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

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Responses to Reviewer 3 Comments

We would like to thank 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 of the original manuscript.

Our response to Reviewer 3 is structured as follows: **Section A** addresses the major comments of the reviewer concerning the Abstract, Introduction and general structure of the manuscript. **Section B** addresses the minor comments of Reviewer 3 on the contents of the manuscript and the accompanying Figures. Our responses are included in **red** and the original Reviewer comments are included in **blue**.

Summary

The manuscript by Tooth et al. presents a detailed and thorough model analysis of the seasonal overturning variability happening between the OSNAP array and the Greenland-Scotland Ridge. Combining insights from a Eulerian analysis at the OSNAP array and a Lagrangian framework where the sensitivity of the transformation to inflow characteristics is tested, the authors show that the majority of the seasonality in the overturning is due to water parcels that exhibit a relatively short (< 8.5 months) recirculation time within the eastern North Atlantic Subpolar Gyre.

The analysis is scientifically sound, very well embedded in the existing literature and is valuable to e.g. better interpret OSNAP measurements and improve our understanding of water mass transformation processes. However, I do agree with most of the comments of the other reviewers. The paper is very long, and, due to the smart but tricky to understand Lagrangian method, it can be challenging for the readers to fully grasp the content. Also, the motivation of the study can be more clearly defined in the abstract and introduction. Therefore, I hope to provide some recommendations and suggestions to improve the readability of the manuscript and would advise minor revisions before publication, but with sufficient revision time to restructure the paper.

Section A

1. **Abstract**

   More clearly state the motivation / current lack of knowledge in your abstract and how your approach provides new insight. E.g. One of your main findings is that you are only able to explain the minimum MOC in autumn seen in the OSNAP measurements if you use a Lagrangian approach ("This convergence of southward... wind forcing"). This is at the moment not clear in your abstract.

We agree with the reviewer that the original Abstract did not clearly define the gap within the existing subpolar overturning literature that we seek to address in our study. We, therefore, decided to considerably revise the Abstract to highlight one of the central motivations of our study, namely, our inability to attribute seasonal overturning variability to seasonal dense water formation owing to the diversity of recirculation timescales found within the Iceland and Irminger basins. Following the reviewer's suggestion, we have also explicitly stated that the autumn minimum in the MOC seasonal cycle can be explained by adopting a Lagrangian perspective.

The statement "recirculation race against time" is nice to mention in the paper, but might confuse readers in the abstract. And I don't think you need it in the abstract, as it is already clear from the last sentence what your main finding is ("The seasonality of Lagrangian overturning... in the eastern SPG").

Following the reviewer's recommendation, we have removed the reference to our analogy of a water parcel recirculation race against time from the Abstract, and this is now only included in the Discussion and Conclusions section [Lines 583-593].

2. Introduction

Try to get to the main research question / motivation for this study within the first two paragraphs. I find some hint for motivation in Ln.78, but I would suggest to get to this much quicker, and state clearly how this is related to the research question and approach of your study.

In general, this introduction can be shortened quite a bit, there are many details that are not needed to understand the motivation of the study, and some can be moved to relevant parts in the manuscript.

[Addressing both of the comments above]
We strongly agree with the reviewer that our original manuscript's Introduction favoured detail on the background of the subpolar overturning circulation rather than concisely motivating the need to bring a complementary Lagrangian perspective to the emerging discussion of seasonal overturning variability within the SPNA. We, therefore, decided to completely rewrite the Introduction and follow the suggested approach of Reviewer 2 to identify a series of key research question(s) that we will go on to address throughout our study.

Ln. 35-39 not necessary in the introduction (can move that to the method section where you explain how you define overturning)

In order to condense the manuscript and emphasise the most important concepts, we decided to remove our original discussion outlining the reasons for favouring a density- versus depth-space overturning definition in the SPNA.

3. General structure of the paper

The structure in the abstract differs from the general structure of the paper, and I think it makes a bit more sense to indeed first fully discuss the insights from the Eulerian analysis, before moving on to the Lagrangian one. That would also help to more clearly state what the added benefit is for looking at the relevant mechanisms from a Lagrangian perspective. So e.g. move largest part of section 6 to follow 3.1. Or, have a full section 3 focused on the Eulerian perspective where you have a dedicated section for validation (what now is mainly section 3.1) to also argue why the model you're using is the right choice to address the seasonal variability and related mechanisms. Furthermore, it would make the interpretation of the Lagrangian results a lot easier when readers have seen the general Eulerian flow structure in this region and the full overturning characteristics from a Eulerian perspective.

We are grateful to the reviewer for this helpful suggestion and have restructured the manuscript and Discussion and Conclusion section therein to match the structure of the Abstract. As such, Section 3 of the manuscript is now dedicated to exploring the seasonal Eulerian overturning variability simulated at OSNAP East and addressing the physical mechanisms responsible, including the important role of seasonal water parcel recirculation times in the upper Irminger Sea. Then, Section 4 introduces our complimentary Lagrangian measure of seasonal overturning variability at OSNAP East before diagnosing the circulation pathways, advective timescales and transformations contributing to the mean strength and seasonality of Lagrangian overturning.

The different seasonal cycle seen when comparing the Eulerian to the Lagrangian framework can be explained a little better. I'm not sure whether readers fully understand this. Maybe as a thought experiment, think what would happen when you would define the Lagrangian overturning "backwards". So, tracing the Southward flow backwards, and define the LMOC overturning in that way. This would again change the seasonal variability observed as you would focus on the seasonality of the outflow, instead of the inflow.

We recognise the reviewer's concerns regarding the comparison between the complementary Eulerian and Lagrangian overturning frameworks used in our study. We believe that much of this confusion will likely have originated from the original structure of the manuscript which did not clearly motivate the need to investigate the overturning seasonality at OSNAP East in our complementary Lagrangian overturning framework in the Introduction, and also failed to separate Eulerian and Lagrangian analyses to avoid ambiguity in their interpretations. On revising the structure of the manuscript and consolidating each of our results sections to better emphasise our most important findings, we believe that a clearer distinction is now made between the Eulerian and Lagrangian frameworks. The reviewer raises an interesting question regarding the decision to trace water parcels forward-in-time from the northward inflows versus backward-in-time from the southward outflows across OSNAP East; however, we would like to highlight two of the reasons underpinning our decision to define the Lagrangian overturning "forwards" in this study:

Firstly, by quantifying the flux of water parcels which are transferred from the upper to the lower limb after their northward crossing of OSNAP East, we ensure consistency with the traditional Eulerian overturning definition used throughout Section 3 (i.e., the net transport of the upper limb of the MOC across OSNAP East, as given by integrating from the lightest to the densest isopycnal surface). This is because our Eulerian and Lagrangian overturning (stream)functions, defined at time *t,* share the same northward volume transport distribution in potential-density space (V_North) and this transport overwhelmingly occupies the upper limb of the overturning circulation at OSNAP East.

Secondly, our decision to define the seasonality of Lagrangian overturning forward-in-time does not influence its physical interpretation as the seasonal signal of dense water formation along water parcel trajectories recirculating north of OSNAP East. If we were to have instead traced the water crossing OSNAP East southwards backward-in-time, we would still have ascribed the seasonal maximum to the stronger flux of water parcel into the lower limb due to intense surface buoyancy loss during the preceding (rather than ensuing) winter months and the seasonal minimum to the weaker volume flux into the lower limb when the fastest recirculating water parcels gain buoyancy along-stream during the preceding (rather than ensuing) summer. By evaluating the Lagrangian overturning "forwards", we are therefore asking: what fraction of water parcels are transferred into the lower limb during their recirculation, given that they arrived at OSNAP East in the upper limb at the start of month *m*? We would argue that this is more meaningful than asking:what fraction of water parcels are transferred into the lower limb during their recirculation, given that they were exported southward across OSNAP East in the lower limb at the start of month *m*? since we have shown that the potential density of water parcels on their initial northward crossing of OSNAP East is a strong predictor of their future contribution to the Lagrangian overturning at the section.

Check the length of your paragraphs, some of them are extremely long. Try to keep it to one or two main take-aways per paragraph, and keep them in general short (e.g. max length ~12 lines in the current template format).

We recognise that many of the paragraphs contained within our original manuscript were highly congested with results and have therefore revised significant portions of the main text to emphasise the most important findings to be drawn from our analysis. For the most part, paragraphs in the main text are now below the 12-line threshold recommended by the reviewer.

4. Discussion and conclusions

Currently the focus is too much on conclusions, and the relevance and importance of the results can be more strongly communicated.
Maybe also put your findings more in the context of the OSNAP observations.

We agree with the reviewer that the Discussion and conclusions of our original manuscript focused heavily on summarising the central results of each of the results sections and did not sufficiently address the importance of our findings to our understanding of subpolar overturning. In addition to restructuring the Discussion to reflect the wider manuscript's structure (seasonal Eulerian overturning variability at OSNAP East now precedes our discussion of seasonal Lagrangian overturning variability), we have now highlighted three important implications of our results in the context of the OSNAP observations.

1. We now emphasise that the proximity of the OSNAP East array to regions of dense water formation (that is, those regions which can transform water masses from the upper to the lower limb of the MOC) exercises an important influence on the seasonality of Eulerian overturning measured at the section. Thus, any future modification of the location of the OSNAP East array may determine the strength of the seasonal signal measured at the section.

2. We have improved our discussion of how interannual modes of variability, such as the North Atlantic Oscillation, might impact our analogy of a water parcel recirculation race against time to avoid irreversible diapycnal transformation into the lower limb. In particular, we hypothesise that the amplitude of seasonal Lagrangian overturning variability at OSNAP East would increase in response to strong positive phases of the NAO, given that corresponding westward retreat of the Subarctic Front favours greater inflow to the Irminger and Central Iceland basins, which dominate the seasonality of Lagrangian overturning in our study.

3. We interpret our Lagrangian analysis in the context of the observational study of Fu et al. (2020), which shows that the strength of the MOC has remained stable over recent decades in spite of large-scale thermohaline variability in the SPNA. We propose that, given a sufficiently long recirculation time within the eSPG, the combination of surface buoyancy loss and interior mixing north of OSNAP East can act as a sink of upper-ocean thermohaline variability advected along water parcel trajectories and thereby maintain a consistent volume flux in the lower limb.

We are currently exploring this final implication in more detail within a hierarchy of ocean hindcast simulations ranging from eddy-parameterised to eddy-rich resolutions as part of a follow-up study which seeks to better understand the stability of the subpolar MOC on decadal timescales.

Section B

1 - Why MOC and not AMOC?

While we recognise that the use of the AMOC acronym is more faithful to the Atlantic Meridional Overturning Circulation, our decision to shorten this to MOC throughout the manuscript was primarily motivated by our intention to distinguish this traditionally Eulerian diagnostic from the use of LMOC to refer to our complementary Lagrangian overturning diagnostic. It should also be noted that both Lozier et al. (2019) and Li et al. (2021) use MOC to refer to the Eulerian overturning observed across the OSNAP array.

2 – I find the SPG abbreviation confusing (maybe change to ESPG?), in particular for people that only read the abstract. Even when mentioning the eastern part of the Subpolar Gyre I have a bigger area in mind than the one North of OSNAP and south of GSR. I think the region of interest should be more clearly defined already in the abstract.
7 – Also here, it is not clear for the reader where exactly you are defining this seasonal cycle (minimum AMOC), I do think you should mention the OSNAP array in the abstract.

We have modified the abbreviation of the eastern Subpolar Gyre to eSPG both in the Abstract [Lines 1-2] and throughout the manuscript as suggested by the reviewer. To better orientate readers as to the domain of interest in our study, we have also made reference to the Iceland and Irminger basins on Lines 2-4. The OSNAP array is now referenced throughout the Abstract and our findings are defined in terms of the OSNAP East array rather than the wider eSPG region.

142 – How did you define the Greenland-Scotland Ridge in your model?

The Greenland-Scotland Ridge was defined arbitrarily within our model to connect the shallowest grid cells between East Greenland – Iceland, Iceland – Faroes and the Faroes to Scotland. Although we recognise that our model-defined Greenland-Scotland Ridge section is considerably further south than observational sections, such as the Kögur section north of Denmark Strait, we would like to emphasise that our intention here is simply to determine where we should remove water parcels which travel northwards across the sills.

2 – If I understand the calculation correctly, it should be V_south(sigma, t<tau<tau_max) , to make clear that any parcel that returns within this period of 7 years is added to the LMOC?

We apologise to the reviewer for the confusion caused by our equation for the Lagrangian Overturning Function. Since the calculation represents an integral over all recirculation times, the equation should have included tau (water parcel recirculation time following initialisation) rather than tau_max. We have now corrected this and also added a brief description of the calculation on Lines [177-179] to make this clearer to readers.

220-225 – You could already make a link here why you need a Lagrangian framework to explain why this is the case (now this text might insinuate that already cold and dense waters transported Northward somehow lead to maximum overturning strength).

We are grateful to the reviewer for raising this excellent point. Since our primary motivation for adopting a Lagrangian overturning framework is the need to explicitly account for the diverse range of recirculation times within the eSPG in our revised manuscript, we have decided to make this observation in our discussion of Lagrangian overturning seasonality on Lines [353-354].

243 – Confusing what the transports mentioned in the brackets are.

We have removed the sentence in question which made reference to both Eulerian and Lagrangian model transports. This is both for editorial reasons since we chose to condense Section 4.2 (formerly Section 3) in our revised manuscript, and because we believed that it would be more valuable to contextualise the meaning of the time-mean Lagrangian overturning with Eulerian observations of the overturning within the Iceland and Irminger basins [Lines 342-345].

244 – 243 – I don't understand what is meant here with 'close correspondence', is that somehow visible in one of the figures? Did you calculate a correlation?

We agree with the reviewer that the term 'close correspondence' is ambiguous in the context of this sentence. We have therefore included the correlations between the LMOC seasonal cycle and the seasonal cycles of sigma_MOC and sigma_LMOC and their corresponding p-values (both $p < 0.01$) on Lines [350-353].

267 and elsewhere. In general I think care should be taken when talking about seasons in relation to the LMOC definition as there is a time lag involved in the actual calculation (e.g. when the transformation of the water masses occurs), so it is very difficult to interpret what a minimum in May actually means.

We are grateful to the reviewer for highlighting this concern. We have modified the manuscript to ensure that where we describe the LMOC in a given month it is clear to readers that this corresponds to the month that water parcels flow northwards across the OSNAP section. Throughout the text, we have also made it clear that the strength of the LMOC should be interpreted as the volume flux from the upper to the lower limb integrated along recirculating water parcel trajectories (e.g. Lines [365-369]).

277 – "in contrast", how does the context of this sentence is in contrast with the previous one?

We have revised this sentence and removed "in contrast" as suggested by the reviewer.

302 – The recirculation time itself is probably also seasonally variable? Maybe already address that here?

We have added a sentence in Section 4.2 *Timescales and origins of seasonal Lagrangian overturning* to acknowledge that the recirculation times of water parcels flowing northward across OSNAP East in the upper 250-m of the Irminger and Central Iceland basins exhibit seasonality (as discussed in Section 3.2 on Mechanisms of seasonal Eulerian overturning variability), however, this seasonality does not influence their contribution to the mean seasonal cycle of Lagrangian overturning. [Lines 404-408]

316 – Unclear sentence, which is better explained in the following sentences. Maybe just say "We have identified a threshold recirculation time of 8.5 months". And then continue with explaining what happens to particles < recirculation time, and then > recirculation time.

We have revised the unclear sentence to instead state: "To summarise, we have found a clear distinction between the origins and advective timescales of water parcels responsible for the mean strength and seasonality of Lagrangian overturning at OSNAP East.". The paragraph then continued to outline the nature of this distinction for water parcels contributing to the seasonality and mean strength of Lagrangian overturning, respectively. [Lines 409-415]

330 and elsewhere – I would change the abbreviation of this pathway to Ic-Irm and Ro-Irm, as all pathways are defined by their entry and exit locations and not by crossing RR. Makes it easier to remember for the reader.

We are grateful to the reviewer for this simplification and have renamed both circulation pathways crossing the Reykjanes Ridge as suggested above both in our manuscript text and the accompanying Figures. [Lines 422-425]

335 – "70%" make clear where the reader can find this result and in which figure.

We determine that 70% of the time-mean strength of the Lagrangian overturning at OSNAP East is sourced from the Ic-Irm and Ro-Irm pathways from Figure 8a (now referenced on Line 428. This comes from (4.8 Sv + 1.4 Sv) / 8.9 Sv, where 4.8 Sv is the volume flux into the lower limb along the Ic-Irm pathway (orange) and 1.4 Sv is the equivalent volume flux along the Ro-Irm pathway (red).

Section 5.2 – This section is extremely long, and due to all the different decompositions very difficult to keep track of what is happening. I would suggest to restructure this, shorten, and maybe split in different sub-sections if needed.

We agree with the reviewer that, on reflection, Section 5.2 on the Transformations responsible for seasonal Lagrangian overturning variability favoured excessive detail in the presentation of our results rather than focusing on the most insightful findings addressing our original research question. We have therefore improved the Section (now 4.4) by implementing many of the suggestions made by the reviewer. These include:

- Consolidating our original Figures 6 & 7 into a single Figure 9 which presents the seasonal cycles of the net diapycnal transformation along the Irminger Gyre, Irminger Current and Ic-Irm pathways together. We elected to remove Figure 6c-d to supplementary Figure A1, alongside the equivalent seasonal cycles of potential density on inflow and outflow crossings of OSNAP East for the IcRo-IcRo and Ic-Irm pathways (including RR crossing as previously shown in Figure 7a).

- Given that Section 4.4 is now followed by the Discussion and conclusions of our study, we have decided to remove the lengthy synthesis of our findings on Lines 467-480 of our original manuscript. Although this was primarily an editorial decision to reduce repetition within our manuscript, we also no longer found it necessary to undertake multiple summaries of our findings after improving the preceding text in Sections 4.3-4.4 to better emphasise our most impactful results.

In total, the changes outlined above have shortened the text in Section 4.4 (formerly 5.2) from 110 lines to 83 lines.

515-519 – This is one of your key findings, the built-up to this result can be made clearer, by already talking about Wang's conclusions in the introduction and stating why these might be insufficient arguments?

We would like to thank the reviewer for this excellent suggestion. On reordering the manuscript to fully discuss the seasonal Eulerian overturning at OSNAP East prior to undertaking a complementary Lagrangian analysis of overturning seasonality, we decided to dedicate the third paragraph [Lines 44-52] of our Introduction to motivating why seasonal density changes alone might be insufficient to account for Eulerian overturning seasonality at OSNAP East. We also emphasise that no study to our knowledge has explored how seasonal variations in the transport and density structure of the Irminger Sea western boundary current might act in concert to modulate the seasonal signal of Eulerian overturning measured across OSNAP East.

Figures

Figure 1

I could not find in the text where you reference panel 1b. Also, refer to 1a relatively early in your introduction, to make clear how you define the Eastern SPG (and maybe then use as abbreviation "ESPG" instead of "SPG").

We have used the abbreviation eSPG for the eastern subpolar gyre throughout both the Abstract and manuscript text as suggested by the reviewer. Figure 1a is referenced and the eSPG is defined geographically as the region south of the Greenland-Scotland ridge on Lines [27-29]. Figure 1b is now explicitly referenced in our definition of Lagrangian overturning on Lines [175-177].

Caption: " volume transports across *the model-defined* OSNAP East *array*." (also in caption Fig. 2 and Fig. 3)

We have modified all relevant Figure captions to refer to a model-defined OSNAP East array as suggested by the reviewer.

Dotted line panel b at 1990 does not seem necessary for the storyline.

We have removed the dotted line referring to January 1990 (the year chosen for the example trajectories in Figure 1a) and renamed Figure 1a to Example trajectories initialised across OSNAP East. The chosen seeding time of the example trajectories presented (January 1990) is still referred to in our Figure caption as in our original manuscript.

Figure 4

Panel b, it would be good to add the main flow features already here (not wait until Fig 8d)

On reordering the text, Figure 4 has now become Figure 8 in our revised manuscript. As a consequence, the main flow features across OSNAP East are now first highlighted in Figure 3(d), which decomposes the accumulated upper limb volume transport across the section during April and October (corresponding the extrema of the MOC seasonal cycle at OSNAP East). We have, however, decided to add labels to Figure 8c to identify the major northward inflows across OSNAP East discussed in the main text (Irminger Gyre, Irminger Current and three NAC branches simulated in the ORCA025-GJM189 hindcast).

Panel b, unclear what the thick black line represents.

We thank the reviewer for highlighting this potential source of ambiguity. The solid black line represents the time-mean isopycnal of maximum Lagrangian overturning, sigma_LMOC, which is now labelled in Figure 8b.

Use of white region vs. white line is confusing, also because the white line is missing in your colorbar. I do like the use of the white line to indicate the threshold-time, but then maybe use gray for the masked areas?

We agree with the reviewer that the use of white colouring for both the regions without northward inflow and the spatial limit of the 8.5-month threshold recirculation time along OSNAP East was a potential source of confusion in the original manuscript. We have therefore implemented both of the reviewers' suggestions in Figure 8b; adding a white reference line in the colorbar and masking southward currents across OSNAP East in light grey. The Figure caption has also been modified accordingly.

Figure 5

You start introducing different decomposites based on pathway at the beginning of section 5.1, but then continue to further decompose them (e.g. IC and IG, and the eastern and western part of the IC-Irm pathway). Maybe it would be good to directly make this clear in one figure, so readers can better follow the story and understand the choices made?

We agree with the reviewer that the successive decompositions of circulation pathways north of OSNAP East undertaken in our original analysis did not facilitate a clear and concise discussion of the along-stream transformations responsible for seasonal Lagrangian overturning variability. As suggested by the reviewer, we have consolidated our circulation pathway decomposition to define five pathways, including the Irminger Gyre and Irminger Current, in Figure 8 (formerly Figure 5).

Specify Ic and Ro separately in the figure, now it is unclear how you kept these two pathways separate in your analysis. Maybe, as the decomposition is based on in- and outflow location, add those separation lines in panel b instead with all relevant abbreviations and switch the two panels (b = a). In panel (b) also add 'Reykjanes Ridge'.

We have modified Figure 8 (formerly Figure 5) to address each of the reviewer's suggestions. Figure 8a now defines the Ic and Ro regions alongside the example trajectories for each circulation pathway. We have updated Figure 8b to include three vertical reference lines at 500 km, 750 km and 1475 km, which define the Irminger Gyre

– Irminger Current boundary, Reykjanes Ridge and Ic – Ro boundary along the OSNAP East section. We have also added a label defining the Reykjanes Ridge as suggested.

Use of color, check the 'colorblind' rules, I think the difference between red and orange is very difficult to distinguish (especially in panel b).

We have modified our choice of colours in Figure 8 to ensure a greater contrast between the Ic-Irm and Ro-Irm pathways.

Figure 6 & 7

What do the colored boxes represent? Again, difference between the purples and blue not well visible. Panel c and d can be left out, as this is also seen in e and f. I would merge this figure with Fig. 7, and panel 7b is not needed. Also make clear why you only look at Ic – Irm, and not Ro – Irm.

Following the reviewer's suggestion, we have merged Figures 6-7 in our original manuscript to form a single Figure 9 which presents the mean seasonal cycles of the transport-weighted mean net change in potential density of the upper Irminger Gyre (IG, previously Figure 6e), upper Irminger Current (IC, previously Figure 6f) and upper Ic-Irm pathways (decomposed into the successive transformations taking place in the Iceland and Irminger basins – previously Figures 7c-d). The coloured boxes define each of the aforementioned pathways, which include only water parcels initialised within the upper 250 m of the OSNAP East section. Since we do not discuss the seasonal cycle of diapycnal transformation along the IcRo-IcRo pathway in the manuscript text, we decided to remove the blue boxes previously included in Figures 6a-b (now Figures 9a-b) and hence the distinction between these colours will no longer be problematic.

Figure 8
As mentioned earlier, move this figure to section 3a.

Figure 8 alongside accompanying Figures 9-10 in our original manuscript have now been moved into Section 3.2 – Mechanisms of seasonal Eulerian overturning variability – as suggested by the reviewer above.