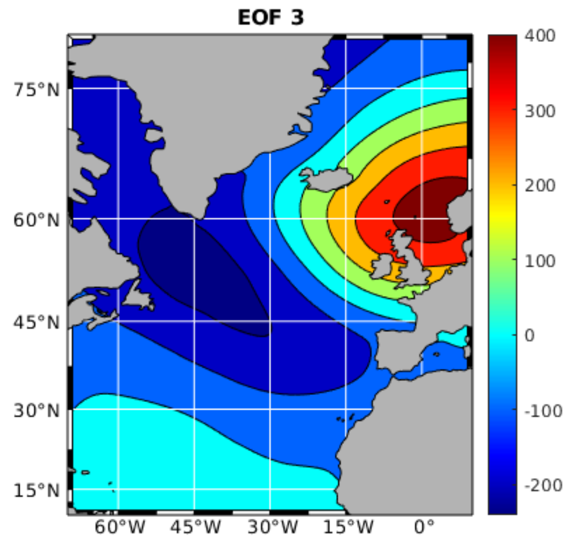


(a) Spatial structure of the second EOF

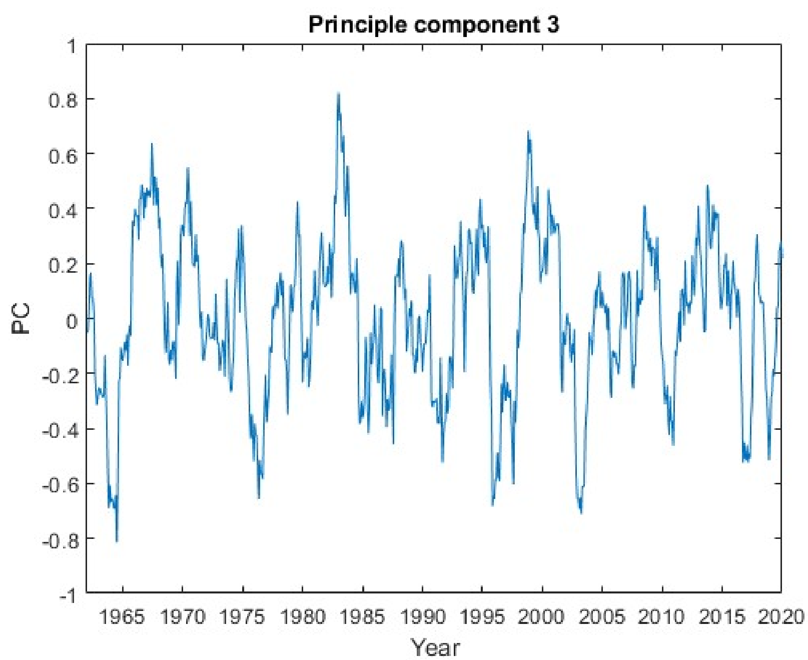


(b) Principal component of EOF2 from 1962 to 2022

Figure 3.3: The second EOF of the SLP - the Greenland Ridge



(a) Spatial structure of the Third mode



(b) Third mode change from 1962 to 2022

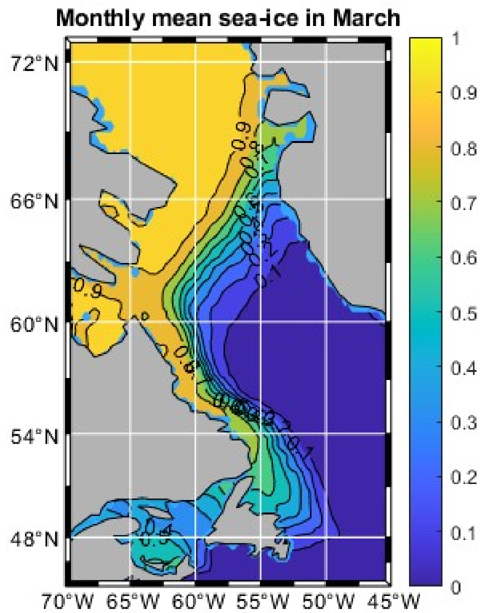
Figure 3.4: The third EOF of the SLP - the Greenland Scandinavian ridge.

Chapter 4

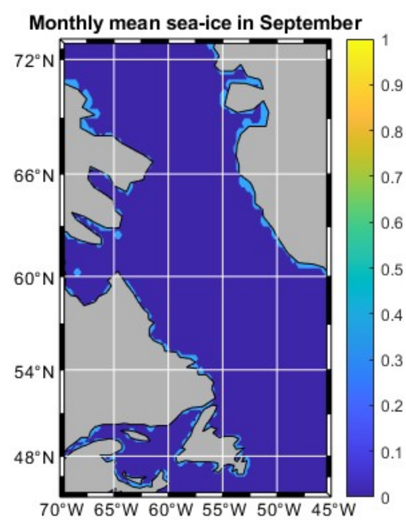
Sea Ice

I applied the same method of EOF analysis to monthly mean data for sea ice concentration. The sea ice has a large seasonal cycle. In winter, it covers most of the shallow northwestern Labrador Sea (Figure 4.1a). The deep part of the Labrador Sea remains ice-free all year. The surface heat exchange with the atmosphere there is very intense during the cold winter period causing cooling and intense mixing (deep convection) of the ocean water masses down to 2000 m depth. The sea ice practically melts in the whole Labrador Sea by the end of the summer seasons (Figure 4.1b).

I apply the method EOF analysis described in chapter 2 to the surface sea ice data to identify the main spatial pattern of sea ice variability. The data matrix A of data anomaly is computed by removing the monthly mean values of sea ice from the data. In this way, the seasonal variations are removed from the anomaly matrix A and it accounts only for the changes in sea ice from year to year. Figure 4.2 shows the variance explained by the first six EOFS.



(a) Monthly mean sea-ice in March from 1962-2022



(b) Monthly mean sea-ice in September from 1962-2022

Figure 4.1: Monthly mean sea ice changes are plotted against the data for representative months in winter and summer.

Based on the results derived from the EOF calculations(Figure 4.3), it is possible to see the percentage of different modes of sea ice. The sea ice concentration is an indication of the proportion of the area of sea ice per unit of sea surface area, so usually the largest changes in sea ice are in the total amount of sea ice, i.e., the overall area of sea ice, and changes in the boundaries of sea ice. Here we take the first two modes and treat the rest of the results as noise.

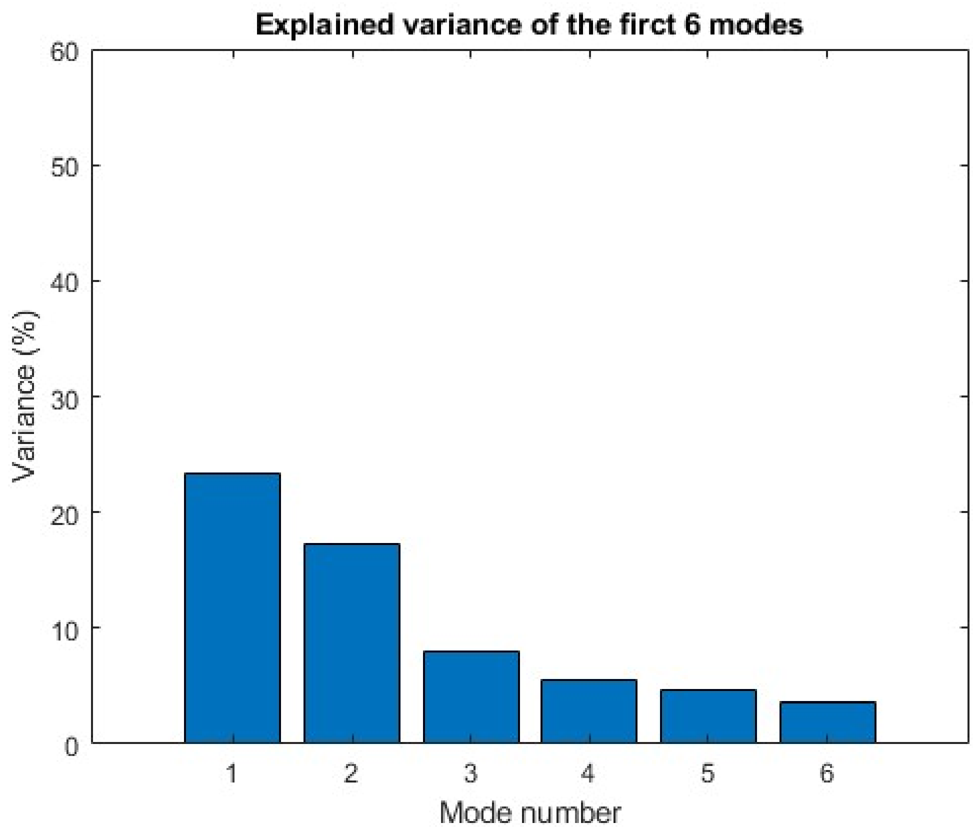
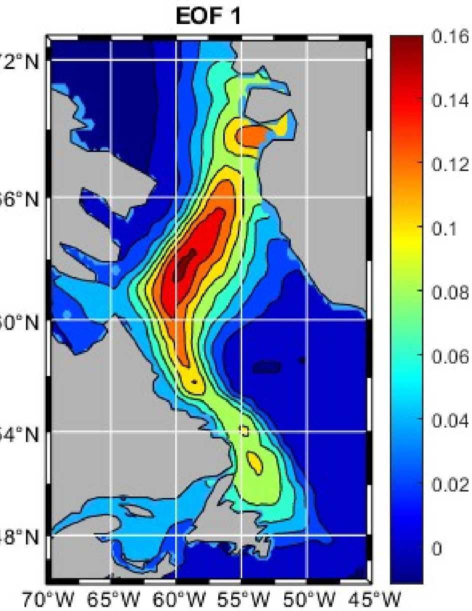
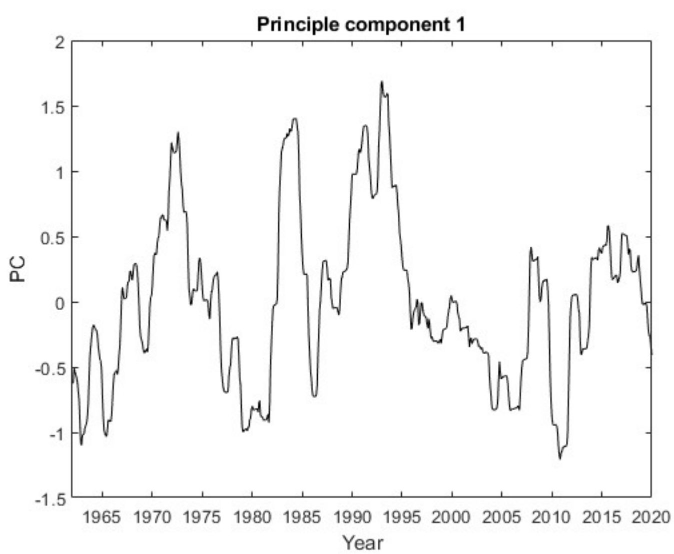


Figure 4.2: Variance by the EOFs from sea-ice concentration

The first EOF (see Figure 4.3) determines the interannual variations of the horizontal extension of the sea ice. These variations determining how the sea ice extension changes from year to year are large off the coast and over the continental slope. Their importance is due to the fact that they determine the variations of the areas of surface ice-free waters involved in intense air-sea exchange.



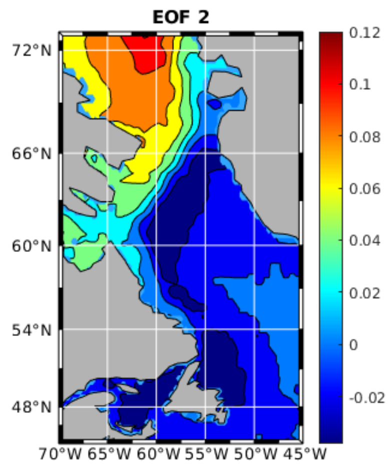
(a) First sea-ice mode



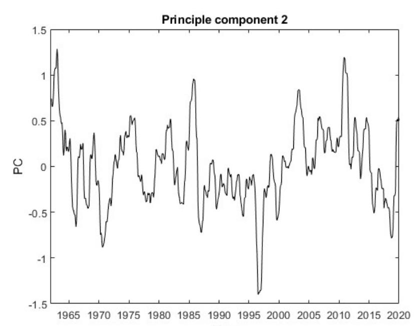
(b) First principal components of sea ice

Figure 4.3: First EOF mode of sea-ice

The second EOF determines the changes in the magnitude of seasonal variation of sea ice amount in the northern part of the Labrador Sea. Beyond the intensity of surface winter cooling, there are a number of other factors that determine the ice concentration in this area like the inflow of ice from the Fram Strait (north of the Labrador Sea) and from Hudson Bay.



(a) Second sea-ice mode



(b) Second principal components of sea ice

Figure 4.4: Second EOF mode of sea-ice

4.1 Link between the interannual variability of sea ice and the patterns of atmospheric circulation

In this section, I present results about the correlation between the time coefficients (principal components) of the EOFs of sea ice and sea level pressure. The principal component of the EOFs determines the magnitude of year-to-year variations amount due to a specific EOF. The principal components of the two sea ice EOFs and the three atmospheric EOFs are shown in Figures 4.5 and 4.6.

All of the modes of atmospheric variability show variations in time scales between two and three years. These are interannual variations that are due to the complex large-scale atmospheric dynamics and the interaction of the subpolar air over the ocean with subtropical and continental atmospheres.

The ocean's response to changes in the atmospheric forcing depends on the time scale of the changes. Having higher density and heat capacity the ocean has much higher inertia than the atmosphere. Therefore, the ocean response is selective and stronger to atmospheric variability which has a long decadal time scale and is not sensitive to two and three years variations.

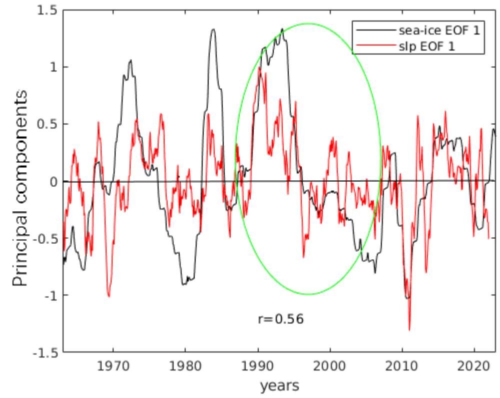
From all modes of atmospheric variability, the NAO shows variations on a time scale of a decade and longer. NAO is a mode of global atmospheric dynamics over the Northern Hemisphere with links to the general atmospheric circulation and dynamics of the vertical cells (Polar cell and Hadley cell) of meridional transport (see Chapter 1). As such it is linked to the large-scale planetary heat and air-mass redistribution. While the principle of the formation of NAO is in general well know, its dynamics, its link to the subpolar jet and its variability are far from being understood. Therefore, there is no good explanation of why the decadal transition in NAO in the mid-1990s occurred.

The Greenland Ridge (which is called also Greenland blocking) and Scandinavian-Greenland blocking modes are products of large-scale quasigeostrophic turbulence over the North Atlantic. As such they have origins in dynamical processes with smaller time scales than NAO.

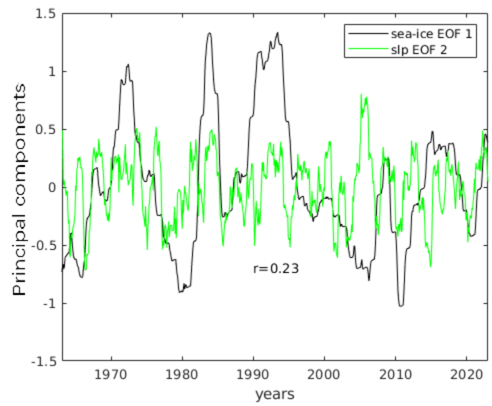
The sea-ice concentration is an ocean parameter that responds to long-term atmospheric variability with an inertia. The sea ice every year depends on the sea surface temperature (SST) at the beginning of the winter and the winter cooling. If sea ice concentration in the previous year was higher than normal, its melt during the summer seasons keeps SST low and the sea ice forms easily at the beginning of the winter. Therefore, the principal component of sea ice EOF1 shows high values of sea ice in years where the NAO (EOF1 of the sea level pressure) was persistently in a positive phase for several years or a decade (see Figure 4.5a). When NAO is persistently in the positive phase, the winters are colder than normal and the high sea concentration each year preconditions the formation of even more ice next year.

The predominant positive values of NAO index Figure 4.5a) in the late 1980s and early 1990s were related to cold winters. Every cold winter produced a large amount of sea ice and affected the SST in the Spring, Summer and Fall of this period of time. These cold SSTs preconditioned the high sea ice production in the following years. The NAO changed the sign to predominantly negative in the late 1990s. That was related to a decadal decay in the sea ice concentration (green ellipse in the Figure 4.5a))

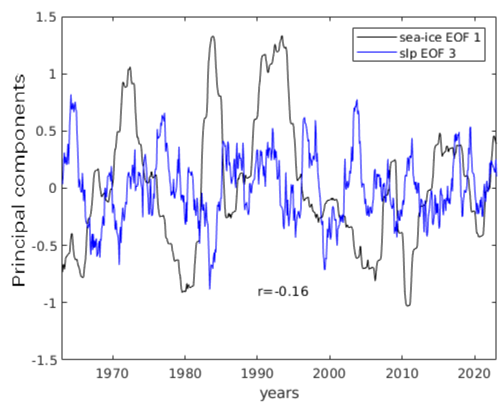
My results suggest that only the first EOF of SLP (NAO) has a significant correlation (r=0.56) which comes from the result of principal component analysis with the first sea EOF determining the variation in the extension of sea ice. The correlations of the second and third sea level pressure principal components with sea ice EOFs are less or about 0.2 and therefore are less significant.



(a) Atmospheric PC1 versus sea ice PC1

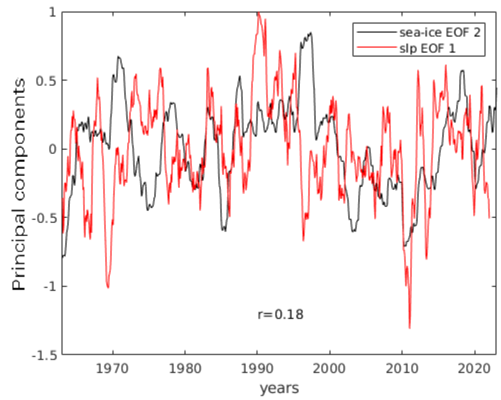


(b) Atmospheric PC2 versus sea ice PC1

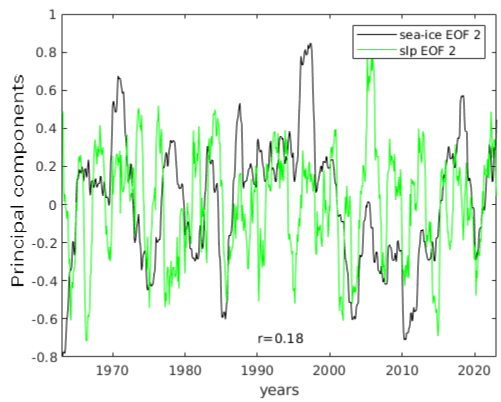


(c) Atmospheric PC3 versus sea ice PC1

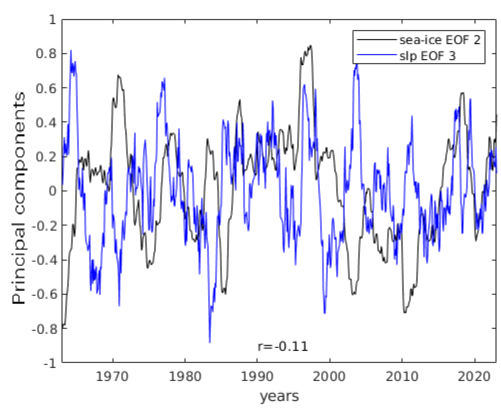
Figure 4.5: Principal components of atmospheric EOFs and first sea ice EOF



(a) Atmospheric PC1 versus sea ice PC2



(b) Atmospheric PC2 versus sea ice PC2



(c) Atmospheric PC3 versus sea ice PC2

Figure 4.6: Principal components of atmospheric EOFs and second sea ice EOF

Chapter 5

Conclusions

This thesis presents EOF analyses about reanalysis data for atmospheric forcing and sea ice concentration. The results suggest that only long-term changes in atmospheric circulation can have a significant impact on sea ice in the Labrador Sea. Among these, the most important is the North Atlantic Oscillation (NAO) which correlates with the variations of the sea ice amount on an interannual time scale. In years of positive NAO the total amount of sea ice in the Labrador Sea increases. When the NAO exhibits periods of positive phase most of the time the sea ice is less than average. In particular, the inter-decadal changes in the NAO index in the 1980s and 1990s were found to correlate well with the inter-decadal changes observed in sea ice.

The results of the relationship between atmospheric circulation and sea ice in the Labrador Sea in this study suggest that an important future question to answer is how the NAO and sea ice variability affect surface ocean characteristics like salinity and temperature. Sea ice in the Labrador Sea forms mostly in its northern part and is exported by ocean currents southward. In this way, the sea ice brings a lot of latent heat and freshwater from southward in the Labrador Sea. An important question is how these transports affect the Labrador Sea dynamics.

Bibliography

[1] How does sea ice affect global climate?, https://oceanservice.noaa.gov/facts/sea-ice-climate.html, November 01, 2011.

[2] H. Bjomsen and S. Venegas. A manual for eof and svd analyses of climate data. 97-1, 1997.

[3] A. Hannachi, I. Jolliffe, and D. Stephenson. Empirical orthogonal functions and relate techniques in atmospheric science: A review. *International Journal of Climatology*, 27(9):1119–1152, 2007.

[4] T. Hauser, E. Demirov, J. Zhu, and I. Yashayaev. North atlantic atmospheric and ocean inter-annual variability over the past fifty years – dominant patterns and decadal shifts. *Progress in Oceanography*, 132:197–219, 2014.

[5] J. Hurrell, C. Deser, and A. Phillips. North atlantic climate variability: The role of the north atlantic oscillation. *Journal of Marine Systems*, 78(1):28–41, 2019.

[6] J. W. Hurrell, Y. Kushnir, G. Ottersen, and M. Visbeck. An overview of the north atlantic oscillation. *The North Atlantic Oscillation: Climatic Significance and Environmental Impact*, 134:1–35, 2003.

[7] R. Lindsey and L. Dahlman. Climate variability: North atlantic oscillation, https://www.climate.gov/news-features/understanding-climate/climate-variability-north-atlantic-oscillation, 2009.

[8] A. Nugent, D. DeCou, S. Russell, C. Karamperidou, and J. S. Griswold. *Atmospheric Science: A Companion Text for ATMO 200 by the University of Hawai'i at Mānoa Atmospheric Sciences Department.*, chapter 11. Pressbooks. This book is licensed under a Creative Commons Attribution 4.0 International License.

[9] R. Thompson. *Atmospheric Processes and Systems.* Routledge, 1998.