# OS-2022-18: Author Comment to Anonymous Referee #2

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

**First of all we thank Referee #2 for their constructive comments.**

## Anonymous Referee #2

This article sheds new light on the main drivers behind the cooling and freshening recently experienced in the upper eastern subpolar North Atlantic. To this end, the authors analyze the outputs of a historical hindcast (years 1980 to 2019) performed with the eddy-rich ocean–sea-ice model VIKING20X, using a variety of techniques and diagnostics, from lagrangian particle tracking, to water mass transformation analyses.

The article is well-timed and well written, the methodology applied is sound, figures are clear, and many of the results will be of high interest to the climate community at large, and to anyone with specific interests in the recent changes experienced in the North Atlantic and its surroundings.

I recommend a minor revision of the manuscript and enclose a list of comments that the authors would need to address to render the article suitable for publication in *Ocean Science*.

**General Comments:**

- Agreement of the VIKING20X-JRA hindcast with observations is mentioned several times throughout the text, but it is mostly derived from visual comparisons, which can be misleading. In some cases the agreement is clear, but in other cases is much less evident (see comments #4, #16 and #18 further down). Supporting these statements with some specific metrics, like linear correlations between the hindcast and the observations, will help to determine more precisely to what extent they agree with each other.

**Model verification has been done extensively in Biastoch et al. (2021) which we refer to frequently throughout the manuscript. We do not want to repeat that verification here. The purpose of the initial comparison between the model and EN4 analysis (figures 1 and 2) is to show that the VIKING20X model produces a freshening and cooling signal analogous to, if not exactly the same as, that in observations, to support the use of the model to investigate this phenomenon. We feel that the visual comparisons presented are sufficient for this purpose and don't believe that further quantitative metrics comparing hindcast and observations are necessary. We will try to make the limitations of the use of an imperfect model, and the fact that what we present is a model-based hypothesis rather than objective truth, clearer in the discussion, as requested in a similar point made by Referee #3.**

**While the EN4 analysis is of sufficient quality and resolution for the initial comparison aimed at supporting the use of VIKING20X in this study, we find it to be of insufficient quality for the more detailed comparison required in the Labrador Sea in section 6.3, resulting in the, fully justified, criticisms of this comparison by all Referees. Here, we completely rewrite the comparison, using observational data (rather than the EN4 analyses) in the Labrador Sea. The new dataset was provided by Igor Yashayaev, tailored specifically to our Labrador Current outflow region and based on the latest version of the data presented here: https://waves-vagues.dfo-**

mpo.gc.ca/Library/40974698.pdf. **The comparison between model and observations here is much closer using this dataset than with EN4, with the observational data clearly showing deepening isopycnals. We believe the difference between this observational data and EN4 analysis to be largely due to the higher resolution and more focussed area used, and to sparse salinity data and relaxation to climatology in EN4 in the earlier part of the period studied making the use of the EN4 analysis here inappropriate. While these remain purely visual comparisons, we hope that because the similarities are now clearer this will allay the Referee's concerns.**

- Given the comprehensive list of processes and mechanisms that are analyzed in the paper, which in many cases are interconnected, it would be very useful to include at the end of the article a schematic figure summarizing the chain of events that give rise to the freshening and cooling of the eastern subpolar North Atlantic, as supported by the model analysis.

**This is a nice suggestion and we will add appropriate schematics/diagram. (Figure 15, a draft attached below).**

- Several figures from other articles are cited throughout the text, urging the readers to keep jumping from one article to another, and thus hindering the overall readability of the article. Some of those figures include indices that could be easily incorporated in others figures of this manuscript (see comments #6, #10 and #11), making intercomparison between those and the VIKING20X indices much more straightforward. I strongly recommend the authors to include them.

**Agreed. We will include the indices from other articles in our plots where possible**

**Specific Comments:**

1. [Lines 18-19] This sentence seems incomplete and inaccurate. It should (1) mention that there is a cooling on the eastern subpolar North Atlantic, not a surface warming anomaly, and (2) it should also specify that this is simulated in response to a "weakening" of the ocean circulation. Also, I recommend the authors to avoid the use of the term "predict" in the sentence, as "predictions" generally refer to historical simulations initialized from observations to phase the model with the observed internal variability. However, the warming hole is a feature that consistently appears in uninitialized historical simulations, and is therefore deemed to be mostly externally forced.

**In common with suggestions from the other reviewers we have focussed the introduction on the short-term exceptional freshening and cooling event, removing the unnecessary and confusing references to the multi-decadal warming hole**

2. [Line 108] It is unclear which "common technique" it refers to.

**Agreed, this will be clarified.**

3. [Figure 4b, caption] Is it "number of days" or "number of years"?

**Years. We will correct the caption.**

4. [Lines 177-181, Figure 2] While the simulated upper temperature variability in the hindcast shows a good agreement with the observed timeseries from both OSNAP and EN4 products, this is not the case for the simulated salinity. This is particularly clear for EN4, which can be compared for a substantially longer period, showing large discrepancies in terms of both the high and the low-frequency variability. Indeed, a close inspection to Figure 2 reveals that the

differences between EN4 and VIKING20X-JRA are not stationary in time, and reflect more than the systematic mean state bias stated in the text. It is true that salinity observations are quite scarce and therefore objective analyses like EN4 are subject to large uncertainties, but it remains to be checked whether the simulated variability is within the range of the observed uncertainty.

**We have replaced figures 1 and 2 with a revised comparison (figures 1.1 and 2.1 below). We now compare x-z area averages of temperature and salinity rather than depth-averages and include the error bars on the EN4 data. We also start the comparison at year 2000, as prior to the early 2000s salinity data were very sparse and EN4 analysis largely reflects the relaxation to climatology. Additionally, EN4 is a lot smoother both in space (see Fig. 1) and time. Even when averaging in space (Fig. 2) or time (Fig 1) there will always be mesoscale structure in VIKING20X output that shows as variability exceeding that of EN4. As stated in response to the general comments above, we believe that these comparisons demonstrate that the model shows sufficient skill in reproducing the particular freshening event to justify its use here. We add consideration of the implication of model skill on the conclusions we have about the mechanisms involved in the discussion.**

5. [Lines 311-313] What do you mean by “contrasting evolution of transit times”? Are their associated histograms (like in Figure 4) substantially different? And in which way?

**This point was not about the histograms in Figure 4, but about the time series in Figure 8. Particles crossing OSNAP-E in the west showed marked lengthening of transit times (and longer track lengths and slower mean speeds) in the 2000s, contrasting with particles crossing further east which showed much steadier speeds and transit times. This will be clarified in the text.**

6. [Lines 334-340] Instead of referring the reader to Figure 10 in Biastoch et al 2021, it would be preferable if the authors included the SPG index in a subpanel of Figure 9, where it can be directly compared with the AMOC indices.

**This is a good idea and will be done.**

7. [Lines 339-340] The two parentheses referring to Figures 5 and 7 need to be closed.
8. [Lines 363-364, Figure 9] Why did you choose to plot the AMOC at 29°N and not at the same latitude of the RAPID array (i.e. 26°N)? It would be indeed very interesting to include a direct comparison of the hindcast with the RAPID data, to learn more about the model realism in representing dynamical aspects, like the North Atlantic ocean circulation.

**This direct comparison between VIKING20X AMOC and the RAPID array is in Biastoch et al. (2021), referred to in the text, and does not need to be repeated here. On the choice of latitude 29°N for the calculations, we will add brief explanation to the text, and include more details here. There is very little, if any, difference between AMOC at 26°N and 29°N and the choice was made entirely for ease of calculation.**

**We chose 33°N for the Lagrangian analysis because it was the furthest north it could be (so keeping tracking times as short as possible) and be confident that particles caught crossing there were from the western STG rather than recirculating in the inter-gyre region for example.**

**However, for the Eulerian analysis we chose 29°N because the flow there is really simple. It lies at about the central latitude of the STG. As it is clear of the Antilles (unlike 26°N), practically all the northward upper layer flow sits on the wide 1000m deep shelf. Further offshore, almost all the**

**DWBC is above the slope at the edge of this shelf, clearly separate in the horizontal from the northward WBC. Then further east still is the broad southward flow in the eastern STG. All three of these are clearly separate in the horizontal, making calculation of STG strength, AMOC, DWBC transport and STG to SPG surface flow all straightforward. Matching the Eulerian section with the Lagrangian at 33°N would make these calculations more complex, with some northward WBC currents overlying the southward DWBC, and many more eddies and recirculations east of the Gulf Stream. Matching with Rapid at 26°N was attractive, but the comparison is not our focus, is included in Biastoch et al. (2021), and again the flow is more complex at 26°N than at 29°N, with the WBC divided between the Florida Straight and the Antilles current, with the latter overlying the DWBC.**

9. [Lines 366-368] I would not say that the AMOC is responsible for a reduction in Gulfstream transport. The Gulfstream does not respond to the AMOC, it is a component of the AMOC and as such contributes to its variability, not the other way around.

**Variability in the GS can be 'associated with' a combination of AMOC and STG variability, as can be seen in Fig 9. The text specifies the GS is *associated* with reduced flows (aka the AMOC), which is not a causal statement. We will seek to clarify this distinction in the text.**

10. [Lines 371-372] This can be directly shown to the reader if, as suggested in Comment #6, the SPG index is included in Figure 9.
11. [Lines 378-380] Here you compare again with an observed index from another article that could be easily included in this one (in Figure 9).

**We will include these indices in our plots.**

12. [Line 386] I do not find this summary statement fully justified. There has been no specific analysis in section 5.2 to rule out the AMOC weakening as a main contributor to the freshening of the eastern subpolar North Atlantic.

**Agreed, we will clarify this. The analysis showing that reduced transport from the Gulf Stream source was not the majority contributor to the freshening was in section 4.3, but the contribution was still estimated at a sizeable minority of 30%. Section 5.2 confirms that this reduced contribution from the Gulf stream source is reduced AMOC.**

13. [Line 394] The parenthesis needs to be closed.

**Done**

14. [Lines 520-521] It is important to specify that the doubling of the annual mean depth of those isopycnals only occurs in VIKING20X-JRA. In EN4, the increase in the depth of the isopycnals is very subtle and only discernible for $\sigma_0 > 27.65$ kg/m3.
15. [Lines 526-528] Figure 14 a-c → Figure 14c (as this is the only panel showing the isopycnals)
16. [Lines 537-539] From Figure 14 it is not possible to say if the model realistically represents the variability in salinity and density. Indeed, as mentioned in Comment #14, the strong deepening of the isopycnals in VIKING20X-JRA (one of the major reasons behind the freshening in the eastern subpolar North Atlantic identified in the paper) is not seen in EN4, and in particular in the upper layers.

**We will completely rewrite this section based on comparison with a more appropriate Labrador Sea dataset and a new Figure 14 (preliminary version attached below as Figure 14.1). For more details see the responses to Referee #1.**

17. [Lines 544-545] Can you explain why it would be counter-intuitive?

**This was simply that we suggest *warming* in the surface Labrador Sea leads, purely by internal ocean advection, to *cooling* in the eastern subpolar gyre. But we rephrase to reduce confusion.**

18. [Lines 589-593] Not all the model results are fully supported by observational data, in particular the deepening of the isopycnals in the Labrador Sea. Furthermore, the evolution of the Labrador Sea vertical structure only compares well with the EN4 data (Figure 14) for temperature. The agreement with the observed salinity and density is much more limited. It would be worth discussing whether, and if yes, in which sense, this poor agreement affects the main findings derived from the VIKING20X-JRA analysis.

**See the response to points #14-16 above.**

## New Figures:

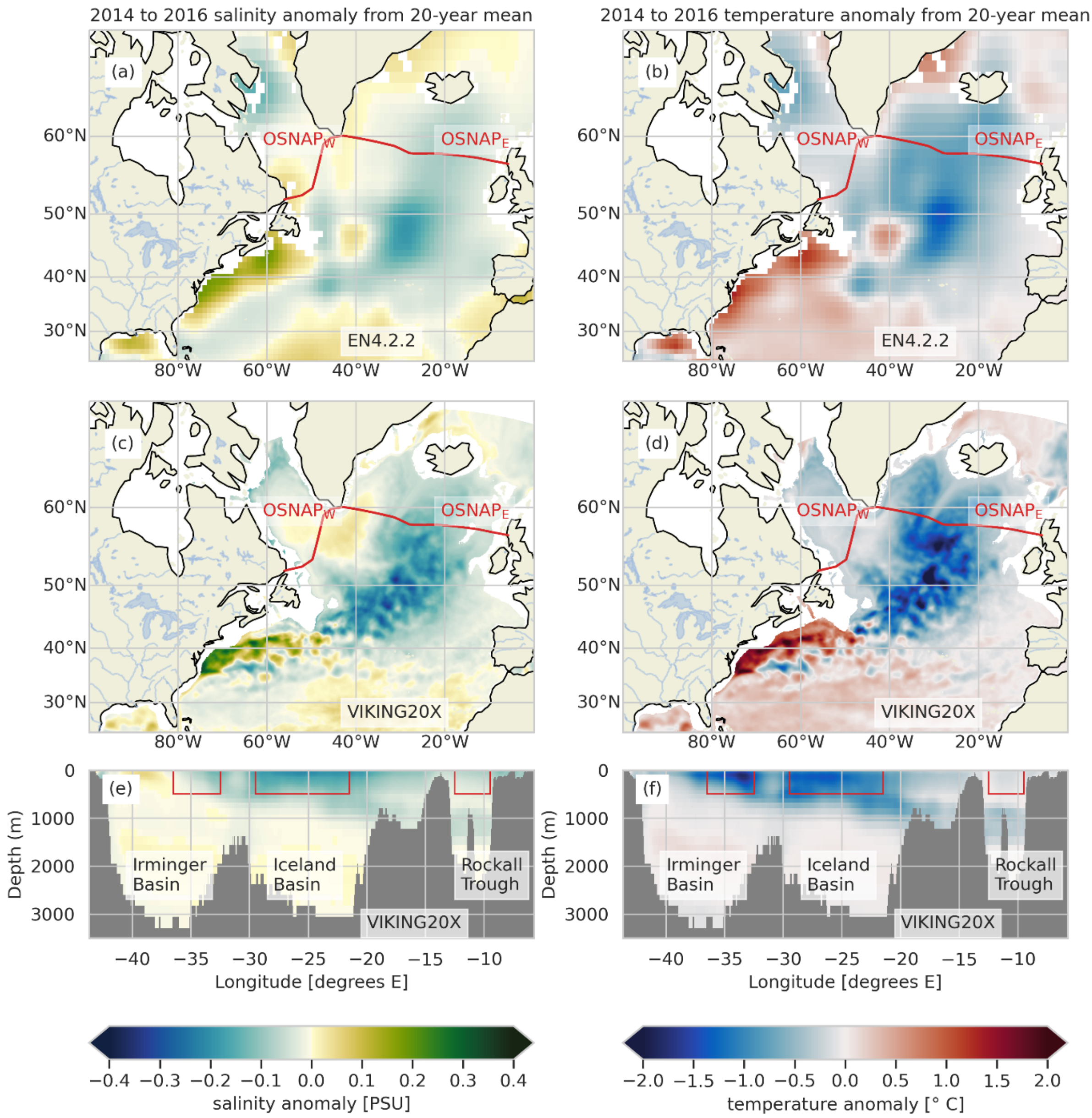
2014 to 2016 salinity anomaly from 20-year mean
2014 to 2016 temperature anomaly from 20-year mean
(a)
(b)
(c)
(d)
(e)
(f)
OSNAP$_W$
OSNAP$_E$
60°N
50°N
40°N
30°N
80°W
60°W
40°W
20°W
EN4.2.2
VIKING20X
Depth (m)
0
1000
2000
3000
Irminger Basin
Iceland Basin
Rockall Trough
−40
−35
−30
−25
−20
−15
−10
Longitude [degrees E]
−0.4
−0.3
−0.2
−0.1
0.0
0.1
0.2
0.3
0.4
salinity anomaly [PSU]
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
temperature anomaly [° C]

*Figure 1.1*

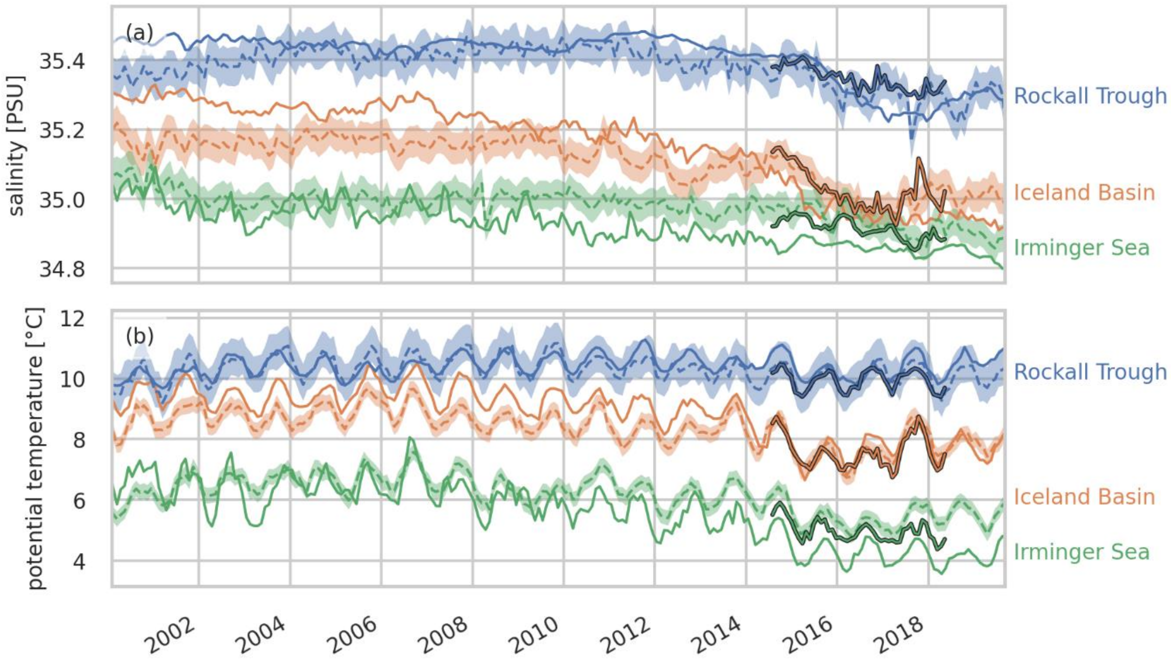


*Figure 2.1*

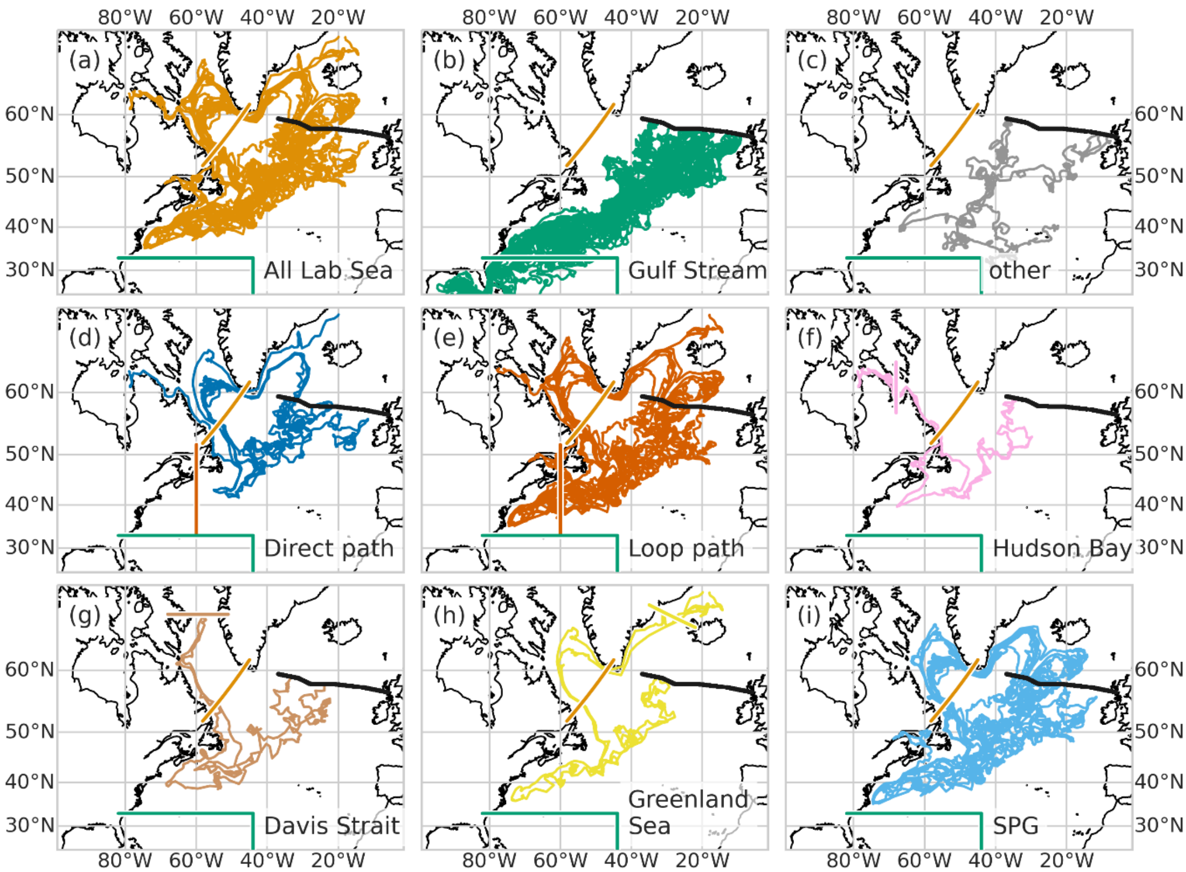


*Figure 3.1*

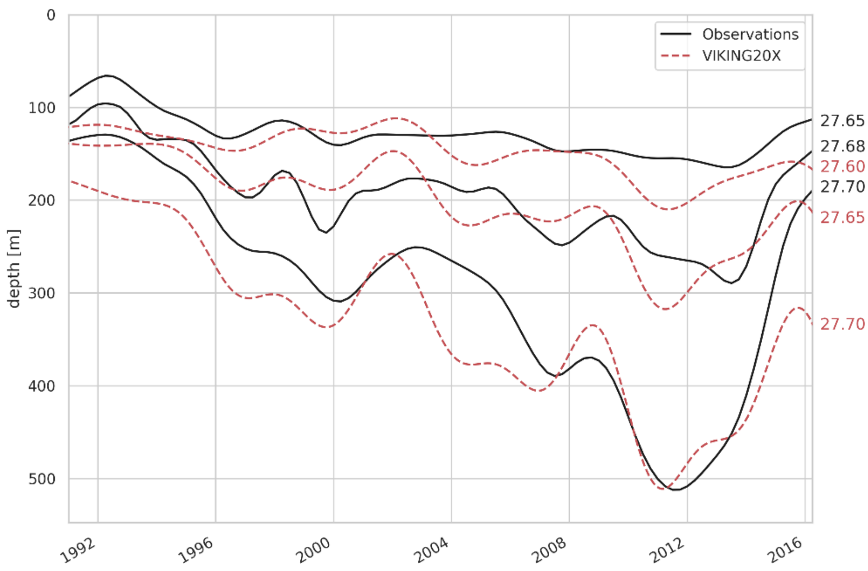


Figure 14.1 2-year low-pass filtered, area-average isopycnal depths in the Labrador Current exit region of the Labrador Sea from observations (black lines) and VIKING20X (red dashed lines). Deepening isopycnals between the mid-1990s and 2010-2014 in the upper water column are clearly seen in both observations 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.

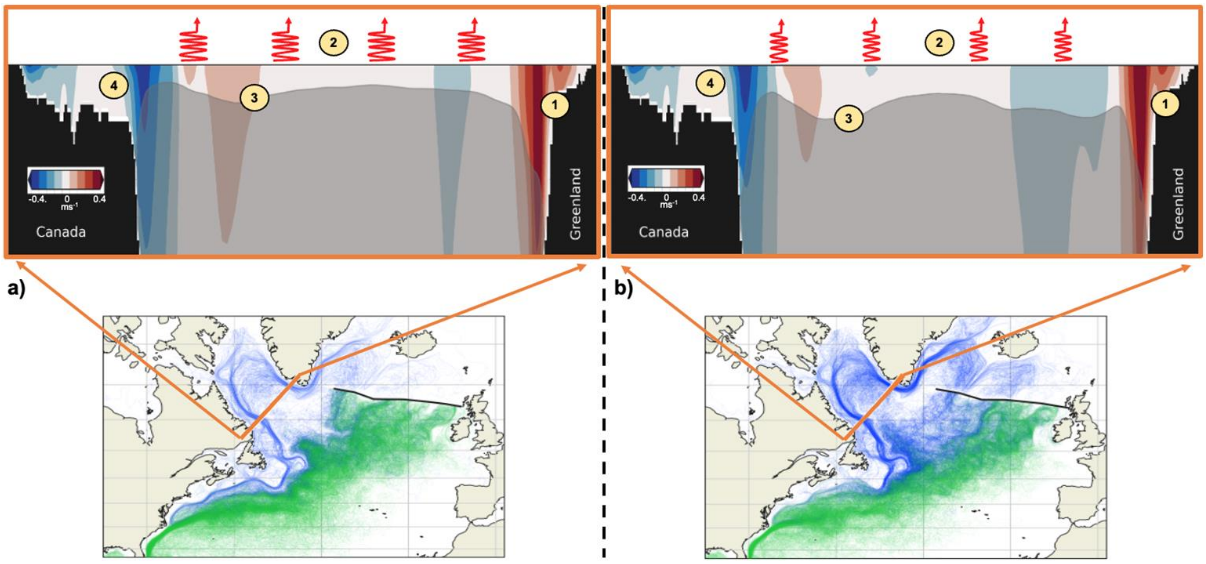


Figure 15.  Diagram illustrating the mechanism for reduced surface heat loss leading to increased outflow from the Labrador Sea: (a) late 1990s/early 2000s for a period of higher heat loss (red zig-zag lines); (b) early 2010s are for the period of reduced heat loss (small red zig-zag lines). The upper panels show water mass densities (less dense upper layer light grey and denser intermediate and deep waters dark grey), and mean velocities across OSNAP_W (red is northward and blue is southward). The lower panels are number of backward tracks crossing OSNAP-E and show the contrasting transport pathways to OSNAP_E. During the two periods inflow of light waters along West Greenland (1) remains similar in thickness and velocity structure. Reduced surface heat loss (2) in the freshening period (b) leads to less transformation from light to deep water, deepening the less dense layer (3) and so increased outflow of the light waters on the Labrador Shelf (4). The lower panel shows how during the freshening event (b) the proportion of water from the Labrador Sea (blue) increases and pushes eastward at OSNAP-E. The Gulf Stream source water decreases in volume and is confined more to the eastern end of the OSNAP section. While total transport from the Labrador Sea is higher in (b) than (a), transport via the loop path southward along the eastern US has decreased in (b) [consequence?]. Most of the increased flow from the Labrador Sea is water circulating in the SPG.