Controls on dense water formation along the path of the North Atlantic subpolar gyre

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We are grateful to both of the reviewers for taking the time to read the manuscript and for providing constructive feedback. We have acted upon each of the suggestions proposed by the reviewers and we believe that these changes have significantly improved the clarity of our conclusions and the limitations of our findings.

Our response to Reviewers is structured as follows: our responses are included in **red** and the original Reviewer comments are included in **blue**.

Responses to Reviewer 2 Comments

Why is the focus of this paper on dense water formation rather than the AMOC explicitly? According to the findings from OSNAP, there is no connection between dense water formation and dense water export (i.e., AMOC), see Zou and Lozier (2016).

We make it clear to readers from the outset that the focus of our study is on dense water formation rather than the AMOC (this is also reflected in the title of the manuscript). This choice was made for two reasons:

1. Our Lagrangian experiment seeks to quantify the formation of NADW by only one component of the subpolar overturning circulation: the boundary current of the SPG. We thus do not quantify NADW formation due to upper limb water parcels transformed in the Nordic Seas and the Arctic Ocean or those flowing directly into the Irminger Sea via the northernmost branch of the North Atlantic Current. To focus our study on the basin-scale overturning in the subpolar North Atlantic, we would need to account for all of these components. This limitation is included on Line 243, where we highlight that the Lagrangian diapycnal overturning strength in the eastern SPG cannot be compared to the traditional Eulerian diapycnal overturning strength at OSNAP East, given that we do not include the contribution of the Nordic Seas overflows.

2. As discussed on Lines 263-269, we would not necessarily expect dense water formation along Lagrangian trajectories circulating around the SPG to imprint onto the Eulerian diapycnal overturning (AMOC) strength. This is because water parcels will enter the lower limb along the entire length of the SPG boundary current, such that the time taken for newly formed NADW to reach OSNAP West and imprint onto the subpolar AMOC strength could vary from days to years. Furthermore, given that we do not continue to track water parcels following their southward crossing of OSNAP West (53N), it is not possible to distinguish between the newly formed NADW

parcels which are exported from the SPNA (thereby contributing to the basin-scale AMOC) from those which are simply recirculated within the SPG. This challenge is highlighted as a topic for further research in our Discussion on Lines 478-481.

Finally, the Reviewer is correct in highlighting that OSNAP observations show a weak (rather than non-existent) relationship between deep convection in the interior of the Labrador and Irminger Seas and the strength of the Eulerian overturning recorded along each array. However, our Lagrangian analysis focuses on the water parcels which are both transformed and exported within the boundary current of the SPG (see Figure 4a) rather than those experiencing wintertime convection in the basin interior. We would also highlight that both Le Bras et al. (2020) and Li et al. (2021) found a much stronger relationship between seasonal water mass transformation (convection) taking place within the boundary current and the downstream export of UNADW across OSNAP East.

Le Bras et al. (2020) https://doi.org/10.1029/2019GL085989
Li et al. (2021) https://doi.org/10.1038/s41467-021-23350-2

The authors should explain how their results impact the idea that temperature or salinity anomalies propagate on a steady ocean circulation (e.g. Sutton and Allen, 1997; Årthun et al., 2017), rather than a varying ocean circulation creates temperature and salinity anomalies (e.g. Foukal and Lozier, 2016; Desbruyères and Chafik, 2021).

We appreciate the Reviewer's suggestion, but note that we do not explicitly consider the origins of temperature and salinity anomalies arriving in the eastern SPG in our study. Rather, we are concerned with their downstream consequences for dense water formation: our results suggest that temperature anomalies are damped along the boundary current of the SPG, while salinity anomalies can persist downstream to impact dense water formation.

In the model, we do find a relationship between upper ocean temperature and salinity anomalies and the state of the subpolar circulation: a weaker, slower SPG circulation (see Fig. 9f) is associated with warmer, lighter upper limb waters (see Fig. 10b) flowing northward across OSNAP East. However, diagnosing the source of the thermohaline anomalies arriving in the eastern SPG is not in the scope of the present study since it would require us to evaluate backward-in-time Lagrangian trajectories to identify changes in the sources of the northward flowing waters arriving at OSNAP East. Such analyses have already been performed by Fox et al. (2022), Foukal and Lozier (2016), and Desbruyeres et al., (2021) as highlighted by the Reviewer, and emphasise that the composition of subtropical- vs. subpolar-origin waters arriving in the eastern SPG acts as an important control on upper ocean properties.

Fig. 1: the model streamfunction is also broader than observations, which indicates that the upper limb waters are lighter than observed and the water mass transformation in the subpolar North Atlantic is larger than observed. Furthermore, there is considerably more formation of very dense waters (sigma>27.75 kg/m3), which implies that this model suffers from the well-known issue of too strong convection in the Labrador Sea (e.g., Menary et al., 2020). This issue should be discussed in the conclusions as a limitation of the study.

We thank the Reviewer for highlighting model biases in the magnitude and composition of diapycnal transformation as a relevant limitation of our study. We have now added a short paragraph on Lines 483-487 of the Discussion highlighting the potential relevance of such biases to our conclusions:

"*We also recognise that model biases may play a role in amplifying the relationship between remote surface buoyancy forcing and DWF along the path of the SPG in this ocean model. For example, the larger-than-observed lower NADW formation (> 27.75 kg m^{-3} in Figure 1b) north of OSNAP West in this hindcast is indicative of excessive Labrador Sea deep convection (a well-established bias in eddy-rich models; Petit et al., 2023, Jackson and Petit, 2023), which would enable the deeper penetration and greater persistence of density anomalies originating from surface buoyancy forcing (Reintges et al., 2024).***"**

Line 100: OSNAP imposes a -1.6 Sv flow through OSNAP West and a +1.6 Sv flow through OSNAP East (Lozier et al., 2019). Did the authors consider the effect of this northward flow across OSNAP East as well?

We already comment on the influence of the weaker than observed net throughflow in the model on the strength of diapycnal overturning at OSNAP East on Lines 95-97: "*... However, this is primarily due to the weaker time-mean net northward transport across the section in the model (0.8 ± 1.1 Sv) compared to the 1.6 Sv imposed in the OSNAP observational calculation.*" If we were to impose a similar 1.6 Sv net throughflow across OSNAP East in the model, the resulting time-mean overturning strength would be approximately 14.3 Sv (13.5 + 1.6 Sv - 0.8 Sv) and hence would compare even more favourably with the 14.5 Sv observed along the OSNAP array. Importantly, our Lagrangian overturning calculations are not influenced by the water parcels which contribute to the net northward transport across the OSNAP East section, given that we remove these water parcels from our experiment on their northward crossing of the Greenland-Scotland Ridge.

Fig. 2: How does the strength of the 'SPG pathway' compare to a Eulerian measure of SPG strength, such as from OSNAP?

We thank the Reviewer for this interesting question. Unfortunately, there is no simple approach to compare the volume transport of an individual Lagrangian circulation pathway, such as the SPG boundary current, to an Eulerian measure of the SPG strength. This is because integrated Eulerian diagnostics, such as the barotropic stream function, will also include the volume transport contributions of the Irminger Gyre, Arctic-origin and Nordic Seas overflow pathways. We highlight the challenge of comparing traditional Eulerian metrics with Lagrangian diagnostics describing an individual component of the flow on Lines 243-244, where we note that the DWF occurring in the eastern SPG cannot be directly compared to the Eulerian overturning stream function calculated at OSNAP East due to the absence of the Nordic Seas overflows in our Lagrangian analysis.

Fig. 3: This is a beautiful figure – please overlay isopycnals on panels b and d to look at baroclinicity in the water column. The strength of the baroclinicity in different parts of the

region could explain why some water masses make it over the Greenland-Scotland Ridge and some are retained in the subpolar basin.

We thank the Reviewer for their excellent suggestion to improve Figure 3. We have now included the time-mean position of the both the 27.3 kg m^{-3} and σ_{DWF} = 27.66 kg m^{-3} isopycnals. These specific isopycnals were chosen since they typically distinguish between the lighter (<= 27.3 kg m^{-3}) waters flowing northward across OSNAP East which continue to flow northward over the Greenland Scotland Ridge and those which recirculate in the SPG (> 27.3 kg m^{-3} & < σ_{DWF}), and, in the case of σ_{DWF}, distinguish between the waters flowing northward in the time-mean upper limb and the lower limb of the subpolar AMOC in this model.

Line 365: Hakkinen and Rhines (2004) used an EOF of SSH to derive their 'gyre index', not a SSH gradient as indicated in the text here. See Foukal and Lozier (2017) for a discussion of the 'gyre index' in comparison to a SSH gradient metric. See also Chafik and Lozier (2025) for further discussion of why the gyre index is not a good metric of subtropical-to-subpolar connectivity.

We are grateful to the Reviewer for highlighting this inconsistency between the Hakkinen and Rhines (2004) reference and the text. Our intention here was to recognise the work of Hakkinen and Rhines (2004) in demonstrating the relationship between sea surface height and the subpolar gyre strength (specifically, that a weakening of the the subpolar gyre circulation is associated with an increase in sea surface height as captured by the 1st temporal mode - PC1). On reflection, however, we believe that the work of Yeager et al. (2020) demonstrating how abyssal thickness anomalies induce changes in the sea surface height gradient across the basin (and hence modify the near-surface geostrophic velocity field) is more relevant to our findings and have now included this in place of the Hakkinen and Rhines (2004) reference on Lines 370-372.

Yeager et al. (2020) https://doi.org/10.1007/s00382-020-05382-4

Line 384-386: This paragraph should include the context that this relationship occurs in the model they are analyzing, and may not apply to the real ocean. The authors should consider adding this caveat to other parts of their paper as well.

We agree with the Reviewer that our summary should have been more precise regarding the source of our conclusions. We have now added "*in an eddy-rich ocean model hindcast*" to the end of Lines 390-392 to make this clearer to readers.

We have also added a similar caveat to the summary on Lines 426-429 in the Discussion:

"... indicating that upper limb potential density anomalies do not feed back onto the strength of DWF and hence diapycnal overturning in this eddy-rich ocean model."

And on Line 496:

“*Instead, decadal variations in the DWF along the path of the SPG are driven remotely by surface buoyancy forcing localised in the central Labrador and Irminger Seas in this model.*”

Figure 1 appears before its first mention (line 90).

We have moved Figure 1 to be positioned at the end of Methods section 2.1 (above Line 125), following its first reference in the text on Line 91, as suggested by the Reviewer.