Exploring the origins of waters at Cape Farewell along pathways through the Irminger Sea

By Lagrangian Particle Tracking

by

Chang Ge

Student Name	Student Number
Chang Ge	5566223

Thesis Committee: Caroline Katsman
Sierd de Vries
Project Duration: October 2022 - June 2023
Faculty: Faculty of Civil Engineering and Geosciences, Delft

TU Delft

Preface

I am delighted to present my master's thesis entitled "Exploring the Origins of Waters at Cape Farewell along Pathways through the Irminger Sea by Lagrangian Particle Tracking." This research project was conducted under the supervision of Professor Caroline Katsman and with valuable guidance from Committee Member Sierd de Vries. The thesis was completed as part of my studies in the Faculty of Civil Engineering and Geosciences at TU Delft.

The motivation behind selecting this topic stemmed from my genuine interest in and passion for the course CIE5325 Coastal and Basin-Scale Physical Oceanography for Civil and Offshore Engineers. Through this course, I have gained a deep understanding of the analysis and problem-solving skills necessary to comprehend oceanic systems. I am grateful to Professor Caroline Katsman for her patient guidance throughout this journey. Her mentorship has been invaluable, and our weekly meetings provided a platform for fruitful brainstorming sessions. She is an exceptional teacher, and I am thankful for her introduction to the field of oceanography.

I would also like to express my gratitude to Committee Member Sierd de Vries for his valuable advice, which helped me refine my research and learning process. I extend heartfelt thanks to my parents, whose unwavering support has always been a source of courage and determination in my life. I am also grateful to my partner Lang Feng, who has been a constant source of encouragement and companionship throughout my master's studies.

Learning is an ongoing process, and the conclusion of this thesis does not mark the end. I aspire to continue exploring and persistently contribute to the field of hydraulic engineering in the future. I am grateful to the Delft University of Technology for fostering an excellent learning environment and providing invaluable resources.

I hope this thesis serves as a contribution to the understanding of the origins of waters at Cape Farewell and their pathways through the Irminger Sea. May it inspire further research and enhance our comprehension of coastal and basin-scale physical oceanography.

ChangGe
Delft, June 2023

Abstract

The Atlantic Meridional Overturning Circulation (AMOC) is an important element in the Earth's Climate System, and it leads to variations in the climate systems, such as heat transformation, carbon dioxide distribution, freshwater distribution, and extreme weather conditions. The dense water formation and export in the North Atlantic contribute to AMOC. Motivated by the aim to understand the strength and processes of AMOC in the Subpolar (SPNA), the water origins and transport routes are explored in this study, based on the inspiration of the previous studies of water pathways in the Labrador Sea.

The objective of this study is to investigate the origin of water in the Irminger Sea and the transport routes before arriving at Cape Farewell, the tip of Greenland where water continues to flow from the Irminger Sea to the Labrador Sea. Based on simulated field data in SPNA obtained from Modular Ocean Model (MOM), the Lagrangian method is applied in the Ocean Model Connectivity Modeling System (CMS), to track particles in the Irminger Sea. The properties of particles, such as location and temperature along their trajectory, are calculated at advection timesteps.

Origins of water reaching Cape Farewell through the Irminger Sea are discovered, including the source from the Denmark Strait, the Iceland-Scotland Ridge, and the South Iceland Basin. Water from these origins follows different routes before arriving at Cape Farewell and qualitative and quantitative analyses of these routes based on particle trajectories and particle numbers, provide insights into how water crosses the Irminger Sea and the importance of the routes.

In summary, water following the route from the Denmark Strait contributes 25 percent of the water through the Irminger Sea arriving at Cape Farewell. Water follows a direct and straight route along the East Greenland Boundary, as the cold source in the surface layer (50-150m). Water staying in the Irminger Basin contributes 50 percent. It travels in curved and blended routes in a deep layer (1200-1500m), as the warm source. Water from Iceland-Scotland Ridge follows a long-distance trajectory, which crosses the Iceland Basin, Reykjanes Ridges, and Irminger Basin. Water in this route contributes 20 percent. They travel in a surface layer as the warm source, while the temperature of water in this route decreases when water arrives at Cape Farewell. Water from the South Iceland Basin is in the surface layer (0-150m) along the routes, with the highest temperatures. The contribution is not accurate as the long-distance route requires a longer tracking period.

The research findings provide valuable insights into the dynamics of water masses in the Irminger Sea. It relates to the currents, and oceanic activities in the Irminger Sea, such as convention and eddies, which contributes to a better understanding of AMOC in SPNA.

Keywords: AMOC, Climate changes, Lagrangian particle tracking, CMS model, Water origins, Overturning.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
AMOC	Atlantic Meridional Overturning Circulation
SPNA	Subpolar North Atlantic
GIN	Greenland-Iceland- Norwegian Seas
NAC	North Atlantic Current
NADW	North Atlantic Deep Current
EGC	East Greenland Current
ISOW	Iceland Scotland Overflow
DSOW	Denmark Strait Overflow Water
IC	Irminger Current
RR	Reykjanes Ridge
IrB	Irminger Basin
IcB	Iceland Basin
DS	Denmark Strait
NIcB	North Iceland Basin
SIcB	South Iceland Basin
WIcB	West Iceland Basin
MOM	Modular Ocean Model
CMS	Connectivity Model System

1
Introduction and Background

1.1. The Atlantic Meridional Overturning Circulation

The Atlantic Meridional Overturning (AMOC) is an ocean circulation system. It is defined by northward surface transport and southward subsurface transport in the North Atlantic Ocean. Due to its transport of heat, the AMOC is a crucial component in the global climate systems. The components of the AMOC and its role in the climate are explained in 1.1.1 and 1.1.2 separately.

1.1.1. Components of Atlantic Meridional Overturning Circulation

The AMOC consists of two components, the warm current in the upper layer and cold water in the deeper layer, as shown in Figure1.1. The North Atlantic Current is the surface water, which is warm and salty, flowing northward across the Atlantic Ocean, into the Nordic Seas. In the wintertime, heat loss to the atmosphere at high latitudes in the North Atlantic makes the northward-flowing surface waters colder and denser. The denser water sinks into the deep layer and flows southward known as North Atlantic Deep Water [Pietrzak, 2021].

1.1.2. Roles of AMOC for Climate and climate change

A full understanding of the process and elements of the Atlantic Meridional Overturning (AMOC) is relevant for predicting climate and climate change. The intensity and structure stability of AMOC has significant impacts on global climate by regulating the heat, carbon uptake, currents, storms, precipitation, and extreme weather events [Intergovernmental Panel on Climate Change (IPCC), 2013].

One of the major ways in which AMOC influences the climate system is by redistributing heat around the world. It transports warm, tropical water to higher latitudes in the North Atlantic, where it releases heat to the atmosphere, regulating temperatures in Europe and North America [Newsom et al., 2021]. A weak or unstable AMOC could result in less heat being transported to these regions, potentially leading to cooler temperatures [Srokosz and Bryden, 2015].

During the process of AMOC transport, it regulates the global water cycle, carbon cycle, as well as other dissolved substances and biology [Yamamoto et al., 2018]. The freshwater is carried from the Atlantic Ocean into the Arctic Ocean by AMOC, which maintains the balance of salinity in the North Atlantic. Additionally, carbon dioxide is stored in the ocean and is transported by AMOC from the surface ocean to the deep ocean. The amount of atmospheric $CO2$ is controlled by AMOC through the transformation of dense water in the subpolar North Atlantic [Jackson et al., 2022]. All the processes are influenced by the dense water mass formation in North Atlantic that drives AMOC.

In the 21st century, the warming climate is expected to weaken the AMOC as greenhouse gases increase. In this case, the atmosphere warms, and the surface ocean beneath it retains more heat. At the same time, increased rainfall and melting ice mean the ocean water becomes fresher too. All these changes make the ocean water lighter and reduce the sinking in the ‘conveyor belt’, leading to a weaker

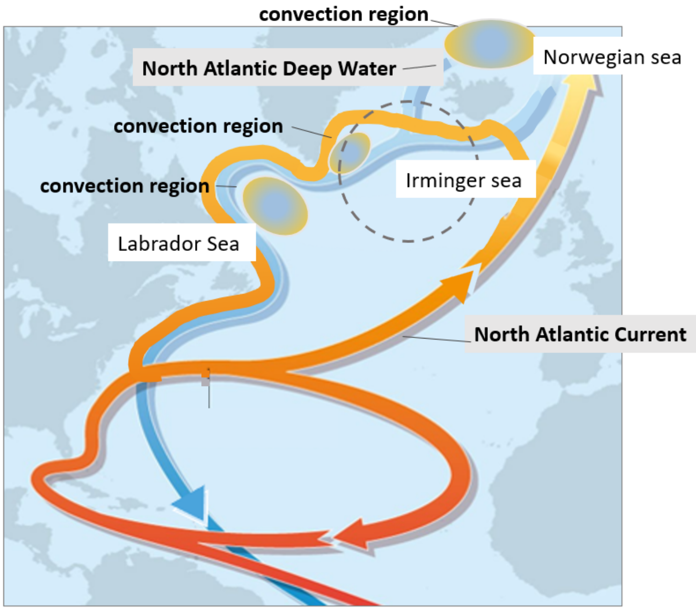


Figure 1.1: Sketch of the Subpolar North Atlantic with the schematic circulation of surface currents (orange line) and deep currents (blue line) that form a portion of the Atlantic Meridional Overturning Circulation (AMOC), and eddies and convections. The component of AMOC: the North Atlantic Current (orange line) and North Atlantic Deep Water (blue line). Source: [Praetorius, 2018] with added (a) convection regions: three ellipses; (b) eddies: small orange circles; (c) Irminger Sea: the black dash line circle.

AMOC [Liu et al., 2020].

The weakened AMOC could have feedback on climate patterns, such as Atlantic Oceanic temperature projection, Arctic Sea ice loss, global rainfall patterns, and troposphere [Rahmstorf et al., 2015]. A weak AMOC could lead to a buildup of freshwater in the North Atlantic, and less carbon uptake by the ocean, potentially exacerbating the effects of anthropogenic climate change [Latif et al., 2022].

1.2. Role of Subpolar North Atlantic for Ocean Circulation

The Subpolar North Atlantic (SPNA) is a region in the North Atlantic Ocean, bounded by the Labrador Sea to the west and the European continental shelf to the east. The SPNA is characterized by a complex system of ocean currents and oceanographic phenomena that together transport large amounts of heat, salt, and other substances from the tropics to higher latitudes. The two main currents, the North Atlantic Current and the North Atlantic Deep Water enter the Irminger Sea from different directions, transporting different sources of water masses in the SPNA. Deep convection occurs in the interior of all seas along the margins, and in the Irminger Basin (Figure1.1), which is an important element in the deep part of the AMOC. This section discusses the oceanographic processes of current circulation and convection in the SPNA as it affects the formation and export of dense water, which further affects the dynamics of the AMOC.

1.2.1. Currents and Circulation in SPNA

Subpolar North Atlantic is the area of the North Atlantic Ocean that is located between 45°N and 65°N latitude, including regions of the Labrador Sea, Greenland Sea, Iceland Sea, Norwegian Sea, and the subpolar gyre (Figure1.1). Currents in the SPNA are complex and are influenced by wind forcing, ocean-atmosphere interactions, and complex topographic steering. This section describes the water sources of the SPNA, which emphasizes the currents entering the Irminger Sea.

The main currents in SPNA are presented in Figure1.2, the East Greenland Current (EGC), the Irminger Current (IC), and the Labrador Current (LC). The Nordic Seas exchange water with the North Atlantic in the upper ocean, where the water masses are transported along the west boundary of the Nordic Sea by the southward-flowing East Greenland Current (EGC). EGC enters through the Fram Strait from the Arctic, as the right blue arrow from the Greenland Sea is depicted in Figure1.2. This current is one of the main pathways for Arctic Sea ice. The bathymetry leads to EGC split into two. The intermediate water in the Nordic Seas leaves through the Denmark Strait and Iceland following EGC, which is one of the sources of cold water in the Irminger Sea. The other one (Eastern Icelandic Current, EIC) transports northward continually around Iceland, which contributed to the dense water formation occurring in the Greenland Sea. This water mass does not reach Cape Farewell and does not appear in the Irminger Sea, so it is not considered to be one of the origins of water in the Irminger Sea.

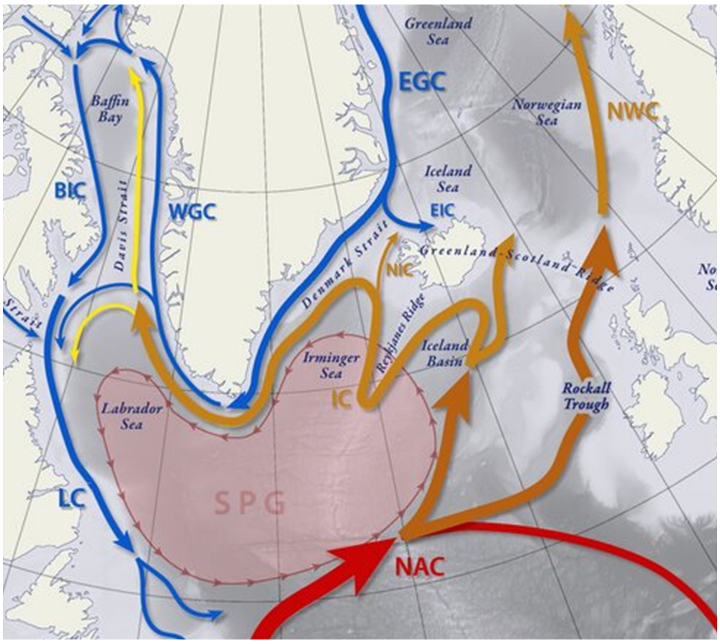


Figure 1.2: Schematic of the main ocean currents in the upper SNPA from adjacent seas, adapted from [Tesdal and Haine, 2020]. Red/orange/yellow arrows denote currents associated with poleward heat and salt transport Atlantic Water, while blue arrows denote currents associated with the transport of Arctic-origin waters into the North Atlantic.

The North Atlantic Currents (NAC) in Figure 1.2 from the south split into two in the Iceland Basin. One source continues northward along the Norwegian (Norwegian Current, NWC in Figure 1.2). The other source from NAC turns to the west becoming the Irminger Current (IC), which transport across the Reykjanes Ridge or along Iceland before entering the Irminger Sea [Strand et al., 2020]. These currents transport water in the SNPA. On the path of water movement, dense waters are formed by convection in the SPNA. The two processes of the dynamic ocean activity in the SPNA together influence the AMOC. The next section explains the general convection in the SPNA.

1.2.2. Convection in Subpolar North Atlantic

Convection in the SPNA drives the deep-water formation in North Atlantic, which drives the AMOC activity. Therefore, convection plays a critical role in maintaining the strength and stability of the AMOC, as well as regulating the uptake of carbon by the ocean as mentioned in chapter 1.1.2. The process of convection in SPNA is described in this section.

Convection happens in the ocean, at the location where the atmosphere cools surface water in winter and makes the water denser. Figure 1.3 gives a schematic of the convection process. In the convective region, warm water masses in the surface layer lose heat to the atmosphere, resulting in a disturbance of the stable stratification of warm water in the upper layer and cold water in the lower layer. The surface water loses heat and becomes denser. When it becomes so dense that the water column is statically unstable, with denser water over light water. Vertical mixing occurs until a stable stratification is established again.

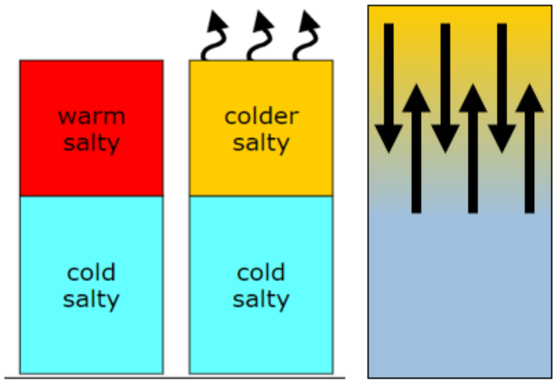


Figure 1.3: Schematic of vertical mixing of water masses. (Left) The stratification of with warm water above, (middle) Warm water losing heat, colder products in the surface leads to unstable (right). The unstable stratification leads to vertical mixing [Pietrzak, 2021].

The deepest convection mixed layers (larger than 1500m) are found as the ellipses' areas in Figure 1.1, in the Labrador Sea, Irminger Sea, the Greenland Sea, and the Golfe du Lion in the Mediterranean Sea [Stramma et al., 2004]. The typical extension of Irminger convection vertical mixing along the eddy is between 100 and 700 meters, but convection depths can reach 1300 m during large convective events in wintertime [de Jong et al., 2018]. And for all other marginal seas, such as the Labrador Sea, the variation of deep convection has a larger magnitude and can be up to 2000 meters [Chanut et al., 2008]. The dense water formed in the GIN seas enters the North Atlantic via Denmark Strait. And the loss of heat from the North Atlantic Current contributes to the convection in the Irminger Sea, which is an important constituent in the subpolar area of AMOC. The process of dense water export will be explained in the following sections.

1.3. Export of dense water via boundary current

1.3.1. Export of dense water by eddy-induced flow

In the subpolar North Atlantic, convection brings the cold and dense water from the surface to the bottom, which is transported by eddies along isopycnals to the boundary current as the cross-shore exchange between the ocean boundary and the interior, as shown in Figure 1.4, a schematic diagram of convective and eddy-forced processes. Eddy activities are important because they not only exchange water mass laterally but also transfer salinity and heat. Large eddies are found in the Labrador Sea and Irminger Sea, the small circles in Figure1.1 [Chanut et al., 2008], which is caused by differences in velocity gradients.

Figure 1.1 shows the expected eddies in the Labrador Sea and Irminger Sea locations which exist close to a narrow topographic gradient. Although eddies are not large current movements, a large number of small eddies separated from the boundary of larger oceanic currents have impacts on the motion of the sea mass dynamics [Fu et al., 2010]. Two types of eddies in the Northern Hemisphere are the warm-core eddies and the cold-core eddies. The cold eddies rotate cyclonically, pumping water upward, while the warm core eddies rotate anti-cyclonically, pumping light downward. It has been illustrated the eddies near the west coast of Greenland regulate the boundary-interior exchanges as well as the heat and energy in the Labrador Sea [Lilly et al., 2003]. The same functions are expected in the Irminger Sea. Based on eddy-driven transport, the process of dense water export is described in the following sections.

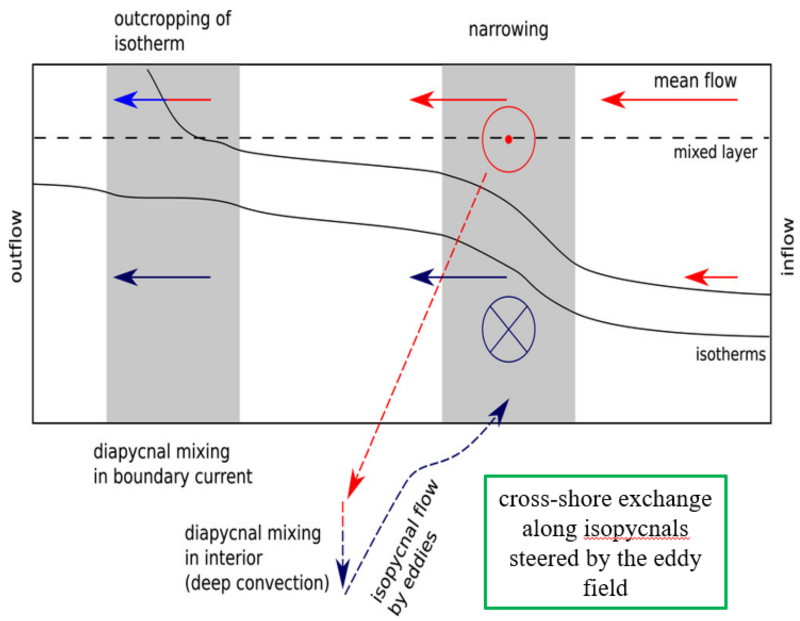


Figure 1.4: Sketch of convection and eddy activities. The red line is warm water mass in the upper layer, and the blue line is cold water in the deep layer. After convection, cold water is driven by eddies exchanged towards the boundary [Brüggemann and Katsman, 2019].

1.3.2. Export in the generic marginal sea

The export of dense water contributes to the deep part of the AMOC [Petit et al., 2020]. In the marginal sea, the dense water is exported following the boundary current, the process is described in this chapter.

As shown in Figure 1.4, in the upper 100m of the ocean surface flow, winds drive ocean currents to the interior of the basin. After the surface water loses heat, deep convection occurs in the interior of the basin. It forms cold water with high density [Clarke et al., 1990]. Convective water driven by eddies is transported laterally from the interior along isopycnals to the boundary. The dense water in the boundary current is entrained at large depths and follows the currents southward, which is demonstrated in the idealized model studies [Spall, 2003] [Georgiou et al., 2019].

This dense water export occurs mainly in areas where the upper part of the boundary current is unstable and sheds eddies. There, the velocity shear of the water is high and the dense waters are sucked back in. Realistic model studies [Katsman et al., 2018] [Waldman et al., 2018] [Sayol et al., 2019] have shown that strong sinking within the buoyant boundary currents of the subpolar eddies in these marginal seas generally occurs after deep convection in the North Atlantic, as described in Figure 1.4. The dense water in the marginal seas will be transported into or out of the basin within the buoyant flow after the exchange between the convective region and the boundary [Spall, 2004].

1.3.3. Water export pathways in the Labrador Sea

The Labrador Sea is characterized by a buoyant boundary current and a denser interior, which is subjected to a prevailing anti-clockwise circulation pattern. It forms the upper constituent of the lower branch of the AMOC, the Labrador Sea Water (LSW), in Figure 1.5, which is a major component of the North Atlantic Deep Water (NADW).

Figure 1.5 explains the paths of Labrador Sea Water transport out. The first path is the direct entrainment of the LSW in the boundary currents. The second path is the LSW formed within the boundary current itself. The third path is the eddy-driven transport of LSW from the interior to the west coast of Greenland. This path of the export process is described in Chapter 1.3.2. The fourth path is the mid-depth recirculation of LSW towards the Irminger Sea. The pathways of water transport out of the Labrador are important because it contributes to the AMOC strength. Similar export paths in the

Irminger Sea are expected as well. The next section will first introduce the oceanic dynamics of the Irminger Sea.

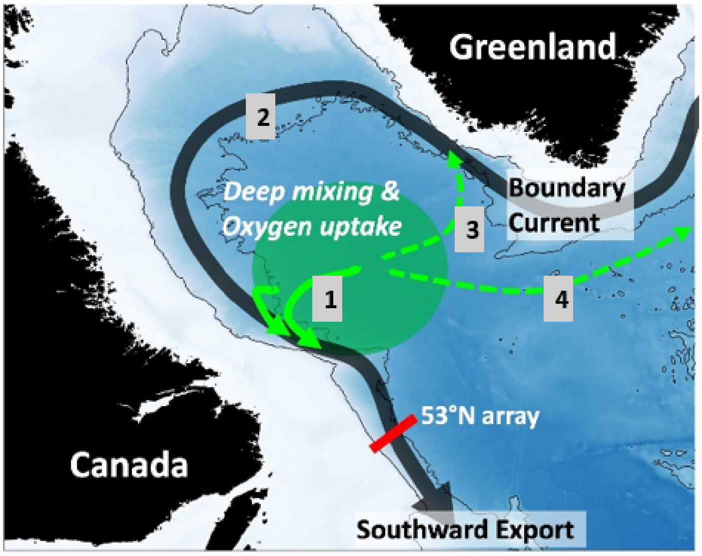


Figure 1.5: Schematic of pathways of water exporting the Labrador Sea. 1. The direct entrainment of LSW; 2. LSW formation within the boundary current; 3. Eddy-driven transport from the interior toward the boundary; 4. Mid-depth recirculation. Grey circulations: deep convection locations in LS. Adapted from [Georgiou et al., 2020]

1.4. Oceanic dynamics in the Irminger Sea

The Irminger Sea is an important component of AMOC activity in the subpolar region. The currents in the Denmark Strait and the Irminger Sea constitute one of the most climatically important and vulnerable regions of the world's oceans and the currents in the regions are significant for Global Ocean Current Circulation and Climate Change. This chapter describes the topography around the Irminger Sea, and the currents enter the Irminger Sea. It contributes to a better understanding of ocean dynamics, such as the currents and eddy transport influenced by topography and sources of water in the Irminger Sea.

1.4.1. Geographic Features around Irminger Sea

The Irminger Sea is a marginal sea of the North Atlantic Ocean, which has a complex topography. The topography influences the currents and eddy transports. Near the Ridge and narrow shelf boundary of East Greenland, eddies can form because of the interaction between the strong currents that flow along Ridge and surrounding water masses. These nearby currents generate large vortices or eddies that can persist for months or even years, which leads to intensive water mass transport or dynamics.

The topography in the Irminger Sea is presented in Figure 1.6. The northern limit of the Irminger Sea is bordered by the Denmark Strait. The southwest of the Irminger Sea reaches Cape Farewell, the southern tip of Greenland, and meets the Labrador Sea at this point. South of the Irminger Sea is bordered by the open waters of the North Atlantic Ocean.

The Denmark Strait (65°N to 68°N) connects the Greenland Sea, an extension of the Arctic Ocean to the Irminger Sea, a part of the Atlantic Ocean. It lies on the Greenland-Iceland Ridge, which runs along the bottom of the sea and separates Iceland from the east coast of Greenland, with over 250 miles of water. Through this strait, the cold East Greenland Current and deep Denmark Strait Overflow Water pass and carry icebergs south into the North Atlantic.

The Irminger Basin (south of 65°N, east of 26°W, north of the Reykjanes Ridge, west of Iceland) is a deep basin located in the center of the Irminger Sea with depths reaching up to 3000 meters. The Irminger Basin has the widest saltwater on Earth. It extends from Iceland to the latitude of Cape Farewell (43°W) at the southern tip of Greenland. Near Greenland, the East Greenland shelf boundary

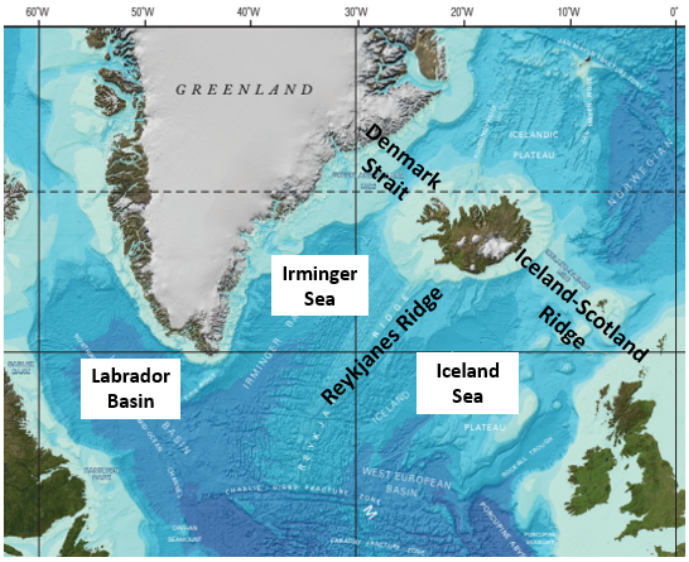


Figure 1.6: Schematic of Irminger Sea bathymetry and its surroundings. Irminger Sea is bordered by the Denmark Strait, the east shelf of Greenland, and the Reykjanes Ridge. The Reykjanes Ridge extends to the center of the Irminger Sea. Colors of blue represent the depth of the ocean. Adapted from [General Bathymetric Chart of the Oceans (GEBCO), 2023]

is the shallow shelf, with depths ranging from 200 to 500 meters, broadly extending from the Greenland coast into the Irminger Sea.

The Irminger Sea is surrounded by the Reykjanes Ridge, the Iceland Sea, and Iceland-Scotland Ridge, which affects the ocean dynamics and water sources in the Irminger Sea. The Reykjanes Ridge is a volcanic ridge running north to south through the Irminger Sea. It extends in the center of the Irminger Sea and separates the region into Irminger Basin to the northwest and Iceland Basin to the southeast. The ridge acts as a barrier for water masses flowing between the two regions because the water masses need to either go over or around it due to its elevation.

1.4.2. Currents and Water Source in Irminger Sea

As shown in Figure1.7, the currents in the Irminger Sea are cyclonic around the Irminger Sea. The most important components of the Irminger Sea are the East Greenland Current (EGC), the Irminger Current (IC), and the dense water overflows.

The North Atlantic Current flows in the upper layers (100-500m) [Våge et al., 2011] and splits into the Irminger Current. The Irminger Current transports buoyant, warm, and saline water northward. It flows westward along the southern coast of Iceland. After going around Reykjanes Ridge, the Irminger Current flows along the east boundary of the Greenland shelf, where it joins the East Greenland Current.

The East Greenland Current (EGC) flows from the Nordic Sea along the East Greenland continental margin. EGC is a cold, low-salinity current that extends from Fram Strait (around 80°N) to Cape Farewell (around 60°N), which is a major contributor to sea ice export out of the Arctic. The water masses mixed in EGC contain Polar Water (0-150m in the upper layer), Atlantic Water (intermediate depth), and Deep Water (from 1000m to the bottom in the deep layer). The cold surface Polar Water is formed by the interaction between the atmosphere and the ocean in the Arctic. The salinity of surface water is highly variable and decreases during sea ice melt, river runoff, and freshwater loss. The Atlantic Water in intermediate depth in EGC has a higher density due to Atlantic Water circulation in the Arctic which sinks into a deeper depth. While the deep water of EGC has a relatively stable salinity and temperature.

Through the Denmark Strait and Iceland-Scotland Ridge, the cold dense water overflows into the Irminger Sea. The Denmark Strait Overflow Water (DSOW) is formed in the Nordic Sea by mixing

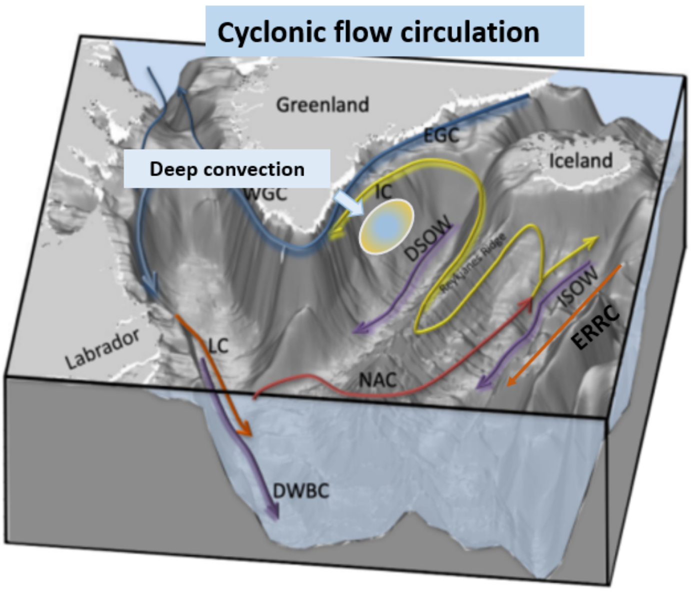


Figure 1.7: Schematic of currents in the Irminger Sea. The yellow arrow is the Irminger Current branches off from the North Atlantic Current in the Iceland Basin. The blue arrow is the East Greenland Current (EGC) from the north. Purple arrows are dense water overflows, Iceland Scotland Overflow (ISOW) across Iceland-Scotland Ridge, and Denmark Strait Overflow Water (DSOW) in the deeper layer. Adapted from [Georgiou, 2021]

with dense water, which then overflows through the Denmark Strait into the Irminger Sea. Iceland Scotland Overflow (ISOW) is formed in the eastern part of the Nordic Sea by the cooling and sinking of more saline water. ISOW from the Norwegian Sea overflows through the Iceland-Scotland Ridges into the North Atlantic.

1.5. Summary

The oceans are important for regulating the Earth's climate. Driven by the Atlantic Meridional Overturning (AMOC) process, a large amount of CO_2 uptake in the ocean is transported, enabling the redistribution of carbon and heat in the Earth's system. The AMOC transports heat and salts from low to high latitudes along ocean currents, regulates the temperature, and maintains freshwater balance around the world. However, under the influence of changing climate conditions, the ocean and its circulation patterns are undergoing unprecedented changes, which greatly affect the strength and dynamics of the AMOC, especially in the Subpolar North Atlantic (SPNA) region, including the Labrador Sea and Irminger Sea. The ocean dynamics in SPNA is crucial for the AMOC and ocean circulation dynamics because it is an essential source area of dense water formation and a location of convective and eddy-driven activity. The formation and export of dense water in the SPNA dominate the upper part of the AMOC. Therefore, exploration of the Irminger Sea, which contains water from different sources that continue to flow out into the Labrador Sea, has therefore stimulated research interest. Understanding the sources and pathways of water entering the Irminger Sea will help improve our understanding of the dynamic activities of the dense water in the SPNA, which contributes to ocean circulation and climate dynamics.

1.6. Research questions

The motivation for this study stems from the need to improve the understanding of the component of the Irminger Sea water, which is an important constituent in the subpolar area of AMOC. The main objective is to find the possible origins and pathways of water entering the Irminger Sea before arriving at Cape Farewell, by the method of Lagrangian particle tracking.

AMOC and its variability can be investigated by two approaches, the Eulerian approach and the Lagrangian approach. Lagrangian approach with a moving frame of reference is mainly used in tracking water masses, for instance tracking the source and pathways of the Subantarctic Model Water, as well as how its temperature and salinity evolve along its path [Koch-Larrouy et al., 2010]and offers insight into the three-dimensional structure and pathways of water masses [Bower et al., 2019]. Through this approach, the dynamics along paths involved in water transport in the Irminger Sea will be explored, contributing to a better understanding of AMOC behavior.

Based on the objectives of exploring the origins and paths of the waters in the Irminger Sea and the Lagrangian particle tracking approach, the sub-questions below will be investigated.

- 1. How does water travel through the Irminger Sea from its origins? What is the contribution of water in each route reaching Cape Farewell?
- 2. Are there indications of specific physical processes that occurred in the Irminger Sea such as convection or eddies, and atmospheric force, leading to the dynamic movements of water in the Irminger Sea during transport?
- 3. How do the currents in SPNA contribute to the water transport in the Irminger Sea?

The structure of this thesis is arranged as follows: Chapter 1 provides the relevant scientific background and concepts thoroughly and raises research questions. Chapter 2 explains the methodology, including the Ocean Models, the process of model set-up and testing, as well as the Lagrangian particle tracking simulation. Chapter 3 explores the origins and pathways of water entering the Irminger Sea before arriving at Cape Farewell and explains Question (a) by plotting particle trajectories and quantitating the particle numbers in distinct paths. Chapter 4 builds insight into the characteristics of the main pathways of waters traveling into the Irminger Sea. Question (b) will be investigated in Chapter 4 by the approach to indicate the modifications of water along the paths and the depth layer and temperature variations between water inflow and outflow in the Irminger Sea. Chapter 5 will discuss the results and conclusion of water transport gained from Chapters 3 and 4. Question (c) will also be discussed in Chapter 5, by considering the currents in the SNPA and Irminger Sea.

2 Methodology

2.1. Research approach

This chapter presents the method to explore the origin and path properties of water using Lagrangian particle tracking. The method is based on the ocean model of the Connectivity Model System (CMS) for the simulation. The CMS Model calculates the ocean properties of water sources in the Irminger Sea by interpolation along the particle paths. The properties including trajectory characteristics, particle number, depth variation and distribution, and temperature are analyzed along the paths. It contributes to a clear understanding of the dynamics of water sources, and physical elements such as convection and eddies that occur along the path in the Irminger Sea.

2.2. Lagrangian Methods for particle tracking

In this study, the Lagrangian approach is used to study the AMOC circulation in the Irminger Sea, based on the previous study of AMOC behaviors [Rühs et al., 2013][Lozier et al., 2019][Bower et al., 2019]. AMOC is transported by convection and eddies instead of the mean flow [Schott et al., 2004][Rühs et al., 2013] and the strength of the AMOC is often characterized by a meridional stream function (zonally integrated transport as a function of latitude and depth). The Lagrangian studies help to change the 2D view to a 3D understanding of the AMOC [Rahmstorf et al., 2015].

Lagrangian particle tracking is a numerical technique in computational fluid dynamics that simulates the tracking of particle paths within a flow field. It analyses ocean dynamics by computing the trajectories of virtual fluid particles, following the Lagrangian perspective of fluid flow, from a specified velocity field. The Eulerian velocity field, computed in an ocean general circulation model, is often used as an input for Lagrangian studies. Under the moving reference frame, the drag forces dominate particle motions moving with the flow, which builds up the spatial and temporal trajectories [Reeks, 1977]. The Lagrangian approach has found use in tracking water masses, for instance tracking the source and pathways of the Subantarctic Mode Water, as well as how its temperature and salinity evolve along its path [Koch-Larrouy et al., 2010]. In the case of offline models, such as the Connectivity Model System (CMS), trajectories can be advected backward in time, which is useful in finding sources of the material being tracked [Van Sebille et al., 2018].

The strength of Lagrangian particle tracking is it saves high computation costs because it only needs to evaluate the position of each virtual particle at the timestep instead of calculating the concentrations of every grid cell [Van Sebille et al., 2018]. In addition, a large number of particles up to tens of thousands in the oceanic model area can be released. When enough particles are set in a specific region, the particle data along the trajectory can be interpolated to determine the Eulerian properties of the velocity field and hydrography [Latarius and Quadfasel, 2016].

2.3. Specification of the Ocean Models configuration

In this study, the Modular Ocean Model (MOM) and Connectivity Model System (CMS) are used for Lagrangian particle tracking in the Irminger Sea. The field data in Irminger Sea are obtained in the MOM, which is used in CMS to calculate the particle properties at the timestep of advected location. This section will explain the specifications of the ocean model MOM and CMS. The setup and test process of CMS will be explained then in the next section 2.4.

2.3.1. Modular Ocean Model (MOM)

The Modular Ocean Model (MOM) is a global ocean-sea ice model used to acquire the field data of annual mean 3D velocities, potential temperature, and salinity fields in the ocean. It is a good tool used in the SPNA to calculate the ocean properties because MOM simulation shows a good agreement with the observed hydrography in the Nordic Seas [Ypma et al., 2019] and the hydrography and currents simulated in MOM represent the observations in the Labrador Sea and Irminger Sea well [Lilly et al., 2003][Pickart et al., 2002].

MOM uses a tripolar B-grid with a horizontal resolution of 0.1 degrees and 50 vertical layers with a resolution of 5m at the surface up to 200m near the bottom. It is also coupled with the GFDL Sea Ice Simulation model, which allows the sea ice to evolve freely. The three-dimensional velocity in MOM contains U, V, and W, which are used to calculate particle velocity at the advected position. The zonal velocity (U) is calculated for particles moving along the meridian direction (positive in the east), the latitudinal velocity (V) is calculated for particles along the zonal direction (positive in the north), and vertical velocity (W) calculates particles transport in-depth space (positive northward). We have daily velocity field data in 0118 in the MOM, including U, V, W velocities. The year 0118 has no physical meaning, which is repeated annually used in the MOM and CMS repeatedly, to ensure the same surface forcing each year when tracking the particles. Therefore, these velocities in 0118 are used repeatedly each year during the tracking particles and to calculate trajectories.

The model domain we used is from 45°N to 68°N in the meridional direction and from 50°W to 10°W in the zonal direction, with a resolution of 0.06° at the meridional direction and 0.1° at the zonal direction. The domain is bordered by open boundaries, the North is the Greenland Sea, and the East is the connection with Iceland Basin and Norway Basin. It contains the region of the Irminger Sea and the Labrador Sea and the North Atlantic.

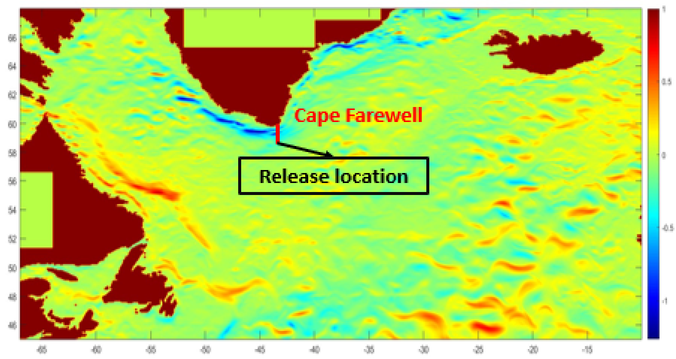
After the MOM calculations, the field properties of the hydrograph of the subpolar Atlantic Ocean are derived and used in the particle tracking process.

2.3.2. Connectivity Model System (CMS)

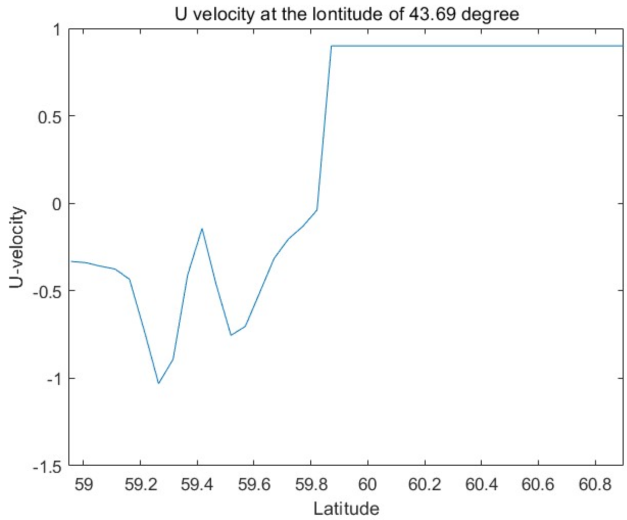
The offline Lagrangian Tool Connectivity Modeling System (CMS) provides a description of the ocean dynamic phenomena of advection, dispersion, and retention [Paris et al., 2013] [Tamsitt, 2018] by computing particle trajectories through explicit time-stepping. In this study, CMS is used to investigate the waters entering the Irminger Sea and track them along the path through the Irminger Sea.

In the CMS, particles are tracked in a nested-grid ocean model domain and advected in RungeKutta scheme timesteps. The Runge-Kutta 4th order stepping in time and a tricubic spatial interpolation are used to determine the new location of each particle in space and time respectively. The Runge-Kutta scheme timestep is set as 1 hour. The output of particle properties on the advecting timesteps, including velocity, temperature, and salinity, is in the form of the location of the trajectory (NETCDF or ASCII format). The output timestep is set at the frequency of 1 day.

Particles are constantly advected in the tracking period, which is set as 5 years in this study using 1 year MOM data. The direction of Lagrangian particles can be tracked forward and backward. In this study, particles are tracked backward, which allows us to determine the sources of particles being tracked flowing into the basin or certain area [Georgiou et al., 2020].



(a)



(b)

Figure 2.1: (a) The map of the zonal velocity field (U-velocity) in the surface layer of the Labrador Sea and Irminger Sea. The velocity direction is positive eastward. The color represents the velocity values. blue for the negative values, and orange for positive values. (b) The plot of surface zonal velocity varies along the latitudes at Cape Farewell (at 43.69°W). It plots the velocity of blue currents at Cape Farewell in panel a.

2.4. CMS set-up and process of testing

This chapter describes the model setup steps and testing process of Lagrangian particle tracking. In the process, particles are released in different depth layers, on distinct dates, and tracked in different periods of time. The steps and results are presented in this section. It helps determine the parameters of Lagrangian particle tracking to explore the trajectories and sources of water in the Irminger Sea, which will be explained in section 2.5.

2.4.1. Location and depth ranges for releasing

This section describes the released location and spatial dimensions, including the latitude, longitude, and depth layer ranges.

The numerical particles are released at Cape Farewell, where waters outflow continuously from the Irminger Sea to the Labrador Sea. As described in Figure 2.1a, it outlines the surface zonal velocity in the Irminger Sea and the Labrador Sea, and the velocity field is obtained from MOM. The blue currents in Figure 2.1b flow along the east shelf boundary of Greenland, continually turning around at Cape Farewell, the tip of Greenland, into the Labrador Sea.

To find the source of water in the Irminger Sea, the released location is determined at the Cape Farewell. Cape Farewell is located at approximately 61° N latitude and 43.69° W longitude. As shown in Figure

7b, the zonal velocity varies along the latitude from the Cape Farewell at 61.00°N to 58.96°N, where the velocity is negative, and the waters flow from east to west. To capture the full currents flowing from the Irminger Sea to the Labrador Sea at Cape Farewell, particles are released in this range of 61.00°N to 58.96°N.

To determine the depth ranges of particles released at Cape Farewell, the tests were performed for Lagrangian particle tracking. Release particles in depth range of 500m, 1000m, 1500m, and 2000m on the model date of 10/11/0118 and track them for one year. The results are presented in Appendix A.

The depth layer of the Irminger Sea is 3000m, with the deepest water approximately larger than 1200m in the Irminger Sea [Våge et al., 2011]. The depth for the boundary currents transport at Cape Farewell is estimated at 1500m [Bacon and Saunders, 2010]. The most dramatic dynamics in the hydrography of the Irminger Sea occur in the intermediate layer of 500m-1200m [Falina et al., 2007], and the deeper depth contains weak currents. As shown in Appendix A, particles released in the 2000m depth range show similar trajectory patterns to those released in the 1500m depth range. Consider that the concentration of particles in the vertical direction is not too high to avoid interactions with each other. The final depth range is identified as 1500m at 10m intervals, containing the most dynamic waters in the intermediate layers and a few deeper layers (1200m-1500m).

As summed, particles are released at Cape Farewell, from 58.96° to 61.00°N, at the released depth range of 1500m, with 10m intervals for every particle.

2.4.2. Release Time and tracking period

The tests for Lagrangian particle tracking are also performed to determine the time to release particles. The velocity threshold is set during the CMS test tracking, which is set as 0.1m/s. The threshold is used to release effective particles with enough velocities not to remain stationary. As shown in Appendix B, the particles are released on the date of 10th of the 12 months in year 0118. The test results in the Appendix B show that the particles released in different moths present different trajectory behaviors, which indicates the current conditions are different in months. To capture the behavior of the water activity traveling through the Irminger Sea for all seasons, the released dates are determined to be day on the 1st and 15th of the 12 months in the year 0118, but the velocity threshold is removed currently, in order to acquire the same number of particles on each release date.

As all the test results showed, most of the particles end up in the inner region of the Irminger Sea (approximately the center of the Irminger Sea) based on the tracking period of 1 year. The final tracking period is identified as 5 years in order to find the origins of waters before they come into the Irminger Sea.

2.4.3. Number of particles

The total number of particles was calculated based on spatial dimensions and released dates. As mentioned before, the range of particle release in latitude is from 61.00°N to 58.96°N with the horizontal seeding resolution dy = 0.05 in degrees. The depth range is 0-1500m, with vertical resolution dz = 10m. The Lagrangian particle tracking to explore the Irminger Sea water source removes the velocity threshold while releasing, so the particle distribution is the same in the spatial dimension at each release date. There were eventually 6300 particles released during the day. Figure 2.2 is a schematic representation of the particles released on 10/11/0118. The blue dots represent the particles and the colors represent the current zonal velocity at the released location.

The particles are released on the 1st and 15th of 12 months of year 0118, for a total of 24 days. Finally, a total of 151200 particles are released during these 24 days. All the parameters for release are summarized in Table 2.1. However, the total number of particles released so far contains invalid particles, which are released in the absence of currents due to the removal of the velocity threshold, as shown in the yellow area in Figure 2.2. These invalid particles will be filtered out, as explained in the next section 2.5.

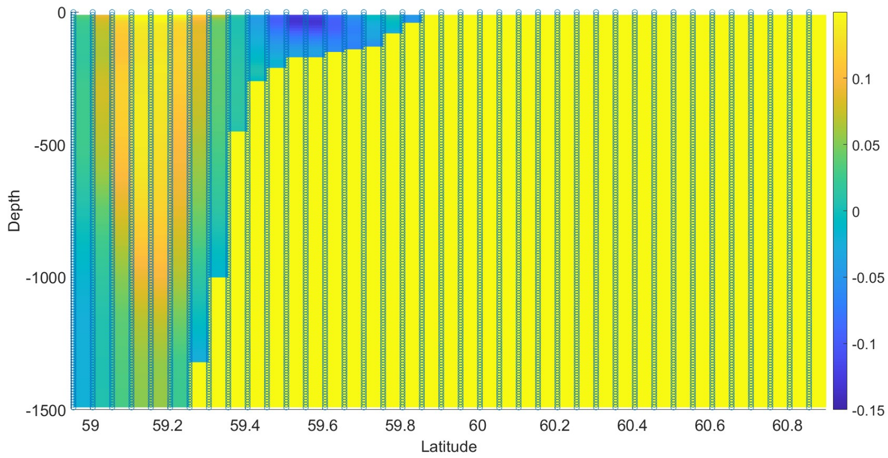


Figure 2.2: The schematic of released particles and current conditions on the day of 10/11/0118 at Cape Farewell. Blue dots represent released particles. Color represents the current velocity.

Table 2.1: Summary of the parameters for released particles

Definition of particle releasing dimensions	Parameters
Longitude	43.69°W
Latitude	58.96°- 61.00°N, with dy = 0.05°
Depth range	1:1500 with dz=10m
Release date	01/01/0118 15/01/0118 … 01/12/0118 15/12/0118 (24 days)
Total number of particles	6300*24=151200

2.4.4. Summary of the Lagrangian particle tracking

After the previous tests, the Lagrangian particle tracking parameters for exploring the waters of the Irminger Sea have now been determined, as shown in Table 2.1. However, the current total of 151200 particles contains invalid particles, which will be filtered out in the next section.

2.5. Filter out ineffective particles

As mentioned before, the velocity threshold is removed while releasing particles, which results in some particles being released where there is no flow to advect them to move. These particles are ineffective so they are filtered out now.

The criteria for filtration is to remove the particles released at times or places where there is no current to start moving, such as the particles in the yellow parties in Figure 2.2. In addition, particles were also filtered out if they remained at the same location for 20 days during their travel, as these particles would have difficulty prompting further movement when traveling to locations in weak currents, which will not be helpful in investigating the origin of the waters in this study.

After filtering, the 29700 active particles remained. These particles flowing in the Irminger Sea are used for further analysis of the water's behavior in the Irminger Sea.

3

Exploring the Origins and Pathways of waters entering the Irminger Sea

3.1. Introduction

Water transporting in the Irminger Sea plays a crucial role in global ocean circulation and climate. By tracking the trajectories of particles through the Irminger Basin, their origins can be determined, which facilitates a better understanding of the waters moving in the Irminger Sea. In this chapter, we investigate the possible origins of particles in the Irminger Sea before arriving at Cape Farewell. The routes of how water sources traverse the Irminger Sea are explored in this chapter, which aims to provide insights into the water compositions and water circulations in the Irminger Sea. It further contributes to the understanding of the essential mechanisms driving water transport and its variation in the Irminger Sea, which will be further explored in the next chapter.

3.2. Qualitative view on waters in the Irminger Sea – Water Origins

Based on the knowledge in Chapter 1.4, different currents enter the Irminger Sea from distinct regions, referred to in Figure 1.7. The routes of currents provide a hypothesis that the waters enter the Irminger Sea from these key regions where currents originated.

All the particle trajectories in the Irminger Sea domain (the north boundary of 68°N, east boundary of 10°W) are present in Figure 3.1. It shows that particles entering the Irminger Sea originate from three distinct regions before reaching Cape Farewell: the Denmark Strait, the Iceland-Scotland Ridge, and the Iceland Basin. By exploring these key entrance regions, which are important sources of water in the North Atlantic, the aim is to comprehend better the intricate transport routes of the waters before reaching Cape Farewell.

The first origin is the Denmark Strait (DS) located to the north of Iceland. The source of the water masses passing through this DS boundary comes from the north of the Greenland Sea, which is one of the components of the Nordic Sea circulation. Referring to the description of the current circulation system in Chapter 1.4, this source of water follows the current EGC or dense water overflow DSOW which is in a deeper layer.

The second origin shown in Figure 3.1 is the particles entering the ocean model domain from the eastern boundary of the Iceland-Scotland Ridge. This source water from the Iceland-Scotland Ridge (IcS) can be considered as the component of the southward North Atlantic Current and a dense overflow from the deep Norwegian Sea. As described in Figure 1.7 in Chapter 1.4, this water source follows the important current IC in the Irminger Sea or a deeper dense water overflow ISOW after entering the IcS.

Finally, particles found in the Iceland Basin (IcB) are from further south. There are two hypotheses

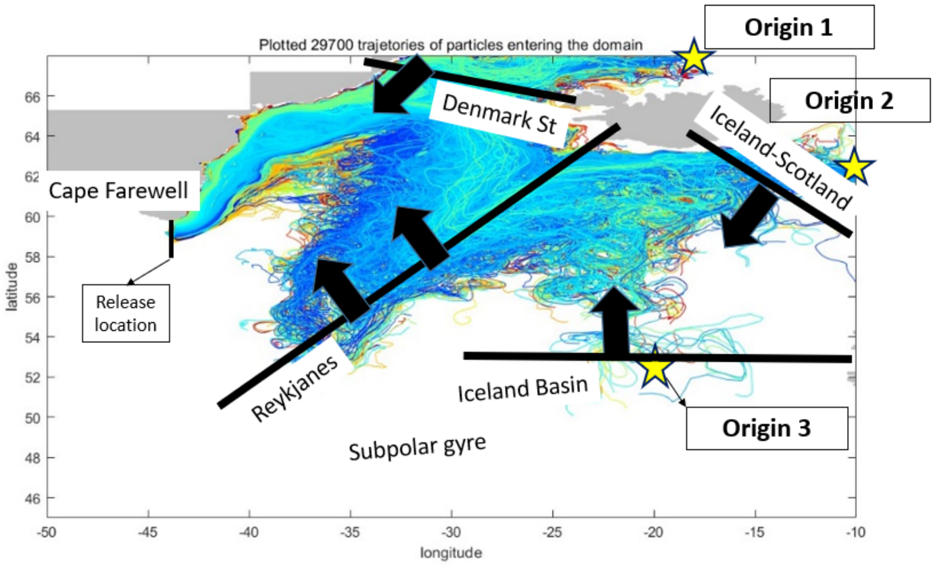


Figure 3.1: The map shows trajectories of all particles from the CMS. The color represents the trajectory of the particle. Three regions are found to be the water origins: the Denmark Strait, the Iceland-Scotland Ridge, and the Iceland Basin. The tilted black line in the middle of the picture is Reykjanes Ridge.

for this source, which could be from the Subpolar Current or the North Atlantic Current.

The origins of the waters of the Irminger Sea are found as described in Figure 3.1, and it is assumed what currents the different water sources will follow as they pass through the Irminger Sea. However, it is difficult to understand the routes of water flow in the Irminger Sea. Next, the trajectories are further separated based on the origins of the waters entering the Irminger Sea, in combination with the topography of the Irminger Sea, in order to qualitatively analyze the transport routes from different origins and quantify the number of particles per route.

3.3. Qualitative view on waters in the Irminger Sea – Transport Routes

In Chapter 1 Figure 1.6, the domain of the Irminger Sea is divided into several regions based on its topography. All particle trajectories in Figure 3.1 can be classified according to their origins, allowing us to obtain the routes of waters from different sources in the Irminger Sea. The qualitative analysis of water movement trajectories is focused on in this chapter.

The criteria for route classification are explained and summarized in Table 3.1 and the routes are sketched in Figure 3.2. The region north of 65°N is referred to as the Denmark Strait Region. Particles from this region follow Route DS. The Reykjanes Ridge (RR) (from 26°W, 65°N to 40°W, 50°N) separates the Irminger Sea and Iceland Sea, as the black arrow line in Figure 3.2, which is used to distinguish whether the particles from different sources pass through the RR. Then the number of particles that cross the RR can be counted.

In the latitude between 58°N and 65°N, north of the Reykjanes Ridge and west of Iceland is the Irminger Basin (IrB), while south of the Reykjanes Ridge is the North Iceland Basin (NIcB). Particles staying in the Irminger Basin follow Route IrB. Particles staying in the NIcS originated from IcS before entering NIcS, following Route IcS.

Particles in the south of the 58°N follow three routes. North of the RR are particles fully across the RR, which route for particles is able to travel to the furthest location extending into the Irminger Sea, named Route RR. Particles in the south of the black arrow line (RR) in Figure 3.2, are staying in the

Table 3.1: Criteria of route classification. Six routes are defined in this table, each with the Latitude and Longitude ranges of water originates regions.

Routes Name	Origin Regions	Latitude	Longitude
DS	Denmark Strait	>65°N	No limited
IrB	Irminger Basin	58°N-65°N	North of RR
IcS	Iceland Scotland Ridge	58°N-65°N	South of RR
RR	Reykjanes Ridge	<58°N	North of RR
WIcB	Iceland Basin	<58°N	South of RR, West of 26°W
SIcB	South Iceland Basin	<58°N	East of 26°W

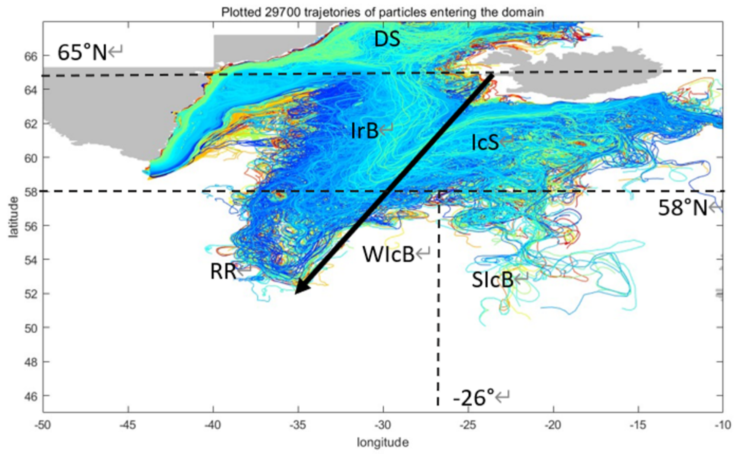


Figure 3.2: The routes of water transport in the Irminger Sea. The black arrow line separates the regions starting from the west point of Iceland (25°W, 65°N) extend to the south boundary of RR (35°W, 51°N), north of which is the particles in the Irminger Basin and across the RR. The separation of the West Iceland Basin Route(WIcB) and South Iceland Basin Route(SIcB) is 26°W. The separation of the Iceland-Scotland Route (IcS) and South Iceland Basin Route(SIcB) is 58°N latitude.

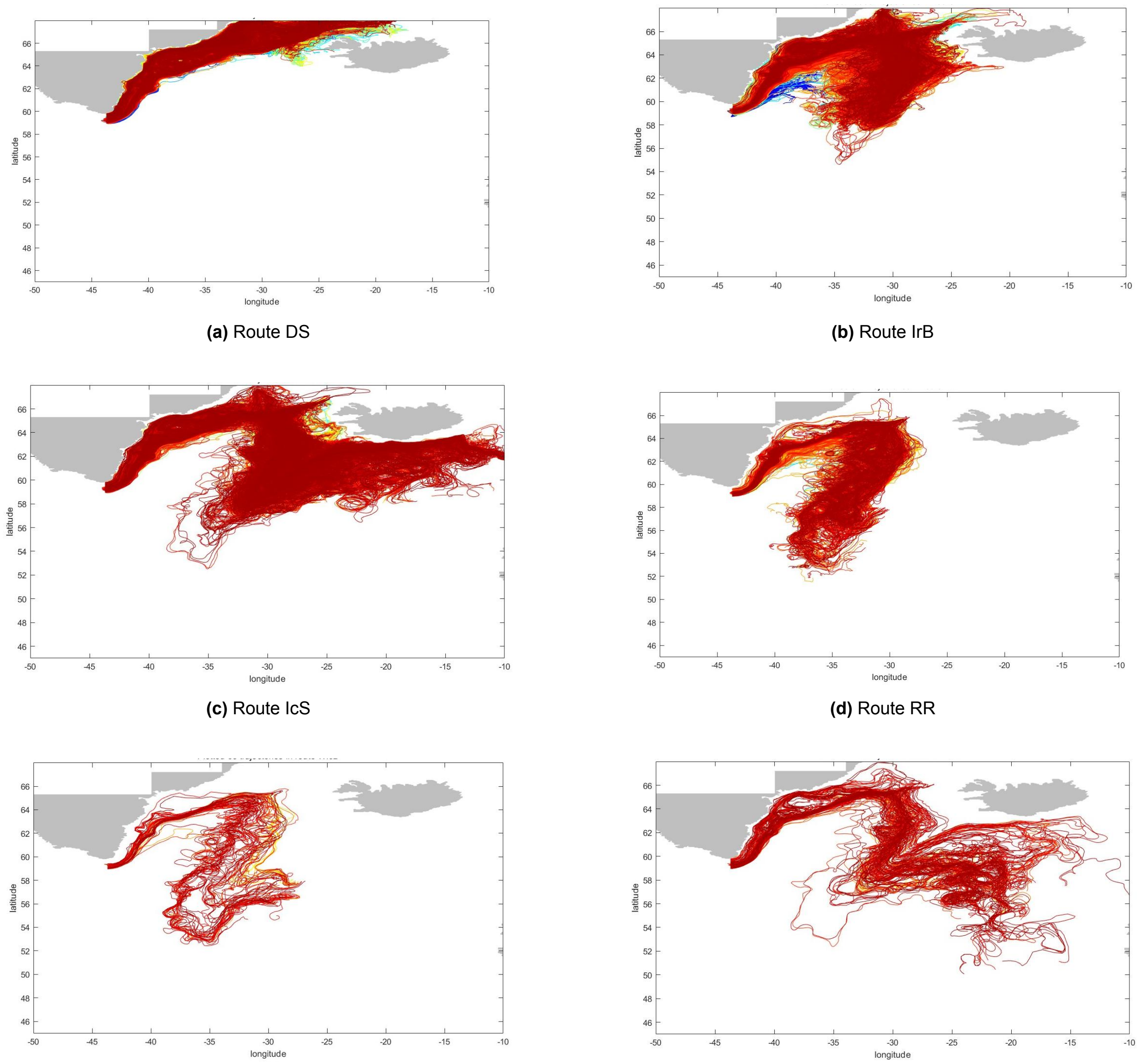
West Iceland Basin (WIcB) (western of 26°W) and the South Iceland Basin (SIcB) (eastern of 26°W). They follow the Route WIcB and SIcB separately.

Figure 3.3 shows the particle trajectories of the six routes in the Irminger Sea, classified based on their different origins. As Figure 3.3a shows, particles in the DS route coming from the Denmark Strait flow along the eastern boundary of the Greenland shelf before reaching Cape Farewell. Most of the particles in the IrB route move around the Irminger Basin while some of them move towards the Denmark Strait and then turn to Cape Farewell, shown in Figure 3.3b.

The particles in Route IcS travel through the NIcB and then cross the RR, or travel along the south of Iceland rather than crossing the RR before traversing into the Irminger Sea, as shown in Figure 3.3c. After entering the Irminger Sea, the particles tend to bypass the Irminger Sea and travel along the eastern boundary of Greenland before arriving at Cape Farewell.

The particles in the Route RR and WIcB come from the NIcB or SIcB before crossing the RR into the Irminger Basin, rather than directly into the Irminger Sea, as shown in Figure 3.3d and Figure 3.3e.

The particles in Route SIcB follow the longest-distance route, which involves traveling through the Iceland Basin, crossing the Reykjanes Ridge, and traversing the Irminger Sea. Comparing Figure 3.3c



(a) Route DS (b) Route IrB

(c) Route IcS (d) Route RR

(e) Route WIcB (f) Route SIcB

Figure 3.3: The particle trajectory of six routes based on the classification in Table 3.1

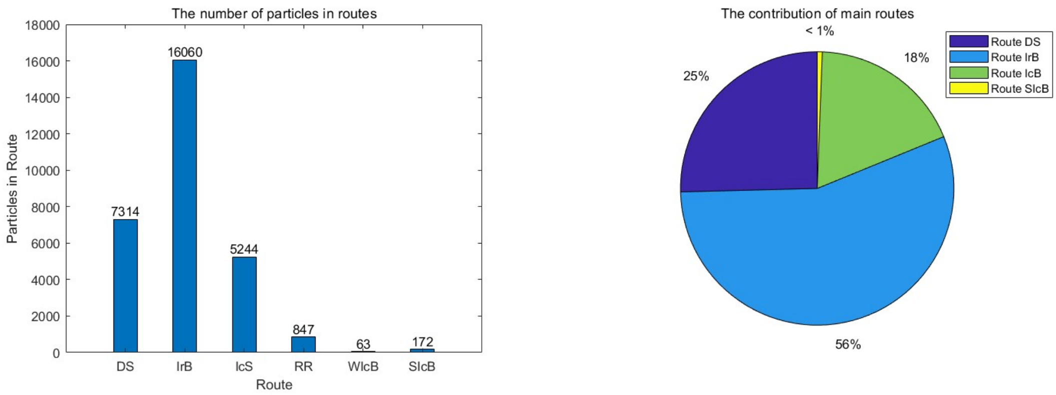
and Figure 3.3f, the trajectory behavior of Route IcS and SIcB as they cross the Reykjanes Ridge is different, although water from both routes originates from the Icelandic basin. The IcS route includes water transport near the south of Iceland and through the southern part of the Reykjanes Ridge, while water from Route SIcB tends to move away from Iceland as it crosses the RR.

The water in SIcB follows the current across the RR, which is the Irminger Current, from the North Atlantic Current in the South Iceland Basin, mentioned in Chapter 1.4. In contrast, some of the water in the IcS is driven by a deeper, dense water overflow, which is the ISOW from IcS. This water is transported along Iceland rather than crossing the RR and then enters the IrB.

3.4. Quantify contribution of pathways of waters

According to the six routes of particle trajectories in the Irminger Sea in Figure 3.3, which are classified based on the water origins of the Irminger Sea, the contribution of each of the routes is calculated.

Figure 3.4a shows the number of particles in the route, and the contribution of the water source in its route is summarized in Table 3.2. 25 percent of the particles originate from the Denmark Strait,



(a) (b)

Figure 3.4: (a) The number of particles in each of the routes; (b)The contributions of four main routes, DS with 25 percent contributions, IrB with 56 percent contributions, IcB with 18 percent, and SIcB is smaller than 1 percent.

along Route DS, and 56 percent of the particles stay in the Irminger Basin. As compared, 18 percent of the particles can travel further, through the Irminger Sea, to the IcS. Therefore, the waters in Route IcS contribute 18 percent. Only 2.9 percent of the particles can completely travel across the RR, to the furthest location in the Irminger Sea. As we can see in Table 3.2, 0.2 percent of the particles stay in the WIcB, where WIcB is a small region. The contributions of waters along Route RR and WIcB are small, and waters can be tracked from IcS or SIcB, so the waters of these two routes are not critical for the study. Although only 0.6 percent of the particles are in the SIcB route, it is an indispensable route because the waters in Route SIcB have possible origins from subpolar gyres or the North Atlantic Ocean, which are important sources of water for the Irminger Sea. The contribution of the route SIcB is small because the SIcB route has the longest distance, and the 5-year tracking period is not sufficient to allow further arrival of large amounts of particles. In conclusion, the route DS, IrB, and SIcB are the most important due to their contribution to the Irminger Sea and critical water sources. They are the main routes focused on in this study, so their contributions are compared, as shown in Figure 3.4b, and their characteristics will be analyzed.

Table 3.2: Summary of contributions of waters in each route.

Routes Name	Particle numbers	Percentages	Origins
Route DS	7314	25	From Denmark Strait
Route IrB	16060	56	Stay in Irminger Basin
Route IcS	5244	18	From Iceland Scotland Ridge
Route RR	847	2.9	Cross Reykjanes Ridge
Route WIcB	63	0.2	From North or South Iceland Basin
Route SIcB	172	0.6	From Subpolar Gyres or North Atlantic Current

As analyzed earlier, Route DS, IrB, and SIcB are the critical routes for further study. A comparison of their contributions to the Irminger Sea is shown in Figure 3.4b. Route DS is a boundary route for the waters traveling in the Irminger Sea, which has a smaller volume of water than in Route IrB and IcS, which travel through the interior of the Irminger Sea. Therefore, it can be assumed that a large amount of water travels through the internal routes of the Irminger Sea than through the boundary route.

3.5. Conclusion and Discussion

This chapter analyzes the water origins and their routes of traveling in the Irminger Sea to the Cape Farewell, which provides a better understanding of the complex transport routes of waters circulation in the North Atlantic. By investigating the particle trajectories, the important origins of waters in the Irminger Sea are found as the Denmark Strait, the Iceland-Scotland Ridge, the Subpolar gyre, and the North Atlantic Ocean. The particle trajectories in the Irminger Sea shows that particles from the Denmark Strait travel southward along the eastern boundary of the Greenland and reach Cape Farewell directly. The particles from the IcS or IcB cross the Reykjanes Ridge and then enter the Irminger Sea before reaching Cape Farewell. Six routes of water sources traveling in the Irminger Sea are investigated, and the contribution of each route to the Irminger Sea is quantified by counting the number of particles in the route. In conclusion, Route DS, IrB, IcS and SIcB are the most important routes, which characteristics will be further analyzed in Chapter 4.

4

The characteristics of the main routes

4.1. Introduction

In this chapter, the characteristics of the main routes in the Irminger Sea is focused on, with the aim of understanding the basic mechanisms that drive the movement of waters in the Irminger Sea. To achieve this, the particle trajectories, depth variation of particles, and temperature variation of example particles in their routes are studied. By analyzing the complexed characteristics of trajectories, we clarify how water crosses the Irminger Sea from different routes. In addition, the depth distribution of particles at origins and Cape Farewell, as well as the depth and temperature variation of example particles along the trajectories are examined, to gain insight into the specific physical process that occurred in the Irminger Sea. These physical mechanisms contribute to the water dynamics in the Irminger Sea, which helps understand the potential role of the Irminger Sea in the larger oceanic system and response to climate change.

4.2. Characteristics of water trajectories

Figure 4.1 shows the example of trajectories for the particles on the main routes traveling through the Irminger Sea before arriving at Cape Farewell. The routes presented in Figure 4.1 are the DS route (blue lines), IrB route (pink lines), IcS route (red lines), and SIcB route (green lines). The trajectory characteristics of these four routes are compared and analyzed next.

The particles in route DS can be classified as the boundary route, while IrB and IcS, and SIcB can be considered as internal routes, because the waters in these three routes travel through the interior of the Irminger Basin, as shown in Figure 4.1. The boundary route DS is along the narrow continental shelf of east Greenland and follows the boundary currents directly to Cape Farewell, rather than through the Irminger Basin. This route DS is a straight and short-distance route. In contrast, waters along the internal routes of IrB, IcS, and SIcB pass through the Irminger Basin or the Iceland Basin, where intensive oscillations exist in the routes, before reaching the Cape Farewell. The three internal routes are curved and blended, which are long-distance water transport routes, and these curved routes within the interior of the basins can result from the bathymetry in the Irminger Sea, and deep eddy activity or wind-driven forces at the surface.

The differences in routes IrB, IcS, and SIcB are compared now. As shown in Figure 4.1, waters in these three routes present similar traveling patterns, cross the RR, and oscillated through the Irminger Basin and along the boundary of Greenland. However, in the same tracking period, waters in the IcS and SIcB travel a longer distance than waters in the Route IrB. This can be caused by the depth layers of the waters of the routes. Since the upper layer water flows faster than the deep layer water, it is assumed that the IcS Route is in a shallower depth layer than the IrB Route because the water from the IcS Route travels a longer distance to the Iceland-Scotland Ridge (IcS) eventually. For the same reason, the water source from Route SIcB is in the shallowest layer, because the water in this route travels further south after reaching IcS.

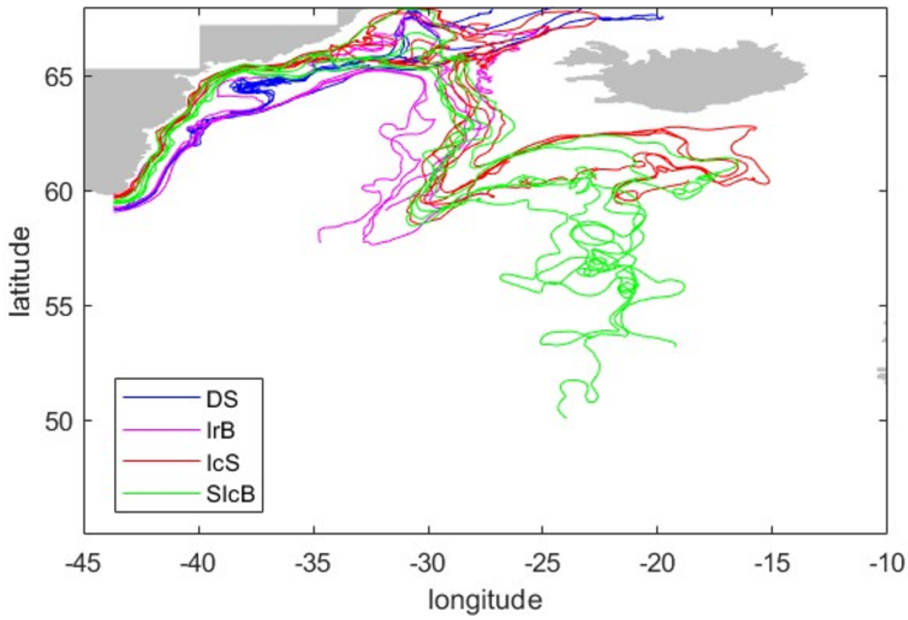


Figure 4.1: Example of the trajectory of main routes. Blue lines are particles in route DS. Pink lines are particles in route IcS. Red lines are particles in route IcS. Green lines are particles in route SIcB.

In addition, the particles of these three internal routes, after crossing the RR, tend to travel around the Irminger Basin instead of penetrating into the interior of the Irminger Basin, which may be caused by the bathymetry or convection in the Irminger Basin.

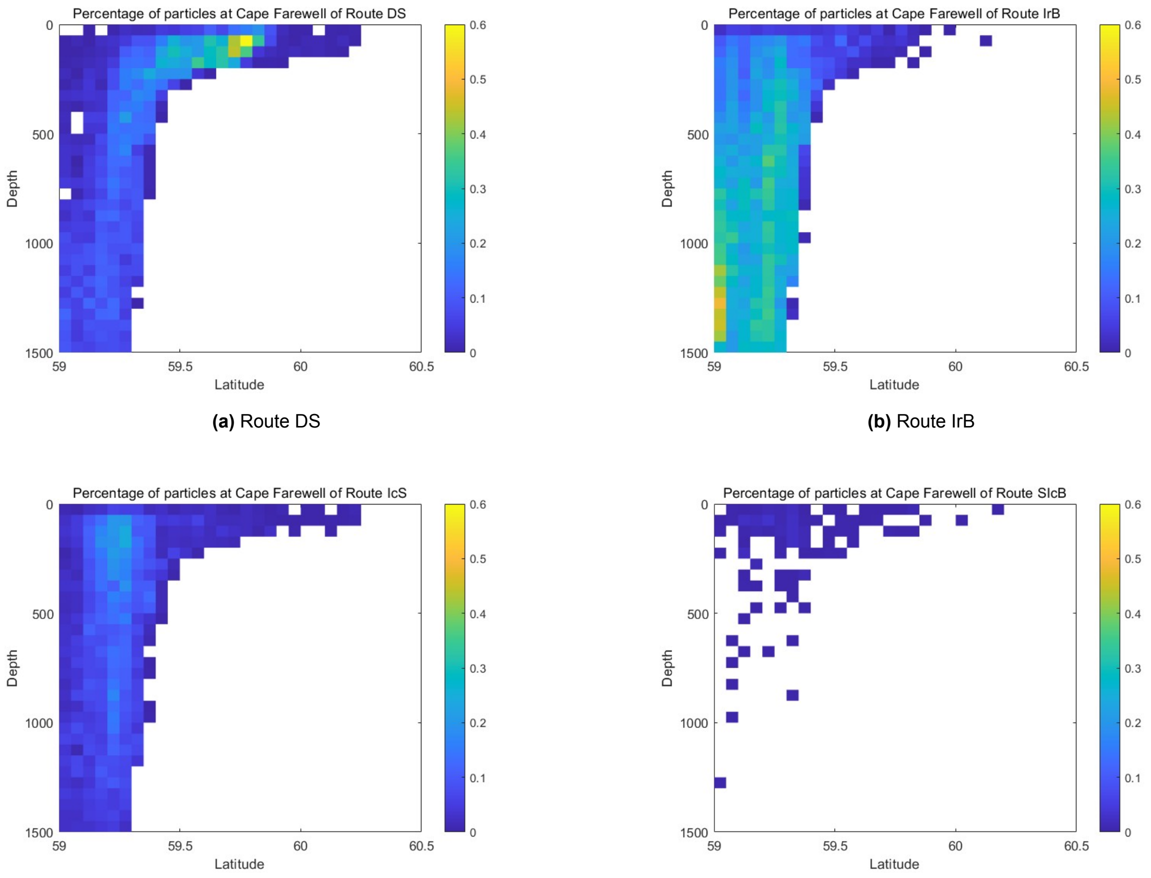
In this section, the characteristics of main routes DS, IrB, IcS and SIcB are studied. As mentioned earlier, the DS route is a straight, short-distance boundary route. In contrast, the other three routes, IrB, IcS, and SIcB are internal routes, which are curved and long-distance. However, the depth layers of routes are not clear now, which will be investigated in the next section.

4.3. Overturning during water transport

This chapter will explore the overturning of the Irminger Sea. The distribution of depth of particles will be investigated at Cape Farewell to clarify the depth of water source for each route. Example particles in the main routes will be tracked to follow the variation of depth and temperature along the trajectory. Based on the presented phenomenon, potential drivers will be analyzed.

4.3.1. Depth Distribution of water arriving at Cape Farewell

The investigation of particle distribution as a percentage of total particles among the four main routes of Cape Farewell in Figure 4.2 shows that water from different origins reaches different depths at Cape Farewell along the routes. And the results for the depth and latitude range when particles arrive at Cape Farewell are summarized in Table 4.1. The particles in the route DS are concentrated in the surface layer (50-200m), between 59.4°N and 59.8°N, which is the shallowest depth and most shoreward of the four routes at Cape Farewell, as shown in Figure 4.2a. And the particle concentrations in the route DS peak in the range of 50-100m, 59.75 to 59.8°N. As Figure 4.2b, the particles in the route IrB arrive in a fairly deep layer (1200-1500m) at Cape Farewell, the farthest offshore from 59°N to 59.3°N. The particles from the IcS are transported in the shallower layers, reaching Cape Farewell at the depth of 50-400 m, from 59.15°N to 59.35°N, as shown in Figure 4.2c. The few particles in the route SIcB are mainly concentrated in the surface layer (0-150m), 59.2°N to 59.55°N at Cape Farewell, as shown in Figure 4.2d.



(a) Route DS

(b) Route IrB

(c) Route IcS

(d) Route SIcB

Figure 4.2: Percentage of particles concentrated at depth and latitude based on the total particles count for the four routes (a) DS, (b) IrS, (c) IcS, and (d) SIcB

Based on the conclusion above water along different routes reaches Cape Farewell at different depths. It is conjectured whether water from each route always remains in the specific depth layer from its origin to Cape Farewell. As mentioned before, each route is classified according to the area where the water originates. Table 4.1, the results of the particle depth distribution show the most obvious difference in routes in the shallow and deep layers. Therefore, the trajectory of particles at Cape Farewell in the surface layer (0-100m) and deep layer (900-1500m) is plotted as shown in Figure 4.3, in order to corroborate whether the waters have a variation in depth along their propagation.

Figure 4.3a shows that particles at the Cape Farewell surface depth (0-100 m) come from the DS, SIcB, and a few from the IcS. Most of the particles at the Cape Farewell surface depth cross the RR before entering the Irminger Basin.

Figure 4.3b shows that most of the particles reaching the Cape Farewell in the deep depth (900-1500 m) stay in the Irminger basin, while a few particles come from the DS and IcS. Particles arriving in this depth range hardly cross the RR, but travel along the southern part of Iceland. As we know before in Table 4, water from the DS and IcS is mainly concentrated in the shallow waters (50-200 m) of Cape Farewell, which also appears in Figure 14b, the deep depth (900-1500m). Therefore, we assume that this water changes its depth along the way. Further analysis of the depth variation of the particles is needed, which will be investigated in the next section.

4.3.2. Depth and temperature variations of example particles along trajectory

In the previous section 4.3.1, we studied the behavior of water in the four predefined routes as it reaches Cape Farewell. It was observed that the water in each route tended to concentrate within specific depth

Table 4.1: Depth and latitude of particles concentrated at Cape Farewell

Routes Name	Depth range	Latitude range
Route DS	50m-100m	59.7°N to 59.8°N
Route IrB	1200m-1400m	59.0°N to 59.05°N
Route IcS	50m-200m	59.2°N to 59.3°N
Route SIcB	0-150m	59.2°N to 59.55°N

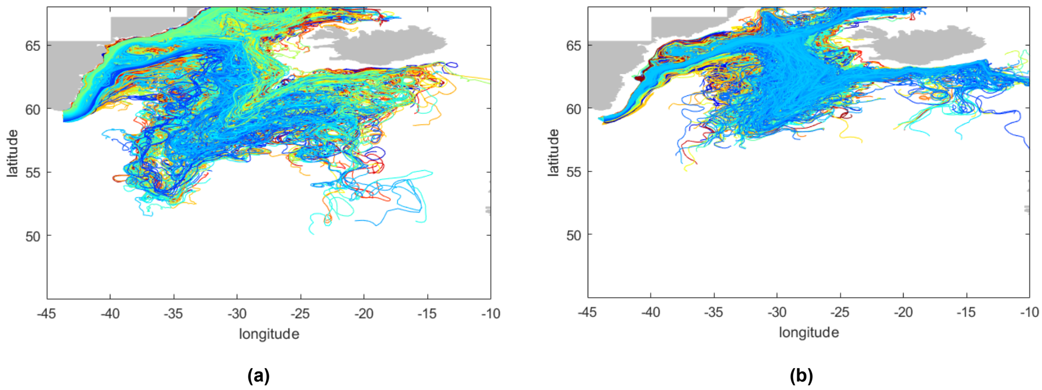


Figure 4.3: Comparison of the trajectory of particles in the (a) surface layer 0-100m, and (b) deep layer 900-1500m at Cape Farewell.

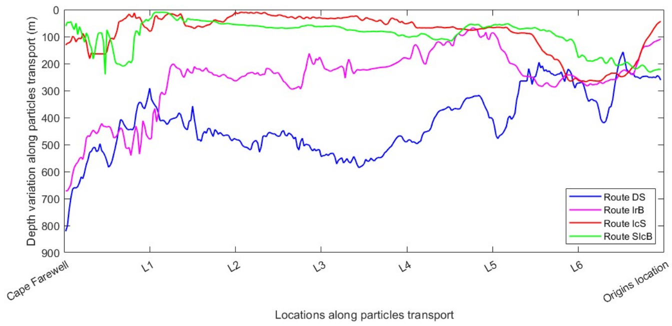
and latitude ranges. Furthermore, the depth of some water changes during its propagation from the origins. In this section, the aim is to track the variations in depth and temperature of representative particles along the main routes. By tracking these variations, it contributes to the understanding of the hydrodynamic activity in the Irminger Sea and provides further insight into the possible factors influencing the water variability. It contributes to a deeper comprehension of the physical processes occurring along the water routes within the Irminger Sea.

The variation of depth and temperature along particle's trajectories as a function of time for the four main routes is compared in Figure 4.4.

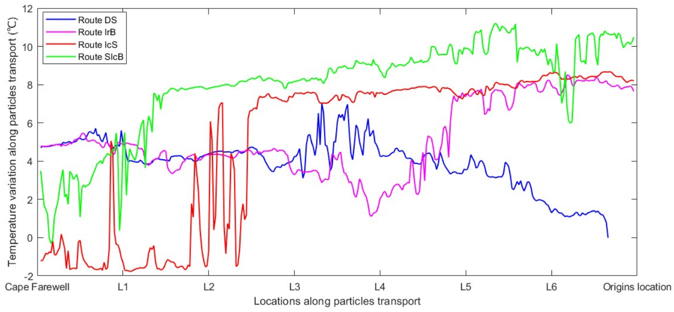
The blue line shows the example particle in the route DS, which is released in the wintertime of December. Figure 4.4a shows the particle from the Denmark Strait moving down in the water column in the shallow water (approximately 300m) along the route. This particle could be the source of polar water from the Arctic, where the Atlantic water circulation causes it to descend to deeper depths. In addition, it could be caused by ice melt and river runoff from the Greenland border, which increases the water depth. Figure 4.4b shows the origin of particles along the cold water, whose temperature increases along the trajectory, which can be influenced by the Irminger Current in the Irminger Sea.

The pink line in Figure 4.4a presents the particle in the route IrB. It moves down in the depth along the trajectory as shown in panel a, which can be caused by convection in the Irminger Basin when the particle moves to the north of the Irminger Sea, where surface water loses heat leading to the convection. Figure 4.4b shows the particle originated in the warm water column, with the temperature decreasing along the route, which can be influenced by the EGC current in the Irminger Basin.

As seen in Figure 4.4a the example particles from DS and IrB (blue and pink lines) both sink around 600m during traveling, to a deeper layer. From Figure 4.4b, the example particles from DS and IrB both reach 5°C at Cape Farewell and in Figure 4.1, the example particles from Route DS and IrB reach the same location offshore at Cape Farewell. Therefore, the representative particles in Route DS and



(a)



(b)

Figure 4.4: (a) Variations of depth for single example particles along the routes. X-axis is the length of the trajectory as a function of time, with an initial condition X(0) at Cape Farewell. Y-axis is the depth along the trajectory. (b) The temperature variations for single example particles along routes DS, IrB, IcS and SIcB.

IrB could be driven by EGC and DSOW.

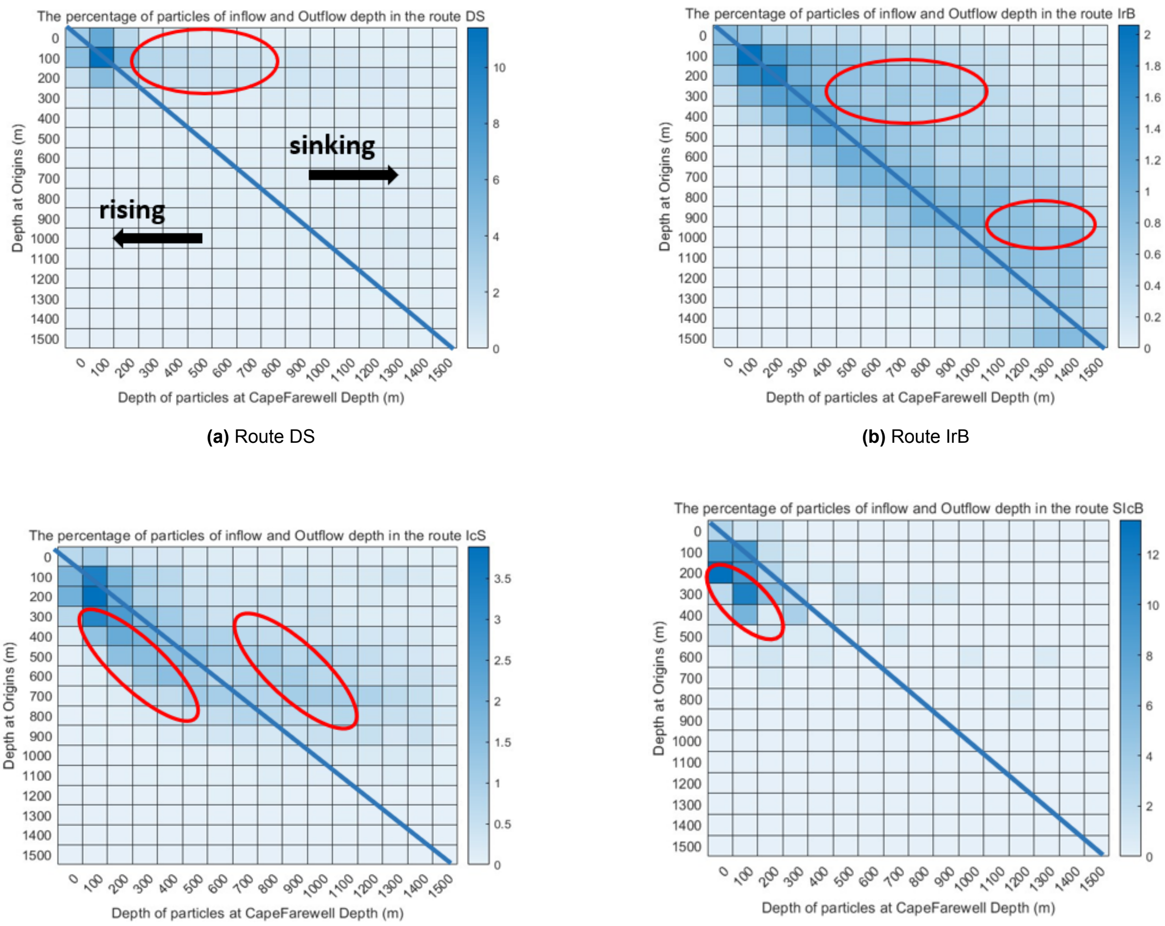
The red line is the particle in Route IcS, and the green line is the particle in Route SIcB. Both particles travel in the surface layer (approximately 100m) along the route, without great changes in depth. Figure 4.4b shows particles from Route IcS and SIcB origin along the warm water column with a temperature decrease of approximately 8-10°C. The particles in Route IcS and SIcB in the surface or shallow layer can be driven by the Irminger Sea, which is cooled by the atmosphere in the surface layer as it transports northward. As shown in Figure 4.1, the particles in Route IcS and SIcB (red and green lines) move into the Denmark Strait after crossing RR, where particle temperatures decrease dramatically between the location L2 and Cape Farewell in Figure 4.4b. The waters in Route IcS and SIcB on the surface can be driven by the Irminger Current.

In summary, the example particles show changes in depth and temperature along their trajectories in the four routes. The patterns of water depth and temperature variation along the routes are expected to be explored. Therefore, the distribution of depth and temperature variation of the particles between their origins and Cape Farewell will be compared next.

4.3.3. Water changes in depth at the origin and Cape Farewell

Figure 4.5 shows the percentage of particles in the depth distribution between the origin and the valedictory angle in the four main routes, which allows us to compare whether the particles of each route sink or rise in depth as they reach the Cape Farewell. The particles distributed along the blue line are those that remain the same depth between the origin and Cape Farewell, and the red circles are the depth range where particles concentrate. The upper part of the blue line in Figure 4.5, is where particles tend to sink into a deeper layer while arriving at Cape Farewell. The red circle below the blue line shows the particles tend to rise into a shallow layer.

As shown in Figure 4.5a, most of the water from the Denmark Strait is concentrated in the shallow depth (0-200m) and remains in the shallow depth at Cape Farewell (0-200m). The red circle shows a



(a) Route DS

(b) Route IrB

(c) Route IcS

(d) Route SIcB

Figure 4.5: Percentage of particles in the depth distribution at the origins and Cape Farewell. X-axis is the depth at Cape Farewell. Y-axis is the depth at origins location. Blue line is the concentration of particles at unchanged depths between origins and Cape Farewell. Red circles are the depths where particles are most concentrated (a) For water in route DS; (b)For water in route IrB; (c) For water in route IcS; (d) For water in route SIcB.

small amount of water sinking from the surface layer at the origin to the deeper layer (300-700 m) at Cape Farewell, as the example particles in Route DS in Figure 4.4a.

As shown in Figure 4.5b, water in route IrB is distributed in all depth layers from 0-1500m, which means this route contains water from all sources. The water in this route is mainly concentrated in the line where the inflow depth at origins equals the outflow depth at Cape Farewell, with some water sinking to a deeper layer, as shown by the red circles in Figure 4.5b.

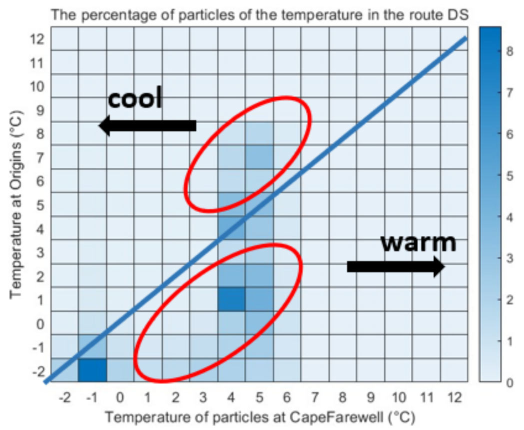
The waters from the IcS route, mostly travel in a shallow depth (100m-200m), as shown in Figure 4.5c. These waters tend to remain at shallow depths while arriving at Cape Farewell. Some water originating from the depths of around 500m to 900m sinks to the deeper depths at Cape Farewell around 700m to 1300m, as shown in the red circle above the blue line. However, there is still a portion of the water rising to the surface to the 100-300m at Cape Farewell.

Finally, Figure 4.5d shows that the most water from the SIcB route stays at the surface layer around 100-300m at the origin and Cape Farewell, while few particles tend to rise with 100 to 200m while reaching Cape Farewell.

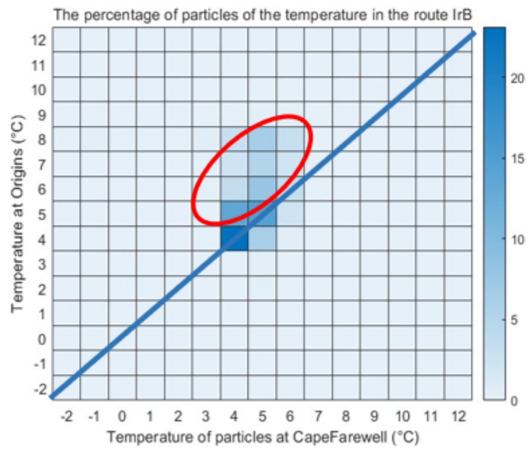
In the next section, the percentage of particles in the temperature distribution at origins and Cape Farewell in each route will be compared as well. Combining the variations of these two factors, depth, and temperature, the water transport patterns of each route can be concluded.

4.3.4. Water changes in temperature at the origin and Cape Farewell

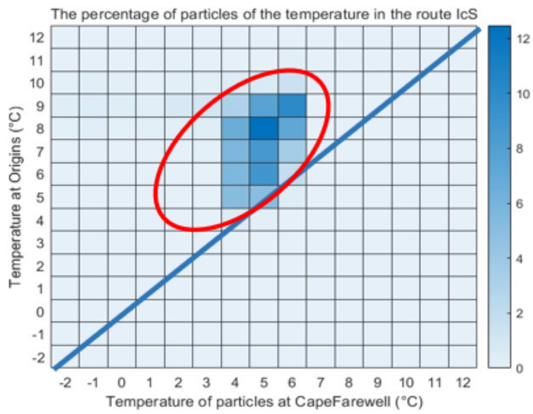
In this section, the temperature distribution of particles at the origins and Cape Farewell is compared in Figure 4.6.



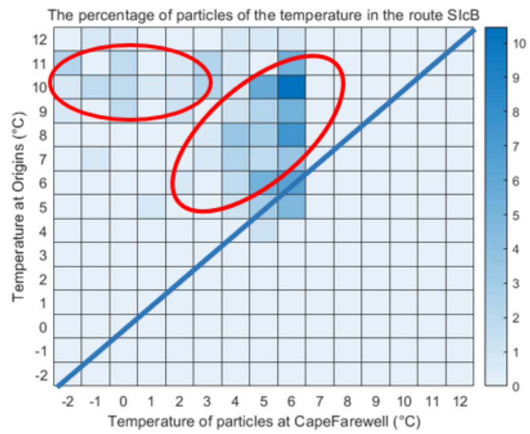
(a) Route DS



(b) Route IrB



(c) Route IcS



(d) Route SIcB

Figure 4.6: Percentage of particles in the temperature distribution at the origins and Cape Farewell. X-axis is the temperature at Cape Farewell. Y-axis is the temperature at the origin's location. The blue line is that particles keep temperature unchanged between origins and Cape Farewell. Red circles above the blue line are where particles are concentrated to be cooled at Cape Farewell, and red circles below are where the particles are warm at Cape Farewell. (a) For water in route DS; (b) For water in route IrB; (c) For water in route IcS; (d) For water in route SIcB.

As shown in Figure 4.6a, most waters in Route DS are cold with temperatures -2°C or -1°C both at origins and Cape Farewell. In addition, another two sources of water, one with a low temperature of around 0-2°C and the other with a high temperature of around 4-8°C exist in Route DS. The cold water tends to be warm and the warm water tends to be cooled at Cape Farewell, which are all become 4-5°C finally at Cape Farewell.

In Figure 4.6b, the water in Route IrB origins a warm source with a temperature of 6-8°C, which temperature decreases to 4-5°C at Cape Farewell. The pattern of Route IcS shows similar changes in temperature, as shown in Figure 4.6c, where water origins as a warm source with a temperature of 6-9°C, which temperature decreases to 4-6°C at Cape Farewell.

While waters in Route SIcB are warm sources as shown in Figure 4.6d, with temperatures around 8-11°C. Two variations occur after they arrive at Cape Farewell, one of the sources is cooled at the temperature of -2-2°C, and the other one is the source cooled a bit at the temperature of 5-6°C at Cape Farewell.

In summary, the water in Route DS exists as a cold source, which keeps as the cold source at Cape Farewell. Water in the other three Routes are warm sources, with temperature decreased to 4-6°C at Cape Farewell. And the water in Route SIcB is the warmest source with a temperature of 8-11°C at origins.

4.4. Conclusion

In this chapter, the characteristics of the four main routes are discussed and summarized, from the trajectory characteristics, depth distribution, and temperature distribution along the routes.

DS route is a straight-line trajectory that delivers water directly along the Greenland border to Cape Farewell. The water is concentrated in the surface layer (0-200m) when it reaches Cape Farewell. A small portion of the water sinks slightly, from surface depth to deeper depth (400-700m). This route contains the coldest water source with a temperature of -2°C, and some water tends to be warmed.

IrB route is a curved trajectory in the Irminger Basin, with oscillations. Water flows along this route in a short distance with low velocities. Water in IrB Route is mostly in the deepest layer (1200-1400m), and water in this route tends to sink by the time it reaches Cape Farewell. There is no huge change in the temperature between origins and Cape Farewell.

IcS Route is also curved with long distances for water transport. Most of the water in Route IcS occurs in the upper layer, where it transports quickly. While there is still some water in the intermediate depth (400-700m) tends to sink into deeper layers (700-1100m). Water in this route origins with high temperature, which decreases at Cape Farewell.

SIcB Route is the longest distance route, with water staying in the surface depth along the route. This route contains the warmest water sources, which temperature decreases at Cape Farewell.

5

Discussion and Conclusion

This study analyzed the water sources and behavior through the Irminger Sea before reaching Cape Farewell by the approach of Lagrangian particle tracking. Based on the investigation of the water trajectories in the CMS, the characteristics of the water transport routes were analyzed, and the contribution of the routes was quantified by counting the number of particles. Further, the depth and temperature distribution of each route, as well as the variation along the route trajectory were investigated, with contributions to the understanding of the water transport dynamics processes in the Irminger Sea. The aim of this study is to address the main objectives of this thesis:

Exploring the possible origins and pathways of water entering the Irminger Sea before they arrive at Cape Farewell.

And for the following sub-questions are answered.

- 1. How does water travel through the Irminger Sea from its origins? What is the contribution of water in each route reaching Cape Farewell?
- 2. Are there indications of specific physical processes that occurred in the Irminger Sea such as convection or eddies, and atmospheric force, leading to the dynamic movements of water in the Irminger Sea during transport?
- 3. How do the currents in SPNA contribute to the water transport in the Irminger Sea?

These sub-questions are answered and discussed in previous chapters and summarized here.

1. How does water travel through the Irminger Sea from its origins? What is the contribution of water in each route reaching Cape Farewell?

Tracking the water in the Irminger Sea for 5 years before reaching Cape Farewell found that water sources originate from the Denmark Strait, the Iceland-Scotland Ridge, and the North Atlantic Ocean. Water from these four origins was identified traveling along the four main routes, DS, IrS, IcS, and SIcB through the Irminger Sea in this study. The characteristics and contribution of the four main routes are explained below, referred to as Figures 3.3 and 3.4b.

The water from the Denmark Strait follows Route DS and travels along the eastern boundary of the Greenland continental shelf directly to Cape Farewell along a straight and short-distance route, rather than traveling through the Irminger Basin. This route contributes 25 percent of water through the Irminger Sea before arriving at Cape Farewell.

The water staying in the Irminger Basin follows Route IrB, a curved route. Their trajectory shows oscillations back and force in the Irminger Basin before reaching Cape Farewell. Water in this route travels in a short distance in the 5-year tracking period, with slow velocity. This route contributes 56 percent of the waters through the Irminger Sea before reaching Cape Farewell.

Water from the Iceland-Scotland Ridge follows Route IcB, which has a longer distance than Route IrB. The water in this route passes through the north of Iceland Basin and crosses the Reykjanes Ridge or along the south of Iceland before entering the Irminger Basin, where the water also shows a curved route before arriving at Cape Farewell. This route contributes 18 percent.

The water in Route SIcB comes from the North Atlantic Ocean. Water in this route is transported along the longest distance from the south of Iceland Basin, across the Reykjanes Ridge, through the Irminger Basin and to Cape Farewell. The contribution of water on this route is 0.6 percent, which is not accurate due to the limited tracking time.

Compare the behavior of water along the main routes through the Irminger Sea before reaching Cape Farewell. Most of the water from the Iceland Basin in the SIcB route tends to cross the Reykjanes Ridge and then enter the Irminger Basin, while some water from the Iceland-Scotland Ridge in the IcS route flows along the southern part of Iceland instead of crossing the Reykjanes Ridge, referring to Figure 3.3c and 3.3f. Water in route DS is expected to flow along the border of Greenland, while water from the other three routes IrB, IcS, and SIcB, is transported in a curved trajectory through the Irminger Sea.

2. Are there indications of specific physical processes that occurred in the Irminger Sea such as convection or eddies, and atmospheric force, leading to the dynamic movements of water in the Irminger Sea during transport?

The possible physical processes in the Irminger Sea were explored by investigating the variation of water depth and temperature along each route.

During passing through the Irminger Sea, water moves up or down along its route, which results in differences in water depths between the origin and Cape Farewell. Water from the DS route mostly stays at the surface depths (0-200m) at the origin and Cape Farewell without overturning along the route DS, while some water tends to sink from the surface depth (0-200m) to deeper depths (400-700m) at Cape Farewell. Water in the IrB route is most concentrated at the deep depth (1000-1400m) at the origin and also tends to sink 100-600m deeper at Cape Farewell. The water from the IcS and SIcB routes is at surface depths (0-600 m) at the origin, and water from these two routes tends to rise 100-400 m shallow by the time it reaches Cape Farewell. (Referred to as Figure 4.5)

The temperature changes of water occur between the origin and Cape Farewell. The only source of cold water comes from the DS route, some parts of which (-2-0°C) remain constant in temperature along the route. This water can be transported along the Greenland border. Another part of the cold water (0-2°C) in Route DS tends to warm (4-6°C) at Cape Farewell, which may be influenced by the mixing process in the Irminger Sea. The waters from the other three routes IrB, IcS, and SIcB are warm source (5-11°C) and tends to be cool to 4-6°C at Cape Farewell. (Referred to as Figure 4.6)

Changes in depth and temperature indicate the possible physical processes in the Irminger Sea. At the surface (0-100m), the atmospheric force act to cool the water. While deeper in the Irminger Sea, cold flow EGC mixes with warm flow IC, leading to the mixing of the water column, and therefore a change in temperature.

The topography of the Irminger Sea causes water to be transported over a specific depth range and the variations in depth along the routes (See Figure 1.7). For the water from the IrB route, the deep depth of the Irminger Sea (3000m) and the steep slope of the RR and Greenland shelf result in the water in the deep layer, which is difficult to transport over long distances at such depths. Whereas other waters from the DS, IcS, and SIcB routes are at surface depths, and in order to maintain their specific depth range during transport, the water travels around the Irminger basin (see Figure 4.1). The steep slope of the RR and the Greenland shelf causes the vorticity to feel the bottom friction, and the water depth contours do not remain constant, leading to variations in water depth along the route.

In addition, warm water is transported northward to the Irminger Basin, where it loses heat and convection occurs. During this process, water sinks to deeper depths (Referred to Chapter 1.2.2 and Figure 1.3). However, since the exact location of convection in the Irminger Sea is not determined, therefore the extent of the impact of the convection process effect is not clear.

Finally, according to the knowledge of Chapter 1.3, the eddy transports water laterally in the Irminger Basin. The study of particle trajectories, shows oscillations on the route (see Figure 4.1), which may be responsible for the eddy activity. These eddies not only exchange the internal water of Irminger Basin with the boundary water of Greenland but also transfer heat and momentum, which produces changes in water temperature and depth oscillations by downwelling and upwelling.

3. How do the currents in SPNA contribute to the water transport in the Irminger Sea?

The role of currents in SPNA is inseparable from the water transport in the Irminger Sea. Based on the previous studies of particle trajectories as well as depth and temperature variations, Figure 5.1 shows a schematic representation of the relationship between the contribution of currents and water transport in each route.

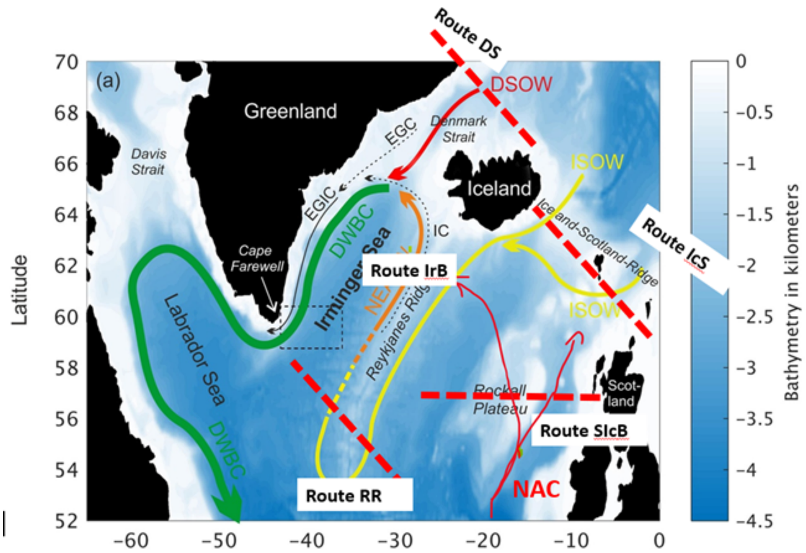


Figure 5.1: Schematic diagram of the currents and circulation in the Irminger Sea, and the connection of the water transport routes and currents in the Irminger Sea. The Irminger Current and East Greenland Current are the two most important components of the Irminger Sea. They drive the largest amount of water transport in the Irminger Sea before arriving at Cape Farewell. (Adapted from [Hopkins et al., 2019]

Water from the DS route is along the EGC in the upper and intermediate depth and a few waters in the further deeper depth driven by DSOW. The shallow water in the IrB route is driven by the IC and the deep water in the IrB is driven by the DSOW. The water temperature variation in the Irminger Sea may be caused by the mixing of EGC and IC in the shallow depth. (Referred by the Figure 1.7)

The water from the IcS route follows IC at the surface depth. It is possible that the water follows ISOW in the deep layer, which was not investigated in this study, because we saw few particles in the deep layer in the route IcS because the tracking time is limited for particles in the deep depth moves such further. The water in route SlcB follows NAC, which is the warmest water source, and it is driven by IC in the Irminger Sea.

In general, the origins and behavior of water in 5-year tracking in the Irminger Sea before reaching Cape Farewell have been investigated. However, some water in the deep depth which flows slowly was not explored, due to the limited tracking period. It is recommended to track particles in a longer period, to further explore the origins and behavior of water in the deep depths and capture the complete trajectory.

In general, the origins and behavior of water in the Irminger Sea before reaching Cape Farewell have been investigated. However, some water in the deep depth which flows slowly was not explored, due to the limited tracking period. There is a need to further explore the origins and behavior of water in the deep depths. This requires extending the tracking period to capture the complete trajectory.

Furthermore, the depth and temperature of water in the routes were analyzed. More properties such as salinity, and transport time of water in each route, are expected to be investigated. By investigating these additional properties, we can gain a more comprehensive understanding of the water transport patterns in the Irminger Sea. This expanded analysis will contribute significantly to our knowledge of the complex dynamics of water circulation in this region.

Bibliography

[Bacon and Saunders, 2010] Bacon, S. and Saunders, P. M. (2010). The deep western boundary current at cape farewell: Results from a moored current meter array. *Journal of Physical Oceanography*, 40(4):815–829.

[Bower et al., 2019] Bower, A., Lozier, S., Biastoch, A., Drouin, K., Foukal, N., Furey, H., Lankhorst, M., Rühs, S., and Zou, S. (2019). Lagrangian views of the pathways of the atlantic meridional overturning circulation. *Journal of Geophysical Research: Oceans*, 124(8):5313–5335.

[Brüggemann and Katsman, 2019] Brüggemann, N. and Katsman, C. A. (2019). Dynamics of downwelling in an eddying marginal sea: Contrasting the eulerian and the isopycnal perspective. *Journal of Physical Oceanography*, 49(11):3017–3035.

[Chanut et al., 2008] Chanut, J., Barnier, B., Large, W., Debreu, L., Penduff, T., Molines, J. M., and Mahout, P. (2008). Mesoscale eddies in the labrador sea and their contribution to convection and restratification. *Journal of Physical Oceanography*, 38(8):1617–1643.

[Clarke et al., 1990] Clarke, R. A., Swift, J. H., Reid, J. L., and Koltermann, K. P. (1990). The formation of greenland sea deep water: double diffusion or deep convection? *Deep Sea Research Part A. Oceanographic Research Papers*, 37(9):1385–1424.

[de Jong et al., 2018] de Jong, M. F., Oltmanns, M., Karstensen, J., and de Steur, L. (2018). Deep convection in the irminger sea observed with a dense mooring array. *Oceanography*, 31(1):50–59.

[Falina et al., 2007] Falina, A., Sarafanov, A., and Sokov, A. (2007). Variability and renewal of labrador sea water in the irminger basin in 1991–2004. *Journal of Geophysical Research: Oceans*, 112(C1).

[Fu et al., 2010] Fu, L.-L., Chelton, D. B., Le Traon, P.-Y., and Morrow, R. (2010). Eddy dynamics from satellite altimetry. *Oceanography*, 23(4):14–25.

[General Bathymetric Chart of the Oceans (GEBCO), 2023] General Bathymetric Chart of the Oceans (GEBCO) (2023). GEBCO_2023 grid. `https://www.gebco.net/data_and_products/gridded_bathymetry_data/gebco_2023/`.

[Georgiou, 2021] Georgiou, S. (2021). *Boundary-interior exchanges controlling the labrador sea dynamics*. PhD thesis, Delft University of Technology.

[Georgiou et al., 2019] Georgiou, S., van der Boog, C. G., Brüggemann, N., Ypma, S. L., Pietrzak, J. D., and Katsman, C. A. (2019). On the interplay between downwelling, deep convection and mesoscale eddies in the labrador sea. *Ocean Modelling*, 135:56–70.

[Georgiou et al., 2020] Georgiou, S., Ypma, S. L., Brüggemann, N., Sayol, J.-M., Pietrzak, J. D., and Katsman, C. A. (2020). Pathways of the water masses exiting the labrador sea: The importance of boundary–interior exchanges. *Ocean Modelling*, 150:101623.

[Hopkins et al., 2019] Hopkins, J., Holliday, N., Rayner, D., Houpert, L., Le Bras, I., Straneo, F., Wilson, C., and Bacon, S. (2019). Transport variability of the irminger sea deep western boundary current from a mooring array. *Journal of Geophysical Research: Oceans*, 124(5):3246–3278.

[Intergovernmental Panel on Climate Change (IPCC), 2013] Intergovernmental Panel on Climate Change (IPCC) (2013). Climate change 2013: The physical science basis. *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, AR5-WG1.

[Jackson et al., 2022] Jackson, L. C., Biastoch, A., Buckley, M. W., Desbruyères, D. G., Frajka-Williams, E., Moat, B., and Robson, J. (2022). The evolution of the north atlantic meridional overturning circulation since 1980. *Nature Reviews Earth & Environment*, 3(4):241–254.

[Katsman et al., 2018] Katsman, C., Drijfhout, S., Dijkstra, H., and Spall, M. (2018). Sinking of dense north atlantic waters in a global ocean model: Location and controls. *Journal of Geophysical Research: Oceans*, 123(5):3563–3576.

[Koch-Larrouy et al., 2010] Koch-Larrouy, A., Morrow, R., Penduff, T., and Juza, M. (2010). Origin and mechanism of subantarctic mode water formation and transformation in the southern indian ocean. *Ocean Dynamics*, 60:563–583.

[Latarius and Quadfasel, 2016] Latarius, K. and Quadfasel, D. (2016). Water mass transformation in the deep basins of the nordic seas: Analyses of heat and freshwater budgets. *Deep Sea Research Part I: Oceanographic Research Papers*, 114:23–42.

[Latif et al., 2022] Latif, M., Sun, J., Visbeck, M., and Hadi Bordbar, M. (2022). Natural variability has dominated atlantic meridional overturning circulation since 1900. *Nature Climate Change*, 12(5):455–460.

[Lilly et al., 2003] Lilly, J. M., Rhines, P. B., Schott, F., Lavender, K., Lazier, J., Send, U., and D'Asaro, E. (2003). Observations of the labrador sea eddy field. *Progress in Oceanography*, 59(1):75–176.

[Liu et al., 2020] Liu, W., Fedorov, A. V., Xie, S.-P., and Hu, S. (2020). Climate impacts of a weakened atlantic meridional overturning circulation in a warming climate. *Science advances*, 6(26):eaaz4876.

[Lozier et al., 2019] Lozier, M. S., Li, F., Bacon, S., Bahr, F., Bower, A. S., Cunningham, S., de Jong, M. F., de Steur, L., deYoung, B., Fischer, J., et al. (2019). A sea change in our view of overturning in the subpolar north atlantic. *Science*, 363(6426):516–521.

[Newsom et al., 2021] Newsom, E. R., Thompson, A. F., Adkins, J. F., and Galbraith, E. D. (2021). A hemispheric asymmetry in poleward ocean heat transport across climates: Implications for overturning and polar warming. *Earth and Planetary Science Letters*, 568:117033.

[Paris et al., 2013] Paris, C. B., Helgers, J., Van Sebille, E., and Srinivasan, A. (2013). Connectivity modeling system: A probabilistic modeling tool for the multi-scale tracking of biotic and abiotic variability in the ocean. *Environmental Modelling & Software*, 42:47–54.

[Petit et al., 2020] Petit, T., Lozier, M. S., Josey, S. A., and Cunningham, S. A. (2020). Atlantic deep water formation occurs primarily in the iceland basin and irminger sea by local buoyancy forcing. *Geophysical Research Letters*, 47(22):e2020GL091028.

[Pickart et al., 2002] Pickart, R. S., Torres, D. J., and Clarke, R. A. (2002). Hydrography of the labrador sea during active convection. *Journal of Physical Oceanography*, 32(2):428–457.

[Pietrzak, 2021] Pietrzak, P. J. (2021). *An Introduction to Coastal and Basin-Scale Physical Oceanography for Civil and Offshore Engineers*. Delft University of Technology, 7th ed. edition.

[Praetorius, 2018] Praetorius, S. K. (2018). North atlantic circulation slows down.

[Rahmstorf et al., 2015] Rahmstorf, S., Box, J. E., Feulner, G., Mann, M. E., Robinson, A., Rutherford, S., and Schaffernicht, E. J. (2015). Exceptional twentieth-century slowdown in atlantic ocean overturning circulation. *Nature climate change*, 5(5):475–480.

[Reeks, 1977] Reeks, M. (1977). On the dispersion of small particles suspended in an isotropic turbulent fluid. *Journal of fluid mechanics*, 83(3):529–546.

[Rühs et al., 2013] Rühs, S., Durgadoo, J. V., Behrens, E., and Biastoch, A. (2013). Advective timescales and pathways of agulhas leakage. *Geophysical Research Letters*, 40(15):3997–4000.

[Sayol et al., 2019] Sayol, J.-M., Dijkstra, H., and Katsman, C. (2019). Seasonal and regional variations of sinking in the subpolar north atlantic from a high-resolution ocean model. *Ocean Science*, 15(4):1033–1053.

[Schott et al., 2004] Schott, F. A., Zantopp, R., Stramma, L., Dengler, M., Fischer, J., and Wibaux, M. (2004). Circulation and deep-water export at the western exit of the subpolar north atlantic. *Journal of Physical Oceanography*, 34(4):817–843.

[Spall, 2003] Spall, M. A. (2003). On the thermohaline circulation in flat bottom marginal seas. *Journal of Marine Research*, 61(1):1–25.

[Spall, 2004] Spall, M. A. (2004). Boundary currents and watermass transformation in marginal seas. *Journal of physical oceanography*, 34(5):1197–1213.

[Srokosz and Bryden, 2015] Srokosz, M. and Bryden, H. (2015). Observing the atlantic meridional overturning circulation yields a decade of inevitable surprises. *Science*, 348(6241):1255575.

[Stramma et al., 2004] Stramma, L., Kieke, D., Rhein, M., Schott, F., Yashayaev, I., and Koltermann, K. P. (2004). Deep water changes at the western boundary of the subpolar north atlantic during 1996 to 2001. *Deep Sea Research Part I: Oceanographic Research Papers*, 51(8):1033–1056.

[Strand et al., 2020] Strand, E., Bagøien, E., Edwards, M., Broms, C., and Klevjer, T. (2020). Spatial distributions and seasonality of four calanus species in the northeast atlantic. *Progress in Oceanography*, 185:102344.

[Tamsitt, 2018] Tamsitt, V. (2018). *Aspects of the Three-Dimensionality of the Southern Ocean Overturning Circulation*. University of California, San Diego.

[Tesdal and Haine, 2020] Tesdal, J.-E. and Haine, T. W. (2020). Dominant terms in the freshwater and heat budgets of the subpolar north atlantic ocean and nordic seas from 1992 to 2015. *Journal of Geophysical Research: Oceans*, 125(10):e2020JC016435.

[Våge et al., 2011] Våge, K., Pickart, R. S., Sarafanov, A., Knutsen, Ø., Mercier, H., Lherminier, P., van Aken, H. M., Meincke, J., Quadfasel, D., and Bacon, S. (2011). The irminger gyre: Circulation, convection, and interannual variability. *Deep Sea Research Part I: Oceanographic Research Papers*, 58(5):590–614.

[Van Sebille et al., 2018] Van Sebille, E., Griffies, S. M., Abernathey, R., Adams, T. P., Berloff, P., Biastoch, A., Blanke, B., Chassignet, E. P., Cheng, Y., Cotter, C. J., et al. (2018). Lagrangian ocean analysis: Fundamentals and practices. *Ocean Modelling*, 121:49–75.

[Waldman et al., 2018] Waldman, R., Brüggemann, N., Bosse, A., Spall, M., Somot, S., and Sevault, F. (2018). Overturning the mediterranean thermohaline circulation. *Geophysical Research Letters*, 45(16):8407–8415.

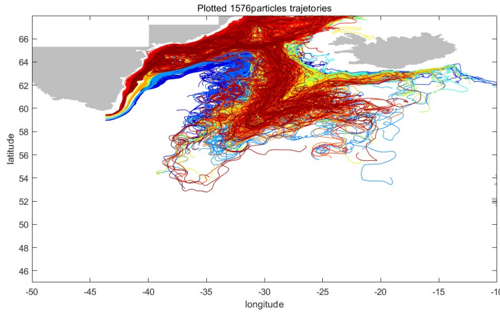
[Yamamoto et al., 2018] Yamamoto, A., Abe-Ouchi, A., and Yamanaka, Y. (2018). Long-term response of oceanic carbon uptake to global warming via physical and biological pumps. *Biogeosciences*, 15(13):4163–4180.

[Ypma et al., 2019] Ypma, S., Brüggemann, N., Georgiou, S., Spence, P., Dijkstra, H., Pietrzak, J., and Katsman, C. (2019). Pathways and watermass transformation of atlantic water entering the nordic seas through denmark strait in two high resolution ocean models. *Deep Sea Research Part I: Oceanographic Research Papers*, 145:59–72.

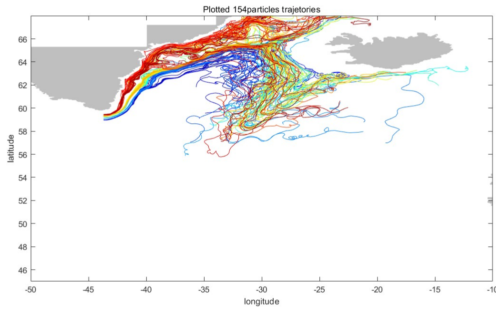
A

Appendix A

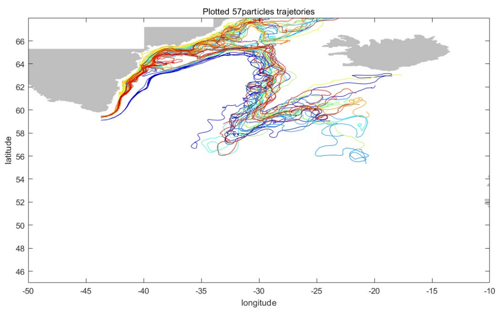
The test results of Lagrangian particle tracking are listed in Appendix A. This section is the result of depth layer tests, of 500m, 1000m, 1500m, and 2000m, also with different intervals. Keep other release information the same, at the date of 10/10/0118, tracking for one year.



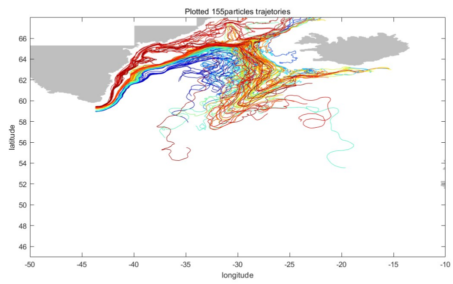
(a) Trajectory of particles released in with depth y=1000m, dz = 1m



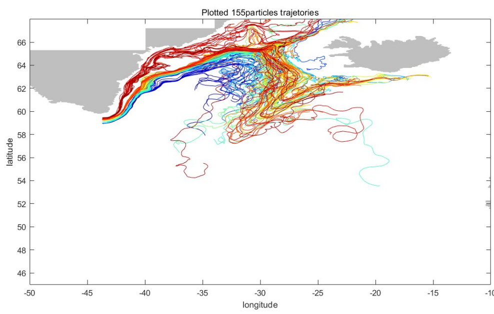
(b) Trajectory of particles released in with depth y=1000m, dz = 10m



(c) Trajectory of particles released in with depth y=500m, dz = 10m



(d) Trajectory of particles released in with depth y=2000m, dz = 10m



(e) Trajectory of particles released in with depth y=1500m, dz = 10m

Appendix B

This section is the results of testing releasing particles in different months, from January to December. But keep other release information and tracking data the same.

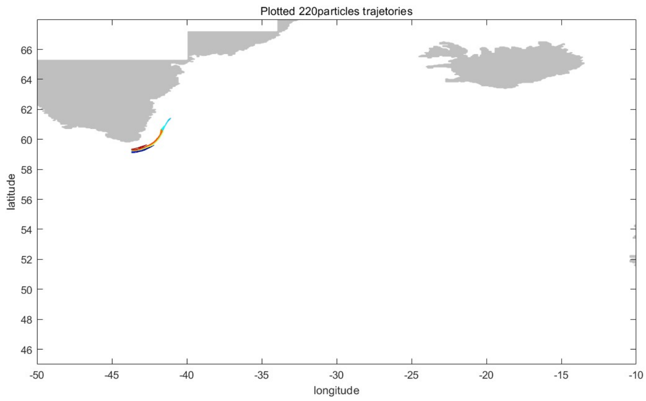


Figure B.1: Release particles in January

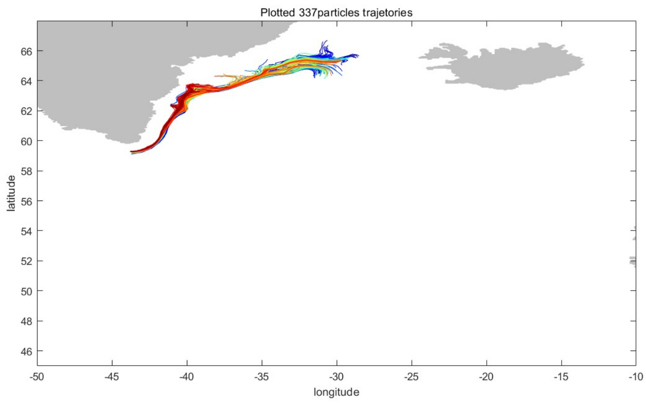


Figure B.2: Release particles in February.

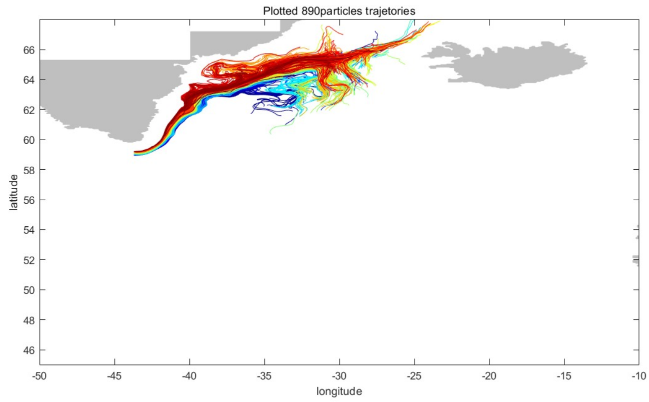


Figure B.3: Release particles in March.

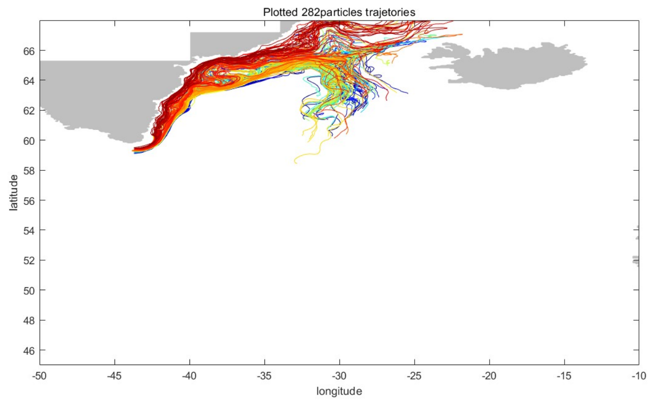


Figure B.4: Release particles in April.

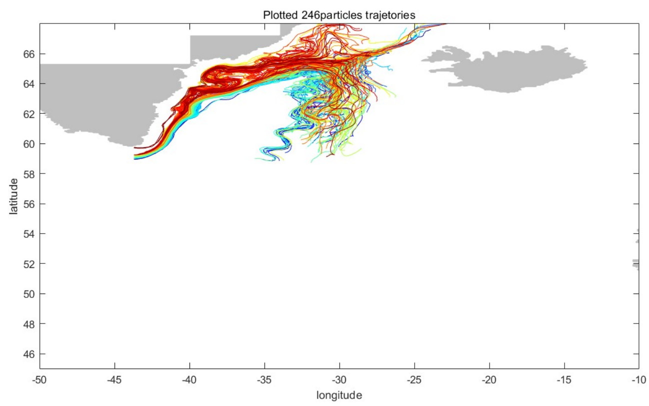


Figure B.5: Release particles in May.

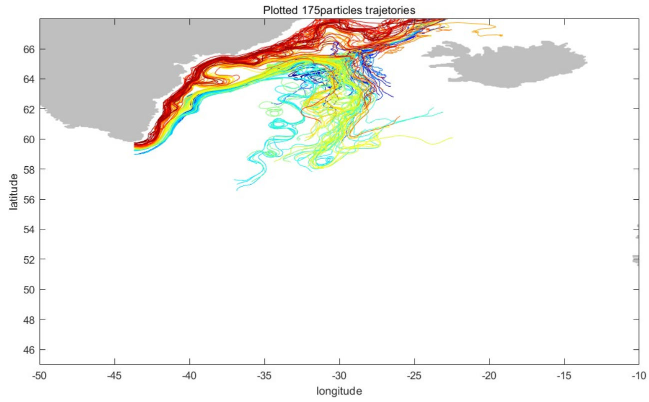


Figure B.6: Release particles in June.

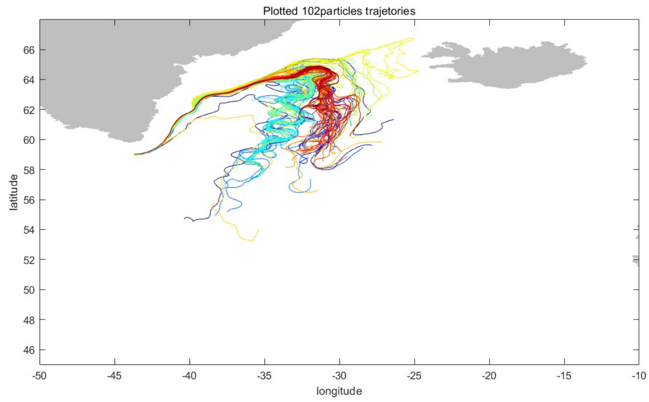


Figure B.7: Release particles in July.

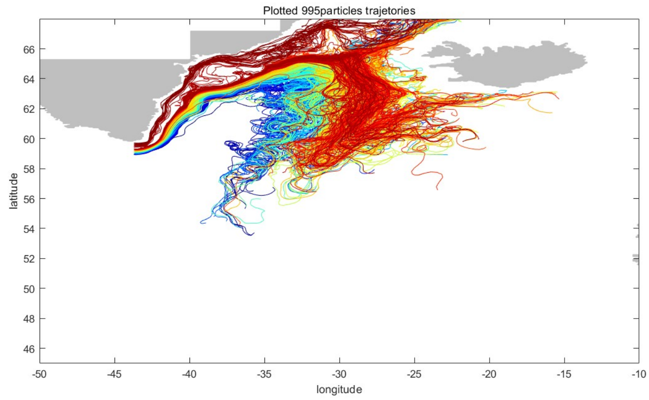


Figure B.8: Release particles in August.

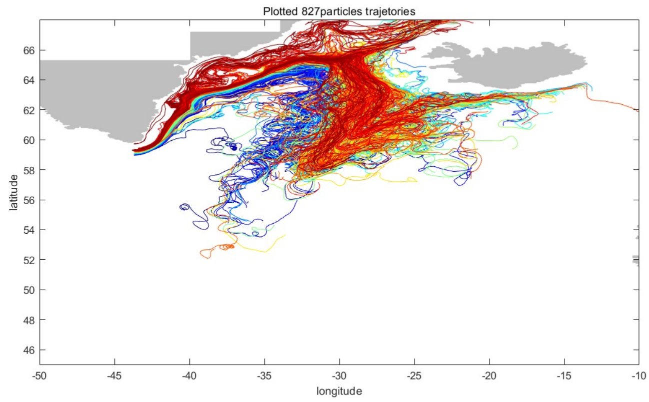


Figure B.9: Release particles in September.

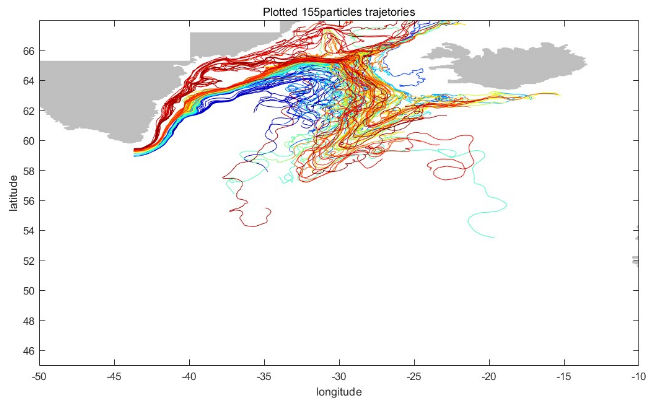


Figure B.10: Release particles in October.

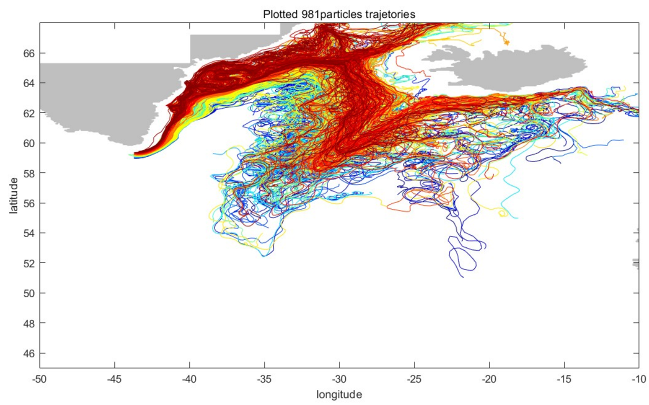


Figure B.11: Release particles in November.

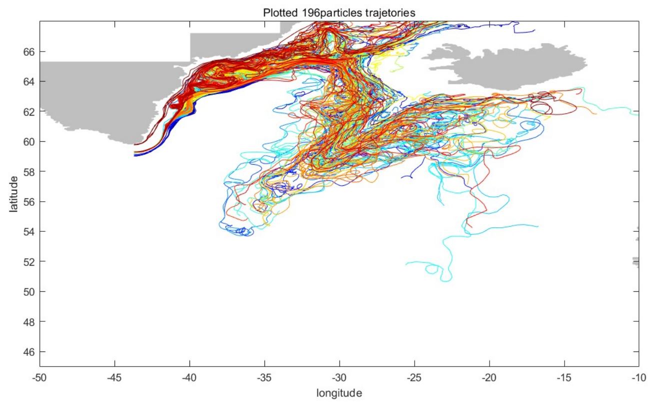


Figure B.12: Release particles in December.