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Mediterranean outflow waters supply North Atlantic convection sites

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ABSTRACT

The northward-flowing branch of the Mediterranean Outflow Water (MOW) carries warm and saline water into the Subpolar North Atlantic, where deep convection contributes to the formation of water masses that feed the lower limb of the Atlantic Meridional Overturning Circulation. Due to its distinctive thermohaline characteristics, the MOW presence may act as a preconditioning factor for the formation of these waters. However, the complex dynamics of the subpolar regions make tracing its pathway beyond $\sim 50^\circ\text{N}$ using conventional tracers and datasets challenging. We use an extensive dataset of Argo float salinity and oxygen profiles acquired over the North Atlantic during more than two decades to track the northward-flowing MOW and characterize its evolution along the way. Here we show that these observations allow for a multi-tracer approach, providing robust evidence of MOW's presence in the subpolar basins, including the Irminger Sea, which has recently been identified as a basin where major deep convective processes occur. These findings highlight the potential role of the MOW in influencing the large-scale overturning circulation.

INTRODUCTION

The inflow of Mediterranean Outflow Water (MOW) into the North Atlantic plays a key role in shaping the physical and biogeochemical structure of the intermediate ocean layers (1). As a warm, saline, and oxygen-poor water mass, the MOW modifies the thermohaline

characteristics of the eastern North Atlantic, contributing to the salt and heat budgets at mid-depths (2). It influences large-scale circulation patterns, enhances stratification, and impacts the distribution of chemical tracers such as nutrients and dissolved oxygen (3,4). Its importance lies also in its potential influence on climate-relevant processes at higher latitudes, including the preconditioning of dense water formation (5).

In the Gulf of Cadiz, the warm and saline Mediterranean water ($CT = 12.91^{\circ}\text{C}$, $AS = 38.58 \text{ g/kg}$) ($\theta = 13^{\circ}\text{C}$, $S = 38.4 \text{ psu}$ in Ref. 6) flowing out of the Strait of Gibraltar entrains the overlying North Atlantic Central Water and mixes with other local water masses to form the Mediterranean Outflow Water (MOW) (7). As it flows downstream from Gibraltar, this water mass gradually loses part of its high salinity content and becomes neutrally buoyant at a depth of approximately 1200 meters near Cape St. Vincent ($CT = 11.79^{\circ}\text{C}$, $AS = 36.57 \text{ g/kg}$, $\sigma_{\theta} = 27.6 \pm 0.1 \text{ kg/m}^3$) ($T = 12 \pm 1^{\circ}\text{C}$, $S = 36.4 \pm 0.1 \text{ psu}$ in Refs. 7,8).

From this region, two distinct cores of MOW have been identified: one spreads westward into the open North Atlantic Ocean, forming a characteristic high salinity tongue (Figure 1a), while the other flows northward along the Iberian continental slope (7). Further north, most of the flow of MOW is deflected into the Bay of Biscay, where part of it is recirculated while the remaining continues to spread northward along the upper continental slope, detected as far north as 50°N , in the region of Porcupine Bank (6,9). Here, the northward-flowing boundary current is divided into two branches: a branch is deflected westward until it converges with the North Atlantic Current (NAC), while the other is observed to penetrate into the Rockall Trough (6,9).

The pathway of the MOW, especially its northward penetration into the eastern North Atlantic basin, has drawn much interest due to the hypothesis that this water mass could be a source of heat and salt to high-latitude waters, thus contributing to the preconditioning for the formation of deep waters (10). However, the fate of the MOW past the region of Porcupine Bank remains largely unexplored.

The importance of the northward branch of this water mass was first recognized by J. Reid in his pioneering studies (11,12,13), where he proposed a scenario in which the MOW is directly advected into the Labrador Sea and Nordic Seas by an eastern boundary current, preconditioning their convective cells and thus contributing to the formation of the North Atlantic Deep Water (NADW) that would then constitute the main body of the southward flowing branch of the Atlantic Meridional Overturning Circulation (AMOC) (14,15).

A second scenario was later proposed in Refs. 16 and 17. These papers suggested that the influence of MOW in the Subpolar North Atlantic (SPNA) is realized through diffusive fluxes and mixing with the waters of the NAC, rather than through its direct northward advection.

These two theories were later unified in a paper (18) in which the authors argue that the penetration of MOW into the subpolar gyre, and its subsequent spreading toward the northern regions of the Atlantic basin, is influenced by the position of the subpolar front,

which fluctuates with the North Atlantic Oscillation, i.e. the teleconnection pattern dominating atmospheric variability across the Northern Atlantic region (NAO, **19,20**).

In the above cited paper (**18**), the northward pathway of the MOW along the Iberian Peninsula and up to Porcupine Bank is well established. However, the further northward progressions are still left undetermined. Investigating whether the MOW reaches the subpolar basins of the North Atlantic is particularly important given the key role of these regions in the formation of NADW.

In this context, recent studies have brought new insights into deep water formation in the Subpolar North Atlantic. While earlier studies identified the Labrador Sea as the primary site for deep water formation, newer findings emphasize the Irminger Sea and the Iceland Basin as the dominant regions for this process (**21,22**).

Previous investigations of MOW pathways and its potential relevance for the AMOC have relied primarily on traditional hydrographic datasets, which are often limited in spatial and temporal coverage. In this work, we use 22 years of Argo salinity and dissolved oxygen observations to track the complete northward pathway of the Mediterranean Outflow Water from the Gulf of Cadiz into the subpolar North Atlantic. Here we investigate the relationship between the NAO and the northward propagation of the MOW, and we show that MOW reaches and branches into both the Iceland Basin and Irminger Sea. By characterizing its evolution along a series of sampling regions spanning the eastern and subpolar North Atlantic, we provide observational evidence for the extension of the MOW pathway into the Subpolar North Atlantic.

RESULTS

Influence of the North Atlantic Oscillation on the MOW's northward extension

The northward penetration of the MOW into the Subpolar North Atlantic is modulated by the phases of the North Atlantic Oscillation (NAO), primarily through changes in the wind stress, which determine a shift in the position of the subpolar front (**18**).

During persistent NAO+ periods, stronger westerly winds cause the subpolar gyre to expand and shift the subpolar front eastward, which can limit the northward flow of the MOW into the SPNA. In contrast, during persistent NAO- phases, weaker winds lead to a westward shift of the subpolar front, facilitating a greater penetration of the MOW beyond Porcupine Bank into the Rockall Trough and the subpolar gyre (**18,25**).

To investigate this mechanism, we analyzed a dataset of Argo float salinity profiles collected in the Eastern SPNA between 2001 and 2022 (see Methods). The first twelve years of this period are characterized by an average NAO index of -0.17, while the last decade shows a transition to a predominantly positive NAO phase, with an average index of +0.19 (Figure 2).

Figures 3a and 3b illustrate the spatial distribution of the maximum salinity values within the MOW density layer during selected NAO- and NAO+ years, respectively. In both phases, relatively saline intermediate waters are detected throughout large portions of the eastern SPNA, although their spatial distribution and relative intensity exhibit noticeable differences between the two periods. In particular, during NAO- years, higher salinity values appear more pronounced along the eastern boundary of the SPNA and within the Iceland Basin, whereas during NAO+ periods the salinity field appears generally weaker and more heterogeneous. The inset schematics in Figures 3a and 3b illustrate the conceptual shift in the subpolar gyre configuration associated with the two NAO phases, following the mechanism proposed by Ref. **18**, and are intended as a dynamical framework for interpreting the observed salinity patterns.

A complementary analysis of salinity anomalies within the MOW density layer (Figure S3) further highlights the spatial heterogeneity of this variability. These anomalies were computed relative to the SeaDataNet climatology (**23**) by extracting, for each profile, the salinity maximum within the characteristic MOW density range ($27.47\text{--}27.67\text{ kg m}^{-3}$). The southeastern subpolar boxes (A–C) broadly follow the pattern proposed by Ref. **18**, exhibiting more positive anomalies during NAO- periods and weaker negative anomalies during NAO+ conditions. In contrast, the northwestern boxes (D–F) display positive anomalies during both phases, suggesting that here the NAO-driven displacement of the subpolar front alone is insufficient to account for the observed regional variability.

Importantly, maximum salinity within the MOW density layer should be interpreted as a tracer-based indicator of the MOW-associated salinity signal, rather than as a quantitative measure of MOW transport or intensity. This distinction is especially important north of Porcupine Bank, where the MOW signal becomes progressively diluted and overlaps with other saline water masses, reducing the specificity of salinity as a tracer. Accordingly, the analysis presented here provides a qualitative assessment of the relative variability of the MOW-associated salinity signal within the SPNA. Restricting the analysis to the characteristic MOW density layer helps focus on the intermediate-depth signal associated with the MOW and minimizes the influence of shallower salinity structures, although it does not fully remove the effects of mixing and regional hydrographic variability.

Overall, the observed patterns are consistent with the interpretation that the NAO may modulate the relative distribution of the MOW-associated signal in the eastern SPNA, while the more complex behavior observed farther northwest suggests that additional processes may contribute to shaping the observed signal distribution, potentially involving basin-scale circulation variability and time-dependent chaotic advection, as suggested by recent Lagrangian analyses (**26**). Resolving the relative contribution of these mechanisms would require dedicated dynamical analyses beyond the scope of the present observational study.

Because MOW-associated signals can be identified in the SPNA during both NAO phases, the following sections analyze the complete Argo dataset (2001–2022) to provide a

statistically robust characterization of the mean spatial distribution and northward occurrence of the MOW in the SPNA.

Mediterranean Outflow Water's pathway up to Porcupine Bank

To investigate the northward progression of the MOW, we selected twelve regions along its hypothesized pathway, as shown in Figure 1b. These regions are strategically placed to sample key stages of the MOW's evolution. The six green boxes (1–6) are located along the well-established southern segment of the path, where the MOW has been detected in previous studies (6,9,17,18). In contrast, the six magenta boxes (A–F) are positioned farther north in the SPNA, along a proposed extension of the MOW pathway. Their placement is guided by the large-scale circulation at intermediate depths, as derived from the ANDRO dataset (24), with a detailed description of the selection criteria provided in the Methods section.

In this section, we identify the northward pathway of MOW all the way to Porcupine Bank, analyzing its climatological hydrographic properties derived from the Argo float profiles collected between 2001 and 2022 within boxes 1-6 (see Methods). The results of this analysis are reported in Table 1.

Overall, the climatological values extracted from the Argo dataset fall within the density range of 27.47–27.67 kg/m³, which corresponds to the upper core of MOW as defined by Iorga and Lozier (1999b). The only exceptions are found in Boxes 1,2 and 3, located in the Gulf of Cadiz and along the Iberian margin, where the salinity maxima correspond to slightly higher densities because they are associated with the denser lower core of MOW (27).

As the MOW advances northward, its hydrographic properties undergo a progressive transformation due to the entrainment of the overlying Eastern North Atlantic Central Water (ENACW, see below) and mixing with surrounding water masses (3,27). In particular, Argo float data reveal a decrease in absolute salinity of approximately 1.14 g/kg, alongside a reduction of the conservative temperature of about 3.6 °C and a progressive thinning of the MOW layer, which gradually reduces from roughly 400 m in the source region to 150–200 m near Porcupine Bank.

Mediterranean Outflow Water's presence in the Subpolar North Atlantic

Following the analysis of the climatological characteristics of the MOW along its already established pathway up to Porcupine Bank, we now focus on its evolution in the SPNA. In particular, we investigate the fate of the core of MOW that is deflected westward beyond Porcupine Bank, until it converges with one of the northeastward-flowing branches of the North Atlantic Current (NAC) (9).

We now focus on Boxes A-C, located in the Iceland Basin, and Boxes E-F, situated in the Irminger Sea (Figure 1b). The SPNA is characterized by a series of processes that complicate

the detection and tracking of MOW. In particular, the presence and seasonal formation of Subpolar Mode Waters (SPMWs), characterized by relatively high salinity values (35.26-35.56 g/kg or 35.1 – 35.4 psu) and occupying the 27.3-27.5 kg/m³ density range (28,29,30), adds ambiguity to the identification of MOW as their properties can closely resemble those of the diluted northward flowing MOW.

Additionally, in this region, the upper core of MOW interacts with the North Atlantic Current and undergoes enhanced mixing, which progressively weakens its distinct salinity signature (6,9), making its detection even more challenging. Consequently, to trace the path of MOW in the SPNA, we used a combination of subsurface salinity maxima and oxygen minima, which are well-established markers of MOW's presence (4,31,32).

In regions where mixing processes attenuate the thermohaline signature of water masses, oxygen serves as a valuable complementary tracer. Although oxygen is a non-conservative property that can also be affected by biological processes and air-sea gas exchange (33), these influences are limited at intermediate depths where the MOW spreads. At these depths, the direct influence of atmospheric forcing is strongly reduced, and water mass properties are primarily shaped by ocean interior processes and mixing (34,35,36). This means that the low oxygen content of the MOW, relative to the well-ventilated surrounding subpolar waters, can persist even after mixing modifies temperature and salinity, making it a more reliable (37,38).

Hovmöller diagrams of absolute salinity, dissolved oxygen concentration and potential vorticity (*PV*) based on Argo float data were used to investigate the pathway and evolution of MOW across the North Atlantic (Figure 4 b,c,d) (see Methods).

Isopycnals are overlaid on all sections (thin black lines in Figure 4 b-d), with the 27.47 and 27.67 kg/m³ isopycnals highlighted as thicker dashed lines to mark the density range of the upper core of the MOW, following Ref. 9. Throughout most of the pathway, these isopycnals are found in the 600-1000 m depth layer, progressively sloping upward as the section extends into the Irminger Sea (Figure 4 b-d).

The characteristic high-salinity tongue of MOW is clearly visible in the southern part of the section (Figure 4b). As MOW progresses northward, this salinity signal follows the isopycnals corresponding to its upper core (27.47–27.67 kg/m³) and remains well distinguishable up to Porcupine Bank (Figure 4 a,b). Beyond this region, as MOW enters the Hatton Basin and the SPNA, the salinity signal gets strongly attenuated due to mixing processes.

In contrast, the oxygen section (Figure 4c) shows that the well-defined oxygen minimum associated with MOW is observed more clearly as it progresses northward into the SPNA. The signal remains aligned with the density layer of MOW and is particularly evident up to the tip of the Reykjanes Ridge (Figure 4 a, c).

Beyond the ridge, the sections extend into the Irminger Sea, a region well-known for deep winter convection (22,39,40,41). In the climatological sections presented here, the hydrographic signature of this convective activity is evident. Elevated oxygen concentrations ($O_2 > 280 \mu\text{mol/kg}$) (Figure 4c) and low potential vorticity values ($PV < 4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$) (Figure 4d) indicate a well-ventilated, homogenized water column reaching depths of approximately 1400 m.

The PV section also provides valuable insight into the identification of the regions of SPMW formation. These water masses are characterized by very low potential vorticity values, in particular where $PV < 4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$ (28,29).

In the southern portion of the section, extending up to the region of Porcupine Bank, the $4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$ PV isolines (highlighted in red in Figure 4d) indicate the presence of ENACW, a mode water formed through winter convection in the Bay of Biscay (1,42,43). In this area, the ENACW predominantly occupies the $27.1 - 27.2 \text{ kg/m}^3$ density range and remains clearly separated from the isopycnals that define the core of MOW. Farther north, in the Iceland Basin, the PV isolines reveal the formation of denser Subpolar Mode Water (SPMW), which resides within the $27.3 - 27.5 \text{ kg/m}^3$ layer (Figure 4d) (28,29,30). Notably, in the region of the Reykjanes Ridge, where the isopycnals begin to slope upward, the PV isolines associated with the SPMW intersect the isopycnals corresponding to the MOW core. This overlap might introduce an ambiguity in the distinction between the two water masses, that we resolve in the next section.

Seasonal variability of potential vorticity and the influence of Subpolar Mode Water

The seasonal distribution of potential vorticity is used to better understand the dynamics of SPMW in this region and to distinguish this water mass from the MOW (see Methods).

Figure 5 presents the seasonal PV sections, with the $4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$ PV isolines highlighted in red.

In winter (Figure 5a), the Iceland Basin is characterized by a homogeneous mixed layer extending from the surface to an average depth of ~ 400 m. This low PV layer ($PV < 4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$) marks the formation of SPMW, driven by intense air-sea fluxes and strong convective mixing (28,29,44). The PV isolines show that SPMW extends into the Irminger Sea, where similarly low PV values are observed throughout the water column, reflecting the presence of a deep convective cell (21,45). In the region of the Reykjanes Ridge, isopycnals begin to slope upward and outcrop, and from this point onward, SPMW occupies the same density range as the MOW core.

In spring (Figure 5b), surface stratification is re-established, as shown by the increased PV values. In the Iceland Basin, the $4 \times 10^{-11} \text{s}^{-1} \text{m}^{-1}$ PV isolines define a thick SPMW layer between ~ 100 and ~ 500 m, extending beyond the Reykjanes Ridge into the Irminger Sea.

Notably, this layer entirely overlaps with the 27.47–27.67 kg/m³ isopycnals associated with the core of the MOW.

In summer (Figure 5c), remnants of SPMW are still present in the Iceland Basin. The $4 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$ isolines highlight a residual core of this water mass intersecting the upper bound of MOW's core density range, particularly along the eastern flank of the Reykjanes Ridge, where the isopycnals slope upward.

In autumn (Figure 5d), the surface mixed layer begins to deepen in both the Iceland Basin and the Irminger Sea. Although the $4 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$ *PV* isolines no longer clearly delineate the presence of SPMW in the Iceland Basin, a small residual of this water mass may still be present along the eastern flank of the Reykjanes Ridge, as suggested by localized low values of *PV* in that region.

Overall, autumn appears to be the season when the influence of SPMW is least evident, offering a better opportunity to detect potential evidence of the presence of MOW in the subpolar basins. Additionally, autumn is the season in which preconditioning for the winter convective activity occurs. Therefore, identifying the presence of MOW during this season (when SPMW is less dominant) would assert the key role of the Mediterranean Outflow Water in the winter deep convective processes.

To assess the impact of seasonality, we extended the analysis to include seasonal climatological sections of salinity and dissolved oxygen along the MOW pathway (Figures S4, S5). These sections were constructed using all available Argo profiles for each season over the period 2001–2022 for salinity and 2003–2022 for dissolved oxygen. The results show that the large-scale structure of the MOW within its density layer is broadly consistent across seasons, with limited seasonal variability along most of its pathway. The main seasonal differences are observed in the northern subpolar regions, where dissolved oxygen reflects the influence of wintertime deep convection and ventilation. These findings support the use of autumn data in the main analysis (see next section), as it minimizes ambiguity with the Subpolar Mode Waters while remaining representative of the overall MOW structure.

Detection of Mediterranean Outflow Water's signal along its complete northward pathway in the Subpolar North Atlantic

Based on these considerations, we tracked the northward pathway of the MOW by detecting its presence within the selected boxes (Figure 1b), specifically targeting the 27.47–27.67 kg/m³ density layer that defines its core (9), and using salinity maximum and oxygen minimum as tracers (37,46, see Methods).

The top panel (Figure 6a) shows a sharp decline in the salinity maximum along the southern portion of the pathway, particularly up to box 6 near Porcupine Bank, indicating strong mixing between MOW and the Atlantic waters. In this region, MOW is still characterized by

high salinity values and the strong gradient with the surrounding water masses enhances mixing, leading to a rapid erosion of its salinity signature (**6,13,47,48**). Beyond this point, as MOW progresses northward into the subpolar basins, strong mixing persists but the salinity contrast diminishes, leading to a more gradual decrease of the salinity maximum (see salinity section, Figure 4b), consistent with the progressive dilution of intermediate water masses along their advective pathways (**48,49,50,51**). In contrast, oxygen concentrations begin to increase gradually in the southern portion of the pathway, where waters are generally less ventilated, and then increase more steeply in the subpolar basins, where the surrounding waters are substantially more oxygenated (see oxygen section, Figure 4c; **51,52,53,54,55**).

The bottom-left panel (Figure 6b) shows the depth evolution of the detected salinity and oxygen peaks. Up to the Hatton Basin (Box A), the salinity maximum lies slightly deeper than the oxygen minimum. However, farther north in the subpolar basins, the salinity signal rises above the oxygen minimum. This transition coincides with the gradual shoaling of the isopycnals in the Iceland Basin and their steeper slope in the Reykjanes Ridge region (see sections, Figure 4). Here, the salinity maximum appears to be lifted upward and entrained into shallower layers following the evolution of the isopycnals, influenced by the gyre circulation and a weakened stratification. In contrast, the oxygen minimum, although it also rises following the sloping isopycnals, persists at deeper levels in SPNA, likely confined in a less ventilated intermediate layer which remains isolated from the surface, consistent with the slower ventilation and longer residence times of intermediate waters (**13,56,57**).

This vertical separation is also evident in density space (bottom-right panel, Figure 6c), where salinity maxima are found at denser levels than oxygen minima up to Box B, but shift to lighter densities farther north. The evolution of the density values of the two tracers remains tightly aligned up to Box B and then diverges as MOW enters the SPNA. This decoupling suggests that salinity is more easily mixed upward along sloping isopycnals, while the oxygen signal remains trapped in denser, less ventilated layers.

Despite this divergence, both tracers remain broadly coherent in their depth evolution, suggesting that they continue to track the same water mass. The observed separation in density space reflects the distinct sensitivities of salinity and oxygen to mixing and is probably associated with complex tracer-specific behaviors.

In particular, the persistence and smoother evolution of the oxygen minimum suggests that it may be less affected by mixing or may reside in more isolated layers, making it a reliable tracer for the MOW. This is consistent with previous studies highlighting the usefulness of dissolved oxygen as a tracer of intermediate water mass properties and mixing processes (**37,38,46,48,50**). Its clear and consistent signal, co-located with a salinity maximum in the

density layer of the core of the MOW, offers strong evidence for the presence of this water mass across all the analyzed boxes, effectively tracing its northward pathway.

To assess the robustness of the extrema-based tracking, we performed a complementary analysis based on the mean of the salinity maxima and oxygen minima identified within the MOW density layer (Figure S6). While the extrema-based approach targets the most pronounced and least mixed remnants of the MOW signal, the mean diagnostic is inherently more sensitive to mixing with surrounding water masses and therefore provides a more integrated representation of the evolving properties of the MOW.

This complementary analysis exhibits a consistent large-scale evolution of both tracers along the MOW pathway, closely resembling that obtained from the extrema-based approach, but with smoother variations particularly in the density evolution in the subpolar regions. This behavior reflects the increasing influence of mixing and ambient variability, which progressively dilute and redistribute the MOW signal along its pathway.

The agreement between the two diagnostics supports the robustness of the identified pathway and confirms that, despite significant transformation, persistent traces of the MOW signature remain detectable across the SPNA. Figures 6c and 6d further support the validity of the obtained results, showing that the identified salinity and oxygen values generally correspond to actual peaks in the respective profiles. The only exceptions that emerge for the salinity data are given by boxes 3 and D.

In Box 3, the detected salinity maximum falls within the correct high-salinity layer but does not precisely correspond to the absolute peak. This inconsistency likely arises because, in this region, the salinity peak occurs at slightly higher densities than the selected MOW core density range (see Table 1 for climatological reference values).

Box D presents a more interesting exception: here no clear salinity peak is observed within the MOW core density layer. This box is located in a region characterized by a complex dynamic, as it includes the Reykjanes Ridge, where the isopycnals slope most steeply. In this context, the MOW signal is likely advected along sloping isopycnals and subject to enhanced mixing, which can lead to a partial redistribution of its properties across density surfaces. As a result, part of the high-salinity signal may be displaced outside the selected density range, making it less detectable within the MOW core layer. As the isopycnals flatten beyond the ridge, the density surfaces become more stable, and the salinity maximum becomes detectable again within the expected range in boxes E and F.

Additional features in the subpolar boxes further highlight the value of combining salinity and oxygen as complementary tracers of the MOW. In Boxes A, B and C, relatively saline overlying waters reduce the vertical contrast between the MOW signal and the surrounding

water masses, making the maximum salinity associated with the MOW less distinct in these regions. This is consistent with the progressive dilution and modification of the MOW signature along its northward pathway.

In this context, the oxygen profiles provide significant complementary information. In particular, Box F shows low oxygen concentrations between approximately 200 and 600 m, whereas elevated salinity is mainly confined to shallower depths, between approximately 100 and 300 m. This vertical separation suggests that oxygen can strengthen the identification of the intermediate-depth MOW signature in regions where its salinity signal becomes less distinct. More generally, the detected oxygen minima align with well-defined extrema in the oxygen profiles, supporting the reliability of oxygen as a tracer, together with salinity, to identify the MOW signal along its northward pathway.

It is important to emphasize that, although the presence of the Mediterranean Outflow Water can be robustly identified through salinity and oxygen extrema, these diagnostics do not provide a direct quantitative measure of its strength or transport. Rather, they allow us to trace its spreading and assess its presence in the subpolar North Atlantic, which is the primary objective of this study. The analysis of salinity anomalies within the MOW density layer (Figure S3) offers additional insight into the variability of its influence in the subpolar basins; however, a more rigorous quantification of MOW intensity would require dedicated analyses that explicitly resolve circulation and water mass transformation processes.

While our results demonstrate that traces of the Mediterranean Outflow Water can be detected in the vicinity of the subpolar convection regions, the present analysis does not allow us to directly assess its role in deep convective processes. Addressing this question would require a targeted, region-specific investigation of the convective sites, aimed at resolving the transformation of MOW properties and their interaction with local water masses during wintertime convection. Such an analysis is beyond the scope of the present study but represents a natural direction for future work.

Overall, this study provides strong evidence for the presence of MOW in the SPNA and introduces a tracer-based methodology to identify its pathways in regions previously considered ambiguous. Moreover, these findings suggest that the MOW may play a broader role in the preconditioning of the SPNA for winter convection. Future work combining high-resolution models and physical and biogeochemical tracers could further clarify MOW's contribution to the structure of subpolar water masses and climate-relevant processes.

METHODS

The influence of NAO on the MOW

To assess the influence of the North Atlantic Oscillation (NAO) on the northward penetration of Mediterranean Outflow Water (MOW) into the Subpolar North Atlantic (SPNA), we first analyzed the NAO index time series provided by NOAA (updated from Ref. **58**). Monthly values spanning from January 1950 were available, but we focused on the period from 2001 to 2022 to match the temporal coverage of the Argo float dataset. Annual averages of the NAO index were computed to produce the time series shown in Figure 2. As previously documented (**59,60**), the first decade of the 2000s was dominated by a predominantly negative NAO phase, followed by a transition to a generally positive phase in the subsequent decade. To assess the impact of this shift on MOW's northward spread, we examined Argo float salinity profiles collected during years representative of each NAO phase.

In particular, we selected the Argo float salinity profiles collected during six NAO- peak years (2005, 2006, 2008, 2009, 2010, 2012) and six NAO+ peak years (2013, 2015, 2017, 2018, 2020, 2022) in the eastern SPNA. For each profile, we extracted the maximum salinity value recorded within the 27.47–27.67 kg/m³ density layer, which has been identified as the density range typical of the core of MOW near its source region (**9**). These in-situ salinity values were converted to absolute salinity using the *TEOS-10* toolbox (**61**). Finally, we mapped the spatial distribution of these maxima separately for NAO- and NAO+ phases to assess whether NAO-driven variability affects the northward spread of MOW (Figure 3 a,b).

Definition of analysis regions (boxes) for the proposed extension of the MOW pathway into the SPNA

The placement of the northern boxes (A–F, Figure 1b) was designed to investigate a proposed extension of the MOW pathway into the Subpolar North Atlantic. Their location was guided by the mean velocity field at 1000 m depth, derived from the ANDRO dataset (**24**), which captures the large-scale circulation at depths corresponding to the MOW layer. In particular, these boxes were positioned along areas of persistent northward and northwestward flow along the eastern boundary and across the Iceland Basin toward the Irminger Sea, following the pathways suggested by the mean circulation. This approach allows us to sample the potential pathway of the MOW as it propagates into the SPNA, while accounting for the influence of the subpolar gyre circulation and regional bathymetric features such as the Reykjanes Ridge (Figure 1a,b).

This configuration is consistent with previous observational studies documenting traces of MOW spreading northwest of Porcupine Bank (**6,9,62,63**), suggesting a potential extension of its influence toward higher latitudes. It is further supported by recent Lagrangian simulations analysis showing that a fraction of MOW-origin water parcels can follow northward pathways into the subpolar gyre, reaching latitudes beyond the Rockall Ridge (**26**). Together, these elements guided the selection of the boxes so as to capture the largest possible spatial extent of the proposed MOW pathway into the SPNA.

The spatial and temporal distribution of Argo observations within the selected regions is not uniform and may potentially affect the robustness of the analysis. To evaluate the observational coverage, we examined the sampling distribution of salinity and dissolved oxygen profiles within each box (Figures S1 and S2). Heatmaps of profile density and seasonal histograms normalized by region were used to evaluate both the spatial and temporal coverage of the dataset.

Salinity observations from the core Argo program provide extensive coverage across all regions throughout the study period. Dissolved oxygen measurements from the BGC-Argo program are less numerous because this program began more recently; nevertheless, they provide substantial coverage, particularly within the subpolar North Atlantic regions (boxes A–F; Figure 1b), which are critical for detecting the northward penetration of Mediterranean Outflow Water. In contrast, the southern regions (boxes 1–6; Figure 1b), located between the Gulf of Cadiz and Porcupine Bank, contain fewer oxygen observations. However, these regions correspond to the well-established pathway of the MOW in the eastern North Atlantic, where its presence has been extensively documented by previous studies.

Overall, the available Argo sampling provides sufficient spatial and temporal coverage to robustly characterize the MOW pathway investigated in this study (64).

The retrieval of the climatological properties of MOW up to PB

In order to determine the climatological hydrographic properties of the Mediterranean Outflow Water (MOW) along its established pathway from the Strait of Gibraltar to Porcupine Bank, we analyzed the Argo float profiles collected between 2001 and 2022 within boxes 1–6 (Figure 1b).

In each box, in-situ observations of temperature and salinity were converted to conservative temperature and absolute salinity using the *TEOS-10* toolbox (61), from which potential density profiles were subsequently derived. We focused on the 600–1300 m depth layer, identified as the typical depth range of MOW in these regions (31,65).

Within this depth layer, we extracted the annual maximum values of absolute salinity from each profile, along with their corresponding temperature, depth, and potential density. For each region, we then computed the climatological mean and standard deviation of these annual values over the 22-year period. The resulting values are summarized in Table 1.

The pathway of the MOW in the SPNA

To investigate the large-scale distribution and evolution of MOW properties across the North Atlantic, we constructed three composite sections using Argo float data: absolute salinity, dissolved oxygen concentration, and potential vorticity (*PV*) (Figure 4 b,c,d). Each section is aligned with the expected pathway of MOW (Figure 4a), beginning with its well-established northward progression up to Porcupine Bank, and extending into the Subpolar North Atlantic

following the hypothesized path outlined by Boxes A–F, in the Iceland Basin and Irminger Sea (Figure 1b).

In this study, we neglect the core of MOW which flows into the Rockall Trough, as this region is characterized by complex hydrographic and dynamical conditions, dominated by tidal flows and interactions with bathymetry (66,67,68,69) that require a more detailed, dedicated analysis. Therefore, the evolution of this core of MOW will be addressed in a future work.

To obtain the sections, Argo float profiles were vertically interpolated onto constant depth levels at 10 m intervals from the surface to 2000 m. The profiles were then spatially binned on a regular $2^\circ \times 2^\circ$ grid covering the entire North Atlantic and averaged over the duration of the dataset: 2001–2022 for salinity and temperature, and 2003–2022 for oxygen.

After binning and averaging the data, the salinity and temperature profiles were converted to absolute salinity and potential temperature using the *TEOS-10* toolbox (61). Potential density profiles were also derived to define isopycnals across all sections.

Potential vorticity (*PV*) was computed as follows:

$$PV = \frac{f}{g} N^2 \quad (1)$$

where f is the Coriolis parameter, g is the gravitational acceleration and N is the Brunt-Väisälä frequency, derived from the absolute salinity and conservative temperature profiles using the *TEOS-10* toolbox (61).

Once all the needed variables were derived, we extracted from the gridded domain the profiles nearest to the designed section path, for each variable. These profiles were interpolated every ~200 km to match the spatial resolution of the grid. The distances along the sections were calculated geodesically using the WGS84 ellipsoid and the distance function in MATLAB.

Bathymetric data from GEBCO (70) were interpolated every 1 km along the section to provide a high-resolution representation of the seafloor.

Seasonal variability in potential vorticity was also assessed by generating seasonal composite *PV* sections (Figure 5). Vertically interpolated Argo profiles were first grouped by season, binned, and then used to compute *PV* following equation (1).

Isopycnals derived from the potential density profiles were overlaid on all sections. Additionally, the $4 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$ *PV* isolines were highlighted in the *PV* sections to indicate the presence of Subpolar Mode Waters (28,29).

MOW detection algorithm

To track the northward flow of Mediterranean Outflow Water (MOW) along its pathway, we analyzed salinity and dissolved oxygen data from Argo float profiles located within the boxes shown in Figure 1b, focusing on the density range that defines the core of MOW (27.47–27.67 kg/m³).

For each box, we identified all Argo profiles collected between 2001 and 2022 for salinity, and between 2003 and 2022 for oxygen. In-situ salinity and temperature values were converted to absolute salinity and conservative temperature using the *TEOS-10* toolbox (61), and potential density was calculated from the corresponding temperature and salinity profiles.

Each profile was then analyzed to co-locate the maximum absolute salinity and minimum dissolved oxygen concentration within the specified density range. For each identified peak and for each box, the corresponding depth and potential density were also extracted. In the case of boxes D, E and F, located in the Irminger Sea and including the Reykjanes Ridge (Figure 1b), the analysis was limited to data collected during autumn (October - December) to minimize the interference from the Subpolar Mode Water (SPMW).

For each box, the primary diagnostic is defined as the maximum of all salinity maxima and the minimum of all oxygen minima identified across the profiles. These extrema represent the most pronounced and least mixed remnants of the MOW signal within each box. The results of this detection are presented in Figure 6a, which shows the spatial progression of these extrema across the North Atlantic, together with the evolution of their depths and potential densities.

To assess the sensitivity of this diagnostic to mixing and ambient variability, we performed an additional analysis in which we computed, for each region, the mean of all salinity maxima and the mean of all oxygen minima, along with the corresponding mean depths and potential densities (Figure S6). This complementary diagnostic is more sensitive to mixing processes and provides a smoother representation of the evolution of MOW properties.

To better visualize the detected peaks, for each box we also identified the maximum salinity and minimum oxygen values at each depth level, constructing representative vertical profiles of absolute salinity maxima and dissolved oxygen concentration minima. Finally, to assess the robustness of the detection, the identified salinity maxima and oxygen minima are marked with black crosses on the respective vertical profiles (Figure 6b).

DATA AVAILABILITY

Sources of the data used in this paper are available in Refs. **23** (SeaDataNet data), **24** (ANDRO argo data), **58** (NAO index, updated), **70** (bathymetry data). The Argo float data are available from <https://dataselection.euro-argo.eu/>

CODE AVAILABILITY

MATLAB scripts used for the analyses described in this study and to create the figures can be obtained from the corresponding author upon request.

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AUTHOR CONTRIBUTION

Methodology: E.C., R.M., M.M.; Data processing: E.C.; Data interpretation: all authors; Writing - original draft preparation: E.C.; Writing - review and editing: all authors; Project administration: E.Z. and P.M.-R.

COMPETING INTERESTS

The authors declare no competing interests.

SUPPLEMENTARY INFORMATION

Supplementary Information is available for this paper.

TABLE

Table 1: Climatological hydrographic properties of MOW along its northward pathway up to Porcupine Bank. For each box, values are averages derived from Argo profiles, computed at the depth of the salinity maximum within the 600–1300 m layer, which is taken here to represent the MOW core.

REGION	ABS. SALINITY (g/kg)	CONS. TEMP. (°C)	DEPTH LAYER (m)	POT. DENSITY (kg/m ³)
Gulf of Cadiz (BOX 1)	36.83 ± 0.38	13.09 ± 3.63	800 – 1200	27.60 ± 0.75
Iberian margin (BOX 2)	36.64 ± 0.10	11.96 ± 0.65	900 – 1250	27.72 ± 0.10
North of the Galicia Bank (BOX 3)	36.15 ± 0.12	10.38 ± 0.47	900 – 1100	27.64 ± 0.05
Bay of Biscay (BOX 4)	36.20 ± 0.09	10.71 ± 0.28	900 – 1100	27.62 ± 0.08
South of Porcupine Bank (BOX 5)	35.87 ± 0.06	9.60 ± 0.32	850 – 1000	27.57 ± 0.05
West of Porcupine Bank (BOX 6)	35.69 ± 0.04	9.47 ± 0.84	650 – 900	27.45 ± 0.14

FIGURE LEGENDS

Figure 1: Study area (eastern North Atlantic).

(a) bathymetric map of the eastern North Atlantic overlaid with climatological absolute salinity (g/kg) contours at 1000 m depth, highlighting the high salinity tongue of the Mediterranean Outflow Water (MOW; source: Sea Data Net, 1980-2020 average (23)). The locations of the main topographic features and ocean basins are also indicated: Reykjanes Ridge (RR, white diamond), Hatton Basin (HB, white triangle), Porcupine Bank (PB, white star), Cape St. Vincent (black circle), SPNA (Subpolar North Atlantic). The schematic representation of the North Atlantic Current (NAC, red) and Eastern Boundary Current (EBC, magenta) is shown on the map. The westward and northward pathways of the MOW are also indicated. (b) map of the 1000 m mean velocity field of the eastern NA derived from ARGO floats displacement, readapted from the ANDRO dataset (24). The twelve analysis regions selected for this study are outlined as boxes. Green boxes (1-6) trace the well-established southern path of MOW, while magenta boxes (A-F) are placed along the hypothetical path followed by the MOW in the Subpolar North Atlantic.

Figure 2: Interannual variability of the mean North Atlantic Oscillation index over the period 2001–2022.

Annual mean North Atlantic Oscillation (NAO) index from 2001 to 2022 (source: NOAA, see Methods). The red vertical line separates a predominantly positive NAO phase in the first decade from a predominantly negative NAO phase in the second. NAO- and NAO+ peak years are highlighted by red and green circles respectively.

Figure 3: The influence of the North Atlantic Oscillation on the northward extension of the Mediterranean Outflow Water.

(a) scatter map of the absolute salinity maxima within the 27.47-27.67 kg/m³ density layer, extracted from the ARGO float data acquired during years characterized by a negative peak of the NAO index (2005, 2006, 2008, 2009, 2010, 2012). **Inset (top right)** schematic representation of the subpolar gyre during the NAO- (purple) and NAO+ (orange) phases, overlaid on the bathymetry of the Subpolar North Atlantic. (b) scatter map of the absolute salinity maxima within the 27.47-27.67 kg/m³ density layer, computed from the ARGO floats data acquired during years characterized by a positive peak of the NAO index (2013, 2015, 2017, 2018, 2020, 2022). **Inset (top right)** schematic representation of the subpolar gyre during the NAO- (purple) and NAO+ (orange) phases, overlaid on the bathymetry of the Subpolar North Atlantic.

Figure 4: Composite sections along the northward pathway of the Mediterranean Outflow Water.

(a) bathymetric map of the eastern North Atlantic showing the composite section track, beginning in the Gulf of Cadiz (source region of the Mediterranean Outflow Water MOW), and approximately following the locations of the boxes from Figure 1b. Distances from the starting point are marked every 1000 km. Key topographic features and ocean basins are labeled: Irminger Sea (IS, white square), Reykjanes Ridge (RR, white diamond), Iceland Basin (IB, white triangle), Hatton Basin (HB, white circle), Porcupine Bank (PB, white star). (b) composite absolute salinity section derived from 22 years of Argo float observations. (c) composite dissolved oxygen concentration section derived from 20 years of Argo float data. (d) composite potential vorticity section computed from the Argo float profiles, with red contour lines indicating the $4 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$ PV isolines. All sections are overlaid with isopycnals (thin black lines), while the thick dashed black lines represent the 27.47 and 27.67 isopycnals, which define the core of the MOW. High-resolution bathymetry from GEBCO (70) is superimposed at the bottom of each section, and major basins and topographic features are annotated above.

Figure 5: Potential vorticity along the northward pathway of the Mediterranean Outflow Water.

Seasonal composite sections of potential vorticity along the northward pathway of the Mediterranean Outflow Water (MOW): (a) winter, (b) spring, (c) summer, (d) autumn. All sections are overlaid with isopycnals (thin black lines), with the 27.47 and 27.67 kg/m^3 isopycnals, defining the density layer of the MOW, highlighted by thick dashed black lines. The $4 \times 10^{-11} \text{ s}^{-1} \text{ m}^{-1}$ PV isolines are marked by red contour lines. High-resolution bathymetry from GEBCO (70) is superimposed on all sections.

Figure 6: Mediterranean Outflow Water detection in the twelve selected boxes.

(a) evolution of the maximum absolute salinity (blue curve) and minimum dissolved oxygen concentration values (red curve), detected within the 27.47-27.67 kg/m^3 density layer, along the northward pathway of the Mediterranean Outflow Water (MOW). (b) depths of the detected salinity maxima (blue) and oxygen minima (red) within each box. (c) density values associated with the detected salinity maxima (blue) and oxygen minima (red) within the boxes. For Boxes D, E, and F (in the Irminger Sea), only autumn data are used to minimize Subpolar Mode Water interference. (d) Maximum absolute salinity profiles for each box, with the identified salinity peak marked by a thick black cross. (e) Minimum dissolved oxygen profiles for each box, with the identified oxygen minimum marked by a thick black cross. All peaks are detected within the core density range of MOW.











