



Freshening of the Barents Sea during the recent decade and its impact on the outflow of dense waters

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Abstract

An important part of the global climate system is the Atlantic Meridional Overturning Circulation, with its deep branch significantly fed by the dense outflow waters exiting the shallow Barents Sea. The formation of dense waters in the Barents Sea, in addition to the changes in temperature is also sensitive to freshwater input into the region. Here, using a suite of satellite, reanalysis and in situ data for the time-period 1993-2024, we investigate the drivers of the interannual variability and recent changes in the salinity of the southern (SBS) and northern Barents Sea (NBS) and its impact on the outflow of dense waters. We present new evidence of the imprint of the extremely low saline waters in recent years in both parts of the Barents Sea resulting from the unprecedented freshening observed in the northern North Atlantic. While the salinity variability in the SBS is found to be affected mainly by the variability of the Atlantic Water salinity transported into the region, the salinity variability in the NBS is additionally influenced by the freshening due to the increased sea ice import from the central Arctic. Further analysis shows that the atmospheric circulation pattern, favouring sea ice and freshwater transport from the central Arctic to the NBS, has also contributed to the freshening in the NBS. The freshening of the Barents Sea in the recent years is further found to result in the lowest density of the dense waters exiting, respectively to the Nordic Seas and to the central Arctic.

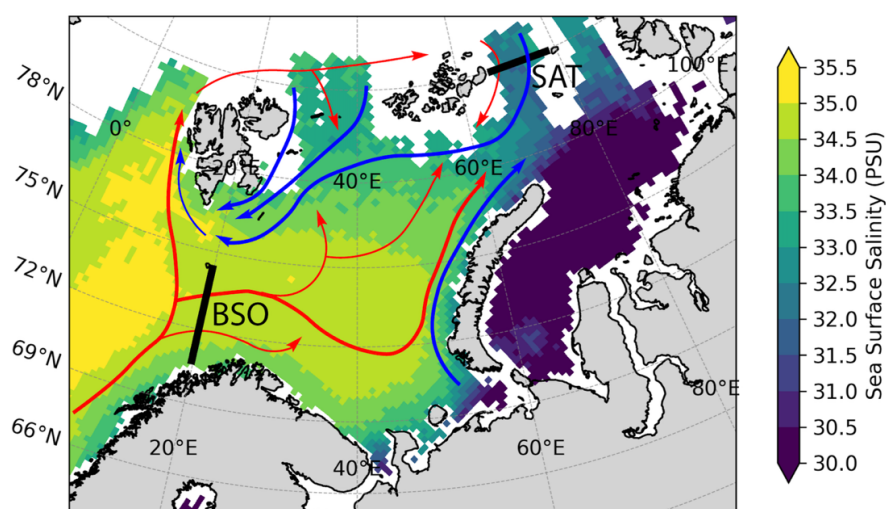
1. Introduction

The Atlantic Water (AW) transport from the North Atlantic to the Arctic Ocean and its densification through buoyancy fluxes while en route is a main driver of the thermohaline circulation (Aagaard, 1981; Rudels et al., 2015). The shallow Barents Sea shelf (mean depth of 230 m) accounts for a substantial part of the dense water that is formed within the Arctic (Martin & Cavalieri 1989). A major source of interannual variability in the Barents Sea hydrography is the inflow of AW (Arthun et al., 2012), branching out from the Norwegian Atlantic Current and



35 entering the Barents Sea from the southwest through the Barents Sea Opening (BSO; Figure 1).
 36 The propagation of temperature and salinity anomalies from the North Atlantic through the Nordic
 37 Seas and into the Barents Sea through the BSO is well documented (e.g., Furevik, 2001; Sundby
 38 & Drinkwater, 2007; Årthun & Eldevik, 2016). These previous studies have found typical
 39 propagation speeds of 2-3 cm/s within the Nordic Seas, yielding a time lag of approximately 2-3
 40 years between the inflow region to the Nordic Seas in the south and the BSO. During the years
 41 2012-2016, an unprecedented freshening was observed in the north-eastern North Atlantic
 42 (Holliday et al., 2020). The freshening was attributed to anomalous winter wind patterns rerouting
 43 Arctic-origin water in the Labrador Current off the continental shelf poleward into the northern
 44 North Atlantic (Holliday et al., 2020). On the other hand, according to Kenigson and Timmermans
 45 (2021), this anomalous event can be linked to the wind-driven displacements of the Subpolar Front
 46 due to persistent positive North Atlantic Oscillation (NAO+) conditions during 2014–16. These
 47 events were possibly superimposed on the decadal variability in the subpolar North Atlantic gyre
 48 circulation, which largely controls the Atlantic Water intrusion in the Nordic seas (Hatun et al.
 49 2005), and exhibited a strong (weak) gyre circulation favouring negative (positive) salinity
 50 anomaly in the AW during 2005-16 (1993-2005) (Chafik et al., 2019). The northward propagation
 51 of the negative salinity anomaly into the downstream Nordic Seas in the recent decade is well
 52 documented (Mork et al., 2019).

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55 **Figure 1.** Satellite-derived mean sea surface salinity (SSS) in the Barents Sea (2010-2023). The
 56 sections, Barents Sea Opening (BSO) and St. Anna Trough (SAT) are indicated by thick black
 57 line. The main circulation features of the region are overlaid (Red: Atlantic Water; Blue: Arctic
 58 Water) on the mean SSS.

59 After entering the southern part of the Barents Sea, a large amount of the heat carried by the AW
 60 is released to the atmosphere (Serreze et al. 2007; Smedsrud et al. 2010), before travelling further



61 north and setting the southward limit of sea ice extent in the northern Barents Sea. In addition to
 62 the AW flow from the south, the hydrographic variability in the northern Barents Sea is dominated
 63 by variations in the inflow of AW from the north (Lind & Ingvaldsen, 2012) and the import of sea
 64 ice and lower salinity Arctic Water from the Polar Basin (Lind et al., 2018). After undergoing
 65 considerable modifications within the Barents Sea, the poleward AW flow enters the Polar Basin
 66 through the St. Anna Trough (e.g., Schauer et al., 2002), thereby contributing to the renewal of the
 67 intermediate and deep water in the Arctic Ocean (Rudels et al. 1994; Jones et al. 1995; Rudels et
 68 al. 2000). Several processes contribute to this water mass modification within the Barents Sea
 69 (Pfirman et al. 1994; Rudels et al. 1994; Ozhigin & Ivshin 1999; Rudels et al. 2004). These
 70 processes include freshwater input from river runoff, sea-ice melting and net precipitation
 71 (Coachman & Barnes 1963; Steele et al. 1995), wind and tidal mixing (Sundfjord et al. 2007),
 72 atmospheric cooling and subsequent sea-ice formation (Aagaard et al. 1981; Jones et al. 1986,
 73 Smedsrud et al., 2013; Skagseth et al., 2020). The dense water formed within, exits the Barents
 74 Sea at the northern part of the BSO and along the St. Anna Trough respectively into the Nordic
 75 Seas and into the central Arctic.

76 During recent years, the Barents Sea has been experiencing rapid changes involving complex
 77 feedback mechanisms that make the region a focal point for understanding ongoing and future
 78 Arctic climate change and its further implications (Lind et al., 2018; Chatterjee et al., 2024; Challet
 79 et al., 2025). While the atmospheric heat loss in the southern Barents Sea has been found to
 80 decrease (Skagseth et al., 2020), it has increased in the northern Barents Sea (Shu et al., 2021).
 81 The reduced heat loss affects the outflow of dense water, which enters the Nordic Seas through
 82 the northern parts of the BSO (Blindheim, 1989; Årthun et al., 2011; Skagseth et al., 2020). The
 83 dense outflow waters exiting the Barents Sea at BSO and the St. Anna Trough are also expected to
 84 be affected by changes in salinity due to the downstream impact of the unprecedented freshening
 85 noted in the northern North Atlantic (Holliday et al., 2020) and due to the changes associated with
 86 freshwater or sea ice import from the north (Lind et al., 2018).

87 In here, we utilize a suite of regional ocean reanalysis, in situ and satellite remote sensing datasets
 88 to document recent changes in the Barents Sea salinity, its drivers, and assess the potential impact
 89 on the dense waters exiting the Barents Sea to the Arctic via the St. Anna Trough and to the Nordic
 90 Seas through the BSO.

91 **2 Data & Methods**

92 **TOPAZ:** Model data used are the Copernicus Marine Service reanalysis for the Arctic region (ref.
 93 1 in Table 1). TOPAZ4, a coupled ocean and sea ice data assimilation system for the Arctic based
 94 on the HYbrid Coordinate Ocean Model (HYCOM), with 50 hybrid z-isopycnal layers at a
 95 horizontal resolution of 12 to 16 km, uses the ensemble Kalman filter method (EnKF; Evensen
 96 2003) to assimilate consistently multiple types of observations in the ocean and sea ice (Xie et al.,
 97 2016). TOPAZ4, forced by ERA5 reanalysis, assimilates observations such as including along-
 98 track altimetry data, sea surface temperatures, sea ice concentrations and sea ice drift from



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satellites along with in situ temperature and salinity profiles. The detailed setup of the TOPAZ4

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reanalysis and its performance is detailed in Sakov et al. (2012) and Xie et al. (2023).

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ESA CCI SSS data:The CCI+SSS project aims to generate improved calibrated global SSS fields

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from all available satellite L-band radiometer measurements, with regional extensions utilising C-

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band radiometer data. This initiative seeks to leverage the full potential of the ESA/Earth Explorer

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SMOS mission, in conjunction with the SMAP and AQUARIUS satellite missions, by assembling

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expert teams in earth observation, satellite data validation, and the study of climate variability.

106

Monthly sea surface salinity product for the Northern Hemisphere on a 25km EASE grid, v5.5,

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available for the time-period 2010 to 2023 is used here (Boutin et al., 2025).

108

ERA-5: Monthly mean sea level pressure data for the time-period (1991-2024) is used in this study

109

to investigate the role of large-scale atmospheric forcing.

110

ICES data: The temperature, salinity, density data at BSO and Svinøy section are obtained from

111

the ICES database (<https://ocean.ices.dk/core/iroc>).

Product ref. no	Product ID & Type	Data access	Documentation
1	ARCTIC_MULTIYEAR_PHY_002_003, numerical models	EU Copernicus Marine Service Product (2025)	Quality Information Document (QUID): Xie and Bertino (2025) Product User Manual (PUM): Ali et al. (2025)
2	MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012, in-situ observations, satellite observations	EU Copernicus Marine Service Product (2023)	QUID: Grenier et al. (2023) PUM: Verbrugge (2023)



3	ESA CCI SSS, satellite observations	NERC EDS Centre for Environmental Data Analysis, https://catalogue.ceda.ac.uk/uuid/0397ca6f625e47f489684bad2bd533bb , last access: August 2025	Boutin et al., 2025
4	In-situ Observations (CTD)	ICES Report on Ocean Climate (IROC), https://ocean.ices.dk/core/iroc , last access: August 2025	González-Pola et al., 2023
5	ERA-5 MSLP, numerical models	Copernicus Climate Change Service (2023): ERA5 monthly averaged data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). DOI: 10.24381/cds.fl7050d7 last access: August 2025	Hersbach et al., (2020)

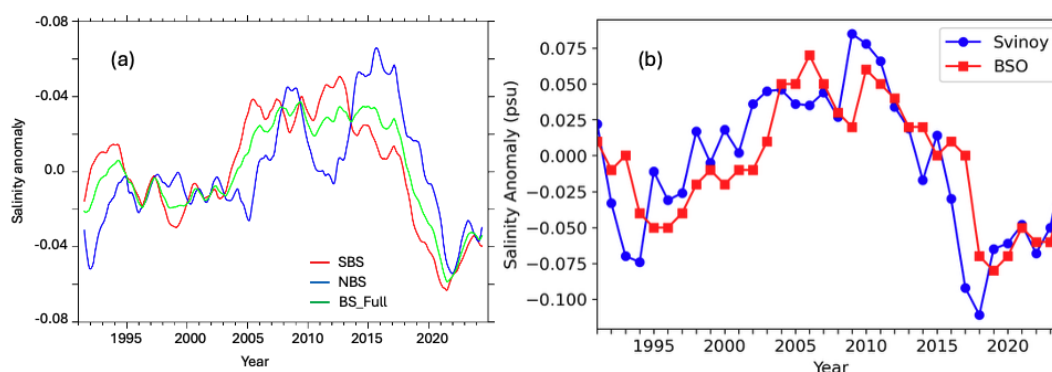
112 3. Results

113 Reanalysis data averaged over the full Barents Sea domain (20E to 60E; 70N to 80N) and from
114 surface to bottom show a rapid decline in the overall salinity in the Barents Sea after 2016-2017,
115 followed by a salinity minimum in 2021-2022. The salinity decline followed a period of gradual
116 salinity increase (1993-2016; Fig. 2a). This salinity minimum aligns with the rapid decline in
117 salinity in the upstream North Atlantic during the period 2012-2016 (Holliday et al., 2020), and
118 subsequently in the Norwegian Sea (Mork et al., 2019), provided an advection time of a few years
119 from the North Atlantic to the entrance of the Barents Sea (Furevik, 2001; Årthun and Eldevik,
120 2016). To understand the regional drivers of this salinity change, we further focus our analysis on
121 the northern (NBS; 20°E to 60°E; 70°N to 75°N) and southern (SBS; 20E to 60E; 76N to 80N)
122 Barents Sea separately. The long-term variability in the salinity of the two regions shows similar
123 trends in general, i.e., an increasing trend followed by a decreasing trend during the recent decades
124 (Fig. 2a). However, there are also major deviations, for example, while the SBS shows an



125 increasing trend in salinity from late 1990s to mid 2010, the increasing trend in the NBS salinity
126 is seen to occur during early 1990s to around 2016-2017.

127 The propagation of salinity anomalies from the Nordic Seas into the Barents Sea via BSO is shown
128 in Figure 2b. In accordance with findings reported in the literature, the salinity variability (upper
129 ocean, 200 m) of SBS follows that at the BSO and Svinøy. The increasing trend in salinity followed
130 by a decreasing trend and the minimum is also seen at BSO and Svinøy, but with a lag. The
131 minimum in salinity at Svinøy is found during 2018, while at BSO and SBS it is at around the
132 time-periods 2019-2020 and 2021-2022 respectively. The lag further confirms the propagation of
133 salinity anomalies and its significant impact on the salinity variability of the SBS.
134



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136
137 **Figure 2.** a. Interannual (12 month running mean) variability of depth-averaged salinity in the southern
138 Barents Sea (SBS; red), northern Barents Sea (NBS; blue) and the full Barents Sea (BS_Full; green)
139 obtained from TOPAZ reanalysis. b. Time series showing annual averaged salinity in the upper 200 m depth
140 at the Svinøy (63°N, 3°E; Figure 1) and Barents Sea Opening (BSO; Figure 1; 73°N, 20°E), from in situ
141 observations during the TOPAZ time period (1991-2024).

142 Extending the analysis to the 1970s using observations from the BSO (Blindheim and Loeng, 1981;
143 González-Pola et al., 2020; Fig. 3b) shows that previous salinity anomalies have been even
144 stronger, most notably in 1978-79 in comparison to one during 2018-2019. Figure 3b,c shows that
145 while the salinity at BSO during the latest salinity anomaly events drops below the low salinity
146 anomalies observed during the late 1980s and late 1990s, the temperature remained relatively high.
147 The lower temperature during those earlier low salinity periods compensated for the lower salinity
148 with respect to density changes. A consequence of the warming in recent decades is therefore an
149 unprecedented (in the instrumental record) low AW density observed since 2015 in the Barents
150 Sea (Fig. 3a).

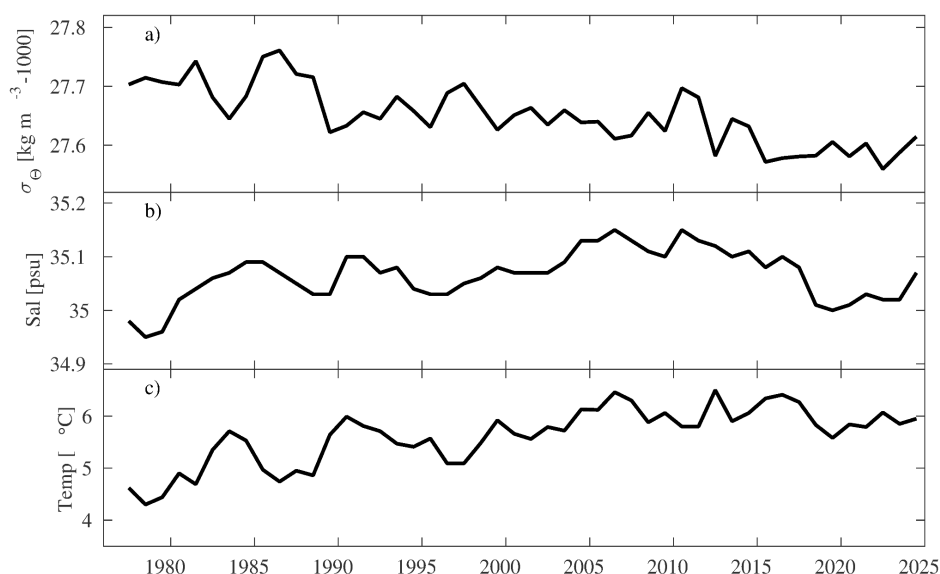
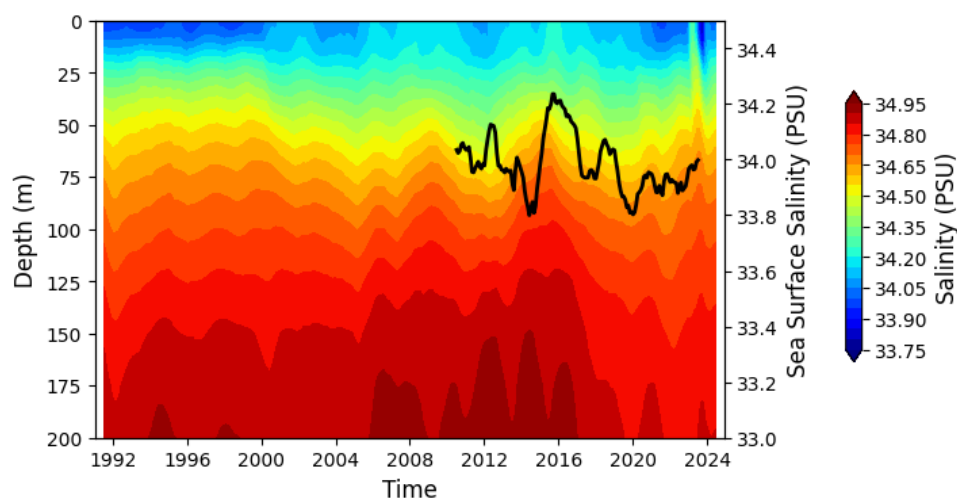


Figure 3: Time series showing annual average a) density, b) salinity, and c) temperature averaged over 50-200 m depth in the Barents Sea Opening section, based on CTD observations during the period 1978-2024.

We now shift our focus to the NBS, which, in addition to being influenced by AW, also is dominated by the exchanges of sea ice and less saline and colder Arctic Water from the Polar Basin (Pfirman et al., 1994; Lind et al., 2018). Moreover, the NBS has two sources of AW; inflow of AW from the SBS (Schauer et al., 2002), and the onshelf intrusion of AW flowing eastward along the northern Barents Sea shelf slope in the Polar Basin (Fig 1, Lind and Ingvaldsen, 2012; Lundesgaard et al., 2022). Our analysis showed an increasing salinity in the NBS till around 2016-2017, followed by a rapid decline from 2017 onwards until 2022 (Figure 2b). The lag between the salinity variability of the NBS and SBS is around 1 year during the latest freshening event (after 2016-2017), which is consistent with the travel time of AW from the SBS to NBS. However, this is not the case for the rest of the time-period, particularly from mid-2000s to around 2016. Thus the change in salinity in the NBS is not fully explained by the lateral transport of anomalously fresh AW from the SBS. Note that in a previous study, Lind et al (2018) attributed the reduced sea ice import from the central Arctic to the increased salinity in the NBS during the same period. Since sea ice import is expected to mainly impact the sea surface salinity (SSS) of the region, we further investigate SSS variability of the NBS. Fig. 4 shows the SSS in the NBS for the recent period (2010-2023) obtained from the ESA CCI satellite mission, along with the vertical profile from the TOPAZ reanalysis for a longer period. A freshening in the NBS region after 2016-2017 can be seen both in surface and deeper depths. The increasing trend in salinity from the mid-2000s to 2016-2017 is also seen in Fig. 4. This increasing trend is consistent with the results of Lind et al. (2018), who showed a similar trend during the time-period due to a decrease in sea ice import



177 from the central Arctic. However, our analysis showed that in recent times this trend has changed
 178 due to a change in the atmospheric circulation pattern in the central Arctic. The recent freshening
 179 in NBS is consistent with an increased sea ice drift into the region (Fig. 5a). When comparing the
 180 period with increasing salinity in the northern Barents Sea (1993-2015) with the period of rapid
 181 decline and lower salinity (2016-2024), we find anomalous northwesterly geostrophic winds that
 182 favour increased sea ice import from the central Arctic through the northern Barents Seas during
 183 the latter period (Fig. 5b). Furthermore, the period of increasing salinity is also consistent with the
 184 decreasing trend in fresher Arctic water import from the eastern Barents Sea, which increased
 185 thereafter (see Figure 7 in Chatterjee et al., 2024).



186

187 **Figure 4.** 12-month running mean of monthly salinity in the upper 200m from TOPAZ reanalysis
 188 (colour) and sea surface salinity from ESA CCI (black line, right Y-axis) averaged over the
 189 northern Barents Sea (76-80N, 20-60E).

190 In the following, we investigate the downstream effects of the changes in the salinity of the Barents
 191 Sea on the dense outflow waters exiting the Barents Sea into the Nordic Seas and the central Arctic.
 192 Figure 6 shows the annually averaged temperature and salinity of the densest 5% of the water
 193 masses in sections crossing the outflow of dense water from the Barents Sea into the Nordic Seas
 194 and into the central Arctic respectively at BSO and St. Anna Trough (SAT; see Fig 1 for locations).
 195 At BSO, the increase in temperature during the 2000s was partly offset in terms of density change
 196 by an increase in salinity. In the last ten years, however, the decrease in salinity has tended to
 197 reduce the density further to unprecedented low levels in the 1993-2024 period (Fig 6a). At SAT
 198 (Fig 6b), the impact of salinity on the density shows a similar pattern, with record low values in
 199 both salinity and density in the most recent years. The cooling of the AW en route through the
 200 Barents Sea has been reported to decline in recent decades (Skagseth et al., 2020). A warming
 201 trend is also reflected in our model results, with the temperatures of the densest water being below
 202 0° C before 2005 and around or above 0° C in all years after 2005 (Fig. 6b).

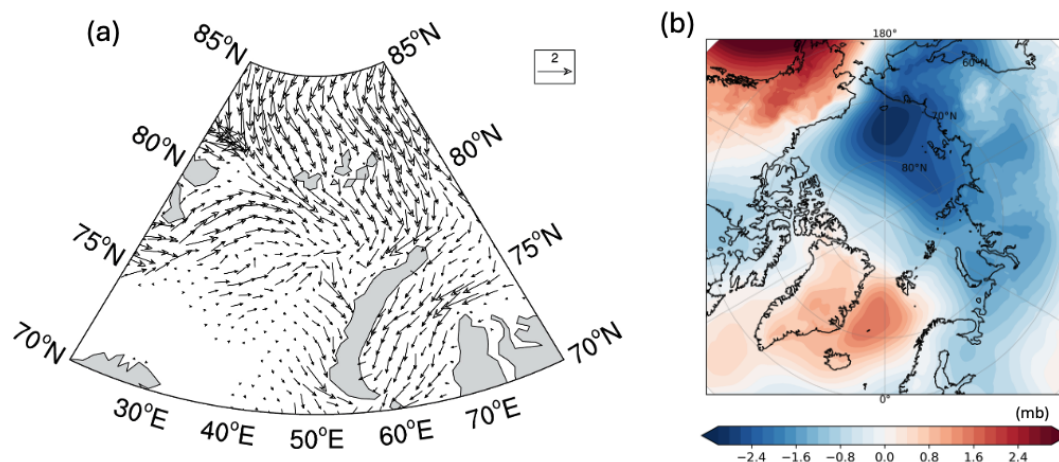


Figure 5. a. Winter mean (NDJFM) sea ice drift velocity (cm/s) from TOPAZ4b reanalysis between the time periods (2016-2024) and (1993-2015). b. Same as (a) but for SLP difference from ERA-5.

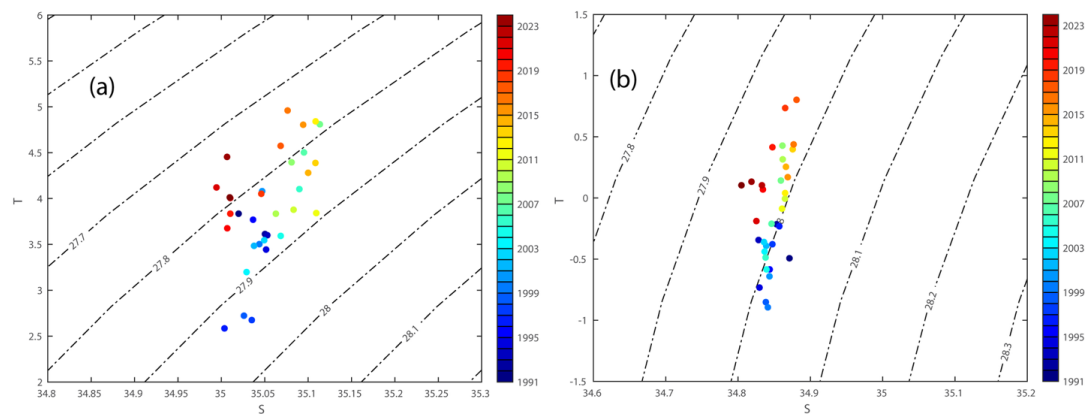


Figure 6. Temperature-salinity diagram showing the hydrographic properties of the densest 5% of the water masses in a) BSO and (b) SAT. The data represent TOPAZ reanalysis annual averages. Color denotes the year of the annual average.

4. Summary and Discussion

In this study, we present the evidence of the recent freshening in the Barents Sea resulting from the unprecedented salinity anomaly observed in the northern North Atlantic during 2012-2016 (e.g., Holliday et al., 2020). The recent salinity anomaly transported into the SBS differs from previous low salinity anomalies (during the late 1970s and 1980s) during when the temperature remained relatively high, whereas previously the temperature and salinity have tended to move in



concert (e.g., Furevik, 2001; Mork et al., 2019). A possible mechanism for the positive correlation between temperature and salinity was suggested by Sundby & Drinkwater (2007), suggesting that atmospheric conditions favoring (working against) increased flow along the Norwegian coast push the temperature and salinity gradients downstream (upstream), causing both temperature and salinity to locally increase (decrease). With respect to the temperature anomalies, although relatively colder AW has intruded into the Norwegian Seas from the North Atlantic since the mid-2000s, a reduced heat loss from the ocean surface has helped in sustaining the temperature anomalies and thereby decoupling the temperature and salinity signal in the Nordic Seas (e.g. Skagseth et al., 2020, Mork & Skagseth et al., 2019, Chatterjee et al., 2024). On the other hand, the magnitude of the salinity anomaly in the upstream Subpolar Gyre has been found to dominate the signal, although there is some indication of a weakening of the salinity anomaly signal northward in the Norwegian Sea (González-Pola et al., 2020) and Barents Sea (Fig. 2b). This is further underpinned by the observation that while the northern North Atlantic low salinity anomaly in 2012-2016 was unprecedented for the last 120 years, direct hydrographic observations from the BSO (Blindheim and Loeng, 1981; González-Pola et al., 2020) dating back to the late 1970s, show that the negative salinity anomaly in the Barents Sea during 1977-1979 was even stronger (Fig. 3). This is indicative of an advective signal that gets diluted as it travels downstream. The salinity variability within the SBS tightly follows the variability of the AW salinity transported in, and is substantiated by the 1-2 year lag consistent with the AW travel time (Fig 2).

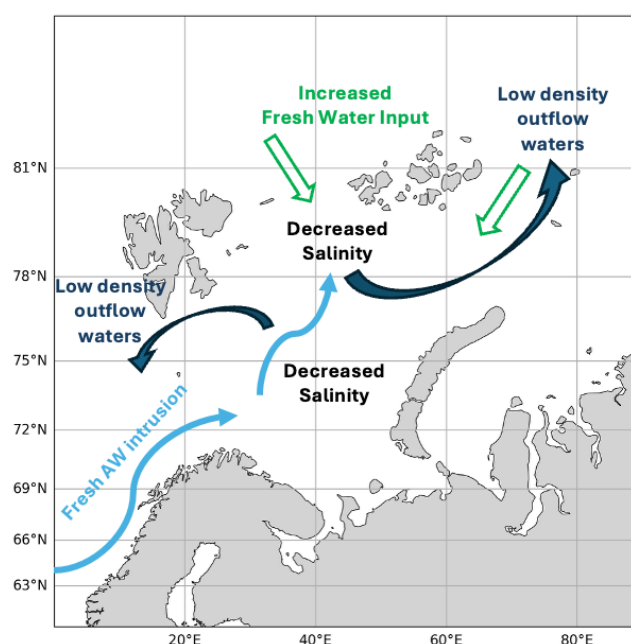
The salinity variability in the NBS is found to be more complex and is found to be influenced by both the sea ice import from the central Arctic as well as the AW salinity variability transported from the SBS. The reduction in sea-ice import into the NBS has been found to increase the salinity of the region during the time period 2003-2016 (e.g., Lind et al., 2018). Our study showed that the increasing trend in the salinity of the NBS no longer exists after 2016; in fact, the salinity of the region has shown a rapid freshening since then. This reversal in the salinity variability is further linked to the increased transport of sea ice into the region, an opposite scenario to that reported by Lind et al. (2018). The increased sea ice import is associated with a change in the atmospheric circulation pattern over the Arctic. Anomalous northwesterly geostrophic winds are found to favour increased sea ice import from the central Arctic through the northern Barents Seas after 2016. Lind et al. (2018) further suggested that freshening could further inhibit vertical penetration of Atlantic water to the surface, reversing a trend that had been developing during the 1990s and onwards. Thus, the recent freshening in NBS was also driven by increased freshwater import from the northern and eastern Barents Sea, reversing the trend identified by Lind et al. (2018).

We also note the difference in lag between the salinity variability of the NBS and SBS (Fig 2a). It is found that during the recent freshening since 2016, the lag between the salinity variability of the two regions is shorter, compared to the earlier period, particularly with the rapid increase in NBS salinity during 2003-2016. We hypothesize that the sea ice import in the NBS can modify this interaction between SBS and NBS salinity variability. During the increased freshwater import after 2016, the enhanced stratification of the upper ocean in NBS allows a more direct downstream impact of SBS salinity anomaly through lateral advection. Whereas, with reduced sea ice import



259 during 2003-2016, as reported in Lind et al., (2018), the weakened stratification in the NBS region
260 favours local vertical mixing, which may play a larger role in driving the NBS salinity over the
261 lateral transport from SBS, resulting in weaker correlation between these two regions.

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263

264 **Figure 7.** Summary diagram of the mechanisms involved in the recent freshening in the northern
265 and southern Barents Sea and its implications.

266 Our model results show that in both outflow regions from the Barents Sea, the densest water
267 masses were warming from the start of our model period in 1993 to 2016 (BSO) and 2018 (SAT).
268 Concurrent with the warming, the salinity was also increasing, partly offsetting the density
269 decrease due to the warming. Then, during the most recent years, the temperature has declined,
270 but a stronger decline in salinity more than offset the reduction in density from the cooling,
271 resulting in the density being at the lowest for the full model timeseries. These hydrographic
272 changes are in agreement with findings based on observations both in the BSO (Skagseth et al.,
273 2020) and the SAT (Zabudkina et al., 2025). Moreover, our results indicate that the trends in the
274 hydrographic properties of the dense water exiting the Barents, in either end, to a large degree
275 reflect the trend in the hydrographic properties of the AW initially entering through the BSO,
276 despite the internal water transformation processes. Historical records, however, indicate this not
277 to always be the case. During the period of unprecedented low salinity of the inflowing AW in
278 1978-79 (Fig. 3b), high-salinity shelf water was observed near the bottom in the northeastern
279 Barents Sea, yielding densities above 28.1 (Midttun, 1985). The reason was the proximity of the
280 Novaya Zemlya Bank, where polynya activity causes strong cooling and excessive sea-ice
281 formation and subsequent brine release. In comparison, in 2008, during the period of maximum



AW salinity, no brine-enriched bottom water was observed and the maximum observed density of 28.09 was slightly less than that observed in 1979 (Lien and Trofimov, 2013). These observations suggest that in today's warmer climate with strongly reduced sea-ice formation in the Barents Sea, the density of the bottom water in the Barents Sea is likely insufficiently large to contribute to intermediate and deep-water renewal during periods of anomalously low salinity.

Author contribution: RR, VSL, SC were involved in the initial study design, analysis, discussion and writing the manuscript. SS was involved in the analysis, while AB and LB were involved in discussions and the writing phase.

References

- Ali, A., Burud, A., Williams, T., Xie, J., Yumruktepe, C., Wakamatsu, T., Melsom, A., Bertino, L., Gao, S.: EU Copernicus Marine Service Product User Manual for the Arctic Ocean Physics Reanalysis, ARCTIC_MULTIYEAR_PHY_002_003, issue 5.20, Mercator Ocean International, <https://documentation.marine.copernicus.eu/PUM/CMEMS-ARC-PUM-002-ALL.pdf> (last access: 5 August 2025), 2025.
- Aagaard, K.: On the deep circulation of the Arctic Ocean. *Deep-Sea Res.*, 28, 251-268. doi:10.1016/0198-0149(81)90066-2, 1981.
- Aagaard, K., Coachman, L. K., and Carmack, E. C.: On the halocline of the Arctic Ocean. *Deep-Sea Res. Part A*, 28, 529-545, 1981.
- Årthun, M., Ingvaldsen, R. B., Smedsrud, L. H., and Schrum, C.: Dense Water Formation and Circulation in the Barents Sea, *Deep Sea Res. Pt. I*, 58, 801-817, <https://doi.org/10.1016/j.dsr.2011.06.001>, 2011.
- Årthun, M., T. Eldevik, and L. H. Smedsrud, Ø. Skagseth, and R. B. Ingvaldsen, 2012: Quantifying the influence of Atlantic heat on Barents sea ice variability and retreat. *J. Climate*, 25, 4736-4743, <https://doi.org/10.1175/JCLI-D-11-00466.1>, 2012
- Årthun, M., and Eldevik, T.: Anomalous ocean heat transport toward the Arctic and associated climate predictability. *J. Clim.*, 29, 689-704. doi: 10.1175/JCLI-D-15-0448.1, 2016.
- Blindheim, J.: Cascading of Barents Sea bottom water into the Norwegian Sea. *ICES/CIEM*, 188, 49-58, 1989.
- Blindheim, J., and Loeng, H.: On the variability of Atlantic influence in the Norwegian and Barents Seas. *Fiskeridirektoratets Skrevne Serie for Havundersøkelser*, 17, 161-189, 1981.
- Boutin, J.; Vergely, J.-L.; Reul, N.; Catany, R.; Jouanno, J.; Martin, A.; Rouffi, F.; Bertino, L.; Bonjean, F.; Corato, G.; Gévaudan, M.; Guimbard, S.; Khvorostyanov, D.; Kolodziejczyk, N.; Matthews, M.; Olivier, L.; Raj, R.; Rémy, E.; Reverdin, G.; Supply, A.; Thouvenin-Masson, C.; Vialard, J.; Sabia, R.; Mecklenburg, S. (2025): ESA Sea Surface Salinity Climate Change Initiative (Sea_Surface_Salinity_cci): Monthly sea surface salinity product for the Southern Hemisphere on a 25km EASE grid, v5.5, for 2010 to 2023. NERC EDS Centre for Environmental Data Analysis, date of citation.



- 319 Chafik, L., J. E. Ø. Nilsen, S. Dangendorf, G. Reverdin, and T. Frederikse, 2019: North Atlantic
 320 Ocean circulation and decadal sea level change during the altimetry era. *Sci. Rep.*, 9, 1041,
 321 <https://doi.org/10.1038/s41598-018-37603-6>.
- 322 Challet, F., Raj, R. P., Chatterjee, S., Herbaut, C., & Bonaduce, A. (2025). Weakening of the Arctic
 323 water outflow from the Barents Sea and consequences on the Fram Strait warming. *Journal of*
 324 *Geophysical Research: Oceans*, 130, e2024JC021054. <https://doi.org/10.1029/2024JC021054>
- 325 Chatterjee, S., T. Semmler, J. Screen et al.: Atmosphere–Ocean–Sea Ice Feedbacks Sustain
 326 Recent Barents Sea Ice Loss despite Cooler Atlantic Water Inflow. *Journal of Climate*, 37, 6519–
 327 6532, 2024.
- 328 Coachman, L. K., and Barnes, C. A.: Surface waters in the Eurasian Basin of the Arctic Ocean.
 329 *Arctic*, 15, 251-277, 1963.
- 330 Dmitrenko, I. A., Rudels, B., Kirillov, S. A., Aksenov, Y. O., Ivanov, V. V., Schauer, U., Polyakov,
 331 I. V., Lien, V. S., Coward, A., and Barber, D.: Atlantic Water flow into the Arctic Ocean through
 332 the St. Anna Trough in the northern Kara Sea. *J. Geophys. Res. Oceans*, 120.
 333 doi:10.1002/2015JC010804, 2015.
- 334 Evensen, G.: The Ensemble Kalman Filter: theoretical formulation and practical implementation.
 335 *Ocean Dynam.*, 53, 343-367, 2003.
- 336 EU Copernicus Marine Service Product: Arctic Ocean Physics Reanalysis, Mercator Ocean
 337 International [data set], <https://doi.org/10.48670/moi-00007>, 2025.
- 338 EU Copernicus Marine Service Product: Multi Observation Global Ocean 3D Temperature
 339 Salinity Height Geostrophic Current and MLD, Mercator Ocean International [data set],
 340 <https://doi.org/10.48670/moi-00052>, 2023.
- 341 Furevik, T.: Annual and interannual variability of Atlantic Water temperatures in the Norwegian
 342 and Barents Seas: 1980-1996. *Deep-Sea Res. I*, 48, 383-404, 2001.
- 343 González-Pola, C., Larsen, K. M. H., Fratantoni, P., and Beszczynska-Möller, A. (Eds.): ICES
 344 Report on Ocean Climate 2019. ICES Cooperative Research Reports No. 350. 136 pp.
 345 <https://doi.org/10.17895/ices.pub.7537>, 2020.
- 346 González-Pola, C., Larsen, K. M. H., Fratantoni, P., and Beszczynska-Möller, A. (Eds.): ICES
 347 Report on ocean climate. ICES Cooperative Research Reports Vol. 358. 123 pp.
 348 <https://doi.org/10.17895/ices.pub.24755574>. 2023.
- 349 Greiner, E., Verbrugge, N., Mulet, S., Guinehut, S.: EU Copernicus Marine Service Quality
 350 Information Document for the Multi Observation Global Ocean 3D Temperature Salinity Height
 351 Geostrophic Current and MLD, MULTIOBS_GLO_PHY_TSUV_3D_MYNRT_015_012, issue
 352 1.2, Mercator Ocean International, [https://documentation.marine.copernicus.eu/QUID/CMEMS-](https://documentation.marine.copernicus.eu/QUID/CMEMS-MOB-QUID-015-012.pdf)
 353 [MOB-QUID-015-012.pdf](https://documentation.marine.copernicus.eu/QUID/CMEMS-MOB-QUID-015-012.pdf) (last access: 5 August 2025), 2025.
- 354 Hatun, H., A. B. Sandø, H. Drange, B. Hansen, and H. Valdimarsson, 2005: In uence of the
 355 Atlantic subpolar gyre on the thermohaline circulation. *Science*, 309, 1841–1844,
 356 <https://doi.org/10.1126/science.1114777>.
- 357 Hersback et al 2020.: The ERA5 global reanalysis. *Q J R Meteorol Soc.* 2020; 146:1999–2049.
- 358 Holliday, N. P., Bersch, M., Berx, B., Chafik, L., Cunningham, S., Florindo-López, C., Hátún, H.,
 359 Johns, W., Josey, S. A., Larsen, K. M. H., Mulet, S., Oltmanns, M., Reverdin, G., Rossby, T.,



- 360 Thierry, V., Valdimarsson, H., and Yashayaev, I.: Ocean circulation causes the largest freshening
361 event for 129 years in eastern subpolar North Atlantic. *Nat. Commun.*, 11, 585, 2020.
- 362 Jones, E. P., and Anderson, L. G.: On the origin of the chemical properties of the Arctic Ocean
363 halocline. *J. Geophys. Res.*, 91, 10759-10767, 1986.
- 364 Jones, E. P., Rudels, B., and Anderson, L. G.: Deep waters of the Arctic Ocean: origins and
365 circulation. *Deep-Sea Res. Part I*, 42, 737-760, 1995.
- 366 Kenigson and Timmermans.: Nordic Seas Hydrography in the Context of Arctic and North Atlantic
367 Ocean Dynamics, 51, 101-114, 2021.
- 368 Lien, V. S., and Trofimov, A. G.: Formation of Barents Sea Branch Water in the north-eastern
369 Barents Sea. *Polar Res.*, 32, 18905, 2013.
- 370 Lind, S. and Ingvaldsen, R. B.: Variability and Impacts of Atlantic Water Entering the Barents Sea
371 from the North, *Deep Sea Res. Pt. I*, 62, 70–88, <https://doi.org/10.1016/j.dsr.2011.12.007>, 2012.
- 372 Lind, S., Ingvaldsen, R. B., and Furevik, T.: Arctic warming hotspot in the northern Barents Sea
373 linked to declining sea-ice import. *Nat. Clim. Change*, 8, 634-639, 2018.
- 374 Lundesgaard, Ø., Sundfjord, A., Lind, S., Nilsen, F., and Renner, A. H. H.: Import of Atlantic
375 Water and sea ice controls the ocean environment in the northern Barents Sea, *Ocean Sci.*, 18,
376 1389–1418, <https://doi.org/10.5194/os-18-1389-2022>, 2022.
- 377 Martin, S., and Cavalieri, D. J.: Contributions of the Siberian shelf polynyas to the Arctic Ocean
378 Intermediate and Deep Water. *J. Geophys. Res.*, 94, 12725-12738, 1989.
- 379 Midttun, L.: Formation of dense bottom water in the Barents Sea. *Deep-Sea Res Part A*, 32, 1233-
380 1241, 1985.
- 381 Mork, K. A., Skagseth, Ø., and Søiland, H.: Recent warming and freshening of the Norwegian Sea
382 observed by Argo data. *J. Clim.*, 32, 3695-3705, 2019.
- 383 Ozhigin, V. K., and Ivshin, V. A.: Water masses of the Barents Sea. PINRO Press. In Russian.
384 Murmansk, Russia, 48pp, 1999.
- 385 Pfirman, S. L., Bauch, D., and Gammelsrød, T.: The Northern Barents Sea: Water Mass
386 Distribution and Modification. In: Johannessen OM, Muench RD, Overland JE, editors. *The Polar*
387 *Oceans and their Role in Shaping the Global Environment. Geophys. Monogr. Ser.*, 84 AGU
388 Washington DC: 77-94, 1994.
- 389 Rudels, B., Jones, E. P., Anderson, L. G., and Kattner, G.: On the Intermediate depth waters of the
390 Arctic Ocean. In: Johannessen OM, Muench RD, Overland JE, editors. *The Polar Oceans and their*
391 *Role in Shaping the Global Environment. Geophys. Monogr. Ser.*, 84 AGU Washington DC:33-
392 46, 1994.
- 393 Rudels, B., Muench, R. D., Gunn, J., Schauer, U., and Friedrich, H. J.: Evolution of the Arctic
394 boundary current north of the Siberian shelves. *J. Mar. Sys.*, 25, 77-99, 2000.
- 395 Rudels, B., Jones, E. P., Schauer, U., and Eriksson, P.: Atlantic sources of the Arctic Ocean surface
396 and halocline waters. *Polar Res.*, 23(2), 181-208, 2004.
- 397 Rudels, B., Korhonen, M., Schauer, U., Pisarev, S., Rabe, B., and Wisotzki, A.: Circulation and
398 transformation of Atlantic water in the Eurasian Basin and the contribution of the Fram Strait
399 inflow branch to the Arctic Ocean heat budget. *Prog. Oceanogr.*, 132, 128-152.
400 [doi:10.1016/j.pocan.2014.04.003](https://doi.org/10.1016/j.pocan.2014.04.003), 2015.



- 401 Sakov, P., Counillon, F., Bertino, L., Lisæter, K. A., Oke, P. R., and Korablev, A.: TOPAZ4: an
402 ocean-sea ice data assimilation system for the North Atlantic and Arctic. *Ocean Sci.*, 8(4), 633-
403 656, 2012.
- 404 Schauer, U., Loeng, H., Rudels, B., Ozhigin, V. K., and Dieck, W.: Atlantic water inflow through
405 the Barents and Kara Seas. *Deep-Sea Res. Part I*, 49, 2281-2298, 2002.
- 406 Serreze, M. C., Holland, M. M., Stroeve, J., 2007. Perspectives on the Arctic's shrinking sea-ice
407 cover. *Science* 315 (5818), 1533–1536.
- 408 Shu, Q, Wang, Q, Song, Z, Qiao, F. 2021. The poleward enhanced Arctic Ocean cooling machine
409 in a warming climate. *Nature Communications* 12: 2966. DOI: [http://dx.doi.org/10.1038/s41467-](http://dx.doi.org/10.1038/s41467-021-23321-7)
410 021-23321-7.
- 411 Skagseth, Ø., Eldevik, T., Årthun, M., Asbjørnsen, H., Lien, V. S., and Smedsrud, L. H.: Reduced
412 efficiency of the Barents Sea cooling machine. *Nat. Clim. Change*, doi.org/10.1038/s41558-020-
413 0772-6, 2020.
- 414 Smedsrud, L. H., R. Ingvaldsen, J. E. Ø. Nilsen, and Ø. Skagseth (2010), Heat in the Barents Sea:
415 Transport, storage and surface fluxes, *Ocean Sci.*, 6(1), 219–234.
- 416 Smedsrud, L. H., Esau, I., Ingvaldsen, R. B., Eldevik, T., Haugan, P. M., Li, C., Lien, V. S., Olsen,
417 A., Omar, A. M., Otterå, O. H., Risebrobakken, B., Sandø, A. B., Semenov, V. A., and Sorokina,
418 S. A.: The role of the Barents Sea in the climate system. *Review Geophys.*, 51, 415-449 doi:
419 10.1002/rog20017, 2013.
- 420 Steele, M., Morison, J.H., and Curtin, T. B.: Halocline water formation in the Barents Sea. *J.*
421 *Geophys. Res.*, 100, 881-894, 1995.
- 422 Sundby, S., and Drinkwater, K.: On the mechanisms behind salinity anomaly signals of the
423 northern North Atlantic. *Prog. Oceanogr.*, 73, 190-202, 2007.
- 424 Sundfjord, A., Fer, I., Kasajima, Y., and Svendsen, H.: Observations of turbulent mixing and
425 hydrography in the marginal ice zone of the Barents Sea. *J. Geophys. Res.*, 112, C05008. doi:
426 10.1029/2006JC003524, 2007.
- 427 Verbrugge, N.: EU Copernicus Marine Service Product User Manual for the Multi Observation
428 Global Ocean 3D Temperature Salinity Height Geostrophic Current and MLD,
429 MULTI_OBS_GLO_PHY_TSUV_3D_MYNRT_015_012, issue 1.2, Mercator Ocean
430 International, [https://documentation.marine.copernicus.eu/PUM/CMEMS-MOB-PUM-015-](https://documentation.marine.copernicus.eu/PUM/CMEMS-MOB-PUM-015-012.pdf)
431 012.pdf (last access: 5 August 2025), 2023
- 432 Xie, J. P., Counillon, F., Bertino, L., Tian-Kunze, X., and Kaleschke, L.: Benefits of assimilating
433 thin sea ice thickness from SMOS into the TOPAZ system. *Cryosphere*, 10(6), 2745-2761, 2016.
- 434 Xie, J., Raj, R. P., Bertino, L., Martínez, J., Gabarró, C., and Catany, R.: Assimilation of sea
435 surface salinities from SMOS in an Arctic coupled ocean and sea ice reanalysis, *Ocean Sci.*, 19,
436 269–287, <https://doi.org/10.5194/os-19-269-2023>, 2023.
- 437 Xie J., Bertino, L.: EU Copernicus Marine Service Quality Information Document for the Arctic
438 Ocean Physics Reanalysis, ARCTIC_MULTIYEAR_PHY_002_003, issue 1.5, Mercator Ocean
439 International, [https://documentation.marine.copernicus.eu/QUID/CMEMS-ARC-QUID-002-](https://documentation.marine.copernicus.eu/QUID/CMEMS-ARC-QUID-002-003.pdf)
440 003.pdf (last access: 5 August 2025), 2025.



441 Zabudkina Z, Osadchiev A, Ivanov V, Makhotin M and Merkulov V (2025). Interannual variability
442 of the Barents Sea branch water in the northeastern part of the Barents Sea and the St. Anna
443 Trough. Front. Mar. Sci. 12:1569186. doi: 10.3389/fmars.2025.1569186