The fate of the Atlantic Water in the North Icelandic Irminger Current

Master Thesis in Physical Oceanography

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The picture on the front page is a picture I took of an iceberg close to Greenland, during a cruise I attended to the Denmark Strait and The Iceland Sea, on-board the RV Knorr during August and September 2011. I participated in this cruise as a part of my Master education, working with CTD and ADCP measurements.

Abstract

The fate of the Atlantic Water within the North Icelandic Irminger Current has long been questioned. The North Icelandic Irminger Current flows along the Icelandic shelf area to the west and north of Iceland, bringing warm saline water to the area. The Atlantic Water has a great importance on the climate and biological conditions north of Iceland. The data record used is received from the Marine Research Institute on Iceland, consisting of 18 years of data, collected quarterly per year. Four repeated hydrographic sections have been used to cover the west and north Icelandic shelf, Látrabjarg, Kögur, Siglunes and Langanes. Salinity, temperature, cross sectional area, geostrophic velocities and the transport of the Atlantic Water have been examined. Mean annual sections of salinity and temperature were examined, showing an annual presence of Atlantic Water at two out of four sections. A clear seasonal and interannual variability within the inflowing Atlantic Water was observed. The Kolbeinsey Ridge, a ridge situated on the northern Icelandic shelf, was found to be crucial point, where the flow of AW was topographically steered offshore from the coast. The highest temperatures and salinities were observed during summer, and during 2003 the whole northern shelf was found to be covered by Atlantic Water. Atlantic Water was also observed in the central Iceland Sea at three occasions, which might have an importance on a newly discovered current believed to be a significant part of the Atlantic Meridional Overturning Circulation.

Acknowledgements

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Contents

Chapter 1

Introduction

It has been known for a long time that the North Icelandic Irminger Current (NIIC), a branch of the Irminger Current (IC), flows north-westward through the Denmark Strait (DS) along the Icelandic shelf [Jónsson & Valdimarsson, 2005] (see Figure 2.1. in Chapter 2). Atlantic Water (AW) is carried within the NIIC, following the Icelandic shelf north-eastward. However, the extent of the AW along the north Icelandic shelf is still questioned. The most recent estimate of the total volume inflow of AW in the NIIC is calculated to 0.88 Sv [Jónsson & Valdimarsson, 2011]. Earlier work has shown large interannual and seasonal variability within this inflow [Jónsson & Valdimarsson, 2005], with a maximum inflow recorded in September [Hansen & Østerhus, 2000]. The AW, when it enters the domain, has a temperature of approximately $6 - 8\,^{\circ}\mathrm{C}$, and a salinity above 35 [Swift & Aagaard, 1981]. However, while the water is transported along the Icelandic continental shelf, the water will be modified due to air-sea interaction and mixing with other water masses. This occurs especially during winter, when the atmospheric temperature gradients between the atmosphere and the ocean are most significant and there is a larger wind stress curl [Malmberg, 1984].

The question is: What will happen to the AW when it reaches the north Icelandic shelf area? Earlier work based on surface drifters shows that a large amount of the AW returns, leaving the north Icelandic shelf and flowing southward through the DS [Valdimarsson & Malmberg, 1999]. Other work based on hydrographic measurements suggest that the AW is confined to the shelf area, and leaves the Icelandic shelf in the east [Jónsson, 2007].

Here historical hydrographic Conductivity-Temperature-Depth (CTD) data has been used to get a better understanding of what happens to the AW along the Icelandic shelf.

This was done using data from four repeated CTD sections (see Figure 3.1. in Chapter 3 for locations). The overall goal is to quantify the circulation, structure, hydrographic properties and cross shelf location of the AW in the NIIC.

The inflow of AW to the north Icelandic shelf is of great importance. The warm AW will result in a milder climate compared to areas at the same latitude, as the NIIC is one of the branches carrying warm, saline water northwards. The warm AW also modifies the biologic productivity, seen from previous studies [Jónsson & Valdimarsson, 2005]. The Icelandic cod has its spawning grounds south of Iceland, cod larvae is then transported from the south within the AW to the nursery grounds along the northern coast of Iceland [Jónsson & Valdimarsson, 2005]. The AW thus has an effect on the fisheries north of Iceland [Valdimarsson & Malmberg, 1999]. The inflow of the AW in the NIIC has recently been proposed to be an important part of the Atlantic Meridional Overturning Circulation (AMOC) [Våge et al., 2011].

This master thesis will give a description of the regional oceanographic setting, followed by a description of the dataset and the method used to analyse the data. In the results part of the thesis, the annual means of salinity and temperature from the four sections will be showed first, then the focus will be on seasonal variability, followed by interannual variability and ending with the along-stream evolution of the AW along the shelf. Finally a discussion along with a summary and a conclusion will be presented. There will also be some suggestions for future work.

Chapter 2

Oceanographic setting

2.1 The Nordic Seas

The Norwegian, Greenland and Iceland seas are collectively referred to as the Nordic Seas (see Figure 2.1). They are separated by submarine ridges, where the ridges rise above sea level at Iceland and the Faroe Islands. The Greenland-Scotland Ridge (GSR) separates the Nordic Seas from the North Atlantic, while the Fram Strait, with a depth of 2600 meters, provides a deep connection between the North Atlantic and the Arctic Ocean (see Figure 2.1). The deepest gap along the GSR is the Faroe Bank Channel, with a sill depth of 850 meters, while the depth of the sill in the DS is approximately 640 meters. The GSR acts like a hindrance for water mass exchanges [Hansen & Østerhus, 2000], even though, water mass exchanges still occurs in the surface layers and through deep gaps in the ridge.

The DS is the area between Greenland and Iceland. On the Greenland side of the strait, the East Greenland Current (EGC) flows southward. At the deepest part of the strait the deep overflow water is spilling over the sill as overflow plumes. On the eastern side of the strait, on the Icelandic shelf, is the NIIC. This is a branch of the IC which carries AW northward onto the north Icelandic shelf area [Hansen et al., 2008].

There are three separate branches of Atlantic inflow into the Nordic Seas; the Shetland branch, the Faroe branch and the Iceland branch [Hansen et al., 2008]. The Iceland branch, the NIIC, is the weakest and most variable of the three inflow branches. The IC bifurcates south of the DS, where one branch turns westward and flows next to the EGC southward along the East Greenland shelf [Malmberg & Kristmannsson, 1992]. The other branch, the NIIC, continues north-eastwards on the north Icelandic shelf. The mean

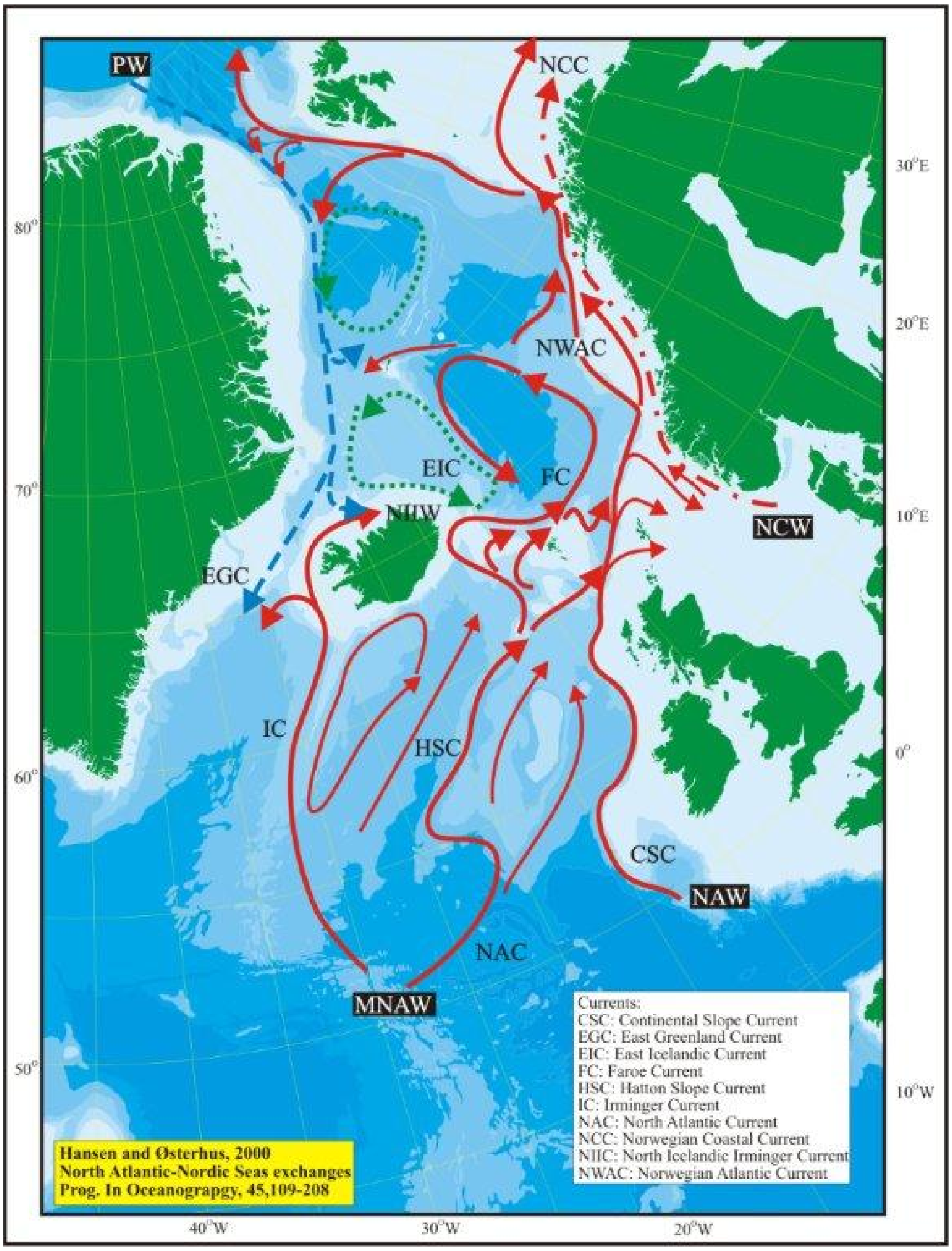

Figure 2.1: Map showing the circulation in the Nordic Seas. The red arrows show the Atlantic inflow, and the blue dashed arrows show the East Greenland Current, carrying cold Polar Water. The green dotted arrows just north of Iceland show the East Icelandic Current. The different currents in the figure are listed in the lower right corner. The figure is adapted from Hansen & Østerhus [2000].

transport of the AW was found to be 0.75 Sv [Jónsson & Valdimarsson, 2005], however the most recent estimate of the transport is 0.88 Sv [Jónsson & Valdimarsson, 2011].

AW is also transported into the Nordic Seas within the Faroe Current (FC) (see Figure 2.1). This water flows between Iceland and the Faroe Islands, across the entire ridge

[Hansen et al., 2008]. A sharp front is formed between the AW and the Arctic Water transported by the East Icelandic Current (EIC) (see Figure 2.1). After having crossed the Iceland-Faroe Ridge (IFR), with a depth of 300-450 meters [Hansen et al., 2008], the AW flows north-eastward along the northern slope of the ridge [Blindheim & Østerhus, 2005]. The mean volume transport of the FC is approximately 3.5 Sv [Hansen et al., 2003].

The last inflow of AW to the Nordic Seas is through the Fareo-Shetland Channel (FSC). This branch of AW is the warmest and most saline of the three branches. The volume transport of AW in this branch was estimated to be 3.2 Sv [Turrell et al., 2003]. The three inflow branches advects warm and saline water relative to the other water masses north of the GSR [Hansen et al., 2008].

In the Greenland and Iceland seas there are large variabilities in the sea ice cover, both seasonally and interannually. The Norwegian Sea and much of the Barents Sea are ice free all year. They differ from the Arctic Ocean, which is mainly ice covered all year [Mauritzen, 1996]. The Norwegian Atlantic Current (NAC) is the main reason for this difference between east and west. The current brings warm AW northward in the eastern part of the Norwegian Sea, while the current in the west, the EGC, brings Polar Water (PW) southward [Mauritzen, 1996].

The regional climate in northwestern Europe and in the Arctic are influenced by the inflow of warm, saline water within the NAC [Hansen et al., 2008]. These areas have a much milder climate than areas at similar latitudes partly because of this heat transport [Dickson, 2008]. The mild climate results from a strong air-sea interaction, where heat is released from the ocean to the atmosphere [Mauritzen, 1996]. The resulting cooled water is densified, and returns southward through gaps in the GSR. The AMOC is dependent on this dense water mass to maintain the deep circulation. The overturning circulation has an impact on the global climate, by bringing warm water northward and cold overflow water southward, but most importantly on the regional climate, through air-sea interaction.

2.2 The Iceland Sea

The main surface water masses present in the IS are listed in Table 2.1. The East Greenland Current carries cold, fresh PW from the Arctic southward along the coast of east-Greenland. From this current PW is allowed to escape through in two branches; the

Water mass	Salinity	Temperature(°C)
Atlantic Water in the NIIC	>34.9	>3
Polar Water in the East Greenland Current	<34.4	<0
Arctic/Polar Water in the East Icelandic Current	34.7-34.9	<0-2
North Icelandic Winter Water on the north Icelandic Shelf	34.8-34.9	2-3
Coastal Water on the Icelandic Shelf	<34	Variable

Table 2.1: Overview of the different surface water masses present in the Iceland Sea

Jan Mayen Current and the EIC.

The EIC transports cold and fresh PW from the EGC [Stefánnson, 1962; Swift & Aagaard, 1981]. This current enters the north Icelandic shelf area at the Siglunes section and flows through the Langanes section (see Figures 2.2 and 2.1), where it flows next to the AW. The amount of fresh water in the EGC is therefore reflected in the EIC. Like the AW, the fresh water in the EIC is affecting the local biology and climate along the north Icelandic shelf region [Jónsson, 2007]. The fresh water in the EIC is contributing to an increased stratification of the water column, and thus a decrease in the deep convection in the central IS [Jónsson, 2007]. The largest velocities in the EIC are found along the northern Icelandic continental slope, while the velocities decrease further offshore into the central IS [Malmberg et al., 2001]. The PW present in the EGC and in the EIC is less saline than 34.4. The water is cold, normally less than 0 °C. The surface layer is, however, heated up during summer, and temperatures can exceed 0 °C.

During winter, North Icelandic Winter Water (NIWW) is formed by mixing of AW and Arctic Water [Jónsson, 1992], one reason for this is air-sea interactions. This water mass has a salinity between 34.85 and 34.9, and the temperature varies between $2-3$ °C.

Flowing clockwards around Iceland is the Icelandic Coastal Current (ICC) [Valdimarsson & Malmberg, 1999]. The ICC is fresh, resulting from runoff from land. During summer this fresh current is heated by solar radiation and may reach temperatures higher than the ambient water masses.

Iceland is situated at the intersection of two large submarine ridges, the Mid-Atlantic Ridge (MAR) and the GSR. The Kolbeinsey Ridge (KR) is a part of the MAR to the north of Iceland (see Figure 2.2). The IS is confined to the area between Greenland, Jan Mayen and Iceland. The area is about 500 000 km^2 and the volume is 400 000 km^3 [Aagaard et al., 1985]. The north Icelandic shelf region is the southern boundary of the IS, and is defined by the area between Kögur in the west and Langanes in the east [Malmberg

Figure 2.2: Showing the upper circulation in the Iceland Sea. The thick red arrows shows the Atlantic inflow, and the North Icelandic Irminger Current can be seen to the west of Iceland. The brown arrows closest to the coast of Iceland represent the Icelandic Coastal Current. The dark blue arrows along the Greenland coast are the East Greenland Current, and the light blue arrows in the Iceland Sea are the East Icelandic Current. The Kolbeinsey Ridge can be seen in a north-south direction extending northward from Iceland. The figure is adapted from Jónsson [2007].

& Kristmannsson, 1992].

In addition to the complicated bathymetry, there are strong fronts in Icelandic waters at the intersections of cold and warm water masses. The proximity of cold and warm waters leads to strong temperature gradients, both horizontally and vertically. Warm AW is transported from the south, and cold PW and Arctic Water are transported from the north [Jónsson, 2007] (see Figure 2.2). These together cause large temperature gradients. Annual variability in the front locations have been observed, resulting in large changes in the local hydrographic conditions [Valdimarsson & Malmberg, 1999]. The climate and ecology are highly influenced by changes in these fronts [Malmberg & Kristmannsson, 1992].

The marine ecosystems on the western and northern Icelandic shelves are highly dependent on the Atlantic inflow onto the shelf area. The inflow of AW is nutrient-rich and provides good conditions for the capelin north of Iceland, which is a food source for the cod stock. The cod mainly has its spawning grounds southwest of Iceland, and the larvae drift clockwise around Iceland into the IS. It has been seen in recent years that spawning also occurs on the north Icelandic shelf, and is dependent on the amount of AW present on the shelf [Jónsson & Valdimarsson, 2005].

For water mass transformation to occur in the central IS, the surface water require an increase in density to make the water column unstable. This might occur if the surface experiences a sufficiently strong cooling. Other mechanism might be a supply of the more saline AW, compared to the existing water masses in the central IS. At similar temperatures, the saline water is more dense than the fresh surface water in the central IS, hence the surface water can experience a densification large enough to become unstable, and mixing will occur.

2.2.1 Early measurements in Icelandic waters

Early maps of the IC suggest that the shelf north of Iceland was dominated by Polar Water and with little influence of AW. Later it was shown that the AW continued eastward onto the North Icelandic shelf [Stefánnson, 1962]. During the second half of the 1900s, oceanographic surveys were carried out in the North Atlantic region [Blindheim & Østerhus, 2005]. The early Norwegian and Icelandic oceanographic surveys were mainly motivated by the fisheries. In later years more thorough oceanographic work has been carried out, in an attempt to gain knowledge of the physics of the oceanographic mechanisms in the Nordic Seas, and the effects on local and global climate.

2.2.2 Current state of knowledge

There are two opposing views of the fate of the AW transported by the NIIC on the north Icelandic shelf.

In a study performed by Valdimarsson & Malmberg [1999] surface drifters were deployed within the IC south of the DS in an attempt to gain knowledge about the circulation in the vicinity of Iceland. These recorded both seasonal and annual variability in the circulation within the area. During winter, the majority of the drifters were transported southwards, following the topography of the Reykjanes Ridge, a ridge in a north-south direction south of Iceland, with a few crossing this ridge, drifting towards the west and north-east of Iceland. During summer the amount of drifters that were recorded moving northwards through the DS increased. The drifter study found that the AW does not reach the north Icelandic shelf area as a continuous flow, but as variably sized eddies. Two separate surface currents were observed. The one closest to the coast was baroclinic, while the current along the slope was highly barotropic [Valdimarsson & Malmberg, 1999]. The KR, a ridge extending northward from Iceland, was found to be a site where the flow was strongly influenced by topographic steering. Few drifters passed across the ridge, with the majority following the ridge northwards and returning to the south with the EGC, resulting in a cyclonic pattern in the vicinity of the ridge [Valdimarsson & Malmberg, 1999].

By contrast, other studies suggest that the AW is confined to the north Icelandic shelf and leaves the shelf east of Iceland [Swift & Aagaard, 1981; Jónsson, 2007]. In this scenario little AW enters the IS.

It is important to find out whether the AW reaches the central IS, where water mass transformation occurs, and the AW could be a contributor to the production of overflow waters [Våge et al., 2011]. A current was discovered along the Icelandic slope at 500-600 meters depth [Jónsson & Valdimarsson, 2004], the same depth as where the overflow in the DS occurs. The current was found to be narrow and with a maximum speed exceeding 40 cm/s, and it was hypothesized that its origin was the IS. With some entrainment from other water masses this jet is large enough to be the main contributor to the overflow observed in the DS [Jónsson & Valdimarsson, 2004]. This current has been named the

North Icelandic Jet (NIJ).

Two hydrographic surveys were conducted in October 2008 and in August 2009 to measure this current. A numerical ocean model was run to simulate the system. The model suggested that the inflow of AW in the NIIC, via water mass transformation in the interior IS, was a source of DSOW [Våge et al., 2011]. From the model they found that the NIIC disintegrates north of Iceland. This is supported by hydrographic measurements in the area, where eddies of AW have been observed in the central IS. The NIJ is believed to contribute about half of the dense overflow through the DS [Våge et al., 2011] and is thus an important part of the AMOC. The fate of the AW in the NIIC and its pathways along the Icelandic coast are therefore very important to understand.

Chapter 3

Data and methods

3.1 Data

The data used in this thesis come from the Marine Research Institute (MRI) in Iceland. Since 1950 MRI has been monitoring the Icelandic waters with annual observations and surveys. Salinity and temperature have been measured at spring around the Icelandic continental shelf at fixed sections. These sections with standard stations have been named after features along the coast line. After the 1970s, data from these stations have been collected quarterly per year; February-March; May-June; August-September; and November-December. The results from these surveys are often used in connection with biological studies. The data from 1992 to 2009 were made available by MRI for this thesis. The long record of data and the high resolution provides a very good data set, making it possible to obtain a robust, long-term mean and investigating the annual variability, and also the seasonal variability, in the inflow of AW. This presents a great opportunity to learn more about the structure of the AW within the NIIC and its along-stream evolution. The sections used in this thesis are Látrabjarg, Kögur, Siglunes and Langanes North East hereafter referred to as Langanes. Locations are shown in Figure 3.1.

The instrument that was used to collect the data was a SBE911+ CTD (www.seabird.com). This system consists of two units, an underwater unit and a deck unit. There are three standard sensors; conductivity, temperature and pressure. The underwater unit is lowered with a speed of approximately 1 m/s and stopped 10 meters above the sea bed. One water sample is taken at the bottom for salinity calibration. The data was processed with a software program called Seasoft, and calibrated following instructions from

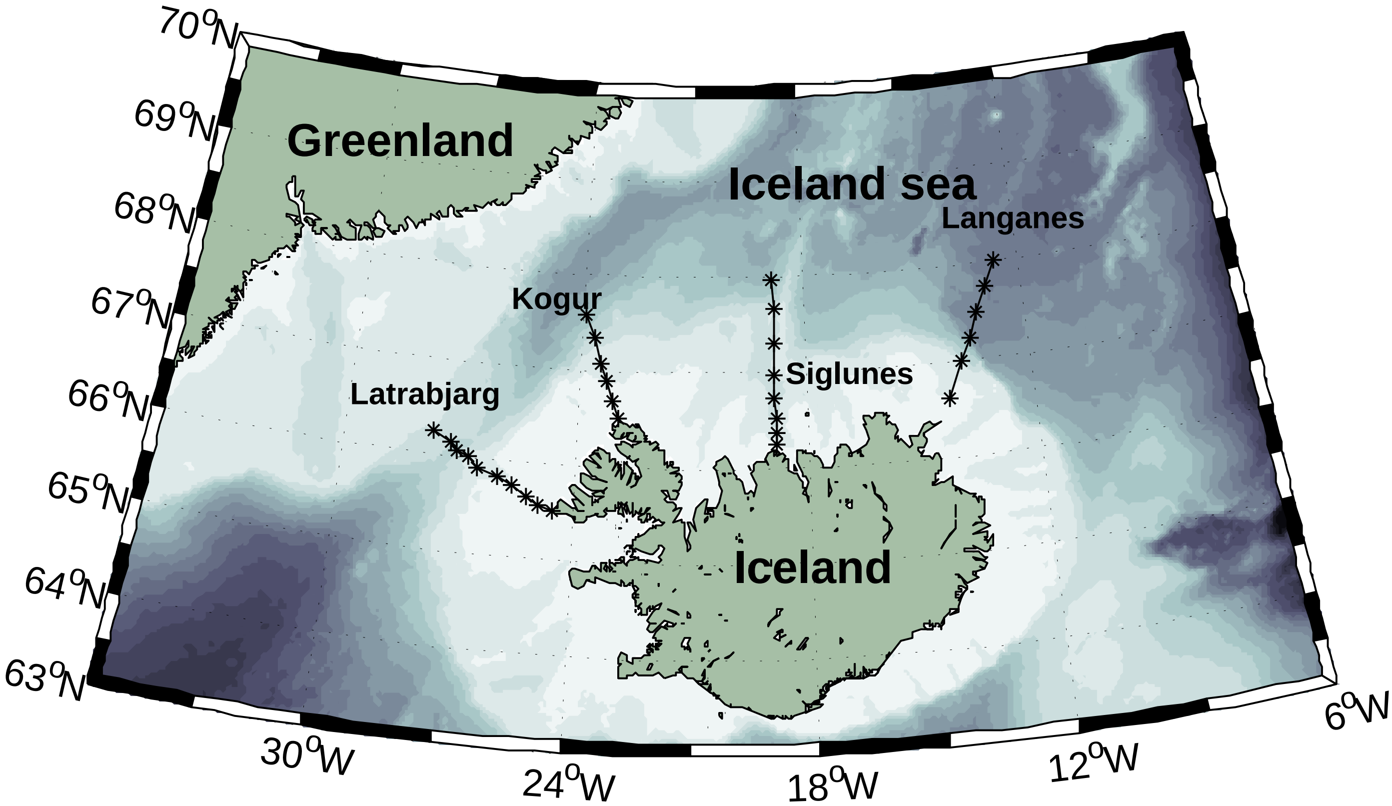

Figure 3.1: Map showing the area of investigation with the four section used in this thesis. Látrabjarg extend across the Denmark Strait, and Langanes extend into the interior Iceland Sea.

Year	Látrabjarg	Kögur	Siglunes	LanganesNE
2009	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
2008	F,M,A,N	F,M,A,N	F,M,-,N	F,M,A,N
2007	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
2006	F,M,–,N	F,M,–,N	F,M,A,N	F,M,A,N
2005	F,M,–,N	F,M,–,N	F,M,–,N	F,M,–,N
2004	F,M,–,N	F,M,–,N	F,M,A,N	F,M,A,N
2003	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
2002	F,M,A,N	–, M,A,N	F,M,A,N	F,M,A,N
2001	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
2000	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
1999	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
1998	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
1997	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
1996	F,M,A,N	F,M,A,N	F,M,A,N	F,M,A,N
1995	F,M,A,N	F,M,A,–	F,M,A,N	F,M,A,N
1994	F,M,–,N	F,M,–,N	F,M,–,N	F,M,–,N
1993	F,M,A,N	F,M,A,N	F,M,–,N	F,M,A,N
1992	F,M,A,–	F,M,A,–	F,M,A,–	F,M,A,–

Table 3.1: Overview of cruises for the different sections, F=February is referred to as winter, M=May and is referred to as spring, A=August is referred to as summer, and N=November is referred to as autumn.

Seabird. Temperature and conductivity sensors are calibrated twice per year. The deck unit is situated inside the ship. Raw data is sent through a cable connecting the two units and the data is shown in real time on a computer screen. Matlab was used to analyse the data set.

3.2 Methods

The 4 sections introduced above were used to describe the along-stream evolution of the AW in the NIIC. The geographic distribution of the four sections used can be seen in Figure 3.1. Látrabjarg has been used as the southern boundary situated west of Iceland, while the north-eastern boundary of the domain is Langanes. The total number of stations vary, but is in general approximately 30 split across the four sections. To preserve as much of the dimensional structure of the AW as possible and to maximize the resolution of the historical data from MRI, synoptic sections were interpolated onto a standard grid (this procedure is explained in detail below). This approach has been used in earlier studies showing good results [Fratantoni & Pickart, 2010; Pickart, 2004]. This is a rather time consuming method, however it results in a more realistic description of a complex system.

The sampling of data by MRI was not consistent. On occasion data was collected outside the location of the fixed sections and station numbers were not followed numerically. Therefore a lot of time was spent rearranging the data set to locate which stations belonged to each section. The distance between the stations had to be calculated separately for each year and season due to variation between cruises. These distances were later used in the gridding procedure.

The data was checked for density inversions. It is assumed that the density increases with depth. If the density decreased with depth, there was an inversion. When exceeding 0.01 kg/m^3, the density inversion was removed by linear interpolation.

To compare quantitatively the different sections, each section was interpolated onto a regular grid. The program used to grid the data is called ppzgrid and was obtained from Chris Linder at the Woods Hole Oceanographic Institute (WHOI). Details of the procedure are provided by Pickart & Smethie [1998]. The grid size was set to δx= 5km, and δy = 10m in the horizontal and vertical respectively. All the grids were stopped 5 km after the last station. The same size was used for every section to keep the data set consistent. The input data for the grids were salinity, temperature and pressure from the original data set. Additional input parameters such as smoothing were adjusted to make the gridded sections appear as realistic as possible. Relatively large distances between the stations added uncertainty to the gridded data set. Interpolation was done between the stations, and the larger the distance, the higher the uncertainty. The output data from the grid is in the form of a matrix. Three matrices resulting from the grid were formed; salinity, temperature and pressure. From these three matrices, potential density (sigma), potential temperature (theta) and depth were calculated. The collection of gridded sections are used as the working data set in this study.

Velocity fields were calculated from the hydrographic sections, using the geostrophic relation. he resulting geostrophic velocity was calculated from

$$\frac{\partial u}{\partial z} = \frac{g}{f\rho}\frac{\partial \rho}{\partial y}. \tag{3.1}$$

Equation 3.1 shows the thermal wind equation used to calculate the geostrophic velocity (u), where f is the Coriolis parameter, g is the gravitational acceleration and ρ is density.

Geostrophic velocities must be calculated relative to a reference level, which in this case has been set to be the bottom. When the isopycnal and the isobaric surfaces intersect, the velocity field is said to be baroclinic. This velocity field contains both baroclinic and barotropic components. In addition there is an unknown velocity contribution at the reference level, which is a barotropic component. The total velocities are thus unknown due to this unknown barotropic component.

The hydrographic limits of AW were set to a salinity > 34.9 and a temperature $> 3\,^{\circ}$C. This allowed AW at Langanes to be identified, where the AW will be modified from processes along the north Icelandic shelf. These criteria for the identification of AW have been used in a previous study [Swift & Aagaard, 1981]. AW is the only water mass in the IS satisfying these criteria.

Using these set limits of temperature and salinity for the AW, the annual mean of the hydrographic conditions of the sections could be found. From the cross sectional area and the geostrophic velocities, the total volume transport was determined by multiplying the cross sectional area with the velocity. This was done only for the area consisting of AW, so the transports shown are only the transport of AW. The cross sectional area is hereby referred to as the area of AW, and it will be given in km^2, and the transport is given in Sv (1Sv = 10^6 m^3 s $^{-1}$).

Chapter 4

Results

4.1 Annual mean hydrography

Annual means of salinity and temperature were computed for each of the four sections. These can be seen in Figure 4.1. The annual mean sections have been investigated to see how well they represent the hydrographic conditions in the four sections. For ease of comparison, all sections are plotted on the same scale, where x=0km corresponds to the Icelandic coast. The color scale is also the same for all sections.

4.1.1 Látrabjarg

Látrabjarg is shown as the first section in Figure 4.1. This is the section closest to the source of the AW (see Figure 3.1 for location). Looking at the salinity, a clear Atlantic core on the shelf area can be seen with a salinity exceeding 35. Close to the coast, a fresh water mass can be seen, which is the ICC. Fresh water in the outer part of the section, i.e the EGC, can also be seen. The temperature from the same section shows that warm water fills the entire shelf area. There is a sharp temperature gradient at the intersection between the warm AW and the cold PW transported by the EGC. The largest density gradients occur within the surface layer and at the outer-most part of the section. The water on the shelf has the lowest density. Little variation in the density within the AW is seen from Figure 4.1. Five out of eight stations are located within the AW, thus the AW fills almost the entire shelf area in this section. The AW extends from 30-120 km off the coast, resulting in a large area of AW.

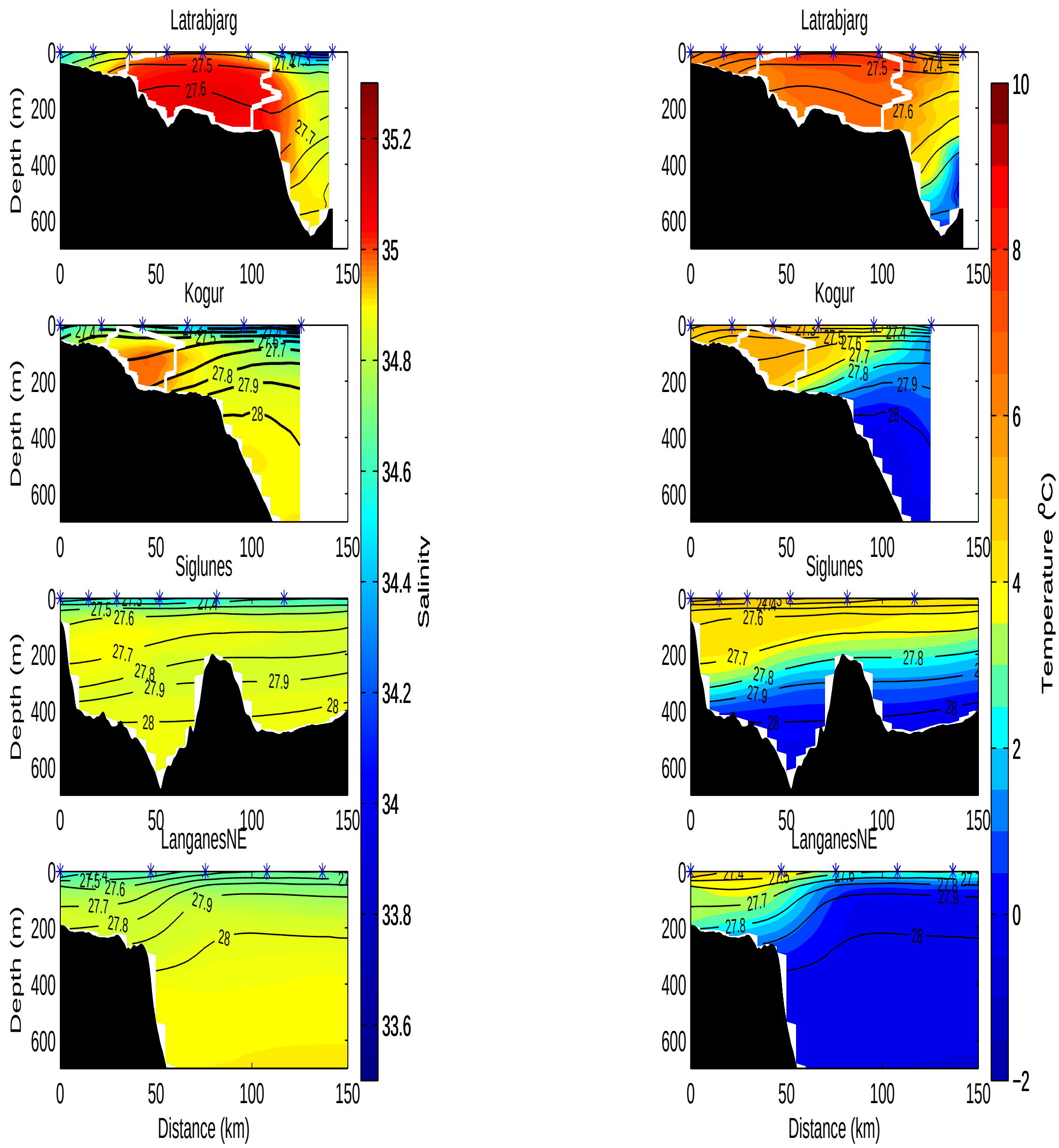

Figure 4.1: Annual mean of salinity and temperature from the four sections, starting with Látrabjarg at the top, followed by Kögur, Siglunes and Langanes. Salinity is shown to the left, and temperature to the right. The contour lines shown are the mean densities. The white line defines the AW, with a salinity above 34.9 and temperature larger than 3 °C. The y-axis shows the depth, and distance from coast is along the x-axis. The asterisks at the top of every section, show the location of the stations.

4.1.2 Kögur

The next section in Figure 4.1 is Kögur, which is situated northwest of Iceland (see Figure 3.1). This is the first section on the north Icelandic shelf. The core of AW is closely confined to the shelf area. The salinity of the core is relatively high, above 35. Away from the core, the salinity sharply decreases, in the horizontal direction. The annual mean temperature at Kögur is relatively high, especially in the surface layer. The warm water at the surface extends all the way out to the last station. The highest temperature is co-located with the maximum in salinity. The largest density gradient is found in the surface layer. From the surface to the bottom of the AW core, the density increases from 27.3 to 27.7. However, the largest density gradient was found in the upper few meters, while the density within the AW shows less variability. The extent of the AW core at Kögur is much smaller than in the previous section. The core is located at 30-60 km off the coast, compared to 120 km at Látrabjarg. There are only two stations within AW core, stations three and four. At all the other stations the water is too fresh to be AW.

4.1.3 Siglunes

Siglunes is the third section and is situated north of Iceland (see Figure 3.1). The Kolbeinsey Ridge (see Figure 2.2) can be seen in this section as the prominent feature approximately 80 km off the cost. A core of AW can not be identified at Siglunes in the annual mean. The most saline water is found on the inner side of this ridge. The salinity shows a minimum at the surface and immediately below the relatively warm, saline layer. The salinity increases towards the bottom below this intermediate fresh layer. From the surface and down to 200 meters, the temperature in the section is high ($4 - 5\,^{\circ}$C). The water below the surface layer is well mixed, seen from the uniform density. Compared to the two previous sections, the density displays a very different behaviour here. In the two previous sections there was a distinct difference between the water present on the shelf and the ambient water. The same situation is not seen in this section; here the same water mass can be seen far beyond the ridge and down to 300 meters. Below 200 meters, high salinities and low temperatures with a uniform density is observed.

4.1.4 Langanes

The last section along the north Icelandic shelf and in Figure 4.1 is Langanes (see Figure 3.1). A fresh surface layer throughout the section was observed. A clear core of AW can not be detected in the section from the annual mean. Below 300 meters a homogeneous water mass with temperatures near 1 °C and salinity near 34.9 is found. A sharp temperature gradient is seen at the shelf break at the intersection between the shelf water and cold water outside the continental slope. The temperature outside the shelf break is very low. The density from this section shows that the water mass on the shelf is lighter than the ambient water.

4.2 Seasonal variability at Kögur

Seasonal variability of AW within the NIIC has been documented [Stefánnson, 1962]. In this section the seasonal variability at Kögur will be investigated. Kögur has been chosen to illustrate the seasonal variability, due to AW being present during all four seasons and a good data coverage. This section is also situated at the intersection between cold PW and warm AW (see Figure 3.1 for location, and Figure 2.1 for description). All the seasons will be discussed, starting with winter, spring, summer and then finishing with autumn. The seasonal variability in salinity and temperature at Kögur can be seen in Figure 4.2.

4.2.1 Winter

The AW can typically be observed at two stations, three and four, during winter. The core of AW reaches all the way up to the surface at this season. Inshore and offshore of the core of AW, less saline water is observed. However, salinity increases with depth outside the continental slope. The lowest temperature within the AW is observed during winter, relative to the three other seasons. The water column is only warmed from the heat stored within the core of the AW during winter, due to little solar radiation, meaning that the shelf area is highly influenced by AW. The area of the AW during winter is seen in Figure 4.3, where the mean winter area is 8.9 km^2. The standard deviations from the mean winter value is seen in Figure 4.3. Looking at the salinity, the largest

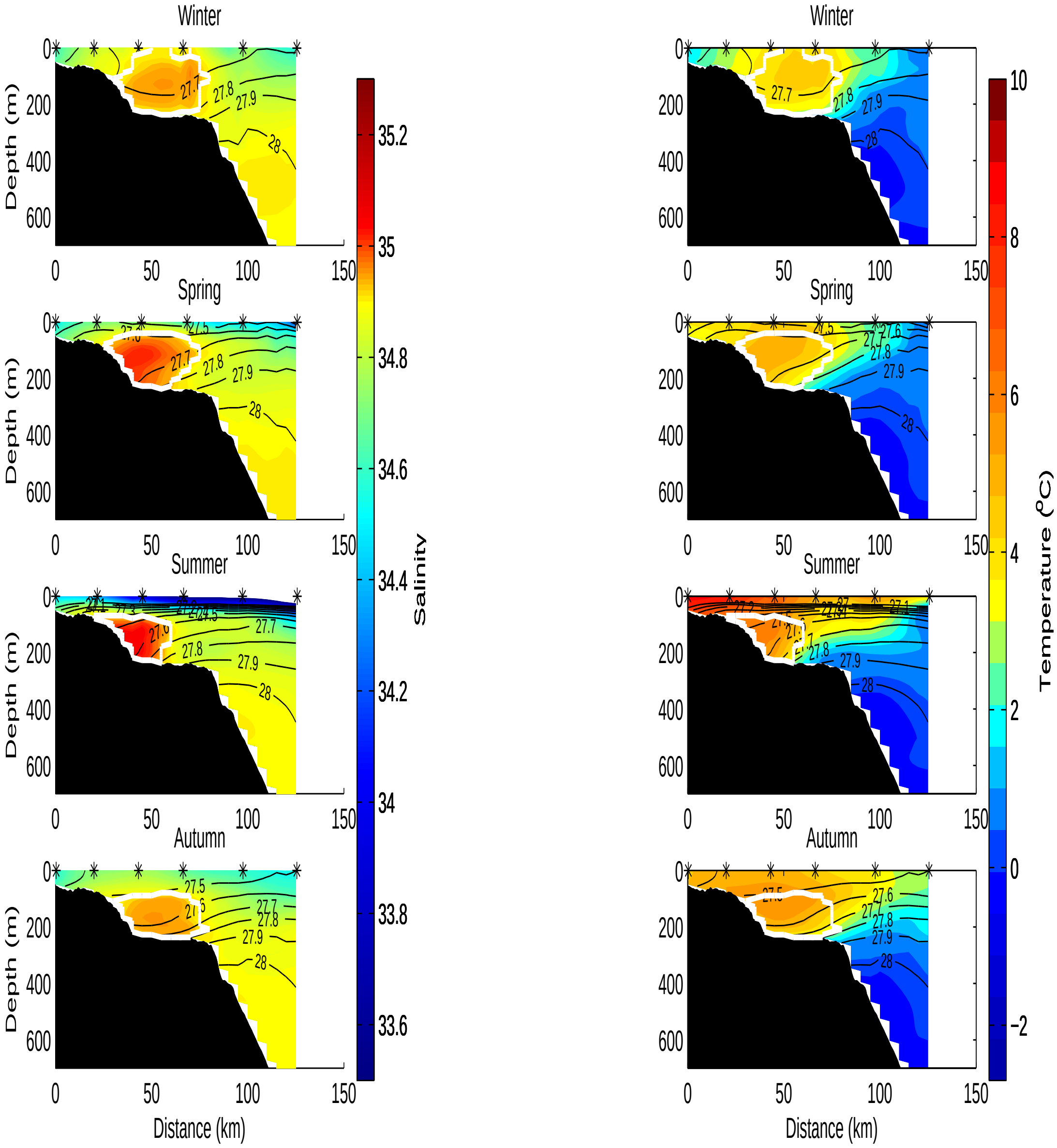

Figure 4.2: Seasonal variability in the mean salinity and temperature fields from Kögur. The salinity is to the left and temperature to the right. The depth (m) is along the y-axis, and distance (km) from coast along the x-axis. Winter is presented on top followed by spring, summer and autumn. The asterisks at the top of every section is the location of the stations within each section. The white lines define the AW with a salinity above 34.9 and temperature above 3 °C.

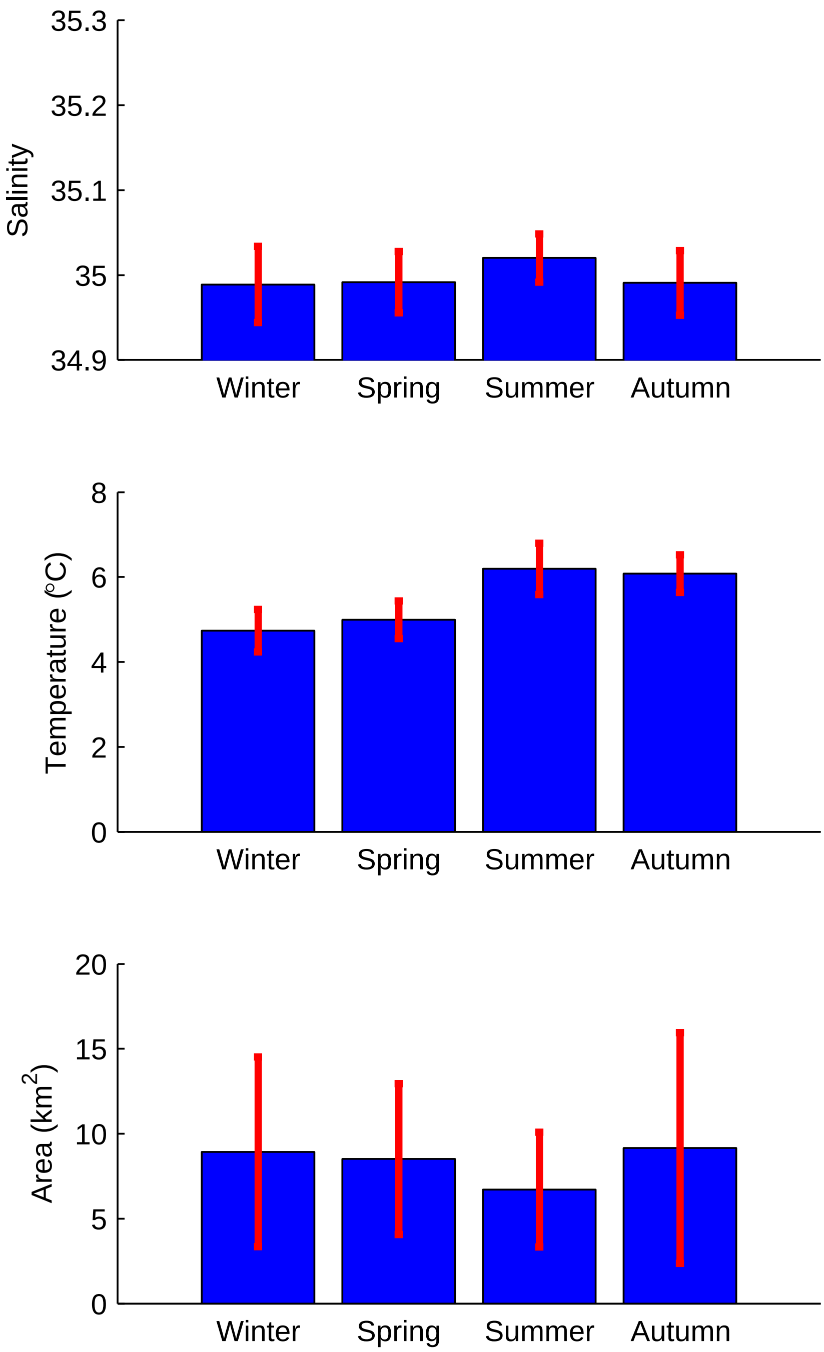

Figure 4.3: Mean of the AW salinity, temperature and area from Kögur during the different seasons. The red lines represent the standard deviations from the mean.

standard deviation from the mean value of 34.98 is observed. The same can not be said about temperature, where all the seasons show close to the same standard deviation of approximately 1 °C. Looking at the area of AW, a large standard deviation from the mean is observed. At approximately 10 km^2, the standard deviation is almost the same as the mean area during winter

4.2.2 Spring

During spring there is a small increase in salinity within the core of AW, from 34.98 at winter to 34.99. A stratified layer is formed at the surface. The core of AW can now be seen at three stations; two, three and four. The fresh water close to the coast can be seen during spring as well, however this is now connected with the fresh surface layer. The water mass close to the coast warms up during spring, and the temperature within the AW core shows an increase of 0.25 °C from the previous season. There is not much change in the cross sectional area of AW between winter and spring (see Figure 4.3), showing a decrease from winter of 0.4 km^2. During spring there is less deviation from the mean relative to winter. This was observed in all the variables presented. However, large variability is still observed in the area of AW.

4.2.3 Summer

The summer has the highest salinity within the AW and is the only season where the salinity exceeds 35 (see Figure 4.3). The core of AW is strongly confined to the shelf during summer. The stratified surface layer is now fully developed and a large difference relative to the layers below is observed. The summer season shows a large increase in temperature. The water at the coast is now above 6 °C. The surface layer has been warmed up throughout the section. The temperature difference between summer and winter is 1.5 °C, and there is a difference in salinity of 0.03. Summer interestingly shows the smallest area of AW of 6.7 km^2 (see Figure 4.3). The summer season also shows the smallest variability in salinity and area of AW (see standard deviation in Figure 4.3). However, temperature shows the largest variability relative to the other seasons.

4.2.4 Autumn

A core of AW can still be detected on the shelf during autumn, yet the salinity has decreased from the previous season. The fresh surface layer seen in spring and summer is still present in autumn however, there is a reduced density difference between the surface layer and the AW. The large area of warm water during summer continues into autumn. All of the stations, apart from the outermost one, show warm water at the surface. The difference in temperature between summer and autumn is relatively low, showing a temperature change of only 0.1 °C. The seasonal signal shows the largest variation in the area of AW (see Figure 4.3). There is an increase in area from summer to autumn, and autumn shows the largest area of the four seasons (see Figure 4.3). This could also be seen in Figure 4.2, where the white line shows the area of the AW. From Figure 4.3 it can be seen that the largest standard deviation in area of AW is found during autumn. However, the standard deviation in temperature is the smallest during autumn.

A shift in the location of the core at the different seasons was observed. During summer and spring the core is mostly confined to the shelf, while the core is shifted offshore during winter and autumn. The largest stratification can be seen during summer, when the fresh surface layer is present.

In all of the sections a sharp front in both salinity and temperature near the shelf break is observed. The density difference is largest between the AW and the water mass observed outside the shelf area during spring and summer. Winter and autumn show a more constant density in the upper layers. The water mass below the AW during winter and autumn area more homogeneous than during the two other seasons.

The core of the AW always shows a temperature maximum relative to the other water masses observed. The warmest water is seen during summer. A defined temperature gradient is observed outside the shelf during all the seasons. Winter, spring and autumn show very similar values of the salinity.

4.3 Interannual variability at Kögur

Large interannual variability in the inflow of AW to the north Icelandic shelf has previously been recorded [Jónsson & Valdimarsson, 2005; Malmberg & Kristmannsson, 1992]. In this section the interannual variability will be studied. Interannual variability could be seen at all sections and all seasons. Only autumn data from Kögur will be presented here. Autumn was found to be representative of the variability also observed during spring and summer, and was the season with the best coverage. Generally summer would have been the natural season to choose due to its high presence of AW however, autumn has the largest data coverage. Figure 4.4 shows salinity, temperature and area of the AW plotted at Kögur for all autumns contained in the record. There are two years in the time series that have no data. These are 1992 and 1995.

4.3.1 Salinity

The mean salinity found from the record at Kögur during autumn is 34.98 (see Figure 4.4). There is a significant deviation around this mean value. Some years during this period show large deviations from the mean value, with the most extreme years being 2003 and 1994. The salinity varied between 34.92 in 1994 and 35.04 in 2003. During this time series only 1996 was found not to contain any AW. Neither a decreasing nor an increasing trend in salinity can be seen in Figure 4.4, however no years were observed not containing AW after 1996.

4.3.2 Temperature

Interannual variability was also observed looking at temperature (see Figure 4.4). The temperature varies around a mean of 5.9 °C. The maximum temperature of 6.6 °C was seen in 2003, which is a deviation from the mean by 0.7 °C. A decrease in temperature is seen from 2007 until the end of the time series. The minimum temperature occurred in 2009, with a temperature of 5.2 °C. The total temperature range between the highest and lowest is 1.4 °C.

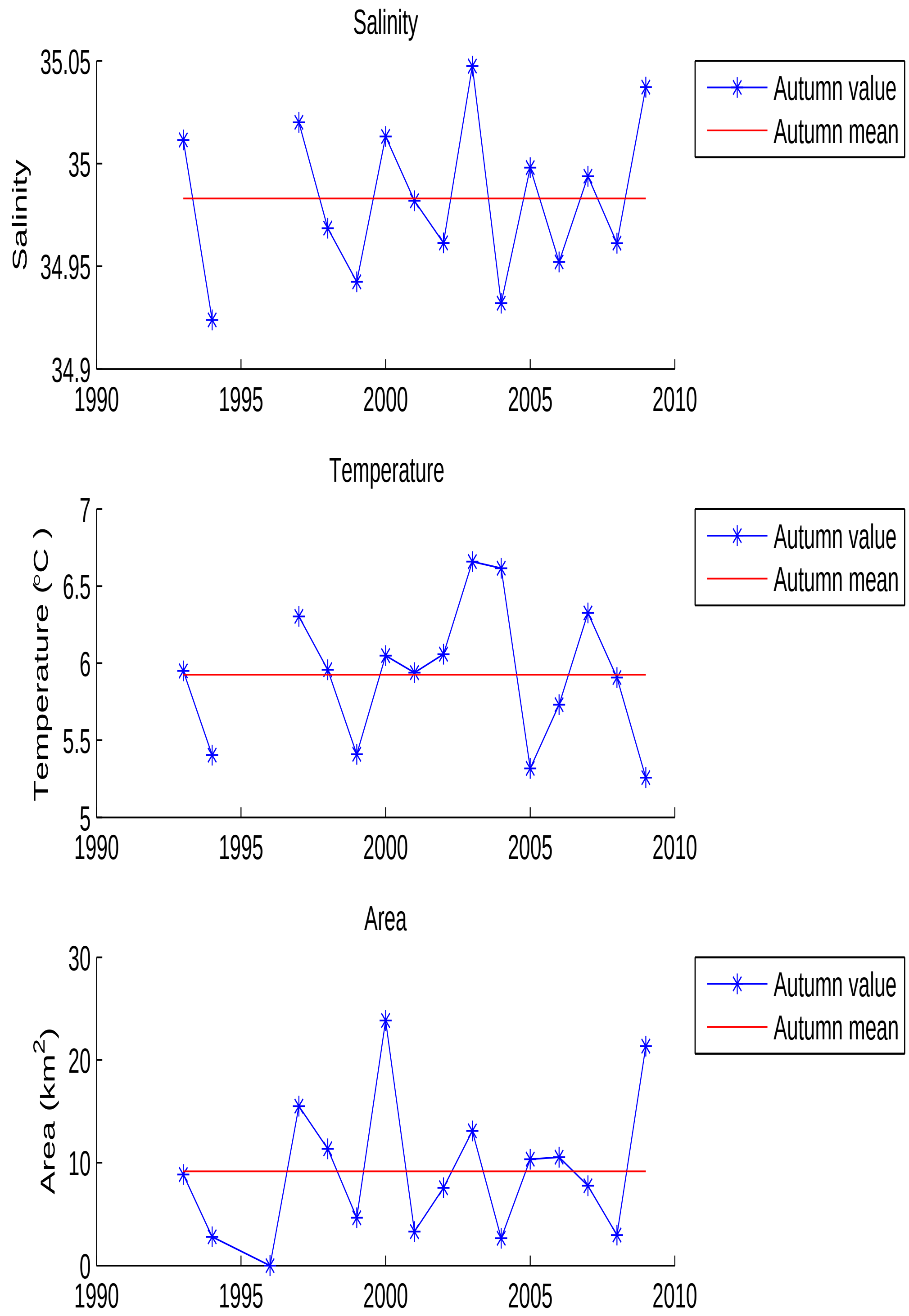

Figure 4.4: Time series from Kögur at Autumn. The top figure shows salinity, followed by temperature and area of the AW. The blue line with the asterisks show the monthly values from all the years in the time series, and the red line shows the mean through the entire time period. The first year with measurements from autumn is 1993, and the last year in the time series is 2009.

4.3.3 Area

The mean cross sectional area of AW of the period is close to 10 km^2 (see Figure 4.4). However, there is a clear deviation around this number. The maximum area is found in 2000 with the second largest area being seen in 2009. There was a large increase in area from 1999 to 2000 and from 2008 to 2009. During autumn 2003, the temperature and salinity rose while the area showed little change.

4.4 Along-stream evolution of the Atlantic Water in the North Icelandic Irminger Current

First the along-stream evolution of the geostrophic velocities are investigated in this section. Using the geostrophic velocities (Equation 3.1.), the transports have been calculated in order to determine how much AW, and thereby heat and salt, is transported into the area.

In the next part of this section the along-stream evolution of the different variables from the four sections are compared. One season has been chosen to investigate the development. None of the sections have data from autumn 1992, thus this year is not present in the time series.

The last part of this section is a comparison between two extreme years within the record. This has been done to investigate differences between two distinct hydrographic regimes on the shelf area. Within this time record, 2003 was shown to be a year where there was observed maximum temperatures. This year was called the "year without winter" by the Icelanders, due to high atmospheric temperatures. Hence this year was chosen to represent a case where there was a high amount of AW present on the shelf, to investigate if there can be seen any connection between the hydrographic and atmospheric conditions. As a contrast, 1996 was a year with very little AW present on the shelf and will be compared to 2003. Autumn 1996 showed no AW at the sections. In this case the summer season will be presented due to better data coverage.

4.4.1 Along-stream evolution of the geostrophic velocities

First in this section the geostrophic velocities will be presented, followed by a time series of the transport calculated from the geostrophic velocities. During the surveys only hydrographic measurements were recorded. Hence direct current observations are not available from the sections in order to calculate absolutely referenced geostrophic velocities. However, direct current measurements were performed at a section called Hornbanki, situated between Kögur and Siglunes on the north Icelandic shelf, and this will be used to estimate the missing transport.

Note that the inflow of AW to the Nordic Seas is always positive, even if the AW at Látrabjarg flows northward, while the AW flows north-eastward at the three remaining sections. Here the along shelf resolution has been used to examine the velocity structure and transport of the AW in the NIIC. Figure 4.5 shows the along stream evolution of the velocity field from Látrabjarg to Langanes. The figure shows the annual mean of the four sections.

Látrabjarg

A weak baroclinic structure can be seen at Látrabjarg (see Figure 4.5) from the largely horizontal isopycnals. In the outer-most part of the section, the EGC can be seen in the large negative values, indicating a southward flow.

Kögur

Kögur is the second section in Figure 4.5. The velocity field from this section shows a maximum at the shelf break, with velocities exceeding 5 cm/s. The highest velocities at Kögur is located at the outer boundary of the AW-core (see Figure 4.1). Close to the coast the velocity field shows smaller values. Outside the shelf break a flow in the opposite direction can be seen.

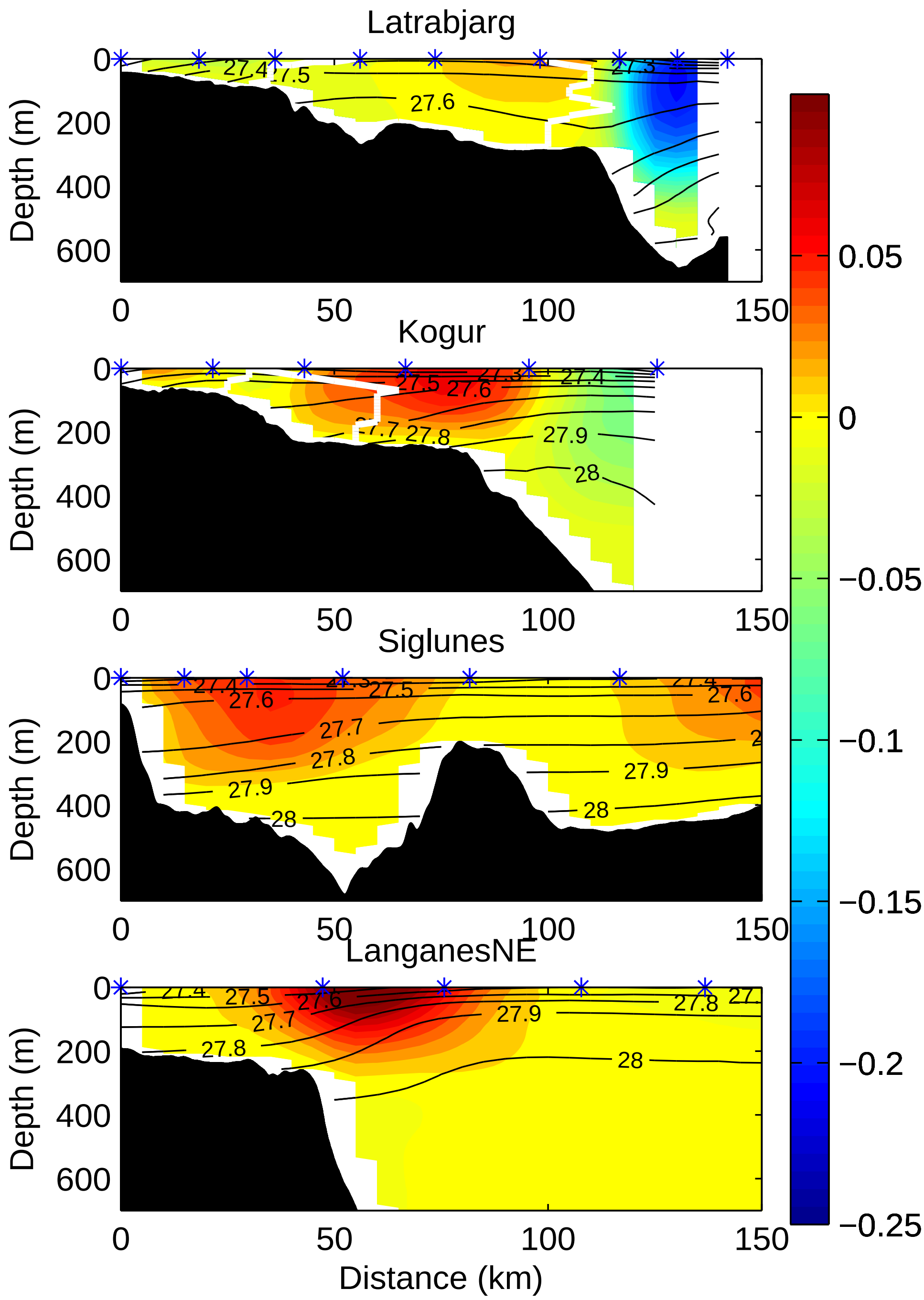

Figure 4.5: Annual mean of the geostrophic velocity fields from the four sections. From the top there is Látrabjarg, then Kögur, followed by Siglunes and Langanes. The colors indicate velocity in m/s, where the values higher than zero show a velocity out of the paper, and negative values show a flow into the paper. The density is shown with the contour lines. The asterisks at the top of the figures are the location of the stations in the sections. The depth is on the y-axis, and the distance from the coast can be seen on the x-axis. The white line outlines the AW with a salinity above 34.9 and temperature above 3 °C.

Siglunes

Looking at the velocity field from Siglunes, the third section from the top in Figure 4.5, two cores can be observed with velocities exceeding 4-5 cm/s. The first is situated on the inner side of the KR and show the largest velocity and the other on the outer side of the ridge with slightly lower velocities.

Langanes

At Langanes, the last section on the north Icelandic shelf, a shelf break current with velocities close to 10 cm/s is observed (see Figure 4.5). This current is located at the outer boundary of where the AW-core is normally seen.

4.4.2 Along-stream evolution of the hydrographic conditions along the north Icelandic shelf

In this section the evolution of the AW in the NIIC along the shelf will be presented. All of the sections are shown in Figure 4.6 using autumn data. Látrabjarg and Kögur have the highest salinity values. Siglunes and Langanes show lower salinity values than the previous two sections. A decrease in salinity was observed in the along-stream evolution. The variability in the salinity (see standard deviations in Figure 4.6) shows that Látrabjarg and Kögur show the largest deviations from the mean salinity. The standard deviation from the mean value is reduced at Siglunes, and Langanes shows very little variability within the autumn salinity.

The temperature evolution from the four sections is shown in Figure 4.6. The temperature evolution between the sections is less pronounced than the salinity, with all sections having temperatures between 5 °C and 7 °C. A decrease in temperature was observed from the first section to the last. Siglunes and Langanes, both situated north of Iceland, show almost the same autumn temperature. From the deviations (see standard deviation in Figure 4.6), it is clear that none of the sections show a significantly variability in autumn temperature, with all sections showing a standard deviation of less than 1 °C.

There is a clear difference in the cross sectional area of AW between the sections.

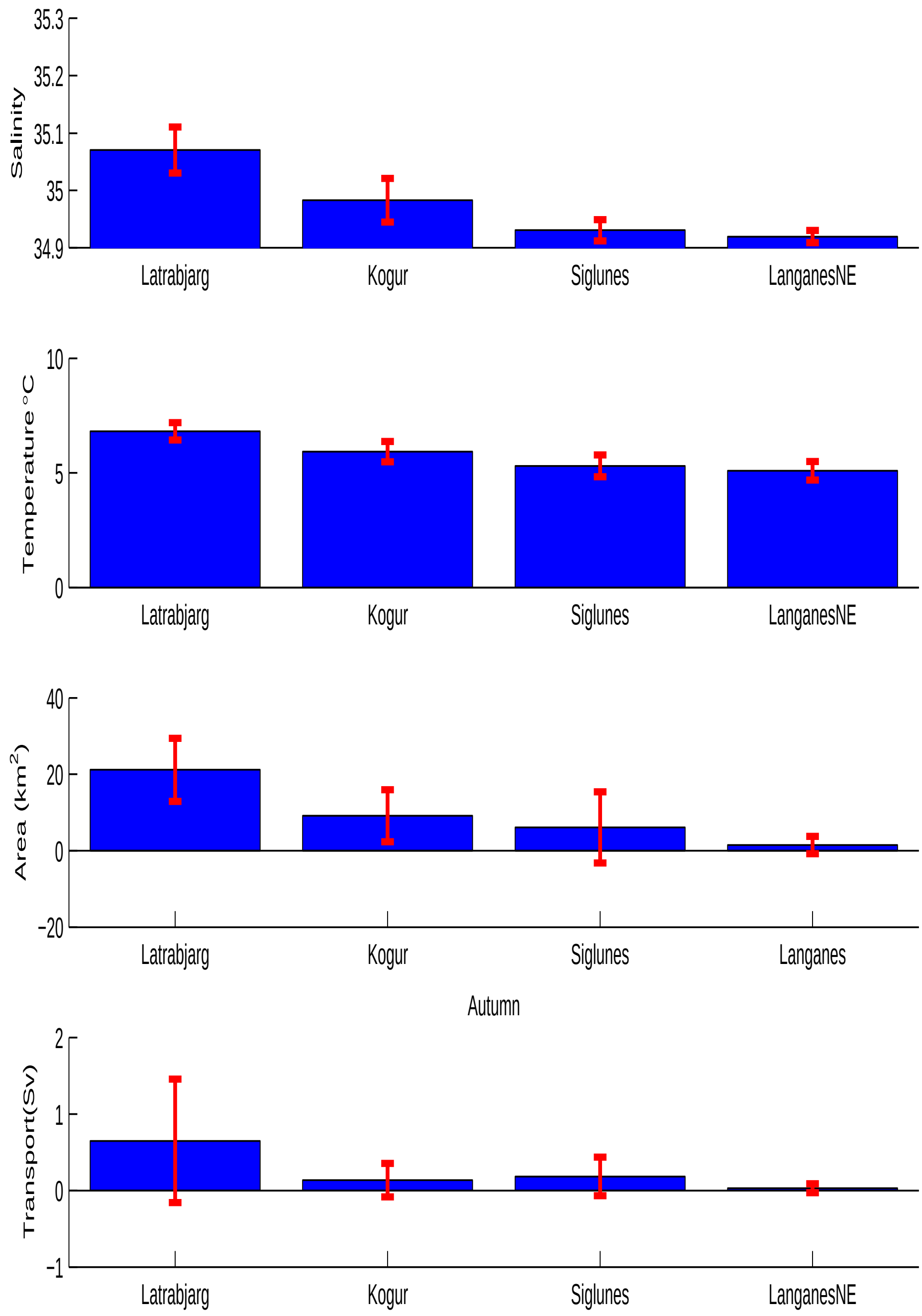

Figure 4.6: Showing the evolution between the sections. From the top is salinity, followed by temperature (°C), area (km^2) and transport (Sv) of the AW. All of the values are from autumn. From the left in each figure is Látrabjarg, then Kögur followed by Siglunes, and Langanes. The red lines represent the standard deviations from the mean.

Látrabjarg shows a clear maximum, which decreases towards the last section. The area is reduced to half of its magnitude from Látrabjarg to Kögur. However, it is clear from Figure 4.6 that there is a large variability within the area of AW at the sections. Siglunes is showing the largest standard deviation from the mean area of AW. The standard deviation from the mean is also very clear at Látrabjarg and Kögur, with Langanes showing the smallest variability of area consisting of AW.

The transport from the four sections can be seen in Figure 4.6. The transport is largest at Látrabjarg showing a reduction at Kögur. A slight increase can be seen at Siglunes, with the smallest transport being at Langanes. Looking at the standard deviations in Figure 4.6, it is clear that the largest standard deviation in the transport occurs at Látrabjarg, with a range between below zero and above 1 Sv. A reduction in variability is observed at Kögur, followed by an increased standard deviation from the mean transport at Siglunes. The transport is small at Langanes, and it is clear from the figure that the standard deviation from the mean transport is also small.

Absolute measurements of AW transport have been made at Hornbanki in the time period 1994-2010. Hornbanki is a repeated section that the MRI records, situated between Kögur and Siglunes on the north Icelandic shelf. The most recent transport estimate is 0.88 Sv [Jónsson & Valdimarsson, 2011]. This estimate is the mean transport from the entire time record. There has also been made a monthly mean, which can be used here to estimate the unknown transport at the reference level. The mean autumn transport at Hornbanki was estimated to 0.8Sv [Jónsson & Valdimarsson, 2011].

Section	Látrabjarg	Kögur	Siglunes
Mean Transport (Sv)	0.64	0.13	0.18
Difference relative to 0.8 Sv	0.16	0.67	0.62

Table 4.1: Mean unreferenced autumn transport from the four sections compared to the absolute transport found at Hornbanki of 0.8 Sv [Jónsson & Valdimarsson, 2011].

Table 4.1 shows the mean autumn transports from Figure 4.6 (assuming the bottom being the level of no motion), including the anomalies relative to the observed total transport at Hornbanki. These anomalies are thus estimates of the unknown barotropic component; at Látrabjarg it is 0.16 Sv, 0.67 Sv at Kögur, and 0.62 Sv at Siglunes.

There is a decreasing trend in all the variables, from the first section to the last. Al-though only autumn is shown, the other seasons show the same decrease. In summer, however, there is a larger area at Siglunes relative to Kögur.

4.4.3 Comparison between two extreme years

As mentioned earlier, the year 2003 is referred to by the Icelanders as the "year without winter" [Valdimarsson 2011, pers comm]. The air temperature in 2003 was remarkably high, and this year will now be studied to see if there was any connection between the warm atmospheric temperature and the hydrographic conditions. 2003 will be compared to 1996, which is known as an extremely cold year. Summer has been chosen to represent these two years, due to better data coverage.

Salinity

Salinity from the two years is shown in Figure 4.7. Looking at Látrabjarg first, a clear difference between the two years both in salinity and the extent of the core of AW was observed (see Figure 4.7). The difference was even more pronounced looking at Kögur. In 2003 the core of AW extended far offshore in this section relative to 1996, when only a small core of AW was observed at one station on the shelf break. Kögur also had a larger area with AW in 2003 than what is normal for the season (see Figure 4.2). Siglunes had a deep-reaching layer of AW in 2003, extending throughout the section and even surfacing on the outer-side of the ridge. The salinity at the section was high, exceeding 35. During 1996, two cores of AW were also observed, but the two cores were smaller and less deep. The difference between the two years could also clearly be seen at Langanes (see Figure 4.7). A small core of AW was observed on the shelf break in 1996. In 2003 the core of AW could be seen extending out into the central IS. The core extended almost 100 km off the coast, and showed a high salinity.

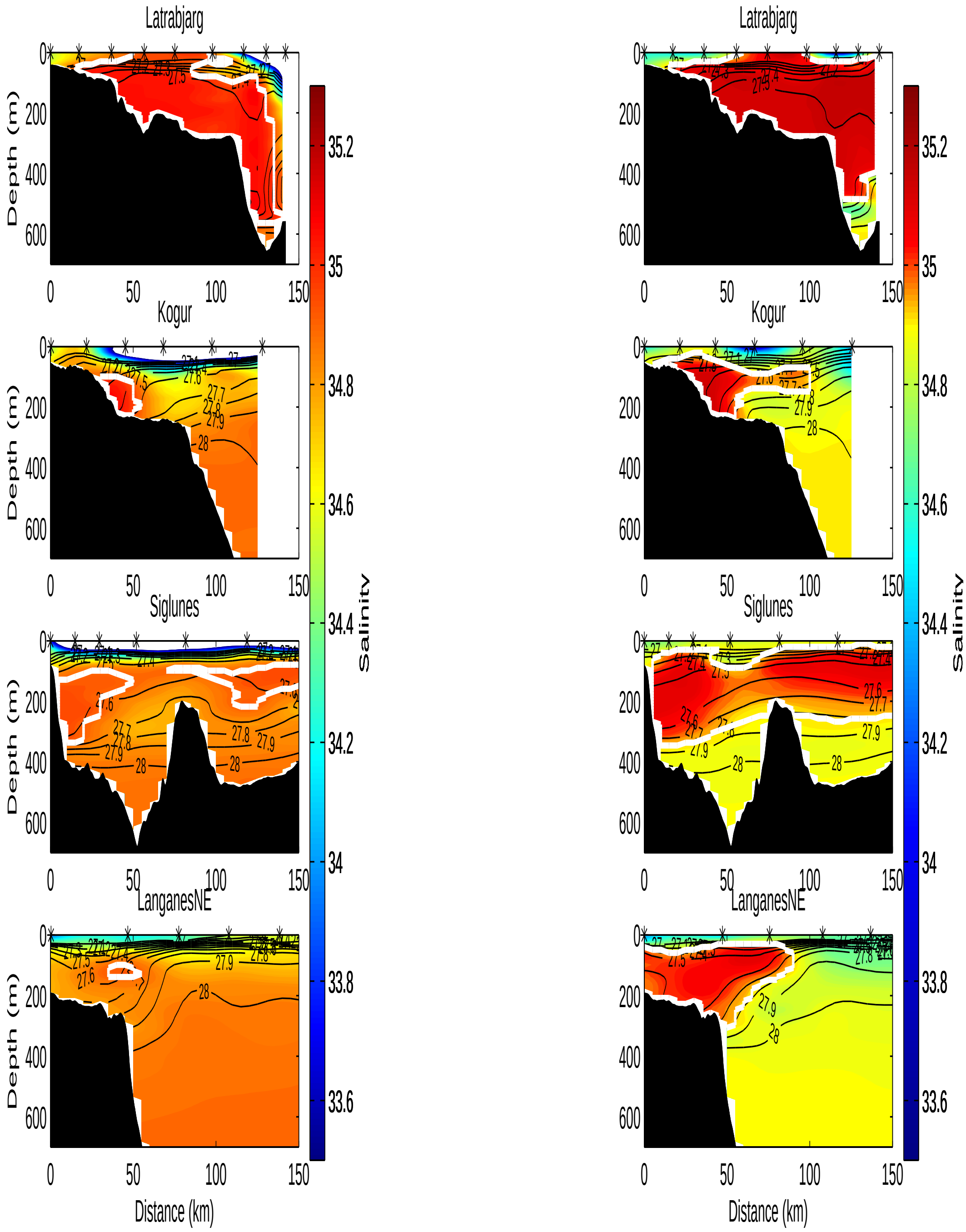

Figure 4.7: Salinity from the four sections during summer 1996 and 2003 can be seen in this figure with 1996 to the left and 2003 to the right. Density is represented by the contour lines. Látrabjarg is shown in the top, followed by Kögur, Siglunes and Langanes. The depth is on the y-axis, distance from the coast is seen on the x-axis. The asterisks on the top of every sections is the location of the stations in the section.

Temperature

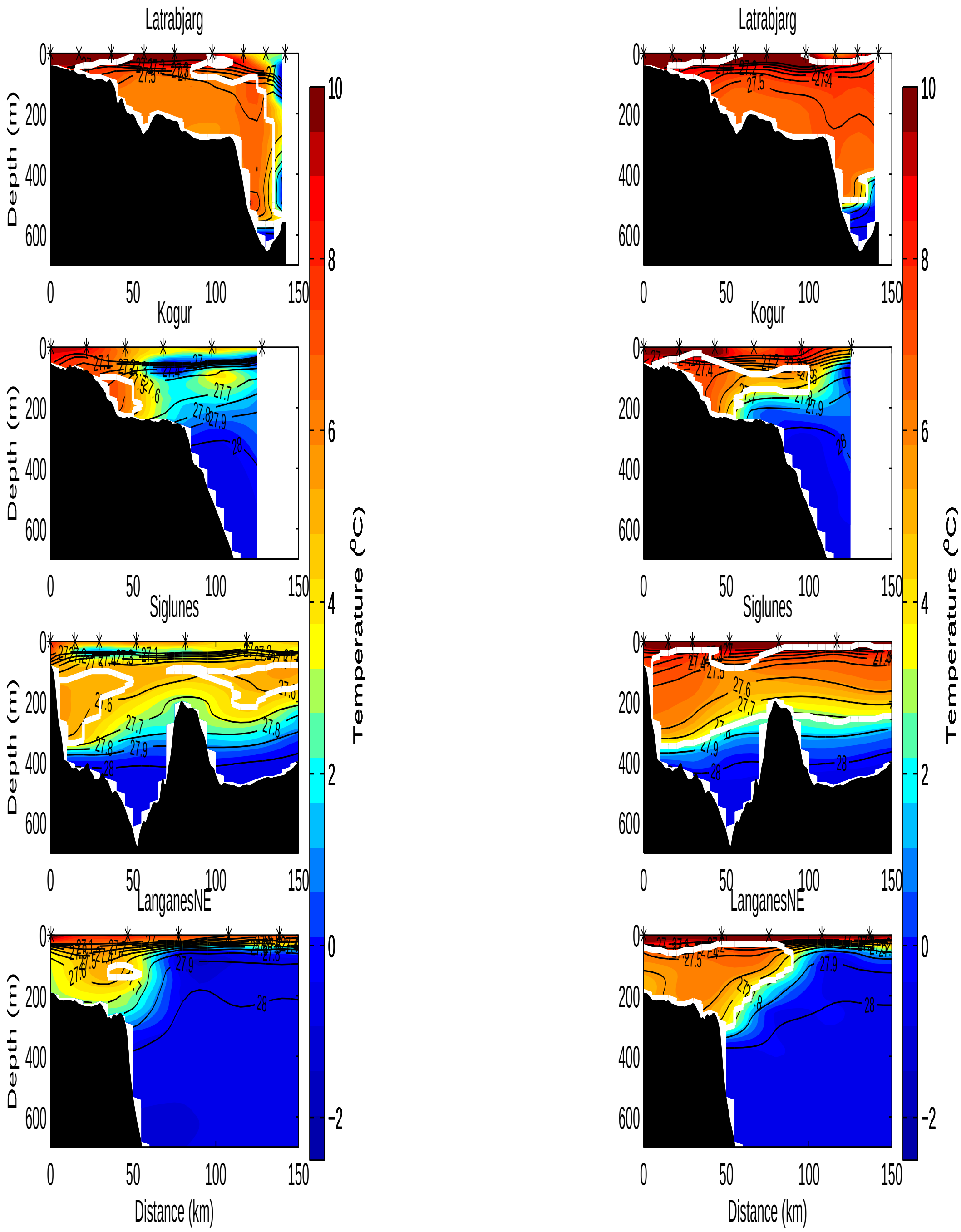

Figure 4.8: Temperature from the four sections during summer 1996 and 2003 with 1996 to the left and 2003 to the right. Density from the four sections are represented by the contours. Látrabjarg is shown at the top, followed by Kögur, Siglunes and Langanes. The depth is on the y-axis, distance from the coast is seen on the x-axis. The asterisks on the top of every sections is the location of the stations in the sections.

Temperature from the two years is shown in Figure 4.8. At Látrabjarg high temperatures were observed both years, but there was a larger area consisting of high temperatures in 2003, extending throughout the section. At Kögur there were also high temperatures observed in 2003, with warm AW reaching almost to the surface and far offshore in the section. 1996 showed a much colder situation, with low temperatures in the surface layers and also at the shelf break. At Siglunes the difference in temperature was significant, showing much higher temperatures in 2003, with temperatures exceeding 7 °C, relative to a temperature of 4 °C in 1996. The difference between the two years was significant also at Langanes, where there was low temperatures within the core of AW in 1996 relative to high temperatures observed in 2003, with only 2009 being warmer.

Near-surface lateral distribution of salinity and temperature

For the two years chosen in the previous section, lateral maps of salinity and temperature figures have been adapted from the MRI (see Figure 4.9 for salinity and Figure 4.10 for temperature). The salinity and temperature values are from 50 meters depth. Autumn have been used to represent these data, due to no data available from summer 1996.

There was a clear difference in salinity between 1996 and 2003, both close to the coast and farther offshore (see Figure 4.9). The 34.9 isoline covered large areas on the northern coast of Iceland during autumn 2003, whereas in 1996 the northern coast are covered with water with a salinity of 34.4. The AW showed a difference in salinity at the 50 meter isobath, of 0.4.

The temperature comparison also shows large differences, with a temperature difference of 4 °C all along the shelf area (see Figure 4.10). In 2003 the whole northern area was above $6-7$ °C, compared to 1996 where most of the surface water was 4 °C. Areas in the interior IS had in 2003 a temperature of 5 °C, whilst in 1996 the temperature was about 2 °C.

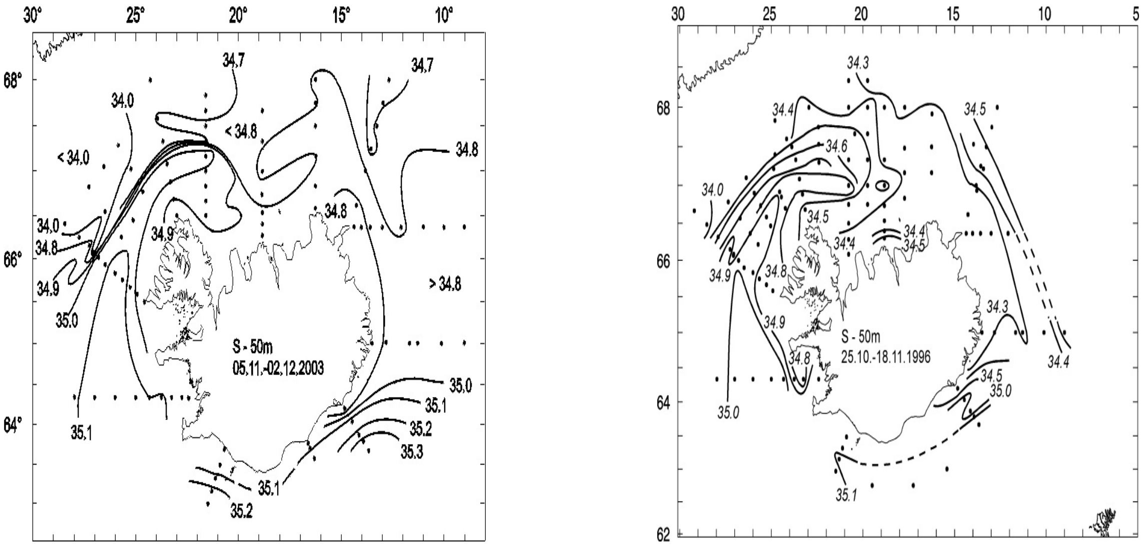

Figure 4.9: Lateral salinity distribution at 50 meters from autumn 2003 to the left and autumn 1996 to the right. The figure is adapted from www.Hafro.is

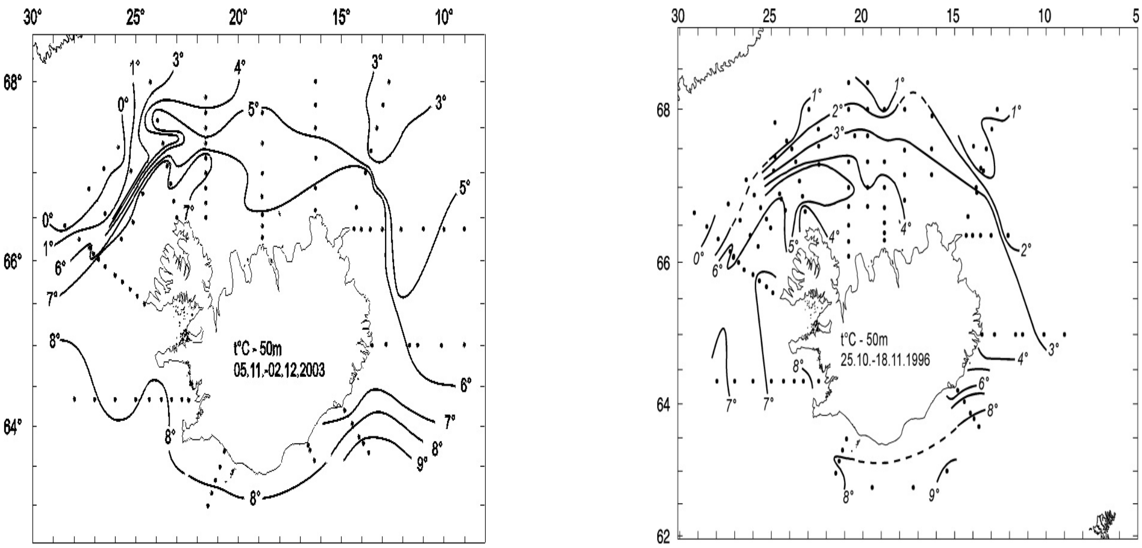

Figure 4.10: Lateral temperature distribution at 50 meters from autumn 2003 to the left and autumn 1996 to the right. The figure is adapted from www.Hafro.is

Chapter 5

Discussion

This chapter will start with a discussion of the annual mean hydrography from section 4.1, followed by seasonal and interannual variability at Kögur from sections 4.2 and 4.3, respectively. Then the focus will be on the variability in the hydrographic conditions, followed by the along-stream evolution in the geostrophic velocities and a comparison between two extreme years within the data record. A discussion of the two opposing hypotheses regarding the fate of the AW will round off this chapter, with one hypothesis suggesting that the AW leaves the shelf at Siglunes [Valdimarsson & Malmberg, 1999], whilst the other hypothesis suggests that the AW stays closely confined to the shelf, and leaves the shelf in the east [Jónsson, 2007].

5.1 Annual mean hydrography

The annual mean sections from Látrabjarg and Kögur revealed an annual presence of AW, see Figure 4.1. The mean salinity and temperature at Látrabjarg has values of 35.04 and 5.59 °C, respectively. AW was not observed at Siglunes and Langanes, however, from high temperatures and low densities it can be seen that the water mass present on the shelf is not the same as the water masses outside the shelf area. The deep water masses present at Siglunes and Langanes are believed to be NIWW, looking at the salinity and temperature from Figure 4.1. The shelf water reaching the two last sections has been modified by the ambient water masses, especially with regards to salinity. This indicates that the water mass present on the shelf is remnants of AW.

Despite showing high temperatures, the surface water at Kögur can not be classified as AW due to the low salinity (see Figure 4.1). Earlier work where the AW has been investigated has used a reference temperature to identify AW, however here it is shown that the temperature alone is not sufficient to identify AW due to the heating of the surface during summer.

5.2 Seasonal variability at Kögur

However, seasonal variability in the AW inflow has been shown to be significant [Swift & Aagaard, 1981]. Therefore the annual mean sections are excluding these important variabilities. The seasonal variability of the AW in the NIIC was investigated at Kögur. This section was chosen because it is located at the intersection between cold PW and warm AW, and that AW has been observed at all the seasons (Figure 4.1), together with a large data coverage. Large seasonal variability from Figure 4.2 and 4.3 was observed, implying that the annual mean sections are not revealing the variability in the inflow of AW. During winter the water mass around the core of AW is not warmed up by atmospheric forcing, meaning that the area north of Iceland is highly influenced by the inflow of AW during this season. When the AW surfaces, it has a temperature of $4 - 6\,^{\circ}\mathrm{C}$. The AW is then warmer than the air temperature north of Iceland at this season. Hence there will be a heat transport from the ocean to the atmosphere. Thus the presence of AW on the north Icelandic shelf area during winter, with resulting heat loss to the atmosphere, is affecting the climate north of Iceland.

The spring melting causes an increased amount of fresh water close to the coast. The fresh water is not as dense as the underlying sea water, thus formation of a light surface layer takes place, resulting in a stratified surface layer. The stratified surface layer stretches the full length of the section, preventing heat loss through air-sea interactions between the atmosphere and the AW. Hence, this time of the year there is little contact between the AW and the atmosphere.

The highest salinity and temperature values were found during summer. However, summer was not the season with the largest area of AW (see Figure 4.3), implying that the flow is more confined to the shelf during summer relative to the other seasons. The windstress is reduced during summer [Malmberg & Kristmannsson, 1992]. A decreased wind stress results in the flow following the topographic features in the area. The flow is confined to the shelf area at Kögur, following the shelf closely. At Siglunes the flow meets the KR. This obstacle will disturb the flow following the shelf, resulting in some water following the ridge outwards. This was also observed in the velocity field in Figure 4.5, where two velocity cores were observed at Siglunes. The inner velocity core may transport AW further east along the shelf through gaps in the KR, hence the AW propagates further along the north Icelandic shelf at summer.

A motion on the ocean will be induced when there is wind blowing along the sea surface. The wind stress can only be transferred to the ocean by viscosity. The viscosity will be balanced by the Coriolis force, assuming no horizontal pressure gradients. The resulting current, being a balance between viscosity and Coriolis force is called the Ekman current [Weber, 2004]. The Ekman current is directed 90° to the right of the wind stress. With the wind blowing along the coast occur downwelling or upwelling will occur. If the wind blows with the coast to the left, surface water will be driven offshore. The water removed from the surface at the coast must then be replaced by the underlying water, which is called upwelling. The opposite occurs if the wind blows with the coast to the right.

An enhanced stratification in the surface layer during the summer was observed, preventing exchanges between the AW and the atmosphere. During winter the wind stress increases [Malmberg & Kristmannsson, 1992]. If the wind would be directed from north-west, which is the most dominant wind direction during winter, the wind will blow parallel with the coast, with coast on its left hand side. Hence, due to the Ekman theory, there would be a net upwelling with nutrient rich water along the north Icelandic coast. Thus colder and relative saline water will be lifted upwards in the water column on the shelf. The result of this mechanism would then be a colder, but still relative saline product located on the shelf. However, if the wind stress would come from the opposite direction, i.e south-west, it would result in a net downwelling along the north Icelandic shelf, where warm, saline water would be transported further down.

The standard deviations (see Figure 4.3) from winter showed that the largest variability was found in area of AW and salinity. Area showed a deviation from the mean on the same scale as the mean area itself. Thus the inflow of AW is highly variable, which will have an impact on the hydrographic conditions on the shelf and also air-sea interaction. Looking at spring, less variability was observed in all the three variables. Thus the inflow of AW during spring can be considered fairly stable. The smallest variability in salinity and area is found during summer (see Figure 4.3). The salinity deviates around 35 during this season, thus the source water from Látrabjarg is preserved within the hydrographic variables when reaching Kögur. This means that the flow of AW is not an object of large modifications between the two first sections. The variability in area of AW is found to be between 5 and 10 km^2. From the standard deviations it is clear that the most stable inflow of AW occurs during summer. However, the largest deviation in temperature is observed during summer. Autumn shows the largest deviation looking at area of AW and salinity, however temperature during autumn shows the smallest deviation.

Seasonal changes were observed at all the sections, with all sections showing a maximum presence of AW during summer. However, the hydrographic properties of AW were diluted in the along-stream direction. During winter, only three years showed presence of AW at Langanes and only one year during spring, hence there is a large difference in the hydrographic properties at Langanes during summer and autumn relative to winter and spring. Siglunes also showed few years during winter and spring with presence of AW. The few years with presence of AW seen at these two sections is the reason why no annual core of AW was detected (see Figure 4.1).

5.3 Interannual variability at Kögur

Autumn was chosen to represent the interannual variability. Autumn was found to be representative of the variability also observed during spring and summer, and was the season with the best data coverage. Large interannual variability at Kögur could be seen (see Figure 4.4). One example is the change from 1996, where there was no AW seen in the section followed by a large area of AW in 1997. This shows that the interannual variability is large, and that there may be little interannual connection between different years. The ranges of interannual variability were 0.12 and 1.4 °C for salinity and temperature, respectively. These values may not seem remarkably large, but there was observed a larger variability in the cross sectional area, from 0 in 1996 to 24 km^2 in 2000 (see Figure 4.4). This has an impact on how far the AW will extend along the Icelandic shelf, the exchange the AW will have with the atmosphere, and possibilities for mixing with other water masses. The connection between the amount of AW at Kögur and the further propagation to the following sections will be described below. There were no occasions without AW at Kögur during autumn after 1996 (see Figure 4.4).

5.4 Variability in the hydrographic conditions

The salinity at Siglunes and Langanes, situated north of Iceland, is reduced relative to the two first sections situated to the west and north-west of Iceland, respectively. Thus there must be some mechanisms modifying the water properties along the north Icelandic coast, in addition to heat exchanges with the atmosphere. One possible mechanism is upwelling or downwelling. During winter there is mainly northerly winds [Jónsson & Valdimarsson, 2005]. Hence the wind would be close to parallel to the northern coast, with the coast on the left hand side. The surface water would be transported to the right, resulting in an upwelling. At Kögur during winter the AW surfaces (see Figure 4.2). This may be an indication of upwelling along the north Icelandic coast, as the underlying water masses are pressed upwards, resulting in that colder and relative saline water would be mixed up in the water column. The resulting water mass would be a mixture of AW and other water masses, showing a more homogeneous water mass on the shelf. Winds coming from the north will also result in a reduced inflow of AW to the north Icelandic shelf [Jónsson & Valdimarsson, 2005]. If the wind instead was coming from the south-west through the DS, the north-west Icelandic shelf would experience downwelling, resulting in the warm saline AW being transported further down in the water column. However, only the autumn situation has been presented here. A decrease in salinity and temperature was observed in the along-stream direction, this might indicate that upwelling occurs, mixing colder and less saline water further up in the water column, making the water mass colder and less saline.

A large variability in area of AW was observed at Siglunes (see Figure 4.6). Observations have shown several occasions where the area at Siglunes is larger than the area at Kögur. A larger area at Siglunes compared to Kögur suggest that the AW is being allowed to escape from the shelf area, following the KR. This is a strong indication of the KR being a critical location along the north Icelandic shelf, where the AW is directed offshore alongside the ridge. The AW coming from Látrabjarg in the west follows the shelf break around the north-west corner of Iceland. When approaching Siglunes, the KR acts as an obstacle for the topographically steered flow. The results presented here indicate that a part of the flow of AW leaves the shelf at this point in accordance with what was observed in the drifter studies of Valdimarsson & Malmberg [1999], while some of the AW continues along the Icelandic shelf in accordance with Jónsson [2007]. Two velocity maxima at Siglunes was detected in Figure 4.5. This suggest that the AW splits into two cores at this point along the shelf. The fate of the flow when meeting the KR, has been questioned. Figure 4.5 shows one core continuing along the shelf on the inside of the ridge, while one is located on the outer-side of the ridge. Thus the AW continuing along the shelf would show a smaller area, due to the splitting of the flow at Siglunes, and there will also be a reduction in transport.

Autumn season was chosen here to represent the transport of AW onto the north Icelandic shelf. However, seasonal variability in the transport has been observed [Stefánnson, 1962; Valdimarsson & Malmberg, 1999; Jónsson & Valdimarsson, 2005]. Stefánnson [1962] indicated that the seasonal variability in the transport of AW was controlled by an increased baroclinic structure due to fresh water run off from land, resulting in an increased geostrophic velocity. Thus the highest velocities would be expected close to the coast. In recent years this have been questioned [Valdimarsson & Malmberg, 1999; Jónsson & Valdimarsson, 2005]. The current has been observed to increase with distance from the coast, which is in accordance with the results presented here (see Figure 4.5). It has also been suggested that the seasonal variability in the transport of AW to the north Icelandic shelf is controlled by the large atmospheric forcing in the area [Valdimarsson & Malmberg, 1999; Jónsson & Valdimarsson, 2005]. The wind system in the area has a tendency of winds coming from the north during winter, resulting in a decreased inflow of AW to the north Icelandic coast [Jónsson & Valdimarsson, 2005]. This is also in accordance with the results presented here, as there was observed a decrease in AW along the north Icelandic shelf during winter (see Figure 4.2), and an increased inflow during summer, resulting in more AW on the north Icelandic shelf.

5.5 Geostrophic velocities

The geostrophic velocities are shown in Figure 4.5. The largest velocities can be found at the edge of the location of the core of the AW at Látrabjarg and Kögur (compare Figures 4.1 and 4.5). At Látrabjarg the largely horizontal isopycnals resulted in weak geostrophic shear. The structure of the current changed in the along-stream direction from Látrabjarg to Langanes, where the velocities increased. A seasonal variability in the geostrophic velocity and variability in the cross sectional area are reflected in the transports, showing a minimum of transport in spring, and a maximum in late summer. Hence, the annual mean of the geostrophic velocities shown in Figure 4.5 does not show the complete picture of the along stream evolution of the AW in the NIIC along the shelf.

In the method used, the reference level velocities from the sections were missing. The best way to obtain absolute referenced velocities would be to compare with concurrent measurements from the time period as the CTD data was recorded. However, current meter data is available from Hornbanki, a section between Kögur and Siglunes. The transport estimated here from the velocity field can be used together with the transport from Hornbanki to find the remaining unknown reference-level component of the flow. The most recent estimate of the total flow at Hornbanki is 0.8 Sv [Jónsson & Valdimarsson, 2011]. Table 4.1 shows the mean autumn transports from Figure 4.6, calculated from the velocity fields. The difference between these transports and the total transport (of 0.8 Sv) is also shown in the table. Thus the differences can be used to estimates the unknown barotropic component. The method used to to find the unknown component can be used at Kögur and Siglunes which is situated relatively close to Hornbanki. However, a part of the flow of AW was shown to leave the shelf at Siglunes. Hence, the flow at Langanes will be reduced and may not be comparable to the flow found at Hornbanki. Látrabjarg being situated on the western coast of Iceland, is not in the vicinity of Hornbanki, but due to being up-stream, all the AW present at Hornbanki must have passed Látrabjarg. However, at Kögur and Siglunes the transport at Hornbanki will be a good indicator of the total transport in the area.

The highest velocities are not situated at the same location as the core of the AW (see Figure 4.5). The baroclinic structure is affected by changes in topography, and it is expected that the velocity within the current will increase with a steepening of the topography. This could be seen in the along-stream evolution. For example, as the topography at Langanes got steeper, the velocity at the shelf break increased. At Langanes the AW flows alongside the EIC, and Jónsson et al. [2005] state that the highest velocities are expected to be found at the front between cold and warm water. In accordance with this, the velocity at Langanes was found to be larger relative to the other sections. Baroclinic instability might occur if small perturbations in the baroclinic motion grow from energy extracted from the potential energy. If the flow become baroclinically unstable, eddies might be released from the main flow [Weber, 2004]. Hence, if the flow of AW at Langanes would be baroclinically unstable, this may result in eddies being released from the main flow into the central IS. This was observed during a survey in 2011, when a large eddy containing AW was seen in the central IS off Langanes.

5.6 Two extreme situations

Two years with different hydrographic properties have been chosen to investigate further. One where there was a high amount of AW present all along the northern shelf, and one where the AW showed very little presence. This was done as an attempt to investigate the variability in the hydrographic properties between the two years, and if there could be found a connection with the high atmospheric temperature observed in 2003. Summer data is used to present these two years.

Large differences in the hydrography between the two extreme years were observed. During 2003 large areas on the north and west Icelandic shelf were covered by AW. At Kögur the core of AW extended far offshore, and at Siglunes the AW extended throughout the section. AW was observed in the central IS off Langanes in 2003 (see Figure 4.7). Hence, AW may contribute to the NIJ, feeding the central IS with warm, saline water.
The salinity within the cores of AW at all sections showed values above 35 during 2003. The temperature from the sections within the AW cores all showed temperatures above 6 °C. The hydrographic situation during 1996 was very different. The salinity within the core of AW was close to 35 at Látrabjarg and Kögur, however close to 34.9 at Siglunes and Langanes, with temperatures close to 4 °C. AW was seen at all sections, but to a much less extent relative to 2003. The large difference clearly had an affect on the local climate and biology. As stated earlier, there is an increased biological activity when there is a large inflow of AW to the north of Iceland, as the AW is nutrient-rich compared to the colder, less saline PW. This will result in favourable conditions during 2003, with the opposite being the case in 1996.

The high amount of AW along the shelf with resulting large air-sea interactions may be the main reason for the high atmospheric temperatures observed in 2003, in the year the Icelanders called the "Year with no winter" [Valdimarsson 2011, pers comm]. 2003 was one of three years showing AW in the central IS off Langanes between 1992 and present. If the AW within the NIIC contributes to the formation of the NIJ, as suggested by Våge et al. [2011], this will have an affect on the AMOC, and also on the global circulation.

The lateral distributions of salinity and temperature from 50 meters depth below surface are presented in Figures 4.9 and 4.10, respectively. The hydrographic properties in these two years were clearly different. During 2003 the entire northern coast of Iceland are covered by AW. Both years will here be presented with autumn data, due to lack of summer data from 1996. At the 50 meter isobath it was observed that the north coast of Iceland was covered with a water mass with salinities of 34.4 during 1996. This is remarkably low relative to 2003. The temperature during 1996 was as much as 4 °C than in 2003. 1996 was the last year in the time record not showing AW at Kögur.

5.7 Opposing hypotheses

It is clear that a large amount of AW leaves the shelf at Siglunes and flows into the Iceland Sea, as observed earlier by Valdimarsson & Malmberg [1999] (see also Figure 4.7). Even if a large amount of AW is lost at Siglunes, there is also AW present at Langanes, mainly during summer and autumn, in accordance with Jónsson [2007]. However, AW was only observed at Langanes at three occasions during winter (one being in 2003) and once during spring. In contrast to what was found by Jónsson [2007], that the AW did not leave the shelf north of Iceland, hence not contributing to the interior IS at Langanes, AW was observed in the IS at Langanes on at least three occasions (see Figures 4.7 and 4.8 for the 2003 case).

The results here suggest that the KR is a critical point along the shelf, where the AW is strongly influenced by topographic steering. The water flow off the shelf topographically steered by the ridge. The topographic steering the water to flow off the shelf in the vicinity of the ridge. From there some of the water may enter the central IS and some might return south toward the DS alongside the EGC, as observed by Valdimarsson & Malmberg [1999]. The fate of the inshore branch of AW seen at Siglunes has been questioned. There is a possibility that the AW follows the isobaths and flow around the KR. The most likely scenario is that the AW stayS confined to the shelf, flowing towards Langanes. The reason for stating this is that AW has been observed at Langanes during summer and autumn, every year after 1998. There is no evidence of AW flowing into the domain from the east, hence the AW observed at Langanes must be AW transported by the NIIC.

Support for both hypotheses has been found in this data set. The KR was found to be a crucial point along the shelf, in accordance with Valdimarsson & Malmberg [1999], where the water followed the ridge offshore. However, AW has consistently been observed at Langanes in recent years. This is in accordance with Jónsson [2007]. AW has also been observed leaving the shelf at Langanes. This warm, saline AW can therefore contribute to the water mass transformation in the central IS. This is important relative to the formation of the NIJ, which amongst other mechanisms depend on the inflow of AW to the central IS for water mass transformation.

5.8 Sources of uncertainties

There was a large distance between the stations in the four sections, resulting in a course resolution. This is particularly true at Langanes, where there was one station situated very close to the coast, and the next at the shelf break. It is known that the AW flows along the shelf and only two repeated stations on the shelf is not much, resulting in that interpolated data between stations must be interpreted carefully. However, what makes the results trustworthy is that AW is seen directly at the stations. It is likely that when there is AW present at two neighbouring stations, there will also be AW present between the stations.

Another source of uncertainty is the fixed definition of AW, as salinity > 34.9 and temperature $> 3\,°\mathrm{C}$. However, looking at the water masses in Table 2.1, no other water masses can be confused with AW. The result here is based on hydrographic properties recorded from CTDs taken over a short time period. The water mass properties in the area have been observed to change significantly within a very short time period. For example, two surveys were carried out in November 1999 with a time difference of two weeks, where the temperature was found to decrease by $3\,°\mathrm{C}$ during the two weeks [Jónsson & Valdimarsson, 2005]. However, due to the long record of data much of the variability has been averaged out, which makes the results more trustworthy.

Chapter 6

Summary and conclusions

A yearly presence of AW was found at Látrabjarg and Kögur (see Figure 4.1). At Siglunes and Langanes AW could not be detected by looking at the annual means of salinity and temperature.

The seasonal variability at Kögur is shown in Figure 4.2 and Figure 4.3. The highest salinity and temperature was recorded within the core of AW during summer even though the cross sectional area of the AW core was at a minimum during that season. Autumn shows the largest cross-sectional area of the four seasons, and the core of AW shows an offshore shift during autumn and winter.

Large interannual variability was also found within this data set. Some years during the time series there was no presence of AW on the north Icelandic shelf, while in other years large areas were covered. Large changes could also be observed from one year to the other, this was especially clear between 1996 and 1997. A high amount of AW was observed in 2003, and an increase was observed during the last years in the time series.

The along-shelf evolution of the AW shows a decrease in salinity and temperature within the NIIC. The highest salinity and temperature were observed at the first section in the west and the lowest salinity and temperature were found at the last section in the north-east. The cross sectional area showed a decrease from the first to the second section. The area of AW , showed an increase at Siglunes relative to Kögur at several occasions. The smallest cross sections area of AW was always detected at Langanes.

The transport was calculated from the velocity fields. The missing transport due to the unknown reference-level transport was estimated from current meter data from Hornbanki. An increase in velocity with increasing distance from the coast was observed, with the maximum velocities observed at the shelf break. The highest velocities were obtained at Langanes, where there is a steep topography and the AW flows beside the cold, fresh EIC.

A comparison between two years with difference in hydrography showed that the hydrographic conditions at the sections are highly variable. When a large amount of AW was recorded at Kögur, it was also recorded at Langanes. In 2003 a large area north of Iceland was covered by AW. This was compared to 1996, showing a completely different hydrographic regime. During 2003, the entire north Icelandic shelf was covered in AW, while in 1996 the AW was nearly absent. High amounts of AW have been shown to be preferable for the larvae coming from the south. With an increase in AW, the biologic productivity would increase. The AW is nutrient-rich relative to the cold, fresh PW. Thus the inflow of AW, and the amount of AW present on the shelf and the resulting hydrographic situation is of high importance for the local biology and also the local climate [Jónsson & Valdimarsson, 2011].

A large part of the AW entering the north Icelandic shelf was influenced by the presence of the KR, a region found to be crucial along the shelf, in accordance with Valdimarsson & Malmberg [1999]. There is an indication that the flow of AW splits in two at Siglunes in the vicinity of the KR, where one branch flows offshore and may return south through the DS next to the EGC. The other branch is confined to the shelf and may flow towards Langanes, where some of it remains confined to the shelf and some might leave the shelf, flowing into the IS. In more recent years, AW has been more present at Langanes, hence some of the water that flows on the inner side of the ridge at Siglunes appears to stay confined to the shelf in accordance with Jónsson [2007]. This indicate that the flow of AW reaches further than what have been observed during previous years. If the flow of AW turns baroclinically unstable at Langanes, eddies may be formed along the shelf break. These eddies may then propagate offshore into the central IS, contributing to water mass transformation in the area.

AW was detected within the IS during two years in the record, 2003 and 2009. During a survey in 2011, AW was also observed off the shelf at Langanes. This shows that there are occasions when AW enters the central IS. It was shown in the ocean model of Våge et al. [2011] that when densification in the weakly stratified central IS occurs, the heat loss in the area is balanced by eddies of warm AW released from the baroclinically unstable NIIC. Thus AW in the NIIC will be a source of heat and salt for the central IS, and crucial to the formation of the NIJ. The presence of AW in the central IS was pronounced during summers 2003 and 2011, when large amounts of AW was seen in the IS.

A difference in the presence of AW at Langanes between summer and autumn relative to winter and spring was observed. This is believed to originate from changes in the wind system. Earlier these variabilities have been linked to large atmospheric systems [Valdimarsson & Malmberg, 1999], such as the North Atlantic Oscillation (NAO). However, also the more regional atmospheric conditions have a large impact on storm tracks and the weather in the area i.e the Icelandic Low and the Greenland High, where the Icelandic Low is central to the NAO.

A larger amount of AW present along the north Icelandic shelf is of great importance to the local biology in the area. The cod larvae prefer nutrient-rich AW relative to cold PW. This will again affect the fisheries in the area, which is many Icelanders living. The fate of the AW along the north Icelandic shelf is also important for the local climate, with an increased inflow resulting in a milder climate. There might also be a larger climate impact of the AW within the NIIC, considering the newly discovered NIJ. The NIJ is found to contribute about half of the overflow water in the DS [Våge et al., 2011]. Hence the NIJ, and thereby the AW in the NIIC feeding the NIJ, is a part of the AMOC, thus affecting the global ocean circulation.

6.1 Future work

Iceland is unsheltered f large weather systems, and the two most dominant features are the Icelandic Low and the Greenland High. These two system will clearly have an affect on the wind systems in the vicinity of Iceland. The wind stress is large during winter, and will clearly show an affect on the inflow of AW onto the north Icelandic shelf. Thus comparisons with wind data from the same time record would be very interesting to compare with the hydrographic data. Wind data from National Center for Atmospheric Research (NCAR) and National Centers for Environmental Prediction (NCEP) could be used for this purpose to create time series of the wind in the same area. There wind data can be provided from http://www.esrl.noaa.gov. Wind data from land is not preferable due to large topographic influences.

Direct current velocity measurements would be very useful to get a better understanding of the currents and circulation in the area. During the surveys carried out during 2010 and 2011 where the writer contributed on the survey, vessel mounted ADCPs (Aqustic Doppler Current Profilers) were used. Hopefully more current measurements will be collected in the area in the future. A collection consisting of both CTD data and ADCP data would be very useful for the investigations in the area, learning more about the processes along the north Icelandic shelf.

Appendix A

Abbreviations

Table A.1: Abbreviations

Abbreviation	Word
NIIC	North Icelandic Irminger Current
AW	Atlantic Water
PW	Polar Water
IC	Irminger Current
IS	Iceland Sea
DS	Denmark Strait
KR	Kolbeinsey Ridge
GSR	Greenland-Scotland Ridge
EIC	East Icelandic Current
EGC	East Greenland Current
ICC	Icelandic Coastal Current
NIWW	North Icelandic Winter Water
AMOC	Atlantic Meridional Overturning Circulation
DSOW	Denmark Strait Overflow Water
MRI	Marine Research Institute
MAR	Mid-Atlantic Ridge
FC	Faroe Current
IFR	Iceland-Faroe Ridge
FSC	Faroe Shetland Channel
NAC	Norwegian Atlantic Current
CTD	Conductivity-Temperature-Depth
ADCP	Aqustic Doppler Current Profilers

Appendix B

Supplementary tables

Kögur Winter

Year	Area (km^2)	Salinity	Temperature($\circ C$)	Transport (Sv)
2009	14.6000	35.0679	5.0283	0.4336
2008	15.4500	34.9788	4.7462	0.2802
2007	5.8500	34.9480	5.1301	0.1970
2006	14.8500	34.9851	5.0753	0.1386
2005	10.4500	35.0296	5.1012	0.3871
2004	11.4500	35.0047	4.3385	0.1251
2003	13.9500	35.0403	5.3447	0.4537
2002	no data	no data	no data	no data
2001	13.7000	35.0305	5.2759	0.3118
2000	12.1000	35.0026	4.2320	0.2829
1999	1.6500	34.9695	4.0033	-0.0040
1998				
1997				
1996	10.0500	34.9296	5.0650	0.0491
1995				
1994	13.2500	34.9276	4.1055	0.2187
1993	5.1500	34.9266	4.0152	0.1872
1992	11.4000	34.9996	4.7043	0.0925

Table B.1: Mean values for Kögur Winter

Kögur Spring

Year	Area (km^2)	Salinity	Temperature($\circ C$)	Transport (Sv)
2009	15.4000	35.0639	5.3650	0.4900
2008	8.2500	35.0259	4.8137	0.3324
2007	5.6000	35.0227	5.3399	0.1648
2006	5.4500	34.9619	5.0177	0.3774
2005	7.3500	35.0291	5.6139	0.2742
2004	11.3500	34.9933	5.1504	0.5049
2003	16.9000	35.0511	5.9250	0.7030
2002	12.8000	35.0098	5.2612	0.1349
2001	11.4500	34.9772	4.8119	0.1250
2000	5.5000	34.9921	4.7974	0.1815
1999	0.4500	34.9255	4.4485	0.0000
1998	2.0500	34.9827	5.2908	-0.0021
1997	8.6500	34.9895	4.9883	0.0544
1996	8.4000	34.9606	5.1013	0.0325
1995	3.0000	34.9508	4.1351	0.0648
1994	8.1500	34.9632	4.7673	0.2783
1993	12.2000	34.9693	4.3682	0.3608
1992	10.2000	34.9849	4.6848	0.1325

Table B.2: Mean variables Kögur Spring

Kögur Summer

Year	Area(km^2)	Salinity	Temperature($\circ C$)	Transport (Sv)
2009	7.7000	35.0470	6.6646	0.5191
2008	5.2500	35.0641	6.8924	0.2587
2007	10.2500	35.0471	6.5186	0.2687
2006	no data	no data	no data	no data
2005	no data	no data	no data	no data
2004	no data	no data	no data	no data
2003	9.5500	35.0128	6.2369	0.3668
2002	7.1000	35.0210	6.1335	0.3764
2001	13.4500	34.9610	6.4145	0.2266
2000	12.3500	35.0356	5.8927	-0.8413
1999	4.9000	35.0371	6.2060	0.2409
1998	15.5000	35.0583	6.9987	0.1648
1997	17.9000	35.0246	6.3774	0.2744
1996	2.5500	35.0053	6.5706	0.0689
1995	3.8000	34.9689	5.4477	0.1516
1994	no data	no data	no data	no data
1993	no data	no data	no data	no data
1992	10.2000	34.9849	4.6847	0.1328

Table B.3: Mean variables Kögur Summer

Kögur Autumn

Year	Salinity	Temperature($\circ C$)	Area(km^2)	Transport (Sv)
2009	35.0372	5.2576	21.3500	0.2014
2008	34.9613	5.9072	2.9500	0.0402
2007	34.9939	6.3257	7.7500	0.0711
2006	34.9445	5.5160	12.4000	0.1985
2005	34.9980	5.3165	10.3500	0.1337
2004	34.9321	6.6163	2.6500	0.0236
2003	35.0476	6.6593	13.1000	0.6428
2002	34.9615	6.0586	7.5500	0.0398
2001	34.9819	5.9388	3.3000	0.1443
2000	35.0111	6.0242	15.7000	-0.2219
1999	34.9425	5.4087	4.6500	0.0486
1998	34.9686	5.9574	11.3500	-0.0750
1997	35.0202	6.3032	15.5000	0.5694
1996				
1995	no data	no data	no data	no data
1994	34.9240	5.4039	2.8000	0.0528
1993	35.0116	5.9492	8.8500	0.3024
1992	no data	no data	no data	no data

Table B.4: Mean values for Kögur Autumn

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