OS-2022-18: Author Comment to Anonymous Referee #1

We thank Referee #1 for their positive comments and for recognising the current work as an interesting and timely contribution. We also thank Referee #1 for their constructive criticism and here we respond to their points and outline the changes we will make to address the comments if invited to submit a revised manuscript.

Referee's comments are in plain text, authors' comments in response are in bold.

Anonymous Referee #1:

The study uses the VIKING20X-JRA-short ocean hindcast simulation to explore mechanisms explaining the anomalously fresh and cold conditions in the subpolar North Atlantic during 2012-2016. Utilizing Lagrangian tracking, the authors show that the freshening/cooling seen at OSNAP-East to a large extent is caused by a higher fraction of Labrador Sea source water due to increased recirculation in the subpolar gyre. The study addresses a timely question, and makes for an interesting contribution in the debate regarding subpolar variability. That being said, I have several questions and comments related to the mechanism proposed and how it relates to previous studies. Moreover, the manuscript is quite dense with results, and being precise with definitions and language will be crucial for getting the main messages across to a reader.

Mechanisms and relationship to related work

The introduction highlights particularly the 'warming hole'. However, as the warming hole is a multi-decadal signal thought to be caused by effects that are not the main focus here (Keli et al. 2020; cloud feedback, low-latitude AMOC), the introduction reads a little misleading. I recommend restructuring so that the 2012-2016 freshening and cooling is the focus, as well as previously proposed mechanisms for interannual to decadal variability (i.e. expand on mechanisms mentioned in l.34-42 and in Section 5).

Both Referees#1 and #3 felt that the introduction wrongly emphasises the multi-decadal 'warming hole' over the exceptional freshening and interannual to decadal variability. We will restructure the introduction to address this.

Throughout, it's unclear to me exactly how the proposed mechanism agree/disagree/link to previous proposed mechanisms in literature. Formulations such as l.575 'we find neither of these to be fully convincing' make it sound like you discard all previous work, but surely your mechanism is not entirely independent of what's been proposed earlier?

We will include more discussion on how our proposed mechanism relates to previous proposed mechanisms, at the relevant points particularly in sections 5 and 6. Although it was not our intention to discard other work, we agree that we need to be more careful with our language and will modify this, while recognising that the reason for embarking on this study was the idea that the previously published work did not offer a complete explanation of the freshening event.

l.314-316, l.322-324 and Fig. 8: You do see signs of an eastward shifted subpolar front, but you seem quite dismissive of horizontal redistribution in the conclusion (l.600-601). In addition to Holliday et al. 2020 and Desbruyres et al. 2021, Kenigson et al. 2020 and Asbjørnsen et al. 2021 are relevant for such horizontal shifts. Asbjørnsen et al. 2021 is also quite similar in terms of the particle tracking approach.

We think this is a fair point and we will revise the conclusion to endeavour not to be dismissive of horizontal redistribution. This passage was intended to be quite speculative, postulating that while horizontal redistribution is clearly occurring (see figure 1) it probably isn't the whole story and the mechanism identified here provides a potential route to additional vertical redistribution of heat and salt.

An interesting additional perspective on both this question and the one above is provided in a recent manuscript of Volkov et al. (Ocean Science Discussions, *preprint,* https://egusphere.copernicus.org/preprints/2022/egusphere-2022-354/). They show both reduced heat loss associated with anomalous positive SSH anomalies in the Labrador Sea (associated weaker western SPG and deeper isopycnals), and that widespread cooling and freshening in the eastern SPG must be predominantly advective. Here we link those two processes.

Are you seeing the subpolar trend reversal in VIKING20X as documented in Desbruyres et al. 2021?

We possibly begin to see some reversal of the subpolar trend (see e.g. Figure 7). It looks like this may be later than in Desbruyres et al., but our section is at the northern edge of the area they consider.

Fig. 8a-b: Eastern and western parts look quite different. Interesting that OSNAP-E-37W-500m total (Fig. 5a) is dominated by what's happening at 37W-21W. A point that should be noted? The fractional evolution seen for the eastern part is more consistent with what is seen for the Nordic Seas inflow in Asbjørnsen et al. 2021.

We will note this in the text. The dominance of western segment over the eastern segment is due to the larger volumes transported through the western segment, and may also be change dominating visually over no change. Asbjørnsen et al. (2021) consider the flow across the GSR to the Nordic Sea, the fractional evolution for this is probably more consistent with the eastern part because transport through GSR is dominated by Rockall Trough/Rockall-Hatton Bank transports. Iceland Basin and Irminger Sea northward transports, while larger, are more likely to recirculate and be transformed to deeper waters south of the GSR.

l.358-360 and onwards: In any sort of AMOC change discussion, it needs to be clear that there is no consensus on whether the AMOC actually has systematically weakened over the 20th century until today (e.g., debate summarized in Jackson et al. 2022, Latif et al. 2022).

Agreed. We will mention this in section 5.2 but we should also point out that long-term AMOC changes are not actually relevant to the sub-decadal scale changes we consider.

l.445-446: Labrador Coastal Current and 'the other' – are both these branches what's typically called the Labrador Current? I also don't get the LC-Arctic and LC-Atlantic distinction (l.411-412).

l.445-446: Yes.

l.411-412 The -Arctic and -Atlantic suffices in LC-Arctic and LC-Atlantic refer to the immediate upstream source of water in the Labrador Current. LC-Arctic has come south through the Davis Strait. LC-Atlantic water has predominantly come into the Labrador Sea from the Irminger Basin in the West Greenland Current. On reflection we concentrate on our source-based categories and introduce the LC-Arctic and LC-Atlantic terminology only to orient the current work in the context of that which has gone before.

You make a convincing case for the freshening/cooling seen at OSNAP-E is due to a higher fraction of Lab. Sea water (Fig. 5, Fig. 7, Table 1) related to longer residence times in the SPG (Fig. 10a). I don't fully get why more SPG recirculation necessarily must be due to reduced heat loss and deepening isopycnals (l.435-441). Do you reference studies showing this mechanism for the SPG anywhere? Perhaps this point needs to be repeated in the conclusions.

L.435-441: This paragraph is speculative, and partly a trailer for what is to come in section 6. It is just expressing a volume transport budget. The idea is that upper water crossing northwards across OSNAP-E does one of three things: crosses the GSR (where it is made denser and returns in deeper layers): is made denser within the SPG sinking to intermediate and deep layers; or recirculates in the SPG. To increase the proportion recirculating, one of the others needs to reduce. The most likely candidate is reduced conversion to denser water in the SPG as flows across GSR appear pretty constant from observations. We will clarify this here with appropriate references. We agree it also needs repeating in the conclusions.

Lagrangian analysis:

Are particles released over the full OSNAP-East line as said in l.75-76 or only over the part of OSNAP-East shown in Figure 3? Are you analysing releases over the upper 1000m as said in l. 76 or the upper 500m as stated in l.111. I think the information in l.111-116 needs to come earlier to avoid conflicting messages.

Agreed. We will clear this up. We did release more particles than we used in the analysis. The reader does not need to know this though. Particularly those particles west of 37W. We will present some headline results from the particles down to 1000 in response to comments by other referees, so will keep the information about the particles released down to 1000 m.

l.84-86: A bit unclear. How about explaining it as: 'Each particle represents a volume transport of 0.001797 Sv. The number of particles released along the 2-dimensional OSNAP-E section is scaled with the model velocity normal to the section at the release time.'

Agreed.

l.87-89: What is the reasoning for choosing Parcels and not a tool like Ariane where streamlines are computed analytically?

We don't believe the choice of tool affects the results and Parcels was chosen for pragmatic and operational reasons. Published experiments with Ariane and Parcels show very similar behaviour with appropriate choice of parameters (timesteps). E.g. Schmidt et al 2021.

l.89-95: I don’t quite get the type of errors discussed here (Errors induced by temporal resolution? Errors related to lacking diffusion? Errors related to particle release number? Errors related to assumption of stationarity?). What are the 32 subsets?

We attempt to clarify this description further in the text. The errors we quantify are those due to using finite particle numbers. As we increase particle numbers each metric we discuss will converge towards a ‘correct’ value. Using random release positions allows us to split the particle set into a number of subsets (32 here), each of which is still random but with each particle representing a (32 times) larger transport. The spread of the estimates from these subsets gives us an idea that we have released enough particles for these sampling errors to be small compared to the signal we are examining. We do not attempt to quantify errors due to lacking diffusion in the tracking, model biases, assumption of stationarity. We include mention of these error sources in a wider ’disclaimer’ requested by Referee #1.

Gulf Stream and Lab. Sea are defined as the two ‘upstream origins’ for OSNAP-E water (l.96). Then you subdivide Lab. Sea ‘origin’ by ‘upstream origin’ again (l.102): Hudson Bay, Davis Strait. Greenland Sea, Denmark Strait, SPG. Later in the manuscript the word ‘source’ is frequently used. I would be very clear with the definitions and use them consistently throughout. Perhaps Lab. Sea and Gulf Stream is your ‘upstream sources’ while the Labrador source region is subdivided by four ‘origin regions’?

We will make these definitions and uses consistent.

Figure 3: I’m confused by the lines on the map. Lines over land should be gone? Are particles crossing the orange line cutting across the Lab. Sea defined as having Lab. Sea origin? Is the north-south orange line the Loop path/Slope Sea pathway definition? I get the east-west green line is the Gulf Stream definition, but what about the north-south thin green line? What about showing definitions for Davis, Hudson, Greenland Sea origins in panels f-h, respectively?

We have hopefully cleared this up with the production of a revised figure 3. We include a draft as Figure 3.1 below.

l.209-212: Such fractions will depend on the depths evaluated over and the source definition used. In Koul et al. 2020, particles are initialised in the upper 100m only. In Asbjørnsen et al. 2021, 26% of the Iceland-Scotland Ridge inflow (upper 1000m or so) has a subpolar or Arctic origin (Davis, Hudson, Denmark straits, or circulation in the SPG), with 42% of the surface inflow being water from Davis Strait and Hudson Bay.

We include fractions calculated over different depth ranges: top 500m, top 1000m, amoc upper limb (as described in section 2.2) and expand the discussion to include Asbjørnsen et al. 2021 numbers.

Minor comments / technical corrections:

1. l.80: reference in parenthesis or write ‘shown in Biastoch et al. 2021’.

OK

2. Fig. 1 and Fig. 2 is not referenced in the text until page 9. Either reference earlier or rethink figure-order.

These figures are mentioned first in the introduction. See L33.

3. l.107-110: Would shorten this point. Doesn’t need to be its own paragraph.

OK

4. Section 2.4: Unless you want to expand on OSNAP measurements and how the EN4 product is produced, I would delete this section and move the sentence somewhere suitable.

This section will be longer with the inclusion of details of the Labrador Sea data used in the revised model-data comparison in section 6.

5. Section 2.5: Not really necessary information – I recommend deleting the section and put the information about code availability in the data statement at the end.

I (AF) think this is important information for openness and reproducibility. We move it to the code availability statement.

6. l.216-217: Stated already in section 2.2, not necessary to repeat.

Deleted

7. Starting sentences with 'So' or 'But' (sometimes) making them not 'full sentences' with a subject, verb, and an object: e.g., l.220, l.247, l.255, l.269, l.427, l.465, l.519, l.546.

We've checked for and removed these minor, but distracting, style and English usage issues

8. l.220-223: No need to repeat the details here.

Deleted

9. l.294-305: I would cut this section and save such summarizing statements for the conclusion. If you are worried some of the interesting results might be 'lost' because the manuscript is quite dense, you could even do a bullet point list summarizing the main results in the conclusion.

We think this section is useful for readability, summarizing results from quite a dense section before moving on to new sections of results/discussion which draw heavily on section 4. We have decided to leave it in place.

10. l.337-340: check punctuation and parentheses.

11. l.341-344, l.411:413: check parentheses.

OK

12. Section 5.3 title: title sounds like you again will discuss what was addressed in 5.1. I would find an alternative pointing to the Labrador Sea focus.

OK

13. l.414-416: ref. Fig. 10?

OK

14. Fig. 10 and l.414-419: What depth is the 'light upper layers' - are you still looking at 0-500m?

These are still the particles we have tracked backwards from the top 0-500m at OSNAP. Further upstream they are not strictly confined to the surface 500m. As the subpolar region is

predominantly an area of sinking, particles launched in the upper layers and tracked backwards will generally stay in the upper layers. We will make this clearer in the text.

15. l.528-532: Too long sentence – difficult to decipher.

Section 6.3 will be rewritten with different observational data. See the response to Referee #1, general comment 3 for more details. Draft new Figure 14 is attached below (as Fig 14.1). So this comment has been superseded.

16. Legends Fig. 7, Fig. 8, Fig. 10 looks quite messy. I would display text as a structured column. Fig. 8 could have one common legend on the side.

No change. I (AF) disagree. I find it difficult switching between lines and legends to repeatedly remind myself which line is which. Labels by the lines on the plots are much easier.

Mentioned literature:

Kenigson et al. 2020 – 10.1175/JPO-D-20-0071.1

Asbjørnsen et al. 2021 – 10.1175/JCLI-D-20-0917.1

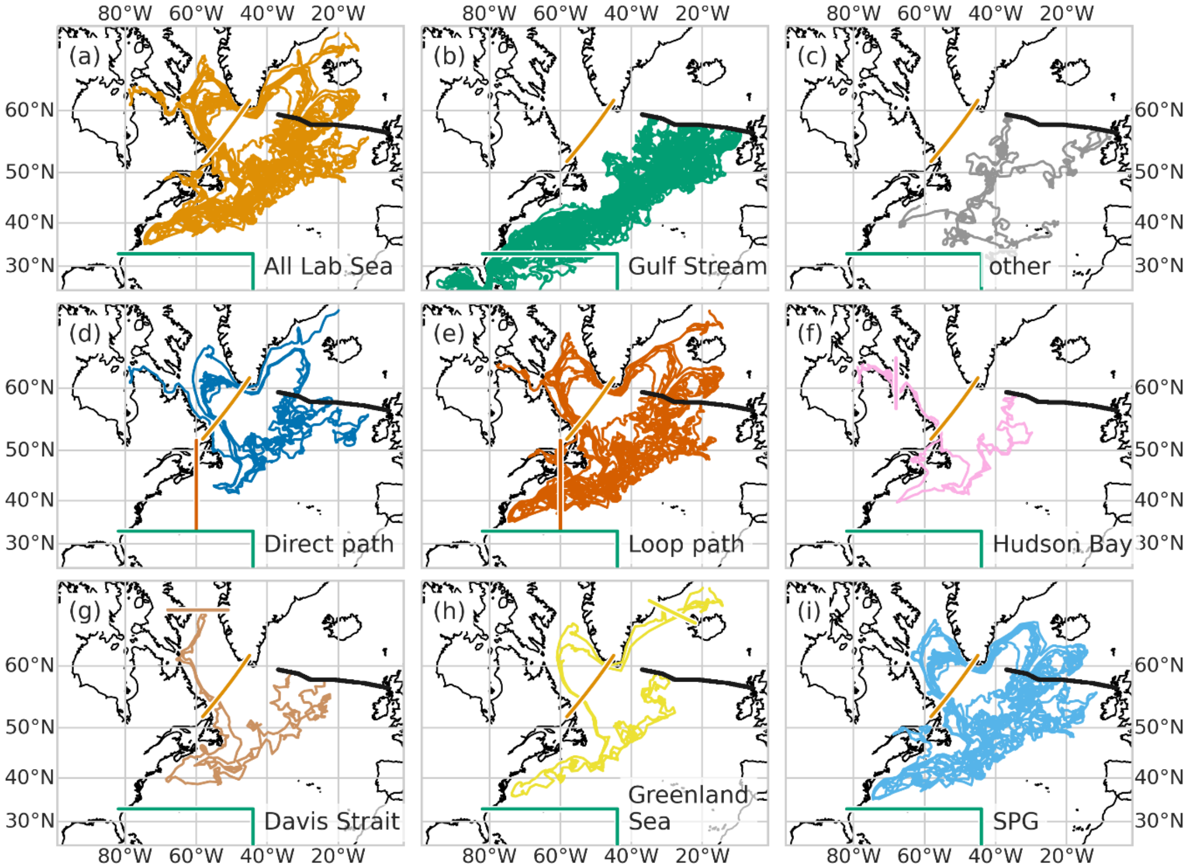
Desbruyres et al. 2021 - 10.1038/s43247-021-00120-y

Jackson et al. 2022 - 10.1038/s43017-022-00263-2

Latif et al. 2022 - 10.1038/s41558-022-01342-4

References:

Schmidt, C., F. U. Schwarzkopf, S. Rühs, and A. Biastoch, 2021: Characteristics and robustness of Agulhas leakage estimates: an inter-comparison study of Lagrangian methods, *Ocean Sci.,* 17, 1067–1080, https://doi.org/10.5194/os-17-1067-2021.



80°W
60°W
40°W
20°W
60°N
50°N
40°N
30°N
(a)
All Lab Sea
(b)
Gulf Stream
(c)
other
(d)
Direct path
(e)
Loop path
(f)
Hudson Bay
(g)
Davis Strait
(h)
Greenland
Sea
(i)
SPG

Figure 3.1

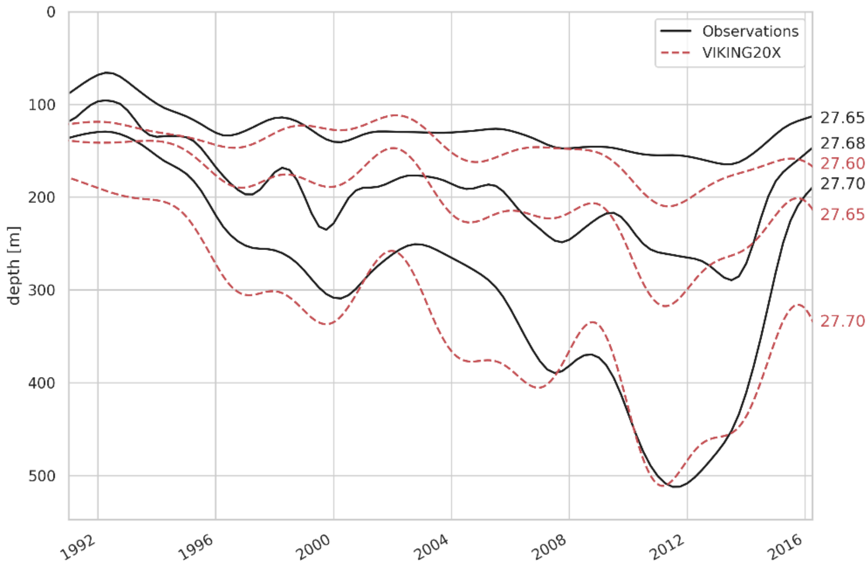


Figure 14.1 2-year low-pass filtered, area-average isopycnal depths in the Labrador Current exit region of the Labrador Sea from observations (black lines) and VIKING20X (red dashed lines). Deepening isopycnals between the mid-1990s and 2010-2014 in the upper water column are clearly seen in both observations and model. Individual isopycnals should not be compared due to slightly different averaging areas and model biases, but the relative isopycnal deepening is consistent between model and observations across a range of density surfaces.