Seasonal overturning variability in the eastern North Atlantic subpolar gyre: A Lagrangian Perspective

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Responses to Reviewer 1 Comments

We would like to thank each of the reviewers for dedicating their time to reading the manuscript and providing constructive feedback. We have acted upon all of the comments and suggestions proposed by reviewers, which we believe has led to a significant improvement in the structure and clarity of the original manuscript.

Our response to Reviewer 1 is structured as follows: **Section A** addresses the major comments of Reviewer 1 concerning the methodology of our study and the structure of our manuscript. **Section B** addresses the minor comments of Reviewer 1 on the contents of the manuscript. In both sections, our responses are included in **red** and the original Reviewer comments are included in **blue**.

Summary

Using a NEMO-based forced global numerical hindcast simulation, the authors characterize the seasonal variability of the overturning circulation across the OSNAP-east section in the Subpolar North Atlantic. Combining Eulerian and and Lagrangian approaches, they found that such seasonality is critically controlled by the transit time of water parcels north of the section, with a 8.5 month threshold beyond which diapycnal transformation is irreversible (i.e. contribution to the mean overturning, not the seasonality). They further describe the pathways and mechanisms underlying the seasonal signal, and show the key role for wind- driven changes in recirculation time of upper water masses in Irminger Sea. Distinguishing the respective pathways and timescales that characterize the seasonal and mean overturning is a key asset of this work.

It was overall a pleasure to read this manuscript. It is well and precisely written, with a rigorous and very comprehensive analysis of well-posed scientific questions. I think it comprises significant findings and will represent, alongside its already-published companion paper on the mean overturning state, a timely contribution to the field. Therefore, I have only a few general and minor comments, which I list below.

Section A

The paper is long, quite dense and detailed, which could give some readers a hard time to eventually extract the key take-home messages. I would suggest shortening the text where possible and only keep the key findings in the main text, and maybe put the complementary diagnostics in supplementary materials. This is more of an advice than a request.

We agree with the reviewer that, on reflection, our original manuscript often favoured detail over the clarity of our central messages and have therefore significantly revised the manuscript to reflect this. In addition to reordering the text to ensure consistency between the structures of the manuscript sections, we have rewritten the Introduction to present a more concise motivation for our key research questions. We have additionally decided to shorten our original Section 5.2 entitled *Transformation along seasonal overturning pathways* by combining our original Figures 6a-b, 6e-f & 7c-d following the suggestion of Reviewer 3 and moving the original panels (Figures 6c-d) detailing the seasonal density changes along each overturning pathway to the Appendix (see Figure A1).

It should be made clearer (in the abstract notably) that the results apply to the OSNAP-east section only. In some instance, the findings are presented as relevant for the entire eastern SPNA (e.g. line 13-16). Although the sensitivity of the results to the specific section location is mentioned at line 579-584, I think this should be better emphasized throughout the paper. In fact, I wonder if replacing "in the eastern North Atlantic subpolar Gyre" by "across the OSNAP-east section" in the title would be indeed more correct.

Following the reviewer's suggestion, we have significantly revised the abstract and main text to make it clear to readers throughout our study that our analysis is conducted at a model-defined OSNAP East section. We agree with the reviewer that the location of OSNAP East plays an integral role in determining the seasonality of overturning recorded at the section and have modified our discussion to better emphasise this point in the context of the Eulerian observations made along the OSNAP array [Lines 564-568]. We additionally acknowledge that the relationship uncovered between seasonal wind stress forcing and overturning seasonality at OSNAP East may not be applicable elsewhere within the SPG and highlight the important role of basin geometry in modulating this relationship [Lines 319-325]. We prefer to keep the title as is to ensure it remains both appealing and accessible to readers who may not be familiar with the OSNAP array.

Although the authors start to elaborate on the possible impact of using higher-resolution runs at the very end of the manuscript, I believe more could be said on their use of a single numerical model to infer general conclusions about the overturning. I think the authors should better acknowledge in their manuscript that their results might be model-dependent, and specifically point out the most sensitive diagnostic/results accordingly.

We have addressed this by restructuring our discussion of the limitations associated with our study to identify two specific results which we anticipate will be most sensitive to changes in model resolution (horizontal and vertical) and the choices of physical parameterisations. As highlighted in our original discussion, we would expect shorter water parcel recirculation times at eddy-rich / eddy-resolving resolution to favour a larger seasonal Lagrangian overturning signal at OSNAP East. Preliminary results from an ongoing model comparison study, investigating the impact of increasing horizontal model resolution on the strength and variability of Lagrangian overturning across the OSNAP sections, support this hypothesis (the amplitude of the LMOC seasonal cycle increases by ~2 Sv at OSNAP East in a simulation at 1/12 degree resolution). Secondly, we acknowledge that the mixing-induced diapycnal transformations sampled along water parcel trajectories are likely to be strongly dependent upon the representation of (sub)mesoscale mixing and therefore the chosen parameterisation of lateral and vertical eddy mixing in the ORCA025-GJM189 simulation [Lines 626-647]. We also acknowledge the potential role of well-established model biases, such as the excessive entrainment of ambient Atlantic water by the Nordic Seas overflows, in shaping our finding that the composition of the lower limb exhibits remarkable stability at OSNAP East in this simulation [Lines 533-536].

On the same topic, references to previous validation of that particular simulation in the SPNA should be added in Section 2.1 (how well does ORCA025-GJM189 represents the basic features of the subpolar North Atlantic?)

We have added a further paragraph to Section 2.1 to address the fidelity of the subpolar North Atlantic circulation and hydrography simulated by ORCA025-GJM189 as suggested by the reviewer. Since the previous studies of MacGilchrist et al. (2020), Asbjornsen et al. (2021) and Tooth et al. (2023) have all presented detailed validations of the ORCA025-GJM189 simulation within the domain of interest in this study, we choose to summarise their existing conclusions rather than reproduce this analysis [Lines 104-117].

I was left wondering whether the results could be sensitive to the chosen parametrization of turbulent convective mixing within the mixed layer (random perturbation of vertical velocities)? Could the authors comment on this in their Methods section?

We are grateful for this excellent question by the reviewer and have included here a supplementary Figure S1 below to address this directly. As noted on Lines 191-193, the strength and variability of the Lagrangian overturning at OSNAP East is not found to be sensitive to our parameterisation of vertical convective mixing along water parcel trajectories in the surface mixed layer. We determined this by comparing our original monthly time series and seasonal cycle of Lagrangian overturning for the shorter period between 1996-2008 with the equivalent diagnostics calculated from water parcel trajectories evaluated without vertical convective mixing in the surface mixed layer.

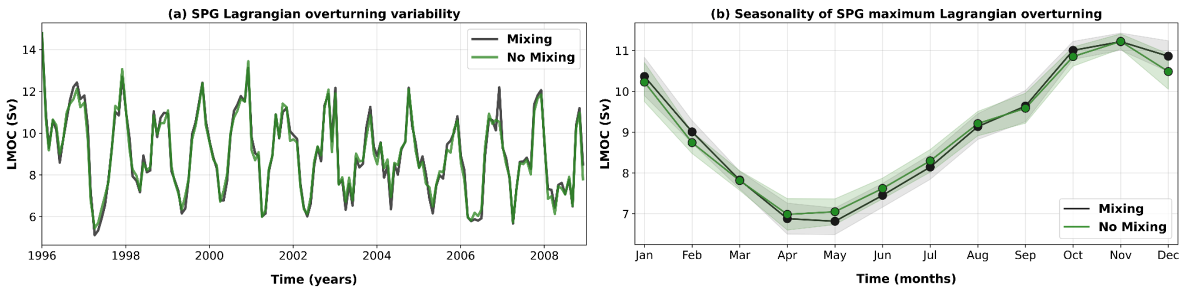

Figure S1. Lagrangian overturning variability of the eSPG at the model-defined OSNAP East section excluding vertical convective mixing in the surface mixed layer. (a) Monthly maximum of the Lagrangian Overturning Function in density-space with (black line) and without (green line) vertical convective mixing in the surface mixed layer between 1996-2008. (b) Mean seasonal cycles of the maximum Lagrangian overturning within the eSPG computed from monthly composites with (grey shading) and without (green shading) vertical convective mixing in the surface mixed layer. Shading represents +/-1 standard error of the monthly estimates.

Section B

65-69: I am not sure to follow the point made here. Comparing the seasonal AMOC amplitude (4 Sv) with that of its potential surface forcing (20 Sv) makes sense (although the volume term hampers this comparison, as stated), but comparing it to the mean strength (16 Sv) is less clear to me.

On revising the Introduction of our manuscript, the sentence highlighted above was removed due to its lack of clarity.

152: Integrating from the sea surface (instead of from the bottom) implies that the MOC strength includes the net transport through the section because one can assume that the northward transport into the Arctic takes place in the shallowest layers. Some studies indeed use bottom-up integration to strictly capture the overturning (in fact the authors here remove this net throughflow to provide the mean at line 190). Therefore, I wonder whether the Eulerian seasonal signal does include a contribution from the seasonal variability of the net throughflow? Was it also removed from the total signal?

We would like to thank the reviewer for posing this intriguing question regarding the decision to exclude or include the net throughflow across the OSNAP East section in our Eulerian overturning analysis. In reflection of its importance, we have added a paragraph in Section 2.3 *(Definitions of the overturning in density-space)* to outline our chosen approach and explain its implications for our central findings [Lines 165-171]. The reviewer is correct that, by electing to integrate the overturning streamfunction from the lightest to the densest isopycnal surface, our definition of the MOC includes the net throughflow across the OSNAP East section. This decision was primarily motivated by our desire to investigate the volume transport structure of the MOC upper limb in Figure 3 (formerly Figure 8) and because, to compensate for the net throughflow, we would have to assume a spatial structure for its distribution along the OSNAP East section which we prefer to avoid. To assess the impact of including a time-varying net throughflow in our Eulerian overturning calculation, supplementary Figure S2 below presents the monthly time series of the maximum Eulerian overturning excluding the net throughflow across the section (i.e., MOC – V_{net}) and the seasonal cycles of the MOC both including and excluding the net throughflow contribution. Importantly, we do not find a seasonal signal in the net throughflow across OSNAP East in our hindcast simulation and thus its inclusion in the Eulerian overturning diagnostic does not change the physical mechanisms identified as underpinning seasonal Eulerian overturning variability in our study [Lines 170-171].

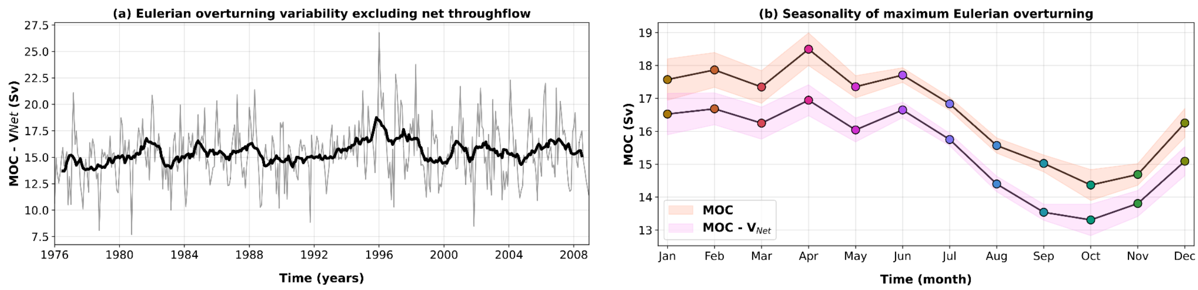

Figure S2. Eulerian overturning variability at the model-defined OSNAP East section excluding the net throughflow to the Arctic. (a) Monthly maximum of the Eulerian overturning in density-space (first available day of each month, grey line) and 1-year annual running mean (black bold line) overlaid for 1976-2008. The net throughflow across the OSNAP East section is removed from the maximum of the Eulerian overturning streamfunction each month. (b) Mean seasonal cycles of the maximum of the Eulerian overturning computed from monthly composites including (orange shading) and excluding (pink shading) the net throughflow across the OSNAP East section. Shading represents +/-1 standard error of the monthly estimates.

249-250: What explains the 1 Sv difference between the peak-to-peak amplitude of the seasonal MOC (4.1 Sv) and LMOC (5.1 Sv)? This should be explained.

We note that, by definition, the Eulerian (MOC) and Lagrangian overturning (LMOC) represent fundamentally different measures of subpolar overturning variability and we would therefore not necessarily expect their seasonal variability at OSNAP East to be of similar magnitude. The Eulerian overturning streamfunction zonally integrates the volume transports normal to the OSNAP East array in density-space at a given point in time (the start of each month in our study), whereas the Lagrangian overturning function measures the total diapycnal transformation a water parcel will go on to experience during its recirculation north of the section. As such, the seasonality in the Eulerian overturning can reflect both discontinuities between the instantaneous northward and southward transport components across OSNAP East (e.g., those resulting from seasonal wind-driven circulation changes as shown in Section 3.2) and seasonal changes in the density structure of the upper ocean along the section. In contrast, seasonal Lagrangian overturning variability reflects changes in the along-stream transformation of water masses into the lower limb of the overturning circulation as a function of when they flow northwards across the OSNAP East section. Thus, the amplitude of the LMOC seasonal cycle can be interpreted as follows: an additional 5.1 Sv of the water arriving at OSNAP East in November is transferred into the lower limb compared with the water flowing northward across the section in May. The amplitude of the Eulerian overturning seasonal cycle instead tells us that an additional 4.1 Sv of water flows northward across OSNAP East in the upper limb of the MOC in April compared with October.

348: Vage et al (2011) is an observational analysis, so it is not obvious whether their definition of boundary-interior limit (500 km) applies in the model too. Are the simulated IG and IC characteristic in line with observed ones ?

As discussed in our previous paper (Section 3 in Tooth et al. 2023), the northward inflows of the Irminger Gyre and Irminger Current across OSNAP East are most appropriately distinguished by their sharp density contrast in the ORCA025-GJM189 simulation. The time-mean velocity field (1976-2015) included in the supplementary Figure S3 below shows that, consistent with the observation of Våge et al. (2011), the lighter, surface intensified Irminger Current inflow is confined to the the western flank of the Reykjanes Ridge (500 km < x ≤ 750 km), whereas the inflows to the Irminger Gyre occupy the basin interior (x ≤ 500 km). We have also included a statement on Line 283 that our decision to use the Våge et al. definition of the Irminger Current and Irminger Gyre transports is supported by our simulated time-mean current structure.

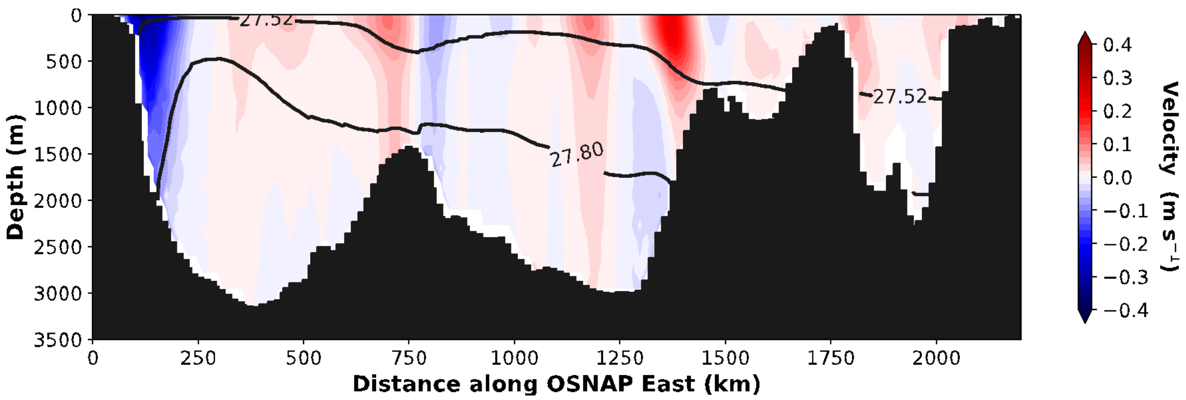

Figure S3. Time-mean Eulerian velocity field (1978-2015) simulated across the OSNAP East section in the ORCA025-GJM189 ocean sea-ice hindcast. Overlaid black lines represent the time-mean isopycnals of maximum Eulerian overturning (27.52 kg m^{-3})and the observed upper limit of overflow waters in the subpolar North Atlantic (27.80 kg m^{-3}).