Evolution of the Irminger Current Anticyclones in the Labrador Sea from Hydrographic Data

by

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Abstract

The continuous supply of heat and fresh water from the boundaries to the interior of the Labrador Sea plays an important role for the dynamics of the region and in particular, for the Labrador Sea Water formation. Thus, it is necessary to understand the factors governing the exchange of properties between the boundary and interior. A significant fraction of heat and fresh water, needed to balance the annual heat loss and to contribute to the seasonal freshening of the Labrador Sea, is thought to be provided by coherent long-lived anticyclonic eddies shed by the Irminger Current. The population, some properties, rates and direction of propagation of these anomalies are known but the evolution and the mechanism of their decay are still far from obvious. In this work I investigated their water mass properties and evolution under the strong wintertime forcing using hydrographic data from 1990-2004 and a 1-dimensional mixed layer model. There were 50 eddies found in the hydrographic data record, 48 of which were identified as anticyclones. Vertical structure of the eddies was investigated, leading to the categorization of all the anticyclones into three classes: 12 - *with* a fresh surface layer and no mixed layer, 18 - *without* a fresh layer and at least one mixed layer, and 18 with ambiguous vertical structure. Four eddies of the second group appeared to have cores extending to as deep as 1500 m vertically and an isopycnal displacement of 400-600 m. A number of eddies without a fresh water cap contained Labrador Sea Water from the previous year at mid-depths.

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Contents

Chapter 1

Introduction

1.1 Overview of the Labrador Sea and open questions

Deep convection is observed only in a few places in the world and the Labrador Sea is one of such places. Occurring only in a relatively small area of the sea and during quite limited time in winter, this process, which leads to the formation of the intermediate-depth water mass, Labrador Sea Water (LSW), has a great impact on the thermohaline circulation of the ocean and climate of our planet. LSW formation rate estimates range from 1.8 to 10.8 Sv (1 Sv = 10^6 m^3) produced annually in the interior of the basin (Rhein and Fischer, [36]) which makes up a significant fraction of the Meridional Overturning Circulation (MOC), Atlantic branch of which carries $\sim 15 - 18$ Sv (Ganachaud and Wunsch, [8]; Lumpkin and Speer, [27]).

The seasonal cycle of the Labrador Sea consists of two phases: convection and restratification. Convection involves cooling of the water column and its densification. Salinity of the Labrador Sea upper layer is maximized at the time of convection. When the surface fluxes cease, the second phase of the cycle, restratification, begins. Restratification itself involves two stages: rapid post-convection phase on the timescales of weeks to months and a slower phase that continues throughout the remainder of the year (Straneo, [41]). During restratification Labrador Sea water column gets warmer, fresher at the surface and lighter becoming closer to the boundary current system properties (Straneo, [41]).

Labrador Sea convection was widely studied during the past decade (Labrador Sea Deep Convection Experiment [16]; Jones and Marshall [13], [14]; Legg and Marshall [21]; Straneo and Kawase, [39] and others). However, many open questions about the restratification remain (Straneo, [41]). Fresh water and heat budgets still need to be more precise, and we need to understand how exactly the boundary current system exchanges these properties with the interior.

The Labrador Sea is a region of annual heat loss to the atmosphere which is balanced by the inflow of warm water from the boundary currents (Spall, [37]; Straneo, [41]). As shown in a number of studies, the heat supply occurs mostly by means of Irminger Current eddies, which form along the Irminger Current off the west coast of Greenland (Katsman et al., [15]; Spall, [37]; Straneo, [41]). These eddies are present in large quantities in the Labrador Sea and it has been estimated that they may balance $\sim$ 25-100 % of the annual heat loss (Katsman et al., [15]; Lilly et al., 2003, hereafter L03, [26]).

Another example pointing to the possible importance of the Irminger Current eddies is connected to the appearance of the fresh water cap at the surface of the Labrador Sea in early spring. Its origin is still not well understood (Straneo, [41]). Precipitation cannot account for such a significant fresh water layer, icebergs and melting of the sea ice are unlikely to supply it as well (Myers, [30]; Straneo, [41]). A primary contributor to this effect is possibly the cold, fresh West Greenland Current system which flows above and inshore of the Irminger Current and may influence the Labrador Sea by means of the Irminger Current eddies (Hatun et al., [12]). The qualitative and quantitative impact of these eddies to the transformation of water masses during the restratification is still an open question.

Irminger Current eddies are likely to play a role for both heat transport from the boundary current to the interior and for the fresh water budget of the Labrador Sea. It is crucial to understand how exactly they provide this connection between regions, where they transfer heat to, at what time of the year this heat exchange is the most intense and other related issues. Understanding the dynamics and properties of the Irminger Current eddies will help to improve the estimates of their contribution to the Labrador Sea heat and fresh water balances.

1.2 Overview of the present study

This work concentrates on the analysis of properties and evolution of the Irminger rings - long-lived coherent eddies radiating from the Irminger Current and propagating into the interior of the sea. Their influence on the formation of the intermediate-deep water mass and the process of restratification is potentially large. They provide a necessary connection between the boundary current and convective region, supplying cold and fresh water in the upper layers and warm and salty in the lower layers (Straneo, [41]), thus helping to balance the net heat loss to the atmosphere in winter. These eddies, predominantly anticyclones, are formed where the Irminger Current diverges from the Greenland shelf, then propagate to the center of the basin. Moving from the source, they lose heat under the strong surface wintertime forcing. They evolve with time, their water mass properties change and eventually they decay somewhere in the basin releasing all the water they contained. It is important to understand the changes in their properties at each step in their lifetime, from origin to decay. The focus of this work is the evolution of these anticyclones under the strong winter forcing on both seasonal and interannual scales. A 15-year hydrographic data record combined with a simple 1-dimensional mixed layer model provides an opportunity to study spatial and temporal evolution of eddies, their water mass properties, development of the mixed layer, and seasonal and interannual variability of eddies.

In this study I will address the following questions:

1. What are the properties and vertical structure of the Irminger Current anticyclones?

2. How do the Irminger Current anticyclones evolve under strong winter surface

fluxes?

3. How different are the Irminger Current eddies from the source and what mechanisms drive their evolution?

In Chapter 2 of this work I give an overview of the Labrador Sea, including its circulation at different depths, convection and its variability during the past 15 years. I will summarize what we *do* know about Irminger Current eddies and what questions still remain unanswered, i.e. what we *don't* know. The last topic of this chapter will consider the balance of forces the eddies obey and structure of the anticyclone obtained analytically.

Description of the hydrographic data set and criteria for distinguishing eddies from the ambient water are provided in Chapters 3 and 4. Fifteen years of hydrographic data are divided by season and station location. The process of calibration and putting the data set on a regular pressure grid is also explained. In Chapter 4 I give an overview of other works regarding the identification of the different kinds of eddies in the Labrador Sea and summarize their methods. I also describe how I have defined the anticyclones and show the resulting distribution obtained with these criteria.

Chapter 5 focuses on the statistical analysis of the eddies found in the data. I provide the population statistics for different groups of eddies: deep and shallow; located close to the formation region and remote; having survived convection and being just formed. Characteristics such as isopycnal displacement, temperature, salinity and density anomalies, monthly distribution and heat content are provided.

Water mass properties of a typical eddy and concepts of its evolution are introduced in Chapter 6. Evolution of the whole water column is examined: a shallow layer from the surface to the depths of $\sim 500 - 1000$ m and an intermediate-deep layer down to $\sim 2000 - 2500$ m. Extinction of the fresh surface cap as the eddy evolves is examined and the depression of the LSW below the deep eddies is investigated. Seasonal and interannual changes in the eddies are demonstrated and followed by appropriate conclusions.

Chapter 7 includes background, model setup, and results of experiments produced with a 1-dimensional model of the mixed layer. It was used to investigate if the eddies' evolution is governed mostly by the one-dimensional fluxes or if the physics of the eddy life cycle cannot be described without including lateral exchange. The possibility of the group of eddies without a fresh cap at the surface to be formed by convection was investigated. Finally, I compared the mixed layer depths in the Labrador Sea interior with mixed layers in eddies with and without fresh water cap. Summary and interpretation of the results are presented in the last chapter of this thesis.

Chapter 2

Background

2.1 Labrador Sea and its circulation

The Labrador Sea is located in the northwest corner of the North Atlantic between Canadian province of Newfoundland and Labrador and west coast of Greenland. This marginal sea is connected to Hudson Bay through Hudson Strait and to Baffin Bay through Davis Strait. The width of the Labrador Sea from Cape Desolation to the Labrador Peninsula is $\sim$ 1000 km. Depth of the interior of the Labrador Sea varies from 2000 to 3500 m and does not exceed 500 m on the shelves.

Labrador Sea plays a significant role in the thermohaline circulation of the ocean as the region of the Labrador Sea Water (LSW) formation. It is one of a few places in the world where dense water is formed in winter and sinks to the intermediate depths providing the ventilation of the ocean.

This region is known for its harsh meteorological conditions: cold and dry Arctic air, frequent storms, Greenland icebergs, pack ice, and great air-sea buoyancy contrasts. It is a site where the cooling of the atmosphere induces a huge buoyancy flux which together with a weak buoyancy stratification of the water results in a deep convection. The mixed layer cooling begins in the fall and continues during the winter destroying the seasonal thermocline over large regions by February. The maximum mixed layer depth down to 2000 m is usually observed in March (LSDCE, [16]; Marshall and Schott, [29]). Restratification of the surface water occurs very quickly and much of the upper column restores to its preconvection state by May (Pickart et al., [32]; Prater, [33]; Steffen and D'Asaro, [38]). The deepest convection and the greatest heat flux are observed near the Labrador Shelf, where the continental winds are the driest and the coldest (LSDCE, [16]; Pickart, [32]). Despite its location and severe atmospheric conditions interior of the Labrador Sea remains free of ice throughout the winter (Pickart, [31]; Pickart et al., [32]). The ice covers only regions adjacent to the land, especially on the Labrador side which causes troubles for the ship observations in winter (Pickart, [31]; Pickart et al., [32]).

Labrador Sea circulation (Figure B-1) consists of the following components: West-Greenland Current (WGC), Irminger Current (IC), Labrador Current (LC), Deep Western Boundary Current (DWBC) and several recirculation cells in the interior of the basin (Cuny et al., [4]; Lavender at al., [17]).
West Greenland Current is a cold ($\theta = -1.8^oC$) and fresh ($S \leq 34.5$ psu) current (Cuny et al., [4]). It originates in the Arctic and brings its waters southward on the shelf of the East Coast of Greenland where it is called the East Greenland Current. After turning around Cape Farewell it changes the name to the West Greenland Current (Reid, [35]).
The warm ($\theta \geq 4^oC$) and salty ($S \geq 34.90$ psu) Irminger Current - one of the branches of the North Atlantic Current entering the Nordic Seas west of Iceland - lies under and off-shore of the West Greenland Current. The Irminger Current core is distinguishable by its pronounced properties down to 700 m vertically and to the shore of 3000 m isobath horizontally (Cuny et al., [4]; Pickart et al., [32]; Prater, [33]). Irminger Current and West Greenland Current flow together along the shelf of Greenland up to 61.5°N, 52°W, and at about this point the Irminger Current diverges from the shelf and continues its path around the basin along the 3000 m isobath. While looping cyclonically around the basin it gradually changes its core properties getting weaker, cooler and fresher (Cuny et al., [4]; Pickart et al., [32]). West Greenland Current continues to carry its waters along the Greenland coast to the Baffin Bay.
On the Labrador side the IC water mass becomes modified, still having relatively

warm and salty waters but of different (visibly colder and fresher) magnitudes than on the Greenland side (Cuny et al., [4]; Pickart et al., [32]). There are several reasons for such a change in properties: small scale mixing with the interior waters, stronger forcing on the Labrador side and shedding of the mesoscale eddies which take a significant volume of the warm and salty water out from the boundary current (Spall, [37]; Straneo, [42]). The modified Irminger Water flows together with the Labrador Current which flows southward from the Arctic basin bringing cold ($\theta \sim -1.5^oC$) and fresh $S \leq 34.5$ psu) waters above the shelf-break area (Cuny et al., [4]). Labrador Current is a branch of the West Greenland Current joint with the Baffin Island Current. In spring and early summer it brings icebergs from the glaciers of Greenland and Arctic southward into the Atlantic Ocean.

In the interior of the sea at mid-depth (~700 m) there is a number of closed regions of cyclonic flow forming a weak anticyclonic gyre in the basin (Lavender at al., [17]). Surprisingly, the path of the Labrador Sea Water after it has been formed is not limited to the flow along the deep western boundary. As Lavender et al., [17], have shown, those recirculation cells provide another pathway for the LSW flushing: it spreads eastward and can be found in 1.6-2.6 years after the formation in the Irminger basin. It can be traced to the Iceland Sea as well. As was shown by Lavender et al., [17], the speeds of these mid-depth recirculation currents are quite low - 1.8 to 8.7 cm/s. The deep circulation of the basin consists of the bottom-intensified Deep Western Boundary Current flowing cyclonically around the basin at 2500 m and carrying North Atlantic Deep Water (NADW) with $\theta \sim 3^o$C and $S \sim 34.92$ psu and deeper the Denmark Strait Overflow Water (DSOW) with $\theta \leq 1.5^oC$ and $S \sim 34.9$ psu from the Nordic Seas (Pickart et al., [32]; Cuny et al., [4]). The transports and velocities of the major currents are presented in Tables A.1 and A.2.

2.2 Convection

Convection is a process taking place both in the ocean and atmosphere. It is caused by unstable density gradients between the different layers of water/air system. Ocean convection is commonly observed in the high-latitude regions such as Greenland Sea, Weddell Sea, Labrador Sea and Irminger Sea where the buoyancy loss is determined by the heat loss from the surface. As an exception, it is also observed in the Mediterranean Sea where it was first discovered and described. In all these regions heat loss from the surface of the ocean is connected to the cyclonic atmospheric circulation over the basin (LSDCE, [16]). In the Labrador Sea, for example, dry and cold air is blowing over the relatively warm waters of the sea ($\sim 2^oC$) resulting mostly in mean heat losses of the values of up to 200-300 W m^{-2} (LSDCE, [16]; Marshall and Schott, [29], Pickart et al., [32]). Heat loss along with the other factors results in convection and formation of an intermediate water mass, Labrador Sea Water. LSW contributes to the global circulation of the ocean both directly and while entrained in the North Atlantic Deep Water (McCartney, [28]). After being formed in the center of the basin, it spreads at intermediate depths southward and eastward and is found in the North Atlantic to the north of 40^{o}N and along its western boundary to 18^{o}N (Talley and McCartney, [43]). Its characteristics are easy to track since LSW is a low PV water mass with pronounced salinity minimum ($\theta \sim 2.9^oC$, $S \sim 34.84$ psu, Pickart et al., [32]).

First, as was mentioned above, the region suitable for convection has to experience large surface buoyancy losses resulting from the atmospheric circulation. Second necessary condition for the deep overturning to occur is that weakly stratified waters are brought closer to the surface for an easier access by the surface fluxes. Weak stratification of the Labrador Sea is maintained by convection from previous years (Marshall and Schott, [29]). Every winter surface fluxes erode a thin stratified layer and reach the layer of homogeneous water mass formed before. Cyclonic circulation of the boundary currents on the scales of a basin is associated with the dome-shaped isopycnals. They are the shallowest in the central part of the basin which provides additional possibility for the waters to overturn and for the denser water to be brought closer to the surface (Figure B-2).

Convection is traditionally described in terms of three phases: preconditioning, deep convection itself and lateral spreading of the dense water mass and restratification of the interior (Deep Convection Experiment, LabSea Group, [16]). During the first phase atmospheric forcing and circulation of the ocean are combined in such a way that they predispose some area of the basin to overturn (Figure B-3). The region is considered to be "preconditioned" when there exists a laterally extended layer of weakly stratified fluid at some depth potentially suitable for overturning if the forcing is applied. When the region becomes preconditioned and the necessary meteorological conditions occur the buoyancy loss destroys a stratified layer at the surface and a weakly-stratified water below starts experiencing direct fluxes. The second phase of convection - "violent mixing" - starts and the "chimney" develops (see Figure B-4). Usually this phase occurs in February-March resulting in the deepest observed mixed layers during these months. "Chimney" is a region created and maintained by the well-mixed vertically water columns - "plumes". Plumes are the structures with a scale of the order of $\sim$ 1 km distributing the dense water vertically and having ascending and descending currents of speeds up to 10 cm/s (Marshall and Schott, [29]). As the forcing continues, chimney deepens and if the conditions become extreme, it can reach the bottom, but it never happened in the Labrador Sea. Chimney itself is the largest existing feature during convection with diameter more than 100 km. When the forcing discontinues, but deep and cold mixed layer is still maintained - vertical heat transfer slows down and the lateral heat transfer begins. In agreement with thermal wind balance the rim current develops around the chimney and becomes baroclinically unstable, shedding eddies (scales of the order of $\sim$ 10 km) to stabilize the density front around the chimney. Finally the last phase of the convection begins: sinking and spreading. Water column restratification begins after the forcing ceases and continues until the next winter comes. Chimney decays by means of the eddies -

they carry the dense water away removing the density gradient between the chimney and the rest of the basin. Convective product spreads horizontally and gradually mixes with the ambient water.

Convection takes place in a variety of temporal as well as spatial scales. Time scales on which the smallest features, plumes, develop are of the order of days and weeks (Marshall and Schott, [29]). Plumes alone can not balance the surface heat flux in winter which suggests that processes with a longer timescale contribute to the one-dimensional heat flux balance as well (Lavender et al., [18]). Only the initial phase of convection is governed mostly by the surface fluxes and can be considered in a 1D space. For the rest of the stages lateral processes can not be neglected. The second largest features of convection, eddies, participate in the water mass redistribution on the timescales from weeks to months, Marshall and Schott, [29]. Finally, it takes from weeks to months for the largest feature of convection, the chimney, precondition, develop and adjust. Not only the total buoyancy loss matters but also its timing. The depth of convection penetration would be different if a constant in time cooling or a few severe storms pass by. In the latter case the lateral processes may be able to mix water in between the storms and stabilize water column. This would result in a shallower depth of convection even when the same buoyancy loss occurred (Marshall and Schott, [29]).

The Labrador Sea experiences a strong seasonal cycle in the upper 200-300 m (Yashayaev, [45]). This cycle consists of the wintertime mixing of the surface layer caused by strong heat loss at the top. Then, it is followed by the summertime warming and a rapid development of a thin stratified layer at the surface. An interesting feature of the Labrador Sea seasonal cycle is an appearance of a fresh layer at the surface right after the convection ceases (Pickart et al., [32]; Straneo, [41]; Hatun et al., [12]). This layer, especially if it is warm as well, makes the water column very stable to convection and prevents it from vertical mixing with the layers below. Seasonal cycle is not fully shown in the hydrographic data since the majority of the sections were occupied in late spring - summer season. Moreover, restratification consists of two phases (Straneo, [41]), the faster one happens in a very short period of time making it hard to capture. Thus, this process is still not fully resolved and understood.

2.3 Interannual variability of the Labrador Sea in 1990-2004

Labrador Sea exhibits a lot of variability on seasonal, interannual and decadal scales. Properties of the water masses inside the basin, circulation, depth of penetration of convection and the volume of the LSW formed are not constant from year to year. Among the factors responsible for this variability are the changes in the wind strength, air-sea fluxes, evaporation and precipitation, heat and fresh water transport from the boundary currents, and their own variability as well. Contribution from the Arctic basin and melting of the Greenland icebergs and ice, variability of the North Atlantic Current and the "memory" of the sea also play a role in these changes.

North Atlantic Oscillation (NAO) index reflects changes in the atmospheric circulation to a large degree, and it differs from year to year (Dickson, [6]; Yashayaev, [45]). NAO index is constructed by taking the difference in surface pressure between two regions, subpolar and subtropical: Iceland and Azores, respectively. Pressure in Iceland is usually low and in the Azores is high. When the index is positive (positive NAO phase), it means that the pressure difference between the Azores and Iceland is greater than normal resulting in more frequent storms in the North Atlantic and in colder and drier winters over the Labrador Sea. During the positive NAO phase cyclonic activity in the ocean is greater and hence the circulation of the cold and dry air is enhanced leading to the larger heat loss from the Labrador Sea. If the situation is the opposite and the NAO index is low (negative NAO phase) - the pressure gradient is smaller than normal which results in the milder temperatures and fewer storms during the winter (Figure B-5). NAO is considered to be one of the most important factors responsible for the interannual variability in the Labrador Sea (Curry and McCartney, [5]). However, the correlation between the depth of convection and the NAO phase is not perfect because so many factors are at work. For instance, NAO index was low in the 1996 after several high-NAO years in a row before but the convection in the winter of 1996-1997 reached 1500 m (Pickart et al., [32]).

Interior of the Sea.

Upper 1000-2000 m. The deepest convection (down to 2300 m) was observed in the early 1990s, in particular, in 1994, when the coldest ($\theta \sim 2.7^oC$), freshest ($S \sim 34.8$ psu) and densest LSW was formed (Yashayaev, [45]). A large and homogeneous volume of the LSW_{1994} was produced as a result of a prolonged strong cooling of the region following the freshening of the upper layer. As shown in this study, in the subsequent years the atmospheric forcing has weakened leading to decreasing of the depth of penetration of the wintertime convection. The mixing no longer penetrated deep enough to provide a necessary supply for the LSW_{1994}. As a result, this layer became thinner and got warmer and saltier with time. The water mass formed during the early 1990s is seen in the θ/S properties of the basin during the whole decade up to 2005, as found by Yashayaev, [45]. Another bulk of LSW formed by the second most significant convection since 1994 was produced in 2000 when the forcing was very intense and enough for the overturning to the depths of $\sim$ 1000 m to happen. Starting from the year 2000, one can distinguish two LSWs at different depths in the basin. One of them - LSW_{1994} still exists in the Labrador Sea and is not completely flushed away south and is located at $\sim$ 2000 m while more recent product of convection, LSW_{2000} occupies the depths of $\sim$ 1000 m. Both of them are seen on the θ/S diagram as pronounced minima of temperature and salinity (see Figure B-6). Starting from 2000, conditions do not predispose the Labrador Sea for a deep overturning - there has been no deep convection since then. As a result, the minima of the Labrador Sea Water continue to get warmer and saltier and if this trend continues, the LSW values can soon reach the warmest and saltiest values on record (Yashayaev, [45]).

Irminger Current and Deep Waters. Irminger Current properties also change from year to year: its salinity and temperature have increased recently (Yashayaev, [45]). It is thought to be linked with the increasing transport of its source - the North Atlantic Current (Yashayaev, [45]). Also, the atmospheric conditions over the Labrador Sea are milder than in the early nineties which causes less heat loss everywhere in the basin including the boundary current region as well (Yashayaev, [45]).
Variability in the deep part of the basin (2300 m and down to the bottom) which consists of the NEADW and DSOW is caused by the processes governing formation and entrainment of these water masses in the regions of their origin and overflow respectively. NEADW has experienced a decrease in salinity and temperature by $\sim 0.15^oC$ and 0.025 psu respectively (Dickson et al., [6]; Yashayaev, [45]). This can be a result of freshening of the Subpolar Mode Waters and mixing with the colder and fresher than usual Labrador Sea Water. In 2000 NEADW became the freshest on record and after this year the trend has changed and the salinity increased. DSOW occupies the bottom 100 m of the sea and is fresher and colder than NEADW. As shown by Yashayaev, [45], variability scales of that water mass are smaller than for the upper layers and frequent periods of warm and salty waters near the bottom are interchanged with years of cooling and freshening. Spatially the DSOW is saltier at the eastern side of the basin, where it enters the basin.

Variability of the eddy field. Eddy field has also changed from the early 1990s to the present time (L03, [26]). Eddies provide connection between the boundary current and convective interior (Katsman et al., [15]; Spall, [37]; Straneo, [41]). Convection in the interior of the Labrador Sea in the late 1990s was not so intense as earlier in the decade (Yashayaev, [45]). Also, an inflow of fresh water at the surface and saline at mid-depth along with an absence of convection made conditions for overturning less favorable, and eddies were able to live longer since they were not destroyed by the surface fluxes (L03, [26]). There was an increase in the eddy population in the southern Labrador Sea during the late 1990s (L03, [26]). That implied that eddies were able to drift in the interior for a long time so as to be able to reach the southern part of the Labrador Sea. As was reported by L03, [26], based on the mooring observations, speed of the interior currents has increased during the years of relatively weak convection which could be a result of an enhanced eddy activity in the Labrador Sea. Altimetry measurements have shown that during the years of increased boundary current instability corresponding to the enhanced eddy kinetic energy (EKE) maximum, lateral heat transport from the boundary region to the interior was greater than usual. This lead to reduction of the convection depth due to significant lateral inflow of warm water from the intensified boundary current (L03, [26]; Eden and Böning, [7]).

2.4 Eddies in the Labrador Sea

Mainly three types of eddies have been observed in the Labrador Sea: convective anticyclonic lenses, cyclonic and anticyclonic Irminger Current eddies (Figure B-7). To my knowledge, there are no observations of convectively generated cyclones available for the Labrador Sea. The reason for that can be either differences in the formation rate or a more unstable nature of convective cyclones and thus different evolution path (L03, [26] and references therein). By and large, there is a pronounced dominance of the anticyclones in the Labrador Sea.

As previously mentioned, the focus of many recent studies was a wintertime convection and its parameters. Until the past decade eddies in the Labrador Sea were only considered as the preconditioning elements for convection. The process, following the winter overturning - restratification and its mechanisms were left in shade. All kinds of eddies participate in restratification: convectively formed lenses are responsible for carrying convectively formed water from the center of the basin to the edges (Katsman et al., [15]) and Irminger Current supply boundary current water to the interior. However, the latter play the most important role for the dynamics of the Labrador Sea and can balance the total amount of heat loss (Katsman et al., [15]; Spall, [37]; Straneo, [41]). Thus all act in the direction of reducing density gradients and mixing the water in the Labrador Sea (Straneo, [41]).

2.4.1 Historical overview

The first observations of eddies in the Labrador Sea are coming from the 1980s (Lazier, [19]; Gascard and Clarke, [9]). They found one or more short-lived features, described their θ/S properties ($\theta \sim 2.9^oC$, $S = 34.84$ psu) and circulation, estimated their radii. However, after this study they were not in the focus of interest and their importance for the circulation in the basin and for the heat and fresh water balances has not been discussed in the literature until the past decade. One of the reasons for the lack of eddies' observations is that, in general, ship measurements are expensive and hard to get in this place of strong winds and cold temperatures. Secondly, the deformation radius is small in high-latitudes and only the strongest features are seen from altimetry data (convectively formed lenses are not seen at all; L03, [26]). Thirdly, the cloudiness over the Labrador Sea makes it hard for the satellite to obtain a clear picture of the sea surface temperature (SST) of the region to detect the warm-core Irminger Current eddies and some of them may not have a surface signal.

In the 1990s when the Deep Convection Experiment began in the Labrador Sea and the first data were obtained, theoretical works regarding the Labrador Sea cyclones and lenses were published. The goal of the LSDCE (Labrador Sea Group, [16]) was the Labrador Sea convection and not the investigation of the eddy population and properties. Observations of the eddies were obtained only accidentally and eddies were considered only as a part of preconditioning mechanism for convection or the result of rim current instability (Legg and McWilliams, [22]; Jones and Marshall, [14]). These modeling and theoretical studies lead to the understanding of the dynamics of the convective lenses and cyclones along with their role in preconditioning and convection. However, Irminger Current anticyclones remained out of the scope. Owing to the development of altimetry and launch of the TOPEX/POSEIDON (1992) the regions of the eddy activity were revealed and the importance of the Irminger rings became obvious (L03, [26]).

One of the first to study spatial and seasonal patterns of the eddy variability was Prater, [33] who used altimetry and RAFOS floats to measure the eddy activity. The floats sampled 3 eddies originating in the Irminger Current: one of which was an anticyclone and two others - cyclones. Prater's motivation for studying eddy variability in the Labrador Sea was to understand the mechanisms of the rapid restratification in the water column after convection and the role the eddies play in the transition from the cyclonic flow at the boundaries to the anticyclonic one in the interior. θ/S properties of the Irminger Current eddies in the upper 375 m were documented along their trajectories; the estimates of radii and velocities were obtained. This study will be discussed in more detail in the subsection "Irminger Current eddies".

Much progress was made in understanding the vertical structure of convectively generated eddies and Irminger Current cyclones trough the study of Lilly et al., 2002, hereafter L02, [25]. This study was based on 6 months of mooring observations at the site of the former Ocean Weather Station Bravo. L02 have identified two types of eddies in the Labrador Sea based on their velocity structures. One was convectively generated anticyclones and the other - cyclones of Irminger Current origin. They have described their core properties and provided an estimation for the radii.

The rest of a 5-year mooring record was analyzed in L03, [26], where the authors have combined the mooring and altimetry observations to document the temporal and spatial variability of the eddy field in the Labrador Sea. It was found that Labrador Sea is quite rich in eddies and that those eddies store and carry a lot of heat. Boundary current dynamics was emphasized to be important both for dynamics and properties of the Labrador Sea. More about the results of this work can be found in the following subsections.

The modeling study of Katsman et al., [15], addressed the process of restratification after the deep convection. An idealized hydrostatic model was used to perform a number of experiments concerning the restratification of the Labrador Sea after convection. Salinity effects were neglected in the simulations for the sake of simplicity

and the restratification is governed only by the heat fluxes. Wind forcing was not applied to any of the model simulations. It was found that the Irminger Current plays a dominant role in restoring the properties of the basin to their preconvection state by shedding eddies. Irminger Current eddies were shown to be the main mechanism of property exchange between the boundary current and interior. Restratification by rim current eddies was shown to be much less efficient compared to the Irminger Current eddies. An estimate of the eddy contribution to the heat balance of the Labrador Sea was estimated to be 50-92 % of the annual heat loss.
The most recent work on the Irminger Current eddies is by Hatun et al., [12]. This study has used the data from 2 gliders, altimetry and floats. Core properties, vertical structure and velocities were obtained from a number of profiles through the eddies. The potential contribution to the restratification both in terms of heat and fresh water balance from an eddy was estimated. The lower layer (200-1000 m) would lose 1 cm of fresh water and gain 43 MJ m^{-2} and the upper 200 m would gain 2.5 cm of fresh water if an eddy is laterally mixed.

As it was mentioned before, there are three types of eddies in the Labrador Sea: convectively generated lenses and Irminger Current eddies of both signs. Since convective lenses was observed much earlier, consider them here first.

2.4.2 Convective lenses

Anticyclonic lenses in the Labrador Sea were first found by Gascard and Clarke in floats and hydrographic measurements in March of 1976.
Record from several moorings during 1994-1999 have revealed a substantial population of all three kinds of eddies observed and described in L02, [25], and L03, [26]. In the papers different sources of data were used to study the eddies: hydrography, altimetry, floats and moorings. The moorings located in the convective area of the sea were densely instrumented and measured temperature, salinity and velocity at

3-12 depths each. These instruments have captured anomalies corresponding to several mid-depth anticyclones and surface-intensified cyclones and anticyclones. The velocity structure revealed that there were no convectively formed cyclones in the sea during that period and two possible explanations for such a rarity were discussed. Numerical studies show that the deformation-scale cyclones are less stable than anticyclones (Legg et al., [22]) and that the topographic beta-effect could account for a formation of the weaker cyclonic part within a dipole. A typical lens is shown in figure B-9. The cores of such lenses were found between 250 and 1250 m and had properties at the cores in the range: $\theta \sim$ 2.6-2.7^oC and S ~34.81-38.82 psu - which is $\sim 0.1^oC$ colder and $\sim$ 0.01-0.02 psu fresher than the ambient water (L02, [25]). θ/S properties suggest that eddies were formed during the winter, presumably when the rim current around the chimney became baroclinically unstable. All lenses recorded by a mooring had clockwise velocities thus were anticyclones. Their angular velocities range from 15 to 30 cm/s and radii from 5 to 15 km, a little over the Rossby radius of deformation for that latitude. All anticyclones have cores of cold and fresh water with a maximum velocity value at the core. The isopycnals are domed above and depressed below the core for about 150-300 m which corresponds to the anomaly in density of $\sim$ 0.01-0.02 g kg^{-1}. Rossby number for this kind of the eddy varies from 0.1 to 0.5. It was found that these lenses often have vertically aligned cores which could be a result of their merging.

2.4.3 Irminger Current eddies

The baroclinic instability of Irminger Current produces both types of eddies: cyclones and anticyclones which sometimes are seen as dipole vortices. Altimetry observations and numerical simulations are in a good agreement with this picture. Irminger rings are the long-lived structures formed where the Irminger and West Greenland Currents split. Theory and models were combined to explain the mechanism for the eddies' formation (Eden and Böning, [7]). It was discovered from the altimetry that there exists a region of enhanced eddy activity located at 61.5°N, 52^{o}W and that the sea

surface height variability has a seasonal cycle with a peak in winter (Prater, [33]; L03, [26]). The second largest maximum in SSH is situated in the central Labrador Sea at 58^{o}N, 52^{o}W and it also undergoes seasonal changes. But the peak of variability at that location is shifted from the one at west Greenland by about 50 days - it occurs in April. The suggested reason for this delay is accounted for the propagation of eddies from the place of their formation in winter to the central sea (L03, [26]).
Typical anticyclone and cyclone are shown on figures B-8 and B-9. Cyclonic eddies are less common in the Labrador Sea likely due to their more unstable nature. In the numerical simulations the number of eddies of both signs at the moment of their generation was approximately the same (Katsman et al., [15]). Prater, [33], has sampled two cyclones using the RAFOS floats which allowed to calculate their diameters ($\sim$ 20-50 km) and azimuthal velocities ($\sim$20-40 cm/s). Unfortunately, the vertical structure of those eddies was resolved only down to 800-1000 m and the longest record was only 60 days in the summer. No salinity measurements were obtained at that time. However, we know from that work that eddies were moving between the 2000 and 3000 m isobaths with a speed of $\sim$10-20 cm/s. Core temperature of cyclonic eddies was $\leq 3.5^oC$ and anticyclonic $\geq 4^oC$. Anticyclone turned out to have a cold layer at the surface as opposed to the cyclones which have warmer surface water. Rossby number of the cyclones ranges from 0.2 to 0.5. L02, [25], have also investigated two cyclonic anomalies passing by the mooring the θ/S structure of which supported the results from Prater, [33]: radius was estimated to be at least 12-20 km, velocities $\sim$10-15 cm/s but the Rossby numbers were lower: 0.1-0.2. There is no inconsistency in those works since the locations, methods and times of the observations were different: the eddies in the central part of the Labrador Sea are more likely to have been modified by the surface fluxes and evolved into features of different properties.

Irminger Current anticyclones (further referred to as Irminger Rings) are the most commonly observed type of the eddy in the Labrador Sea. Altimetry observations by L03, [26], show that from 33 anomalies detected, 31 were anticyclonic eddies of the Irminger Current origin. A distinguishing feature of this class of eddies is a warm and salty core at depths of $\sim$ 300-500 m underlying cold and fresh layer at the top, which was recently observed by Hatun et al., [12]. This θ/S structure also suggests formation in the boundary current since it is known that the WGC and IC form a system of warm and salty water underlying cold and fresh water. Isopycnal displacement within such eddies is of the order of $\sim$ 300 m compared to the mean Labrador Sea water according to L03, [26]. All the eddies originating in the Irminger Current are surface intensified with velocity of 30-80 cm/s and radii varying from 15 to 30 km (L03, [26]).

As reported by L03, [26], multiple cores are a common feature of the Irminger Rings which have two or more warm mixed layers stacked one on top of the other (Figure B-10). At least half of the observed eddies had secondary core at depth of $\sim$1-1.5 km which was seen in the density field as an enhanced isopycnal depression. This multiple core structure is seen in all the fields: temperature, salinity and density which suggests that these homogeneous mixed layers are the results of prolonged contact of the water with cold air causing deep overturning. The depth of each of the cores can be as deep as 500 m which points out to the fact that the water column was exposed to the fluxes for a long time. Yet it is still unclear how these multiple-cored eddies can be formed. It seems unlikely that the deepest core is a product of convection - given that realistic heat fluxes cannot drive mixing of the water column to 1500 m. Thus the hypothesis of the formation of such complicated structure of the mixed layers due to a convection followed by restratification and a second convection is not likely to be the case. The other possibility for this structure to develop is the merging of two separate eddies with their own mixed layers under certain conditions. And indeed altimeter measurements show that the majority of eddies are formed at the beginning of winter, in January (Prater, [33]; L03, [26]) Hence, theoretically by the end of winter the eddies are able to develop deep mixed layers and if they merge after a little restratification, one might get the vertical profile similar to the one shown on Figure B-10 (L03, [26]).

Mixed layer can be an interesting thing to look at: its depth can provide information not only about the fact that the eddy has already experienced convection, but it can also indicate the number of convective winters the eddy has survived. For example, one eddy was thoroughly surveyed with XBTs during the winter cruise of the 1998 right during the time of strong buoyancy loss (L03, [26]). Surprisingly, mixed layer in that eddy was ~500 m as opposed to the mixed layer in the surrounding water of the depth of ~250 m. This result is striking since from the numerical experiments of Legg and McWilliams, [23], it would be expected that the deepest mixed layer would occur in the cyclones, the features with domed isopycnals and dense water close to the surface. On the other hand, Irminger rings have a core of warm and buoyant water and thus are expected to be more stable to the forcing than the ambient water. But the explanation to this still can be found. As discussed by L03, [26], since they are isolated from the water around them, the restratification process inside such structures happened much slower with the lack of lateral fluxes. Warming of the eddy after the convection ceases is due only to the heating from the sun and thus only a very shallow layer at the surface restratifies. In such a way, eddy becomes preconditioned to the next year's convection since it has dense and once-convected water below a thin stratified layer which is easy to erode, L03, [26]. When the next winter comes and the buoyancy loss occurs, this thin surface layer breaks up very quickly and convection starts mixing the water from the depth of last year convection and below. Hence, the deepest mixed layer was observed inside an anticyclonic eddy shown on the example of wintertime 1998 anticyclone (L03, [26]).

The amount of heat stored in the eddies was calculated by L03 [26]. Based on the profile shown on B-10, the heat content of the unit area of the water column is

$$H(z) = \rho_0 c_p \int \theta(z')dz'; \tag{2.1}$$

where ρ_0 is a reference density, c_p - heat capacity of water under constant pressure, z - vertical coordinate, positive upwards. The difference in the heat content of an eddy and the mean Labrador Sea profile down to 2000 m is 4.6 GJ m^{-2}, as estimated by L03, [26]. If the average radius of an eddy is 20 km and the radius of the Labrador Sea interior represented as a circle is 325 km, then the eddies can contribute up to

40% of the annual heat loss according to the calculations done by L03, [26].

While some properties of the Irminger Rings are known, their evolution, the mechanisms responsible for changes in the eddy's structure are still not fully understood. Each of the works mentioned above have contributed enormously to the eddies' investigation but some unresolved issues still remained. There were several problems: first of all, the moorings have a discrete set of measurements and do not resolve the surface ~100 m, thus limiting the possibility of studying the changes in the whole water column. This upper layer is particularly important since it was shown that just formed eddies have fresh water at the top (Hatun et al., [12]) - thus, might be able to contribute to the freshening of the Labrador Sea during the summer months. Secondly, all the measurements took place in the same locations limiting the possibility to investigate the spatial distribution of properties in the eddies. All the eddies which have passed by any of the moorings were at least couple of months old and thus have already been exposed to the surface fluxes and their core properties might have changed. It is proposed in the present work to analyze the properties of the whole water column of the eddies from the surface to the bottom, paying particular attention to the differences in the structure and water mass properties of the wintertime eddies; to study their interannual and seasonal variability.

2.5 Theoretical Background

Irminger Current eddies are in the gradient wind balance meaning that Coriolis force is in balance with pressure gradient force and centrifugal force (Figure B-12). Thus, dynamics of the Irminger Current anticyclones can be described by the following equations (in cylindrical coordinates):

$$-\frac{u^2}{r} - fu = -\frac{1}{\rho_0}\frac{\partial p}{\partial r} \tag{2.2}$$

where u is an orbital velocity, f - Coriolis parameter, p - pressure,
and hydrostatic balance:

$$0 = -\frac{\partial p}{\partial z} - \rho g. \tag{2.3}$$

Since eddies are perturbations around the mean, density and pressure values can be represented as the sum of background filed and perturbations:

$$\rho = \rho_0(z) + \rho'(r, z), \tag{2.4}$$

$$P = P_0(z) + P'(r, z). \tag{2.5}$$

If P and ρ are substituted into equations (2.2 and 2.3) and appropriate simplifications are made, one gets the expressions for the perturbations:

$$-\frac{u^2}{r} - fu = -\frac{1}{\rho_0}\frac{\partial p'}{\partial r}, \tag{2.6}$$

$$0 = -\frac{1}{\rho_0}\frac{\partial p'}{\partial z} - \frac{\rho'}{\rho_0}g. \tag{2.7}$$

Knowing that eddy's dynamics obey these equations and assuming that the eddies are axisymmetric, we can choose velocity which decays from the center of the eddy and calculate the corresponding density anomaly (as Legg et al., [22], calculated for a cyclone). For finding the expression for density we differentiate equation (1) in z and equation (2) in r, and substitute one into the other, we get:

$$\frac{g}{\rho_0}\frac{\partial \rho'}{\partial r} = -f_0\frac{\partial u}{\partial z} + \frac{2uu_z}{r}. \tag{2.8}$$

Velocity is taken to be dependent of two parameters - radius and depth:

$$u(r, z) = u_0 \cdot F(z) \cdot G(r); \tag{2.9}$$

And if this expression is substituted into the equation (2.8) then final equation for density looks like:

$$\rho' \frac{g}{u_0 \rho_0} = f_0 \, G' \int F dr - 2 \, u_0 \, G \, G' \int \frac{F^2}{r} dr. \tag{2.10}$$

Given the velocity, the value of the Coriolis parameter and radius of the eddy - estimated to be $\sim$ 20-30 km (L03, [26]), one can find the distribution of density and isopycnal displacements corresponding to an eddy (Figures B-14 and B-15). Velocity profile is taken to be linear in the eddy and decaying exponentially outside an eddy (Prater, [33]; Hatun et al., [12]). The opposite problem when the density field is given and the velocity is to be found can be performed as well.

In the data eddies are seen in temperature, salinity and density fields. How does one know what to refer as cyclone or anticyclone? In temperature and salinity fields we are looking for the water masses corresponding to the ones of the eddy sources. In density field the values can be compared as well but eddies can be seen even with an unarmed eye: by the isopycnal depression or uplift.

In the Labrador Sea, we know that the doming of the isopycnals correspond to a cyclone and depression of isopycnals to an anticyclone based on the fact that in the mooring works the former had counterclockwise velocities and the latter - clockwise, i.e. had cyclonic and anticyclonic flows respectively (L02, [25] and L03, [26]). θ/S properties were in agreement with the described above structure.

Chapter 3

Data Set

3.1 Description of hydrographic data

The questions raised in the previous chapter are addresses using the hydrographic data from 1990-2004. The majority of measurements was obtained along the WOCE section AR7W. Every year starting from 1990 until the present time the Bedford Institute of Oceanography has been occupying this line in the Labrador Sea as one of Canada's contributions to the WOCE. The objectives for the surveys vary from studying the chemical composition and biological activity to the interannual variability of the water masses and strength of convection. All the cruises include not only the hydrographic measurements but also the deployment of different types of floats, drifters, mooring deployments and recoveries. Recently the Expendable Bathythermographs (XBTs) have been deployed along the AR7W as well. Each cruise occupied traditional WOCE section AR7W and some of them sampled boundary current areas and interior of the Labrador Sea as well. Schematic map of these sections is shown on Figure B-1. The extension of AR7W is not the same every year, it varies from 700 to 1000 km. Depending on the cruise goals, AR7W may be sampled more frequently at the boundary current regions or at the place where convection takes place. Continental slopes are generally not included in the measurements in winter and in some of the spring sections. It is mostly caused by danger of colliding with icebergs on the Greenland side and by the presence of the pack ice on the Labrador side.

In 1997 a section parallel to AR7W was made to resolve the convection better and to provide additional information about the properties of the Labrador Sea outside AR7W. Most of the cruises took place in the late spring or early summer due to the difficulties of getting the data under the winter conditions in this region. There are only two years of winter observations in the Labrador Sea and which were obtained during winters of 1997 and 1998 by PIs R.Pickart and E.D'Asaro. For seasonal distribution see Table A.3.

In 22 sections out of 33 the data were collected on the way from Labrador Peninsula to Greenland, however, the cruises where the line was repeated in both directions also exist. Vertical resolution of the data measurements varies from year to year and within a section as well: boundary current regions and the upper part of the Labrador Sea is sampled with better resolution as opposed to the interior. Unfortunately, distance between the CTD stations can be as large as 200 km so the horizontal structure of the sea can be investigated only on the scales of a basin. For example, each hydrographic section allows to estimate the area occupied by convectively formed water but horizontal dimensions of a smaller features like eddies can not be obtained.

The measurements along the AR7W exist for every year, however, two years of observations are not considered in this work. Year 1991 is not used due to a low vertical resolution (as low as 1 point for every 50-500 m at different depths as opposed to every 5-10 m for other years). In 1992 there were no complete lines across the basin, only the sampling of the boundary current sections was made.

There are several sources of hydrographic data in the Labrador Sea: Bedford Institution of Oceanography, BIO, (Canada); Woods Hole Oceanographic Institution, WHOI (USA) and the Leibniz Institute of Marine Sciences at the University of Kiel, IFM-GEOMAR, (Germany). All the data used in this work were put together by I. Yashayaev, an active participant of most of the BIO cruises to the Labrador Sea and a scientist who calibrated the BIO data from 1993 onward.

3.2 Processing and calibration of the data

In all the cruises a CTD (Conductivity-Temperature-Depth) package that includes sensors and bottles mounted on a frame was used for the hydrographic measurements. Usually it consists of 24 bottles for water sampling and SeaBird sensors for conductivity, temperature, pressure and oxygen. All these values are measured at each CTD location from the surface (or 5-10 m below in the rough seas) and down to the bottom. Data are collected on both downcasts and upcasts, however this dataset contains only the downtrace data. It is more precise than the upcast since the water column was not perturbed prior to the measurement and no stops for the bottle closing were made. The difference between the up- and down-casts is computed and if some errors seemed to be observed, the upcast is also taken into account. Some of the stations were repeated because of the problems happening during the cast. In these cases casts shallower than 300 m were neglected while duplicate casts were averaged in depth. The CTD data were calibrated and subsampled into different depth intervals (I. Yashayaev, personal communication). Vertical resolution for the data set differs from year to year and also varies with depth (some years had the as good as 2 db resolution while the others were sampled and calibrated on the irregular grid of 3-11 db). Data from the years with plausible vertical resolution is transferred to a regular 10 db grid.

All CTD sensors are usually calibrated before and after the cruise. The institutions which collected the data calibrated using different procedures but the general mechanism is the same. Pre- and post-cruise laboratory calibrations are made to generate the tables of corrections, which are applied to the obtained CTD data afterwards. During the cruise, salinity and oxygen data from the bottles are used to calibrate or check the CTD sensors. From 1990 to 2000 the temperature accuracy is 0.005^oC, salinity – 0.001-0.002 psu, and from 2001 onward the values are 0.002^oC and 0.001 psu respectively (Yashayaev, personal communication).

Chapter 4

Identification of the eddies in the observational data

This chapter focuses on the eddy identification from different kinds of data. I will cover previous studies which used mooring, float and glider data to study Labrador Sea eddies. Each study developed a criterion for whether an observed feature *was* or *was not* an eddy. Here I review these criteria and then explain how eddies were identified in the hydrographic data in this study.

4.1 Previous works: mooring data, RAFOS floats and gliders

Moorings.

A five-year mooring record was collected from the Labrador Sea in 1999. The mooring included an ADCP (acoustic Doppler current profiler), 6 current meters with temperature sensors, 7 temperature-salinity measuring sensors and a Weather Observation Through Ambient Noise (WOTAN) recorder (Figure B-11). Data available from the mooring record included current speed, direction, temperature and salinity at several depths with an interval of an hour. Unfortunately, the uppermost temperature sensor failed and the water column was resolved only from 120 to 3486 m.

By the end of the observational period, 33 eddy-like anomalies were observed. In the first work, L02 [25], the authors analyzed only the first year of measurements and therefore only a subset of those 33 anomalies (6 eddies) was described. Four of those eddies were convectively generated anticyclones and the other two were Irminger Current cyclones (for more description see Section 2.4.2-3). An eddy was identified as having simultaneous anomalies in θ, S and velocity over a range of depths. Each of those eddies had anomalies at 110-1250 m: temperature $> 0.05^oC$, isopycnal displacement of > 100 m and velocity anomaly > 10 cm s^{-1}. All convectively generated lenses had mid-depth cores of cold and fresh water with anticyclonic currents.

The rest of a 5-year record was analyzed in L03, [26]. This study provided results for both convectively generated and Irminger Current eddies. Speed and direction of a current recorded by a mooring were the first-order parameters to look at in the time series of measurements. The authors were able to distinguish between an eddy-like event and apparent non-eddy based on a careful analysis of the velocity structure and space and time duration of the anomaly. To conclude that a certain feature is an eddy one should support the "first guess" from velocity field by matching temperature and salinity signals typical for the eddies. Since lenses are summarized above, we consider the identification of Irminger Current eddies. As opposed to the convectively generated *depth-intensified* eddies, Irminger Current eddies were identified by a strong *surface* signal recorded by both sensors at 260 m and 510 m in velocity, salinity and temperature ($V = 30 - 80$ cm s^{-1}, $S \sim 34.85$ psu and $\theta \sim 3 - 4.15^oC$). These eddies are much warmer than the interior at these depths and than convectively generated lenses.

Floats.

Eddies can sometimes be easily identified in RAFOS float trajectories. Prater's work, [33], is based on float measurements combined with altimetry to look at the properties of the Irminger Current eddies. All the floats trapped in the eddies were not put in there initially but were caught at some time during their missions. The most noticeable signature of an eddy in the data is found in the float trajectory. During their mission, trajectory of the floats changed from being in the boundary current, following bathymetry, to a rapidly rotating trajectory and drifting to the center of the sea. The floats recorded pressure and temperature along their paths so the changes in the style of drifting were also accompanied by changes in the water mass properties. Since each of the floats made vertical profiles every seven days, one could even observe the evolution of the eddy's core properties as the float was getting further from the eddy center. The cyclone cores were characterized by a slightly cooler temperature than the Irminger Current at depths ($< 3.5^oC$) and a slightly warmer temperature at the top ($\sim 3.8^oC$). The measurements of the floats in an anticyclonic eddy were as warm as 4.9^oC at about 200 m depth and colder (3.1^oC) at the surface, which was consistent with the theory explaining the mechanism of the eddy generation (Prater, [33]; Eden and Böning, [7]). The West Greenland Current system is bounded on one side by the Greenland coast. Due to this fact, eddies generated as a result of the baroclinic instability of this current have different water mass properties depending on whether the current meandered in-shore or off-shore. Anticyclones are the result of a shoreward deviation and thus at the surface are cold (contain only shelf water), and warm at depth (contain only Irminger Current water). Cyclones are warmer at the surface since shore water is mixed with a warmer, interior water. But at the same time they are colder at depths because Irminger current is mixed with a colder interior water.

Gliders.

Gliders used by Hatun et al., [12], are autonomous instruments preprogrammed to reach a certain region at some predetermined time. Their trajectory is known and combined with the measurements of the water mass properties which makes it possible to identify eddies in the glider data. Hatun combined data from two gliders with ARGO floats and altimetry to provide a better spatial and temporal picture.

After the mission was complete, the paths of the gliders were over-plotted with the SSH (sea surface height) and SST (sea surface temperature) data. The signals of the anomalies in these pictures looked like cold (and fresh) filaments of West Greenland current corresponded to the doming of the sea surface indicating appearance of the Irminger ring with a warm core below. This study provided *the first* observation of a recently formed eddy which had a strong signature of West Greenland Current, cold and fresh in the top 100-150 m ($\theta \sim 2.5^oC$, S $\sim$ 34.3 psu). At a depth of 200-900 m, a warm and saline core was seen ($\theta \sim 4.6 - 5.2^oC$, S $\sim$34.9 psu). The vertical structure of the eddies containing cold and fresh layer at the surface was captured for the first time. The signature of the glider's trapping in the eddy was appearance of an anticyclonically looping trajectory together with measurements of θ/S and velocity structure. These signals could not be interpreted ambiguously but for more confidence the track of the glider was modeled theoretically and both trajectories were in a good agreement.

In summary, identification of the eddies from mooring observations was based on finding three simultaneous anomalies: in velocity, temperature and density fields. RAFOS floats provided looping trajectories together with temperature and velocity measurements - that was enough to decide whether the float was in or outside of the eddy. Gliders were caught in an eddy recorded temperature, salinity and velocities inside its core. The trajectory of the glider inside an eddy is similar to the one of the float.

It was helpful for the eddy appearance verification that the measurements in all these works have taken place during a long time. If just a single anomaly in one of the fields occurs, it is not sufficient for an anomaly to be called an eddy. Frequent (in time) records were important for the eddy-defining purposes providing the necessary resolution.

In all these studies there are some common features characterizing the eddies. All of them are either cold (convective lenses) or warm (Irminger Current eddies) anomalies with respect to the mean at 500-2000 m or at the 200-800 m respectively. The cores of the eddies are revealed by either upward (IC cyclones), downward (IC anticyclones) or both (lenses) isopycnal displacements in the center of the core. Radii of the eddies are relatively small in the high-latitudes due to a small deformation radius and vary from 5 to 25 km (the smaller value corresponds to convective lenses and the greater to the Irminger Current eddies). Basic properties of the eddies are summarized in Table A.4.

There are many advantages these methods of measurements have, but there are some disadvantages as well. Moorings did not resolve the whole water column and thus some surface and small-scale features of the eddies could have been missed. Moreover, they did not provide information on the surface structure of the eddies eliminating the possibility of observing the fresh cap. Secondly, the eddies which reached the mooring site have all been subjected to the surface forcing for some time thus limiting the possibility of studying their evolution. Also, one of the constraints of this method was the requirement of a slowly changing advecting flow, the violation of which could have lead to misidentification. RAFOS floats didn't sample salinity and both them and gliders resolved only the upper 1000 m. Gliders sampled only two eddies and both of them were in the boundary current. Unlike RAFOS floats, the gliders managed to stay with the eddies in the wintertime during the active buoyancy loss from the water, however, the summertime post-convective warming was not observed.

4.2 Eddies in the hydrographic data

Eddies are identified from hydrographic data in the present work. Hydrographic data do not contain any direct velocity measurements or trajectories so the identification of the eddies must be based on water mass properties alone. In general, objective eddy identification criteria are difficult to develop. Anomalies at fixed depths are not necessarily a good indication of an eddy due to a large variability both in the interior properties and in the properties of the eddies. A subjective criteria is presented below.

Since the present work is focused on the Irminger Current eddies, in particular, anticyclones, I will look in the hydrographic data for their typical characteristics known from previous studies. I will be identifying eddies based on their θ/S properties. I will look for both absolute values of temperature, salinity and density in the ranges described above at 200-800 m and for warmer, saltier and lighter anomalies compared to the mean Labrador Sea values.

In almost all the sections one can see at least one anticyclonic eddy, e.g. figure B-16. Measurements at stations 19 and 20 (and possibly 18) were obtained within an anticyclonic eddy. Station 14 was likely to be in a cyclonic eddy. Such a frequency of eddy observations even in the hydrographic data suggests that probability of having a profile within an eddy while occupying AR7W is high. No eddies were observed in 10% of the hydrographic sections. I was looking for temperature, salinity and density anomalies presented in the Table A.4 as a "first guess". For my work, since I am interested in anticyclones, I will look for warm ($\theta \geq 4^oC$) and salty (S $\sim$ 34.9 psu) in the depth range of $\sim$ 200-1000 m and fresh at the surface 100 m (S $\leq$ 34.85 psu) values. In this particular example, when one sees a very clear eddy-like signal, temperature in the surface layer warm which does not correspond to the expected cold temperatures of the West Greenland Current system. The reason is in the fact that this section was occupied in May when the surface layer in the Labrador Sea begins to warm up. Station number 14 was presumably occupied in a cyclonic eddy or in a part of a dipole eddy. Dipole eddies are self-advecting structures containing warm surface water in the cyclonic half and cold - in the anticyclonic. They are rarely sampled in the Labrador Sea (one example was presented in L02, [25]), but are seen from altimetry (Prater, [33]). The distance between the cores of the possible dipole is about 50 km which is not in contradiction with the previous observations: the radius of the Irminger ring can be as large as 30 km. It is hard to conclude from the only snapshot given by a CTD section what the full three-dimensional structure of eddies looks like.

Unfortunately no quantitative conclusions about the size of the eddy or its dipolar/monopolar structure can be made due to the lack of knowledge obtained from hydrography. One does not know whether the station was taken in the center of the eddy or on the edge, however in the case of station 14 distance between the stations suggests the sampling of the edges. Without knowing where exactly this measurement was obtained with respect to the vertical axis, one should make some assumptions about spatial structure or strength of an eddy. Although, according to Hatun et al., [12] the core of the eddy has horizontally homogeneous properties in about 2/3 of its volume. Since the core is homogeneous over the larger area than it is variable one can assume that the probability of the station to be in the homogeneous part of the eddy is greater than on the edge.

There are certain things one cannot get from the hydrographic data such as, for instance, sea surface height anomaly and velocities, radii or any information about the path of an eddy. The consequences of this are that one can not even be sure based only on the hydrographic record whether the cyclone or an anticyclone is being observed. That was one of the reasons for using multiple sources of data in the previous works.

In general, based on hydrographic data alone, not much can be said about temporal or spatial distribution of the eddies in the Labrador Sea since all the eddy-like events are captured only along several lines in the Labrador Sea once or twice a year. Temporal resolution is limited in a way that one can hardly sample the same eddy twice with more than a daily interval. Thus, the information about the size of the eddy, its dipolar/monopolar structure and other horizontal properties can not be obtained from the hydrographic data set. Horizontal structure of the Labrador Sea from the hydrographic measurements can be investigated only on the scales of a basin. For the purposes of studying properties and evolution of the eddies one should still make several assumptions. First, the hydrographic section is considered to be a snapshot in time. This assumption is mostly made for the purposes of calculating the mean state of the Labrador Sea and not for dealing with eddies. Second, as was mentioned above, we assume that the eddy was sampled in the center. Third, since I am using

previous studies as a guidance, I assume that eddy velocity structure in this data set is similar to the structure observed by the mooring and gliders. This means that if, for example, I see a depression of isopycnals and a warm core - I assume that this eddy is an anticyclone since these signals were typical for an anticyclone in the previous works (L03, [26]; Hatun et al., [12]).
Despite all these disadvantages, hydrographic data set has a lot of advantages. It resolves the entire water column from the surface (or, in rough conditions from $\sim$ 10 m below the surface) to the bottom with resolution of 1-2 db. In each station location such values as temperature, salinity, pressure, oxygen and sometimes other chemical water properties are obtained. Unlike mooring data collected only at one location, hydrographic data set covers a larger area and thus can potentially capture eddies close to their formation region. Due to a great lateral extension of the section, eddies are sampled at different distances from the source which suggests different times of their formation since they propagate at about the same speed (L03, [26]). Repeated hydrography allows to monitor the interannual and decadal water mass changes, their production rates and depths of penetration. Data from different seasons reveals typical seasonal features of the Labrador Sea allowing to compare properties of the eddies observed under different conditions.

Since almost all the sections contain at least one eddy the majority of which are anticyclones, statistical tools can be used.

First, one needs to find the eddy-like anomalies to work with. In the context of the present work any perturbation from the mean is an anomaly. Mean for all the sections is calculated by averaging the profiles within interior of the Labrador Sea eliminating the anomalies from the count. Interior of the Labrador Sea is often defined as the region encircled by a 3300 m isobath (L03, [26], and references therein). Once the mean values for all the sections in potential temperature, salinity and potential density are calculated, they are subtracted from the corresponding full section. After such procedure the section of the perturbations along the AR7W are obtained (Figure B-17). All this deviations from the mean are further considered as potential eddy candidates. Overall in 15 years of hydrographic data, 88 anomalies were found.

Two of those anomalies were unstable in the density field and thus were eliminated from further analysis.

At the moment of eddy formation, its core properties are very similar to the properties of the Irminger Current (Hatun et al., [12]). After being detached from the source, some eddies drift to the interior of the Labrador Sea, the others are advected into the boundary current, undergoing some changes in their cores. If the eddies were not evolving then the difference between them and the interior waters would always be as large as the difference between the IC and LSW. But the eddies do evolve, lose/gain heat and get mixed under the surface fluxes, and their properties are not identical to the ones of the Irminger Current anymore. However, for the purposes of eddy identification, I averaged potential temperature and salinity of all the anomalies over the density range of the Irminger Current taken from an average hydrographic section ($\sigma_t \sim 27.64 - 27.72$), shown on figure B-18. Irminger Current eddies were defined as features with all three anomalies being positive ($\theta' > 0$, $S' > 0$, $|\sigma_t'| > 0$) in the density range of $\sigma_t \sim 27.64 - 27.72$ and anticyclones were identified by applying a restriction on density which should be lighter than the mean. This histogram shows all the eddy-like features identified as Irminger Current anticyclones. Temperature and salinity anomalies of the anticyclones are positive with respect to the mean and density anomaly is negative. Based on this criteria there are 48 Irminger Current anticyclones and 2 Irminger Current cyclones in this data set. Values of the anomalies agree well with the ones found in the previous works for these types of eddies. For comparison see Table A.5. There are some differences in the values obtained from the hydrographic data set and from the mooring. First of all, the values from the mooring are given at 500 m depth whereas for the hydrography the range is in isopycnal surfaces ($27.64 - 27.72$) which, however, includes this depth but still is a wider range. This result is only qualitatively sensitive to the density range of the Irminger Current taken for the calculation and thus can be considered only as a guidance to proceed. The shape of the histogram does not change even if the values of the anomalies slightly change. Isopycnal displacements for all the remaining after applying θ/S

criteria anomalies were greater (by absolute value) than 100 m which agrees with the previous studies well (L02, [25]).

Chapter 5

Statistical analysis of the Labrador Sea eddies

Statistical analysis of the eddies derived from the hydrographic data alone can not cover all the aspects of eddy distributions and properties in this region. However, it still gives an idea of the most frequently sampled type of eddy, an Irminger Current anticyclone, and helps to approach such questions as: how likely will one see an eddy while occupying a hydrographic section across the sea; how much heat can an average eddy contribute to the budget of the Labrador Sea and what the mean properties of these eddies are and get quantitative estimates of eddy parameters. Eddy-like anomalies can be described from different prospectives: their location in the Labrador Sea, water mass properties, isopycnal displacement, vertical core structure, heat capacity and the others. In this chapter I will consider these parameters calculated using the hydrographic data set.

The 15-year hydrographic record consists of 33 sections across the Labrador Sea and as it was mentioned earlier, almost every section contains an eddy. On average, there are 19 stations along the line; average distance between the CTD stations is 50 km in the interior and 10 km at the boundaries. Only 3 out of 33 sections did not contain any eddy-like events, while some of the years sampled up to five anomalous structures. The spatial distribution of the data is not suitable for calculation of the number of eddies present and/or decaying each year in the Labrador Sea since all the measurements were taken only along several lines and did not cover the whole area of the basin. There were 86 eddy-like anomalies measured along the AR7W line during the 15-year period (FigureB-19). They were equally distributed along this section and in the other sections which indicates that the Labrador Sea has eddies not only in the proximity of the boundary current region. Based on this hydrographic record, that the chances of measuring an eddy-like event while occupying a section are quite high. However, not all the anomalies were identified as Irminger Current eddies due to the imposed restriction given by $\theta' > 0^oC$ and $S' > 0$ psu. After applying these criteria, we were left with only 50 eddies. The definition of an eddy is very subjective since some weak anomalies could have been rejected while they were decaying eddies and vice versa, some anomalies could have been called eddies while they were some different structures.

Irminger Rings are warm, salty and light anomalies at 200 m or greater depths since they contain Irminger Current water. Thus, I first reduced the number of eddies using these criteria: temperature and salinity anomaly with respect to mean should be greater than zero and density anomaly should be less than zero. Then we are left with only 48 anticyclones out of 50 which satisfy these conditions (and if density anomaly is greater than zero, we get the rest 2 cyclones). To be more accurate, let us restrict ourselves to defining a strong eddy as a structure which temperature, salinity and density are greater or equal than the mean for all the eddies. Further, due to the weakness of the signal for some of them and relatively small depth of anomaly penetration, the number was reduced to 29 eddies by applying criteria $\theta' > 0.2^oC$, $S' > 0.01$ psu and $|\sigma'| > 0.01$ over the IC density range. As expected, 27 strong anticyclonic eddies are lighter than the interior waters with exceptions of the wintertime eddies; warmer except for a thin layer at the surface typical for the eddies which have a cold and fresh layer at the surface and salty core at depth. θ/S properties of the eddies will be considered in the next chapter in more detail.

The distribution of the eddy-like anomalies can show the most probable places of finding eddies in the Labrador Sea interior and boundary current regions. Since there were many more measurements along AR7W then along the other sections, I will limit the analysis to the distribution only along AR7W. Average distance from the source of eddies sited around 61.5^{o}N, 52^{o}W is about 450 km along the section but it does not mean that the majority of eddies can be found at the center of the region. Indeed if one looks at Figure B-21 the most populated regions are within 300-350 km and about 600 km from the source. All the eddies found in these distance bands are located not far from the boundary: on the Greenland side in the first case and in the Labrador side in the second. The first peak is obviously due to the proximity of the Greenland part of the AR7W to the formation point of the eddies and the second peak could be explained by the fact that some of the eddies are swept by the boundary current and thus their path follows the 3000 m isobath as well (Hatun et al., [12]).

Monthly distribution of the eddies is shown on Figure B-20. The majority of eddies (38 out of 50) were observed during late spring - early summer. Such a distribution does not reflect the peaks in the eddy formation which is maximized in winter at the source and is recorded in the central Labrador Sea in April (L03, [26]). This distribution of eddies is mostly a consequence of the fact that the line AR7W is occupied more often in the warm time of the year. There were no sections done in April or September thus there are no eddies observed during those months. For the purposes of studying the evolution of the eddy field in the Labrador Sea this picture is not a problem. However, only the qualitative analysis and the evolution path can be examined with no reference to how often any of the phenomena are observed.

The difference between Irminger Current cyclones and anticyclones is not very well seen in the hydrographic data because no velocity measurements are available. Temperature and salinity properties of these two groups do not differ one from the other significantly: cyclones are just slightly cooler than anticyclones at mid-depth and warmer at the surface. Properties of the Irminger water and Labrador Sea Water differ from year to year (Yashayaev, [45]) thus smoothing the differences between the cyclones formed during the warming period and anticyclones from a cool one. Anticyclones have a more pronounced salty core at mid-depth and depending on the time of formation and stage of the evolution might or might not have a cold/fresh layer at the top. Thus possible cyclones and anticyclones are identified based only on their relative isopycnal displacement with respect to the mean corresponding to some average water mass properties characteristic for such eddy. The magnitude of velocity can only been assumed from the thermal wind balance but since the level of no motion is not properly defined, this method can also lead to misidentification. By combining together all these possibilities for identification and division into cyclones and anticyclones I was able to distinguish them qualitatively. However, some of the anomalies still have an unknown status due to the ambiguity in some of the characteristics (36 anomalies out of 86). In this data set the majority of eddies were found to be anticyclones: only 2 cyclones are observed out of 50 anomalies and 48 eddies turned out to be anticyclones (27 out of 48 - strong anticyclones). Since the focus of this study is the anticyclones, investigation of the properties of cyclones and their evolution is left for the future studying. The dominance of anticyclonic eddies is qualitatively consistent with previous works (L03, [26]; Katsman et al., [15]). The identification of anticyclones is better proven than of the cyclones due to their stronger signals in the temperature/salinity fields and greater values of the isopycnal displacement (up to 600 m in the anticyclones and 150 m at most in cyclones).

The isopycnal displacement is related to the strength of the eddy and to the thickness of the core: the thicker the core, the bigger the displacement is, the stronger eddy is observed. In this study the isopycnal 27.68 typical for the Irminger Current was chosen to represent the core of the eddy. In this context strength of an eddy is proportional to its velocity via the thermal wind relation. The faster the eddy rotates, the stronger and more energetic it is. Radius of the eddy is an important issue to consider while defining the strength and energy of an eddy but since I am not trying to estimate quantitatively the energy of an eddy I will only show the isopycnal displacement and depth of the core (Figure B-22). On this figure 48 anticyclonic eddies are plotted: both strong and weak. For weak anomalies the isopycnal displacement is small which reflects division into those groups. The range of the core thickness is quite large in this data set. Likely because anticyclones were observed at the different stages of their evolution and under different conditions. Furthermore it is not known whether the eddies are formed of the same strength or not and if they have the same initial conditions. The hypothesis is that the more energetic and strong eddies are formed in winter (L03, [26], Prater, [33] and others), as it was seen from satellite altimetry but it was not proven from the core properties of the eddies. For some of the eddies signal from the core diminishes by 200-300 m ($\sim$ 9), others penetrate to as deep as 400-600 m ($\sim$ 12) and the latter group has pronounced different properties to the depths of 600-1000 m.

Heat content of the eddies plays a very important role for the heat budget of the whole Labrador Sea. The amount of heat available for release in the interior of the Labrador Sea from each of the eddies can be calculated if the radius of an eddy is known. In this data set no information about the horizontal scale of the anomaly can be obtained so a radius of 20 km was taken for calculations as in L03, [26] for comparison. Heat content of an eddy can be calculated using the following formula:

$$H(z) = \rho_0 \, c_p \int_{-h}^{0} \theta(z) dz \tag{5.1}$$

where ρ_0 is a reference density and c_p - a specific heat of the water column. The heat content of the eddy-like anomalies is calculated with respect to the mean of each section containing the eddy obtained by the same mechanism as before. For each eddy all the profiles from the corresponding section from the Labrador Sea deeper than 3300 m are averaged horizontally excluding all the eddies and signatures of the boundary currents. Heat content of the anticyclones integrated over 2000 m is shown in figure B-23. There is a strong correlation between the isopycnal displacement and heat content (figure B-24). This is expected since the more isopycnals are displaced, the thicker the core is and the more heat it contains. An estimate of how much heat each eddy will contribute to the interior of the Labrador Sea once destroyed, is shown on figure B-25. The area of the Labrador Sea was calculated as an area of a circle with radius 325 km, area of an eddy was 20 km. If the radius is taken to be larger and smaller it influences the resulting heat content release. Some eddies provide a zero heat content contribution. At first sight it seems strange since the eddies are warm and salty. But one should not forget about the cold and fresh cap some of them have which compensates their contribution of heat when integrated in depth. Hatun et al., [12], have found that an anticyclone contributes only - 0.8 MJ m^{-2} if averaged over the upper 300 m and 40 MJ m^{-2} if averaged below. The same calculation made for the anticyclones from the hydrographic data set is presented on figure B-26. One should remember that Hatun et al., [12], have sampled an eddy in the boundary current - an eddy which was recently formed and consequently containing more heat. In this data set, however, we can not estimate when the eddies were formed but all of them are likely to be much less recent than the one Hatun et al., [12], have observed. His eddies were sampled in the boundary current, while the closest to the source eddy in the hydrographic data set is located $\sim$ 100 km.

The evolution of an eddy sometimes involves interacting and merging with other eddy-like anomalies. The signature of a possible merging in the past can be represented in the eddies as two mixed layers of different properties inside one anticyclone. The first evidence of those composite structures was obtained by L03 and the authors stated that at least half of the eddies have a second core. Interaction of two eddies leading to the formation of the multiple core eddy can possibly happen in winter and the majority of the wintertime eddies have a second core at depth. There are 7 (out of 48) eddy-like anomalies with this vertical structure. In both cores there exists a well-developed mixed layer, however, of different θ, S and density values. This indicates that they have experienced wintertime forcing in the different places of the Labrador Sea. An example of such an eddy is shown on B-10. Not all the eddies show such a strong division between the cores, in some cases one of the cores can extend to as little as 100m depth. The majority of the eddies with similar structure were observed in the winter months which supports the hypothesis of their origin. However, the process of stacking and necessary conditions for it to happen are not well understood. Another group of multiple core eddy-like anomalies consists of 16 (out of 48) features that have two cores as well but the vertical structure of them is quite different (Figure B-27). The cores are not well-mixed and only two of the eddies with such a profile are observed during the winter. Our result is close to the one observed by L03, [26], where the authors stated that at least half of the eddies had multiple core structure. In the hydrographic data set we have there are 23 eddies out of 48, which is almost half as well.

The eddies in the Labrador Sea can also be grouped by the fact whether they have a fresh water cap or not. The anomalies which have a fresh layer at the surface remind the boundary current structure by θ/S properties. The ones which have a fresh cap removed have a mixed layer with homogeneous properties and no typical for the boundary current system signature. Based on their properties, Irminger Current anticyclones were divided into groups of 12 *with* a fresh cap and 18 *without* fresh water cap anticyclones.

Chapter 6

Evolution of the Irminger Current anticyclones in the Labrador Sea

6.1 Evolution of the upper and intermediate water columns

One of the most important unresolved questions is the one concerning the mechanism of heat transfer by eddies from the boundary current to interior. Properties of the Irminger Current contained in the eddies can only influence interior waters when the eddy is weak or decaying. Only then eddy water masses can effectively mix with surrounding water masses and change their properties. Thus, the mechanism of the eddy destruction and dynamics of the processes leading to the decay are important to understand. Hydrographic data used in the present work contains eddies sampled at different moments of their evolution which makes studying of the properties change possible.

This chapter consists of analysis of different groups of anticyclones and investigates possible ways of evolution of these eddies. Changes seen in the upper layer lead to distinction between the Irminger Current anticyclones which have not experienced convection and to the ones which were modified by the wintertime forcing. Intermediate layer properties were studied and in some of the eddies they have confirmed the hypothesis that the eddies are able to survive convection. Groups of barotropic and multiple core anticyclones were examined and possible mechanisms of their formation were discussed.

Irminger Current anticyclones have different characteristics as seen from statistical analysis and consequently they may have different life histories. By evolution of an eddy in the present work I mean a sequence of different stages each anticyclone passes from the moment of its formation until decay. Different processes can possibly influence dynamics of this transformation: wind forcing, E-P (evaporation minus precipitation) fluxes, lateral and vertical fluxes. However, as it was shown by L03, [26], Irminger rings are mostly isolated from the lateral processes during restratification. Modifications in these eddies to the leading order are the result of the atmospheric forcing. There are several features typical for each evolution stage which help to understand if an anticyclone was just formed, or survived convection or was experiencing the wintertime forcing at the moment of observation.

The water mass properties of the surface and intermediate layers of the Irminger Current anticyclones are very different so it is logical to consider the evolution of those layers separately. Surface layer contains cold and fresh water from the West Greenland Current and is easily modified by the surface fluxes. This water mass changes dramatically during the lifetime of an anticyclone. Upper layer undergoes a seasonal cycle: from the development of the mixed layer in winter to the summertime restratification. Based on the few wintertime observations, convection in the anticyclones is usually limited to the upper 500 m (7 of 11 wintertime eddies) and never reaches depths greater than 1000 m. Intermediate layer mostly consists of the warm and salty Irminger Current water mass but in a few cases of deep eddies, lower part of the eddies contained Labrador Sea Water. No conclusion about the seasonal changes in the lower layer can be made due to the lack of observations of the deep eddies. However, LSW located below the core of Irminger water allows to investigate the age of eddies.

This is a summary of what we observed:

- 12 eddies with a freshwater cap at the top, further called "unmodified eddies". They all have the following properties:

1. Salinity profile has a strong signature of West Greenland Current - fresh cap at the upper layer;
2. Temperature profile has a cold signal in the upper layer as well. However, in some cases cold layer may be overlaid with a thin warm layer at the surface due to summertime warming. Still surface temperature of this group of eddies is colder than of the other type of eddies described below.
3. No mixed layer is present in any of the profiles.
4. Shape of the eddy profile on θ/S diagram reminds the shape of boundary current profiles.
5. Measurements of the eddies were mostly obtained in the boundary current regions in May or June. This does not contradict with possibility of formation of this group of eddies after convection since eddy velocities, as calculated, are not exceeding 5 km/day.

- 18 eddies without fresh water cap, further called "convected eddies". Their typical signatures are listed below:

1. Salinity profile shows *no* fresh cap at the surface.
2. Temperature profile is either convected in the surface layer or has a thin layer of warm restratified water. No cold water, signature of the West Greenland Current, is observed.
3. At least one well-developed mixed layer is present in all the profiles.
4. Shape of the eddy profile in θ/S space does no longer remind boundary current profile. Upper part of the water column is well-mixed and thus has homogeneous properties. In the subset of restratified eddies their upper layer is vertically elongated in θ/S space which means that almost no change in salinity happens during the restratification, only temperature increases.

5. None of these eddies were found in the boundary current region, instead all but one were sampled to the center of 3200 m isobath. Month of the observation varied from February to December.
6. Some of the "convected" eddies contain old Labrador Sea Water at intermediate depths, the possible explanation for this phenomenon can be found in the section 6.1.2.

These groups of eddies and properties distinguishing one subset from the other are seen from the observations. In the next subsections the possibility of their origin will be discussed.

6.1.1 Evolution of the upper layer

Consider first the evolution of the surface layer. At the time of formation Irminger ring has a structure reflecting the place of its origin, a known couple: West Greenland Current and Irminger Current as discussed by Hatun et al., [12]. This can also be noticed in the hydrographic data (Figure B-28). As seen from this figure, recently formed eddies are very similar to the boundary current. Two anticyclones found less than 100 km from the source are shown on figure B-29 as an example of recently formed, "unmodified" eddies. Water mass properties of these eddies were not significantly changed by the time of the observation and it would be difficult to guess only from θ/S structure what season those observations belong to. However, as time progresses, these eddies evolve, modified by the surface fluxes and obtain a seasonal signature in the upper layer.
Depending on the time of the anticyclone formation, two eddies observed, for instance, in the summer can have quite different profiles. One of them may be from an eddy which *has* experienced convection and restratified and the other - from an eddy which *has not* experienced convection but restratified as well. Anticyclones of the wintertime origin start feeling strong surface fluxes straight away, the upper part of the water column mixes and mixed layer develops. If the forcing is very intense, water column can be mixed down to several hundreds meters implying that salinity

structure no longer consists of two layers. Fresh cap does not exist anymore - it was mixed with salty Irminger Water layer below. If the eddy is formed after convection ceased, it feels the summer heating, its cold layer is warming up with no significant changes in salinity. The evolution of the surface layer consists not only of the winter overturning but also of the process which is of the same or greater importance: re-stratification. During this stage the upper layer of an anticyclone is heated by surface fluxes and its temperature increases.

Since Irminger Current anticyclones are the closed structures for the most of their life, L03, [26], fresh layer removal is unlikely to be caused by some lateral processes such as mixing with the ambient water or blowing off by the wind, (Han and Tang, [10]). The mechanism of its destruction is most likely one-dimensional: vertical mixing with the water below. Only wintertime convection can provide such a strong mixing and lead to the disappearance of layered salinity structure. Observations and model experiments discussed later support this hypothesis: figure $B-31$ shows two eddies of both types and interestingly, the value of salinity for the convected eddy can be obtained by mixing of the unmodified eddy. Later it will be also confirmed using one-dimensional mixed layer model.
The evolution of the upper layer is well seen on the θ/S diagram as well (Figure B-32). Initial profile belongs to the unmodified eddy which has cold and fresh water at the surface ($\theta \sim 0.5^oC$ and S $\sim$ 33.7 psu) and much warmer ($\theta \sim 4.3^oC$) and saltier (S $\sim$ 34.9 psu) values below. This profile reminds the boundary current structure with slightly cooler temperature values at the surface. This points out to the recent time of formation since the θ/S properties are almost identical to the ones of West Greenland Current at the surface and Irminger Current at the intermediate depths. The second profile, labeled "2" is experiencing convection at the time of measurement. It was observed in 1997 during one of the few winter cruises. The upper layer of this eddy is well-mixed down to 800 m, temperature and salinity are homogeneous ($\theta \sim 2.6^oC$, S $\sim$ 34.79 psu). The fresh cap is mixed with salty water below as a result of the overturning and the value of salinity is an average of the Irminger and West

Greenland Currents values. The third profile is from an anticyclone found in one of the summer AR7W sections. Salinity of the upper 1000 m lies in a very narrow range (34.78 psu $<$ S $<$ 34.85 psu) which suggests that this layer was homogenized in the past, otherwise the difference between the two different water masses of the typical unmodified eddy would be seen. Fresh cap no longer exists at the surface and the salt and fresh water are mixed and homogeneously distributed over the upper layer. Temperature of this summer anticyclone also suggests its survival of convection in the past. Subsurface mixed layer temperatures are colder than Irminger Current water mass temperatures typical for the depths of 300-500 m in the eddies. Surface layer is warmer than West Greenland Current since the restratification has already taken place and the surface has been heated up by the summertime fluxes ($\theta \geq 5^oC$). In support of this analysis I would like to add that the majority of the "unmodified"eddies were found either in the boundary vicinity on the Greenland or Labrador side with only 3 eddies being in the interior of the sea. Another thing to point out is that only 2 profiles of the "unmodified" group were recorded in February and October. The rest of the eddies were sampled in the summer months, mostly June. One might want to check the possibility of all these eddies being formed after convection. If we assume, that convection was over by the end of March and the eddies were formed at about this time of the year and found in the interior in June, they had to have velocities of the order 5 km/day or less to reach the places where they were observed. This estimate is in agreement with velocities obtained by L03, [26].

In this subsection the possible scenario of the upper 800-1000 m evolution was considered. It was shown that the eddies are able to survive at least one convection. An indication of that can be the presence of a well-developed mixed layer overlaid with a thin restratified water on top found the group of convected eddies. Lower layer undergoes some changes under wintertime forcing as well and will be considered in the next subsection.

6.1.2 Evolution of the intermediate layer

More evidence that Irminger Current eddies survive convection can be seen from the properties of their intermediate layers. This layer is not always present in the eddies due to the fact that signal from the majority of eddies diminishes by $\sim$ 300-500 m. There are only a few eddy-like anomalies with pronounced signature below 700 m. Consider AR7W section taken in May of 2004 (Figure B-16) with profiles 19 and 20 occupied inside an anticyclonic eddy. A pronounced core of warm, salty and light water is revealed by the measurements. The properties of this eddy are quite typical for the Irminger Current anticyclone. However, despite its relatively close distance from the source and similarity of properties to the boundary current, this eddy belongs to the group of convected eddies. In both temperature and salinity fields the well-developed mixed layer at the depths of 400-800 m is observed which confirms the winter survival hypothesis. Investigation of the deeper layers provides more information on changes in the water column in winter. Consider in a θ/S space the profiles inside, on the left and on the right sides of this anticyclone (Figure B-33). Interestingly, the profile of the salinity minima typical for the Labrador Sea Water is saltier and warmer in the profiles recorded from an eddy (shown in red) as opposed to the adjacent profiles shown in light blue on θ/S diagram. Labrador Sea has been getting saltier and warmer since early nineties and this trend still continues (Yashayaev, [45]). As LSW in the eddy is warmer than the rest of the section, it suggests that this anticyclone observed in the spring of 2004 was present in the Labrador Sea since 2003. To test this hypothesis I plotted the mean profile from the Labrador Sea on the same θ/S diagram (in black). Profile from 2003 was obtained as a mean of all the stations deeper than 3300 m and without any anomalies (i.e. excluding eddies). As it is seen from the figure, the Labrador Sea Water minima of the 2004 anticyclone and of 2003 mean profile matched very well. One possible explanation for this phenomenon is that the eddy trapped the LSW in 2003 which remained unmodified while it was carried by this anticyclone throughout 2004. This fact can explain different properties of the same water mass observed in 2004 section. The Labrador Sea Water in the basin became warmer and saltier compared to 2003 while the LSW_{2003} trapped by an anticyclone kept its 2003 properties. It remained closed from the lateral processes and was isolated under the influence of this anticyclone. This example if not unique, such a trapping of the "old" Labrador Sea Water occurs in more than 5 sections. The anticyclones holding the LSW from a previous year were carefully investigated and none of them contained water older than a year. It does not mean that anticyclones cannot survive more than one winter, it just shows that in this data set no 3 or 4 year old eddies were observed.

6.1.3 Deep and multiple-cored eddies

According to the result from mooring observations by L03 [26], more than half of anticyclones in the Labrador Sea have a multiple core structure. Since hydrographic record allows to consider more than 40 eddies I have looked at this aspect as well and found 23 eddies with multiple cores. Some of them have well-developed mixed layers stacked one on top of the other (Figure B-34); some of them have non-homogeneous cores at different depth which can be distinguished by temperature/salinity maxima at different levels of the water column (Figure B-27). The first case is relatively easy to distinguish since the cores are elongated vertically and have a typical signature of a wintertime mixed layer. Second type of the multiple core anticyclones is not obvious: almost every hydrographic profile has some local instabilities due to the measurements of internal waves or intrusions of the ambient water. In the second case the number of cores is determined by a number of positive temperature and salinity anomalies separated by non-anomalous pieces of the profile.

Four eddies from the subset of the "convected" eddies appeared to be very barotropic. The signal from all of them penetrated to as deep as 2000 m and their properties were remarkably different from the rest of the anticyclones. All of them were eddies which have survived convection or being observed in winter and were in the interior of the Labrador Sea which experiences the most significant surface forcing. Since none of these eddies were "unmodified", all of them had no fresh cap at the surface and were

well-mixed (Figure B-35), since none of the "unmodified" eddies extended to such depths as any of these, one of the hypotheses is that these eddies were somehow energized by wintertime forcing. All of the deep eddies have an isopycnal displacement of 400-600 m, as opposed to the average displacement of 100 m, they penetrate to $\sim$ 2000 m, compare with usual 300-500 m. There are several other hypotheses which can possibly explain this phenomenon too: stacking of two anticyclones of either Irminger Current origin or convective origin, energizing of the eddies by convection driven both by gravitational and centrifugal forces - slantwise convection. Finally, it is possible that the strongest eddies are formed during the winter.
Each of these eddies could have consisted of several other eddies which stacked under the strong surface fluxes as was proposed by L03,[26]. The mechanism of such stacking is based on the initial difference in density. Consider two anticyclones during the winter which are relatively close to each other and have possibility to interact. Before convection started, eddies had slightly different densities of the cores. Under strong surface fluxes mixed layer develops in both eddies. If they come close enough to each other, they stack into one structure: eddy with lighter density of the core turns out to be on top of the eddy with less dense core. Final profile has two mixed layers formed during one year. From the observations, all but one eddy had at least two well-mixed cores, which could have belonged to two different eddies prior to the convection which supports this hypothesis. A good way to test this idea would be to look at the oxygen data which will reveal the time of the formation of the water masses inside the deep eddies. Unfortunately, no oxygen data were available for the present study. Another possibility for energizing of these eddies is that the Irminger Current anticyclone interacts with convectively formed anticyclone and as a result such a deep eddy appears. This mechanism seems to be theoretically possible however there are no evidence making it more favorable. In general, there were not many convectively formed lenses observed in this data set and none of them appeared to be a part of such deep eddies.

Seasonal variability of the eddies can be studied only to a limited extent with this data set since there are much more observations of the summertime eddies than during the rest of the year. If one decides to look at the monthly changes in the eddies properties then their evolution will mostly be dominated by the wintertime fluxes considered in the subsection 6.1.1. Magnitudes of the mixed layer depth and the thickness of the restratified layer vary from year to year and in general, qualitatively reflect seasonal changes in the Labrador Sea. However, some differences still exist: summer restratified layer in the eddies is thinner than in a mean profile from the central Labrador Sea due to the isolated nature of the eddy (L03, [26]). Depth of the mixed layer in winter can be either less than the outside water in case the eddy survives the first winter or greater in a case of repeated convection (L03, [26]) In chapter 7 this issue will be discussed in more detail.

6.2 Spatial "evolution" of the Irminger Current anticyclones

In previous subsections I considered the changes in the eddy properties in time. Evolution in space requires more assumptions and includes more unknown facts than known: it is not clear whether the eddies are formed of the same strength or not; how many of them propagate along the 3000 m isobath after the formation and how many drift to the center; if the strength of the formed eddies is different then when the most energetic eddies are produced. Without knowing the answers to these and other questions about the formation of Irminger rings the conclusions are arguable. Still it will be attempted to describe the spatial evolution of the anticyclones because of the availability of one section across the Labrador Sea unusually rich in eddies: there were four anomalies observed in January-February of 1998. This section was occupied in less than 10 days so I consider the time of this snapshot the same for all the anomalies. However, distance from the Irminger Current and location with respect to the convection place are different. Time of formation is likely to be different for all of them as well. An interesting observation can be made if one looks at all these anomalies in a θ/S and in a property-depth spaces, remembering that all the profiles belong to different eddies and do not represent the evolution of a single eddy as it progresses from the boundary (Figure B-36). The closest anticyclone to the boundary current region has properties of the boundary current - the warmest and saltiest water at the depths of 200-300 m. However, it is much colder (by about 2^oC) than boundary current profile and has no signature of the West Greenland Current at the surface in comparison to the boundary current system. Mixed layer depth is the smallest of all the eddies as expected ($\sim$ 200 m) - the fluxes are not so intense as in the interior of the Labrador Sea. No fresh layer is observed in any of the eddies since water column has been experiencing convection and the surface layer has already been mixed down to 200-600 m in different eddies. The farther the eddy is located along the AR7W section from the Irminger Current, the more heat its core has lost and the fresher it has become than the IC water. The mixed layer has deepened and reached 600 m in the central Labrador Sea. Surface fluxes are the greatest there and the deepest convection is usually observed (LSDCE, [16]). At the proximity of the Labrador coast the boundary current properties appear again but of the smaller magnitudes. Fresh layer at the surface is very shallow and temperature and salinity maxima below the surface reach only the values of $\sim 3.8^oC$ and $\sim$34.85 psu as opposed to $\sim 4.5^oC$ and $\geq$ 34.9 psu on the Greenland side of the basin (Pickart et al., [32]).

Concluding I'd like to point out that properties of the eddies captured in winter of 1998 vary along AR7W line. It is likely to be connected to the difference in surface fluxes along the section acting on anticyclones (B-37). The deepest mixed layers were observed at the well-known convective region shown on figure B-2 and the shallowest - closer to the boundaries. This example also suggests that surface heat flux is one of the most important if not the leading order parameters governing the evolution of the eddy. The result of the eddy evolution developed only by acting of the surface fluxes will be seen in section 7.

6.3 Interannual variability

Having eddies in almost every section from different seasons for the past 15 years of hydrographic record it seems to be logical to check the possibility of interannual and seasonal variability. And, moreover, as it was discussed earlier, Labrador Sea interior itself together with the surrounding it boundary currents undergoes interannual changes. Warming trend both in the interior and in the West Greenland Current system which has begun in the early nineties, continues until the present days (Yashayaev, [45], Buch, [1]). One might expect to see some kind of trend in the eddies produced by the boundary current as well. All the eddies found in the data were put together in a chronological order considering both month and year of observation and checked for any pattern in their properties (Figure B-38). As seen from the figure, Labrador Sea water becomes warmer and saltier at depths of greater than 800-1000 m and less than 2500 m. However this trend as might be thought from the first sight has nothing to do with the variability in the eddies. It reflects only interannual changes in the Labrador Sea Water since the eddies signal rarely penetrates to these depths. Typical Irminger Current water mass located between the isopycnals $\sim 27.64 - 27.72$ does not seem to be correlated with time either. The only difference in this density range between the early nineties and the recent years is that there are fewer eddies with a cold and fresh layer at the surface observed recently. It would be incorrect to draw any conclusions based on the number of observations available: it can either be a signal from the warming of the boundary current or the "chance" factor of sampling the eddies.

In this chapter evolution of the Irminger Current anticyclones was considered from different prospectives. Stages of eddy modification from the moment of its formation until decay are desired to understand. Eddies carry significant amounts of boundary current water, different from the interior. Thus, it is important to understand where and when they release their content. Here I attempted to shed some light on eddy properties and structure during different episodes of their evolution both in time and in space.

Chapter 7

One-dimensional mixed layer model

7.1 Background

Evolution of Irminger Current anticyclones is a complicated process depending on initial conditions, surface and lateral fluxes, and interactions with other mesoscale structures. To understand the stages of this evolution, including development of the mixed layer and changes in eddy properties, a simple one-dimensional model of the mixed layer is applied. In this chapter, the zero order physics of the mixed layer development and properties of the water mass undergoing wintertime changes are described. As was discussed in section 2.2, convection takes place on a variety of temporal and spatial scales governed by different mechanisms. Evolution of the small scale features (eddies and plumes) is quite rapid and is mostly due to the vertical fluxes. One-dimensional models give a reasonable prediction for the mixed layer depth in such features, as was shown in a number of works (Marshall and Schott, [29]; Steffen and D'Asaro, [38]; Legg et al., [23] and others).

One-dimensional models have always been attractive because of they are relatively simple, and yet capable of explaining zero-order mixed layer development physics on short timescales. One of the first works to model the deepening of the mixed layer was described in a book by Turner, [44]. He discussed various aspects of convection, formation of the mixed layer and balances of heat and salt. His book deals with a variety of processes caused by density differences from buoyant convection to the mixing in stably stratified fluids. One of the most serious restrictions of this work is the limitation of the discussion to non-rotating fluids: rotation is considered negligible in comparison with buoyancy and inertia forces. Moreover, all the processes were considered only from an analytical perspective without going into the details of numerical representation.

The work of Price et al., [34] paid more attention to the numerical modeling of the mixed layer development in response to the wind stress and buoyancy flux at the surface. Using the example of diurnal thermal cycle a one-dimensional model of mixed layer was introduced. The evolution of the density profile was driven by the parameterized surface fluxes of heat and momentum. Density is taken from the linear equation of state

$$\rho = \rho_0 + \alpha(T - T_0) + \beta(S - S_0), \tag{7.1}$$

with $\rho_0 = 1025$ kg m^{-3}, $T_0 = 17^oC$, $\alpha = -0.23$ kg m^{-3} $^oC^{-1}$, $S_0 = 36$ ppt and $\beta = 0.76$ kg m^{-3} ppt^{-1} for the region in the subtropical Pacific. Mixing parameterization was based on stability criteria including stability of the density profile, static and sheared flow stability caused by the wind. This model is forced by the air-sea heat loss and freshwater fluxes. At each time step the density profile is calculated and checked for all the kinds of stability. In case it is unstable, water column is mixed to become stable. The mechanism for salinity and momentum budgets is the same.

However, all the schemes described above were not developed specifically for the regions of deep convection where the presence of plumes, eddies and other parameters typical for convective sites may be important. For this reason the development of models which are able to resolve these small scale rapidly evolving features has begun. One such model was adapted to the Labrador Sea case by Harcourt et al., [11], using a non-hydrostatic model with a nonlinear equation of state. Several experiments simulating deep convection on a variety of scales concluded that Lagrangian floats can measure dynamical statistics of the deepening mixed layer. This implies that rapidly occurring convection can be modeled to zero order as a one-dimensional process.

Steffen and D'Asaro, [38], have considered a one-dimensional mixed layer model based on heat content change of two subsequent profiles. Heat content difference from these profiles can be converted into an atmospheric heat flux estimate. This simple model is somewhat inverse of the one used in the present work: it gives an estimate of heat flux when the depth of the mixed layer is known. We will use a known heat flux to calculate mixed layer depth. Salinity effects were not considered in the model by Steffen and D'Asaro, [38], due to the availability of only temperature profiles from the floats measurements. After applying this model to the floats and CTD profiles from the winters of 1997-98, the authors came to the conclusion that lateral motions are negligible during the strong convection phase, but play an important role during restratification. This result implied that for the purposes of studying eddy evolution under strong wintertime forcing, representing convection by a 1-D mixed layer model is a good approximation.

Straneo and Kawase, [39] have restricted their model by taking into account only the heat loss influence. They discussed the results for the conditions of the Labrador Sea. Their one-dimensional model is taken as one of the guidances for the present work. The governing principle is the following: buoyancy flux at the surface is known and applied during a predetermined time to the vertical column of water to predict the depth of the mixed layer. Mixing of the water column occurs when buoyancy that has been removed from the water column makes it unstable. Convection occurs at once and mixes water to the depth where the density profile is stable. The experiments require knowledge of an initial buoyancy profile and the values of the surface buoyancy flux Q as a function of time. This model was used assuming a linear equation of state. Since it was applied for studies of convection, and the authors were not interested in the distributions of temperature and salinity within mixed layer, only density (buoyancy) field was considered.

For the purposes of studying convection in the Labrador Sea and calculating the heat content of the water column, L03 have successfully used a 1-D mixed layer model as well. In their model, the depth of mixed layer in θ and S profiles as well as the available heat storage are determined by the surface forcing. Density is represented as

$$\Delta\rho = \rho_0(-\alpha\Delta\theta + \beta\Delta\ S); \tag{7.2}$$

where

$$\alpha = -\frac{1}{\rho_0}\frac{\partial\rho}{\partial\theta}|_{S,\,p} > 0; \quad \beta = \frac{1}{\rho_0}\frac{\partial\rho}{\partial S}|_{\theta,\,p} > 0. \tag{7.3}$$

Evaporation and precipitation fluxes are included in this model together with heat flux, and all together they represent a buoyancy flux from the surface. A variety of experiments were performed with this one-dimensional model: from removing of a fixed amount of heat to calculate the mixed layer depth for the hydrographic stations in the Labrador Sea, estimation of "available heat content" of an anticyclone observed in 1998 (available heat content is an amount of surface heat or buoyancy loss removed to create a mixed layer down to a certain depth), and comparison of the mixed layer depths inside and outside of the eddy.

Previous experience of successful use of one-dimensional models and ability to explain rather complicated processes with simple 1D physics is encouraging for the development of a similar model for studying the evolution of the Irminger Current eddies. The combination of hydrographic data with a model can reveal interesting aspects of the evolution of the eddy. In particular, it can provide information on changes in the eddies during intense wintertime forcing, evolution of the mixed layers in θ/S space, and properties of the mixed layers. It can also help to understand if the evolution of the eddy's properties is due mostly to the vertical fluxes, or if wind and lateral influence should not be neglected.

7.2 Model set up

To study the evolution of the Irminger Rings I have used a simple 1-D model built on the basis of the work by Straneo and Kawase, [39], to better understand the processes during the wintertime evolution of the eddies. The model used in the present work represents the balance of buoyancy removal by the atmospheric forcing and buoyancy storage in the water column. Main differences from the previous works are that this model does not include the process of restratification and has no dependence on evaporation or precipitation (as it was shown before, buoyancy flux over the Labrador Sea is dominated by a thermal component, Marshall and Schott, [29]; Katsman et al., [15] and others). Salinity is passively mixed within a mixed layer. The model is based on the following assumptions: the water column does not interact with the surrounding columns, i.e. there is no lateral transport of properties; the evolution of water column is caused and maintained only by the surface fluxes; the mixed layer is homogeneous after development; mixing of the water column occurs instantaneously, i.e. no small-scale events can be observed; and forcing is monthly and spatially averaged.

The balance used in this model is:

$$\int_{-h(t)}^{0} \rho_0 dz \; - \int_{-h(t)}^{0} \rho(-h(t)) dz \; = -\frac{\alpha}{\rho c_p} \int_{0}^{t} Q(t) dt \,, \tag{7.4}$$

where $c_p \sim 4 \cdot 10^4 Jkg^{-1}\,{}^oC^{-1}$, $\alpha = (0.8 - 1.6) \cdot 10^{-4}$, ρ_0 - initial density profile, $Q(t)$ is shown on figure B-40 and is positive upwards, $h(t)$ - depth of the mixed layer.

The model principle is the following. Given initial profiles of density, salinity and temperature, heat flux from the surface and time during which the forcing is applied (Figure B-39), salinity is mechanically mixed in the layer from the surface to the depth h, keeping the amount of salt in the water column constant. Finally, the temperature profile is computed from the nonlinear equation of state using the known density and salinity.

Coefficients of the equation of state are nonlinear and are functions of temperature, salinity and pressure. The results of the model calculations depend on α but almost do not depend on β. In the conversion of the heat flux into buoyancy flux and when possible in the equation of state, α and β were calculated from the Matlab Sea-Water routine (Figure B-41). However, there were cases when it was not possible to obtain α for numerical reasons. In these model runs α and β are taken to be constants but every time before obtaining any results the model was checked for consistency. The density profile calculated from temperature and salinity taken from the data, using the equation of state with given α and β, was compared to the density profile observed (real data). If those profiles were significantly different in the upper 1000-1500 m, coefficients of the equation of state were altered until two density profiles matched. Forcing for all the experiments is taken from NCEP (National Centers for Environmental Prediction) Reanalysis (Figure B-40). Data are averaged over the whole area of the Labrador Sea. The heat flux for this model is also averaged over more than 50 years which smooths the differences between mild and harsh winters.

7.3 Experiments and results

A number of experiments were performed to shed more light on the processes governing the evolution of the Irminger Rings and changes of the water masses during the wintertime forcing. Results of this investigation allow to clarify aspects concerning development of the mixed layer in the eddies, their water masses during active wintertime forcing, differences between properties of the Labrador Sea and two types of eddies (unmodified and convected) described above.

Eddy evolution, as well as the evolution of the ambient water during convection, is mostly determined by vertical fluxes as has been shown numerically in a number of studies (Lilly et al., [24]; L02, [25]; Legg et al., [23]). To test this hypothesis applied to the real eddy data I have performed a number of experiments. First of all, it is necessary to understand that all the results of this section should be interpreted qualitatively. They can only provide information about *possible* evolution mechanisms.

First of all, the changes in the water mass properties of the eddies are due to the vertical fluxes only to the leading order. This statement is likely to be true for the major part of the eddy life, however, while decaying, eddy will actively exchange properties with the ambient water. At this time, its evolution can not be described with 1-D model. Second constraint on the use of this model is that it can only deal with the unmodified eddies and simulate the forcing for them and for the eddies which are being convected at the time of the observation. Restratification of the eddies is not modeled at this time and the full lifetime cycle of once-convected eddies can not be reconstructed.

The first experiment shows that one-dimensional fluxes can define the evolution of the eddy to the leading order. To show that I take an average boundary current profile from October of 1996 and apply the heat flux for the next 6 months starting from October. Eddies observed in March 1997 allow to make some qualitative comparison. If the assumption that the boundary current profile represents the eddy at the moment of its formation, i.e. is an initial profile for the Irminger Ring is valid, one can look at the evolution of that "eddy" profile in time under the influence of 1-D forcing shown on Figure B-40. The model result is shown on figure (B-42). Mixed layer development is seen in all the fields: temperature, salinity and density; but for a better view of the properties change consider θ/S space. On this diagram one sees initial profile which was exposed to the heat loss and development of the mixed layer in the lower part of the plot as a function of time. The resulting mixed layer is marked with a blue star and for comparison the eddy from the data is plotted in light blue. Indeed, the boundary current mixed layer θ/S properties lie very close to the properties of a real anticyclone from hydrographic data. The properties of the final product of convection match the properties of an eddy to the leading order but it would be important to understand how exactly the mixed layer has developed. Once the forcing is applied, the water column starts cooling and at the same time mixing which leads to the homogenization of West Greenland and Irminger Currents salinity. Salinity difference between those two layers can be greater than 1 psu and as the water column mixes one would expect the resulting salinity to lie somewhere between the values of WGC and IC. However, the influence from IC on the final product is much greater since the vertical extension of this water mass is 4-5 times larger than of the WGC. At the time when mixed layer has reached the values of $\theta \sim 1^oC$ and $S \sim 34.0$ psu a dramatic drop in the temperature occurs. It is caused by the shape of the θ, S and density profiles: When the forcing was applied, all the profiles were more vertical and convection occurred easily. At the point of $\sim$ 120m the slope became more horizontal which is harder to convect. The heat was still taken from the surface but very little mixing occurred (as seen from salinity) and to compensate this heat loss the temperature has to drop.

Several other experiments were carried out to investigate appropriateness of the convectively modified nature of "convected eddies". "Unmodified eddies" were taken and exposed to the heat flux as in the first experiment. The result of each of these was compared with a "convected eddy". The result of one of the runs is shown on figure B-43. The profile of the unmodified eddy has water mass composition very close to the one of the boundary current: fresh water overlying salty water. And the proportions are about the same as can be see even from θ/S space: the marks are largely spaced in the upper part and gathered at depth which indicates the number of measurements in the eddy. When the forcing is applied, water column mixes vertically which is seen in all three fields. As in the case of the boundary current, Irminger Current watermass contained in an eddy dominates its resulting salinity. The model output shown in black on figure B-43 represents the depth of the mixed layer as a function of time. Real eddy which has experienced convection in the Labrador Sea and the model result have similar properties. Salinity is different by only 0.01 psu and temperature is 0.3^oC warmer in the real profile. Mixed layer depth is the same for both eddies and is $\sim$ 800-850 m and densities lie within 0.025 range. If a greater forcing is applied simulating a stronger than the mean convection then the evolution of mixed layer will go along the black curve resulting in the match of profiles. The change in the heat flux can be explained by the fact that in any case these values of the forcing are not perfect. There are many uncertainties such as sampling of different eddies and comparing them with the ones from different year; neglecting the fact that some winters are very different in meteorological conditions and that locations of eddies within the Labrador Sea was not taken into account in this experiment. But with all these uncertainties this experiment still shows that it is possible to force unmodified eddy and get a convected one. This picture is in agreement with figure B-32 which suggests based only on the observations from the data that it is appropriate to call a "convected eddy" this way because its structure is indeed the result of convection.

The model was also very useful in comparing the differences between developing of the mixed layer in the eddies and the mean Labrador Sea water. This case turns out to break into two possible scenarios: first - when mean is compared to the "unmodified eddy" and second - mean is compared to the eddy which has survived one winter already. In the first case (Figure B-44) as it would be intuitive to think, the mixed layer in the eddy develops to a shallower depth than in the interior of the Labrador Sea. Eddy contains a bulk of much warmer than interior water and thus requires more heat taken away for achieving the same depth of the mixed layer. However, if the eddy has once survived convection and is subjected to a forcing for the second time, then mixed layer in it is deeper than in the interior of the Labrador Sea (Figure $B-45$). This fact can be explained if one looks at the initial profile of such an eddy (any of the "convected profiles" from figure B-32). Those eddies contain a well-developed mixed layer from last winter with a very thin layer of warm water on top. This warm water is a result of the summer restratification. However, as opposed to the mean profile, its layer in the eddy is much thinner and its temperatures are usually warmer than in the interior. An explanation for a deeper mixed layer inside a convected eddy lies in the fact that the temperature under the restratified layer in the eddy is much colder and the eddy is already preconditioned for convection. Once the thin stratified layer on top is broken, mixed layer almost immediately mixes down to a greater depth where the former mixed layer was. In the interior of the Labrador Sea, however, the mechanism of convection is a usual one: the water gradually cools and the mixed layer develops. These long-lived anticyclones can become places of the deepest convection in the Labrador Sea in winter.

This result supports the idea L03 have described in their work. They assumed that the eddy is an isolated structure and even if the surface fluxes are the same for the interior of the Labrador Sea and the eddies, they do not exchange water with the surroundings. Thus, without exchanging by means of lateral fluxes, it takes longer for the anticyclones to restratify. Indeed, forcing of a once-convected eddy leads to a greater mixed layer than in the interior of the sea. The opposite result is true for an "unmodified eddy".

It would be useful to know how much heat needs to be removed from a convected and restratified eddy to break this thin restratified layer at the top. If an eddy shown on figure B-34 is exposed to the surface fluxes and if only 0.15 GJ m^{-2} is removed, a stratified layer breaks and overturning of the whole upper layer occurs. Only 0.17 GJ m^{-2} is required for mixing down to 400 m. If the same experiment is carried out for the mean of the same year, then one needs to remove 0.66 GJ m^{-2} to obtain a 100 m mixed layer and 1.1 GJ m^{-2} to convect to 400 m. Much larger heat fluxes needed for a restratified eddy to convect again emphasize the difference between the restratification processes an eddy and an interior undergo. Isolation of an eddy prevents it from a formation of a deep restratified layer as opposed to the interior which later results in the deepest mixed layers in once convected eddies.

To summarize, the model combined with the data is a powerful tool to study the evolution of anticyclones. First, a group of unmodified eddies found at different times in the Labrador Sea was exposed to 1-D fluxes to show that the terminology used in the previous chapter is appropriate and that the most important, leading order mechanism for their modification, is likely to be one-dimensional vertical mixing driven by surface fluxes. Lateral fluxes become important at the time of the eddy's destruction when vertical fluxes no longer dominate. For the majority of the cases properties of the forced unmodified eddies have almost the same salinity as the wintertime eddies from the data and lie in a very narrow density range so "convected eddies" are indeed the products of convection.In a second experiment I compared the evolution inside an eddy and in the interior of the sea. The result was different for "unmodified" and "convected" eddies. In the former case the mixed layer developed to a shallower depth but in the latter - to a greater. This difference is explained by the fact that the process of restratification in the eddies and in the interior is governed by different mechanisms. A mixed layer in the convected eddy appears to be very thin since it occurs only as a result of the surface heating with very little lateral exchange. Thus it requires only a relatively small amount of heat to be taken away to convect again since the feature is already"preconditioned". Interior, instead, restratified largely due to the lateral processes which quickly build a thick stable layer at the surface.

There are a number of parameters in those experiments which can cause uncertainties such as the fact that there were no eddies sampled twice, the evolution hypothesis was tested on different eddies, sometimes even from different years; surface fluxes are monthly averaged over the Labrador Sea. All the results cannot be used in predicting the exact mixed layer depths for a given year or season and serve only for better understanding of the processes influencing the evolution of anticyclones.

Chapter 8

Summary and Conclusion

The goal of this work was to document the population and properties of the Irminger Current anticyclones, investigate the differences in their vertical structure, and governing mechanisms of the eddy evolution.

Understanding the dynamics and properties of the long-lived Irminger Current eddies, which mostly appear to be anticyclones, is of crucial importance for a number of reasons. They appear to be one of the main mechanisms providing water mass exchange between the boundary current and interior. They carry significant amounts of heat and fresh water from the region of their formation and can possibly contribute both to the restratification and formation of the fresh cap over the Labrador Sea. Present in large quantities they may act to homogenize properties of the Labrador Sea.

In order to investigate water mass structure of the Irminger Current anticyclones, to understand stages of their evolution in time and potential for contributing to the fresh water capping effect, and modification of the Labrador Sea interior the problem was approached using a hydrographic data set and a one-dimensional mixed layer model.

8.1 Summary

The 15-year hydrographic data set used for this study provides the largest number of in situ eddy observations. It contains 86 eddy-like structures, 50 of which were identified as Irminger Current eddies. The majority of these eddies (48 out of 50) were identified as anticyclones.

Spatial distribution of the eddies is not very representative since all the measurements were taken along several sections across the Labrador Sea. However, some observations about population of eddies along the most frequently occupied section AR7W can still be made. The majority of eddies were found in the proximity of the boundary current due to the formation on the Greenland side. Another populated region first observed from the hydrographic data appeared to be on the Labrador side due to transport by the boundary current (Hatun et al., [12] have documented the possibility of such a transport). 23 eddies were found within a 350 km distance from the formation place (61.5°N, 52°W) and 7 on the Labrador side of the basin. Five eddies were sampled closer than 250 km from the source and the rest of the eddies were located in the interior of the sea.

The majority of anticyclones were observed during spring-summer season due to the fact that only 7 hydrographic sections out of 30 including eddies were occupied during fall and winter. Still, with such a distribution of stations wintertime eddies make up 1/4 of the whole eddy dataset. One can not extend this fact and make any conclusions about the frequency of wintertime eddy formations based on hydrographic data set only. However, this observation does not contradict previous descriptions of a wintertime eddy kinetic energy maxima.

θ/S properties and isopycnal displacement of the observed anticyclones varies from case to case due to the different seasons of observation and vertical structures of the eddies. On average, the isopycnal displacement of the eddies is of the order of

100-200 m with some wintertime eddies having the displacement of 400-600 m. Potential temperature of the core ranges between $\theta \sim 3.9^oC$ and $\theta \sim 5.5^oC$ and salinity $S \sim 34.85 - 34.91$ psu . These values are warmer and saltier than interior waters by $\theta \sim 0.2 - 0.9^oC$ and $S \sim$ 0.01-0.06 psu. Some eddies contain typical West Greenland Current cold and fresh layer of water at the top which makes their upper layer colder than ambient water ($\theta \sim 0.1 - 4^oC$ and $S \sim 0.1 - 0.6psu$).

A group of the Irminger Current anticyclones contain the water masses of their source - West Greenland and Irminger Currents. However, some eddies appear to be modified by surface and lateral fluxes and their θ/S signature becomes different from the Irminger Current. It is still unclear what mechanisms allow eddies to contribute to the properties of the interior waters. Irminger Current eddies store large amount of heat and decaying release it in the Labrador Sea. Thus one would like to know what stages precede this decay and how the properties of the eddy evolve during its life. Since the main question of the current work concerns the evolution of the eddies, how their properties change under the strong wintertime forcing, typical for the Labrador Sea, all the eddies were divided into groups according to the differences in vertical structure. All anticyclones from the data set were divided into three classes: eddies with fresh water layer at the top and no mixed layer - "unmodified eddies" (12), eddies with no fresh layer at the top and at least one mixed layer - "convected eddies" (18) and the remaining eddies. All the eddies from unmodified group had a strong signature of the boundary current while convected eddies have a well-developed mixed layer and sometimes a Labrador Sea Water from the previous year. It was found that 4 eddies having signal penetrating down to 1500-2000 m and isopycnal displacement of 400-600 m were a subset of the "convected eddies".

Despite the existence of the fresh cap in some eddies, their heat contribution to the interior is still significant. Assuming that each eddy radius was 20 km, on average, eddy contains about 0.2-0.3 GJ m^{-2} and if this amount is distributed over the whole Labrador Sea, the contribution would be of the order of 1-2 MG m^{-2}.

A significant fraction of the eddies (23 out of 48) have a second core at mid-depth. The structure of the core can be different: either a homogeneous well-mixed core or a second core of the same shape but slightly weaker properties.

8.2 Interpretation of the findings

This work has attempted to shed some light on the concepts of the evolution of Irminger Current anticyclones, their water mass change as a result of the strongest forcing of the year, the wintertime forcing, and investigate the possibilities of different scenarios of the evolution.

"Unmodified eddies" have a strong signature of the boundary current with a fresh cold layer overlying warm and salty water. The differences from the Irminger Current appear only at depth since the eddies contain a much larger fraction of Labrador Sea Water below Irminger Water as opposed to the deep boundary current having a greater volume of the waters from the Nordic Seas. Those unmodified eddies can be found in a relative proximity of the region of formation or along 3000 m isobath if they are carried by the current. Unfortunately hydrographic data does not allow to investigate the whole spectrum of their locations since horizontal coverage of the sections is very limited.

"Convected eddies" were identified by the presence of a well-pronounced mixed layer or several mixed layers pointing to the fact that they had experienced wintertime forcing before or were experiencing it at the time of observation. Mixed layer is seen in all the fields with especially interesting result in salinity profiles. All convected eddies have no fresh water cap at the surface. Instead, it is replaced with a layer of almost homogeneous water of much saltier than West Greenland and fresher than Irminger Current water. Such salinity value is a result of vertical mixing of the water column containing WGC and IC roughly in proportions 1:4 which is supported by both data and 1-D mixed layer model. Hatun et al., [12], suggested that fresh water contained in the eddies is released into the interior of the Labrador Sea, thus contributing to the "fresh capping effect" appearing at the surface of the Labrador Sea shortly after convection ceases.

The deep layer of the eddies may also carry a signature that reveals the history of an anticyclone. Some of the convected eddies contained the Labrador Sea Water of the previous years, in particular, LSW of the year preceding the observation. Since Labrador Sea Water is experiencing a warming and salting trend during the past decade, the year of formation can be derived from the water mass analysis. The fact that eddies contain LSW formed in a previous year can possibly be explained by the ability of some eddies to trap water below and carry it around for at least a year. Or, another possible explanation lies in various patterns of the Labrador Sea Water distribution in different years. The exact location of the last year LSW is unknown after its formation and it is possible that the eddy was formed in 2004 in a place which still contained LSW_{2003} at depth.

A subset of the eddies containing the signature of last year's LSW had a very barotropic signal down to 2000 m and had an isopycnal displacement twice as large as the rest of the eddies. Those eddies were the most energetic structures in the whole data set. The amount of available potential energy is connected to the depression of isopycnals. Since the isopycnal displacement was the greatest in the deep eddies and assuming the radius of eddies is the same for all the eddies, the amount of energy stored in those deep eddies is much greater than in the usual ones. While it is possible that this is just a coincidence, I note that none of these eddies had a fresh water cap at the surface and all of them belong to the group of "convected eddies".

Another type of eddy was observed in the data set - eddies which have two or more cores of different θS properties. A subset of those multiple core eddies have cores which were clearly formed by the wintertime convection. Those cores are very homogeneous and are vertically extended for 200-500 m. Those mixed layers are stacked vertically and have slightly different properties which allows to distinguish one mixed layer form the other. A hypothesis of formation of those multiple core eddies is originating from the work of L03, [26] where the authors argue that eddies could "stack" and form such a complicated structure. This mechanism is also possible for the formation of the energetic eddies discussed earlier in the text.

Several experiments with a one dimensional mixed layer model were performed to show that the evolution of an Irminger Ring can be determined to the leading order by 1D processes. It is possible to obtain Irminger Rings by forcing the boundary current which supports the hypothesis of the mechanism of eddy formation. The model result also points out to the validity of breaking the eddies into "unmodified" and "convected" subsets. Indeed, it is possible to force an unmodified eddy and obtain a convected one - thus, those two groups are connected and the latter can be the result of the forcing of the former.

The mixed layer model was also a powerful tool in comparing the mixed layers within eddies and in the mean Labrador Sea interior. An interesting results supporting the previously stated hypothesis were the outcome of our experiments. If an eddy and a mean profiles are subjected to the same forcing it is possible to predict where the mixed layer would be deeper. If the eddy belongs to an "unmodified" group then the mixed layer in it would be shallower than in the interior of the Labrador Sea but if it has already been convected and is exposed to the surface fluxes for the second time then its mixed layer would be deeper than in the interior. This could be explained by the fact that once-convected eddy already has a mixed layer and it is covered only by a thin layer of restratified fluid. Oppositely the water column of the interior profile has much thicker layer of restratified fluid due to the contribution of the lateral fluxes. Anticyclones restratify only because of the heating from the top with no lateral exchange with ambient water which makes the process longer and results in a thinner stable layer.

Hydrographic data used in this study was rich in different types of eddies: summertime and wintertime eddies, unmodified and convected eddies, multiple core and single core eddies, cyclones and anticyclones. Properties of all groups of eddies were investigated and the possible evolution paths were outlined. A 1-D model was used to test the hypothesis of 1D evolution of anticyclones and to compare the mixed layer depths and properties of eddies forced with a model and obtained from the data. Many challenges appeared during this study and at different stages several assumptions had to be made. First of all there are not much data from the Labrador Sea resolving the eddies: these long-lived structures are very intense and even if their sea surface height elevation is distinguishable, they can not be tracked individually with altimetry. Altimetry tracking of the eddies could make the identification of the eddy age more accurate is it allows to reconstruct the trajectory from the source. More wintertime data are desired for getting more observational evidence of eddy behavior under the strong heat fluxes.

Hydrographic data used in this work captures the eddy-like events purely by chance and thus the measurements are unlikely to be located in the center of the eddy. However, according to the work of Hatun et al., [12], Irminger Rings have horizontally homogeneous properties over roughly 2/3 of the cores. This fact increases the probability that a hydrographic cast occurred in the central part of the eddy, however this is still an assumption. The model runs used the heat flux averaged over more than 50 years and over the whole area of the Labrador Sea. This could have caused the mismatches of the forced profiles with the profiles from eddies observed in the Labrador Sea.

Evolution of the water masses inside Irminger Rings in the Labrador Sea is a question of great importance. The Labrador Sea is not the only site of deep convection and the results obtained for this region can be also used in the works regarding other convective sites such as the Mediterranean, Greenland and Irminger Seas. All of them have a buoyant boundary current encircling the sea and shedding eddies. The desired goal is to be able to understand the dynamics of the eddies so well so as to be able to parameterize them in the general circulation models. These eddies exist in large numbers in the Labrador and other seas and can substantially modify the properties of the interior during and after convection.

The discoveries of the present study have revealed new aspects of the Irminger Current anticyclones. New observations concerned both population and properties of the eddies. Another pathway by which Irminger Current eddies could reach the Labrador side of the basin, mentioned by Hatun et al., [12], was documented for the first time in the present study. This implies that Irminger Current eddies have two directions of propagation: southward from the source and westward carried by the boundary current along 3000 m isobath. Thus, water of the boundary current origin can reach interior in two different ways. Contribution of this work shedding more light on the properties and of eddies and their response to convection comes from the identification of the group of "convected eddies", eddies without a fresh layer at the surface. This group shows how the eddy structure changes as a result of wintertime forcing. The fresh water contained originally at the surface no longer exist and the mixed layer develops. However, it appears from both models and observations that the amount of fresh water is conserved inside an eddy. This implies a more complicated mechanism of eddy contribution to the fresh water capping effect than described by Hatun et al., [12].

Future work will include a more careful analysis of the multiple core and deep eddies, investigation of the different mechanisms responsible for their formation. Model studies are expected to use more realistic heat fluxes and include all the eddies and not only the most pronounced structures of different kinds. Several other experiments are planned for testing the possibility of different sites of origin of the mixed layers inside the multiple core eddies and calculating the net fresh water and heat influence of the eddies on the interior of the Labrador Sea.

Appendix A

Tables

Current	*Transport*	*Author*
Irminger Current	11Sv	Clarke, [3]
West Greenland Current (at Cape Farewell)	3Sv	Clarke, [3]; Cuny et al., [4]
Labrador Current	11 ± 4Sv	Lazier and Wright, [20]
NADW (past Cape Farewell)	34-50Sv	Clarke, [3] and others

Table A.1: Transports of the major currents transport in the Labrador Sea.

Current	*Velocity*	*Author*
Irminger Current	30-90cm/s	L03, [26]
West Greenland Current	12-35cm/s	Lavender et al., [18]; Cuny et al., [4]
Labrador Current	10-40cm/s	Cuny et al., [4]; Lazier and Wright, [20]
NADW	~2-5 cm/s	Ganachaud and Wunsch, [8]; Cuny et al., [4]

Table A.2: Velocities of the major currents of the Labrador Sea

Year	*Month*	*Section*
1990	July	AR7W (2); $\perp$AR7W (2)
1991	June	AR7W
1992	June	$\frac{1}{2}$ AR7W (2)
1993	June	AR7W (3)
1994	June; November	AR7W (2+1)
1995	June	AR7W
1996	May; October; November	AR7W (1+1+1); $\perp$AR7W
1997	February; March; May; June; July	AR7W (3); $\frac{1}{2}$ AR7W (3) $\perp$AR7W (2); $\Vert$AR7W (2)
1998	January; July	AR7W (2)
1999	July	AR7W (2)
2000	June	AR7W (2)
2001	June; August	AR7W ($1\frac{1}{2}$); $\perp$AR7W
2002	July; December	AR7W (2+1)
2003	July	AR7W
2004	May	AR7W

Table A.3: Place and time of the hydrographic sections. Number in the parenthesis represents the number of sections taken. $\frac{1}{2}$AR7W means the section across convective region, $\Vert$AR7W - the northernmost section, $\perp$AR7W - south-east to north-west section.

	Convective lenses	*Irminger Current cyclones*	*Irminger Current anticyclones*	*Observed by*
Mooring	$\theta_{500-750m} \sim 2.6 - 2.7^oC$ $S_{500-750m} \sim 34.81 - 38.82psu$ $\sigma_{250-1250m} \sim 0.01 - 0.02gkg^{-1}$ $R \sim 5 - 15km$ $V \sim 15 - 30cms^{-1}$	$\theta'_{500m} \sim 0.1 - 0.2^oC$ $S'_{500m} \sim 0.05 - 0.1psu$ $\sigma'_{500m} \sim 0.02 - 0.04gkg^{-1}$ $R \sim 15km$ $V \sim 11.6 - 19.8cms^{-1}$	$\theta \sim 3.3 - 4.4^oC$ $R \sim 15 - 25km$ $V_{surface} \sim 30 - 80cms^{-1}$ $V_{1000m} \sim 20 - 40cms^{-1}$	L02, [25] L03, [26]
Float	no observation	$\theta \sim 3.59 - 3.86^oC$ $R \sim 10 - 18km$ $V_{375m} \sim 22 - 40cms^{-1}$ $V_{translation} \sim 10 - 20cms^{-1}$	$\theta \sim 4.75^oC$ $R \sim 25km$ $V_{375m} \sim 42 - 40cms^{-1}$ $V_{translation} \sim 2.5 - 8cms^{-1}$	Prater,[33]
Altimetry	not seen	$SSH \sim 10 - 20cm$	$SSH \sim 25 - 40cm$ $SSH \sim 10 - 18cm$ $V_{southward} \sim 5cms^{-1}$	L03, [26] Hatun et al., [12] L03, [26]
Glider	no observation	no observation	$\theta'_{surface} \sim -0.5^oC$ $S'_{surface} \sim 0.4psu$ $\theta'_{400m} \sim 1.5^oC$ $S'_{400m} \sim 0.06psu$ $R \sim 21 - 35km$ $V \sim 30 - 50cms^{-1}$ $V_{south-westward} \sim 15cms^{-1}$	Hatun et al., [12]

Table A.4: Eddies in the Labrador Sea from different sources of data

	Irminger Current anticyclone	*Irminger Current cyclone*
Temperature anomaly	$\theta'_{27.64-27.72} \geq 0.2^oC$	$\theta'_{27.64-27.72} \sim 0.16 - 0.22^oC$ $\theta'_{500m} \sim 0.1 - 0.2^oC$
Salinity anomaly	$S'_{27.64-27.72} \geq 0.01$ psu	$S'_{27.64-27.72} \sim 0.03 - 0.04$ psu $S'_{500m} \sim 0.05 - 0.1$ psu
Density anomaly	$\sigma'_{27.64-27.72} \geq 0.01$ g kg^{-1}	$\sigma'_{27.64-27.72} \sim 0.01$ g kg $^{-1}$ $\sigma'_{500m} \sim 0.02 - 0.04$ g kg^{-1}

Table A.5: Comparison of the anomaly values for Irminger Current anticyclones and cyclones

Appendix B

Figures

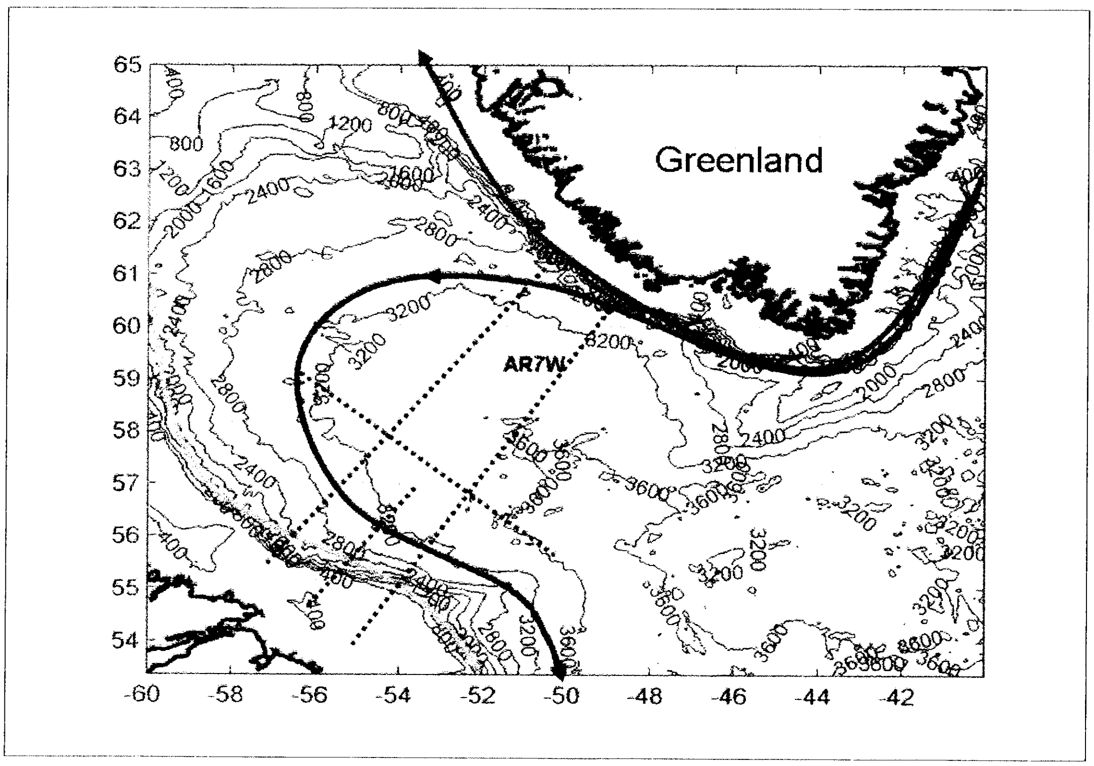

Figure B-1: Map of the Labrador Sea with surface currents and locations of hydrographic sections sketched. Dark blue - East and West Greenland Currents (WGC), red - Irminger Current (IC), light blue - Labrador Current (LC). Dashed lines - locations of hydrographic sections. Numbers on the black contours indicate bathymetry.

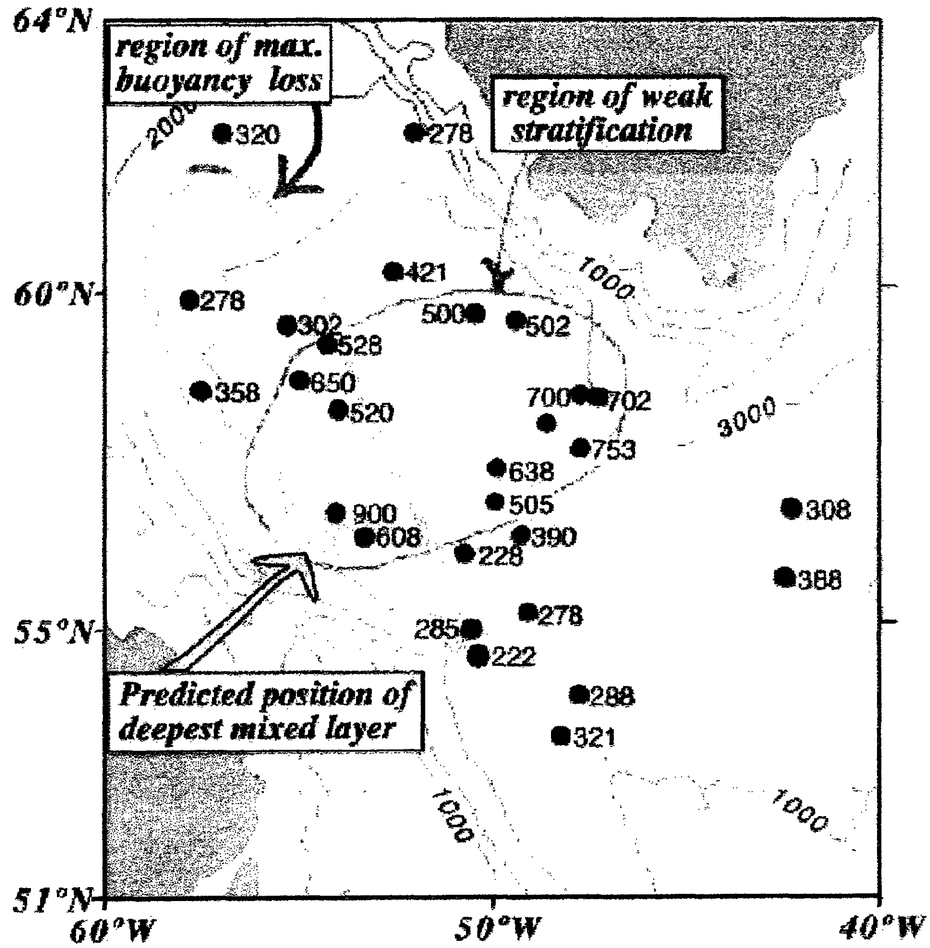

Figure B-2: Conditions for the convection to occur are satisfied in the Labrador Sea (Figure from LSDCE, 1998).

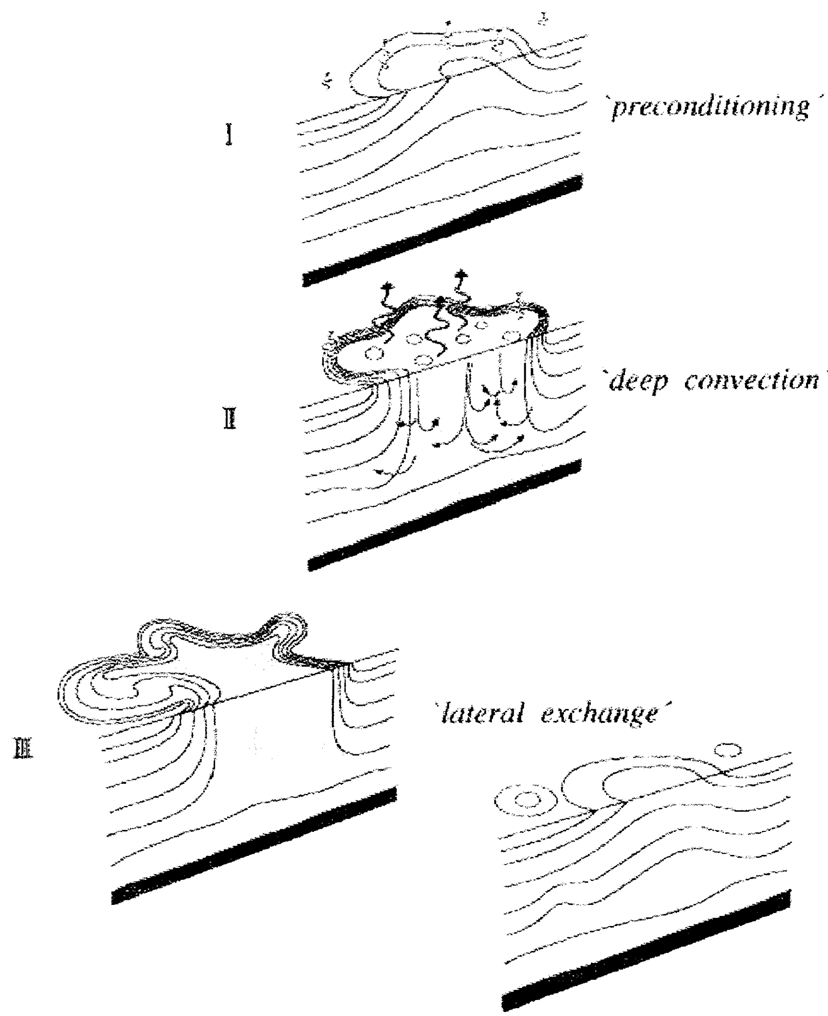

Figure B-3: Phases of convection (Marshall and Schott, [29]).

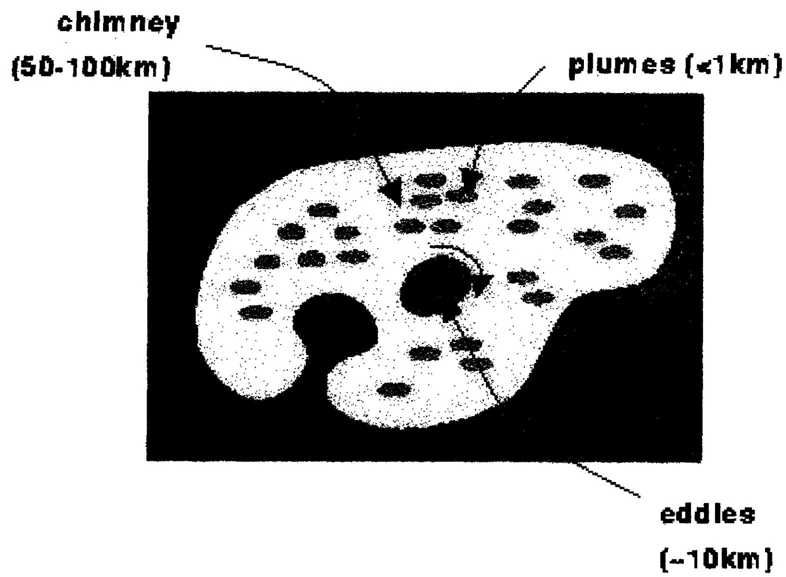

Figure B-4: "Chimney" structure. Dark blue represents the water surrounding the chimney, light blue - chimney itself, gray circles are the plumes and a patch of a dark blue in the center of the chimney is a convectively generated eddy.

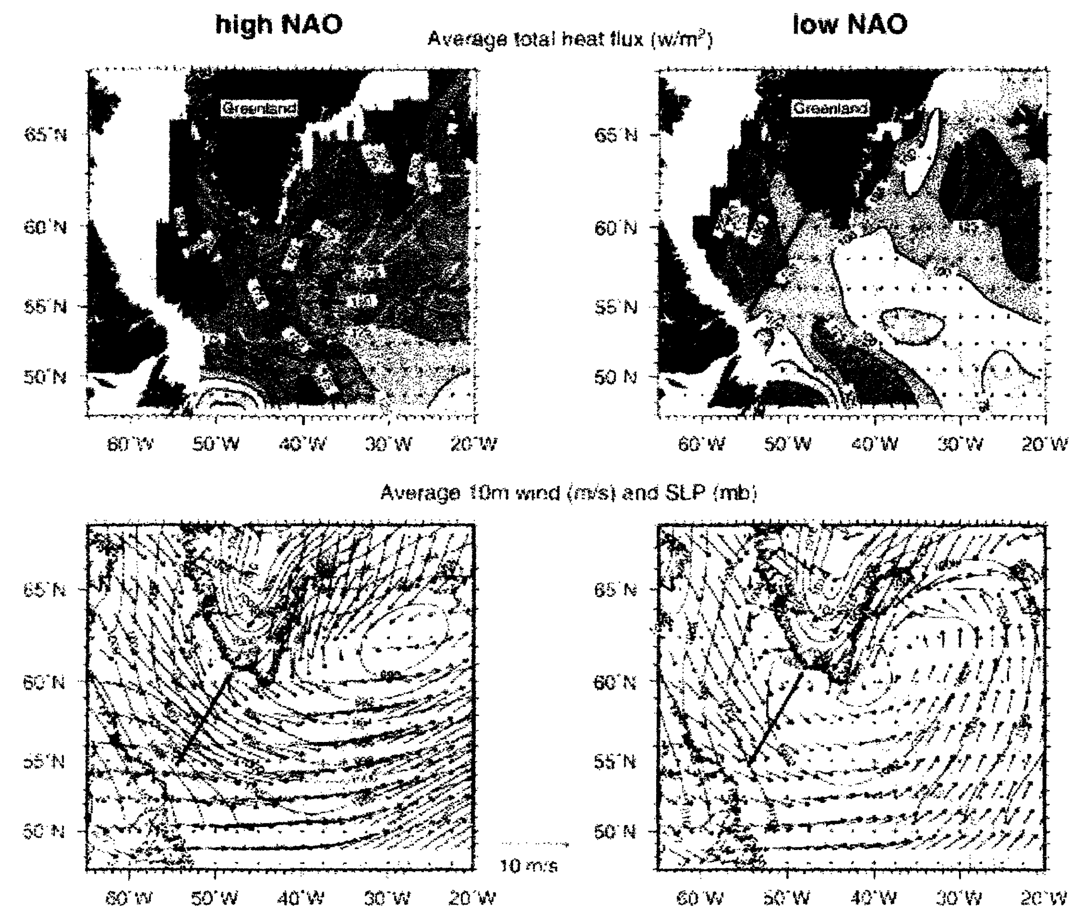

Figure B-5: High and low NAO index years are shown in columns. Upper panel - average total heat flux; lower panel - corresponding winds over the Labrador Sea. Figure from Pickart et al., [31]

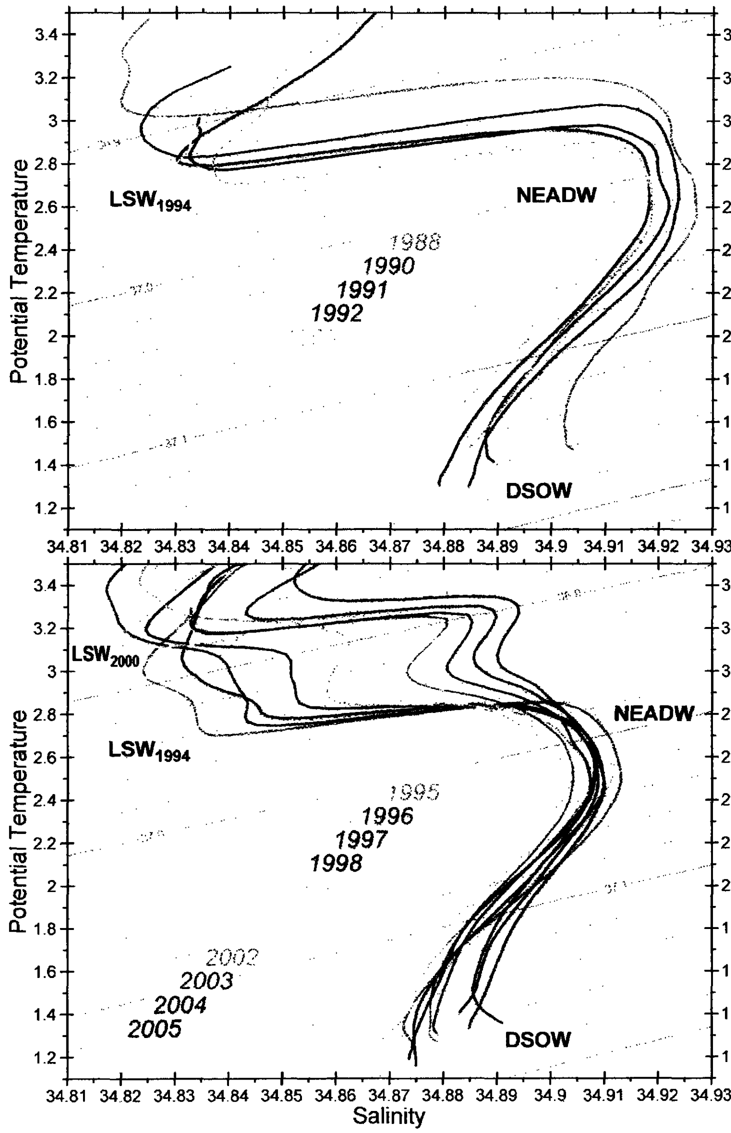

Figure B-6: θ/S diagrams showing interannual changes in the properties of the Labrador Sea Water. Upper panel represents the years 1987-1997 and lower panel - from 1994 onwards. (courtesy of I. Yashayaev, [45])

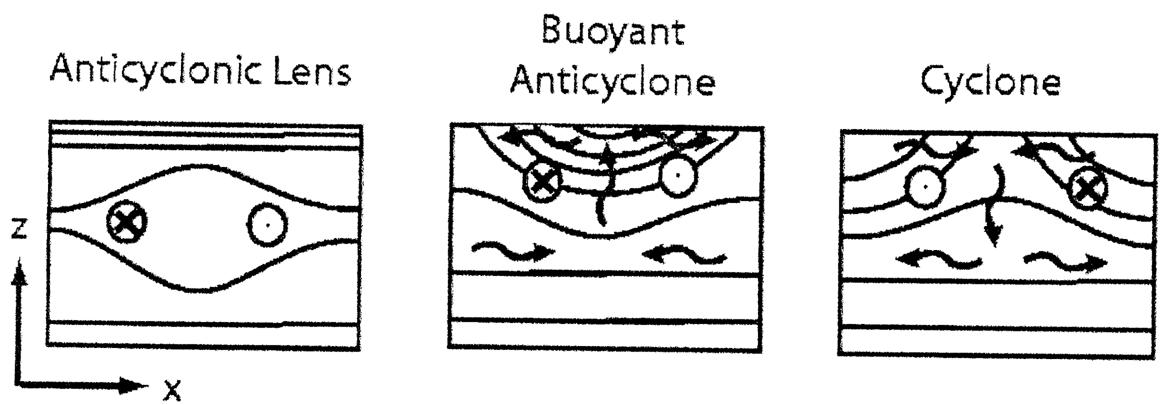

Figure B-7: Three types of eddies in the Labrador Sea (courtesy of F. Straneo, personal communication). Circles with symbols inside represent the currents in the eddies: cross - the current into the page, dot - the current out of the page. Curved arrows show the secondary circulation.

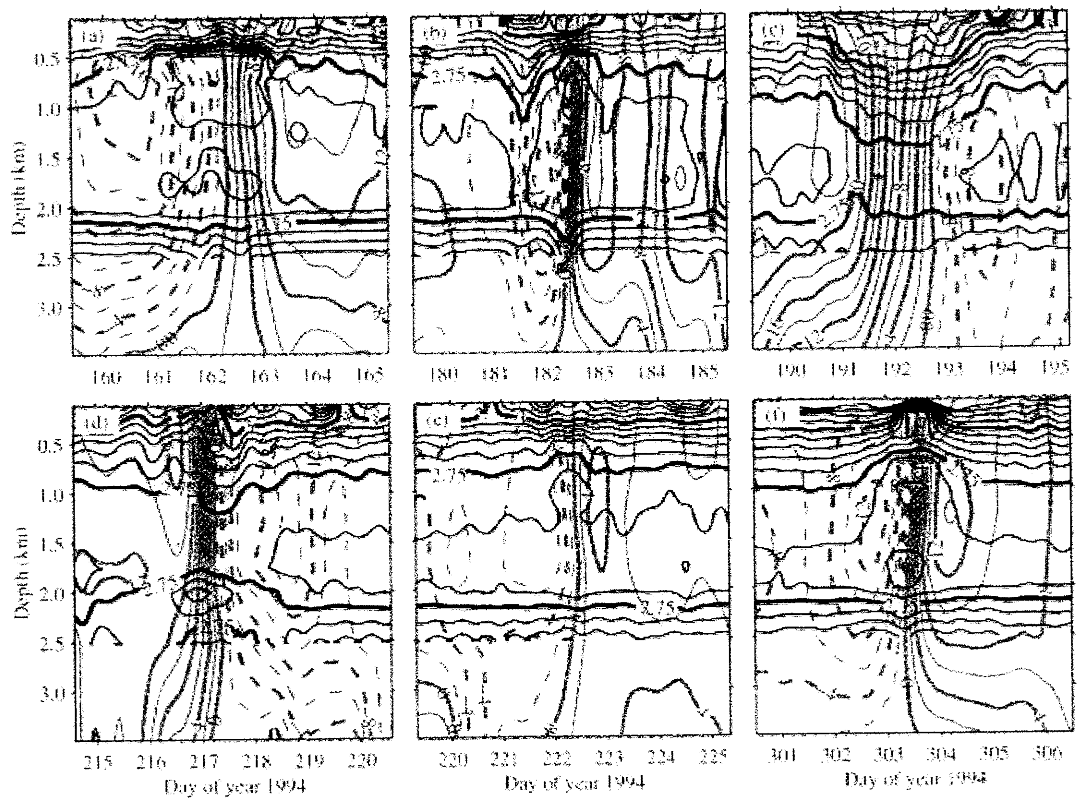

Figure B-8: Vertical structure of convectively generated lenses and Irminger Current cyclones as observed by a mooring (from L02, [25]).

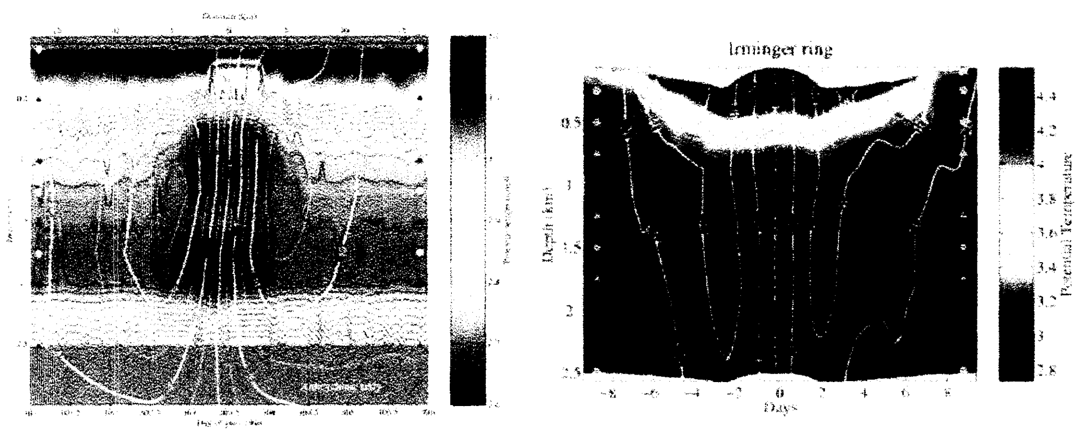

Figure B-9: Vertical structure of an anticyclonic lens and an Irminger Current anticyclone obtained from a mooring (courtesy of J. Lilly). White contours indicate velocities; colors - temperature field. Triangles and circles represent locations of the mooring sensors.

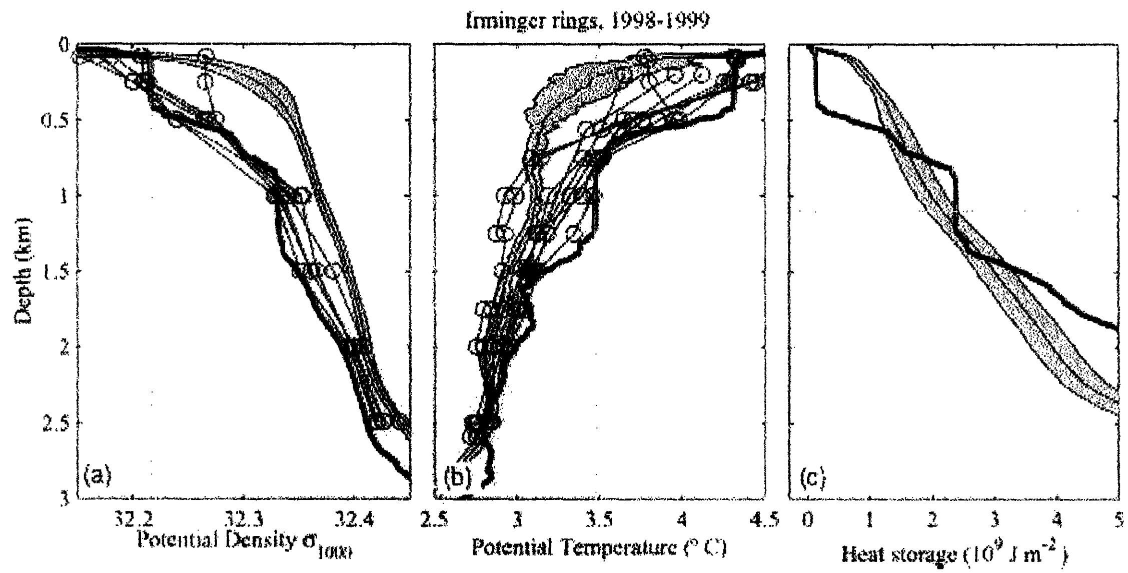

Figure B-10: Multiple core eddy observed and analyzed by L03. [26]. For more information see L03.

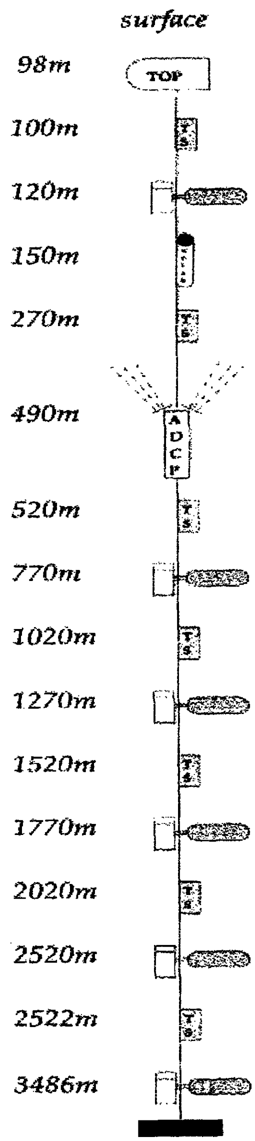

Figure B-11: Sketch of a mooring with sensors indicated (Figure from L99, [24]). More information can be found in the cited paper.

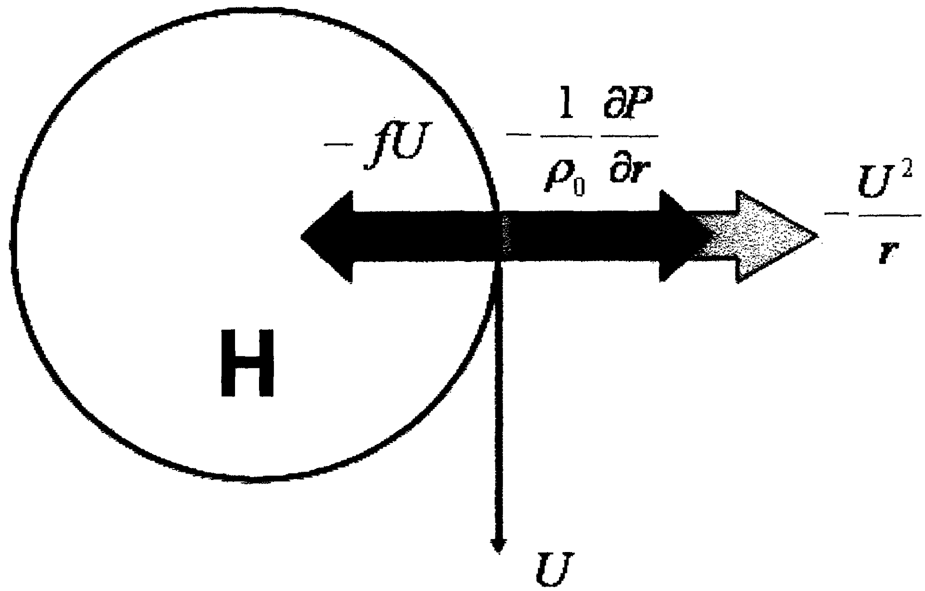

Figure B-12: Balance of forces in the anticyclone.

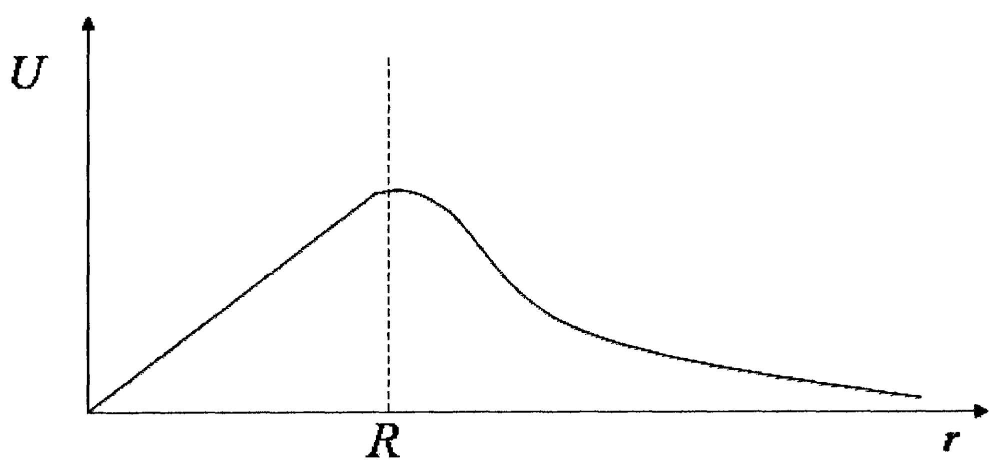

Figure B-13: Velocity structure of an anticyclone.

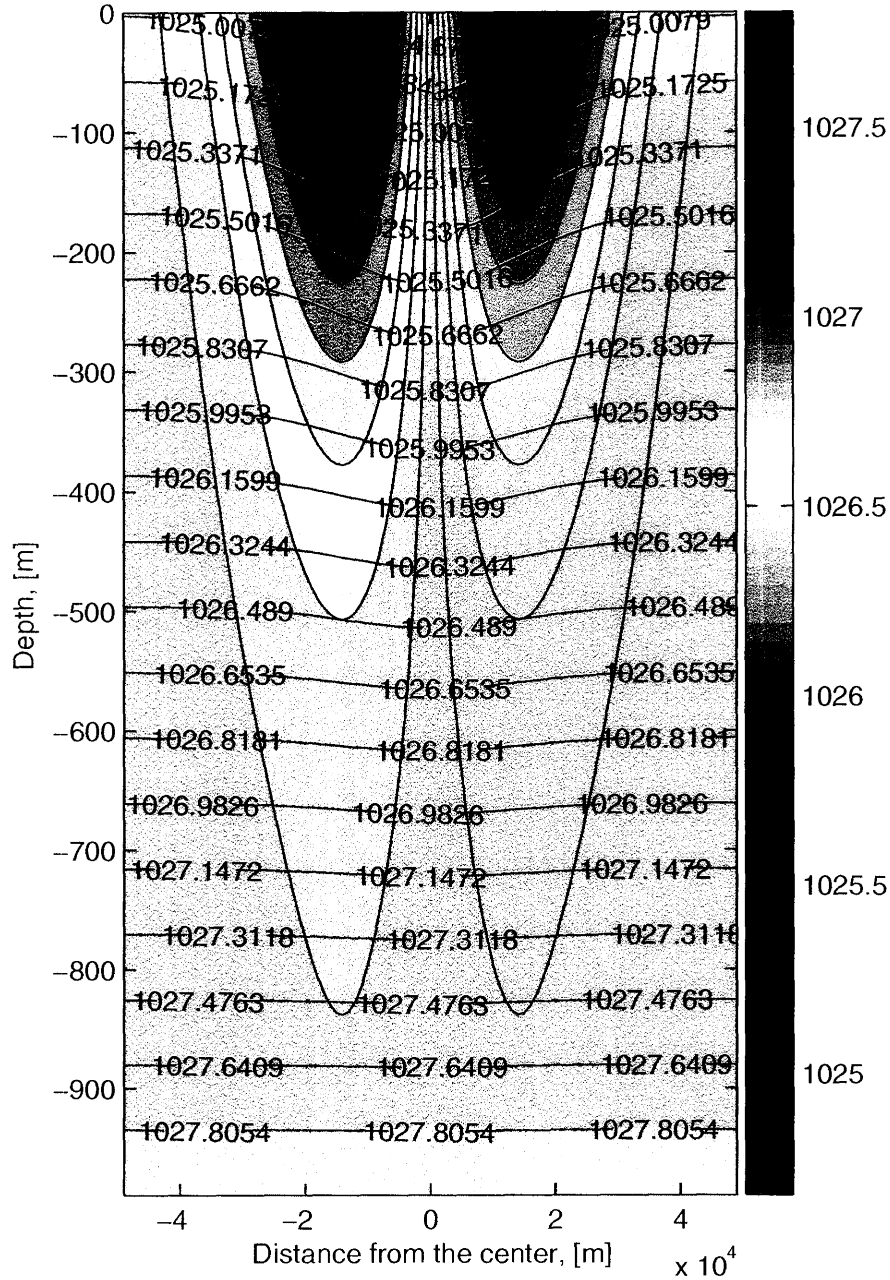

Figure B-14: Density structure of an anticyclone obtained from analytical model. Colors represent velocity field, contours - isopycnals.

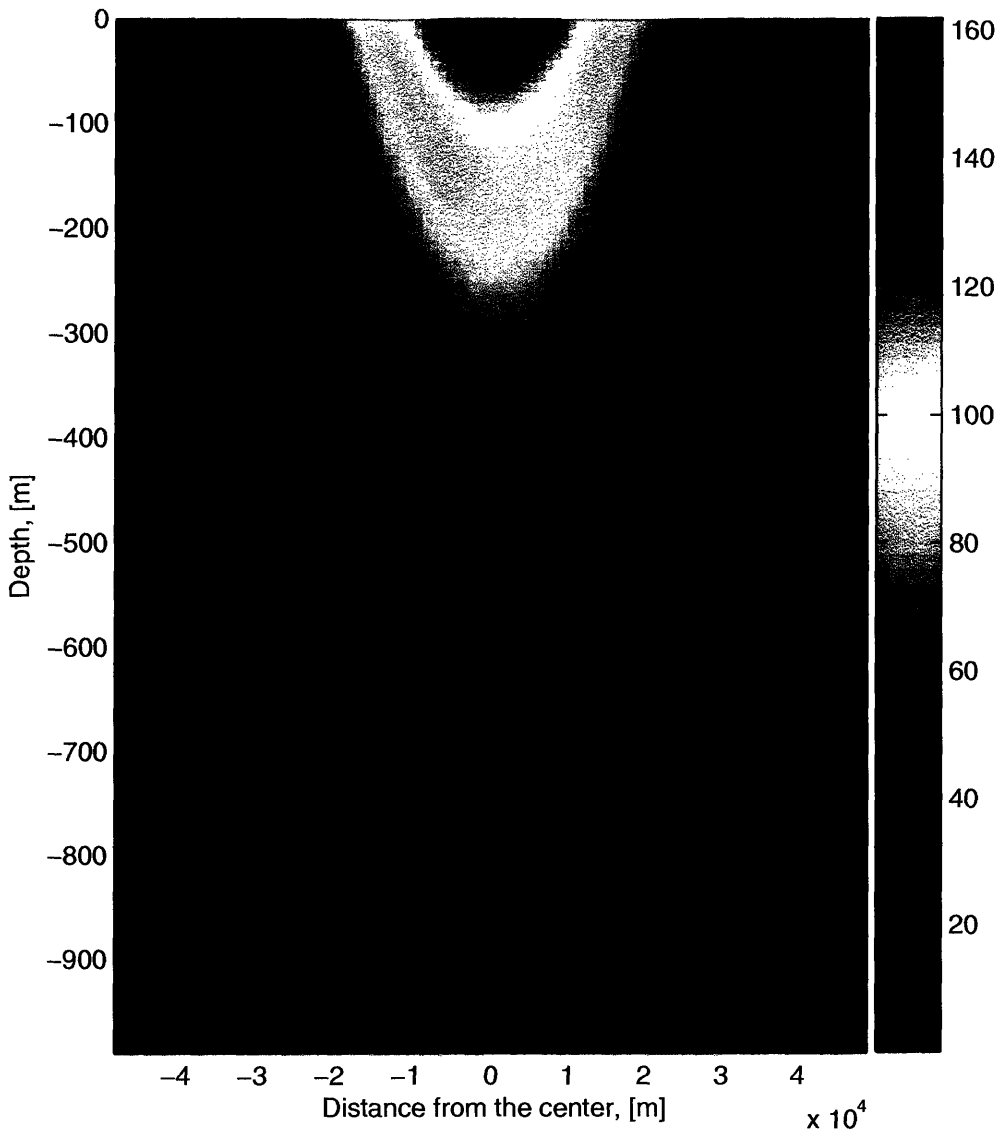

Figure B-15: Isopycnal displacement of an anticyclone obtained from analytical model.

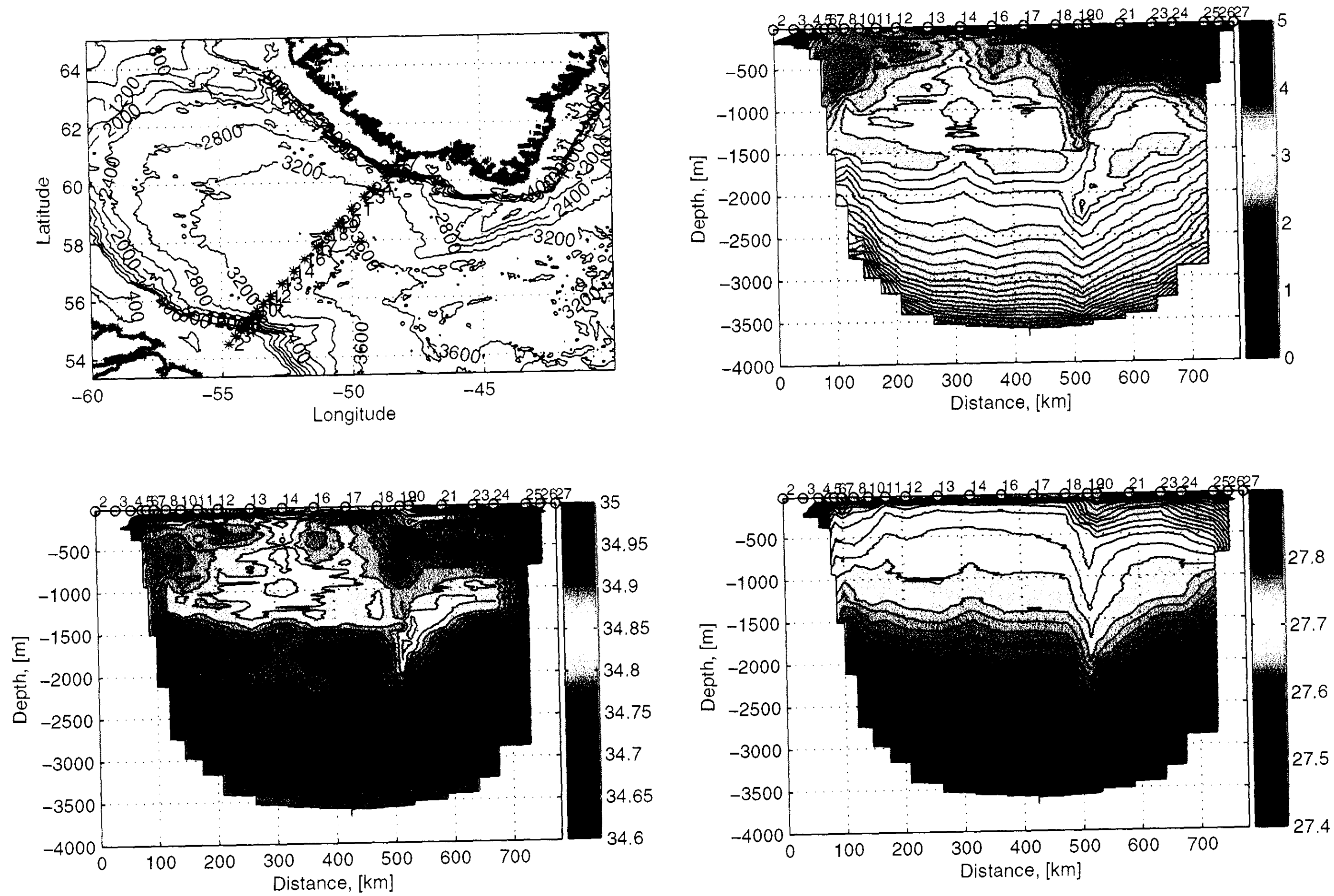

Figure B-16: Hydrographic section along AR7W, May 2004. Map shows location of the stations in the Labrador Sea (upper left corner); Potential temperature along AR7W (upper right corner); Salinity along AR7W (lower left corner); Potential density (lower right corner).

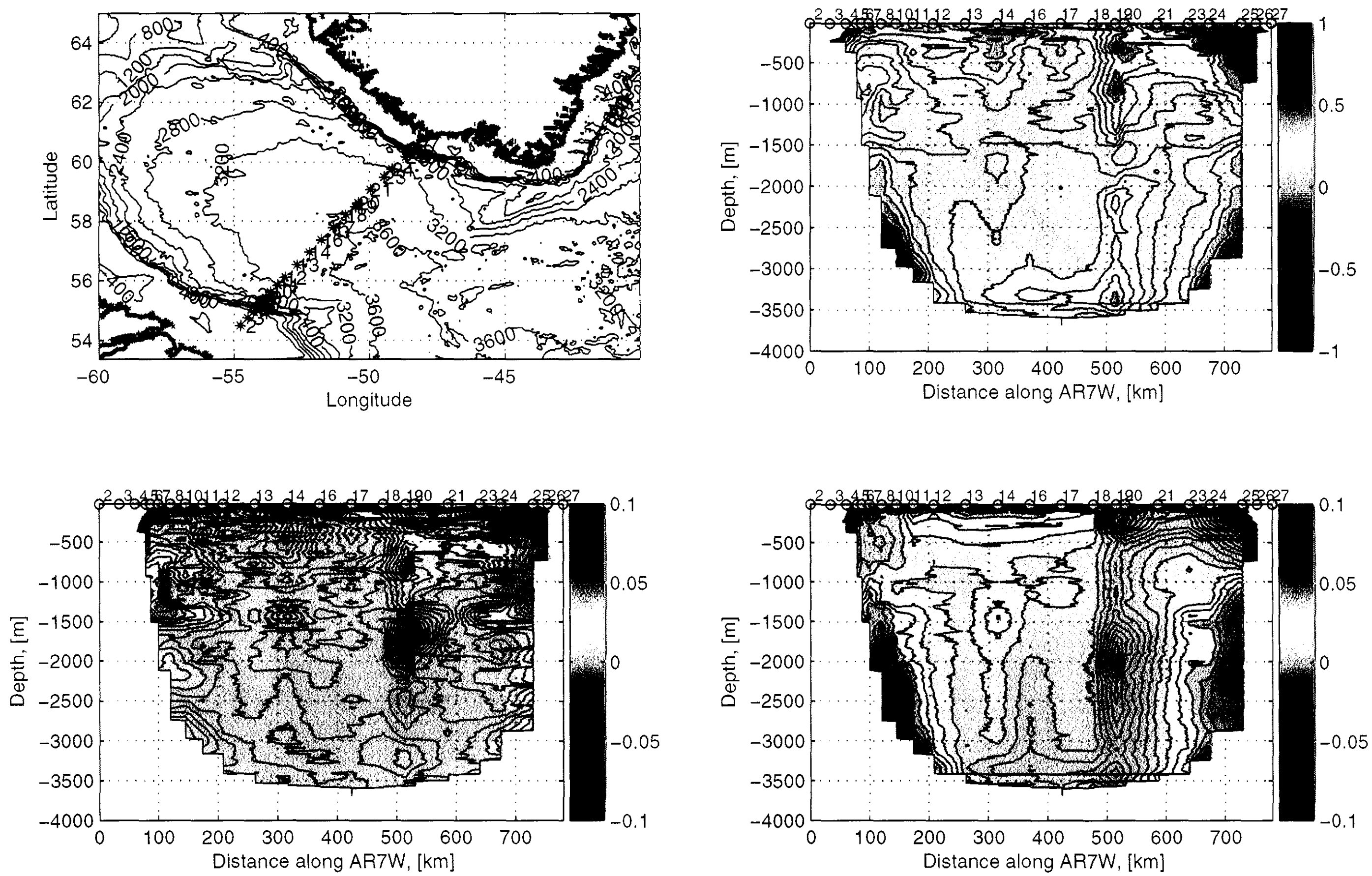

Figure B-17: Hydrographic section along AR7W. Map shows location of the stations in the Labrador Sea (upper left corner); Perturbation of potential temperature along AR7W (upper right corner); perturbation of salinity along AR7W (lower left corner); perturbation of potential density (lower right corner).

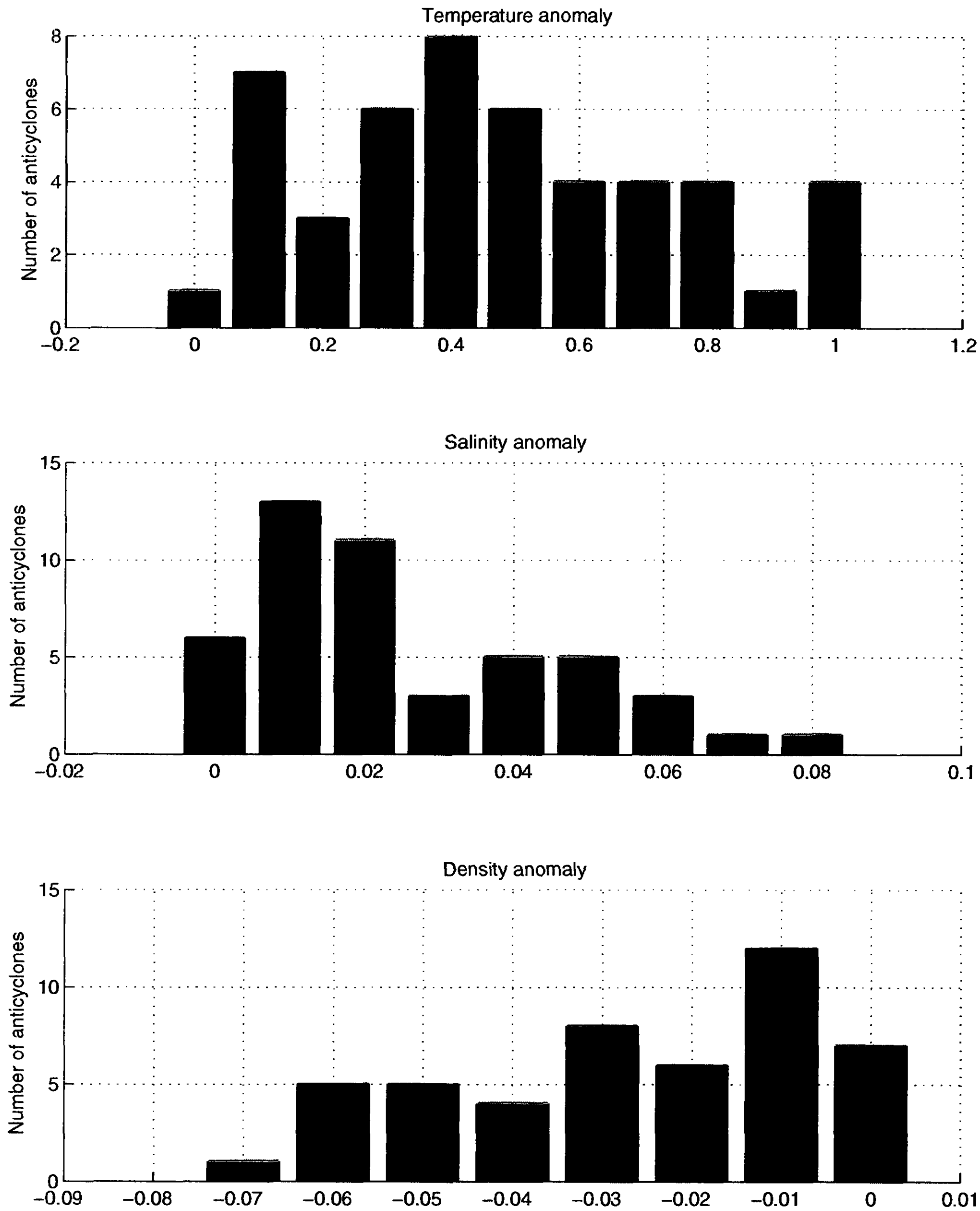

Figure B-18: Potential temperature (upper panel), salinity (middle) and potential density (lower panel) of 48 anticyclones identified in the hydrographic data set.

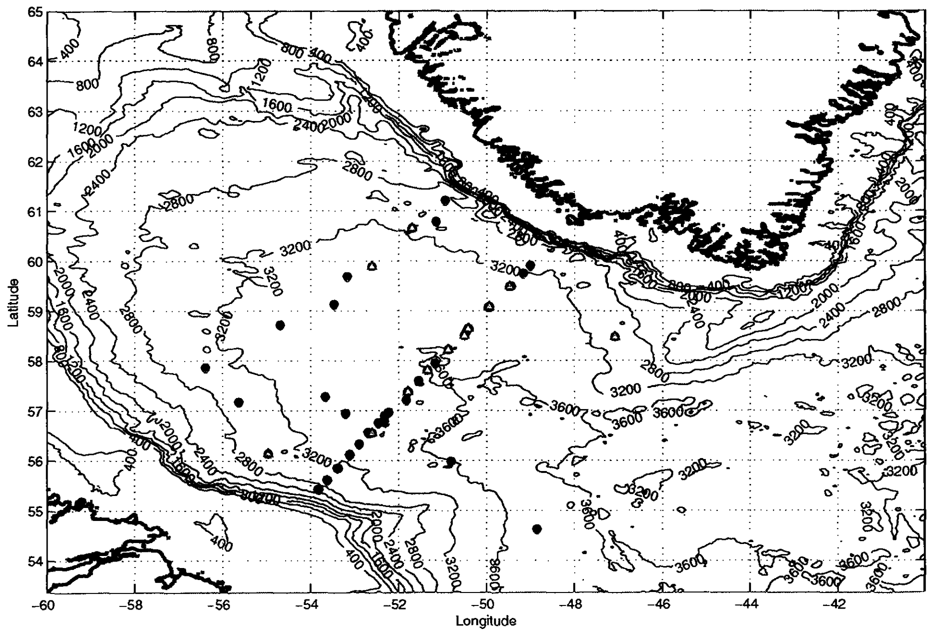

Figure B-19: Locations of all eddy-like anomalies found in the hydrographic data set (blue circles); Irminger Current anticyclones (red circles); eddies without fresh layer at the surface or "convected eddies" (green triangles).

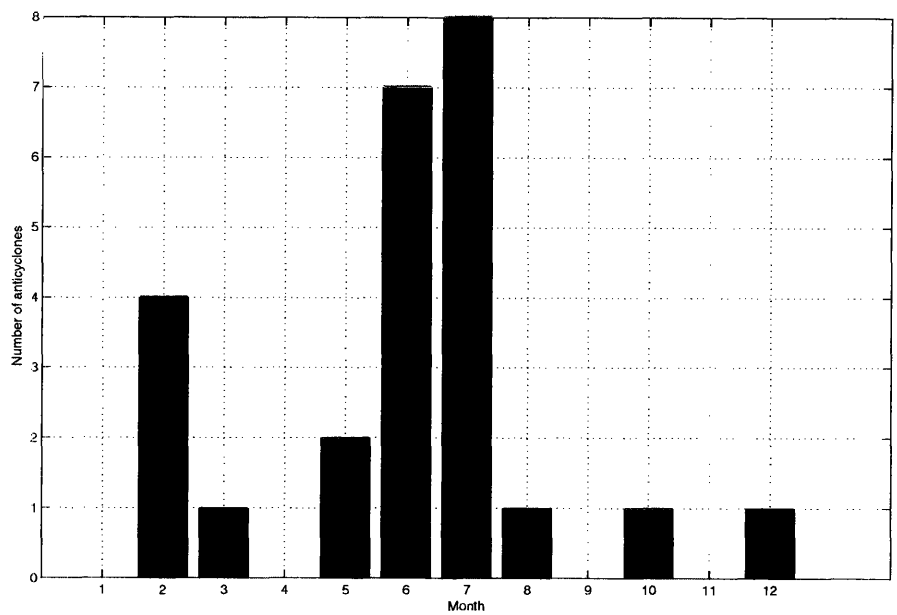

Figure B-20: Monthly distribution of the anticyclones found in hydrographic data set. "Unmodified eddies" are shown in red, "convected" - in blue.

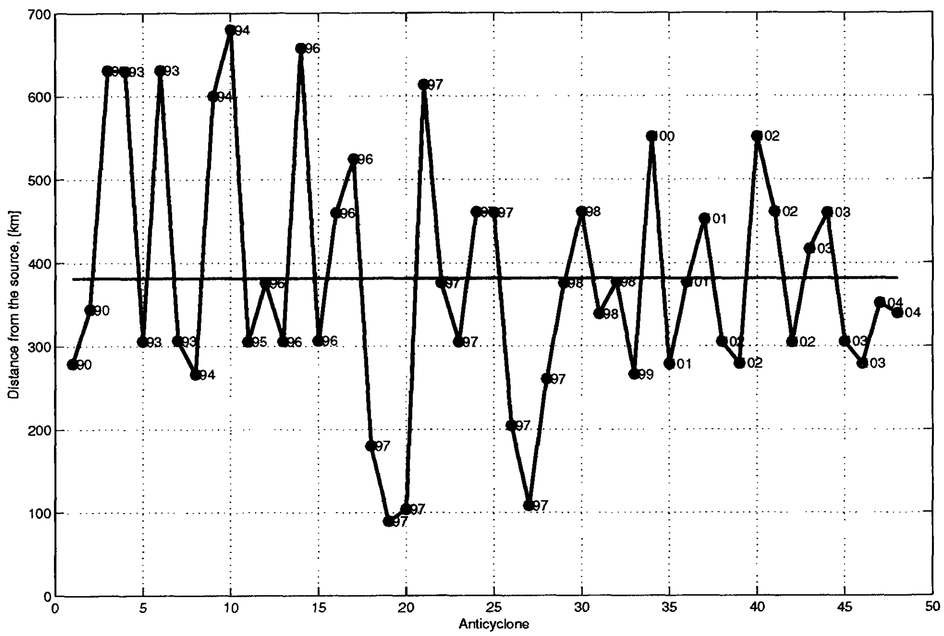

Figure B-21: Distance from the source for all the anticyclones. Blue line shows the mean distance. Number is the year of measurement.

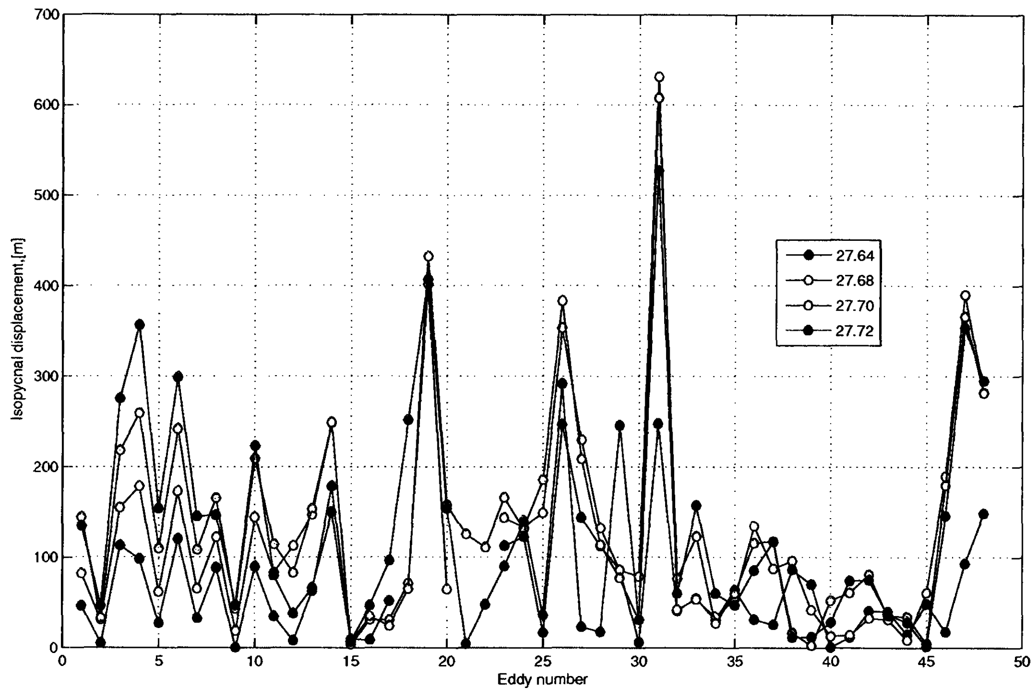

Figure B-22: Isopycnal displacement is shown for different isopycnals.

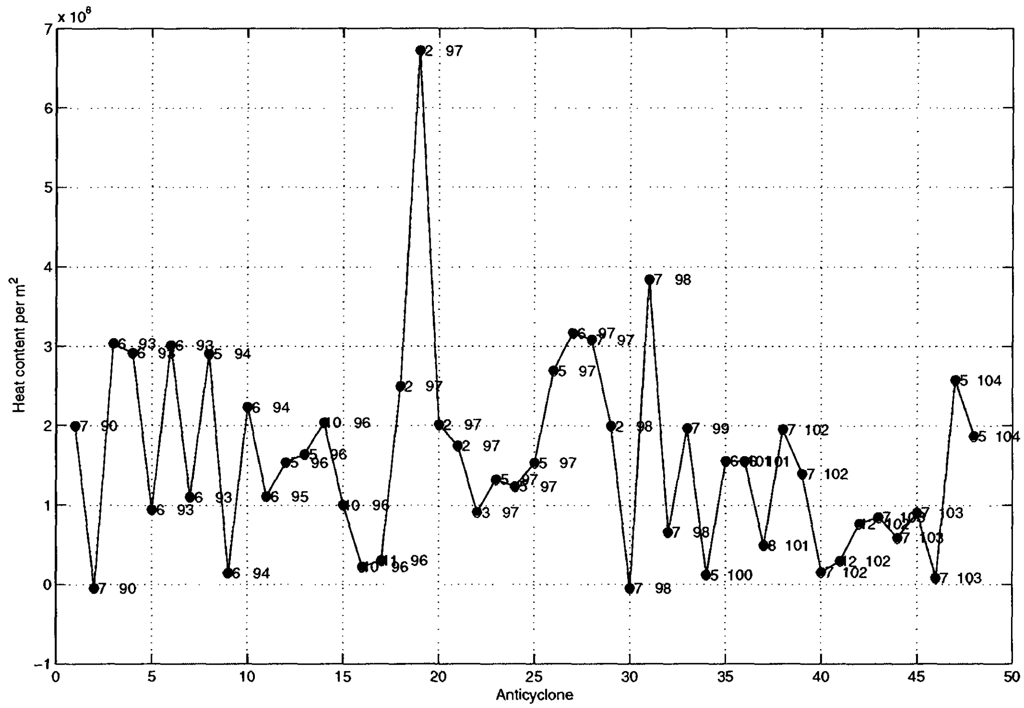

Figure B-23: Heat content for anticyclones per m^2. Label shows month and year of observation.

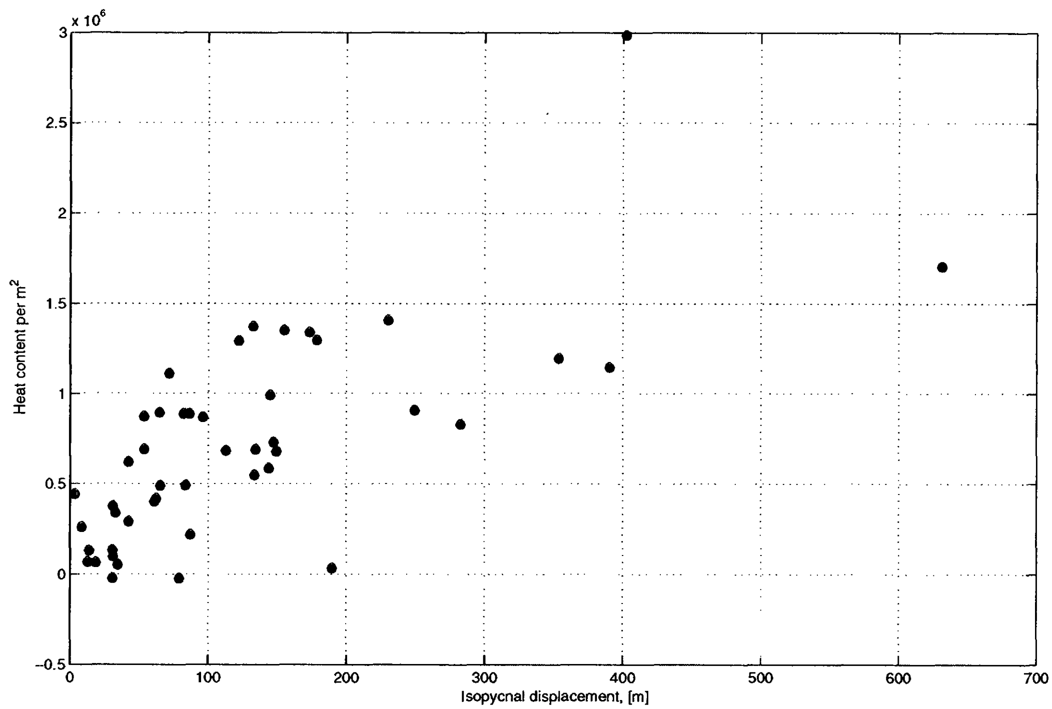

Figure B-24: Heat content for anticyclones per m^2 as a function of isopycnal displacement.

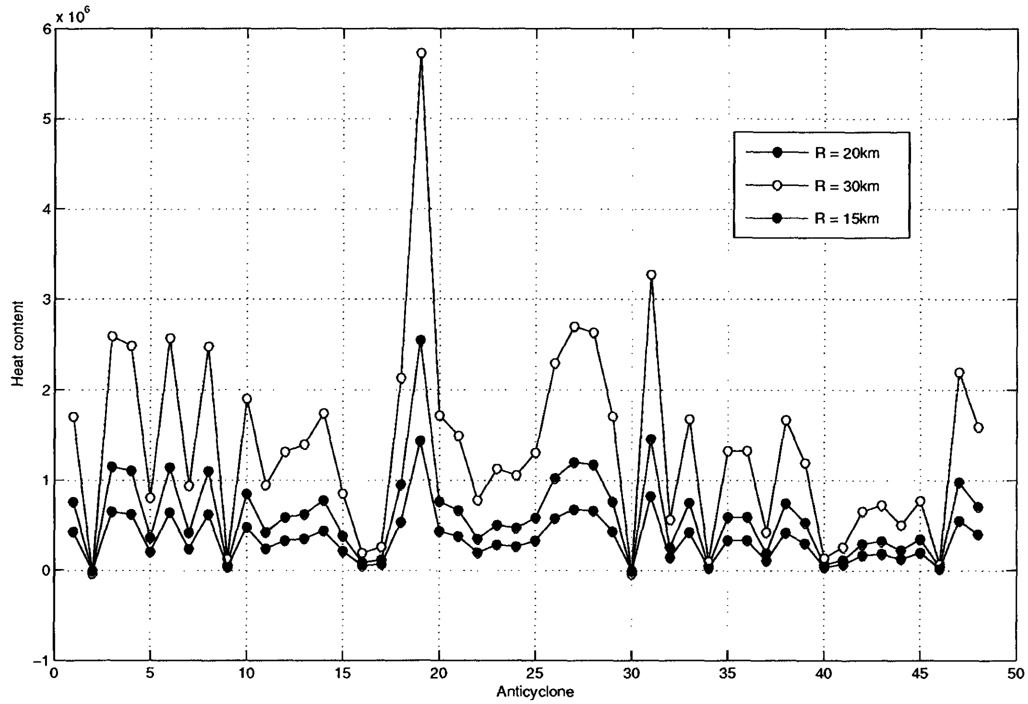

Figure B-25: Contribution to the heat budget of the Labrador Sea from eddies of different radii.

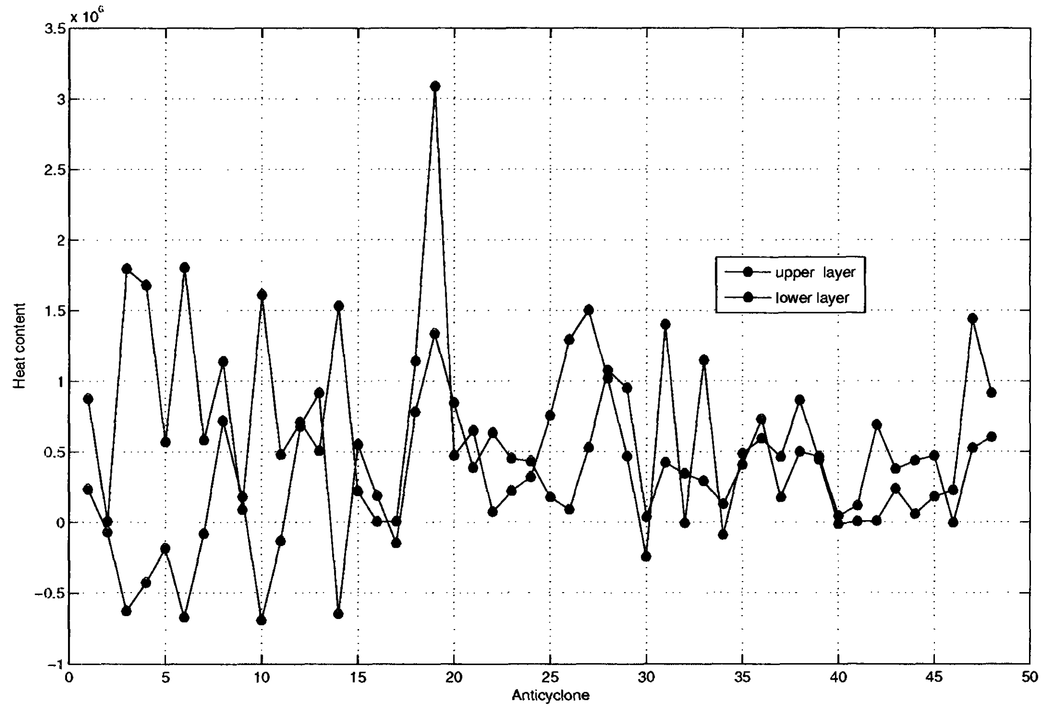

Figure B-26: Upper 300 m (red) and lower 300-1000 m (blue) heat content of the anticyclones.

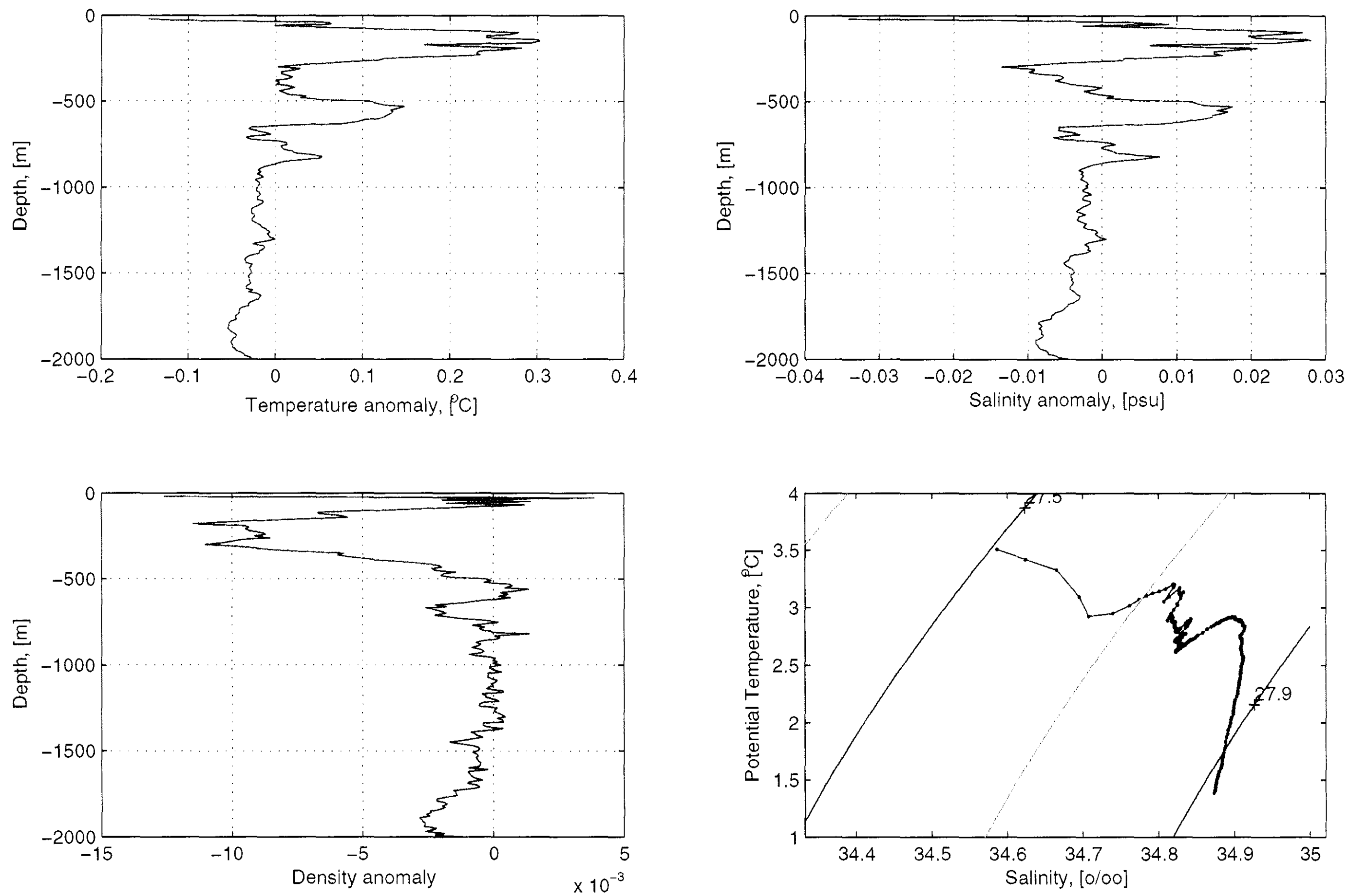

Figure B-27: Anticyclone with multiple cores: potential temperature (upper left panel), salinity (upper right panel), potential density (lower left panel), θ/S diagram (lower right panel).

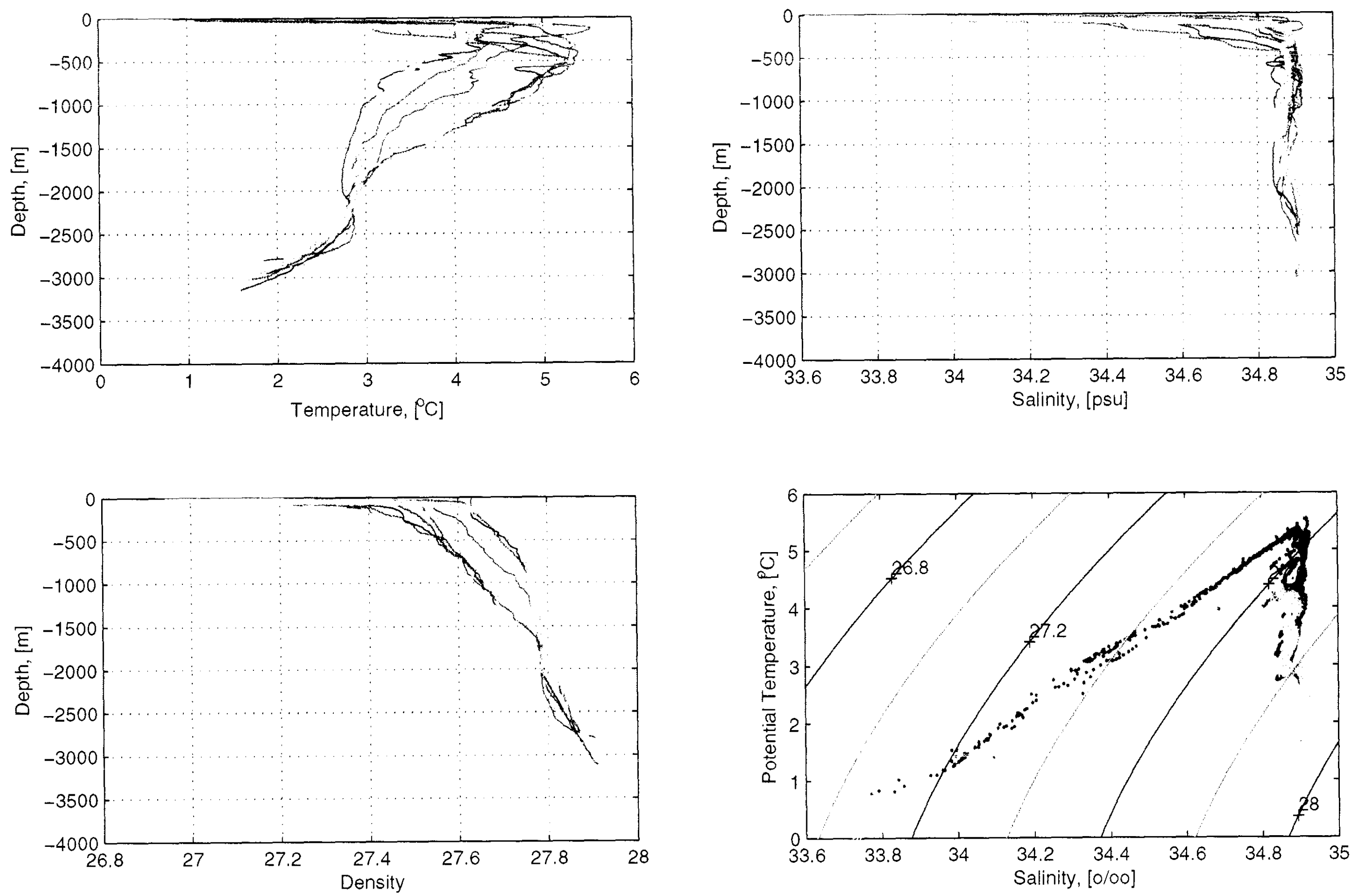

Figure B-28: Comparison of the boundary current profiles (in color for potential temperature, salinity and potential density and in red for θ/S diagram) with the profile from an "unmodified eddy" (always in green).

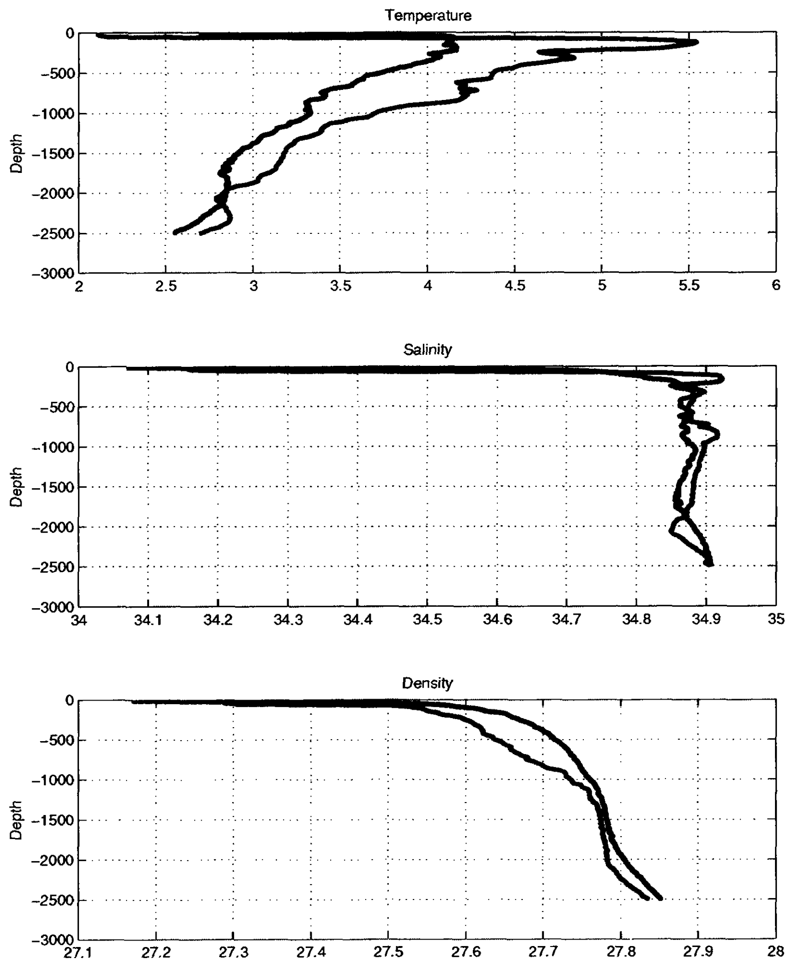

Figure B-29: "Unmodified" eddies from different seasons: blue - from the winter and red - from the summer, found in a proximity of the boundary current.

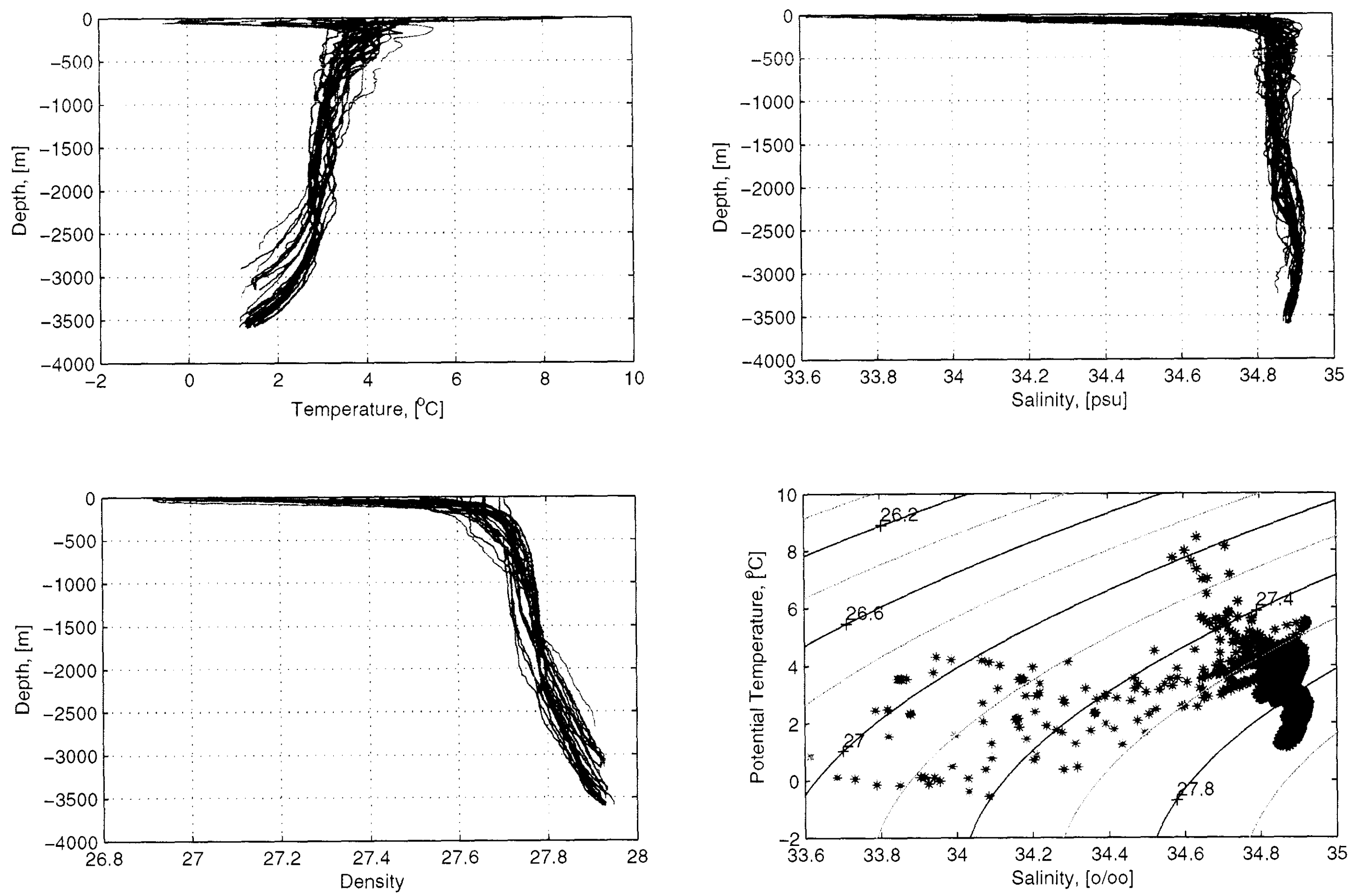

Figure B-30: Comparison of unmodified and convected eddies in potential temperature (upper left panel), salinity (upper right panel), potential density (lower left panel) and θ/S (lower right panel) spaces.

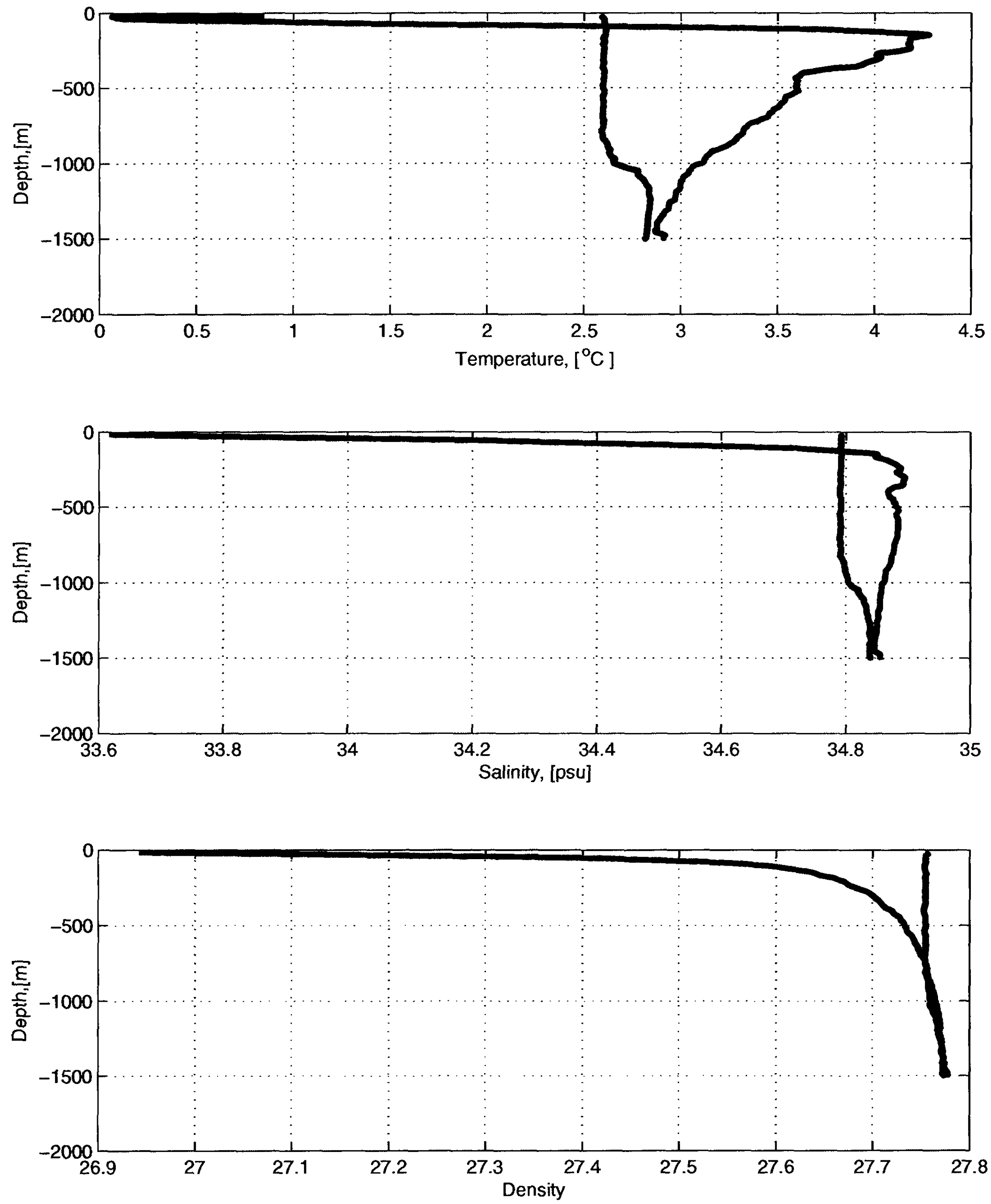

Figure B-31: Comparison of unmodified (red) and convected (blue) mixed layers

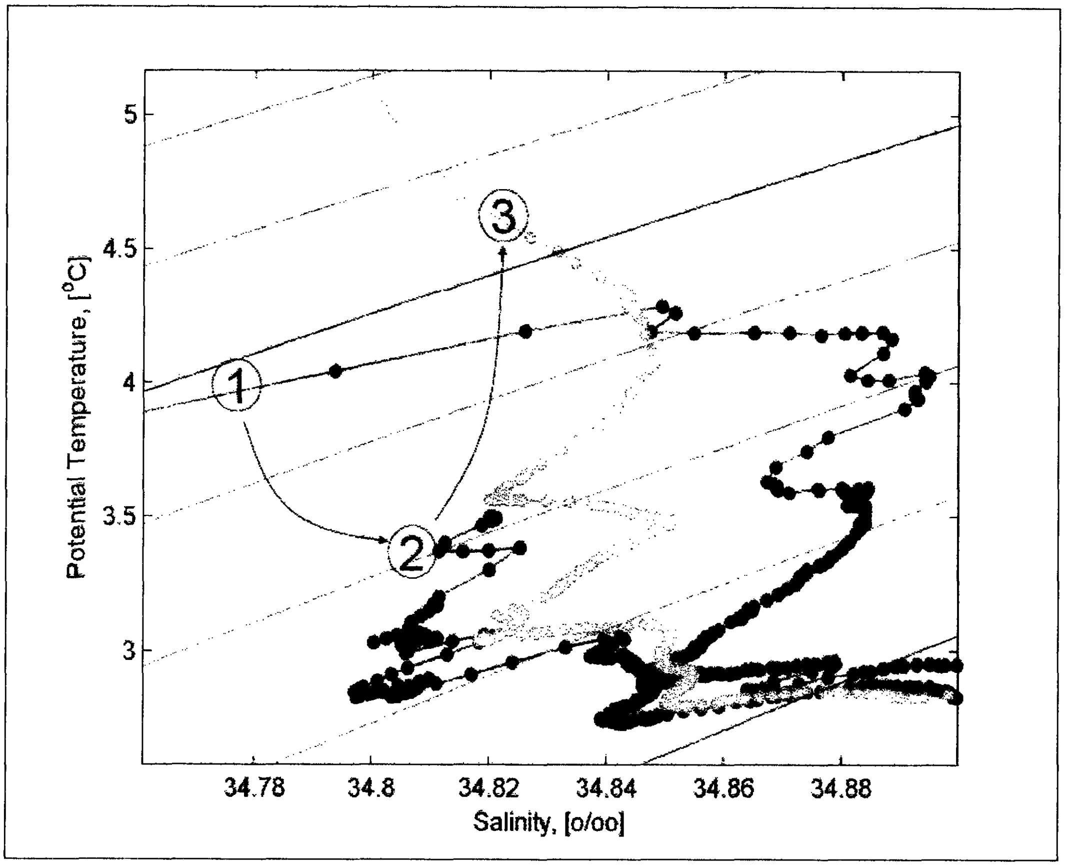

Figure B-32: Comparison of unmodified (1), convected (2) and restratified (3) eddies in θ/S space.

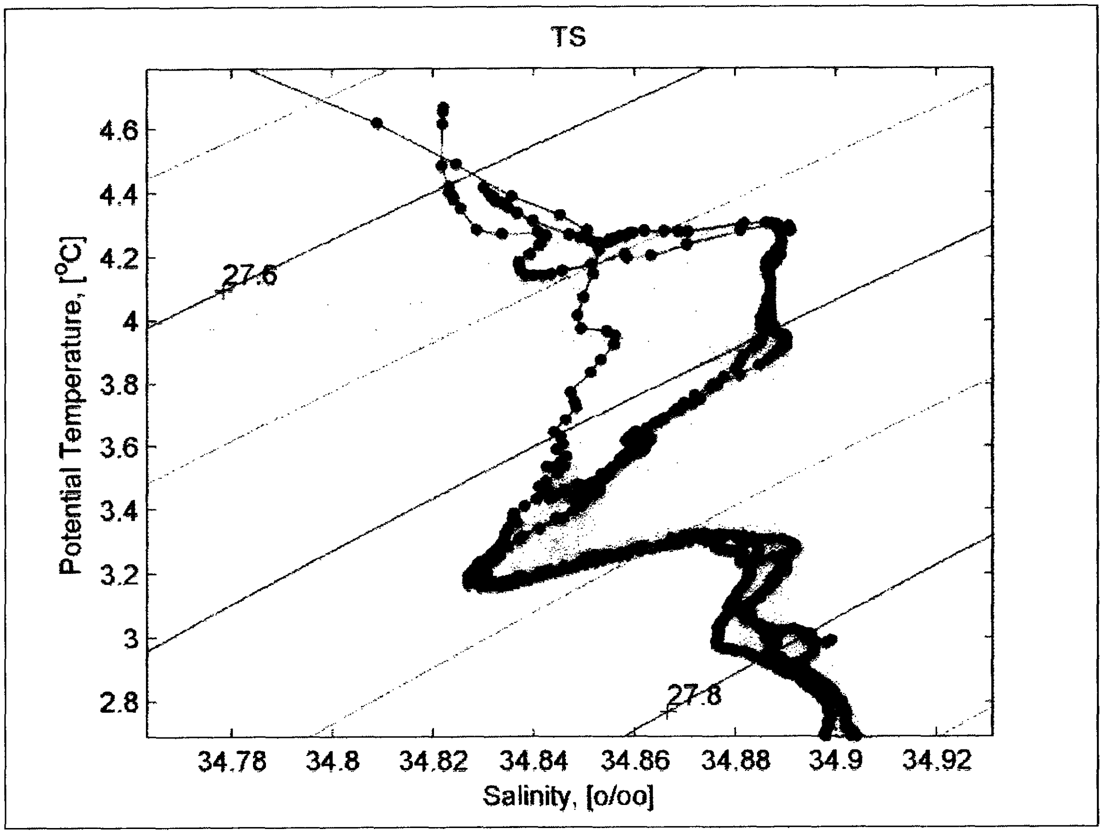

Figure B-33: Comparison of profiles within an anticyclone (red) with the ones outside it (light blue) in year 2004. Anticyclone contains "old" Labrador Sea Water from 2003 (mean interior profile from 2003, shown in black).

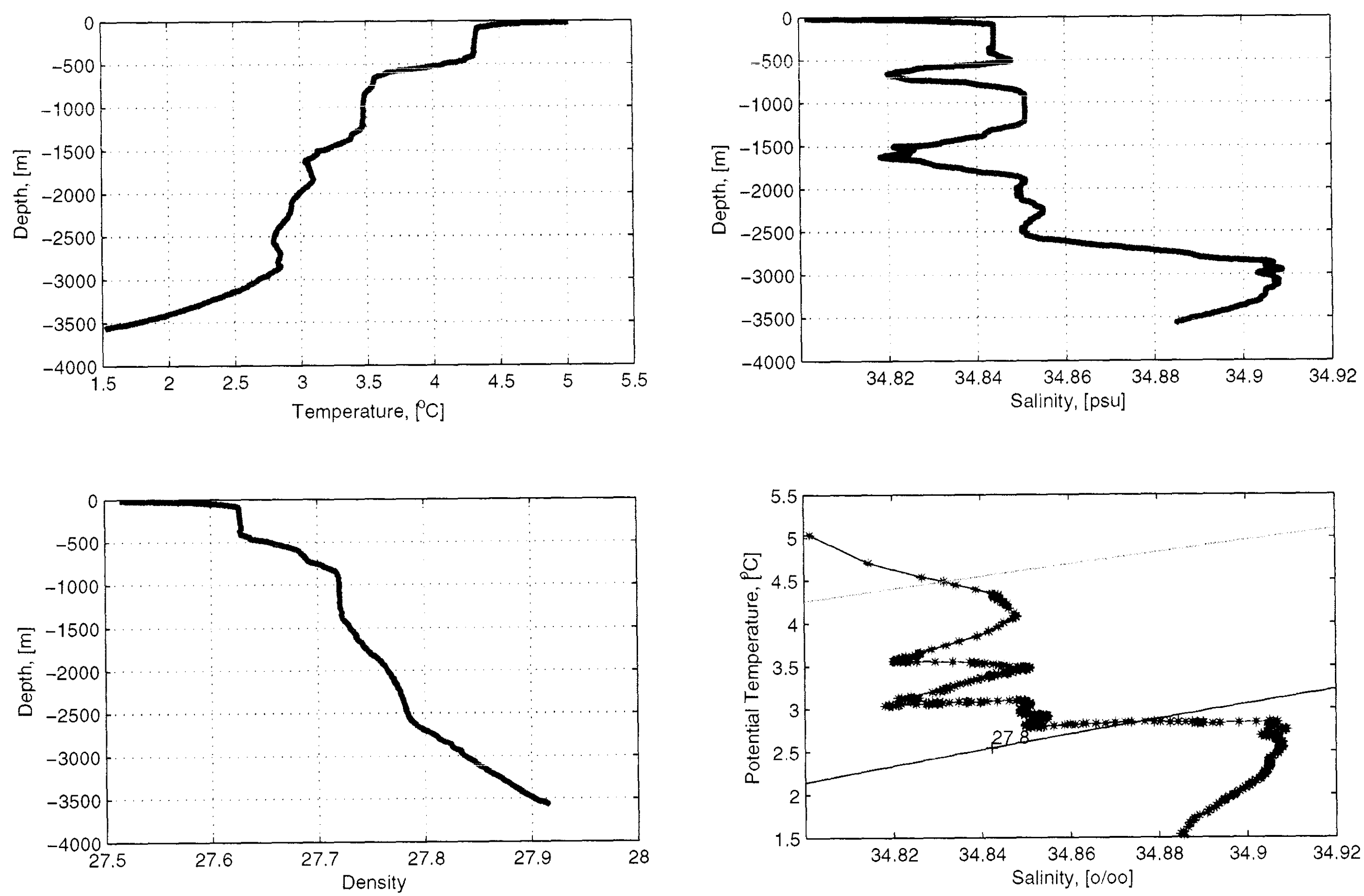

Figure B-34: Anticyclone with several cores from the year 1998 (was also described by L03, [26]). Upper left panel - potential temperature, upper right panel - salinity, lower left panel - potential density, lower right panel - θ/S diagram.

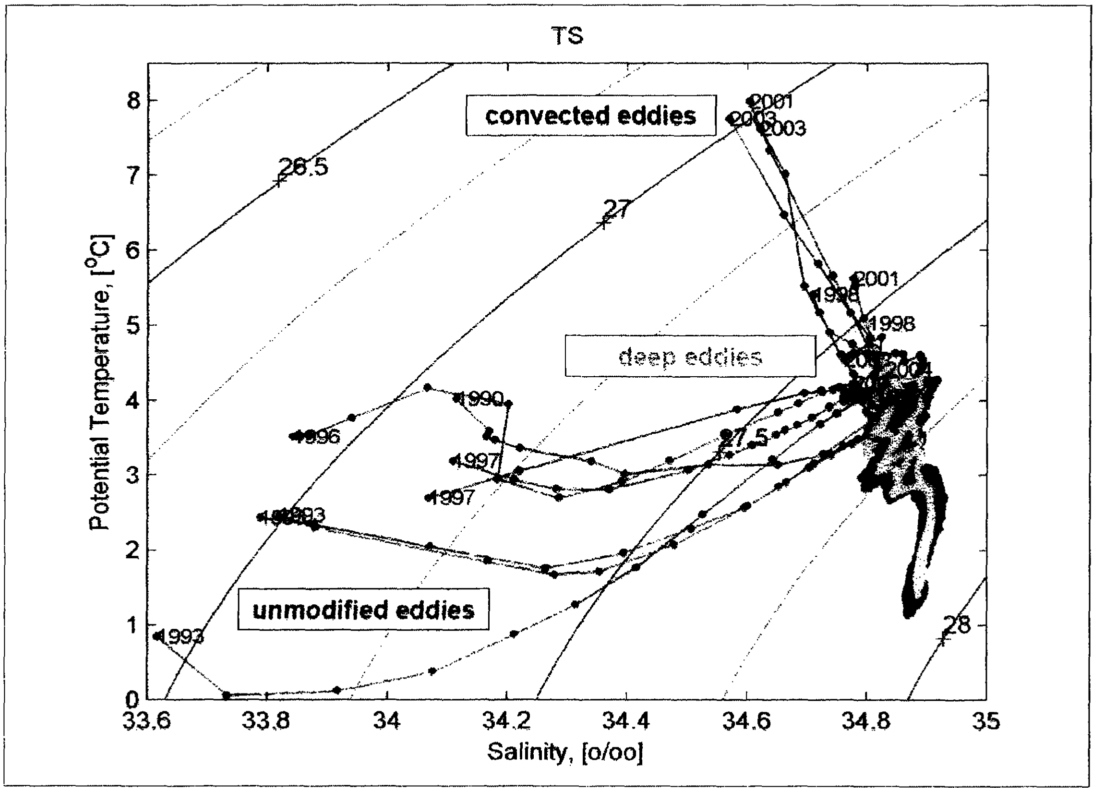

Figure B-35: Subset of deep eddies on the θ/S diagram. Number represents the year of observation.

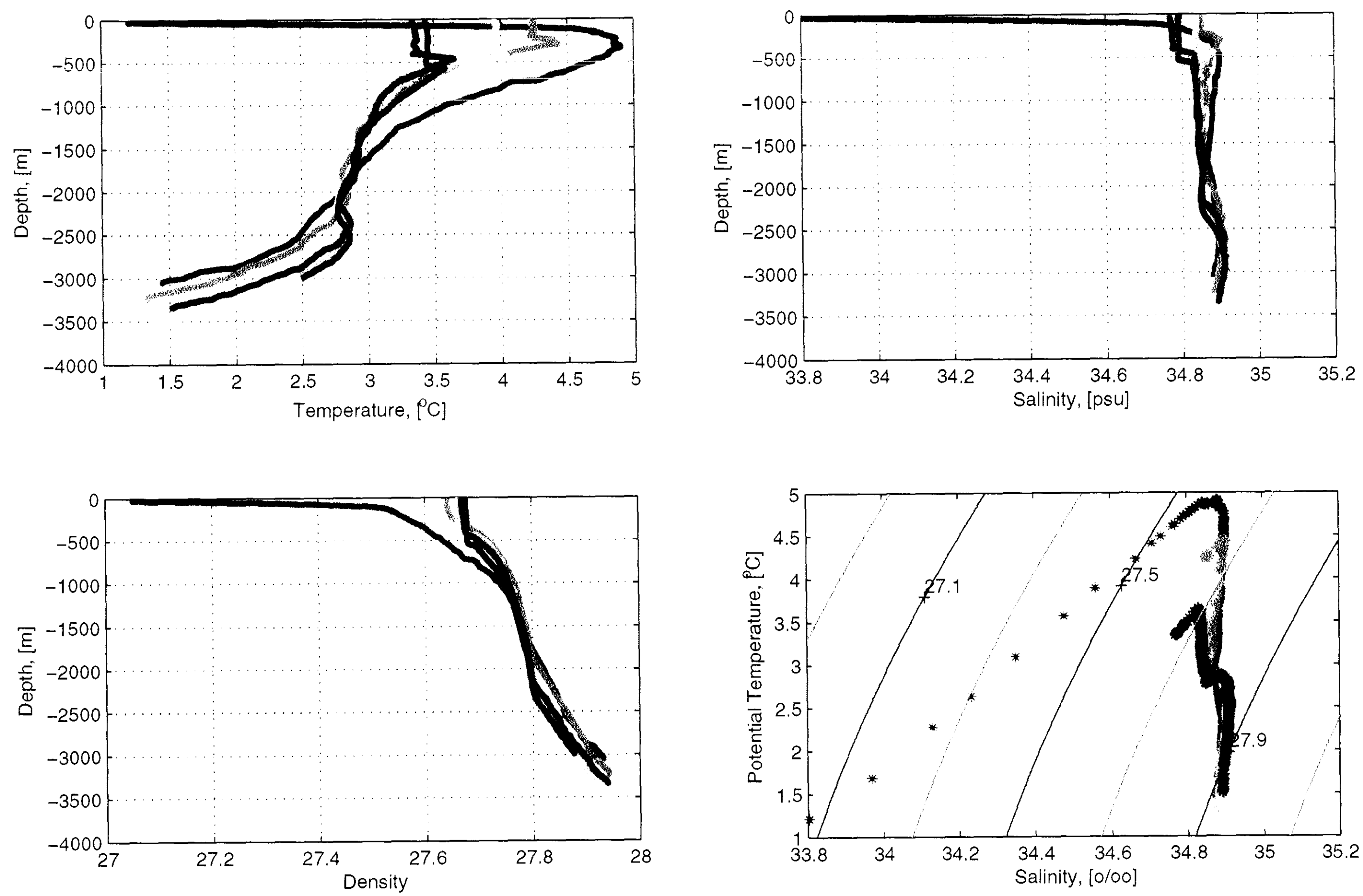

Figure B-36: AR7W occupied in winter 1998. Boundary current (red), anticyclones: closest to the Greenland side (magenta), the second closest (green), the third closest (blue), anticyclone on the Labrador side (black).

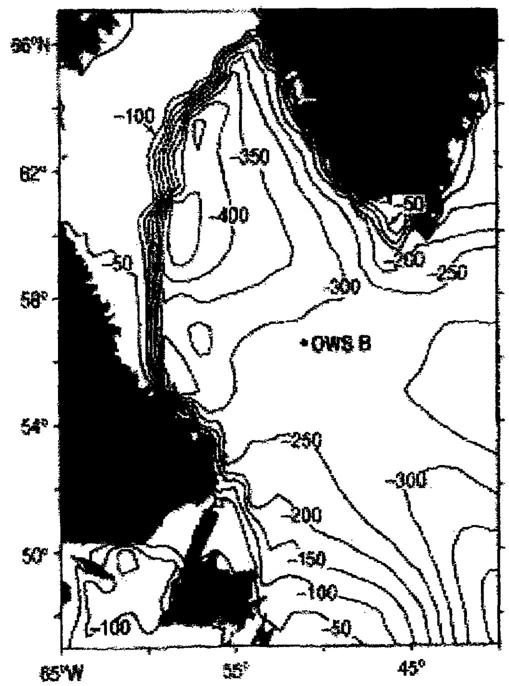

Figure B-37: Contours of wintertime surface heat fluxes for the Labrador Sea (from Marshall and Schott, [29]).

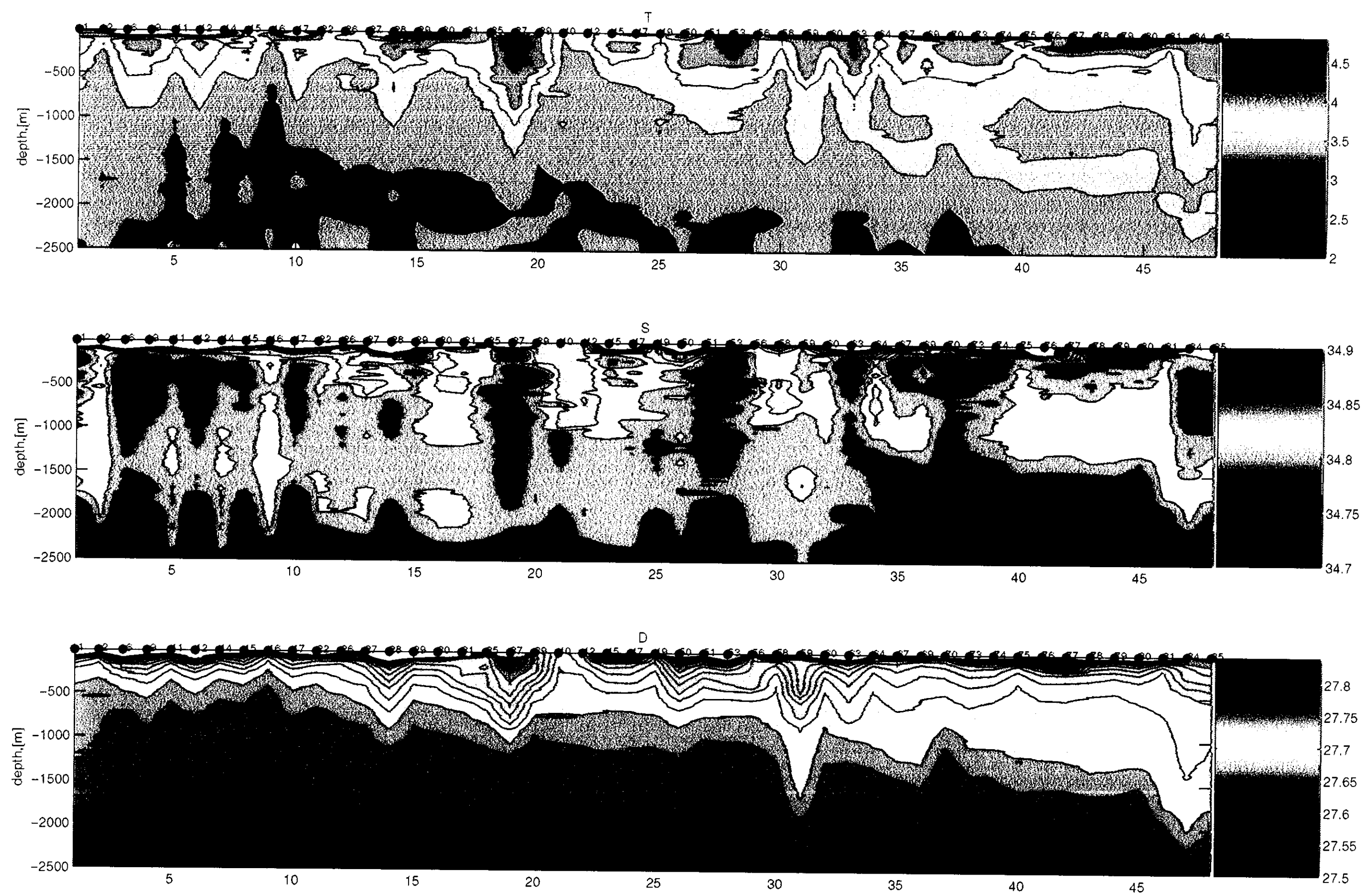

Figure B-38: Interannual variability of the anticyclones: upper panel - potential temperature, middle panel - salinity, lower panel - potential density.

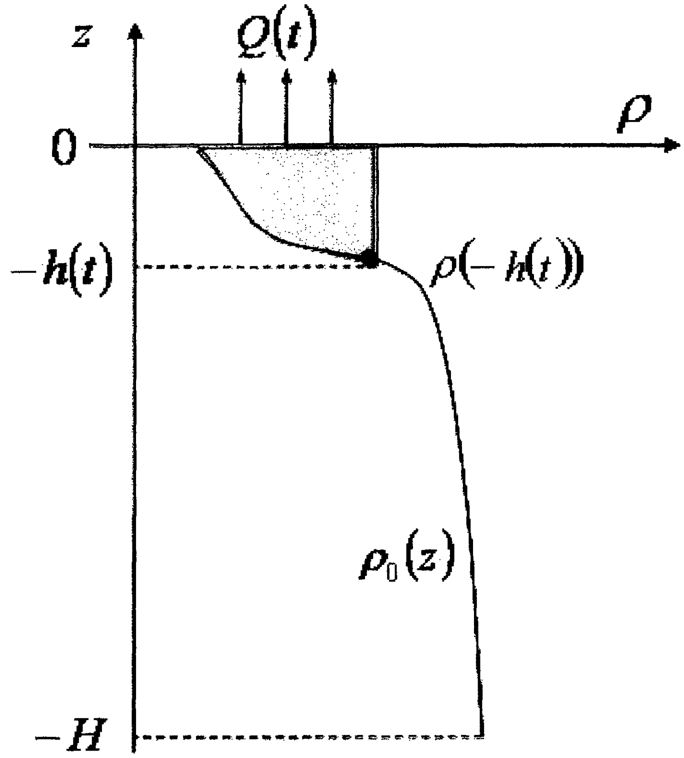

Figure B-39: Model setup (see text for description).

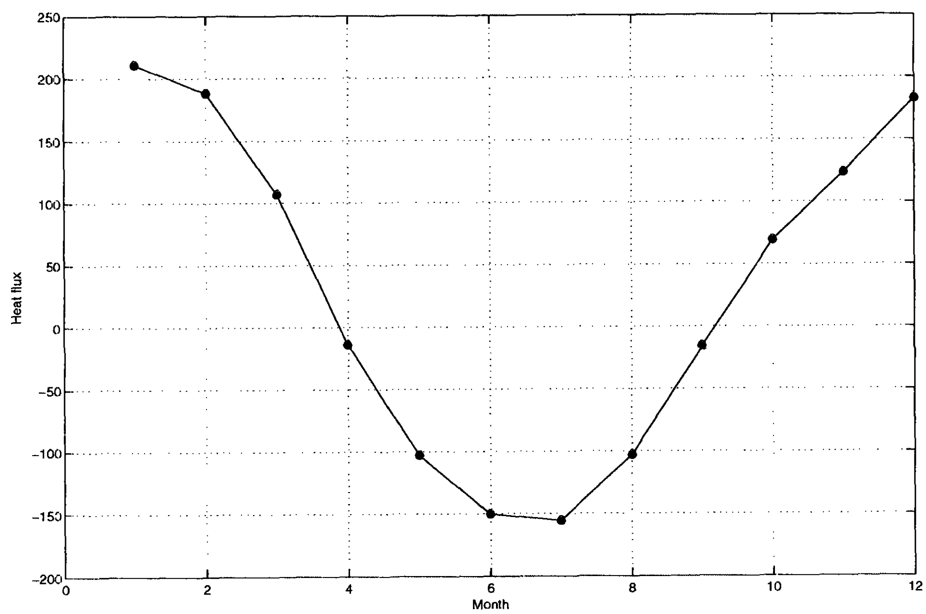

Figure B-40: NCEP Reanalysis heat flux used for the experiments with 1-D model.

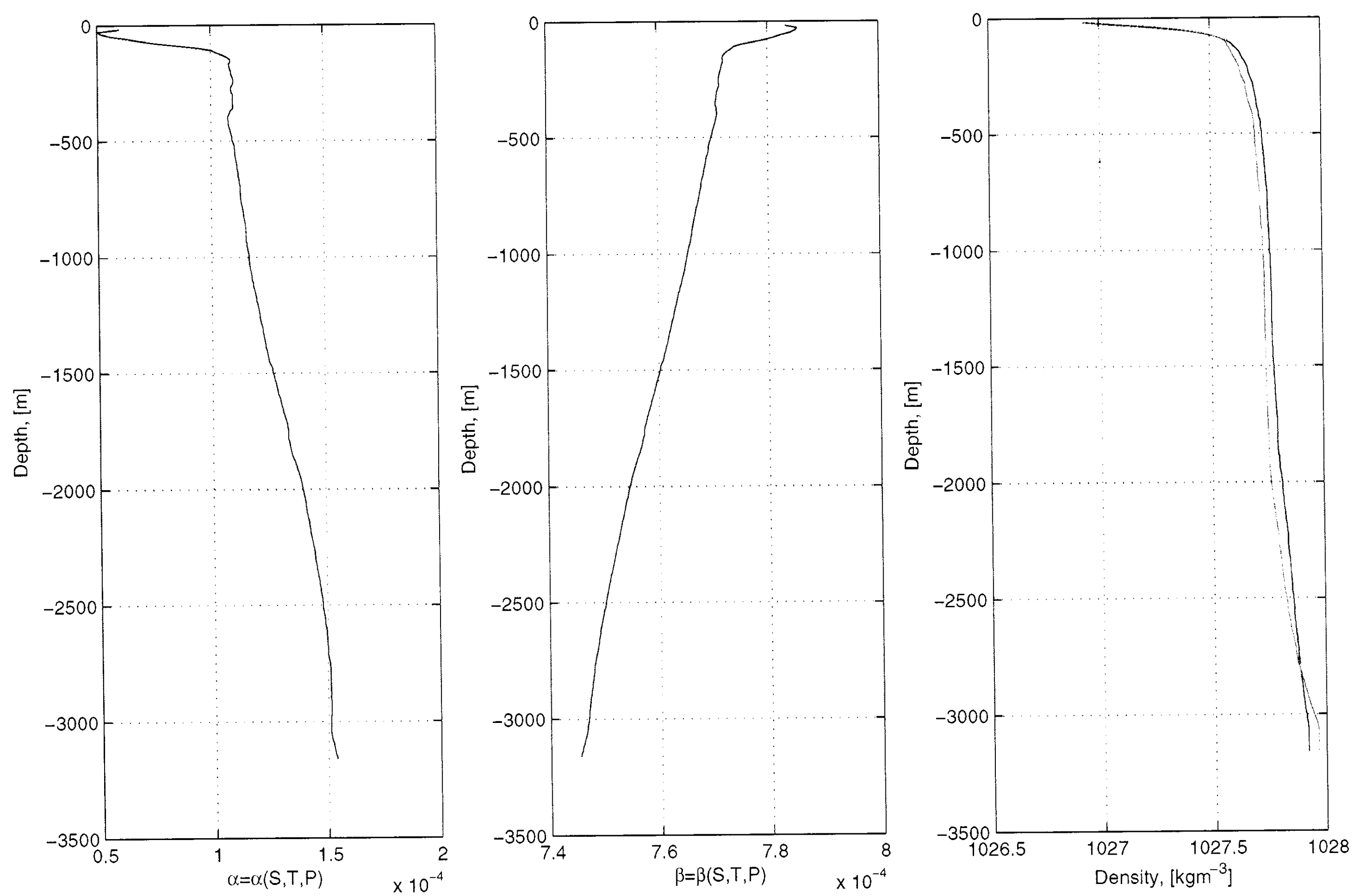

Figure B-41: Test for the match of density: one obtained from the data directly (black) and the other calculated using α and β (red).

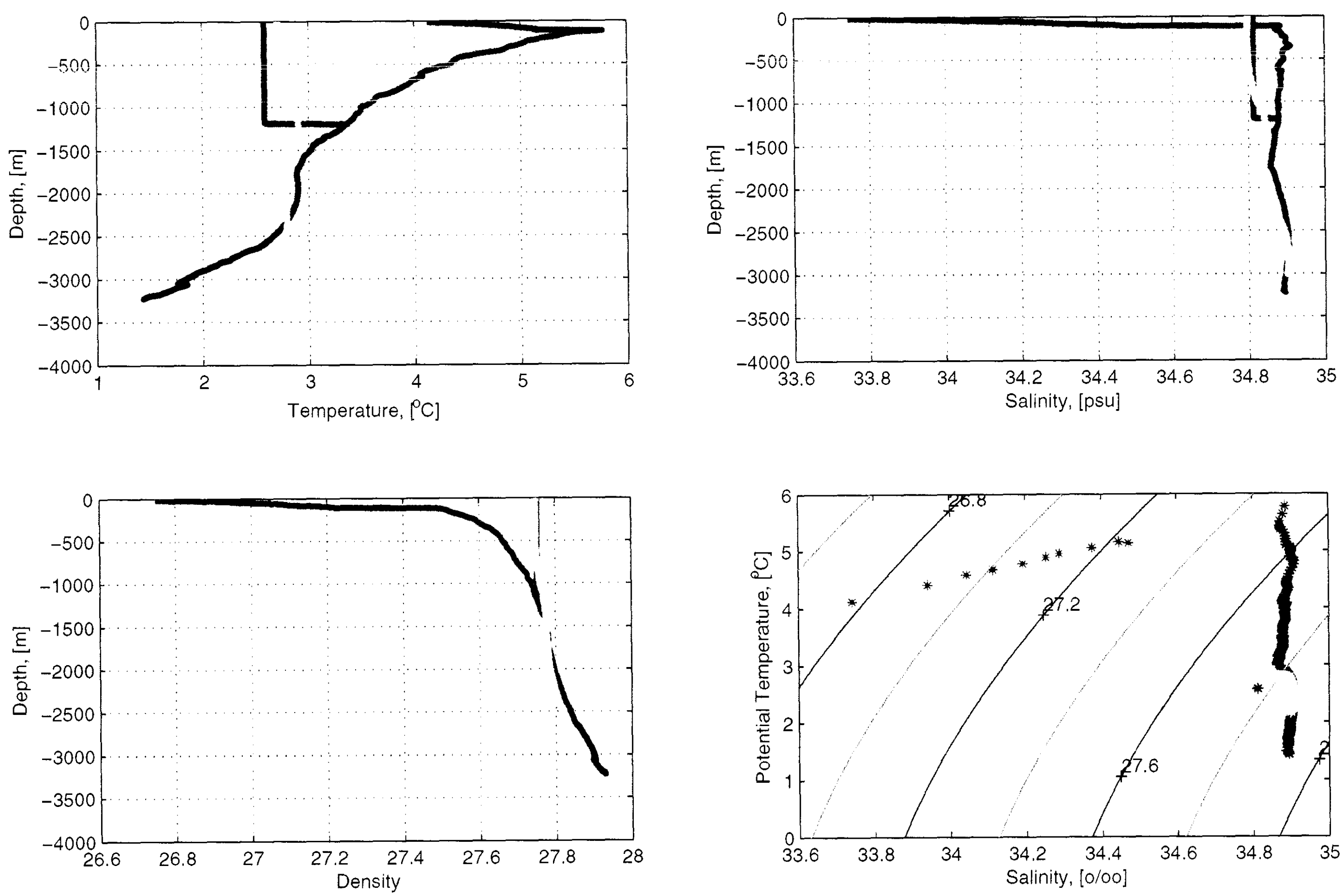

Figure B-42: Forcing of the boundary current (red) from 1996 and comparison with a wintertime eddy of 1997 (light blue). Final product of forcing is shown in blue. Evolution of the mixed layer in time is shown in green.

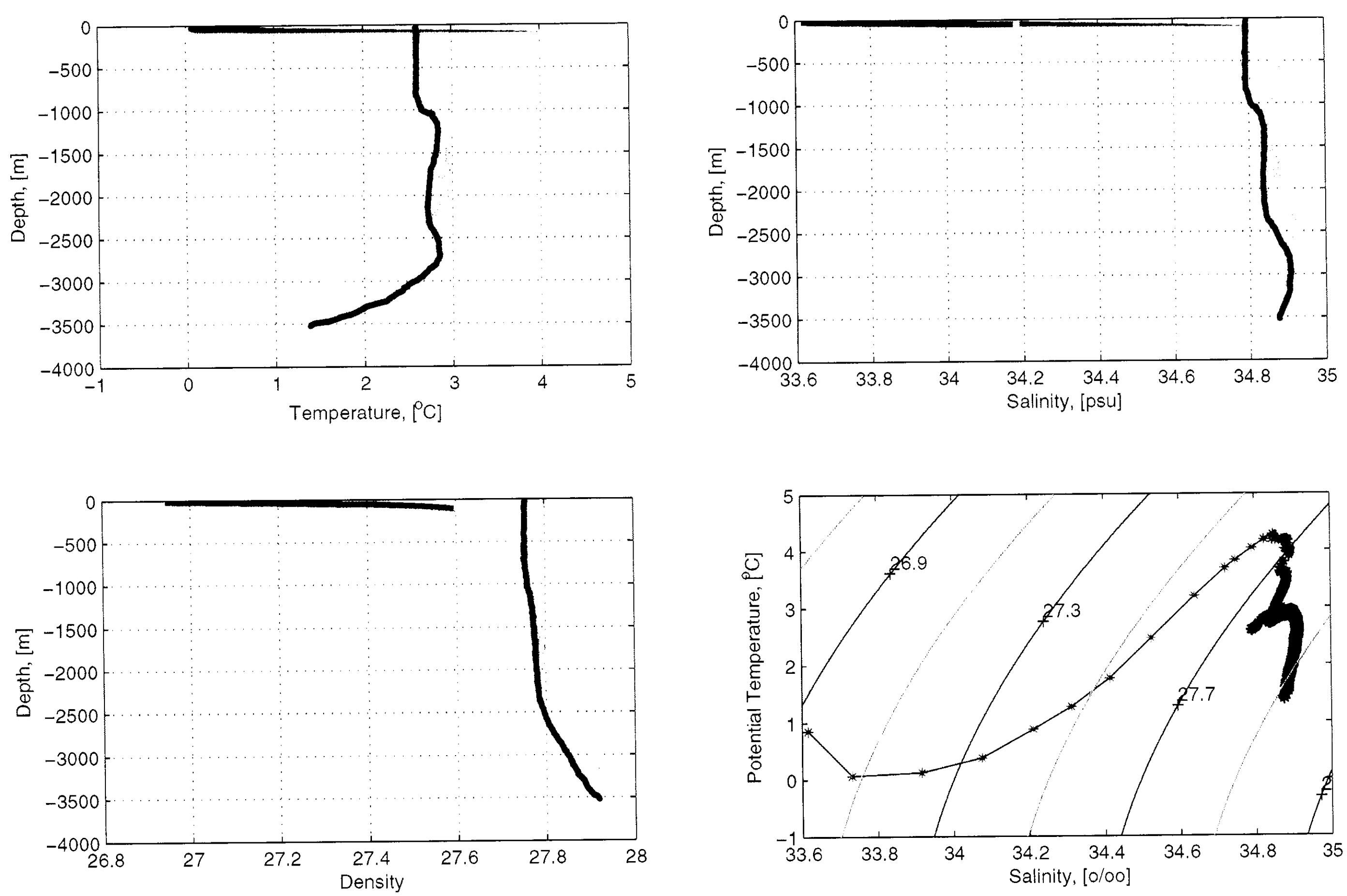

Figure B-43: Unmodified eddy (red) is exposed to the surface fluxes which results in the development of a mixed layer (green profile is the final one). Unmodified eddy is compared to convected eddy (blue). In θ/S space green crosses represent the evolution of mixed layer properties in time.

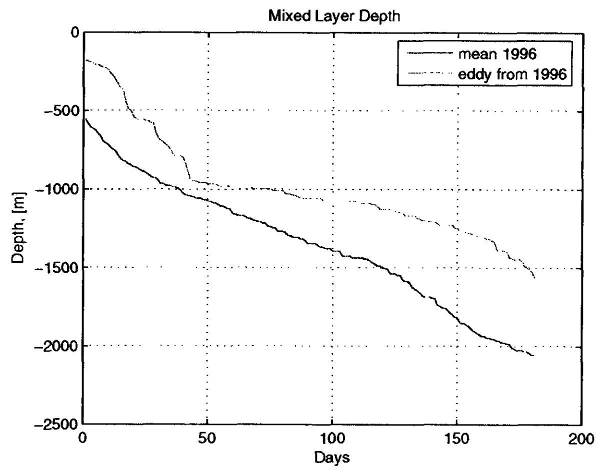

Figure B-44: Unmodified eddy mixed layer evolution (red) compared to the mean Labrador Sea profile evolution (blue).

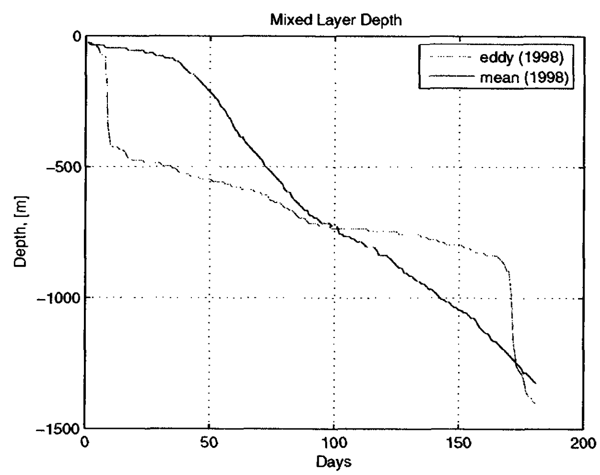

Figure B-45: Convected eddy mixed layer evolution (red) compared to the mean Labrador Sea profile evolution (blue).

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