

Pathways and watermass transformation of Atlantic Water entering the Nordic Seas through Denmark Strait in two high resolution ocean models

Ypma, S. L.; Brüggemann, N.; Georgiou, S.; Spence, P.; Dijkstra, H. A.; Pietrzak, J. D.; Katsman, C. A.

DOI

[10.1016/j.dsr.2019.02.002](https://doi.org/10.1016/j.dsr.2019.02.002)

Publication date

2019

Document Version

Accepted author manuscript

Published in

Deep-Sea Research Part I: Oceanographic Research Papers

Citation (APA)

Ypma, S. L., Brüggemann, N., Georgiou, S., Spence, P., Dijkstra, H. A., Pietrzak, J. D., & Katsman, C. A. (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. <https://doi.org/10.1016/j.dsr.2019.02.002>

Important note

To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright

Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy

Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

Pathways and watermass transformation of Atlantic Water entering the Nordic Seas through Denmark Strait in two high resolution ocean models

S.L. Ypma^{a,*}, N. Brüggemann^b, S. Georgiou^a, P. Spence^c, H.A. Dijkstra^d,
 J.D. Pietrzak^a, C.A. Katsman^a

^a*Department of Hydraulic Engineering, Delft University of Technology, Civil Engineering and Geosciences, Environmental Fluid Mechanics, Delft, Netherlands.*

^b*Faculty of Mathematics, Informatics and Natural Sciences, University of Hamburg, Hamburg, Germany.*

^c*Climate Change Research Centre, University of New South Wales, Sydney, New South Wales, Australia.*

^d*Institute for Marine and Atmospheric Research Utrecht, Utrecht University, Netherlands.*

Abstract

The pathways and watermass transformation of the North Icelandic Irminger Current (NIIC) in the Nordic Seas are investigated by tracing the NIIC watermass in two ocean circulation models: the Modular Ocean Model (MOM) and the Parallel Ocean Program (POP). The two simulations use identical atmospheric forcing and have a horizontal resolution of 0.1° . However, the models differ strongly in their representation of the sea-ice cover in the Nordic Seas and, possibly as a consequence, display a different hydrography. Results from observational studies point towards a fast overturning loop north of Iceland that connects the NIIC watermass to the Denmark Strait Overflow Water (DSOW). However, our Lagrangian analysis shows that only 0.2

*Corresponding author: Stefanie Ypma, s.l.ypma@tudelft.nl, Environmental Fluid Mechanics, Stevinweg 1, 2628 CN, Delft, The Netherlands

Sv of the entering NIIC water exits as DSOW in the two models. In POP, the main transformation to dense water takes place along a short path north of Iceland. In MOM however, the contributing part of the NIIC to DSOW takes a long path through the Nordic Seas and reaches Denmark Strait as part of the East Greenland Current (EGC). A small contribution of the NIIC watermass to the Iceland Scotland Overflow Water (ISOW) is found in both MOM and POP (7.8%, respectively 2.1% of the NIIC watermass). In the model simulations studied, the part of the NIIC watermass that is not connected to the overflows takes many different pathways through the Nordic seas. Analysis of the depth distribution and the thermohaline changes of the particles indicates that the watermass transformation that takes place north of Iceland is crucial for diversifying the pathways of the NIIC water.

Keywords: North Icelandic Irminger Current, North Icelandic Jet, Denmark Strait Overflow Water, Water mass transformation, Nordic Seas, Atlantic Water pathways

1. Introduction

The transformation of Atlantic Water (AW) north of the Greenland-Scotland Ridge is one of the key mechanisms for controlling the strength of the Atlantic Meridional Overturning Circulation (AMOC) via the overflows through Denmark Strait and across the Iceland-Scotland Ridge. The warm AW flows poleward into the Nordic Seas and beyond through three main gateways (see schematic in Figure 1) (e.g. Hansen and Østerhus, 2000). Two of these, through which the majority of the AW flows north, are located east of Iceland. West of Iceland, AW is transported by the North Icelandic Irminger

10 Current (NIIC). This third branch flows north along the western Icelandic
 11 slope and has been monitored since 1985 (e.g. Jónsson and Valdimarsson,
 12 2005), though the fate of the NIIC has only recently been studied in more
 13 detail. Water mass transformation of the AW in the NIIC is thought to be
 14 linked to the densest part of the Denmark Strait Overflow Water (DSOW)
 15 (Våge et al., 2011). However, as of yet it is unclear which path the NIIC
 16 takes after entering the Nordic Seas and where watermass transformation
 17 from the NIIC to DSOW takes place. The aim of this study is to investigate
 18 the paths and watermass transformation of the NIIC in detail in two ocean
 19 models using a Lagrangian approach.

20 Previous studies suggest three possible pathways for the NIIC. The first
 21 path was described by Swift and Aagaard (1981) as well as Jónsson (1992),
 22 who observed Atlantic Water at the north Icelandic continental shelf, without
 23 any propagation into the central Iceland Sea. They found that east of Iceland
 24 the water leaves the shelf and propagates in the direction of the Norwegian
 25 Sea. Stefánsson (1962) showed that part of the NIIC watermass mixes with
 26 surface water from the Iceland Sea, forming a watermass that connects to
 27 the Iceland Scotland Overflow Water (ISOW).

28 ISOW, which has a similar magnitude as DSOW, is formed by a mixture of
 29 watermasses that, combined, are generally labelled as Modified East Icelandic
 30 Water (MEIW). The main constituents of the MEIW are the North Icelandic
 31 Winter Water, the East Icelandic Water, the Norwegian Sea Deep Water and
 32 the Norwegian North Atlantic Water, where the latter is partly formed by
 33 transformation of the NIIC watermass (e.g. Hansen and Østerhus, 2000). The
 34 main outlet of these watermasses is through the Faroe-Shetland Channel.

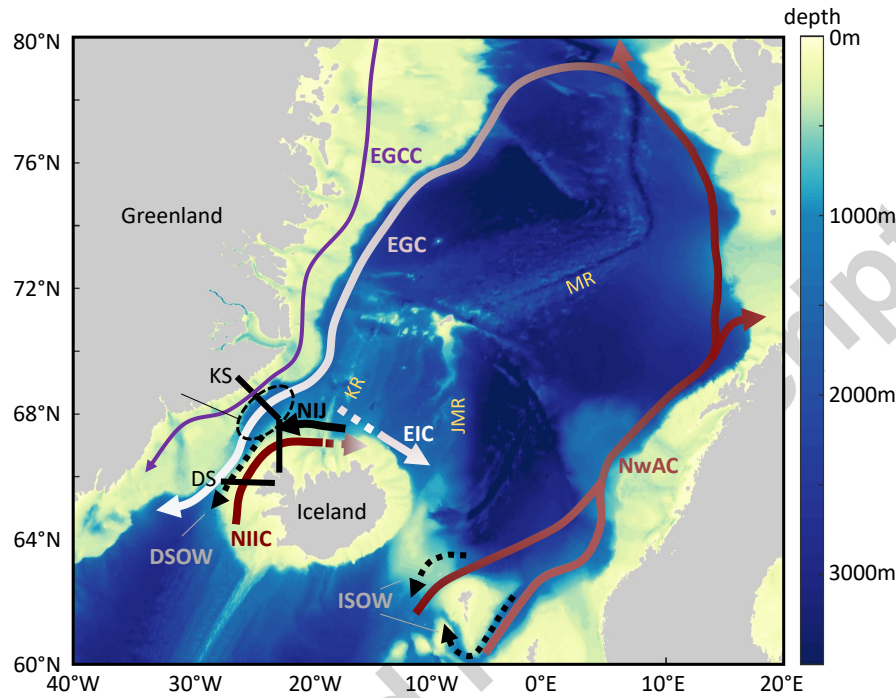


Fig. 1: Schematic of the circulation in the Nordic Seas and bathymetry. Shown in red are the warm and salty inflowing currents: the North Icelandic Irminger Current (NIIC) and the Norwegian Atlantic Current (NwAC). The East Greenland Current (EGC) and the East Icelandic Current (EIC) are shown in white and the East Greenland Coastal Current (EGCC) in purple. Dense currents are shown in black: the North Iceland Jet (NIJ), the Denmark Strait Overflow Waters (DSOW, dashed line) and the Iceland Scotland Overflow Waters (ISOW, dashed lines). The bathymetric features pertinent for this study are indicated in yellow: the Kolbeinsey Ridge (KR), the Jan Mayen Ridge (JMR) and the Mohn Ridge (MR). The release location of the particles at 66°N in Denmark Strait (DS) and the Kögur Section (KS) are shown in black. Note that the bathymetry is from ETOPO2v2, and not the model bathymetry.

35 Using surface drifters, Valdimarsson and Malmberg (1999) observed a
 36 second possible path for the NIIC, where most of their drifters seemed to be
 37 topographically steered northward by the Kolbeinsey Ridge (see Figure 1)
 38 and returned south through Denmark Strait in the East Greenland Current
 39 (EGC).

40 More recently, analyses from multiple hydrographic transects along the
 41 coast of Iceland suggested a third possible pathway. They point to a close
 42 relationship between the NIIC and the North Icelandic Jet (NIJ) (e.g. Våge
 43 et al., 2011, 2013, 2015). The NIJ transports the densest component of the
 44 Overflow Water through Denmark Strait (Våge et al., 2011). The other
 45 two currents advecting dense water from the north through the strait are
 46 the shelf break current and the separated branch of the EGC (Harden et al.,
 47 2016). The observations show several indications of a connection between the
 48 NIIC and the NIJ. First, both currents can be traced along the continental
 49 slope of Iceland until their signal disappears at the northeast corner of the
 50 island (Våge et al., 2011). Along the Icelandic shelf, the currents seem to
 51 be dynamically linked by sharing a pronounced density front (Pickart et al.,
 52 2017). Second, the volume transport of both currents is very similar. It is
 53 estimated to be 1 Sv and 0.88 Sv for the NIJ and NIIC, respectively (Jónsson
 54 and Valdimarsson, 2012; Harden et al., 2016).

55 Våge et al. (2011) showed, by using an idealized model set-up, that the
 56 mechanism that links the NIIC and the NIJ is similar to the one described
 57 by e.g. Spall (2004) and Straneo (2006). These studies suggest that buoyant
 58 water from the NIIC is transported to the interior of the Iceland Sea by eddies
 59 due to baroclinic instability of the NIIC. In these idealized models, the heat

60 flux from the boundary current to the interior balances the atmospheric cool-
 61 ing over the interior that induces convection. The dense watermass returns
 62 to the Icelandic slope where it sinks and forms the NIJ.

63 So far, follow-up studies have not been able to corroborate the connection
 64 between the NIIC and the interior of the Iceland Sea. Using measurements
 65 from eight shipboard surveys, Pickart et al. (2017) find a strong, in phase
 66 correlation in salinity between the NIJ and NIIC. In case the two currents
 67 are linked, this would imply the existence of a very fast overturning. To
 68 accomodate this short time-scale, they hypothesize that the overturning can
 69 not take place in the central Iceland gyre, but instead takes place northwest
 70 of the gyre where deep mixed layers are observed. In their discussion it
 71 remains unclear how the water of the NIIC reaches this area. Additionally,
 72 de Jong et al. (2018) do not find a connection between the interior Iceland
 73 Sea and the NIJ either. In their study, based on the analysis of deployed
 74 RAFOS floats, they highlight the importance of the East Icelandic Current
 75 (EIC, Figure 1) that potentially blocks the exchange between the Iceland
 76 Sea gyre and the Icelandic slope region. This branch might not be captured
 77 by the idealized model of Våge et al. (2011). Tracking the NIJ watermass
 78 back in time in a high resolution ocean model (Viking20) leads to a similar
 79 insight: no exchange with the interior of the Iceland Sea is seen and most
 80 of the NIJ originates from the shelfbreak EGC (Behrens et al., 2017). It is
 81 therefore still unclear what role the NIIC plays for the formation of Denmark
 82 Strait Overflow Waters.

83 Lagrangian studies as Behrens et al. (2017) can be very useful as particle
 84 tracking in global ocean models has the advantage that a large number of

particles can be used in comparison to observations, providing better statistics of variable pathways. However, different ocean models lead to different conclusions. For example, backtracking the overflow waters in the $1/20^\circ$ horizontal resolution Viking20 ocean model, Behrens et al. (2017) find that the bulk part of the Denmark Strait Overflow Water in the model (60%) has an Arctic origin. In contrast, in the $1/10^\circ$ ocean model used by Köhl (2010) the largest part of the DSOW originates from watermass transformation taking place within the Nordic Seas. Köhl (2010) argues that the pathways vary spatially depending on the magnitude of the wind stress. Thus, he concluded that the differences in ocean models regarding forcing and set-up may lead to significantly different results.

In addition to the variables mentioned by Köhl (2010), the horizontal resolution, discretization in the vertical, topography, mixing parameterizations and boundary conditions like applied atmospheric forcing and sea-ice conditions impact the mixed layer dynamics and therefore the circulation in the models (Willebrand et al., 2001; Langehaug et al., 2012; Courtois et al., 2017). A correct representation of the convection regions is crucial for the transformation processes of watermasses. However, ocean models still show large differences in mixed layer depth, both in low- and high resolution ocean models (e.g. Tréguier et al., 2005; Danabasoglu et al., 2014).

The aim of this study is to investigate to what extent the inflowing Atlantic Water through Denmark Strait contributes to the Overflow Water and whether its transformation is related to the location of convection regions within the Nordic Seas as proposed by Våge et al. (2011). A Lagrangian perspective is chosen, where the NIIC watermass entering the Nordic Seas

through Denmark Strait is tracked in two ocean models that differ substantially in their representation of deep convection: the Modular Ocean Model (MOM) and the Parallel Ocean Program (POP). The models have the same horizontal grid with a resolution of 0.1° degree and identical atmospheric forcing. However, their sea-ice representation and consequently the hydrography in the Nordic Seas is different. This paper presents the pathways of the NIIC water in these two models, a quantification of the contribution of the NIIC to the overflows and a discussion on where and how the NIIC watermass is transformed.

The paper is structured as follows. Section 2 describes the model simulations analysed and the particle tracking method. In section 3 the performance of both models in the Nordic Seas is compared to observations. This is followed by the main results of this study, where the pathways of the NIIC watermass are described in detail in section 4 and the watermass transformation along the pathways is discussed in section 5. A discussion and the conclusions are provided in section 6.

2. Methods

In this study, a Lagrangian analysis is conducted to trace the NIIC watermass. Numerical particles are advected offline using the velocity fields of the model output. The particles' location, depth, temperature and salinity are saved and used to determine the pathways and watermass transformation of the NIIC water. This method is applied to two ocean models that differ substantially in their representation of deep convection and sea ice in order to investigate the sensitivity of the results to the location of deep mixed

134 layers and heat fluxes.

135 *2.1. Global ocean model configurations*

136 The particles are advected in the Modular Ocean Model global ocean-
 137 sea ice model (MOM) and the Parallel Ocean Program ocean-only model
 138 (POP). The ocean model configurations are described in detail by Spence
 139 et al. (2017) (MOM) and Weijer et al. (2012) (POP) and form the ocean
 140 component of frequently-used climate models (MOM in GFDL-CM2.6 and
 141 POP in CESM1.0). The models have the same horizontal resolution of 0.1°
 142 and use a tripolar B-grid. This yields ~ 4.5 km resolution at 65°N . Nurser
 143 and Bacon (2014) estimated the first Rossby Radius of deformation to be
 144 ~ 7 km in the Norwegian Sea and ~ 3 km in the Iceland and Greenland Sea.
 145 Therefore, these ocean models are only partly eddy resolving in the region
 146 of interest. In the vertical, MOM (POP) has 50 (42) layers with a resolution
 147 of 5m at the surface up to 200m (250m) in the deeper layers.

148 Both models are forced by prescribed atmospheric conditions using the
 149 Coordinated Ocean-ice Reference Experiments Normal Year Forcing (COREv2-
 150 NYF) reanalysis data (Griffies et al., 2009; Large and Yeager, 2009). COREv2-
 151 NYF provides a climatological mean atmospheric state estimate at 6-hour
 152 intervals at roughly 2° horizontal resolution. The atmospheric state is con-
 153 verted to ocean surface fluxes by bulk formulae, so there are no air-sea feed-
 154 backs. The Normal Year Forcing is derived from 43 years of the interannual
 155 varying atmospheric state from 1958 to 2000. Since the same seasonal forcing
 156 is applied every year, the interannual variability is small. Using normal year
 157 forcing is advantageous for this study as the results will not depend on the
 158 release year of the numerical particles. For practical reasons, only one year

159 of velocity data representative for the mean ocean state of the models is used
160 in this study.

161 The KPP parameterization is used for the parameterization of convection
162 in both models (Large et al., 1994). Further, vertical viscosities and diffusiv-
163 ities are set by KPP and in the horizontal, biharmonic viscosity and diffusion
164 are used. In MOM, the surface salinity is restored on a 60-day timescale. In
165 POP, the surface salinity is restored during the first 75 years of the spin-up
166 period. From that moment onwards, ‘mixed boundary conditions’ are ap-
167 plied, derived from the monthly-averaged restoring flux of the final five years
168 of the spin-up.

169 The models differ in their sea-ice configurations. MOM is coupled to the
170 GFDL Sea Ice Simulator model, so the sea ice evolves freely. In POP, the sea-
171 ice edge is fixed and defined by the -1.8°C isotherm of the SST climatology
172 from COREv2-NYF. Under the diagnosed sea ice, temperature and salinity
173 are restored with a timescale of 30 days. The approaches regarding the sea-ice
174 configurations in MOM and POP lead to large differences in the maximum
175 sea-ice extent in the Nordic Seas, as shown by the black line in Figures 2b and
176 2c. In POP the maximum sea-ice extent is confined to the continental shelves
177 of Greenland, whereas in MOM the sea ice covers most of the Greenland and
178 Iceland Seas in winter months. Additionally, Figure 2 shows that the modeled
179 hydrographic fields of the two models differ as well. Section 3 will further
180 elaborate on these differences with respect to observations.

181 2.2. *Tracking the Atlantic Water north through Denmark Strait*

182 Lagrangian particles are released daily for a duration of one year in the
183 northward flowing Atlantic Water in Denmark Strait. The particles are re-

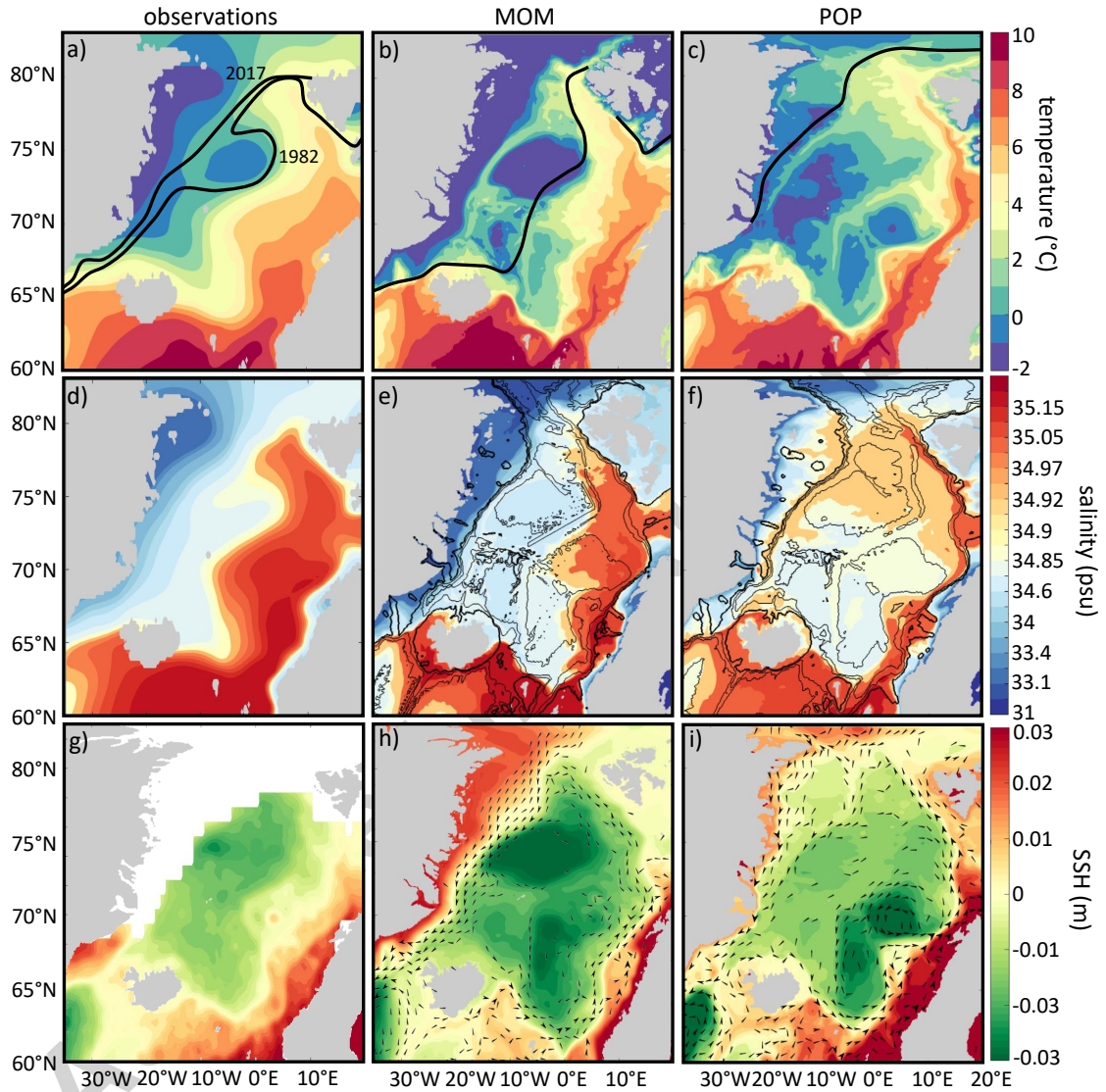


Fig. 2: Mean temperature (top) and salinity (middle) at 50m depth and sea surface height (bottom) from (a,d,g) observations, (b,e,h) MOM and (c,f,i) POP. The observational hydrographic fields show the mean from 1995 to 2010 and are obtained from the Climatological Atlas of the Nordic Seas (Korablev et al., 2014). Panel (g) shows the mean absolute dynamic topography over the same period from the AVISO satellite altimetry. The black lines in (a-c) indicate the sea-ice extent in March. In (a) the extent in 1982 and 2017 are shown from the Sea Ice Index (Fetterer et al., 2017). The contour lines in (e) and (f) show the model isobaths at 400m (thick black line), 1000m, 1500m and 3000m depth. The black arrows in (h) and (i) show the mean surface velocity field for flow stronger than 0.05 m/s.

184 leased at a zonal transect at 66°N between Iceland and 28.9°W (black line
 185 in Figure 1 in Denmark Strait) at a resolution of 0.1° longitude and 20m in
 186 the vertical. The particle is only traced when the initial meridional velocity
 187 is positive (hence flowing to the north) and when the initial temperature is
 188 higher than 5°C (hence Atlantic Water). Each particle is tagged with its
 189 corresponding volume transport that is defined as the meridional velocity
 190 multiplied by the area of the cell face in which the particle is released (Döös,
 191 1995).

192 The particles are advected forward in time with a timestep of 1 hour
 193 within the daily averages of the 3D velocity field output of the ocean model
 194 using the Connectivity Modeling System (CMS) (Paris et al., 2013). The
 195 CMS model uses a tricubic interpolation spatially, and a 4th order Runge
 196 Kutta stepping scheme in time. No horizontal or vertical diffusivity is added
 197 to the particles, so the particle motion is purely advective. Mixing is only
 198 taken into account as far as it is represented by resolved eddies. The CMS
 199 model does include the option to parameterize the vertical movement in
 200 mixed layers by adding a random kick in the vertical to the particle trajec-
 201 tories (van Sebille et al., 2013). Results of including this option are compared to
 202 results without the parameterization, and no significant changes were found
 203 in the particle pathways and the watermass transformation along the paths.
 204 The change in density of the particles in the convection region defines the
 205 future path, as the particles have to follow isopycnals. It does not matter
 206 at which depth the particle is located within the mixed layer, since the T-S
 207 properties of the mixed layer are continuously homogenized by the convec-
 208 tive adjustment used in the model simulations. Therefore, the results of the

209 CMS model without the parameterization of the vertical movement in mixed
210 layers have been used in this study.

211 In total 226407 (284412) particles are tracked in MOM (POP). The total
212 advection time of the particles is chosen to be 6 years and is executed by
213 looping through the available dataset of one year of model output. The
214 resulting pathways and timeseries of temperature and salinity of the particles
215 do not show large variations from the end of December to the beginning of
216 January, which justifies this method. After six years, the majority of the
217 particles has left the Nordic Seas (81% in MOM and 69.8% in POP, see
218 section 4 and Figure 6).

219 The resulting pathways are then visualized using a particle density plot
220 (see section 4 and Figure 5). To this end every particle location is regrided
221 on a $0.1^\circ \times 0.1^\circ$ latitude-longitude grid. Each position can only be occupied
222 by the same particle once, to avoid the obscuration of the pathways by long
223 residence times as described by Behrens et al. (2017). The particle density
224 is given by the transport carried by the particles at each location divided by
225 the total transport. This way, the paths that the particles are most likely to
226 take are highlighted.

227 **3. Model performance in the Nordic Seas**

228 Apart from the different sea-ice configuration and the SSS restoring, the
229 set-up of the two models is very similar, as described in section 2.1. Still, the
230 resulting hydrography and circulation is remarkably different. In this section,
231 a comparison of the two models is made and the modeled fields are validated
232 against observations to highlight possible consequences of the different model

233 configurations. Also, the interpretation of the findings from the Lagrangian
 234 approach in sections 4 and 5 requires knowledge of the Eulerian background
 235 velocity and hydrography. The first part of this section compares the Nordic
 236 Seas hydrography and the mixed layer depth from each model to observations.
 237 The second part addresses the circulation in both models and the third part
 238 discusses the hydrography at the Kögur section (see Figure 1) to investigate
 239 the properties of the NIIC and the Denmark Strait Overflow Water.

240 *3.1. Hydrographic properties*

241 The mean temperature and salinity at 50m depth of both models is com-
 242 pared to the observed fields of the Nordic Seas from 1995 to 2010 in Figure
 243 2a-f. A depth of 50m is chosen, since at this depth the difference in temper-
 244 ature between the eastern and western basins is more pronounced than at
 245 the surface. Apart from some local discrepancies, both models compare well
 246 to the observed hydrography in the Nordic Seas. The hydrographic fields in
 247 MOM differ from the observations on the western side of the Nordic Seas.
 248 The Greenland Sea and Iceland Sea are colder than observed ($\Delta T \sim 2^\circ\text{C}$, Fig-
 249 ure 2b) and the waters near the Greenland coast are too fresh ($\Delta S \sim 0.5$ psu,
 250 Figure 2e). In POP, a warm and saline signal that is not present in observa-
 251 tions, seems to propagate onto the northern Greenland shelf region at 80°N
 252 (Figures 2c and 2f). Furthermore, the lateral spread of the Atlantic Water
 253 throughout the eastern basins is minimal in POP. Instead, a local minimum
 254 in temperature is seen in both the Lofoten Basin and the Norwegian Basin
 255 (Figure 2c). Further, the Atlantic Water returning in the EGC is warmer
 256 in MOM than in POP, indicating that the boundary current in POP loses
 257 more heat than the boundary current in MOM (see also table 1).

258 The location where deep convection takes place in both models is very
 259 different. Figure 3a and 3b show the maximum mixed layer depth (MLD)
 260 in MOM and POP. In order to use a common criterion for both models,
 261 the MLD is defined as the depth where the density difference compared to
 262 the surface is larger than 0.125 kg/m^3 as described in Danabasoglu et al.
 263 (2014). The density is determined from the temperature and salinity fields
 264 using the UNESCO nonlinear equation of state (Millero and Poisson, 1981).
 265 The maximum in MLD is reached at the end of winter and beginning of
 266 spring. The models display a clear difference in both the magnitude and the
 267 location of deep convection. In MOM the convection reaches 1000m depth,
 268 and the deepest mixed layers are seen southwest of Svalbard and within
 269 the Norwegian Atlantic Current (Figure 3a). In contrast to MOM, POP
 270 has mixed layers with a maximum of 1500m depth along the shelf break
 271 of Greenland, into the Greenland Basin and north of the Icelandic Plateau
 272 (Figure 3b).

273 The location and depth of deep convection are strongly dependent on the
 274 atmospheric forcing, the sea ice and the stratification of the water column
 275 (e.g. Moore et al., 2015; Harden et al., 2015; Våge et al., 2018). Comparing
 276 the location and the depth of the deep convection to the atmospheric heat
 277 flux (contours in Figure 3) and the sea-ice edge in March (dashed lines in
 278 Figure 3) confirms this. In MOM the edge of the deep convection region
 279 coincides with the -100 W/m^2 heat flux contour (Figure 3a). Furthermore, it
 280 is clear that the deep convection in the western basin is absent because the
 281 sea ice is preventing the cooling of the ocean surface by the atmosphere. In
 282 POP the sea-ice edge, which is located much closer to the Greenland coast

(see dashed line in Figure 3b), also plays an important role for the location of the deep convection. The strongest heat fluxes are found along the sea-ice edge, which makes the water column more prone to deep convection.

Observational estimates of the mixed layer depth in the Nordic Seas are limited due to the lack of year-round observational data. Mixed layers with depths of 560m have been observed in the Lofoten and Norwegian Basins (Nilsen and Falck, 2006; Richards and Straneo, 2015). The deep convection in the Greenland Sea is highly variable and can extend to depths of 2000m (Rudels et al., 1989; Latarius and Quadfasel, 2016). Combining all available observational data in the Iceland Sea, Våge et al. (2015) found that the deepest mixed layers in this basin ($\sim 300\text{m}$) are located in the northwest, close to Greenland. These findings suggest that the deep convection in the Greenland Sea is better represented in POP and the deep convection in the Lofoten Basin is better represented in MOM. Further, POP overestimates the maximum MLD in the Iceland Sea, whereas in MOM deep convection does not occur in this region. These differences are likely a direct consequence of the difference in sea-ice behavior between the models. Recall that the sea-ice extent in POP is fixed to observed values, whereas in MOM the sea ice is dynamically active. Apparently, the sea-ice model used in MOM is overestimating the sea-ice extent in the Nordic Seas, which suppresses deep convection in the western basins.

3.2. Nordic Seas Circulation

The circulation pattern in the Nordic Seas is strongly controlled by topography, while the strength of the circulation is influenced by the wind

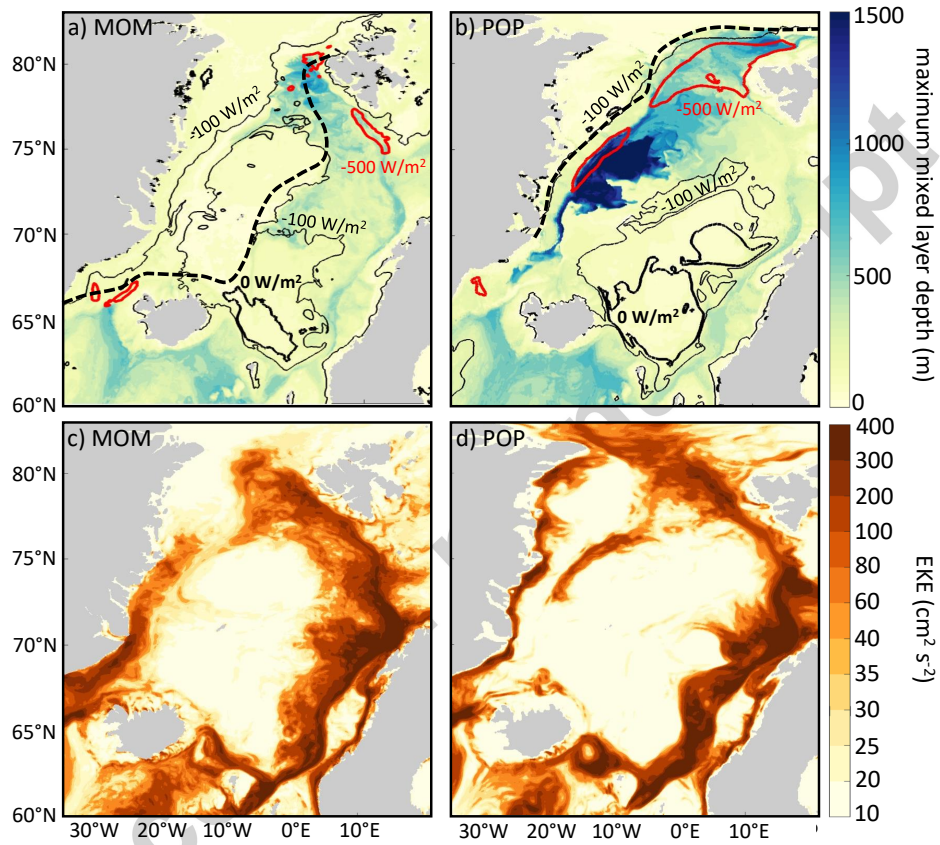


Fig. 3: Maximum mixed layer depth (top) and eddy kinetic energy (bottom) for MOM (left) and POP (right). Solid contours in (a) and (b) show the -500 W/m^2 (in red), -100 W/m^2 and 0 W/m^2 (in black) March mean heat flux. The dashed contours indicate the sea-ice extent in March.

308 forcing and hydrography (e.g. Blindheim and Østerhus, 2005; Spall, 2010).
 309 Figures 2g-i show the mean sea surface height (SSH) from observations, and
 310 in MOM and POP. The SSH in both models compares quite well to obser-
 311 vations, except in the Lofoten Basin. Especially in POP a depression in SSH
 312 is clearly seen in the Lofoten Basin, whereas a positive SSH anomaly is com-
 313 monly observed in this area associated with the Lofoten Vortex (e.g. Sjøland
 314 et al., 2016; Fer et al., 2018). The arrows in Figures 2h and 2i show the mean
 315 surface velocity in both models. The location and direction of the currents
 316 compare well to the observed surface circulation derived from drifters by e.g.
 317 Jakobsen et al. (2003). The model results differ regarding the strength of
 318 the currents. POP has a very strong cyclonic gyre in the Lofoten Basin and
 319 the Norwegian Basin, but the circulation in the Greenland and Iceland Basin
 320 is weaker. In MOM cyclonic gyres are most pronounced in the Greenland
 321 Basin and the Norwegian Basin. As the EGC in POP is very weak (see also
 322 table 1), most Arctic Water is transported southwards by the East Greenland
 323 Coastal Current. In MOM this current is less pronounced.

324 When the circulation is compared to the structure of deep convection in
 325 the basin (Figures 2h-i to 3a-b), the regions with convective activity coin-
 326 cide with regions of low velocity in both models. This seems contradictory
 327 at first, since deep convection in the interior of ocean basins is thought to
 328 be positively correlated with the strength of the cyclonic boundary current
 329 that is surrounding the basin: as the interior of the ocean basin is cooled
 330 during winter, the temperature gradient between the boundary current and
 331 the interior increases and the boundary current strengthens as a result of the
 332 thermal wind balance (e.g. Spall, 2004; Tréguier et al., 2005). However, in

our simulations a strong cooling coincides with a weak temperature gradient between the interior and the boundary current and therefore with a reduced geostrophic transport. The reduced temperature gradient is probably caused by the stronger cooling over the boundary current area compared to the interior. This heat loss seems to be so strong that the supply of warm water from the boundary current upstream is not sufficient and thereby, the boundary current temperature decreases.

The eddy kinetic energy (EKE) is shown in Figures 3c-d. Although the model resolution is not sufficient to fully resolve all eddy activity in the Nordic Seas, most of the variability is captured. The largest eddy variability is seen west of the Lofoten islands. Here, the EKE exceeds $400 \text{ cm}^2\text{s}^{-2}$, which compares relatively well to observational estimates (e.g. Wekerle et al., 2017). North of Iceland a small band of increased EKE from the NIIC can be seen. Both observational estimates of the eddy variability in this region and estimates from higher resolution model simulations show slightly larger values for EKE of $\sim 100 \text{ cm}^2\text{s}^{-2}$ compared to $\sim 60 \text{ cm}^2\text{s}^{-2}$ in MOM and POP (e.g. Jakobsen et al., 2003; Wekerle et al., 2017).

3.3. Hydrographic properties at Kögur section

Next, the properties of the inflowing Atlantic Water and the outflowing Overflow Water through Denmark Strait are compared between the models and mooring observations at the Kögur section (Harden et al., 2016). This transect is well documented from observations and the characteristics of both the inflowing NIIC and the outflowing dense waters can be distinguished along the section. Further, to enable direct comparison between the models and observations, table 1 shows the mean temperature, salinity and volume

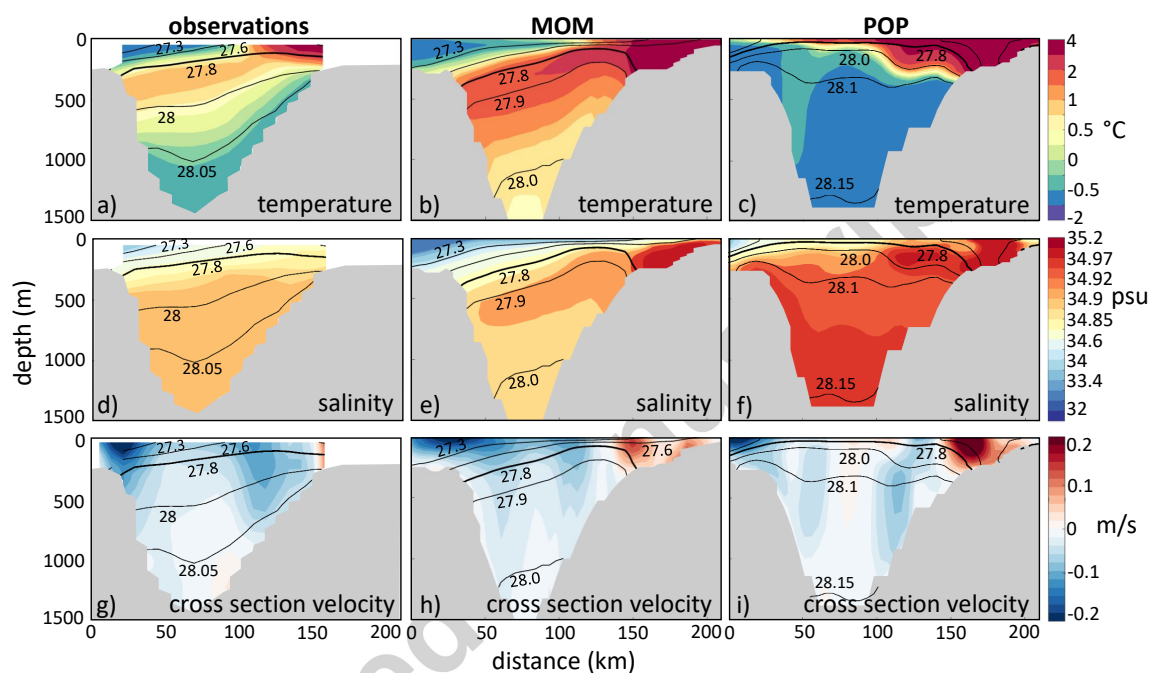


Fig. 4: Sections of temperature (top), salinity (middle) and cross section velocity (bottom) at the Kögur section (transect given in Figure 1). The x-axis shows the distance along the transect, starting at the Greenland coast. Positive velocity indicates northward flow. The left column shows the mean fields from observations described by Harden et al. (2016). The middle and right column show the mean fields of MOM and POP respectively. Density is given by the contourlines, where the thick black line corresponds to $\sigma = 27.8 \text{ kg/m}^3$. Note that the colorbars for temperature and salinity are non-linear.

	NIIC			DSOW			NIJ			EGC (76°N)		
	obs	MOM POP		obs	MOM POP		obs	MOM POP		obs	MOM POP	
Ψ (Sv)	1.1 ^[1]	1.1	1.8	3.2 ^[4]	2.5	3.1	1±0.17 ^[6]	0.5	1.3	5-7 ^[7]	7.5	2.8
T (°C)	3-6 ^[2]	6.2	6.6	0.1-0.5 ^[5]	2.5	-0.5	-0.4-0 ^[3]	1.4	-0.4	2-4 ^[7]	2.3	0.7
S (psu)	35-35.15 ^[3]	35	35.1	34.82-34.94 ^[5]	34.9	35	34.9-34.91 ^[3]	34.9	35	34.9-35.1 ^[7]	34.9	35

Table 1: Mean transport (Ψ), temperature (T) and salinity (S) of the NIIC, DSOW, NIJ and EGC from observations and the model simulations. Observational values are estimated from [1] Våge et al. (2013), [2] Jónsson and Valdimarsson (2005), [3] Pickart et al. (2017), [4] Jochumsen et al. (2017), [5] Eldevik et al. (2009), [6] Harden et al. (2016) and [7] Håvik et al. (2017).

transport estimates of the NIIC, DSOW, NIJ and EGC.

Figure 4 shows the mean temperature, salinity and the cross-section velocity (positive indicates northward flow) at the Kögur section. The mean temperature along the Kögur transect in MOM captures the observed pattern well (Figure 4b), although the deep waters are too warm ($\Delta T \sim 1^\circ\text{C}$, Figure 4b). In POP, the stratification is much stronger than observed, with warmer water at the surface ($\Delta T \sim +2^\circ\text{C}$) and colder waters below ($\Delta T \sim -1.5^\circ\text{C}$, Figure 4c). The salinity shows similar discrepancies, where the surface and deep layers are too fresh in MOM and too salty in POP by ~ 0.1 psu compared to the observations (Figures 4e and 4f). Combining the findings for temperature and salinity, the in- and outflowing waters in MOM are slightly too light and the in- and outflowing waters in POP are too dense.

In the cross-section velocity at the Kögur section different branches can

371 be distinguished (Figures 4g-i). The NIIC is present in both models and is
 372 characterized by a warm and salty water mass flowing north on the Icelandic
 373 shelf. The NIIC transport is 1.1 Sv in MOM and 1.8 Sv in POP compared to
 374 0.88-1.1 Sv estimated from observations (Jónsson and Valdimarsson, 2012;
 375 Våge et al., 2013). As a result of the model bias in density, the overflow
 376 water is characterized by different isopycnals. The 27.8 kg/m³ respectively
 377 28.0 kg/m³ isopycnals are chosen to represent the overflow water mass in
 378 MOM and POP. This results in an overflow transport into the Atlantic of
 379 2.4 Sv in MOM and 3.1 Sv in POP, which is slightly lower than the observed
 380 estimate of 3.2 Sv from Jochumsen et al. (2017). Compared to observations,
 381 the NIJ is better represented in POP than in MOM (see table 1).

382 In summary, this section discussed the differences between the models
 383 and observations. Overall, the models capture the main characteristics of
 384 the Nordic Seas well, but disagree on the location of deep mixed layers, the
 385 gyre strength in the Nordic Seas and the hydrographic characteristics of the
 386 Denmark Strait Overflow Water. The remainder of this paper will focus on
 387 whether these differences influence the pathways of the NIIC water and the
 388 location and strength of the watermass transformation.

389 **4. Pathways of the NIIC watermass in the Nordic Seas**

390 The density plot of the particles seeded in the NIIC (see section 2.2)
 391 reveals the pathways of the NIIC watermass in the Nordic Seas (Figure 5).
 392 After entering the Nordic Seas, most particles follow the 400m isobath around
 393 Iceland to the east (see inlays Figure 5). From there, multiple pathways can
 394 be identified following the shelfbreak and the main topographic features of

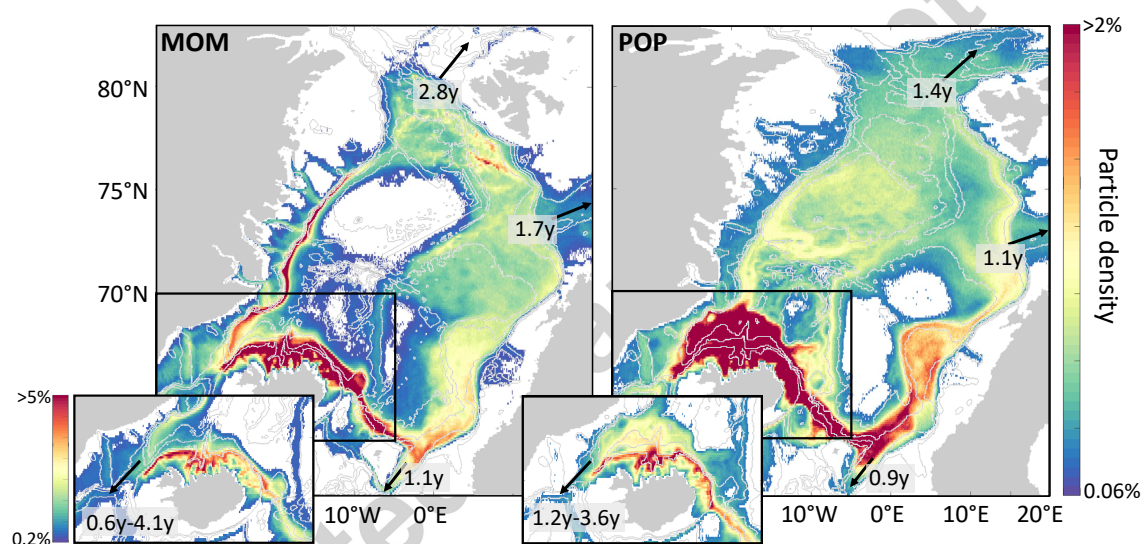


Fig. 5: Density plot of the particle position in MOM (left panel) and POP (right panel). The inlay shows the pathways near Iceland in more detail (note the different colorscale in the bottom left). The median travel time for the particles to reach the exits of the Nordic Seas is given in years.

the Nordic Seas; the Vring Plateau and the Jan Mayen- and Mohn Ridges
(see Figure 1).

These particle density plots show that the paths along which the particles enter the interior of the Nordic Seas are completely different between the two models. Particles mainly occupy the Lofoten Basin in MOM, whereas in POP the particles occupy the Greenland Basin. In MOM, particles are captured by eddies near the Lofoten Islands and travel westward until they reach the Mohn Ridge. There, the majority of the particles flows to the north and eventually joins the EGC. In POP, the particles are not captured by eddies near the Lofoten islands, but are transported in the strong cyclonic gyre of the Lofoten Basin and the Norwegian Basin instead. At the western side of the Nordic Seas, particles travel throughout the Greenland Basin, without displaying one distinctive path.

The residence time of the particles within the Nordic Seas is highly variable and depends on where the particles leave the basin. The median travel time is given in Figure 5 for the particles that enter and leave the Nordic Seas within the time interval of 6 years (section 2.2). The shortest residence times of ~ 1 year are found for particles taking a short path crossing the Greenland-Scotland Ridge, whereas the particles that follow the path along the rim of the Nordic Seas take ~ 4 years to do so. On average, the travel time towards Fram Strait is one year shorter in POP than in MOM, which indicates that the particles flow much faster from the Lofoten Islands to Fram Strait in POP than in MOM.

In order to distinguish between the different paths, particles are selected based on which exit they take out of the Nordic Seas. This particle category

420 rization process is illustrated in Figure 6a. Furthermore, a selection is made
 421 based on whether particles enter the interior of the Nordic Seas, or stay close
 422 to the boundary with respect to the coastlines of Iceland, Norway, Svalbard
 423 and Greenland. Although the categorization is sensitive to the choice of the
 424 transects shown in Figure 6a, inspection of the individual particle trajectories
 425 indicates that the transect locations used in this study lead to a meaningful
 426 separation.

427 The result of this categorization process is summarized by Figures 6b
 428 and 6c. In both models, most of the NIIC watermass leaves the Nordic Seas
 429 toward the Atlantic Ocean by crossing the Greenland-Scotland Ridge (66.7%
 430 in MOM and 42.5% in POP). A smaller fraction of the NIIC watermass flows
 431 into the Arctic via Fram Strait or the Barents Sea (14.3% in MOM and 27.3%
 432 in POP). The part of the NIIC water that takes longer than 6 years to leave
 433 the Nordic Seas (19% in MOM and 30.2% in POP) is found mostly in the
 434 interior of the basin (not shown). A much longer advection time would be
 435 needed to advect all of the originally seeded NIIC particles out of the Nordic
 436 Seas.

437 The particles leaving the Nordic Seas through Denmark Strait can do so
 438 following different paths as indicated in Figures 6b-c; via a short loop north of
 439 Iceland (the DSs, short, path), via the rim of the Nordic Seas (the DSl, long,
 440 path), via the interior of the Nordic Seas (the DSm, middle, path) and via the
 441 coastal shelf area of Greenland (the DSc, coastal, path). As the connection
 442 of the NIIC to the overflow is the main interest of this study, the remainder
 443 of this paper is focused on the NIIC water returning to the Atlantic Ocean.
 444 Although the sea-ice cover, the mixed layers, and the transport of the NIIC

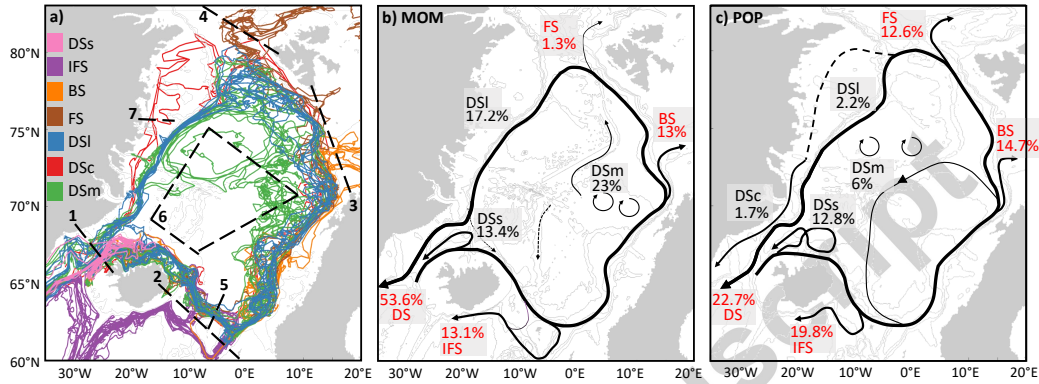


Fig. 6: (a) Example of 63 randomly chosen particle trajectories from both MOM and POP and their categorization (color coding). DSs (Denmark Strait short, pink) are particles that leave the Nordic Seas crossing transect 1, without crossing transect 5. IFS particles (Iceland-Faroe-Shetland, purple) are particles that leave by crossing transect 2. BS (Barents Sea, orange) are particles that travel into the Barents Sea crossing transect 3. FS (Fram Strait, brown) are particles that travel into the Arctic Ocean by crossing transect 4. DSL (Denmark Strait long, blue) are particles that travel along the rim of the Nordic Seas, crossing transects 5 and 1. DSc (Denmark Strait coast, red) are particles that follow the same route as DSL, but travel on the shelf region of Greenland crossing transect 7. DSm (Denmark Strait middle, green) are particles that enter the interior of the Nordic Seas indicated by box 6 and leave the Nordic Seas through transect 1. (b-c) The black arrows indicate the paths of the NIIC water in the Nordic Seas where the percentage gives the distribution of the NIIC watermass over the different pathways. The total fraction of the NIIC watermass that leaves through each exit is given in red. 19% (30.2%) of the particles are still in the Nordic Seas after 6 years in MOM (POP).

show a seasonal dependence in the two model simulations, the pathways of the NIIC watermass are not sensitive to the time of release of the particles.

Both models show the existence of a short loop along the inflowing NIIC back to Denmark Strait (the DSs path). At first sight, this path seems similar to the hypothesized path of Våge et al. (2011). However, only 13% of the volume that entered the Nordic Seas in the NIIC is taking this path in both MOM and POP, in contrast to the fast one-to-one connection between the NIIC and the NIJ proposed by Pickart et al. (2017). Furthermore, investigation of the particles' depth is needed in order to see whether this outward branch is actually part of the NIJ. To this end, the vertical distribution of the in- and outflowing branches of the different pathways at the Kögur section are visualised in Figures 7a and 7b. To derive this figure, the particles crossing this transect are mapped on a $0.1^\circ \times 10\text{m}$ longitude-depth grid. Only the contour that encompasses more than 80% of the particles is shown to highlight the main position of each pathway in the watercolumn.

In both models, most of the DSs watermass originates from the upper 100m of the NIIC (solid pink contour in Figures 7a-b), and this path is therefore shallower than the other paths. The particles follow the shelf break of Iceland and turn northwards at Kolbeinsey Ridge. In MOM, the particles return to Denmark Strait following the 1000m isobath along the Icelandic slope. In POP, some particles circulate in the Bloesville Basin (Figure 1) as well. On their outward journey, there is no indication in MOM that the DSs particles are connected to the NIJ, since the returning particles are all located in the upper 100m of the water column (pink dashed line in Figure 7a). In POP, however, there is a clear signal of outward flowing particles

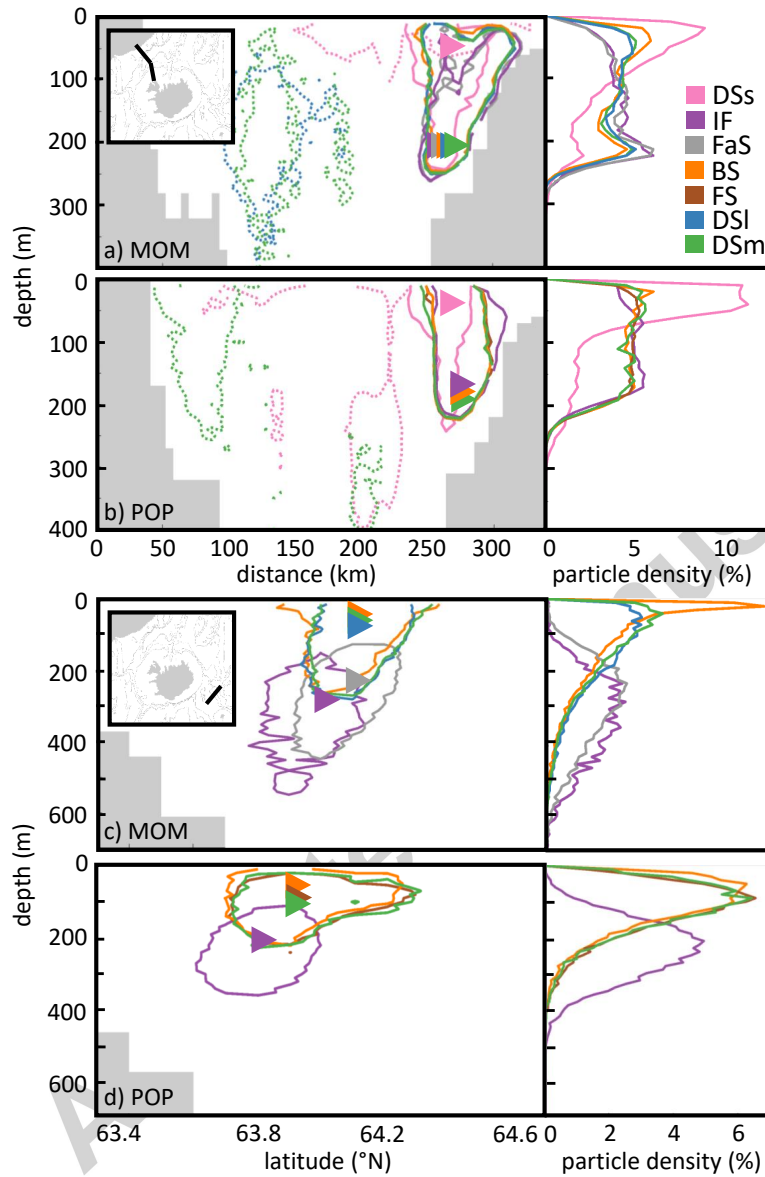


Fig. 7: The depth distribution of each pathway at (a,b) Kögur section and (c,d) a section east of Iceland (see inlays). The left panels show the contour, colored per pathway, that encompasses $>80\%$ of the particles. The triangles give the location where the maximum particle concentration of the pathway is found at these transects. The solid contours show the distribution of the particles that flow into the Nordic Seas, the dashed lines show the distribution of the pathways on their outward journey. The right panels show the normalized depth distribution of each path integrated along the transects. The IFS particles are separated in those that leave the Nordic Seas between Iceland and the Faroe islands (IF, in purple) and those that leave the Nordic Seas between the Faroe Islands and Scotland (FaS, in gray). Only the paths that carry more than 5% of the NIIC water are shown.

470 between 200m and 400m depth close to the Icelandic slope (pink dashed line
 471 Figure 7b), showing that in this model the outward branch is part of the NIJ.
 472 This indicates that the watermass transformation of the particles following
 473 the DSs path is different in both models. This will be further discussed in
 474 section 5.

475 As only 13% of the NIIC watermass takes the DSs path, the majority of
 476 the water is transported by other paths. A significant fraction of the NIIC
 477 watermass leaves the Nordic Seas between Iceland and the Shetland islands
 478 in both models (the IFS path, 13% in MOM and 20% in POP). In POP,
 479 all of the IFS particles leave the Nordic Seas between Iceland and the Faroe
 480 Islands (the IF path), whereas in MOM the majority of the IFS particles
 481 (>60%) leaves through the deeper channel between the Faroe Islands and
 482 Scotland (the FaS path). Again, the vertical distribution of the pathways
 483 is investigated by mapping the particles on a $0.1^\circ \times 10\text{m}$ latitude-depth grid
 484 of a transect east of Iceland (Figure 7c and 7d). Clearly, the IFS particles
 485 (purple color in Figure 7c-d) are located deeper in the water column than the
 486 particles of the other pathways. In MOM, the particles leaving between the
 487 Faroe Islands and Scotland are located slightly farther offshore. Therefore,
 488 they follow the 1000m isobath to the Faroe-Shetland Channel. The possible
 489 connection of the IFS path to the Iceland Scotland Overflow Water (ISOW)
 490 will be discussed in section 5.

491 Investigation of the vertical distribution of the pathways at the Kögur
 492 section and the transect east of Iceland gives insight why some particles flow
 493 south (the IFS path) and why some flow northward east of Iceland (the
 494 BS, FS, DSm, DSl and DSc paths). At the start of their trajectory, the

495 maximum concentration of the particles that do not take the DSs path is
 496 found at 200m depth in both models (see triangles in Figures 7a and 7b).
 497 However, east of Iceland, the particles that continue their journey north are
 498 all shifted upwards in the water column, whereas most particles that flow
 499 south are found below 200m depth (compare the purple and gray contours to
 500 the other colors in Figure 7c and 7d). The upper part of the water column
 501 east of Iceland is characterized by the Atlantic Water flowing north in the
 502 NwAC. Particles that are located near the surface are therefore likely to
 503 mix with the inflowing Atlantic Water and flow north, whereas the deeper
 504 particles follow the topography to the south.

505 These results indicate that processes that take place between the two
 506 investigated transects are crucial for setting the ratio of the southward and
 507 northward flowing fraction of the NIIC. The instability of the NIIC in this
 508 region (see Figure 3c-d) could provide one possible mechanism for setting
 509 these pathways apart. The generation of eddies coincides with local up- and
 510 downward movement of isopycnals and this process could separate particles in
 511 depth (Ypma et al., 2016). Another possible mechanism is that the particles
 512 are set apart in depth by local mixing within the mixed layer, which influences
 513 their density. It is beyond the scope of this study to determine the dominant
 514 processes in this region that are important for the transformation of the
 515 NIIC watermass. However, it is likely that the ratio of the southward and
 516 northward flowing fraction of the NIIC is subject to interannual variability.

517 The particles that flow north in the NwAC can take different routes.
 518 They either flow into the Barents Sea, flow through Fram Strait or return
 519 south along Greenland to Denmark Strait. One of the main differences be-

520 tween MOM and POP is that more than half of the NIIC watermass leaves
 521 through Denmark Strait in MOM, where most particles take the long way
 522 around (along the DSI and DSm paths). In POP, only 23% leaves through
 523 Denmark Strait, which may be explained by the weak EGC in POP and the
 524 long residence time of the particles in the Greenland Basin. Using a longer
 525 advection time of the particles would possibly increase the fraction of the
 526 NIIC watermass leaving the Nordic Seas through Denmark Strait in POP.

527 In summary, according to the two model simulations investigated in this
 528 study the connection between the NIIC and the NIJ is either weak (in POP)
 529 or non-existent (in MOM). Furthermore, the model simulations suggest a
 530 possible connection between the NIIC and the ISOW.

531 **5. Watermass transformation along the pathways**

532 In order to investigate the watermass transformation along the pathways
 533 of the NIIC water in the Nordic Seas, the temperature and salinity are traced
 534 for each particle. As an example, Figure 8a shows the trajectory of one of
 535 the particles that takes the DSI route in POP. Along this path, a net cooling
 536 and freshening of 7°C and 0.13 psu is seen (Figure 8b), leading to an increase
 537 in density of 0.68 kg/m³. The transformation predominantly takes place at
 538 times when the particle is located inside the mixed layer (shaded periods
 539 in Figures 8b and 8c). Note that the magnitude of the cooling that takes
 540 place is not necessarily related to the depth of the mixed layer, neither to
 541 the strength of the heat flux at the surface. As seen in Figure 8b between
 542 location 1 and 2, the particle changes its thermohaline properties to a warmer
 543 and saltier watermass, while traveling to a location with a deeper mixed layer

544 and a stronger atmospheric cooling. Most likely, the warming and increase
 545 in salinity is a result of mixing with Atlantic Waters that enter the Nordic
 546 Seas east of Iceland. Two periods of strong cooling along the path of the
 547 particle can be distinguished. The cooling that takes place north of Iceland
 548 (upstream of number 1 in Figure 8a) at the start of the trajectory coincides
 549 with a reduction in salinity. This could indicate another mixing process with
 550 cold and fresh waters from the north. The second cooling event takes place
 551 when the particle is south of Svalbard (between location 6 and 7 in Figure 8a).
 552 During this cooling event, the salinity change is rather small and the particle
 553 is close to the sea surface, indicating that the reduction in temperature is
 554 most likely due to atmospheric cooling.

555 Note that, not only this particle, but all particles change their density
 556 predominantly, when they are located within the mixed layer. This is be-
 557 cause diapycnal mixing below the mixed layer is small (e.g. Ledwell et al.,
 558 1993). In the model simulations, diapycnal mixing originates from the ver-
 559 tical background diffusion and in case of steep fronts from horizontal bihar-
 560 monic diffusion. In addition to diapycnal mixing, there can be isopycnal
 561 mixing (mixing of temperature and salinity without a change in density) ei-
 562 ther by the explicitly resolved eddies or by horizontal diffusion. However,
 563 the effect of isopycnal mixing on temperature and salinity is much smaller
 564 than the diapycnal and diabatic water mass transformation within the ocean
 565 mixed layers. This is evident in Figure 8b-c from the much smaller temper-
 566 ature and salinity changes when the particle is below the mixed layer.

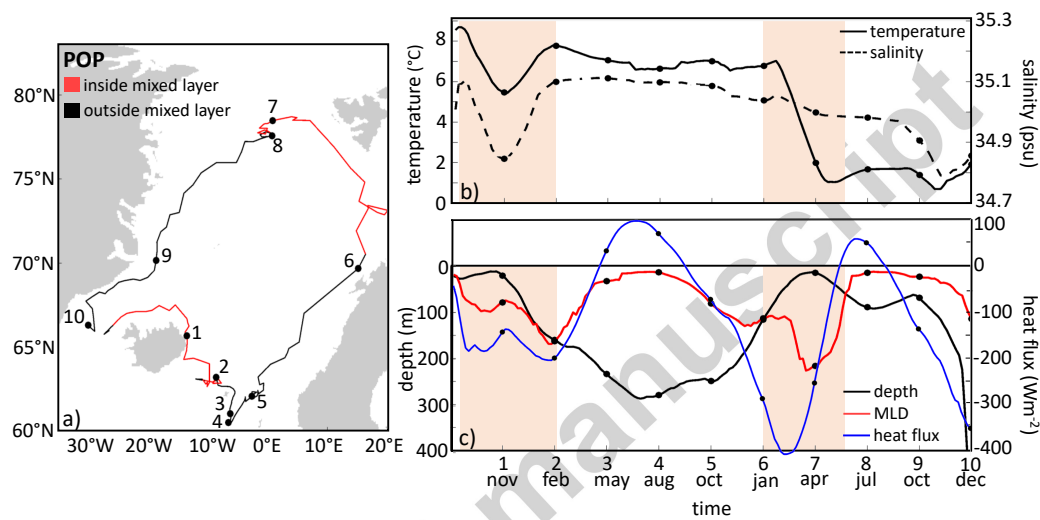


Fig. 8: (a) Example trajectory of a DSI particle in POP that is part of the DSOW. The line is red where the particle is traveling inside the mixed layer, the line is black outside the mixed layer. (b) Temperature (solid black line, left axis) and salinity (dashed black line, right axis) along the path of the particle trajectory shown in panel a. (c) Depth of the particle (in black), the mixed layer depth along the trajectory (in red) and the heat flux at the sea surface along the trajectory (in blue, negative means cooling). The shaded orange periods in (b-c) indicate when the particle is in the mixed layer. The numbers along the time axis of panel b and c correspond to the numbers in panel a, showing the particle location at the specified time.

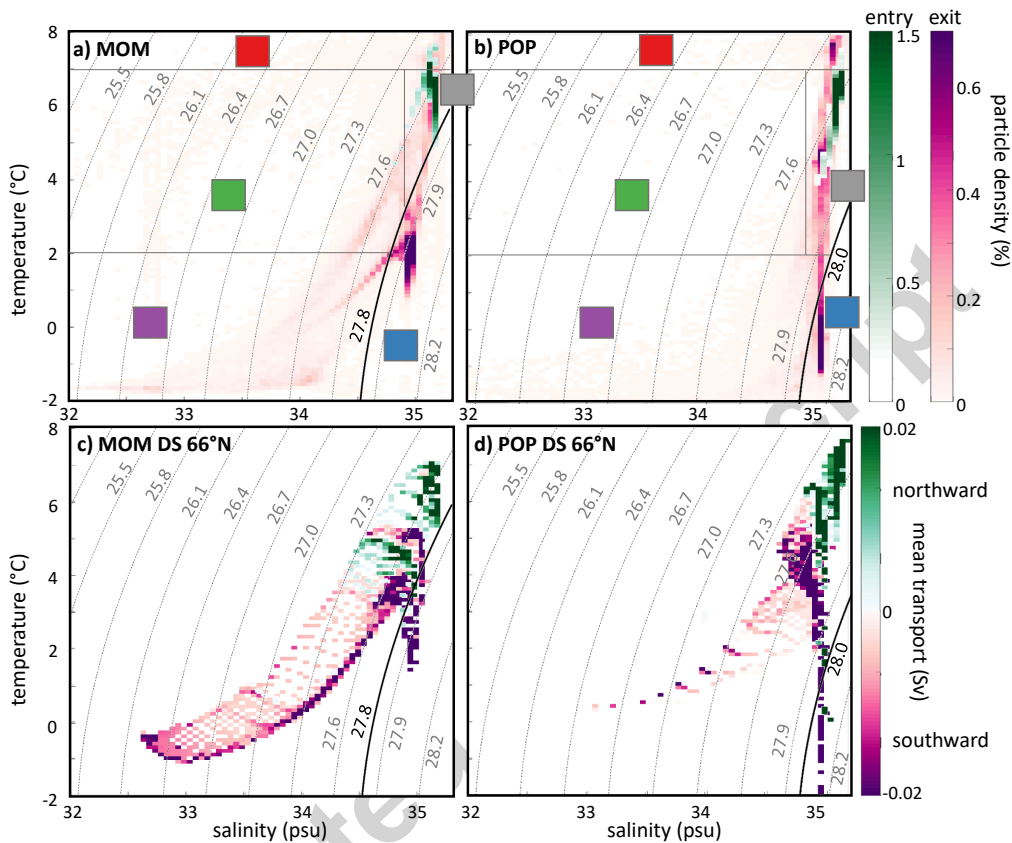


Fig. 9: (a-b) T-S diagrams of the thermohaline properties of the particles when entering the Nordic Seas (in green) and exiting the Nordic Seas at any of the exit locations (in purple) for (a) MOM and (b) POP. The transport weighted particle density is shown per $\Delta T = 0.1^\circ\text{C}$ and $\Delta S = 0.05$ psu interval. The horizontal and vertical gray lines separate the T-S categories used in Figure 10. (c-d) Mean volume transport from the Eulerian velocity fields at Denmark Strait (66°N) as a function of temperature and salinity in MOM (left) and POP (right). Transport into the Nordic Seas is shown in green and transport out of the Nordic Seas in purple. In all panels, contours are density (kg/m^3), where the thick black line indicates the density threshold for the overflow waters (see section 3.3) in MOM respectively POP.

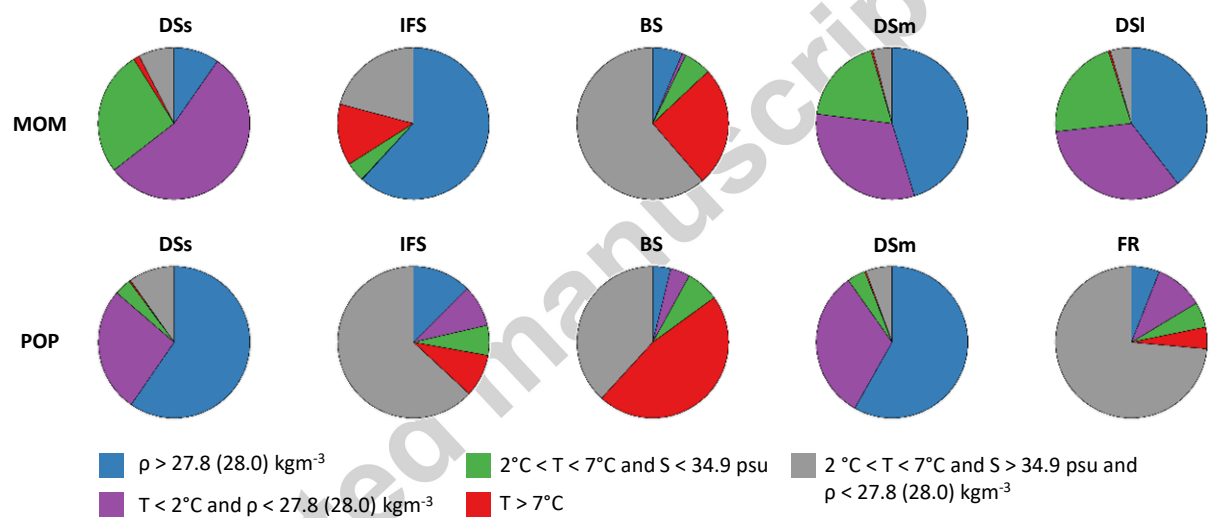


Fig. 10: Fraction of particles per pathway leaving the Nordic Seas within specific T-S categories, described in Figures 9a-b. Only the paths that carry more than 5% of the NIIC water are shown.

567 *5.1. Contribution of the NIIC water to overflow waters*

568 The investigation of this single particle pathway already elucidates many
 569 aspects of density changes that can occur in the Nordic Seas. To analyze the
 570 watermass transformation of the NIIC and its contribution to the overflows,
 571 all particles need to be taken into account. The change in temperature and
 572 salinity of the particles is visualized in the T-S diagrams in Figures 9a and 9b,
 573 where T-S properties of the particles that enter the Nordic Seas (in green) are
 574 compared to the T-S properties of the particles that exit the Nordic Seas at
 575 either Denmark Strait, crossing the Iceland-Scotland Ridge, into the Barents
 576 Sea or through Fram Strait (in purple). The temperature and salinity of
 577 the particles is gridded on a $\Delta T = 0.1^\circ\text{C}$ and $\Delta S = 0.05$ psu temperature-
 578 salinity grid. In both models a clear shift to lower temperatures is seen (ΔT
 579 $\sim 4\text{--}7^\circ\text{C}$) and little change in salinity.

580 Using the thermohaline properties of the particles, an estimate can be
 581 made to what extent the NIIC watermass contributes to the overflow waters
 582 in both models. Figures 9c and 9d show the mean volume transport of all
 583 the water crossing Denmark Strait as a function of temperature and salinity
 584 for MOM and POP, derived from the Eulerian mean velocity fields. The
 585 thick density contour shows the minimum density of the overflows defined
 586 in section 3.3. The same contour is also shown in Figures 9a and 9b. Using
 587 this threshold density, 27% (14.7%) of the water transported by the NIIC
 588 reaches a density that is larger than 27.8 kg/m^3 (28.0 kg/m^3) when leaving
 589 the Nordic Seas in MOM (POP).

590 To investigate along which paths this dense water is transported, the
 591 outflow temperature and salinity of the particles is split over five T-S cate-

gories, indicated by the gray lines in Figures 9a-b. The categories are based on whether the density along the pathway increased sufficiently to resemble the overflow (category 1), whether both temperature and salinity decreased (category 2), whether mainly the salinity decreased (category 3), whether the temperature increased (category 4), or whether the thermohaline properties of the particles remained roughly similar (category 5).

Applying this categorization process to each pathway (Figure 10) directly reveals along which pathways the dense water that eventually contributes to the overflows is transported (blue color in Figure 10). In MOM, the NIIC water that contributes to DSOW is transported mainly via the DSI and DSm path (18.2%, 0.20 Sv). In POP, 10.8% (0.19 Sv) of the NIIC water reaches Denmark Strait as DSOW, which is mainly transported via the DSs pathway and partly by the DSm path.

The NIIC watermass is also connected to the overflow between Iceland and Scotland (ISOW) in both models via the IFS path, and this connection is stronger in MOM than in POP (7.8%, 0.09Sv in MOM and 2.1%, 0.04Sv in POP). In MOM, the majority of the IFS particles are transformed to the overflow density (blue color Figure 10), whereas in POP most particles have T-S properties that are similar to those at entering the Nordic Seas (gray color Figure 10). However, just before entering the Iceland-Faroe Channel (at the transect shown in Figures 7c-d), the T-S properties of the particles in POP are very similar to those in MOM (not shown). A possible explanation for the sudden decrease in density is the slightly deeper mixed layer depths in the Iceland-Faroe Channel found in POP, making the IFS watermass more prone to mixing with the warm and salty Atlantic Water layer. This is linked

to the fact that the IFS particles in MOM leave mainly through the deep channel east of the Faroe Islands, whereas the IFS particles in POP leave west of the Faroe Islands (section 4). In both models the isopycnal that serves as the upper threshold for the overflow waters is located at $\sim 500\text{m}$ depth at the Iceland-Scotland Ridge. As the channel between Iceland and the Faroe Islands is only 500m deep, most of the ISOW has to leave east of the Faroe Islands, where the channel is 1100m deep.

Most of the particles that flow into the Barents Sea show either similar temperatures or an increase in temperature with respect to their original properties when flowing into the Nordic Seas. As a result, both simulations show only few particles with an overflow density entering the Barents Sea and the Arctic Ocean (1% in MOM and 1.8% in POP). It is likely that a part of the watermass that enters the Barents Sea and the Arctic Ocean will transform to denser waters further north, but this is outside the scope of this study.

5.2. Location of watermass transformations

To shed more light on the differences and similarities between the two model simulations regarding the watermass transformation along the paths, the location of the thermohaline changes along the pathways is investigated (Figure 11). The rate of change of temperature and salinity is determined and spatially binned on a $0.5^\circ \times 0.5^\circ$ latitude-longitude grid. Next, this rate of change is multiplied by the residence time of the particles at each gridbox, to obtain the total change in temperature and salinity that the particles undergo at each location. Then, the results are averaged at every gridbox when the particle number in the gridbox exceeds 100 particles.

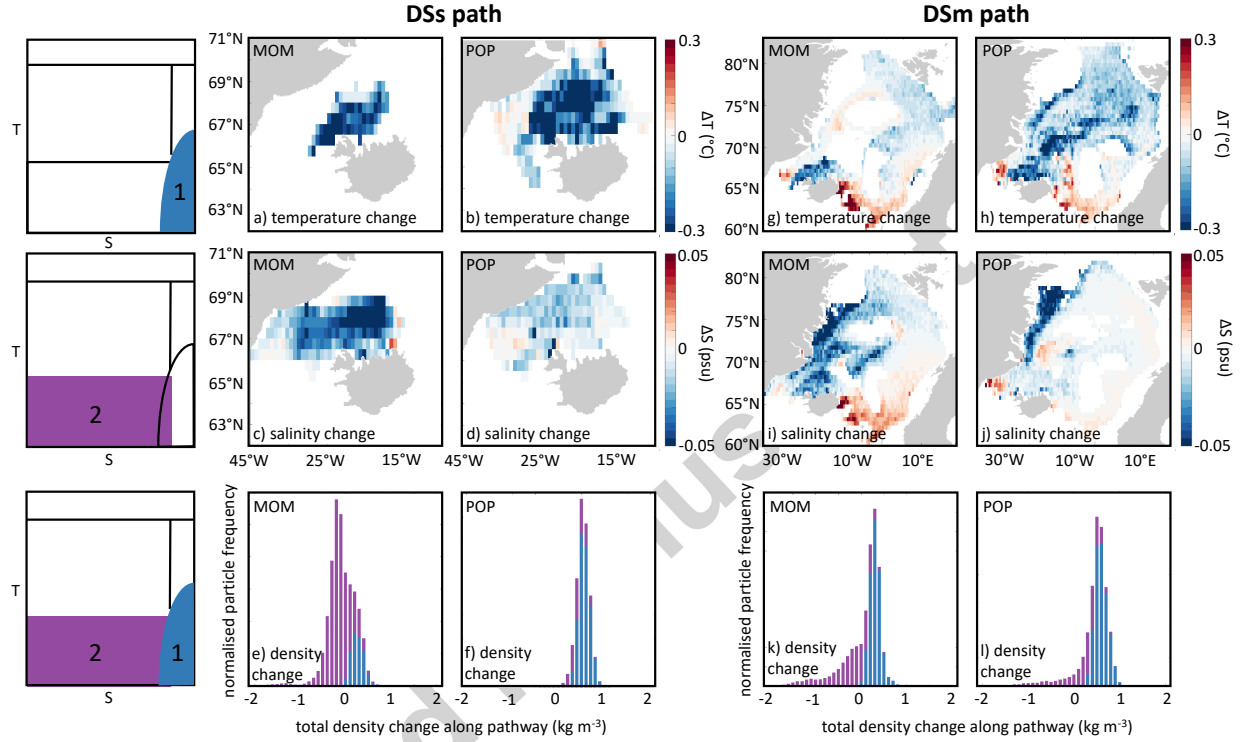


Fig. 11: Temperature change per $0.5 \times 0.5^\circ$ lon-lat gridbox (a-b, g-h), salinity change per $0.5 \times 0.5^\circ$ lon-lat gridbox (c-d, i-j) and total density change (e-f, k-l) along the DSs path (a-f) and the DSm path (g-l). The upper row shows the temperature change of the particles whose density at leaving the Nordic Seas is larger than 27.8 (28.0) kg/m^3 (T-S category 1, see Figures 9 and 10). The middle row shows the salinity change of the particles whose temperature and density properties at leaving the Nordic Seas are smaller than respectively 2°C and 27.8 (28.0) kg/m^3 (T-S category 2, see Figures 9 and 10). The third row shows the distribution of the total density change of each particle along the pathway (positive indicates a density increase), with the particles that connect to the DSOW (T-S category 1) in blue and the particles that leave the Nordic Seas with the T-S properties of T-S category 2 in purple.

642 The watermass transformation along the DSs path displays the largest
 643 difference between the two simulations. In MOM, the majority of the par-
 644 ticles change their thermohaline properties to a fresher watermass (purple
 645 area Figure 10), whereas in POP a strong transformation to a cold and salty
 646 watermass takes place (blue area Figure 10). Figures 11a-b show the tem-
 647 perature change for the particles that leave the Nordic Seas as DSOW. Both
 648 simulations show strong cooling. In MOM, this cooling is confined to the
 649 region just north of Iceland, whereas in POP the water flowing along the
 650 DSs path cools over the entire area between Iceland and Greenland.

651 The differences between both model results become more apparent in Fig-
 652 ures 11c-d, where the salinity change is shown for the particles that change
 653 their thermohaline properties to a colder and fresher watermass (T-S cat-
 654 egory 2, purple area Figure 10). Where in MOM the strongest cooling is
 655 found directly at the release location of the particles (66°N , Figure 11a), the
 656 strongest freshening takes place further downstream ($\sim 68^{\circ}\text{N}$, Figure 11c). In
 657 POP, the reduction in salinity is significantly smaller and takes place closer
 658 to the Greenland coast (Figure 11d). The total density change along the
 659 DSs pathway (Figures 11e-f) indicates that the decrease in salinity in MOM
 660 outweighs the temperature decrease and most of the DSs particles become
 661 lighter along this path. In POP, the salinity decrease is small and most of
 662 the particles become denser along the DSs path (Figure 11f). This explains
 663 why the DSs particles are found at the surface in MOM and at depth in
 664 POP, when flowing south through Denmark Strait (Figures 7a-b).

665 The changes seen in the particles' properties along the DSs path can be
 666 related to the location of the sea ice (Figures 3a-b). As the maximum sea-

ice edge extends to the center of Denmark Strait in MOM, cooling by the atmosphere is confined to the region close to Iceland as seen in Figure 11a. In POP, the region between Iceland and Greenland is ice free year-round, and atmospheric cooling is not hindered by sea ice. Further, it is likely that mixing takes place with the cold and fresh waters that flow south along the Greenland coast. In MOM, the salinity gradient in the Denmark Strait region is much larger than in POP (see Figures 2e-f). The fresher surface waters seen in MOM can be due to the ice melt, but also due to the different surface freshwater boundary conditions. Therefore, similar mixing will lead to a stronger freshening in MOM than in POP.

The pathway along which the total density change is similar in both simulations is the DSm path (Figures 10 and 11k-l). However, the locations where the thermohaline changes take place are different. In MOM, the strongest cooling is found just north of Iceland, similar to the DSs path (Figure 11g), while in POP, cooling is also seen along the shelfbreak of Greenland and in the interior of the Nordic Seas (Figure 11h). Both models show freshening along the Greenland coast, where the water mixes with the Polar Water of the EGC (Figures 11i-j). In MOM, freshening is also seen just southeast of the Greenland Basin.

Both MOM and POP display local maxima of watermass transformation in the interior of the Nordic Seas (cooling in POP and freshening in MOM, Figures 11h-i). As seen in Figures 2h-i the flow speed is significantly lower in the interior of the Nordic Seas than at the boundaries and therefore the local maxima seen in Figures 11h-i are a result of the larger residence time of the particles in these areas. Just like for the DSs path, the atmospheric cooling

is limited by the sea-ice extent over the western side of the Nordic Seas in MOM as seen in Figure 11g and the freshening southwest of the Greenland Basin is likely a result of ice melt. The model simulations show an increase in both temperature and salinity southeast of Iceland. This transformation is a result of mixing with the Atlantic Water that flows into the Nordic Seas east of Iceland (Figure 1). The location of watermass transformation along the other pathways was investigated as well, but did not differ substantially from the watermass transformation along the DSm path shown in Figure 11g-j.

In summary, both simulations show a similar contribution of the NIIC to the DSOW of 0.2 Sv. However, the pathways along which the transformation takes place differ. This is a result of the differences in sea-ice cover in the Nordic Seas, and likely due to the different freshwater boundary conditions of the model simulations. As hypothesized in section 4, investigation of the thermohaline properties of the particles elucidated a weak connection between the NIIC and the ISOW.

6. Discussion and conclusions

In this paper Lagrangian particles have been used to investigate the pathways and the watermass transformation of the North Icelandic Irminger Current (NIIC) in the Nordic Seas in two ocean models. The volume of the NIIC water along each pathway and the contribution of the NIIC watermass to Denmark Strait Overflow Water (DSOW) and Iceland Scotland Overflow Water (ISOW) have been quantified. Further, the locations of the watermass transformation have been studied to investigate their relation to the location of the convection regions within the Nordic Seas.

Based on observations, some studies propose a strong connection between the NIIC and the DSOW, where the NIIC watermass is transformed north-west of the Iceland gyre and flows back into the Atlantic Ocean via the North Icelandic Jet (NIJ) through Denmark Strait (Våge et al., 2011; Pickart et al., 2017). The indication that both currents carry a similar volume transport and the assumption that the EIC does not contain a large part of the NIIC watermass, led to a suggested one-to-one connection between the NIIC and the NIJ (e.g. Pickart et al., 2017). The results from this study provide a different view than that deduced from the observations. The models suggest that the inflowing NIIC watermass is divided over several pathways in the Nordic Seas, and that only 13% of the NIIC watermass flows till Kolbeinsey Ridge to follow the short suggested loop. The region north of Iceland seems to play a crucial role in diversifying these pathways. The connection from the NIIC to DSOW via the NIJ has only been found in POP, since in MOM strong freshening takes place near the surface.

As was shown in Figure 7, the particles that follow the short DSs path originate from the upper 100m of the NIIC, whereas the deeper part of the NIIC flows farther east along Iceland. This could explain why Valdimarsson and Malmberg (1999) concluded that the DSs path was the main route for the NIIC, since this was the only path they could observe using surface drifters. Jónsson (1992) observed the NIIC watermass at the northeast corner of Iceland, slightly deeper in the watercolumn. In light of the results of our study, it is possible that he measured the fraction of the NIIC watermass that eventually leaves between Iceland and Scotland (the IFS path). Both models used in this study show a very strong watermass transformation

north of Iceland. Therefore it is possible that observations underestimate the Atlantic Water originating from the NIIC east of Iceland. Also, the part of the NIIC water that travels offshore of Iceland is indistinguishable from the EIC. Therefore, this study fits well with previous work that concluded that the EGC is most likely not the only source for the EIC (e.g. Logemann et al., 2013).

The results of this study strongly indicate that the DSs path is topographically controlled and that the fraction of the NIIC water following this path is set by the vertical structure of the current. Our results indicate that the path itself is not sensitive to sea-ice cover and atmospheric conditions and hence it is likely that similar conclusions can be drawn when repeating this research in models with interannually varying forcing. Further, as the instability of the NIIC is only slightly underestimated in the model simulations presented in this study, it is not expected that a fully eddy-resolving simulation would show a significantly stronger connection between the NIIC and the NIJ.

Both models display only 0.2 Sv NIIC contribution to the Denmark Strait Overflow Water, although the paths along which this water is transported back to Denmark Strait differ. This means that in these models the NIIC can not be the main source for the NIJ watermass. This is in line with the Lagrangian analysis conducted previously by Behrens et al. (2017), who found that only a small part of the DSOW originated from the NIIC. Note that as their study concerned only backtracking of the DSOW, no statement could be made on what fraction of the NIIC watermass contributes to the overflow as is done in this study.

766 Interestingly, both MOM and POP show a small contribution of the NIIC
 767 watermass to the ISOW of 7.8% respectively 2.1%, which is a weak connec-
 768 tion that might be hard to detect by observations (e.g. Stefánsson, 1962;
 769 Perkins et al., 1998). Part of the Modified East Icelandic Water originates
 770 from the North Icelandic Shelf and is formed during winter convection and
 771 modified due to strong mixing with surrounding watermasses (Stefánsson,
 772 1962; Read and Pollard, 1992). It is likely that the IFS path found in the
 773 models resembles this contribution.

774 The model simulations used in this study show agreement on both the
 775 pathways of the NIIC watermass and the contribution to the overflows, re-
 776 gardless of the large differences in the sea-ice cover, the hydrography and the
 777 circulation patterns between the simulations. This gives confidence that the
 778 conclusions drawn from the simulations regarding the NIIC pathways are not
 779 a model artifact, but apply to actual processes in the Nordic Seas.

780 The models do show some differences regarding the pathways along which
 781 DSOW is created. The agreement between the models in the NIIC contri-
 782 bution to DSOW of 0.2 Sv could therefore be a pure coincidence. In MOM,
 783 a mean freshening is seen along the DSs path and dense water is only trans-
 784 ported to Denmark Strait along the deeper part of the EGC by the DSI
 785 and DSm paths. In POP, the EGC is weak and is only reached by a lim-
 786 ited number of particles (2.2%). However, since the DSs path in POP does
 787 not display a strong decrease in salinity, this pathway serves as the main
 788 connection between the NIIC and the DSOW in this model.

789 The models have a very different approach regarding the sea ice, which
 790 might explain why the watermass transformation to DSOW is different. The

791 sea-ice cover in MOM between Greenland and Iceland is substantial and in
 792 POP non-existent (see black lines Figures 2b and 2c). Therefore, the strong
 793 freshening seen in MOM along the DSs path could be a result of sea-ice melt
 794 northwest of Iceland. Also the strength of the EGC seems to be affected by
 795 the location of the sea ice. It could be that a reduction in the sea ice in MOM
 796 would lead to a smaller decrease in salinity along the DSs path, leading to
 797 a larger contribution to DSOW. At the same time, the reduction in sea ice
 798 might lead to a stronger cooling of the EGC by the atmosphere which could
 799 resolve into a reduction of this current as is seen in POP. These relations
 800 are hypothetical and require further research outside the scope of this paper.
 801 What this study does show is that while the DSOW transport might be
 802 well captured by ocean models, the path of the dense water to Denmark
 803 Strait is highly sensitive to the hydrographic properties of the modeled ocean
 804 circulation.

805 In conclusion, this paper has shown that the connection between the
 806 North Icelandic Irminger Current and the Denmark Strait Overflow Water
 807 in MOM and POP is not as strong as proposed by observations. Further-
 808 more, this paper confirms that the NIIC is connected to the Iceland Scotland
 809 Overflow Water as well. The watermass transformations taking place north
 810 of Iceland and the vertical structure of the NIIC play a crucial role in setting
 811 the future pathways of the NIIC watermass. The pathways along which the
 812 dense water is formed is different between the two models, highlighting the
 813 sensitivity to the model's representation of the hydrography and circulation
 814 in the Nordic Seas.

815 Acknowledgments

816 S.L. Ypma, S. Georgiou and N. Brüggemann were supported by NWO
 817 (Netherlands Organisation for Scientific Research) VIDI grant 864.13.011
 818 awarded to C.A. Katsman. P. Spence was supported by an ARC DECRA Fel-
 819 lowship DE150100223. H.A. Dijkstra acknowledges support by the Nether-
 820 lands Earth System Science Centre (NESSC), financially supported by the
 821 Ministry of Education, Culture and Science (OCW), Grant no. 024.002.001.
 822 Computing services for the MOM simulations were provided by the National
 823 Computational Infrastructure (NCI) in Canberra, Australia. Use of the
 824 SURFsara computing facilities for the POP simulations was sponsored by the
 825 Netherlands Organization for Scientific Research (NWO-E) under the project
 826 15502. The model data used in the analyses in this paper has been described
 827 in Spence et al. (2017) (MOM) and Weijer et al. (2012) (POP). The observa-
 828 tional dataset at the Kögur section was made available by Benjamin Harden.
 829 The altimeter products were produced by Ssalto/Duacs and distributed by
 830 Aviso+, with support from Cnes (<https://www.aviso.altimetry.fr>). We would
 831 like to thank five anonymous reviewers whose helpful comments greatly im-
 832 proved this paper.

833 Behrens, E., Våge, K., Harden, B., Biastoch, A., Böning, C.W., 2017. Com-
 834 position and variability of the Denmark Strait Overflow Water in a high-
 835 resolution numerical model hindcast simulation. *Journal of Geophysical*
 836 *Research: Oceans* 122, 2830–2846.

837 Blindheim, J., Østerhus, S., 2005. The Nordic Seas, main oceanographic
 838 features. *The Nordic seas: an integrated perspective*, 11–37.

- 839 Courtois, P., Hu, X., Pennelly, C., Spence, P., Myers, P.G., 2017. Mixed layer
840 depth calculation in deep convection regions in ocean numerical models.
841 Ocean Modelling 120, 60–78.
- 842 Danabasoglu, G., Yeager, S.G., Bailey, D., Behrens, E., Bentsen, M., Bi, D.,
843 Biastoch, A., Böning, C., Bozec, A., Canuto, V.M., et al., 2014. North
844 Atlantic simulations in coordinated ocean-ice reference experiments phase
845 II (CORE-II). Part I: mean states. Ocean Modelling 73, 76–107.
- 846 Döös, K., 1995. Interocean exchange of water masses. Journal of Geophysical
847 Research: Oceans 100, 13499–13514.
- 848 Eldevik, T., Nilsen, J.E.Ø., Iovino, D., Olsson, K.A., Sandø, A.B., Drange,
849 H., 2009. Observed sources and variability of Nordic Seas overflow. Nature
850 Geoscience 2, 406.
- 851 Fer, I., Bosse, A., Ferron, B., Bouruet-Aubertot, P., 2018. The dissipation of
852 kinetic energy in the Lofoten Basin Eddy. Journal of Physical Oceanogra-
853 phy 48, 1299–1316.
- 854 Fetterer, F., Knowles, K., Meier, W., Savoie, M., Windnagel, A.K., 2017.
855 Sea Ice Index, Version 3 , Boulder, Colorado USA. NSIDC: National Snow
856 and Ice Data Center.
- 857 Griffies, S.M., Biastoch, A., Böning, C., Bryan, F., Danabasoglu, G., Chas-
858 signet, E.P., England, M.H., Gerdes, R., Haak, H., Hallberg, R.W., et al.,
859 2009. Coordinated ocean-ice reference experiments (COREs). Ocean Mod-
860 elling 26, 1–46.

- 861 Hansen, B., Østerhus, S., 2000. North Atlantic–Nordic Seas exchanges.
862 Progress in Oceanography 45, 109–208.
- 863 Harden, B.E., Pickart, R.S., Valdimarsson, H., Våge, K., de Steur, L.,
864 Richards, C., Bahr, F., Torres, D., Børve, E., Jónsson, S., et al., 2016.
865 Upstream sources of the Denmark Strait Overflow: Observations from a
866 high-resolution mooring array. Deep Sea Research Part I: Oceanographic
867 Research Papers 112, 94–112.
- 868 Harden, B.E., Renfrew, I.A., Petersen, G.N., 2015. Meteorological buoy ob-
869 servations from the central Iceland Sea. Journal of Geophysical Research:
870 Atmospheres 120, 3199–3208.
- 871 Håvik, L., Pickart, R., Våge, K., Torres, D., Thurnherr, A., Beszczynska-
872 Möller, A., Walczowski, W., von Appen, W.J., 2017. Evolution of the East
873 Greenland Current from Fram Strait to Denmark Strait: Synoptic mea-
874 surements from summer 2012. Journal of Geophysical Research: Oceans
875 .
- 876 Jakobsen, P.K., Ribergaard, M.H., Quadfasel, D., Schmith, T., Hughes,
877 C.W., 2003. Near-surface circulation in the northern North Atlantic as
878 inferred from Lagrangian drifters: Variability from the mesoscale to inter-
879 annual. Journal of Geophysical Research: Oceans 108.
- 880 Jochumsen, K., Moritz, M., Nunes, N., Quadfasel, D., Larsen, K.M., Hansen,
881 B., Valdimarsson, H., Jonsson, S., 2017. Revised transport estimates of
882 the Denmark Strait overflow. Journal of Geophysical Research: Oceans
883 122, 3434–3450.

- 884 de Jong, M.F., S  iland, H., Bower, A.S., Furey, H.H., 2018. The subsurface
885 circulation of the Iceland Sea observed with RAFOS floats. *Deep Sea*
886 *Research Part I: Oceanographic Research Papers* .
- 887 J  nsson, S., 1992. Sources of fresh water in the Iceland Sea and the mecha-
888 nisms governing its interannual variability, in: *ICES Marine Science Sym-*
889 *posia*, pp. 62–67.
- 890 J  nsson, S., Valdimarsson, H., 2005. The flow of Atlantic water to the North
891 Icelandic Shelf and its relation to the drift of cod larvae. *ICES Journal of*
892 *Marine Science* 62, 1350–1359.
- 893 J  nsson, S., Valdimarsson, H., 2012. Water mass transport variability to
894 the North Icelandic shelf, 1994–2010. *ICES journal of marine science* 69,
895 809–815.
- 896 K  hl, A., 2010. Variable source regions of Denmark Strait and Faroe Bank
897 Channel overflow waters. *Tellus A* 62, 551–568.
- 898 Korablev, A., Baranova, O.K., Smirnov, A.D., Seidov, D., Parsons, A.R.,
899 2014. Climatological atlas of the Nordic Seas and northern North Atlantic
900 .
- 901 Langehaug, H.R., Medhaug, I., Eldevik, T., Otter  , O.H., 2012. Arc-
902 tic/Atlantic exchanges via the subpolar gyre. *Journal of Climate* 25, 2421–
903 2439.
- 904 Large, W.G., McWilliams, J.C., Doney, S.C., 1994. Oceanic vertical mixing:
905 A review and a model with a nonlocal boundary layer parameterization.
906 *Reviews of Geophysics* 32, 363–403.

- 907 Large, W.G., Yeager, S., 2009. The global climatology of an interannually
908 varying air-sea flux data set. *Climate Dynamics* 33, 341–364.
- 909 Latarius, K., Quadfasel, D., 2016. Water mass transformation in the deep
910 basins of the Nordic Seas: Analyses of heat and freshwater budgets. *Deep*
911 *Sea Research Part I: Oceanographic Research Papers* 114, 23–42.
- 912 Ledwell, J.R., Watson, A.J., Law, C.S., 1993. Evidence for slow mixing across
913 the pycnocline from an open-ocean tracer-release experiment. *Nature* 364,
914 701.
- 915 Logemann, K., Ólafsson, J., Snorrason, Á., Valdimarsson, H., Marteinsdóttir,
916 G., 2013. The circulation of Icelandic waters - a modelling study. *Ocean*
917 *Science Discussions* 10.
- 918 Millero, F.J., Poisson, A., 1981. International one-atmosphere equation of
919 state of seawater. *Deep Sea Research Part A. Oceanographic Research*
920 *Papers* 28, 625–629.
- 921 Moore, G.W.K., Våge, K., Pickart, R.S., Renfrew, I.A., 2015. Decreasing
922 intensity of open-ocean convection in the Greenland and Iceland seas. *Nature*
923 *Climate Change* 5, 877.
- 924 Nilsen, J.E.Ø., Falck, E., 2006. Variations of mixed layer properties in the
925 Norwegian Sea for the period 1948–1999. *Progress in Oceanography* 70,
926 58–90.
- 927 Nurser, A., Bacon, S., 2014. The Rossby radius in the Arctic Ocean. *Ocean*
928 *Science* 10, 967–975.

- 929 Paris, C.B., Helgers, J., Van Sebille, E., Srinivasan, A., 2013. Connectivity
930 Modeling System: A probabilistic modeling tool for the multi-scale track-
931 ing of biotic and abiotic variability in the ocean. *Environmental Modelling*
932 & Software 42, 47–54.
- 933 Perkins, H., Hopkins, T., Malmberg, S.A., Poulain, P.M., Warn-Varnas, A.,
934 1998. Oceanographic conditions east of Iceland. *Journal of Geophysical*
935 *Research: Oceans* 103, 21531–21542.
- 936 Pickart, R.S., Spall, M.A., Torres, D.J., Våge, K., Valdimarsson, H., Nobre,
937 C., Moore, G., Jonsson, S., Mastropole, D., 2017. The North Icelandic Jet
938 and its relationship to the North Icelandic Irminger Current. *Journal of*
939 *Marine Research* 75, 605–639.
- 940 Read, J., Pollard, R., 1992. Water masses in the region of the Iceland–Faeroes
941 Front. *Journal of Physical Oceanography* 22, 1365–1378.
- 942 Richards, C.G., Straneo, F., 2015. Observations of water mass transformation
943 and eddies in the Lofoten Basin of the Nordic seas. *Journal of Physical*
944 *Oceanography* 45, 1735–1756.
- 945 Rudels, B., Quadfasel, D., Friedrich, H., Houssais, M.N., 1989. Greenland Sea
946 convection in the winter of 1987–1988. *Journal of Geophysical Research:*
947 *Oceans* 94, 3223–3227.
- 948 van Sebille, E., Spence, P., Mazloff, M.R., England, M.H., Rintoul, S.R.,
949 Saenko, O.A., 2013. Abyssal connections of Antarctic Bottom Water in a
950 Southern Ocean state estimate. *Geophysical Research Letters* 40, 2177–
951 2182.

- 952 Søliland, H., Chafik, L., Rossby, T., 2016. On the long-term stability of
953 the Lofoten Basin Eddy. *Journal of Geophysical Research: Oceans* 121,
954 4438–4449.
- 955 Spall, M.A., 2004. Boundary currents and watermass transformation in
956 marginal seas. *Journal of Physical Oceanography* 34, 1197–1213.
- 957 Spall, M.A., 2010. Non-local topographic influences on deep convection: An
958 idealized model for the Nordic Seas. *Ocean Modelling* 32, 72–85.
- 959 Spence, P., Holmes, R.M., Hogg, A.M., Griffies, S.M., Stewart, K.D., Eng-
960 land, M.H., 2017. Localized rapid warming of West Antarctic subsurface
961 waters by remote winds. *Nature Climate Change* 7, 595.
- 962 Stefánsson, U., 1962. North Icelandic waters. *Atvinnudeild Háskólans,*
963 *Fiskideild.*
- 964 Straneo, F., 2006. Heat and freshwater transport through the central
965 Labrador Sea. *Journal of Physical Oceanography* 36, 606–628.
- 966 Swift, J.H., Aagaard, K., 1981. Seasonal transitions and water mass for-
967 mation in the Iceland and Greenland seas. *Deep Sea Research Part A.*
968 *Oceanographic Research Papers* 28, 1107–1129.
- 969 Tréguier, A.M., Theetten, S., Chassignet, E.P., Penduff, T., Smith, R., Tal-
970 ley, L., Beismann, J., Böning, C., 2005. The North Atlantic subpolar
971 gyre in four high-resolution models. *Journal of Physical Oceanography* 35,
972 757–774.

- 973 Våge, K., Moore, G.W.K., Jónsson, S., Valdimarsson, H., 2015. Water mass
974 transformation in the Iceland Sea. *Deep Sea Research Part I: Oceanographic Research Papers* 101, 98–109.
- 976 Våge, K., Papritz, L., Håvik, L., Spall, M.A., Moore, G., 2018. Ocean con-
977 vection linked to the recent ice edge retreat along east Greenland. *Nature*
978 *Communications* 9, 1287.
- 979 Våge, K., Pickart, R.S., Spall, M.A., Moore, G., Valdimarsson, H., Torres,
980 D.J., Erofeeva, S.Y., Nilsen, J.E.Ø., 2013. Revised circulation scheme
981 north of the Denmark Strait. *Deep Sea Research Part I: Oceanographic*
982 *Research Papers* 79, 20–39.
- 983 Våge, K., Pickart, R.S., Spall, M.A., Valdimarsson, H., Jónsson, S., Torres,
984 D.J., Østerhus, S., Eldevik, T., 2011. Significant role of the North Icelandic
985 Jet in the formation of Denmark Strait overflow water. *Nature Geoscience*
986 4, 723.
- 987 Valdimarsson, H., Malmberg, S.A., 1999. Near-surface circulation in Ice-
988 landic waters derived from satellite tracked drifters. *Rit Fiskideild* 16,
989 23–40.
- 990 Weijer, W., Maltrud, M., Hecht, M., Dijkstra, H., Kliphuis, M., 2012. Re-
991 sponse of the Atlantic Ocean circulation to Greenland Ice Sheet melting
992 in a strongly-eddy ocean model. *Geophysical Research Letters* 39.
- 993 Wekerle, C., Wang, Q., Danilov, S., Schourup-Kristensen, V., von Appen,
994 W.J., Jung, T., 2017. Atlantic Water in the Nordic Seas: Locally eddy-

- 995 permitting ocean simulation in a global setup. *Journal of Geophysical*
996 *Research: Oceans* 122, 914–940.
- 997 Willebrand, J., Barnier, B., Böning, C., Dieterich, C., Killworth, P.D.,
998 Le Provost, C., Jia, Y., Molines, J.M., New, A.L., 2001. Circulation char-
999 acteristics in three eddy-permitting models of the North Atlantic. *Progress*
1000 *in Oceanography* 48, 123–161.
- 1001 Ypma, S., van Sebille, E., Kiss, A., Spence, P., 2016. The separation of the
1002 East Australian Current: A Lagrangian approach to potential vorticity and
1003 upstream control. *Journal of Geophysical Research: Oceans* 121, 758–774.