OS-2022-18: Author Comments to Anonymous Referee #3

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

We would like to thank Referee #3 for their constructive comments. In common with other Referees, Referee #3's major concerns are with the model-observation comparisons at the start – supporting the use of VIKING20X – and at the end – in support of our conclusions about a proposed mechanism. We substantially revise both these sections and provide drafts of revised, more relevant, Figures which better support our conclusions.

Anonymous Referee #3

In this study, the authors investigated mechanisms of the exceptional freshening event in the eastern subpolar North Atlantic using a high-resolution VIKING20X model run. The authors conducted a thorough study starting with a Lagrangian tracking analysis that leads step by step to the conclusion that the freshening event in the eastern subpolar gyre is due to reduced heat loss in the western subpolar gyre. Overall, I find the manuscript logically organized with convincing conclusions. However, I believe several general concerns need to be addressed before the manuscript can be accepted for publication.

General comments:

1. This study is based on the high-resolution VIKING20X-JRA-Short hindcast simulation, which is able to capture the great freshening and cooling event in 2014-2016. The pattern and timing of the freshening and cooling from the model is very consistent with those derived from EN4. However, the magnitude of the freshening and cooling in the model is substantially larger than in EN4. Since the hindcast is a free run without data simulation and bias correction, the authors argue that the model serves as a dynamically consistent tool to examine the freshening event.

The original mapped comparisons between VIKING20X and EN4 (Figure 1) exaggerated the differences in magnitude of the freshening and cooling. This was due to the use of a long reference period during which model and EN4 temperatures and salinities were different. These differences in the means fed into the anomaly calculations resulting in the model freshening and cooling signal appearing have a notably magnitude than the signal in EN4. This exaggeration could be seen by examining the time series (Figure 2) where freshening and cooling between 2012 and 2016 were of much more comparable magnitudes. To remove this misconception we have removed the unrealistic basin-scale long-term trend from the model before producing new figures 1 and 2 (Figure 1.1 and Figure 2.1 here) and focussed more closely on the exceptional freshening and cooling signal by showing anomalies from a shorter period during which EN4 and model were temperature and salinity fields were closer. Figure 1.1 and 2.1. This may allay some of the concerns expressed in the first concern below.

This leads to my first concern: given the large simulated bias in the magnitude of the freshening/cooling event, the model could be overly sensitive to a certain mechanism (e.g., heat loss in the Labrador Sea) that contribute to the freshening, while it may underestimate other mechanisms (e.g., AMOC). The authors point out that warm and salty bias prior to the 2014-2016 event is a common feature of hindcast simulations. However, this is not a valid argument that we shall expect a stronger freshening in the model than in observation. Can the authors explicitly explain the reason for this much stronger freshening in the model? Do other realizations of the VIKING20X hindcast simulations show a similar freshening event? If the answer is yes, can the same mechanism explain the freshening? In any case, a clearly stated disclaimer is needed in the discussion to remind readers that compared to observations, model bias both prior to and during the freshening event is strong. The proposed mechanism may be subject to model bias.

The bias in magnitude of the freshening and cooling event is not as large as it appeared in the original version of Figure 1, but we accept the point that the model could be over-sensitive to some mechanisms and under-sensitive to others. This is part of the reason why we present our conclusions as a model-based hypothesis. It is incorrect to characterize the model signal as 'much stronger freshening' – a misconception which was entirely our fault due to the presentation of the original Figure 1. We cannot explain the differences in detail between model and observed signals, and feel this is beyond the scope of the current paper in which we attempt a coherent explanation of the mechanisms behind the overall freshening rather than particular details. We have not examined the freshening event in other realizations of the VIKING20X hindcast and, due to the complexity of particle tracking and the time and resources involved, it is not possible to repeat the particle tracking in other model runs. We feel that the new, more representative comparison between the freshening event in the model and the EN4 analysis supports the use of this hindcast without examination of other VIKING20X hindcasts, and as the Referee #1 suggests, we will address the points about the possible influence of model bias on the results in a clearly-stated disclaimer.

2. In section 5.2, the role of the AMOC in driving the freshening is discussed. It is concluded that the weakening Gulf Stream source, determined via particle tracking, is associated with the AMOC in the subtropics and is not related to the subtropical gyre circulation. What I find missing here is the AMOC in the subpolar north Atlantic. What is the role of the subpolar AMOC in the great freshening event? Does the subpolar AMOC also weakens around a similar timing in VIKING20X? How is the magnitude and time of the weakening (or maybe strengthening) of the subpolar AMOC in the model compared to the subtropical AMOC? The authors have studied the great freshening event in the subpolar North Atlantic, used OSNAP East section as the termination of the Lagrangian tracking method, and determined that the Labrador Sea heat loss plays a key role in driving the freshening event. However, the authors have avoided investigating the AMOC in the subpolar North Atlantic.

Biastoch et al. 2021 (referenced in the paper) do a detailed analysis of subpolar and subtropical AMOC in VIKING20X with comparisons with RAPID and OSNAP data, so we do not include that here. We also don't find the subpolar AMOC index to be useful tool in diagnosing the causes of the freshening (at least not as useful as the subtropical AMOC index which can be considered a measure of the volume of water exchanged between subpolar and subtropical regions). This is because subpolar-gyre-scale mechanisms with the potential to cause the observed freshening and cooling can be effectively neutral with respect to subpolar AMOC. However, it is interesting to consider how the proposed mechanisms interact with subpolar AMOC (considered in density space). Both the main mechanisms we consider involve the upper limb of AMOC. The reduced flow

from the Gulf Stream source, associated with reduced subtropical AMOC, will just feed through into reduced subpolar AMOC as the transformation to denser water is almost entirely north of the OSNAP line. The subpolar-gyre scale mechanism is more complex. The increased southward flow of lighter water from the Labrador Sea, could be effectively neutral on subpolar AMOC in the longer term as the lighter water leaving the Labrador Sea recrosses northwards. The time difference between these crossings should contribute to interannual changes in subtropical AMOC, but these are difficult to detect among the other sources of upper limb subpolar AMOC variability. However, the mechanism identified behind the increased outflow of lighter water involves reduced transformation of lighter AMOC upper limb water to denser lower limb water in the Labrador Sea north of the OSNAP line. This should directly reduce AMOC measured at both subpolar and subtropical latitudes, with some lag. We add this consideration, as outlined here, in the discussion.

> 3. I do not find Section 6.3 convincing. First, I do not see how the modeled isopycnal depths "agree closely" with observation. The model has substantially shallower isopycnals, particularly at large depths. This means that the model has a substantially higher density in the Labrador Sea. However, I cannot understand how the model can have fresher and warmer water and at the same time higher density throughout the water column.

Problems with this section were highlighted by two of the Referees, many of the concerns were due to problems of comparison of the model with EN4 analyses; the different resolutions, the use of climatology to fill gaps in EN4 salinity in particular. We overhaul this section completely with comparison to a more appropriate dataset specific to the Labrador Sea outflow region over the modelled period, and a new Figure 14 (included here as Figure 14.1). We are now careful to distinguish between mean misfits (models typically cannot match sigma up to the second decimal place) and changes/trends. This comparison is much stronger and we feel the isopycnal depth changes – the fundamental variable in our argument -- do 'agree closely' with this more relevant observational dataset. The new dataset was provided by Igor Yashayaev, based on the latest version of the data presented here: https://waves-vagues.dfo-mpo.gc.ca/Library/40974698.pdf. We add a brief description of this dataset in the methods section.

For completeness, and as the discussion paper remains available, we thank Reviewer #3 for spotting the mistake here. I (Alan Fox) have mixed Absolute Salinity (for EN4) and Practical Salinity (for VIKING20X) in the original Figure 14, explaining how the model appears fresher and warmer and at the same time denser.

Minor comments:

1. I do not think it is necessary to start the introduction with the "warming hole". It might be more straightforward if you directly start with text describing the recent "freshening and cooling" event.

Two Referees made similar comments, and on reflection we agree. We will reduce the reference to, and emphasis on, the multi-decadal scale 'warming hole' bringing the focus more firmly on to the multi-year timescale freshening event

2. In Figure 2d, why is there direct-path water crossing 60°W.

I think this refers to Figure 3d. It was explained in the caption as water which has made more than one complete loop of the subpolar gyre, and we allocate paths on the first loop. However, a new version of the figure is included to remove the confusion. (attached here as Figure 3.1)

3. Section 5 need to be reorganized. Both section 5.1 and 5.3 are subpolar-gyre-related mechanisms. And what does it mean by basin-scale in section 5.2? Gyre circulation is also basin-scale.

We leave the sections here ordered as before – we tried other ways of organising these and this felt the most natural. However, we clear up the scale descriptions. We were using 'basin-scale' to signify whole North Atlantic (or even whole Atlantic) scale processes, and 'gyre-scale' for processes centred on the subpolar region.

4. Line 364, how is "subtropical gyre recirculation" defined?

This is will be defined more clearly. It is used to refer to that part of the northward Gulf Stream flow which returns southward in the broad interior flow in the subtropical gyre, as against that part which continues northward to subpolar latitudes.

5. Line 377, I do not think there is a consensus on whether the AMOC has declined since the 1990s. Models and proxies suggest that AMOC has declined (e.g., Rahmstorf et al., 2015; Ceasar et al., 2018, 2021), while observation-based reconstructions have not found a significant AMOC decline (Fu et al., 2020; Worthington et al., 2021; Caínzos et al., 2022).

Agree. We will modify the text accordingly, including the relevant additional references where required. Thank you.

6. Lines 459, please specify the density of the "lighter" waters.

OK.

7. Lines 461, it is confusing to call waters lighter than 27.50 kg m^{-3} as the "lightest" waters.

OK. We clarify this.

8. In Section 6.2, it is concluded that due to reduced heat loss over the Labrador basin, transformation from lighter to denser water mass is weakened. Therefore, the steady inflow in the upper layer (<27.65 kg m^{-3}) must be balanced by an enhanced outflow also in the upper layer. Does this indicate that the overturning in the Labrador Sea weakens, while gyre circulation in the Labrador sea strengthens? This leads back to Section 5.1, lines 335-340, where it is found that the SPG is not responsible for the freshening. How would the authors reconcile the discrepancy here?

We clarify this to remove what we think is possible confusion rather than a discrepancy. The reduced transformation does indicate reduced overturning at this density in the Labrador Sea, but it does not necessarily follow that gyre circulation strengthens. We find increasing lighter water outflow at a time of weak, and constant or further weakening SPG strength (the appropriate SPG index will be included in Figure 5). Rather than being associated with increased gyre circulation (which is mostly barotropic) the increased upper layer outflow is associated with reduced lower layer outflow.

9. 14 needs to be reorganized. Fig. 14(d,e,f) is cited before Fig. 14(a,b,c).

This will be superseded by replacement Fig 14 and rewritten section 6.3.

10. Line 536, salinity issue does not make temperature comparison reliable, the sentence needs rephrasing.

Superseded by the full overhaul of the model-observation intercomparison as detailed under the general comments above.

Reference:

Rahmstorf, S., et al. (2015). Exceptional twentieth-century slowdown in Atlantic Ocean overturning circulation. Nature Climate Change, 5(5), 475–480

Caesar, L., et al. (2021). Current Atlantic meridional overturning circulation weakest in last millennium. Nature Geoscience, 14(3), 1–120

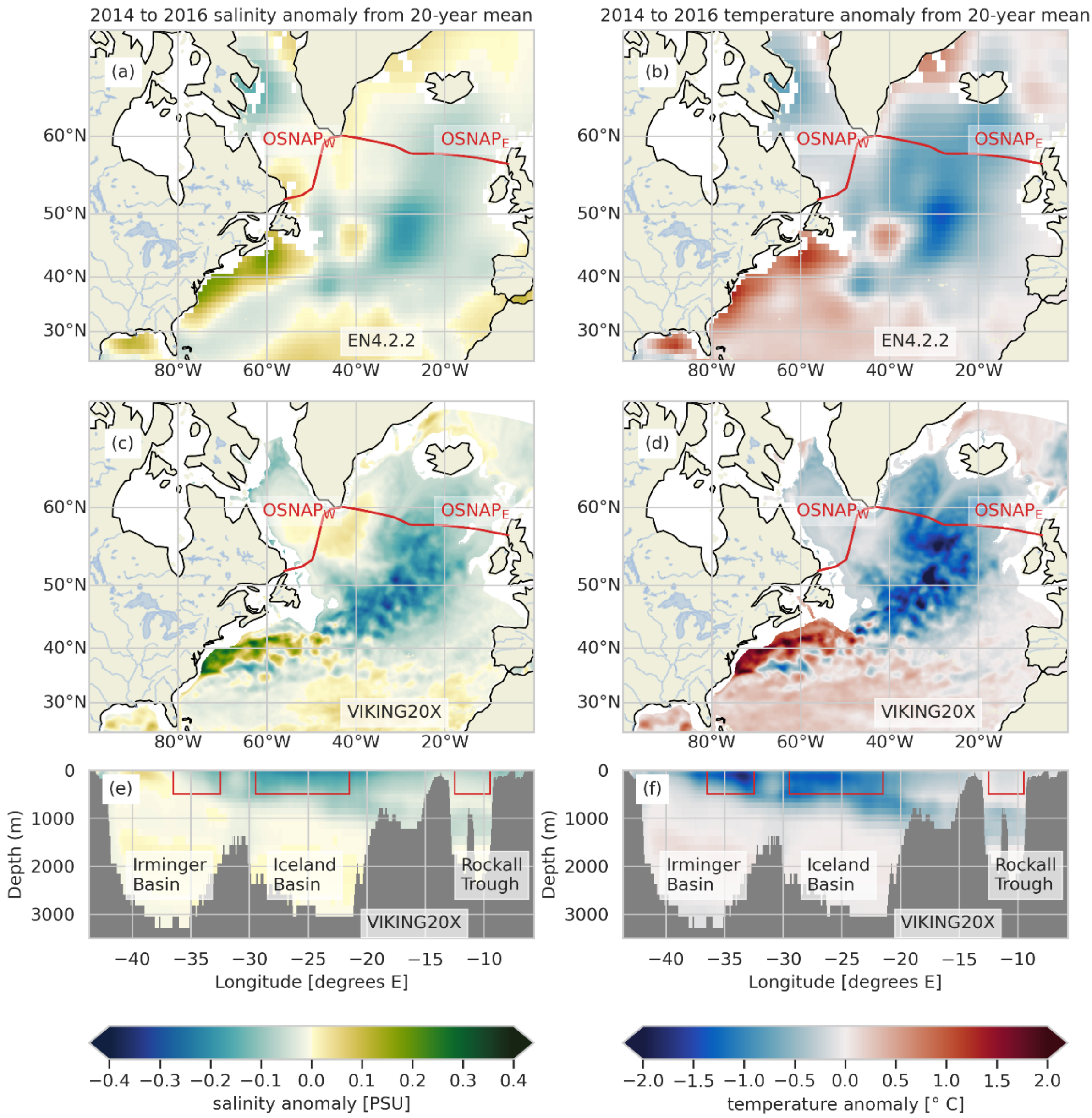
Caesar, L., et al. (2018). Observed fingerprint of a weakening Atlantic Ocean overturning circulation. Nature, 556(7700), 191–196

Fu, Y., et al. (2020). A stable Atlantic meridional overturning circulation in a changing North Atlantic ocean since the 1990s. Science Advances, 6(48), eabc7836

Worthington, E. L., et al. (2021). A 30-year reconstruction of the Atlantic meridional overturning circulation shows no decline. Ocean Science, 17(1), 285–299

Caínzos, V., et al. (2022). Thirty years of GOSHIP and WOCE data: Atlantic overturning of mass, heat, and freshwater transport. Geophysical Research Letters, 49, e2021GL096527

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$_E$
EN4.2.2
VIKING20X
60°N
50°N
40°N
30°N
80°W
60°W
40°W
20°W
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

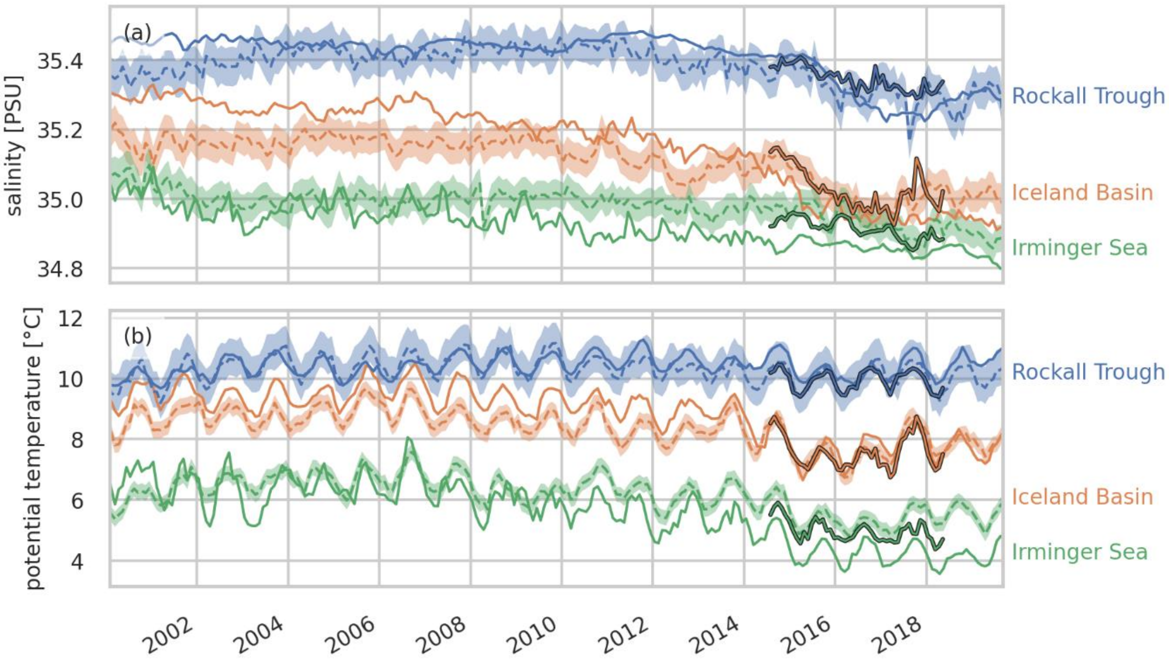


Figure 2.1

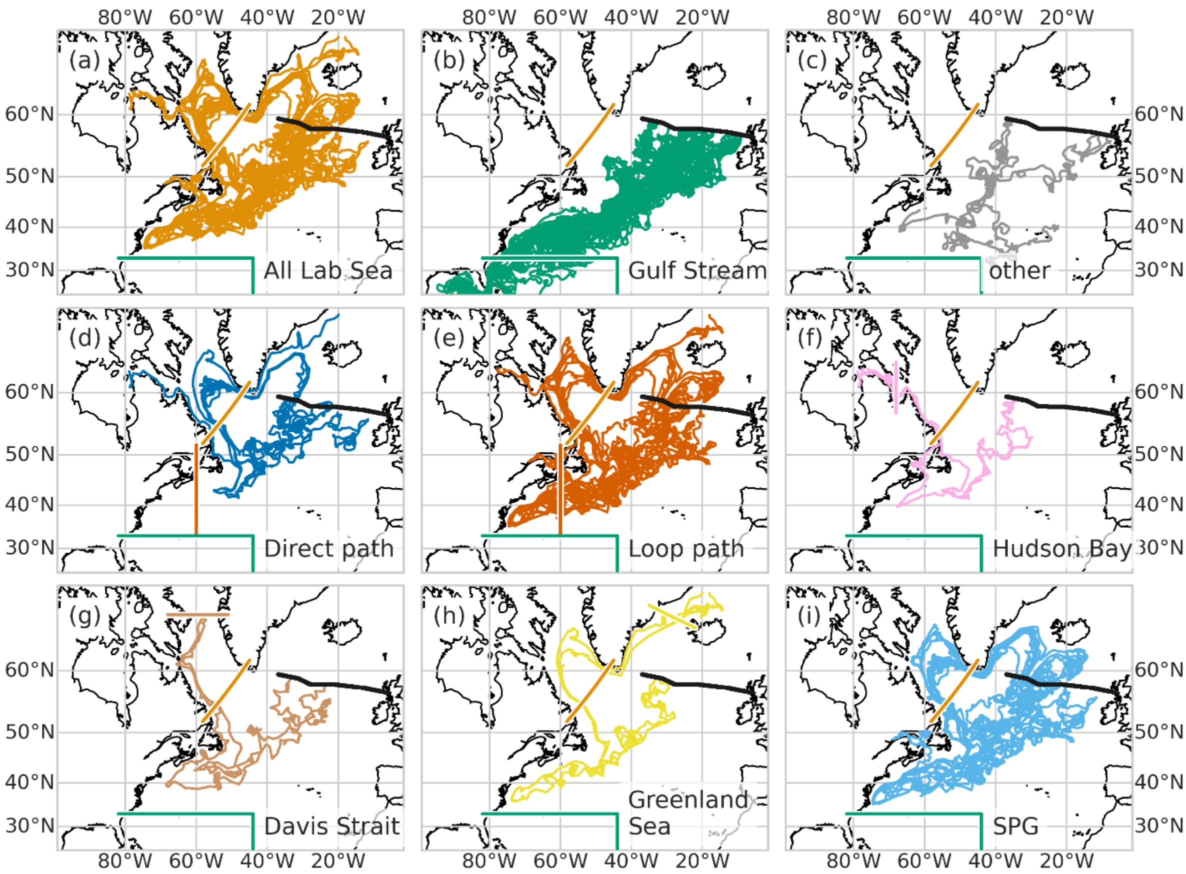


Figure 3.1

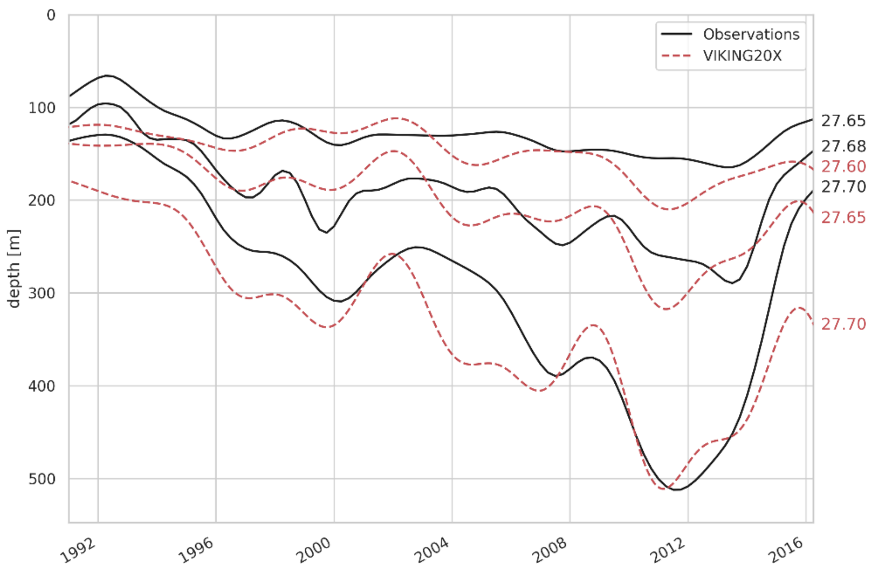


Figure 14.1 2-year low-pass filtered, area-average isopycnal depths in the Labrador Current exit region of the Labrador Sea from observations (black lines) and VIKING20X (red dashed lines). Deepening isopycnals between the mid-1990s and 2010-2014 in the upper water column are clearly seen in both observations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