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North Atlantic Ocean Circulation and Related Exchange of Heat and Salt Between Water Masses

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Key Points:

- In the interface between the North Atlantic Subpolar and Subtropical Gyres, waters exchange heat and salt with each other down to 1,000 m
- About 75% of the loss in salinity of the northwards flowing water, between 30° and 60°N, is gained by the subpolar water
- The overturning in the North Atlantic Ocean is separated into four pathways, each of which is important for the total Overturning Circulation

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Abstract The meridional transport of mass, heat, and salt in the North Atlantic Ocean is often described for separate regions and parts, but rarely are all components of the circulation followed at once. Lagrangian trajectories have here been used to divide the North Atlantic Ocean circulation into four different pathways. In the boundary between the Subpolar and Subtropical Gyres, we show that the northward flowing waters exchange heat and salt with the water originating from the subpolar regions. This subsurface water mass exchange takes place in the first 1,000 m and is a key piece of the puzzle of how the Atlantic Meridional Overturning Circulation transports heat and salt. Between 30° and 60°N the northward flowing water loses 8.8 Gg/s salt to the Subpolar Gyre and an equivalent loss of only 1.7 Gg/s to the atmosphere due to the net fresh water influx.

Plain Language Summary The ocean circulation in the North Atlantic is important for Earth's climate and more directly for the climate we experience in Europe. As water moves through the Atlantic, it brings heat, salt, and other nutrients with it. Waters with different amounts of heat, salt, and nutrients can mix with each other, and thus exchange these properties. In this study, we look at the movement of water in the North Atlantic Ocean by using Lagrangian trajectories, which are the pathways of individual parcels of water. The combined effect of many parcels of water has been investigated by separating the trajectories into four different pathways in the North Atlantic Ocean, and that water in these pathways exchange heat and salt with each other. In the northernmost parts of the Atlantic Ocean, we show that water originating from the south meets water from the north and exchange heat and salt through mixing. This also visualizes how the Subpolar Gyre gains some of the heat and salt that the Subtropical Gyre loses.

1. Introduction

The circulation in the Atlantic Ocean is a key component of the Earth's climate system (Bindoff et al., 2019; Bower et al., 2019; Weijer et al., 2020). The Atlantic Meridional Overturning Circulation (AMOC) transports surface water to the northernmost parts of the Atlantic Ocean. On its way, the water looses heat and freshens, which results in a net increase in density. These changes are due to a combination of air-sea interactions, such as heat fluxes through the surface or evaporation and precipitation, and through internal mixing (Berglund et al., 2017; Bower et al., 2019; Lozier, 2012). When the water reaches the northern parts of the Atlantic Ocean it is sufficiently dense to sink and return southwards. This watermass transformation from light to dense waters is gradual on its northward path and to a large extent subsurface within the North Atlantic Current and in the Subpolar Gyre in a depth range of 800–1,500 m (Chafik & Rossby, 2019; Evans et al., 2022; Zhang & Thomas, 2021). In the present study, we will investigate to what extent this subsurface transformation is due to mixing with other water masses and thus not only due to the heat and freshwater fluxes through the sea surface. The northward heat transport, associated with the AMOC, is considered to be one of the reasons for the relatively mild climate of Europe (Bindoff et al., 2019; Bower et al., 2019; Caesar et al., 2018; Lozier, 2012; Weijer et al., 2020). Surface winds largely control the heat transport in the Atlantic Ocean, and changing wind patterns can have a large impact on the heat transport (Ferrari & Ferreira, 2011). The heat transport into the Nordic Seas has increased since 2001 (Tsubouchi et al., 2021), whereas the volume transport of the AMOC at low latitudes has decreased (Bindoff et al., 2019; Chafik & Holliday, 2022; Weijer et al., 2020), demonstrating the complexity of the AMOC and its associated heat and mass transports.

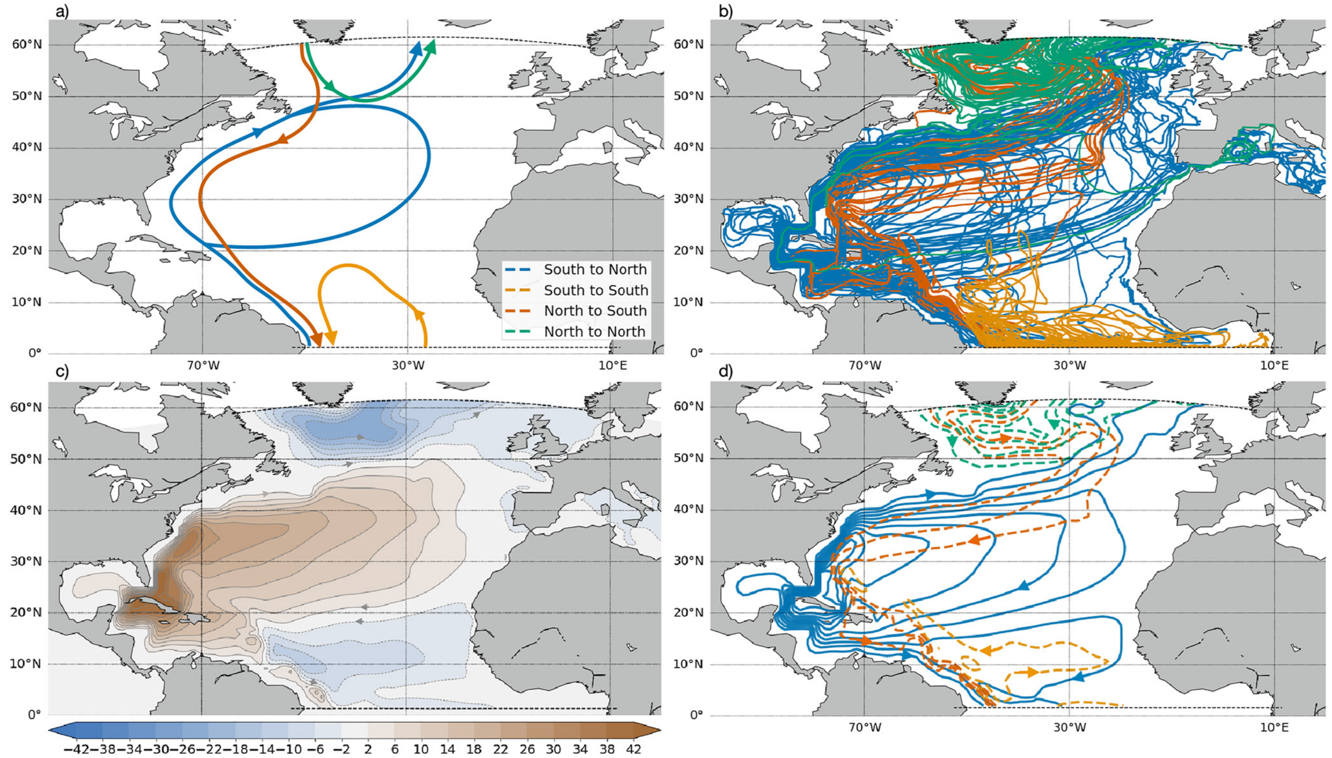

Figure 1. (a) A schematic representation of the simulated trajectories in the study area in the Atlantic Ocean. Black dotted lines denote start and end positions of trajectories in TRACMASS. In total there are four pathways that trajectories can take, either from the equator to the subpolar Atlantic (blue arrow), from the equator and back to the equator (yellow arrow), from the subpolar regions to the equator (orange arrow) or from the subpolar regions returning to the subpolar regions (green arrow). (b) A portion of the trajectories that are simulated for each pathway, colored in the same manner as in panel (a). (c) The Eulerian barotropic stream function computed for the entire period between 1850 and 2014. The contour interval is 4 Sv (1 Sv = 10^6 m^3 s^{-1}. Solid contours are clockwise while dashed contours are anti-clockwise. (d) The Lagrangian barotropic stream function for each of the four pathways in the North Atlantic Ocean, colored in the same way as (a, b). The contour interval is 4 Sv, starting from 2 Sv for solid contours and −1 for dashed contours.

AMOC circulation pathways can be studied with Lagrangian methods using observations (from floats), and also from numerical simulations of Lagrangian parcels (Bower et al., 2019; Fox et al., 2022; Fröhle et al., 2022). Using Lagrangian methods has allowed the assessment of AMOC pathways and their connections between hemispheres and gyres, and also the study of the temperature and salinity fluxes of the northward flowing component of AMOC (Berglund et al., 2017), the connection between the North Atlantic Subtropical and Subpolar Gyres (Berglund et al., 2022; Brambilla & Talley, 2006; Burkholder & Lozier, 2011, 2014), the connection between South Atlantic entrance from the Drake Passage and The Agulhas current system (Friocourt et al., 2005; Rühs et al., 2013, 2019), mixed layer subduction (Thomas et al., 2015), and the inflow to the Nordic Seas (Asbjørnsen et al., 2021).

The North Atlantic Subtropical and Subpolar Gyres, seem to be connected at mid-depths, rather than at the surface (Brambilla & Talley, 2006; Burkholder & Lozier, 2011, 2014), therewith potentially allowing for mixing between Subtropical and Arctic waters. Using Lagrangian trajectories, Berglund et al. (2017) traced the northward flowing component of the AMOC and specified where and how that water cooled and freshened. They found a connection at middepth and mid-latitude, between water coming from southward flowing water from the very North Atlantic and the water flowing northward from the Subtropical Gyre. Also found was that this made the southward flowing water saltier and warmer. The study by Asbjørnsen et al. (2021) further strengthens the idea of mixing between Arctic waters and subtropical water in the inflow to the Nordic Seas.

In this study we combine both Lagrangian and water-mass frameworks to quantify existing and new pathways and their related heat, salt, and mass transports. The North Atlantic Ocean circulation is divided into four different pathways (Figure 1a) using Lagrangian trajectories that are computed with mass fluxes from the Earth System Model EC-Earth3. The results demonstrate the connection between different AMOC pathways and their exchange of heat and salt with each other in the first 1,000 m. We confirm well-known circulation pathways, but also identify less known pathways, showing that the circulation in the Subpolar Gyre and subsurface mixing processes play important roles in water mass transformation.

2. Method

2.1. Data

In the present study the EC-Earth-Veg version 3.3.1.1 was integrated following the CMIP6 guidelines (Döscher et al., 2021; Eyring et al., 2016). EC-Earth-Veg 3.3.1.1 uses the Integrated Forecast System CY36R4 of the European Centre for Medium Range Weather Forecasts (ECMWF) including the land surface module HTESSEL. The terrestrial biosphere component of EC-Earth-Veg is the dynamical vegetation model LPJ-GUESS. The ocean component is the Nucleus for European Modeling of the Ocean (NEMO) that includes the Ocean model OPA and the sea-ice module Louvain-la-Neuve Ice Model version 3.6 (LIM3) (Döscher et al., 2021). The resolution used for NEMO is the ORCA1 grid with a 1° resolution and 75 depth levels, which is similar to most CMIP6 models, but with a higher vertical resolution (Döscher et al., 2021; Griffies et al., 2016; Tsujino et al., 2020).

The model is thus non-eddy-resolving, impacting especially the Gulf Stream that usually separates from the coast too far north and can have too high speeds (Chassignet & Marshall, 2008; Marzocchi et al., 2015). Eddy-permitting models on the other hand tend to overestimate the deep water formation in the Labrador Sea more than coarser models, which in turn affects the Subpolar Gyre and the AMOC (Hirschi et al., 2020; Koenigk et al., 2021). It is, however, not expected that the low horizontal resolution of the ocean model will materially affect the net circulation and mixing deduced in the present study, since a comparable Lagrangian analysis found that such broad ocean features were not much different in coarse-resolution and high-resolution ocean models (Berglund et al., 2022).

The grid is tri-polar, leading to a slightly higher resolution around the equator (Madec & Team, N.D.). At the atmosphere-ocean interface, the atmosphere sends fluxes to the ocean while the ocean provides state variables to the coupler, OASIS3-MCT. We have performed an historical run from 1850 to 2014, where data fields that are saved follows the CMIP6 protocol (with added variables for temperature and salt budgets) following Griffies et al. (2016), Eyring et al. (2016), Griffies et al. (2016), and Madec and Team (N.D.). This historical run was a continuation from on a pre-industrial 1,600-year long spin-up (Döscher et al., 2021).

2.2. Lagrangian Model

The TRACMASS code version seven is used in the present study to compute Lagrangian trajectories (Aldama-Campino et al., 2020; Döös et al., 2017). The TRACMASS scheme is mass (volume) conserving since it is based on mass fluxes between the grid cells and not velocities and that the continuity equation is used to compute the vertical mass fluxes in the same way as in the NEMO configuration. One important consequence of this is that a trajectory keeps the same mass transport throughout the entire simulation. This makes it possible to compute mass transports between different sections and thus Lagrangian stream functions (Döös et al., 2017). The Lagrangian trajectories follow the water in the same way as the momentum equations. This means that a parcel following a trajectory adopts the salinity and temperature of its surroundings, at every subsequent step. These changes, which are due to mixing or air-sea interaction, are therefore tracked and we thus observe how the temperature and salinity are changed along the trajectories. This makes it possible to compute separate Lagrangian stream functions for each path and estimate how the waters are mixed. Note here that the temperature and salinity changes along a trajectory are those that the ocean model NEMO is computing, which means that although we are only using monthly means, the mixing is still simulated at each model time step of the ocean circulation model. These Lagrangian trajectories of water parcels are passively advected with the flow in the same way as stream functions are computed from these flows. The parcels will hence change their salinities and temperatures as they flow across the isotherms and isohalines, which are due to mixing or air-sea interaction. They are not advected by the diffusive fluxes like tracers. This is a fundamental difference between tracers and Lagrangian trajectories.

This mixing along the trajectories in the North Atlantic was studied in a similar study by Berglund et al. (2022) with both the present 1° resolution and a 1/4° resolution simulation. It is, however, not expected that the low horizontal resolution of the ocean model will materially affect the net circulation and mixing deduced in the present paper, since a comparable Lagrangian analysis found that such broad ocean features were not much different in coarse-resolution and high-resolution ocean models (Berglund et al., 2022). The TRACMASS code is integrated with mass-fluxes from the EC-Earth-Veg3 run from the period 1850 to 2014. Simultaneously, the temperature and salinity fields of EC-Earth-Veg3 are interpolated along the trajectories both in time and space. This also makes it possible to compute the density (σ_0) along the trajectory using the TEOS-10 scheme (as is used in NEMO).

2.3. Lagrangian Simulation

In the present study trajectories were started at two different cross-sections in the Atlantic Ocean. The first was located at 1°N, since it is located almost at the equator, it will be referred to as the equator. The second was placed along a section in the northern parts of the North Atlantic, by the southern tip of Greenland, with varying latitude. The location of the northern section was chosen to be in the middle of the Subpolar Gyre in order to capture both the water arriving from the Arctic as well as heading toward the Arctic. Since the NEMO grid is tri-polar, a model index will have changing latitudes (see Figure 1 for the exact position of the northern boundary). At the equator, trajectories started through all depths and longitudes where the Eulerian mass flux (i.e., velocity) was directed northwards. At the northern boundary, trajectories started through all depths and longitudes if the mass flux was directed southwards. All simulated trajectories, from both boundaries, ended if they reached either the equator or the northern boundary, resulting in four different pathways in the Atlantic Ocean (Figure 1). The volume transports for all pathways are shown in Figure 1a. Trajectories were started during the year 1850, with new trajectories initiated each month. The trajectories were then simulated for 2,000 years, during which 99.9% of the trajectories reached a boundary. The fields are monthly means from the period 1850 to 2014. The length of the run means that the data used have to be looped, so that after December 2014 the data starts over from 1850. This can give rise to changes in temperature, salinity and thus density that are artificial. However, only 5.3% of the trajectories needed this looping; the remaining 94.7% exited through a boundary withing the 1850–2014 period. Looping data when simulating trajectories has been discussed in previous studies and do not generate large errors (e.g., Berglund et al., 2017, 2021; Thomas et al., 2015; Van Sebille et al., 2018). Trajectories that exited through the sea surface during the simulation were treated separately and gave rise to a total of 0.9 Sv for all water in the Atlantic Ocean. These are excluded in the results discussed below. The volume transport at the start is set by the meridional velocity and area of the grid box. In the present study, the volume transport of a trajectory was limited to 1,500 $m^3 s^{-1}$. This means that if the volume transport in a grid box was greater than 1,500 $m^3 s^{-1}$, more trajectories were started. Thus, more trajectories were hence started in grid boxes with a high volume transports. There were a total of 582,532 trajectories started at the equator, and 365,599 started at the northern boundary.

3. Pathways in the Atlantic Ocean

We have divided the Atlantic circulation in four pathways: (a) north to south, (b) south to north, (c) south to south, and (d) north to north (Figure 1). Here we will describe the horizontal and the overturning circulations as well as the heat and salt transports of the four different circulation pathways in the Atlantic Ocean (Figure 1a). We use Eulerian and Lagrangian stream functions (Figures 1c, 1d, and 3) and the flow distributions at the section boundaries (Figure 2).

3.1. Horizontal Circulation

The water starting south and finishing north are a well-known part of the AMOC (blue contours, Figure 1), and is similar to the flow tracked in Berglund et al. (2017). The general circulation patterns are similar, except for a larger recirculation into the Caribbean Sea in the present study. This is probably because the increased vertical resolution of the model allows for more water to enter through the Caribbean islands by better resolving the depth. The northward flowing water leaves the Gulf Stream and continues northwards with the North Atlantic Current, and mostly ends in the Iceland basin, presumably entering the Nordic Seas. Only a small fraction of the flow enters the Rockall Trough near Great Britain and as Irminger current, west of Iceland (Figure 1).

The water starting north and finishing south, represents the North Atlantic Deep Water (NADW) flow (red contours, Figures 1 and 2) that starts on the eastern flank of Greenland in the East Greenland Current. As the water leaves the East Greenland Current, it continues with the Subpolar Gyre until it separates from the flow and

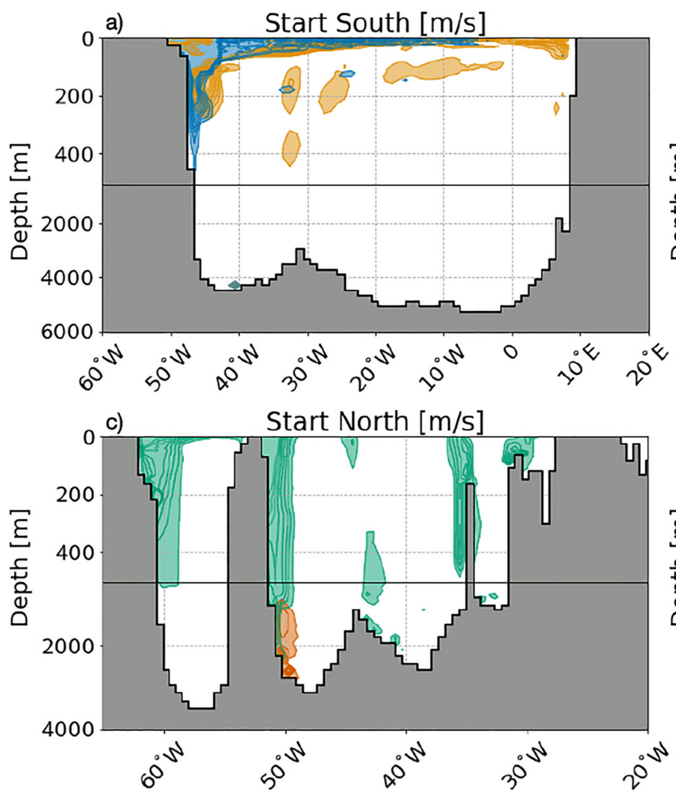

Figure 2. (a, b) Show the distribution of waters at the southern section (1°N) entering and leaving, respectively. (c, d) Show the distribution of water movements at the northern section entering and leaving, respectively. All contours are in m s^{-1}. The upper 500 m are zoomed in to finer resolve the surface flow. Colors represent the four possible pathways in Figure 1, thus blue contours show the flow going from south to north, yellow contours show the flow going from south back south, green contours show the subpolar North Atlantic Ocean waters going from north back north, and the orange contours show the deep water going from north to south. Note that these four colors have no shading. Their amplitudes are only expressed by the isolines, with intervals of 0.01 ms^{-1}, starting at 0.01 m s^{-1}.

turns southwards on both sides of the mid Atlantic Ridge (red contours in Figure 1). At depth, the flow broadens, while moving in south-west direction. At the American coast, the flow deepens, narrows and flows along the bathymetry, while moving toward the equator (Figure 2d). This flow is clearly separated from the Brazilian current above it, flowing in the opposite direction.

The water starting north and finishing north (green contours, Figure 1) has only been observed in a few studies and often excluded in general schematics of the AMOC. It mostly initiates in the upper 500 m as a southward flow in the Labrador Current or the Irminger Current, except for a small fraction that starts further to the east (Figure 2c). Water coming from the Labrador Current flows southwards to the Grand Banks near Newfoundland, where it turns eastwards and joins the North Atlantic Current. A small fraction even circuits the Subtropical Gyre before turning back northwards with the North Atlantic Current (Figure 1). Yet, the common feature of these pathways is that they end in the Irminger Sea and Iceland basin (Figures 1d and 2). This circulation pattern is in agreement with previous studies on the inflow to the Nordic Seas (Asbjørnsen et al., 2021; Chafik & Rossby, 2019). There is also a large fraction of the subpolar waters that start in the Irminger Current (green contours, Figure 1b), flow within the Subpolar gyre, and end directly on the western side of Greenland (Figure 2d). Overall, this north-north circulation is a significant component of the circulation in the North Atlantic Ocean.

The water starting south and finishing south (orange contours, Figure 1) mostly returns within 30°N. The return flow is shallow (upper few hundred meters, Figure 3b) and spreads out over the width of the basin, but with the largest fraction in the western boundary, well above the NADW return flow.

3.2. Meridional Overturning Circulation

The meridional overturning circulation in the North Atlantic Ocean is described in Figure 3 from depth, density (σ_0), temperature, and salinity perspectives. The water traveling from south to north describes the northward,

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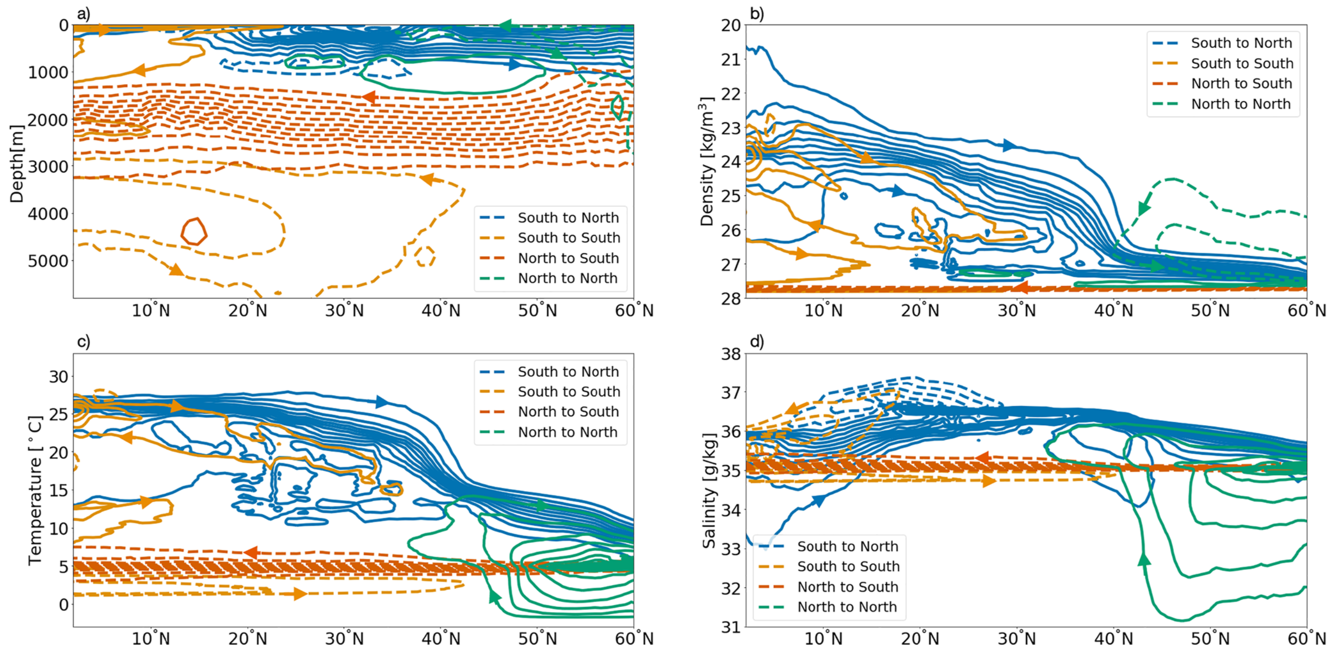

Figure 3. The Lagrangian meridional overturning stream function as a function of (a) depth, (b) density, (c) temperature, and (d) salinity. The contours are color-coded as in the previous figures, with blue contours for the south to north flow, green contours for the north to south, red for the north to north and orange for the south to south flow. The direction of the flow in each figure is indicated by arrows. Dashed contours indicate an anti-clockwise circulation while solid contours show a clockwise circulation. The contour intervals are 1 Sv and starts at 0.5 for solid contours and −0.5 for dashed contours.

upper flow, of the AMOC. During its transition through the North Atlantic Ocean it decreases in temperature, which results in an increase in density (Figures 3b and 3c). Between the equator and 30°N salinity increases, and a recirculation cell is present where water gets more saline as it turns back southwards (Figure 3d). Berglund et al. (2022) suggested, in a similar study to the present, that this salinification was due to a spiraling effect withing the Subtropical Gyre and every time a particle passed through the eastern part of the gyre it got more saline due to evaporation and mixing with the more saline waters. At 30°N, the water has reached its maximum salinity, which is in line with where the most saline waters of the Atlantic Ocean are found (Curry et al., 2003). North of this, the water freshens and leaves the northern boundary with a similar salinity distribution as it had at the start (Figure 3).

Water that enters through the most northern parts of the North Atlantic Ocean and returns northwards is cold and fresh at the start (Figures 2c and 2d) but gets warm and saline as it returns. The increase in temperature and salinity occurs between 40° and 50°N, in the same region where the northward flowing water cool and freshens (Figure 3). In fact, the water masses exchange these properties with each other. Further north, where the water masses leave the basin they have similar temperature and salinity distributions.

The change in density of the water originating from the north is dominated by the increase in salinity rather than the temperature increase; a temperature increase would decrease the density, whereas in this case the density increases (red contours Figure 3). A similar pattern is seen if the stream function is computed with $\sigma_{0.5}$ or σ_1 (i.e., the density referenced to a depth of 500 or 1,000 dbar). The climatic consequences of these temperature and salinity distributions, such as the melting of glaciers in the north, is as yet unclear. However, since the water masses rely on their exchange of properties with each other, a change in the water-mass temperature and salinity distributions may change the circulation patterns and the associated heat and salt transports.

At depth, the Antarctic Bottom Water (AABW, deep orange circulation in Figure 3a) upwells to depths where the NADW (red in Figure 3a) is found. As the AABW becomes somewhat warmer and more saline, the opposite partly holds true for the NADW, which instead cools and freshens. The upper part of the NADW is, on the other hand, getting slightly warmer and more saline (Figures 3c and 3d), probably as it exchanges heat and salt with the waters above that originate from the south. However, the density stream functions in Figure 3 are computed using σ_0, which may be unrealistic for the AABW and NADW since they are located at deeper depths. There is also a

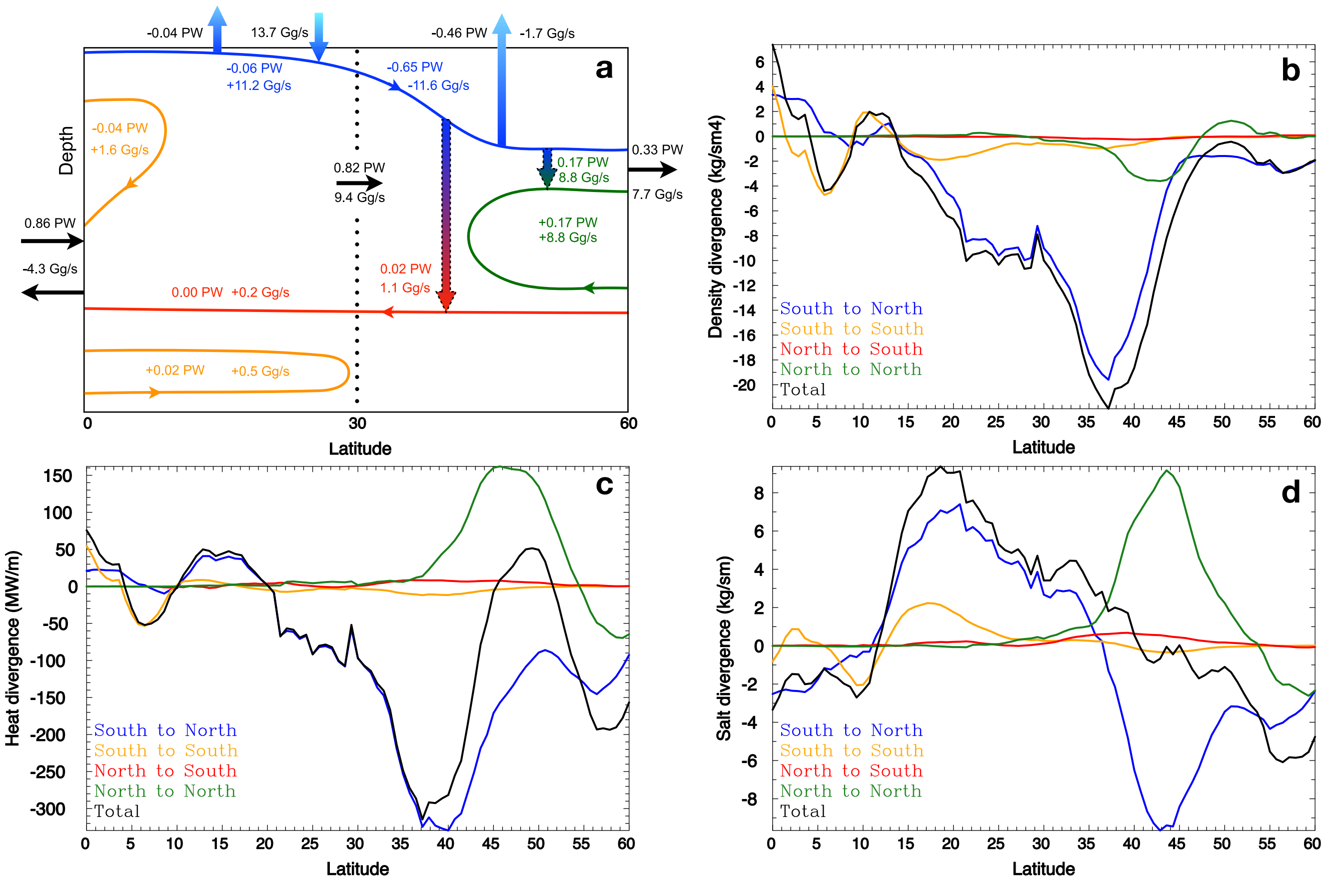

Figure 4. Panel (a) shows a schematic illustration of the heat and salt transports. Black arrows denote the total meridional transports at 1°, 30°, and 60°N. The light blue arrows are the transports through the sea surface either integrated between 1° and 30°N or between 30° and 60°N. The dashed arrows are transports between the paths due to mixing integrated over the entire domain. Each path will be subject a heat and salt changes as they travel through the basin and are denoted with respective color. Panel (b–d) are the meridional divergences of the density, heat, and salt for each of the four paths. The sum of the paths is the total (in black) and hence the divergence due to fluxes through the sea surface.

shallow south-to-south cell that flows northward as far as 30°N before returning toward the south, shown by the orange solid streamlines in Figure 3a. On its northward journey it tends to follow to the north-to-north path with decreasing temperature and increasing salinity as well as density. On its southward journey back to the Equator the water will again warm up and decrease its salinity but not as much as when it left the Equator. This results in an increase of its density due to net heat loss and salt gain of this cell. The combination of Figures 1 and 3 gives a clear picture of the circulation in the North Atlantic Ocean. It provides an understanding of the circulation, not only geographically but also with respect to temperature and salinity. Some of the features that are seen in Figures 1 and 3 are not possible to see in the Eulerian view of the flow, especially in areas where streamlines cross each other.

4. Heat and Salt Exchange

The meridional heat and salt transports of the four pathways and their inter-exchange by mixing as well as their fluxes through the sea surface are shown in Figure 4. The meridional heat and salt transports (in units of W and kg s^{-1}) were computed by integrating the Lagrangian stream functions "vertically" over the temperatures and salinities, for each of the four pathways, of Figure 3 as follows

$$F^H(y) = \rho_0 c_p \int_{T_{\min}}^{T_{\max}} \frac{\partial \Psi(y,T)}{\partial T} T \, dT \quad ; \quad F^S(y) = \rho_0 \int_{S_{\min}}^{S_{\max}} \frac{\partial \Psi(y,S)}{\partial S} S \, dS, \tag{1}$$

where $T_{\min}$, $T_{\max}$, $S_{\min}$, and $S_{\max}$ are the minimum and maximum temperatures and salinities, $\rho_0 = 1{,}035$ kgm^{-3} is the average density of the seawater and the specific heat for seawater is set to $c_p = 3{,}992$ J(kg °C)$^{-1}$. These meridional transports change with latitude since the pathways will exchange heat and salt between each other trough mixing as well as heat and fresh water fluxes through the sea surface. These latitudinal dependencies were used to quantify the meridional divergences of the heat and salt transports as

$$D^H(y) = \frac{\partial F^H(y)}{\partial y} \quad ; \quad D^S(y) = \frac{\partial F^S(y)}{\partial y}, \tag{2}$$

which have the units W m^{-1} and kg s^{-1} m^{-1} and are shown in Figures 4c and 4d. This is thus heat and salt divergences zonally integrated across the Atlantic for the four paths. The flux through the sea surface is simply the sum of the four paths since heat and salt are conserved and are shown by the black curves in Figures 4c and 4d. This reveals that most of the heat and salt exchanges occur in the northern part of our domain. We have therefore made a separate heat and salt budget, shown in Figure 4a for the southern and northern parts separated through 30°N.

The northward flowing branch of the AMOC looses a large amount of heat (0.65 PW) and salt (11.6 Gg s^{-1}) between 30° and 60°N (blue curve in Figure 4). Seventy-one percent of this heat is lost to the atmosphere (0.46 PW) and a 26% (0.17 PW) is lost through mixing with waters originating from the north that turns back north. The salt loss of this path is, in contrast to its heat loss, mainly due to mixing with the north-to-north path with a transfer of 8.8 Gg s^{-1} and only an equivalent loss of 1.7 Gg s^{-1} to the atmosphere due to the net freshwater influx. This strengthens the conclusion above: the water masses are exchanging heat and salt with each other, making one warmer and more saline as the other is getting colder and fresher. It further demonstrates the complementary roles of the heat and salt for the pathways of the overturning circulation in the North Atlantic Ocean.

The salinity of the northward flowing water increases as the water moves toward the Subtropics, and reaches a maximum just south of 40°N. Thereafter it looses salt (blue curve in Figure 3d). On the other hand, the subpolar waters are found to get more saline north of 40°N (green streamlines in Figure 3d). Similarly as for heat, this show that the water masses are exchanging salt. The exchange of heat and salt between the waters takes place mainly between 40° and 50°N, which is in the region of the northern flank of the Subtropical Gyre, where the Gulf Stream leaves the coast and the flow either continues southwards in the Subtropical Gyre or northwards with the North Atlantic Current.

This exchange explains the homogeneous water distribution found further north in previous studies (Asbjørnsen et al., 2021; Brambilla et al., 2008), and also the similar hydrography of the waters in the Subtropical to Subpolar Gyres (Burkholder & Lozier, 2014). The Overturning in the Subpolar North Atlantic Program has generated estimates of the AMOC in the subpolar North Atlantic and has shown its highly temporal variability (Li et al., 2021; Lozier et al., 2019). Changes in the distribution of heat and salt in the Subpolar Gyre may lead to changes in the exchange of heat and salt both between the water masses as well as the atmosphere (Petit et al., 2020, 2021). Evans et al. (2022) found that the mixing continues to cool and freshen the Atlantic Water beyond the northern boundary used in this study. What role this mixing and air-sea exchange will have in a changing climate is therefore urgent to understand.

5. Summary and Conclusions

We have shown that waters in the North Atlantic Ocean exchange heat and salt in the northern parts of the basin, either through lateral or vertical mixing. However, part of these changes may be related to seasonal water mass transformations, which can be both due to mixing with other water masses and air-sea interaction. The exchange of heat and salt between the water masses as well as the impact of the heat and fresh water fluxes through the sea surface were studied by decomposing the circulation in the North Atlantic into four pathways using Lagrangian trajectories. As the northward flowing upper branch of AMOC circulates in the Subtropical Gyre and the Gulf Stream, before continuing northwards in the North Atlantic Current, it looses heat and salt. Some of this heat and salt is gained by the water originating from the subpolar Atlantic Ocean, and thus the water masses exchange heat and salt by water mass transformation. These two waters masses are thus merged into one and continue northward into the Arctic Ocean (north of 60°N). These results show that there is an important subsurface mixing process, leading to an exchange of heat and salt between the northwards flowing waters of the AMOC and waters originating from the Arctic Ocean. The separation of circulation pathways further demonstrates where the NADW and the AABW meet in the interior of the North Atlantic Ocean, mix and jointly flow toward the south and end as a deep boundary current at the equator. This is in line with the schematic shown by Talley (2013), where AABW transforms into the shallower NADW.

A recent study by Asbjørnsen et al. (2021) on the variable inflow to the Nordic Seas point to a similar result as that found in the present study. Arctic Water from the Davis and Hudson straits transform as it meets the Subtropical waters. However, their study focuses on the Nordic Seas, whereas in the present study we put focus on the AMOC and the exchange between each pathway of the circulation. Further, we have shown this transformation in a stream function and from the perspective of a heat and salt transports. Previous studies also point to the region of the eastern subpolar North Atlantic as an important area for water mass transformation (Brambilla et al., 2008). This thus strengthens our results, and points to the complexity of the overturning circulation in the North Atlantic Ocean.

The data used to compute the Lagrangian trajectories is from EC-Earth3, which is used in the CMIP6 project to understand the Earth's climate and its change (Döscher et al., 2021). The resolution of the ocean component implies that it is non-eddy-resolving. However, most CMIP6 Earth System Models are at this stage non-eddy resolving even though some are eddy-permitting (Chen et al., 2021). A recent study by Berglund et al. (2022) has shown that Lagrangian trajectory studies such as those discussed here yield similar conclusions whether studied using eddy-permitting or non-eddy-permitting models. To see if this conclusion holds, it would be valuable to apply this method to a high resolution eddy-resolving model. Consequently the role of eddies for both the circulation and the exchange in heat and salt can be understood in more detail, which is important as eddies are known to have a large impact on the circulation and its and its associated heat and salt transports (Chassignet & Marshall, 2008; Tréguier et al., 2014). Although the exact nature of the mixing processes remain to be examined, it will be a combination of the along-isopycnal stirring by mesoscale eddies of contrasts in temperature and salinity, acting in conjunction with small-scale turbulent diapycnal mixing (e.g., breaking internal waves) that acts on the enhanced gradients of temperature and salinity.

By dissecting the flow in the Atlantic Ocean, it is revealed that the total heat and salt transport in the North Atlantic Ocean can only be explained by a combination of different pathways. A change in these pathways, under changing climate conditions may result in a different distribution of heat and salt in the North Atlantic Ocean. The Lagrangian time mean requires, however, in contrast to the Eulerian one that the trajectories have time to go through and exit the studied domain. This causes a challenge to Lagrangian climate studies since its change is occurring on a time scale shorter than the deep ocean circulation. Hence, how changes in pathways under different climate scenario's would itself impact both circulation and climate conditions in Northern Europe remains to be investigated.

Data Availability Statement

The Lagrangian trajectory model TRACMASS v7.0 can be downloaded from https://doi.org/10.5281/zenodo.4337926 (Aldama-Campino et al., 2020). The trajectory data for the present TRACMASS simulation is available on https://doi.org/10.5281/zenodo.6346246. The CMIP6 run with EC-Earth-Veg3 is freely available and can be downloaded from https://esgf-node.llnl.gov/search/cmip6/ by specifying "EC-Earth3-Veg," "historical," "r11i1p1f1."

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