Response to Reviewer 2

Thank you for your helpful and constructive comments on our paper. The comments are listed below in black, with our response to each in blue. We hope that you are happy with the improved manuscript and find it suitable for publication.

The manuscript presents an in-depth analysis of the onset and evolution of the cold anomaly in the North Atlantic over the 2013-2017 period. Two versions of the ECCOv4 model were used to analyse in detail the different terms of the mixed-layer temperature budget. The new result from this study is the importance of vertical diffusion term in the re-emergence of the SST anomaly in summer, while the advection term is one order of magnitude smaller. This is explained by the strong temperature gradient at the base of the mixed layer, induced by anomalously high surface heat fluxes and subsequent cooling during the previous winters.

The manuscript is very well written, and figures are particularly nice and clear. This is a careful and very interesting study that deserves publication. Considering the temperature temporal variation instead of the usual heat budget is sometimes tricky to understand, but the authors are very careful to accompany the reader through the subtleties of the interpretation. Overall, I have one major remark that needs consideration, and then minor revision comments.

Thank you for the encouraging comments, we hope that you find the responses to your recommendations satisfactory.

My general remark on the method is that the main result bears on the importance of vertical diffusion. However, this is precisely the term parameterized to close the budget, so to my point of view, it needs more than the figure in the appendix to justify this chosen parametrisation. To my knowledge, Kv~2 cm2/s is in the “high range” of values usually used in OGCMs. Could you comment more on this? I explain: imagine that the winter heat fluxes are underestimated in the model. Then the data assimilation will “correct” the insufficient cooling of the mixed layer, and this artefact will necessarily appear in the parameterized term, and I don’t understand why the closed mixed layer budgets gives an answer to this problem lines 370-375). I suppose that you have access to the diagnosed Kd in the model: could you make a comparison?

The diffusion at the base of the mixed layer is not comparable with the background mixing in the model; this has now been made clear in the methods section of the manuscript. There are multiple mixing schemes present in the model that represent diffusion, including isopycnal and diapycnal background diffusion, GGL mixed layer turbulence closure, and a convective adjustment for the winter MLD. It is therefore not clear which value(s) the budget diffusivity should be compared against. Instead, we simply choose diffusivity values that are optimal for closing the budget within this specific region. However, the fact that the diffusion term of our budget is still close to that of the mixed layer budget suggests that the values we have chosen do a good job of reproducing the impact of the mixing schemes in the model, and in particular in reproducing the cooling anomalies due to diffusion that are focused on in this paper. The figures showing the closed budgets have now been moved to the main text of the paper (Fig. 5b and 6b) for a clearer comparison between the closed budgets and approximated budgets. We have now discussed the choice of diffusivity further within the methods section.

The closed budget does not answer the problem that the data assimilation could be correcting for insufficient cooling via diffusion. However, the ERA-interim used to force the models have been shown to be consistent with independent observations of surface heat fluxes in the North Atlantic. This has now been further discussed in Section 4.5. However, this is always a caveat when using state estimates to investigate variability.

In the article, the role of horizontal advection is minimized, although it clearly plays two roles in the 2015 cold anomaly origin: onset of the cold anomaly in winter 2013-2014 (25%, line 222) and advection of cold water below the mixed layer during the following summer/autumn (lines 384-386). Although this does not concern directly the processes responsible for the 2015 anomaly, I think it should be more emphasized (in the abstract and conclusion) to contrast with what happened in 2015.

We agree that the impact of advection was poorly expressed in the manuscript. The text and schematics have now been revised to emphasise the role that advection plays in driving the initial cooling of the cold anomaly, as well as the cooling of the sequestered anomaly beneath the mixed layer.

Minor revision:

I think you should merge Fig. 1 and Fig2

Thank you for the suggestion, Fig. 1 and 2 have now been merged.

Fig. 5 and section 3.3: I would put the sum of terms in solid line (as the contributing terms) et and model tendency in dashed line (this is more intuitive).

In all budget figures, the dashed and solid lines have now been switched, so that the budget tendency is shown by the solid line.

Could you add this figure 5 but in the northern and southern box in the appendix (to emphasize the difference in the entrainment term)?

The climatology of the mixed layer heat budget averaged over the northern and southern boxes have now been added to the Appendix (Fig. A3).

lines 189-190: How do you explain that the difference between your budget and the model between May and June? Which assumption is the most problematic to your point of view? Is the possible warming just below the calculated MLD responsible for it?

It’s difficult to pinpoint the exact cause of any particular error. The surface flux term is correct for the model as it is calculated in the same way as for the closed budget, however there are sources of error in each of the remaining terms. During summer, it is unlikely that

entrainment is causing the error as the deepening of the mixed layer is still small during this period. It is therefore likely to be the advection and/or diffusion term causing the error, and cooling via diffusion is lower than in the closed budget. It is possible that temperature changes below the mixed layer could be causing some of the error, particularly if the choice of definition for the ΔT term is not optimal, leading to the underestimate in cooling of the mixed layer.

The most problematic terms of the mixed layer budget equation are the diffusion and entrainment terms as they require the most assumptions/parameterisations, including the parameterisation of diffusivity and the definition for entrainment velocity and ΔT. Despite the error, the similarities between the terms of the mixed layer budget and the equivalent terms within the closed budget, as well as how close the seasonal cycle of the budget is to closure, give us confidence in the method used to approximate the mixed layer budget. The potential reasons for error have now been added to the text (lines 208-216).

Section 3.4: you write that horizontal advection is responsible for about 25% of the cooling in December 2013. However, you disregard this result later on. The advection is more important in the southern box in your analysis (your Fig. 9), so it could confirm the schematics of Holliday et al. (2020), their figure 10. In conclusion, I disagree with the statement lines 383-385: “advection still played only a small role in the initial cooling in comparison to surface forcing”. 25-30% is not small.

We agree that the role of advection was wrongly understated. This has now been changed throughout the text to emphasise the role advection plays in the initial forcing of the cold anomaly. Thank you for pointing out the connection between the role of advection and the findings of Holliday et al. (2020); this has now been included in the discussion.

Figure 8: very nice: it concerns mainly 2014, doesn’t it? To better understand, please add a figure in the appendix with the absolute values of Fig. 6b so that there is no confusion on the actual sign of each term. Consider adding a small arrow for advection in the first box, and also below the mixed layer in spring and summer to explain why the temperature keeps decreasing (although this is not proven in this ms).

Thank you for the suggestions. The schematic has been edited to include the contribution of advection. The mixed layer budget without the seasonal cycle removed has been added to the Appendix (Fig. A1).

Discussion: Some points are difficult to follow because most figures are anomalies (except diffusion term fig.7c), so we don’t know the actual sign of each term. Otherwise, see my main comments above.

Figures showing the absolute values of each budget term, before the seasonal cycle has been removed, have been added to the Appendix (Fig. A1, A4), as well as figures showing the components of the budgets without the seasonal cycle removed (Fig. A2, A5). The sign of each of the terms has also been referenced in the text when applicable, hopefully making the explanations clearer.