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

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Responses to Reviewer 2 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 responses are included in **red** and the original Reviewer comments are included in **blue**.

Summary

The manuscript describes an in-depth analysis of Lagrangian-derived overturning in the eastern subpolar gyre, with an emphasis on the seasonal cycle. The analysis is conducted wholly in the ORCA025 model run that extends from 1958-2015. The authors compare the Eulerian AMOC in the model to a Lagrangian-derived AMOC by seeding Lagrangian particles in the northward currents across OSNAP East and calculating their net water mass transformation by the time the water particles recirculate southwards across OSNAP East. The authors find that the seasonal cycle across OSNAP East is primarily driven by fast-moving particles that recirculate in the region within 8.5 months.

I found the manuscript fascinating and the figures beautiful. The text is quite long, but each of the sections provided interesting information. I commend the authors for the amount of work and diligence it must have taken to prepare a manuscript with this much material. For this reason, I was torn about how to review this paper: on one hand, the paper is extremely polished, while on the other hand, I found a few major concerns about the manuscript (described below). I have decided to recommend the paper be reconsidered pending major revisions, mostly because my concerns underlie the basis of the paper, and they give me serious pause when trying to learn what to take away from the paper. Without sufficiently addressing these concerns, the manuscript lacks a central message despite the fascinating results along its circuitous journey (which is analogous to the journey these Lagragian particles take around the Iceland Basin...).

Major Comments

1. It is unclear to me what the goal of the paper is and/or what signal the authors are trying to explain. Is it the observed seasonality at OSNAP East? Or possibly the model’s version of seasonality at OSNAP East? If the authors are trying to explain the observed seasonality at OSNAP East, it has not yet been identified in the published literature, so it seems strange to try to explain it without the signal being identified. Can the authors diagnose the OSNAP East seasonal cycle from the publicly-available data and use that as a motivation for the current study? And if it is the model’s seasonality, the authors should explain the importance of a single model’s representation of the seasonal cycle, especially whether it resembles the observations.

We have completely rewritten the Introduction and made significant edits elsewhere to make it clear that the goal of the paper is a thorough understanding of what determines seasonal variability in overturning at the model's OSNAP East section. This should help us understand what we see in the observations once that time-series is published. See the response to point 2 below for further details on the changes made.

2. Part of my concern in #1 arises from ambiguity in the introduction – individually the sentences are factually correct and well-written, but I often didn't understand how one sentence led to the next. This is true throughout the section, though I will highlight the sentence starting "It therefore remains an open question..." (line 80) because it is critical to motivating this paper. The previous sentences were discussing seasonal versus interannual variability, then in this sentence the authors shift to comparing the mean AMOC to its seasonal cycle. I generally agree with the sentences individually up to this point, I just don't know how it leads to the authors' question that they seek to address in the paper. I also didn't understand the importance of this question: why does it matter whether the particles that determine the mean state are the same as the ones that determine the seasonality? To address this issue throughout the introduction (not just the example I provided), I recommend the authors highlight a single (or set) of questions that they aim to address in the manuscript, and provide motivation for why those questions are important in the introduction. Otherwise, the text seems to ramble through a lot interesting topics, but lacks clear, identifiable results. I also believe that much of the text could be condensed and made more readable if the goals of the study were outlined early.

On reflection, we can see why the reviewer found significant ambiguity in the aims of our original manuscript and have therefore made extensive revisions to the entire text. While the reviewer is correct to point out that OSNAP was unable to identify a statistically significant seasonal cycle in the Eulerian overturning measured at OSNAP East between 2014-2018, Fu et al. (*submitted)* document a statistically robust observed overturning seasonality determined from the longer 6-year MOC time-series recorded at the section between 2014-2020. With that said, previous observations, such as Mercier et al. (2015) at the OVIDE section, and observationally constrained reanalyses (Wang et al. 2020) have already reported pronounced seasonal overturning variability within the eastern subpolar North Atlantic. Given that the amplitude of such overturning seasonality amounts to a comparatively small fraction of the seasonal buoyancy-driven transformation in this region, we, therefore, seek to understand the extent to which seasonal dense water formation drives seasonality in the overturning evaluated at OSNAP East.

Previous studies, adopting the traditional Eulerian overturning framework, have attributed seasonal overturning variability entirely to seasonal changes in the density structure of the Irminger Sea western boundary current. However, we are able to demonstrate that this explanation fails to recognise how wind-driven seasonal changes in the volume transport of the boundary current might also contribute to the seasonal signal of Eulerian overturning at OSNAP East. Moreover, we should also ask whether the traditional Eulerian framework is best placed to understand the seasonality of overturning, given that it is predicated upon the efficient export of newly ventilated water masses within several months of their formation upstream. We instead argue that adopting a Lagrangian perspective which quantifies the formation of dense water masses along the circulation pathways of the eastern SPG (within the Iceland and Irminger basins) is more appropriate since this explicitly accounts for the wide distribution of recirculation times north of OSNAP East. We now explicitly state the purpose of our study is "to identify the circulation pathways responsible for seasonal overturning variability at OSNAP East and characterise their advective timescales and along-stream transformations within the eSPG" on Lines [66-68].

We have also modified the structure of our manuscript to ensure that the Eulerian and Lagrangian analyses are presented separately to avoid ambiguity in the interpretation of our central results.

3. The authors use ORCA025 exclusively and do not motivate why this would be a good, or even sufficient model to use for this analysis. There are certainly higher resolution models run for similar time periods readily available, so I would hope that there is a reason to use this model over the others (e.g. HYCOM, VIKING, other NEMO-based model runs, ECCO, etc.).

The reviewer was right to highlight the lack of motivation for our use of the ORCA025-GJM189 hindcast in our original manuscript. To address this, we have added two new paragraphs on Lines [97-117] in the Methods section to communicate our reasoning, which can be summarised as follows:

1. This specific ORCA025-GJM189 simulation has been used in previous Lagrangian analyses investigating the circulation pathways of the subpolar North Atlantic Ocean.

2. While there are naturally biases in the circulation and hydrography at eddy-permitting resolution (predominantly at depth where there is a poor representation of the Nordic Seas overflows and hence an absence of deep stratification), the horizontal resolution of the ORCA025-GJM189 model is approximately four times finer than the typical resolution used in the ocean component of CMIP6 climate models. Furthermore, the ORCA025 configuration is more typical of the climate model involved in the previous HighResMIP and upcoming CMIP7 experiments (e.g. the HadGEM3-GC31-MM model included in HighResMIP uses the eORCA025 configuration of NEMO as its ocean component). We argue that it is therefore critical to document the physical mechanisms governing the seasonality of subpolar overturning at this resolution, given that the accurate assessment of long-term trends in the strength of the MOC is predicated on adequately resolving higher frequency variations, including those occurring on seasonal timescales.

3. The ORCA025 configuration has been extensively validated in the subpolar North Atlantic. We have also included a further paragraph highlighting the results of the validation of the ORCA025-GJM189 hindcast previously undertaken by Tooth et al. (2023), as well as the findings of earlier ORCA025-based process studies in the subpolar North Atlantic. [Lines 108-115]

Though resolution is not the only component of a model that determines its quality, I am concerned that a 1/4° resolution model cannot resolve some of the important processes in the eastern subpolar North Atlantic shown in the literature (e.g. Gary et al., 2018; Houpert et al., 2018; Zhao et al., 2018; Devana et al., 2021), specifically the transformation of water, and any vertical velocities, both of which are highly resolution-dependent, yet important to the AMOC. I am also concerned that a 1/4° cannot properly resolve the three currents that enter the Iceland Basin (Holliday et al., 2020), which are critical to understanding the circulation in the region.

Alongside the addition of a summary of previous validations of the ORCA025 model configuration, we have also added further comparisons between the simulated overturning and gyre circulation and relevant observational estimates made in the eSPG. For example, we compare our simulated strength of the MOC, the isopycnal of maximum Eulerian overturning, the net throughflow across the OSNAP East section, historical trends in the MOC strength between the 1970s-1990s and 1990s-2000s to relevant observations in Section 3.1. [Lines 196-215] We have also modified Section 4.1

(formerly Section 3.2) to highlight the fidelity of our simulated time-mean Lagrangian overturning between OSNAP East and the Greenland-Scotland Ridge by comparing this value to observed estimates of the overturning in this region from volume budget calculations [Lines 342-345].

To better acknowledge the limitations of the ORCA025-GJM189 hindcast simulation, we have extended our discussion to highlight two particularly relevant uncertainties for this study. These are: (i) the impact of horizontal resolution on recirculation times and (ii) the impact of both the chosen physics parameterisations (including sub-grid scale) and model resolution on the mixing-induced diapycnal transformations captured along water parcel trajectories. We strongly agree with the reviewer's comment that model resolution alone does not necessarily lead to a more accurate representation of the circulation and water mass properties and would highlight the work of Chassignet et al. (2020) as a particularly notable example. In particular, we emphasise that while eddy-rich simulations undoubtedly yield significant improvements in the fine-scale structural representation of circulation pathways in the SPNA, this should be weighed against their well-documented biases in subpolar hydrography (salinification of the Labrador and Irminger Sea), which imprint detrimentally onto the diapycnal overturning simulated at eddy-rich resolution. Thus, an accurate depiction of the subpolar overturning circulation requires that both the simulated velocity *and* density (potential temperature and salinity) fields are well represented in comparison with observations. [See Lines 626-647].

We would also like to highlight that preliminary results from our ongoing model intercomparison study, investigating the impact of increasing horizontal model resolution on the strength and variability of the Lagrangian overturning simulated at OSNAP West & East, suggest that the principal conclusions of this study remain robust at eddy-rich resolution.

Finally, we have included the simulated time-mean velocity field across OSNAP East (1979-2015) below to directly address the reviewer's concerns regarding the ORCA025-GJM189 hindcast's ability to reproduce the three North Atlantic Current branches entering the Iceland basin (northern and central branches) and Rockall Trough (southern branch).

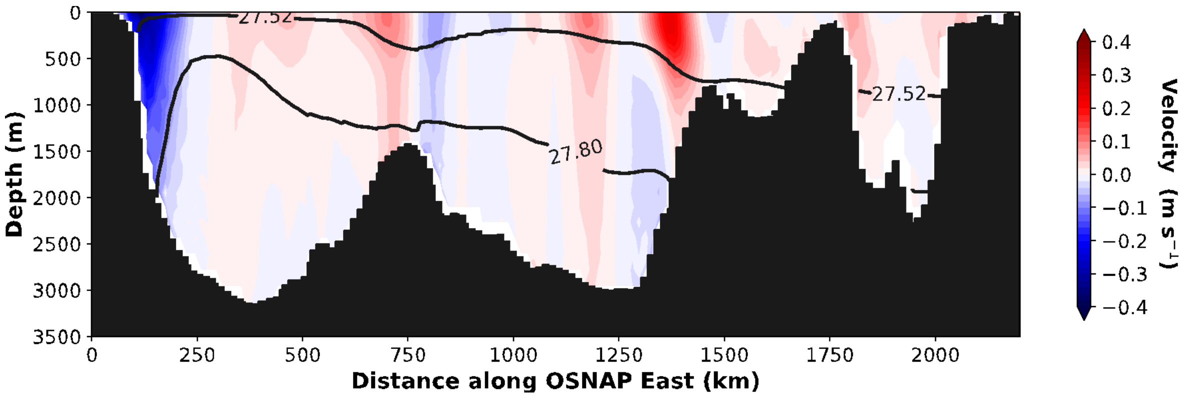

Figure S1. Time-mean Eulerian velocity field (1978-2015) simulated across the OSNAP East section in the ORCA025-GJM189 ocean sea-ice hindcast. Overlaid black lines represent the time-mean isopycnals of maximum Eulerian overturning (27.52 kg m^{-3})and the observed upper limit of overflow waters in the subpolar North Atlantic (27.80 kg m^{-3}).

My final concern about the resolution of the model concerns running Lagrangian trajectories through a coarse-resolution velocity field involves a lot of interpolation between points, with the resultant figures (which are beautifully presented) at much higher resolution than the underlying data, and potentially evoking higher confidence in the results than one might otherwise given 1/4° data. The authors acknowledge this issue in the last paragraph of the paper, but it needs to be addressed in the data and methods section (if not earlier).

We are grateful to the reviewer for highlighting this concern. As explained in Tooth et al. (2023), where we first document the Lagrangian experiment used in this study [Lines 128-130], TRACMASS solves the trajectory path through each model grid cell analytically by assuming that each component of the simulated 3-dimensional velocity field is a linear function of its corresponding direction [i.e., $u = u(x)$]. In this experiment, we evaluated water parcel trajectories using the regular step-wise stationary scheme, which linearly interpolates the ORCA025-GJM189 velocities between successive 5-day mean velocity fields using a series of intermediate time-steps (see Döös et al, 2017 for further details). Thus, by assuming that the resulting velocity field remains stationary during intermediate steps, an exact solution of the resulting differential equations can be found, representing the streamlines within each grid cell. The only exception is within the surface mixed layer, where we parameterise the effects of vertical turbulent mixing along water parcel trajectories. The trajectories appear very detailed in our Figures because we chose to output the positions along each water parcel trajectory at every model grid cell crossing so that we could analyse the properties of water parcels on their westward crossing of the Reykjanes Ridge in Tooth et al. (2023). To make this clearer to readers, we have now added details of the output frequency of water parcel positions and properties along their trajectories on Lines [146-147].

Again, I want to underscore how impressed I was with the quality of the paper, which reflects quite strongly on the authors.