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

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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

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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.

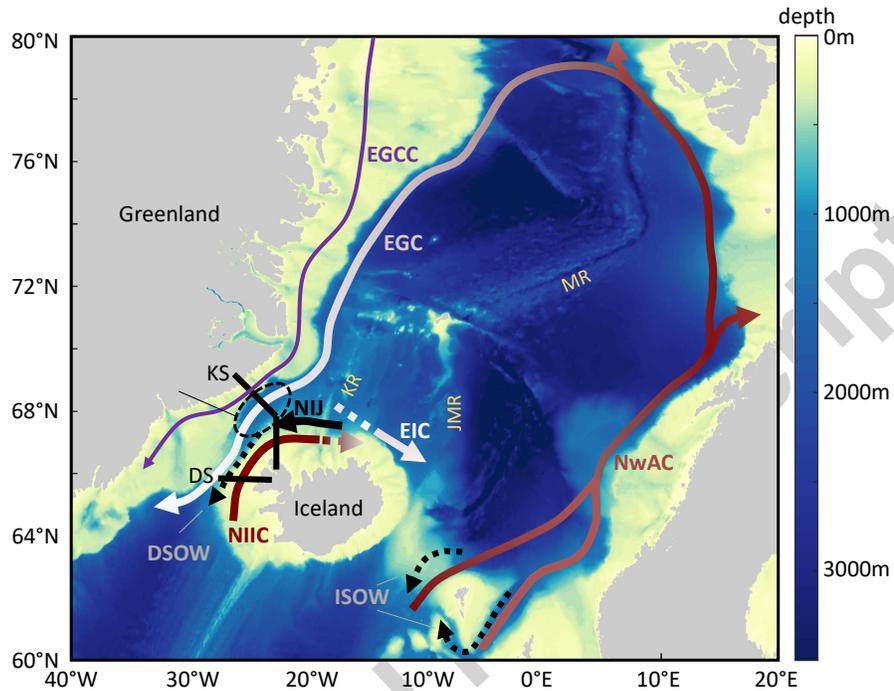


Fig. 1: Schematic of the circulation in the Nordic Seas and bathymetry. Shown in red are the warm and salty inflowing currents: the North Icelandic Irminger Current (NIIC) and the Norwegian Atlantic Current (NwAC). The East Greenland Current (EGC) and the East Icelandic Current (EIC) are shown in white 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

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

96 In addition to the variables mentioned by Köhl (2010), the horizontal
97 resolution, discretization in the vertical, topography, mixing parameteriza-
98 tions and boundary conditions like applied atmospheric forcing and sea-ice
99 conditions impact the mixed layer dynamics and therefore the circulation in
100 the models (Willebrand et al., 2001; Langehaug et al., 2012; Courtois et al.,
101 2017). A correct representation of the convection regions is crucial for the
102 transformation processes of watermasses. However, ocean models still show
103 large differences in mixed layer depth, both in low- and high resolution ocean
104 models (e.g. Tréguier et al., 2005; Danabasoglu et al., 2014).

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

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

119 The paper is structured as follows. Section 2 describes the model simula-
120 tions analysed and the particle tracking method. In section 3 the performance
121 of both models in the Nordic Seas is compared to observations. This is fol-
122 lowed by the main results of this study, where the pathways of the NIIC
123 watermass are described in detail in section 4 and the watermass transfor-
124 mation along the pathways is discussed in section 5. A discussion and the
125 conclusions are provided in section 6.

126 2. Methods

127 In this study, a Lagrangian analysis is conducted to trace the NIIC wa-
128 termass. Numerical particles are advected offline using the velocity fields of
129 the model output. The particles' location, depth, temperature and salinity
130 are saved and used to determine the pathways and watermass transforma-
131 tion of the NIIC water. This method is applied to two ocean models that
132 differ substantially in their representation of deep convection and sea ice in
133 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-

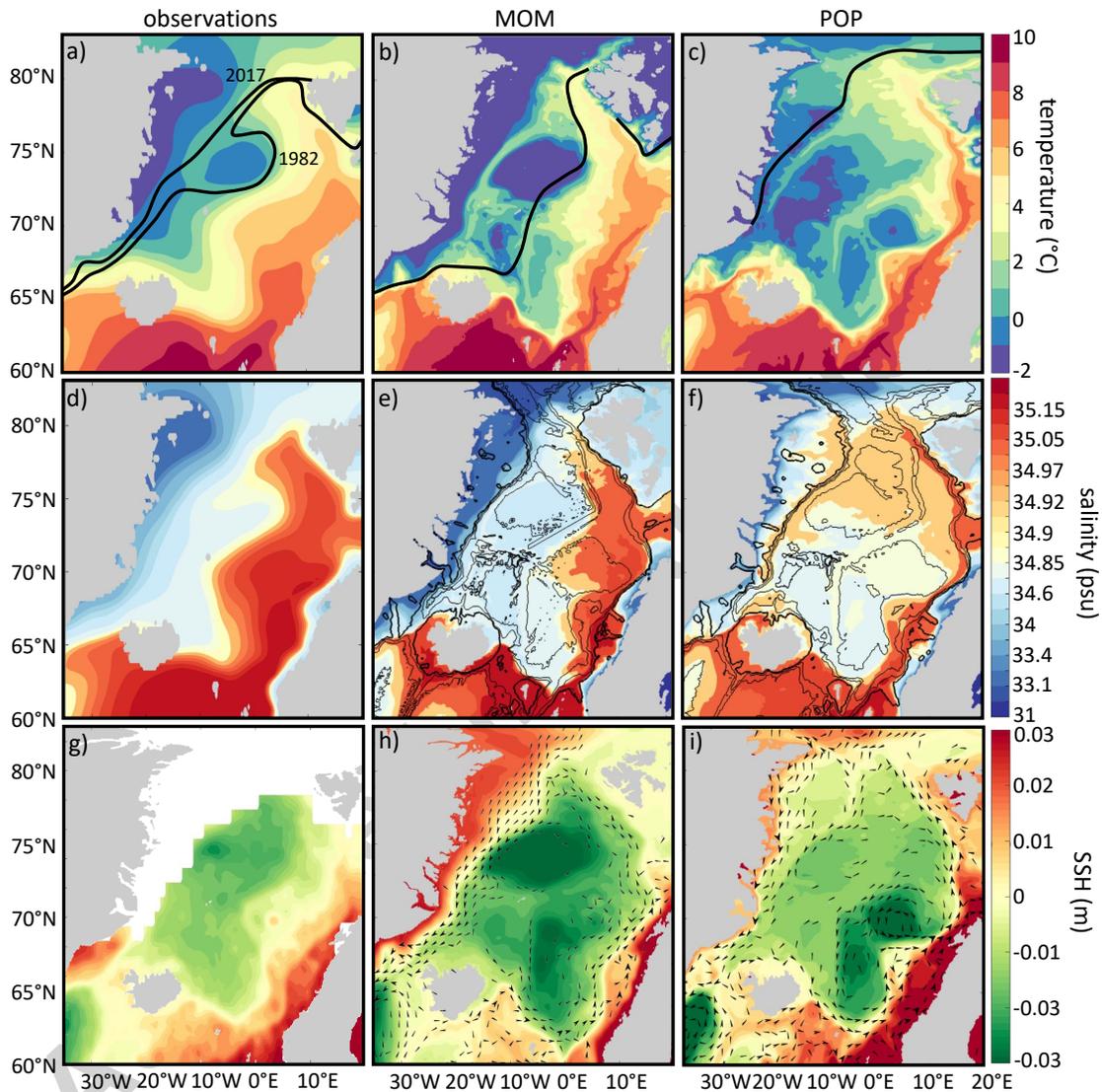


Fig. 2: Mean temperature (top) and salinity (middle) at 50m depth and sea surface height (bottom) from (a,d,g) observations, (b,e,h) MOM and (c,f,i) POP. The observational hydrographic fields show the mean from 1995 to 2010 and are obtained from the Climatological Atlas of the Nordic Seas (Korablev et 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 4^{th} 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

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

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

304

305 *3.2. Nordic Seas Circulation*

306 The circulation pattern in the Nordic Seas is strongly controlled by to-
307 pography, while the strength of the circulation is influenced by the wind

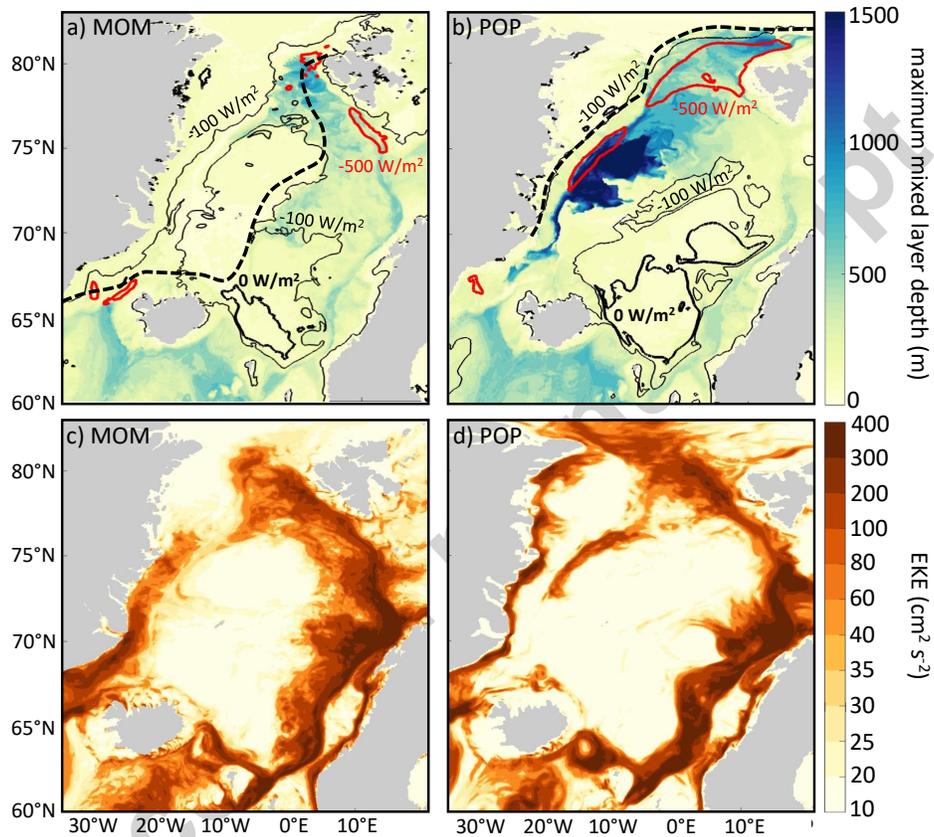


Fig. 3: Maximum mixed layer depth (top) and eddy kinetic energy (bottom) for MOM (left) and POP (right). Solid contours in (a) and (b) show the -500 W/m^2 (in red), -100 W/m^2 and 0 W/m^2 (in black) March mean heat flux. The dashed contours indicate the sea-ice extent in March.

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. Søyland
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

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

340 The eddy kinetic energy (EKE) is shown in Figures 3c-d. Although the
341 model resolution is not sufficient to fully resolve all eddy activity in the
342 Nordic Seas, most of the variability is captured. The largest eddy variability
343 is seen west of the Lofoten islands. Here, the EKE exceeds $400 \text{ cm}^2\text{s}^{-2}$,
344 which compares relatively well to observational estimates (e.g. Wekerle et al.,
345 2017). North of Iceland a small band of increased EKE from the NIIC can
346 be seen. Both observational estimates of the eddy variability in this region
347 and estimates from higher resolution model simulations show slightly larger
348 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
349 (e.g. Jakobsen et al., 2003; Wekerle et al., 2017).

350 3.3. Hydrographic properties at Kögur section

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

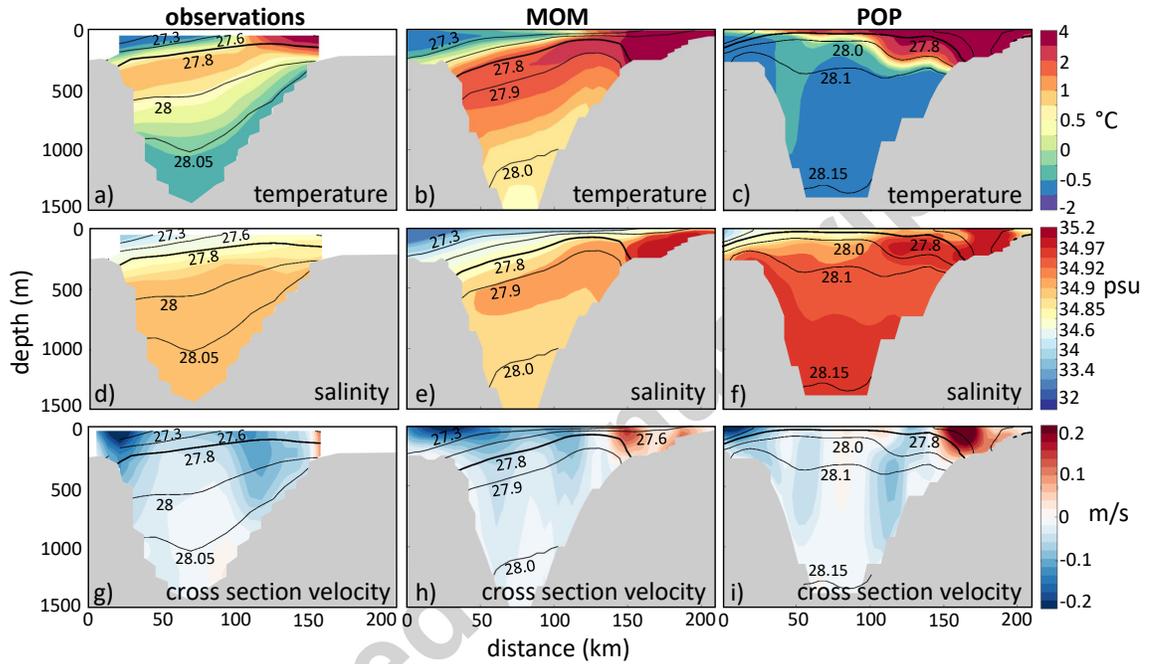


Fig. 4: Sections of temperature (top), salinity (middle) and cross section velocity (bottom) at the Kögur section (transect given in Figure 1). The x-axis shows the distance along the transect, starting at the Greenland coast. Positive velocity indicates northward flow. The left column shows the mean 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).

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

359 Figure 4 shows the mean temperature, salinity and the cross-section ve-
360 locity (positive indicates northward flow) at the Kögur section. The mean
361 temperature along the Kögur transect in MOM captures the observed pattern
362 well (Figure 4b), although the deep waters are too warm ($\Delta T \sim 1^\circ\text{C}$, Figure
363 4b). In POP, the stratification is much stronger than observed, with warmer
364 water at the surface ($\Delta T \sim +2^\circ\text{C}$) and colder waters below ($\Delta T \sim -1.5^\circ\text{C}$,
365 Figure 4c). The salinity shows similar discrepancies, where the surface and
366 deep layers are too fresh in MOM and too salty in POP by ~ 0.1 psu com-
367 pared to the observations (Figures 4e and 4f). Combining the findings for
368 temperature and salinity, the in- and outflowing waters in MOM are slightly
369 too light and the in- and outflowing waters in POP are too dense.

370 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

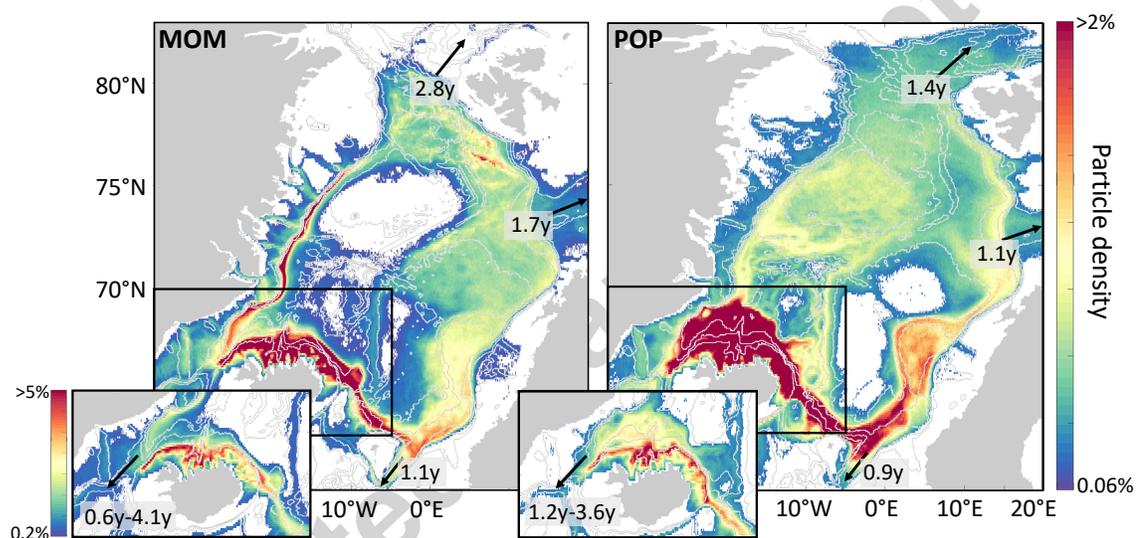


Fig. 5: Density plot of the particle position in MOM (left panel) and POP (right panel). The inlay shows the pathways near Iceland in more detail (note the different colorscale in the bottom left). The median travel time for the particles to reach the exits of the Nordic Seas is given in years.

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

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

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

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

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 DS_m, middle, path) and via the
441 coastal shelf area of Greenland (the DS_c, 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

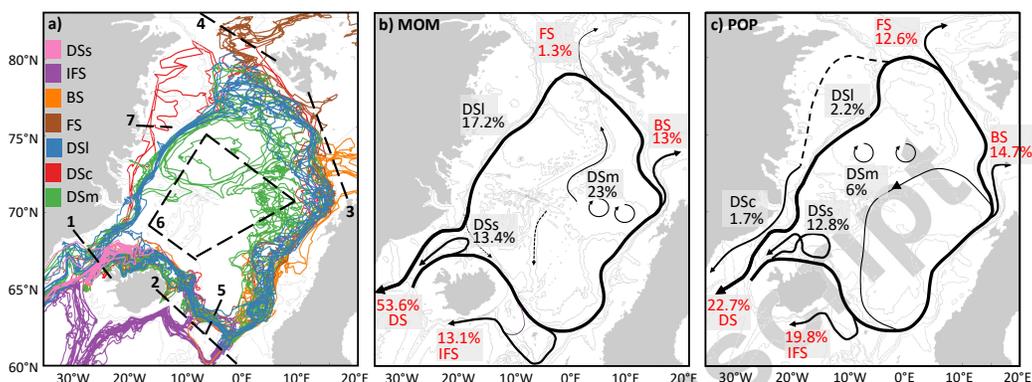


Fig. 6: (a) Example of 63 randomly chosen particle trajectories from both MOM and POP and their categorization (color coding). DSs (Denmark Strait short, pink) are particles that leave the Nordic Seas crossing transect 1, without crossing transect 5. IFS particles (Iceland-Faroe-Shetland, purple) are 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).

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

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

460 In both models, most of the DSs watermass originates from the upper
461 100m of the NIIC (solid pink contour in Figures 7a-b), and this path is
462 therefore shallower than the other paths. The particles follow the shelf break
463 of Iceland and turn northwards at Kolbeinsey Ridge. In MOM, the particles
464 return to Denmark Strait following the 1000m isobath along the Icelandic
465 slope. In POP, some particles circulate in the Bloesville Basin (Figure 1)
466 as well. On their outward journey, there is no indication in MOM that the
467 DSs particles are connected to the NIJ, since the returning particles are all
468 located in the upper 100m of the water column (pink dashed line in Figure
469 7a). In POP, however, there is a clear signal of outward flowing particles

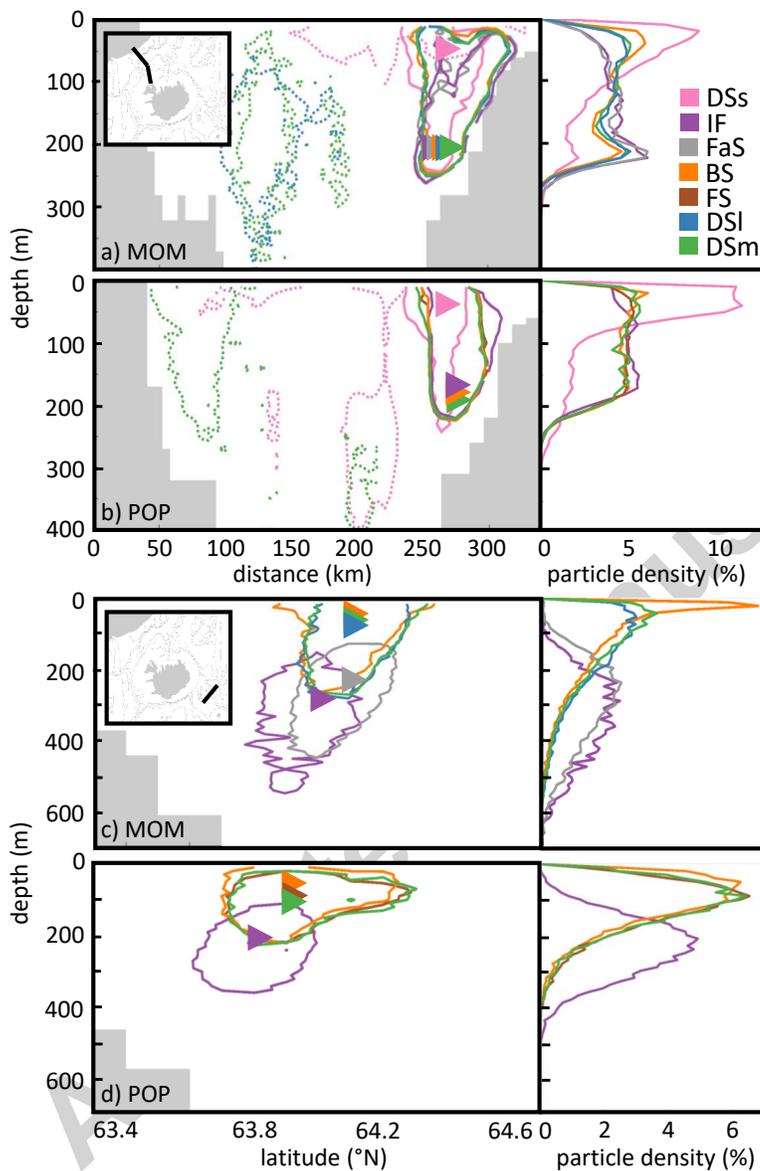


Fig. 7: The depth distribution of each pathway at (a,b) Kögur section and (c,d) a section east of Iceland (see inlays). The left panels show the contour, colored per pathway, that encompasses $>80\%$ of the particles. The triangles give the location where the maximum particle concentration of the pathway 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, DSI 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.

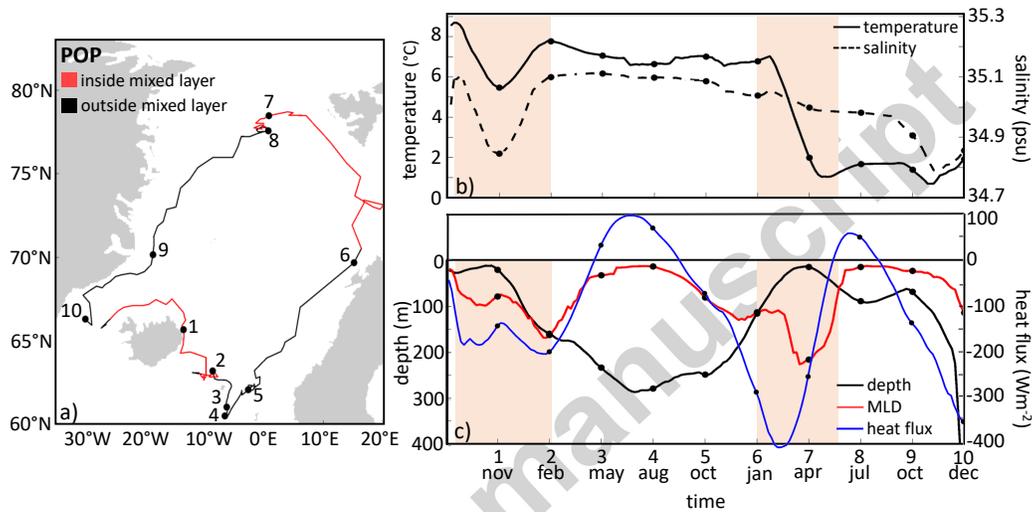


Fig. 8: (a) Example trajectory of a DSI particle in POP that is part of the DSOW. The line is red where the particle is traveling inside the mixed layer, the line is black outside the mixed layer. (b) Temperature (solid black line, left axis) and salinity (dashed black line, right axis) along the path 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.

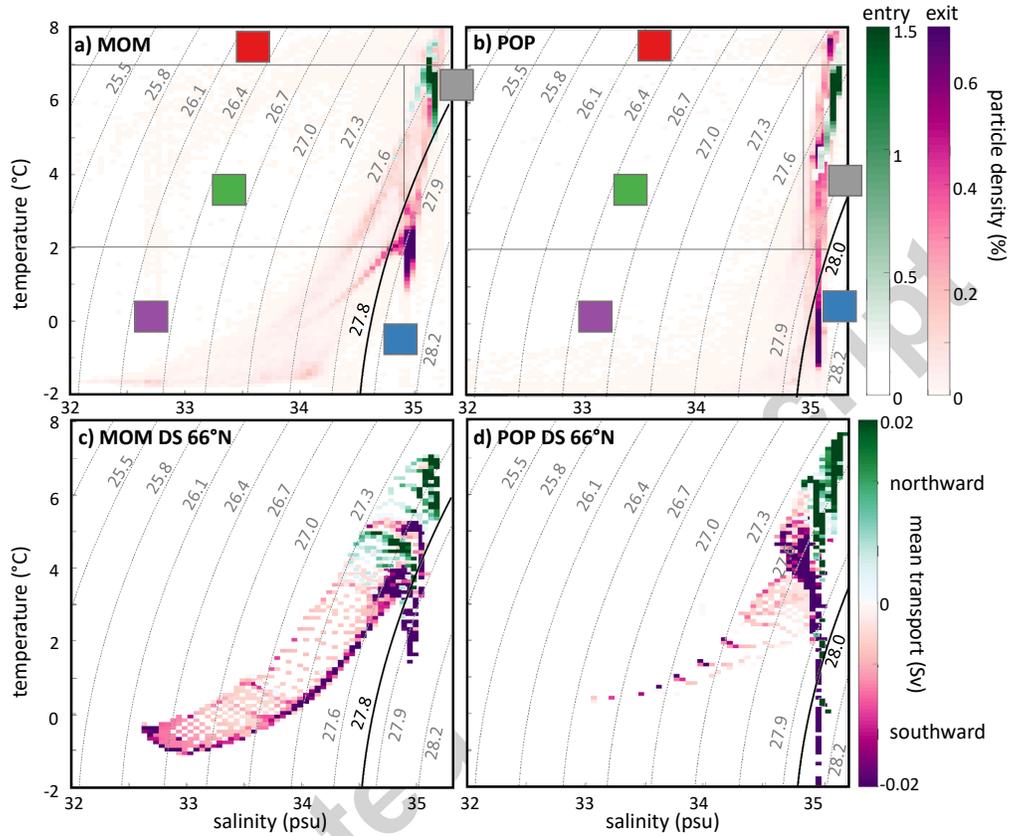


Fig. 9: (a-b) T-S diagrams of the thermohaline properties of the particles when entering the Nordic Seas (in green) and exiting the Nordic Seas at any of the exit locations (in purple) for (a) MOM and (b) POP. The transport weighted particle density is shown per $\Delta T = 0.1^\circ\text{C}$ and $\Delta S = 0.05$ 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.

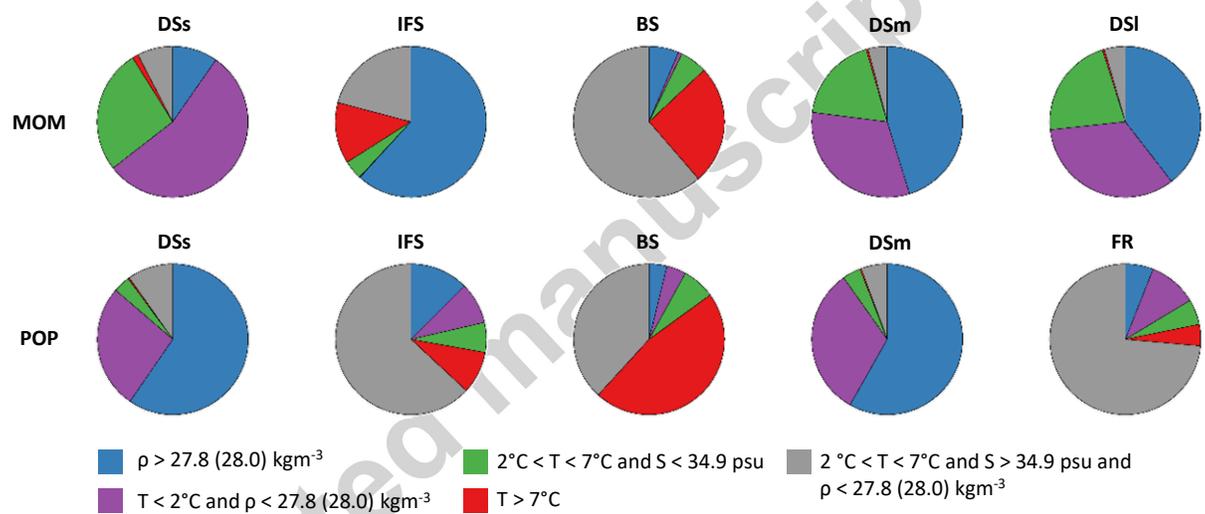


Fig. 10: Fraction of particles per pathway leaving the Nordic Seas within specific T-S categories, described in Figures 9a-b. Only the paths that carry more than 5% of the NIIC water are shown.

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-

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

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

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

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

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

632 *5.2. Location of watermass transformations*

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

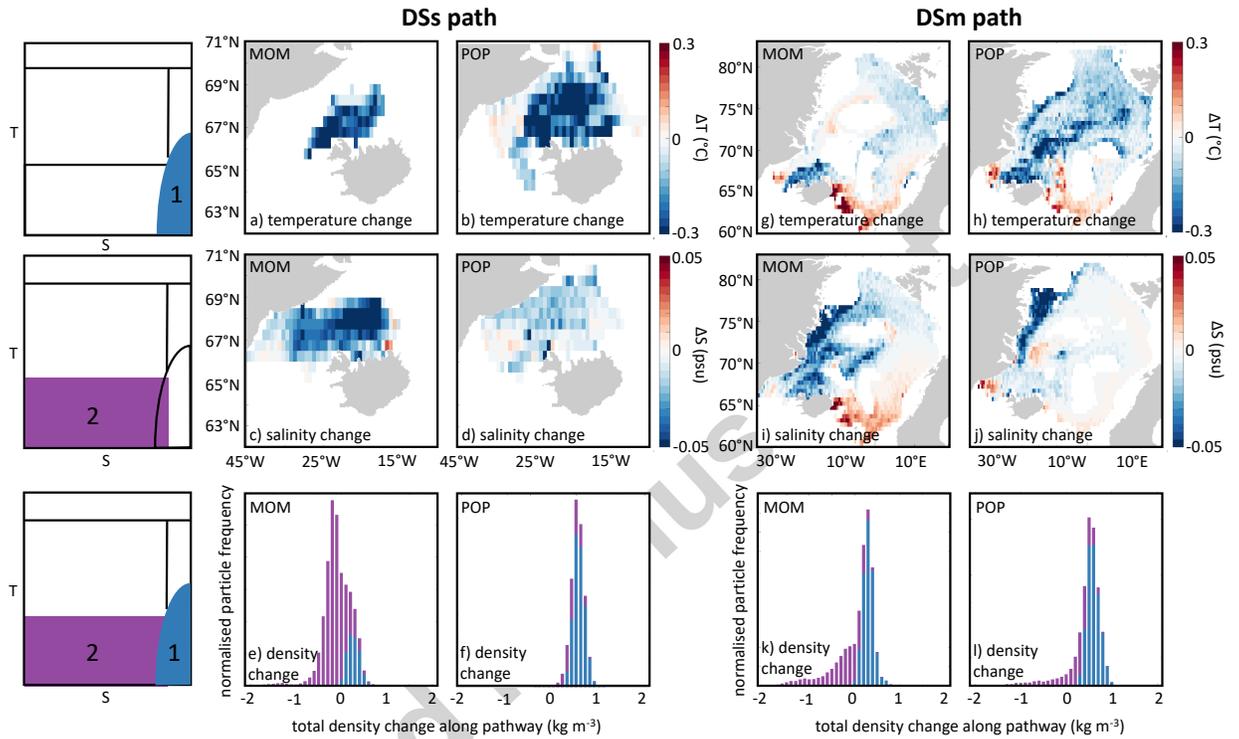


Fig. 11: Temperature change per $0.5 \times 0.5^\circ$ lon-lat gridbox (a-b, g-h), salinity change per $0.5 \times 0.5^\circ$ lon-lat gridbox (c-d, i-j) and total density change (e-f, k-l) along the DSs path (a-f) and the DSm path (g-l). The upper row shows the temperature change of the particles whose 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-

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

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

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

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

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

707 **6. Discussion and conclusions**

708 In this paper Lagrangian particles have been used to investigate the path-
709 ways and the watermass transformation of the North Icelandic Irminger Cur-
710 rent (NIIC) in the Nordic Seas in two ocean models. The volume of the
711 NIIC water along each pathway and the contribution of the NIIC watermass
712 to Denmark Strait Overflow Water (DSOW) and Iceland Scotland Overflow
713 Water (ISOW) have been quantified. Further, the locations of the watermass
714 transformation have been studied to investigate their relation to the location
715 of the convection regions within the Nordic Seas.

716 Based on observations, some studies propose a strong connection between
717 the NIIC and the DSOW, where the NIIC watermass is transformed north-
718 west of the Iceland gyre and flows back into the Atlantic Ocean via the North
719 Icelandic Jet (NIJ) through Denmark Strait (Våge et al., 2011; Pickart et al.,
720 2017). The indication that both currents carry a similar volume transport
721 and the assumption that the EIC does not contain a large part of the NIIC
722 watermass, led to a suggested one-to-one connection between the NIIC and
723 the NIJ (e.g. Pickart et al., 2017). The results from this study provide a
724 different view than that deduced from the observations. The models suggest
725 that the inflowing NIIC watermass is divided over several pathways in the
726 Nordic Seas, and that only 13% of the NIIC watermass flows till Kolbeinsey
727 Ridge to follow the short suggested loop. The region north of Iceland seems
728 to play a crucial role in diversifying these pathways. The connection from
729 the NIIC to DSOW via the NIJ has only been found in POP, since in MOM
730 strong freshening takes place near the surface.

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

741 north of Iceland. Therefore it is possible that observations underestimate the
742 Atlantic Water originating from the NIIC east of Iceland. Also, the part of
743 the NIIC water that travels offshore of Iceland is indistinguishable from the
744 EIC. Therefore, this study fits well with previous work that concluded that
745 the EGC is most likely not the only source for the EIC (e.g. Logemann et al.,
746 2013).

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

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

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