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Freshwater-Induced Surface Cooling of the Subpolar North Atlantic in a Large-Ensemble, High-Resolution, Coupled Model

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Abstract As a gateway between the Arctic and subtropics, the subpolar North Atlantic plays a key role in large-scale climate variability. In recent decades, the region has experienced pronounced freshening. While much attention has been paid to the expected long-term weakening of the Atlantic Meridional Overturning Circulation, the impact of freshwater on surface fluxes and seasonal to decadal air-sea coupling remains poorly understood. Here, we explore the detailed mechanism by which the sea surface salinity in the subpolar gyre is linked to the local sea surface cooling with the CANARI Large Ensemble of the HadGEM3-GC3.1 climate model. Our analyses suggest that freshwater fluxes modulate upper ocean dynamics, which enhance local cooling in winter and can explain the North Atlantic warming hole without the need to invoke large-scale ocean circulation changes as a driver. Moreover, by shaping the local air-sea heat fluxes, the freshening can have further-reaching implications.

Plain Language Summary The northernmost part of the North Atlantic Ocean plays a key role in global weather and climate. Many studies focus on how deep ocean mixing in this region responds to increasing freshwater from Arctic and Greenland ice melt, but the broader effects of this freshwater across seasons and years are not well understood. In our study, we use a high-resolution global climate model to examine how especially fresh conditions affect the upper ocean. We find that added freshwater may trigger a chain of events that leads to cooler surface temperatures. This surface cooling can influence the atmosphere and potentially affect weather over the surrounding continents. The effect is strongest in winter and has become more pronounced in recent decades while melting has increased.

Key Points:

- A state-of-the-art climate model indicates that freshening of the subpolar North Atlantic can enhance local surface cooling in winter
- The freshening occurs from summer to winter, but its effect on sea surface temperatures is most pronounced in winter
- The model indicates that the warming hole is caused by freshening, not circulation changes

Supporting Information:

Supporting Information may be found in the online version of this article.

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1. Introduction

The North Atlantic Subpolar Gyre (SPG) is a dynamically complex region, acting as a gateway between the subtropical Atlantic and the Arctic Ocean. By carrying warm, salty surface waters north-eastward and returning cooler, fresher waters southward at depth, the subpolar gyre forms an important part of the Atlantic Meridional Overturning Circulation (AMOC) (Buckley & Marshall, 2016; Lozier, 2023). The Labrador and Irminger Seas are among the few global sites of persistent deep convection, the downward branch of the AMOC, making the SPG a key region for ocean overturning and air–sea coupling (Marshall & Schott, 1999).

Recent observational and modeling studies have identified a persistent freshening trend across the SPG (Bamber et al., 2018; Carmack et al., 2016; Holliday et al., 2020) linked to enhanced Greenland runoff, Arctic freshwater export via Fram Strait, and increased river discharge (de Steur et al., 2009; Khan et al., 2015; Kumar et al., 2020). The addition of freshwater alters the buoyancy of surface waters, enhancing upper ocean stratification and suppressing vertical mixing. Large freshening could thus decouple surface and deep layers, potentially weakening the AMOC, a theoretical risk first outlined by Stommel (1961) and supported by many recent studies (e.g., Jackson et al., 2022; Liu et al., 2019; Sévellec et al., 2017; Yang et al., 2016). Predictions across large scale climate models further confirm the highly supported consensus that freshwater-induced buoyancy changes may trigger a mid-century AMOC slowdown, setting off longer-term heat-flux driven density changes (e.g., Drijfhout et al., 2025).

One prominent surface indicator of these changes is the North Atlantic Warming Hole (NAWH), a region of subdued warming (or local cooling), in the SPG frequently associated with altered heat and freshwater transport and AMOC variability (e.g., Caesar et al., 2018; Keil et al., 2020; Madan et al., 2024; Rahmstorf et al., 2015; van

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Westen et al., 2025). The direct causality between AMOC variability and the NAWH persistence is reasonably established. Some studies emphasize buoyancy-driven changes linked to Greenland melt and Arctic freshwater input (e.g., Caesar et al., 2018; Haine et al., 2023; Rahmstorf et al., 2015; Yang et al., 2016; Zhang & Thomas, 2021), whereas others further highlight the role of the atmosphere and internal variability (e.g., L. Li et al., 2020). Furthermore, SPG region SST and surface density changes may induce immediate modulations to large-scale atmospheric patterns, including the NAO, storm tracks, and European weather extremes, in contrast to the relatively slower ocean interactions (Gastineau & Frankignoul, 2015; Kramer et al., 2024; Oltmanns et al., 2020, 2024).

Observational analyses indicate that winter SST anomalies in the SPG are closely linked to density-compensating (or nearly density-compensating) salinity variations (Oltmanns et al., 2024). Some studies indicate the density decrease caused by the freshening increasingly exceeds the density increase associated with cooling, leading to a transition from an alpha-dominated (temperature-controlled) to a beta-dominated (salinity-controlled) regime as freshwater input increases (Caneill et al., 2022; Marsh et al., 2024; Stewart & Haine, 2016). CMIP6 and CMIP5 models project an intensification in the NAWH under continued greenhouse forcing, though uncertainties remain in how salinity feedbacks affect mixed-layer depth (e.g., Cheng et al., 2013; Drijfhout et al., 2012; Liu et al., 2020).

Despite progress, significant uncertainties persist. Many existing studies are limited by coarse models or short observational records, missing essential mesoscale and coupled processes (Böning et al., 2016; Mecking et al., 2017; Menary et al., 2015; Yu, 2020). In-situ observations of salinity are limited by mooring and ship survey locations and satellite observations have relatively short records compared to SST, with large biases, making it difficult to establish the role of salinity in stratification, surface fluxes, and atmospheric variability (Zou et al., 2019, 2020). High-resolution, large-ensemble simulations are therefore critical for separating forced trends from internal variability and for diagnosing the mechanisms by which salinity anomalies affect stratification, mixed-layer depth (MLD), and surface heat fluxes.

Here we use the CANARI high-resolution single-model large ensemble to assess how surface freshening alters winter stratification and surface temperature in the SPG. Due to the large ensemble size, high resolution, and state-of-the-art physics, the simulations are suited to isolate the influence of salinity variability on coupled ocean-atmosphere processes in the SPG.

2. Methodology

2.1. Data

Using simulations from the historical CANARI Single-Model Initial Condition Large Ensemble (SMILE) data set (Schiemann et al., 2026a, 2026b), based on the UK Met Office fully coupled climate model HadGEM3-GC3.1-MM (Williams et al., 2018), we focus on an area of the inner North Atlantic gyre region known to be exhibiting localized cooling (Figure 1a; 45–60°N, 25–45°W). We examine trends in sea surface salinity (SSS) and their relationship with on surface temperature and stratification. The model uses N216 atmospheric resolution (approximately 60 km at mid-latitudes) via the Met Office Unified Model (MetUM), and ORCA-0.25 ocean resolution (approximately 25 km at mid-latitudes) using the NEMO ocean model (Williams et al., 2018). The ensemble comprises 40 members, each initialized with small atmospheric and oceanic perturbations, providing a robust sample of internal variability and forced response. The simulations cover 1950–2014 under CMIP6 historical forcing (Eyring et al., 2016).

Freshwater fluxes are represented through coupled atmosphere–ocean exchanges of precipitation minus evaporation (P–E), river runoff, and sea-ice brine rejection and melt fluxes through CICE–NEMO coupling. Freshwater input in the North Atlantic includes Greenland runoff, iceberg discharge, and Arctic export through Fram Strait. A limitation is the absence of dynamically evolving ice sheets; Greenland melt is imposed as a climatological boundary condition rather than a fully coupled feedback. Nonetheless, the historical period considered here minimizes this limitation, and the ensemble reproduces observed freshening trends across the subpolar gyre (Figure 1d).

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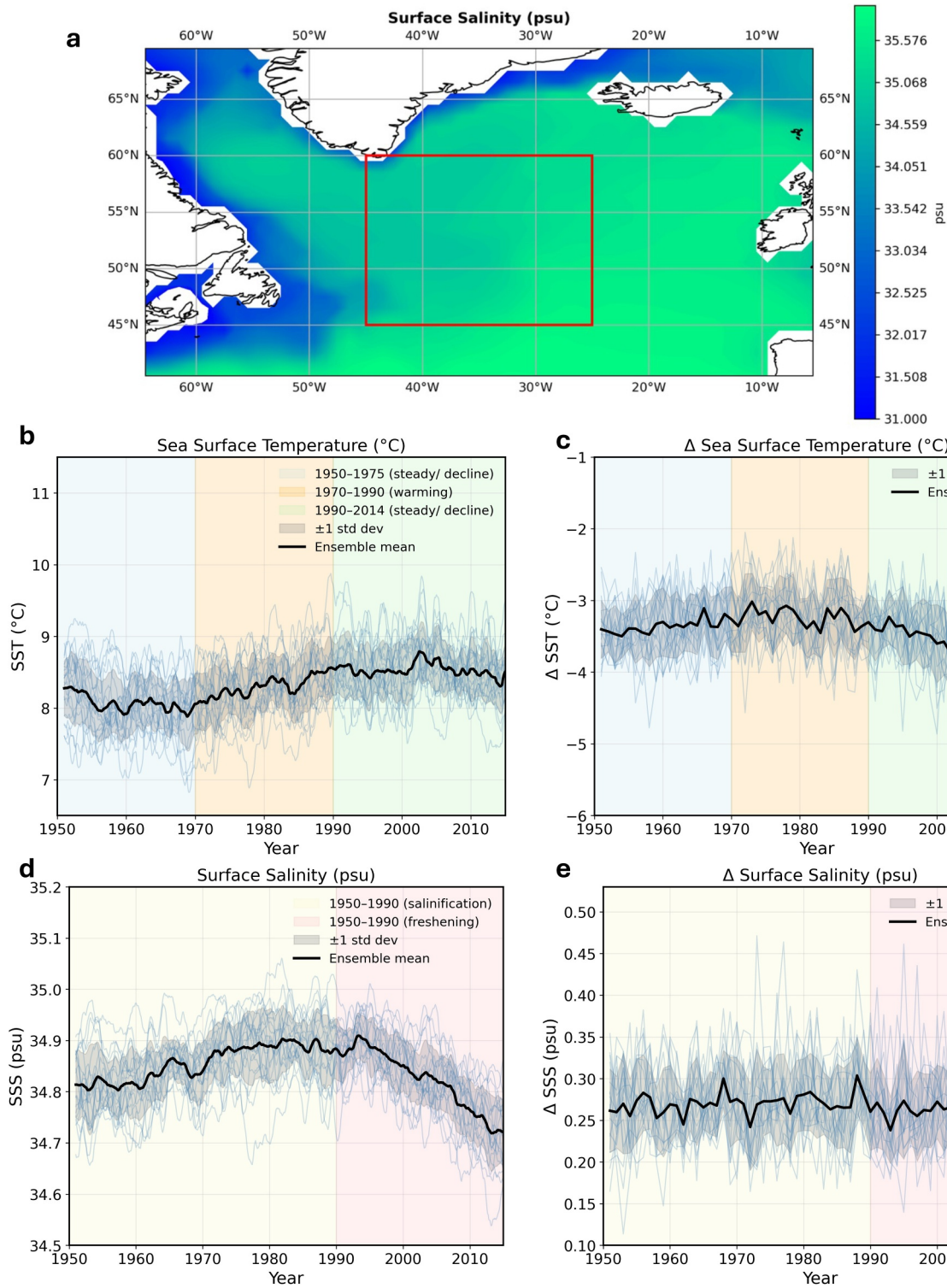

Figure 1. Historical (1950–2014) CANARI-LE (a) average sea surface salinity, with red box for region of analysis (45–60°N, 25°–45°W). (b) Annual mean sea surface temperature (black line) with all ensemble members in light blue, and the 1 σ ensemble spread gray and the changes in the direction of the mean trend highlighted with blue (stead/decline), warming (orange), green (late steady/decline) trends (b) difference between (Δ) winter and summer sea surface temperature. (d) as a but for sea surface salinity with highlighted yellow (salinification) and pink (freshening) trends. (e) Difference between winter (DJF) and summer (JJA) sea surface salinity.

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2.2. Diagnostics

Hypothesizing a regime shift in the upper ocean around the NAWH, we analyze the evolving relationship between sea surface temperature (SST) and sea surface salinity (SSS). Temporal trends and correlations are computed from 1950 to 2014, averaged over the inner subpolar gyre region (red box, Figure 1a). A clear transition from increasing to decreasing salinity occurs around 1990, coinciding with intensified regional freshening (Figure 1d). When assessing the SSS and SST ensemble mean trends for the full timeseries, we find that SSS has a gradual increase of ∼0.1 psu from 1950 to 1990, followed by a decrease from 1990 to 2014 of ∼0.2 psu. In temperature (Figure 1b), there is a steady period between 1950 and 1970, then an increase of ∼0.5°C between 1970 and 1990, followed again by a steady period and slight decrease by ∼0.25°C between 1990 and 2014. The strongest seasonal changes occur in winter, reflected in an increasing summer–winter SST contrast of up to ∼4.5°C (Figure 1c).. We hypothesize that the increase in the seasonal SST contrast is linked to the overall salinity decrease (Figure 1d), rather than the minimal change in seasonal SSS (Figure 1e).

Motivated by these trends, we evaluate differences between two periods: 1970–1990 (saline phase) and 1990–2014 (fresh phase), to assess the mechanisms underlying these temporal changes. The 1990 threshold corresponds to the ensemble mean transition point, but results are insensitive to small shifts due to high inter-annual variability (Figures S1 and S2 in Supporting Information S1). To complement this, we construct composite regimes based on winter (DJF) SSS. For each ensemble member and winter, the DJF-mean SSS in the analysis region is calculated and classified as either a fresh winter (SSS < 35.1 psu) or a saline winter (SSS > 35.15 psu). Thresholds were identified through sensitivity testing by statistically evaluating values before and after 1990, as well as at the specific point in time of maximum salinity across the ensemble members, and assessing their relationship with SST (Figures S1 and S2 in Supporting Information S1). However, the results are not highly sensitive to the exact threshold. Winters with intermediate SSS values are excluded from the analysis. Composite fields are then obtained by averaging all winters belonging to each category across all ensemble members, such that each winter-member combination is treated as an independent sample. The ensemble mean contains 29 saline winters and 16 fresh winters. This threshold-based composite method captures conditions that are representative of pre- and post-freshening states while accounting for internal variability across the ensemble and isolating the regime shift independently of simulation year. To further investigate the underlying processes and seasonal dependencies, we compute Pearson correlation coefficients between SSS and SST for each season. This enables us to identify the relationship between freshwater anomalies and surface temperature changes in periods where stratification and vertical mixing are markedly different.

To explore the physical drivers and consequences of these changes in SSS and SST, we assess correlations between SSS and key process-related variables. These include the density-based mixed layer depth (MLD), which indicates changes in convective mixing, and the net surface heat flux, which reflects the magnitude and direction of ocean-atmosphere heat exchange. The objective of the analysis is to provide insights into how freshwater-driven changes in salinity modulate ocean mixing and may impact the SST and atmospheric response. Statistical significance is calculated via *t*-tests with Benjamini-Hochberg corrections (Benjamini & Hochberg, 1995) across all results.

3. Results

3.1. Freshening and Cooling of the North Atlantic Winter

In winter, area-averaged surface salinity in the subpolar gyre decreases by up to 0.3 psu after 1990, with the strongest freshening centered over the gyre core (Figure 2a) and extending across the outer gyre. The largest freshwater anomalies (up to −0.5 psu) occur along the Greenland and Labrador boundary currents, consistent with the idea that these currents transport freshwater from glacial and sea ice melt. This freshening in the gyre core is accompanied by statistically significant winter surface cooling of approximately 1°C (Figure 2c), spatially coincident with the NAWH.

In summer, there is no statistically significant cooling, only a warming hole at the same location (Figure 2d), despite the persistence of freshening signals (Figure 2b). Compared to salinity, the summer SST pattern exhibits greater spatial variability, producing localized cooling without a coherent gyre-scale signal. This seasonal contrast indicates salinity's stronger influence on upper-ocean stratification and surface heat loss during winter,

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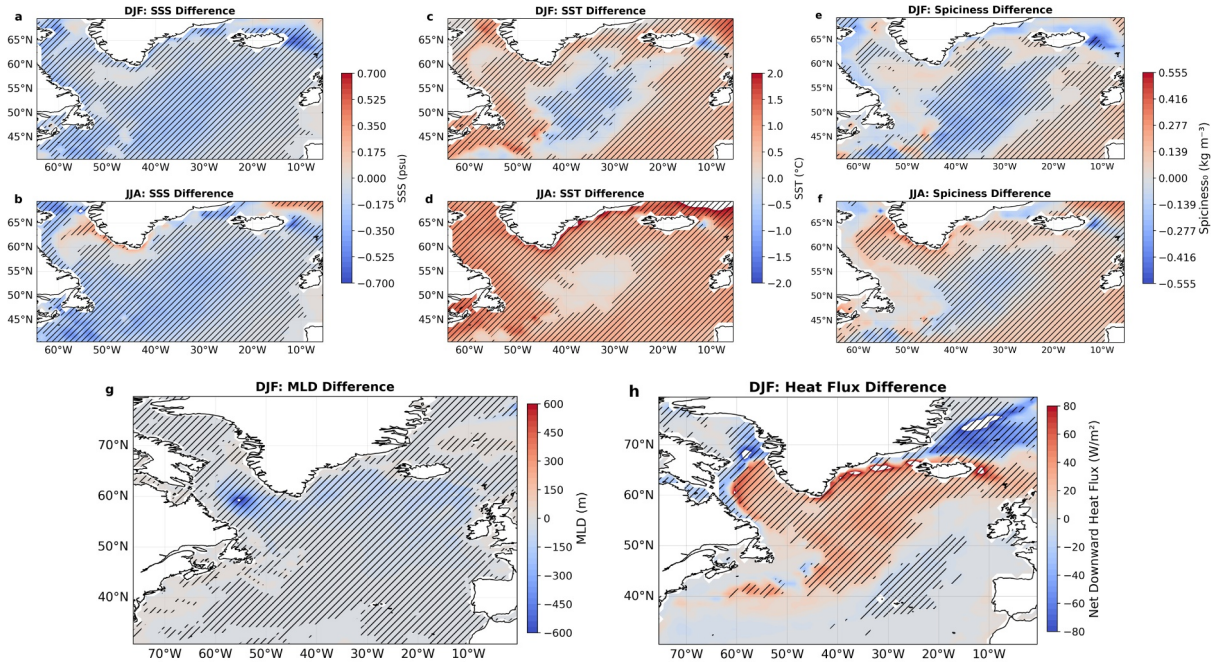

Figure 2. Seasonal anomalies between post- and pre- 1990 surface salinity for (a) winter (DJF), and (b) summer (JJA). (c and d) as (a and b) for surface temperature, (e and f) as (a and b) for spiciness, where positive relates to warm and salty and negative relates to cold and fresh. Winter (DJF) anomalies between post- and pre- 1990 mixed layer depth (MLD) for (g), and (h) as a but for net surface downward heat flux. Stippling indicates the 95% significance level by *t*-test and the Benjamini-Hochberg procedure.

whereas in summer pre-existing thermal stratification patterns from atmospheric heat fluxes limit vertical exchange and dampens the SST response.

Changes toward a fresher and colder surface ocean are further illustrated by the surface spiciness, a measure of simultaneous temperature and salinity changes at constant density (McDougall & Barker, 2011). Post-1990, the gyre center becomes markedly less "spicy," with the associated freshening accompanying a surface density decrease of -0.4 kg m^{-3} (Figure 2e). This is consistent with the transition documented by Marsh et al. (2024) whereby stratification becomes increasingly controlled by surface salinity rather than temperature, and the influence of high-salinity subtropical waters declines. In summer, spiciness changes are smaller (-0.2 kg m^{-3}; Figure 2f) and confined to the southeastern subpolar gyre, highlighting a residual salinity influence in the central cooling region, despite overall warming and general dominance of temperature influence throughout the SPG region. The observed reduction in winter spiciness indicates a shift in water-mass properties. This therefore provides further evidence that the post-1990 freshening reflects a reduced influence of warm, saline subtropical waters and an increased contribution from colder, fresher subpolar waters, consistent with the evolving salinity control on upper-ocean stratification. Separating the relative contributions of SST and salinity to changes in density (Figure S4 in Supporting Information S1), further confirms this and shows that the salinity contribution to the density change even exceeds that of the temperature.

3.2. MLD, Stratification, and Heat Flux

Considering the potential influence of the freshening on stratification and, in turn, the SST in winter, we next focus on the winter season, with summer results included in Supporting Information S1 for comparison.

MLD differences are strongly seasonal, reaching up to ∼250 m in winter (Figure 2g) and thinning to ∼12 m in summer (Figure S6 in Supporting Information S1), consistent with the much larger climatological mixed layer depths in winter. Under fresher post-1990 conditions, the winter MLD shoals by up to ∼75 m at the NAWH location (Figure S7 in Supporting Information S1), indicating enhanced stratification despite concurrent surface cooling that would otherwise favor convection.

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Net surface downward heat flux anomalies are positive in both winter (Figure 2h) and summer (Figure S6 in Supporting Information S1), indicating reduced upward flux from the ocean to the atmosphere in winter. In more saline years, deeper convection enables subsurface heat release and maintains higher SSTs. In contrast, under fresh conditions, a shallow halocline may trap heat below the pycnocline, cooling the surface while warming subsurface layers.

3.3. Mixed Layer Heat Budget

To gain a deeper physical understanding of the identified links between temperature and salinity, we carry out a scaling analysis of the mixed layer heat budget:

$$\frac{\partial T_m}{\partial t} = \frac{Q_{net}}{\rho_0 c_p h} - \boldsymbol{u_m} \cdot \nabla T_m + \kappa \nabla^2 T_m - \frac{w \Delta T}{h} \quad (1)$$

where T_m is the mixed layer temperature, Q_{net} are the net surface heat fluxes, h is the mixed layer depth, $u_m \cdot \nabla T_m$ is horizontal advection, $\kappa \nabla^2 T_m$ represents diffusion and $w \frac{\Delta T}{h}$ represents entrainment/detrainment (Dong et al., 2007; Wang et al., 2024). We have only ignored the downward radiative flux at the bottom of the mixed layer since it is negligible for our purposes. Assuming that mixed layer temperature changes are communicated to the sea surface (and SST), we next assess the relative importance of each term in the heat budget for the cooling signal from summer to winter (Figures 1c and Figure S3 in Supporting Information S1).

Surface heat fluxes: The surface heat fluxes cannot account for the cold anomaly, as the sign of the heat flux difference between the colder and the warmer subpolar SST period is positive (Figure 2h). If the surface fluxes were driving the cooling, the sign would be negative. Since the sign is positive, the ocean temperature is driving the heat flux anomaly. The effects of wind speed are implicitly included through the calculation of heat flux.

Horizontal advection: If the cold anomaly would be advected into the region, we could identify a source region and track the anomaly from summer to winter. However, the cooling appears locally in a confined region of the subpolar North Atlantic (Figure S3 in Supporting Information S1).

For ocean circulation changes to explain the cold anomaly, moreover, we would require an active driver causing a diapycnal flow. With neither the surface fluxes (Figure 2h) nor winds (not shown) being able to account for such an active, diapycnal transport, any (buoyancy-driven) circulation changes associated with the cold anomaly can only be a response to, not a cause of the freshening.

Diffusion: On these large scales, spanning the full subpolar North Atlantic, diffusion cannot account for the cold anomaly. When estimating the contribution of diffusion, we divide the temperature anomaly (~1°C) by the square of the spatial scale (~1,000 km) and multiply by the eddy diffusivity κ, which we estimate to be ~500 $m^2\ s^{-1}$ when averaged over the full gyre (Nummelin et al., 2021) The resulting diffusion term (~5×10^{-10}°C s^{-1}) is two orders of magnitude smaller than the temperature change on the lefthand side of Equation 1, which we estimate to be ~6×10^{-8}°C s^{-1} from summer to winter (Figure S3 in Supporting Information S1), even when accounting for a slightly weaker mixed layer temperature signal compared to the SST.

Entrainment: Finally, the cold anomaly could result from entraining deeper water from below. However, the mixed layer depth is shallower in the colder period relative to the warmer period (Figure 2g). There is also no conceivable driver which could drive enhanced entrainment as the associated surface heat losses are weaker (Figure 2h).

As a result of this scaling analysis, we conclude that the cooling can only be explained by shallower mixed layers in the first term on the righthand side of Equation 1. The heat losses are weaker, but they act over a shallower depth range, making them more effective. We excluded all other possible drivers of the cooling. While a detailed quantitative assessment of the role of salinity for the cooling is impeded by subsequent feedbacks to the cold anomaly, such as the SST response to the reduced surface heat losses and circulation changes, our analysis indicates that only enhanced stratification can account for the cooling, and only freshening can account for the enhanced stratification.

By comparing the pre- and post-1990 periods with each other, the mixed layer heat budget analysis implicitly considered multi-decadal changes. However, spatial correlations within each period demonstrate that the

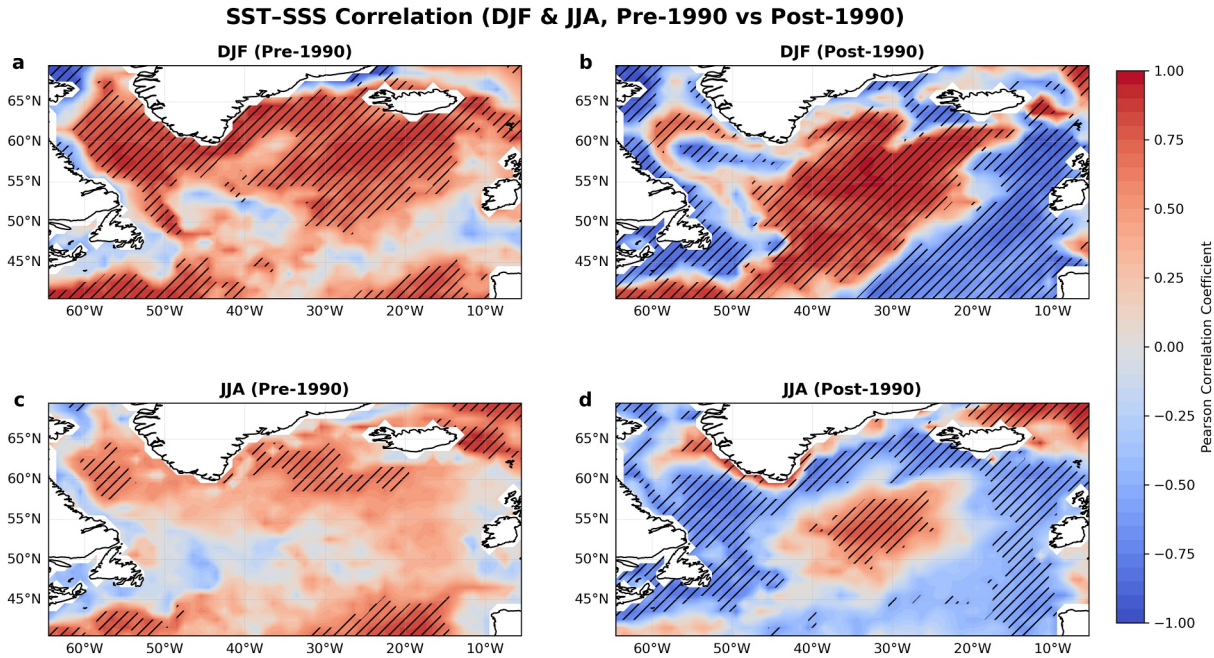

Figure 3. Spatial correlation coefficients between temperature and salinity for the more saline, calculated with monthly data, pre-1990, for winter (a) and summer (c). Spatial correlation coefficients between temperature and salinity for the less saline, post-1990, for winter (b) and summer (d). Stippling indicates the 95% significance level by *t*-test and the Benjamini-Hochberg procedure.

identified links also hold on interannual timescales (Figure 3). Specifically, we find that post-1990, spatial correlations between SST and SSS intensify in a large region around the NAWH compared to pre-1990 (Figures 3a and 3b), indicating the concurrence of warm-saline versus cold-fresh conditions. Correlations with the surface fluxes and mixed layer depth as additional diagnostics provide further support of the proposed impact of freshening on the SST (Figure S5 in Supporting Information S1). The relationship between the wintertime SST and SSS is so strong that it even imprints on the summer-relationship (Figures 3c and 3d), contrasting the negative SST–SSS correlations around the NAWH, where the alternation between warm-fresh versus cold-saline conditions could signify the repeated emergence of strongly stratified warm and fresh surface layers in summer (Oltmanns et al., 2018). While correlations do not imply causality, it is difficult to conceive an alternative mechanism that could explain the specific spatial characteristics, supporting the conclusion from the heat budget.

4. Discussion and Conclusions

This study uses a high-resolution large ensemble to investigate how surface salinity modulates stratification, SST, and air–sea heat exchange in the subpolar North Atlantic, a key region for the large-scale ocean circulation. The ensemble design allows us to diagnose the salinity's control on vertical processes, complementing earlier process-based studies.

The results suggest that winter freshening enhances upper-ocean stratification and suppresses vertical mixing, leading to local surface cooling despite reduced ocean-to-atmosphere heat losses. Thus, our results support the hypothesis that freshening of the SPG plays a central role in regulating the winter SST (Grist et al., 2025; Oltmanns et al., 2020).

In the most anomalously fresh years (post-1990), winter SSTs are up to 1°C cooler across the center of the gyre, with statistically significant anomalies aligned with the NAWH. This is consistent with observational studies reporting persistent cold anomalies in the SPG region over recent decades. The identified cooling coincides with a shallowing of the mixed layer by up to 75 m, indicating stronger stratification and reduced deep convection. Spatial correlations between SSS, SST, and MLD and heat fluxes further support the proposed mechanism, which is summarized in Figure 4:

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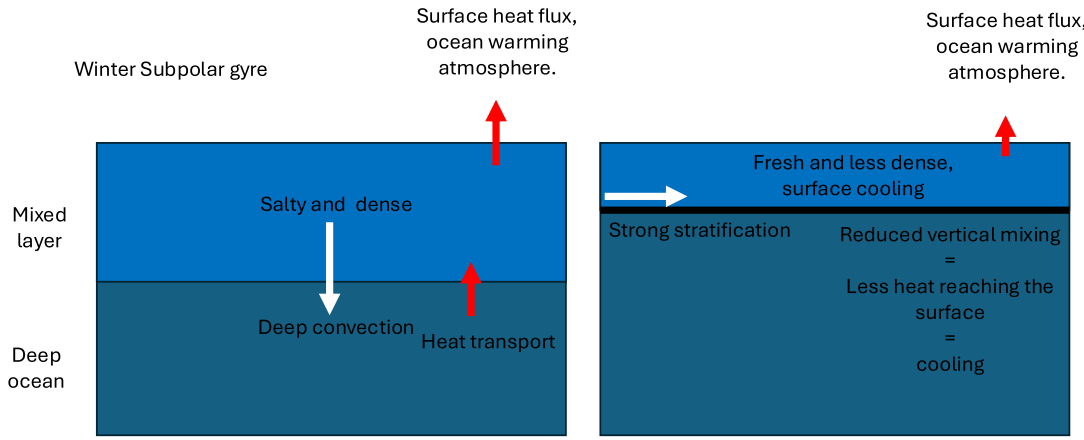

Figure 4. Schematic of winter subpolar gyre freshening influence on mixed layer depth and surface warming, showing how the winter subpolar gyre region shifts from a more well mixed, temperature driven mixing regime to a more stratified, salinity driven regime. This demonstrates the impacts on vertical mixing and its direct impact on surface temperature.

According to this proposed mechanism, freshening supresses vertical mixing leading to shallower mixed layers. The shallower mixed layers, in turn, lead to reduced ocean heat losses to the atmosphere as less ocean volume is in contact with the atmosphere. At the same time, the shallower mixed layers, lead to a faster and more intense surface cooling (Equation 1). This mechanism can explain the persistence of the NAWH without the need to invoke large-scale or remote ocean circulation changes.

In this framework, AMOC weakening emerges as a likely response to surface density changes rather than their cause. If there is more freshwater, then northward oceanic heat transport is reduced, meaning less warm water reaches the subpolar gyre (K. Y. Li & Liu, 2025). Seasonal asymmetry further reinforces this mechanism: summer warming partly offsets but does not erase winter cooling, leading to net multi-decadal persistence. This mechanism may link freshwater-induced stratification and SST to subsequent atmospheric impacts, including extreme weather downstream (Chevuturi et al., 2025; Oltmanns et al., 2020, 2024), particularly as freshening is expected to increase in the future (Figure S8 in Supporting Information S1).

There are, however, important limitations. First, although the model resolution is higher than standard CMIP6 runs, it still does not fully resolve mesoscale eddies or narrow boundary currents known to influence freshwater transport and vertical mixing (Böning et al., 2016; Marzocchi et al., 2015). It may therefore still underestimate the freshening and its effects. Additionally, the quantification of impacts remains difficult because of the intense air-sea interaction with ocean and atmosphere, often reinforcing each other's signals. Thus, while we can diagnose freshwater as an initiator of the cooling and subsequent feedbacks, we may not necessarily be able to fully quantify its effect due to atmospheric feedbacks. This also means that it remains difficult to attribute subsequent impacts solely to freshwater. Despite these limitations, the model correctly reproduced the principal dynamics of salinity driving stratification, surface fluxes and in turn, SST signals, as observations had previously suggested (Oltmanns et al., 2020, 2024).

In conclusion, our study highlights the central role of salinity-driven stratification in shaping and amplifying subpolar heat content and SST variability. Considering the importance of the North Atlantic SST variability for the large-scale atmospheric circulation, the simulations thus indicate freshwater as an increasingly important player in North Atlantic climate variability. The mechanism identified here operates on seasonal to decadal timescales, bridging surface freshening to longer-term climate impacts. Improving the representation of salinity processes in coupled models is therefore critical for predicting North Atlantic variability and its downstream atmospheric consequences.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

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Availability Statement

All model data used in this study are available through the CEDA archive as part of the CANARI Large Ensemble (CANARI-LE) priority variables. For access to the data, see Schiemann et al. (2026a), https://catalogue.ceda.ac.uk/uuid/4b62fafc68ae4c3784fb2819f652c537. The model description paper is available at Schiemann et al. (2026b) https://doi.org/10.5194/egusphere-2026-2281.

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