Referee #1

We would like to thank the reviewer for the constructive comments. Our responses are given below in black type (reviewers comments in blue italics).

Q1.A) It is tacitly assumed that open water deep convection by the parameterization is what is needed to more accurately simulate the Labrador Sea and other deep convection sites. However, there is substantial observational and theoretical evidence that convection influenced by lateral boundaries is more important for the overturning mass flux (e.g., https://doi.org/10.1175/2011JCLI4130.1, https://doi.org/10.1175/JPO-D-24-0019.1).

The academic approaches developed and used by Spall (2010, 2011, 2024) have shown that downwelling is concentrated near the boundary where eddies break away from the current. Therefore, buoyancy-induced downwelling in the Labrador and Irminger Seas, which drives the North Atlantic meridional overturning circulation, is concentrated along their eastern boundaries and not in the center of the basin.
In essence, Spall (2011) showed that coastal downwelling sets up to maintain mass conservation and the balance of thermal winds in the incoming and outgoing flows across the basin.
Based on a vorticity budget in an idealized configuration of buoyancy-driven subtropical and subpolar gyres, Spall (2024) showed that the downwelling near the western boundary results primarily from the balance between the stretching of planetary vorticity and the viscosity induced by eddies, and to a lesser extent from the meridional advection of planetary vorticity. In thermodynamic terms, the net downwelling (W) was expressed as a function of the temperatures of the incoming flow (Tin), the outgoing flow (Tconv), and the gyre center (T0), where deep convection occurs.
Typically, this expression $W \propto (Tin - Tconv) / (Tin - T0)$ shows that the downwelling depends on T0, which is the temperature controlled by the loss of buoyancy at the surface and, ultimately, by convection.
In his simulations, Spall (2010, 2011, 2024) increases the vertical diffusion coefficient (Kz) to 1000 m^2/s for statically unstable conditions to represent vertical convection.
The EDMF parameterization aims precisely to replace this increase in Kz with a mass-flux scheme in order to accurately represent convection and, ultimately, to more realistically simulate the temperature T0 in convection zones, and ultimately the coastal downwelling.

Q1.B) I think you may be missing a major source of convection in under-resolved "Ekman buoyancy flux" that is known to induce strong submesoscale convection (https://doi.org/10.1175/JPO2737.1). This can be included into convective parameterizations straightforwardly (http://dx.doi.org/10.1016/j.ocemod.2016.12.003). This lateral transport can overwhelm the surface buoyancy fluxes in the presence of strong fronts (e.g., https://doi.org/10.1016/j.dsr2.2013.02.025).

Thomas and Lee (2005) and Thomas (2008) showed that potential vorticity (PV) destruction can occur at density fronts under down-front winds. Under such conditions, the Ekman transport advects denser water over lighter water, thereby destabilizing the upper ocean (Thomas and Ferrari, 2008). The associated frictional PV flux, which scales as dTau/dz*DUg/dz, induces an equivalent buoyancy flux (EBF) 10 to 100 stronger than the surface buoyancy loss, as observed at the subpolar front of the Japan Sea (Thomas and Lee, 2005) and along the Ligurian Current in the Western Mediterranean Sea (Giordani et al., 2017). EBF results from the interaction between surface winds and currents, and can

directly destabilize the ocean upper layers and induce vertical mixing by diffusion and convection. The EDMF parameterization does not explicitly diagnose EBF forcing, but responds to its effect on the local density stratification (Giordani et al., 2017). Therefore, when EBF-induced processes destabilize the water column and generate convective conditions, their effects can be represented by EDMF through its response to the resulting unstable stratification.
Following this comment and the previous comment Q1A, we now clarify in the manuscript (lines **158-160)** that EDMF responds to convective instability regardless of its origin, including that induced by surface cooling or salinification, EBF, or coastal downwelling.

Q1.C) Figures 2&3 lack a "control case". Outside of the EDMF parameterization, it is not clear how to interpret the w_p. I suggest comparing the vertical diffusive, total, and convective heat fluxes in the time window shown in Fig. 2 to the vertical total heat fluxes in the EVD simulation at the same location and time. I guess the point is that the MF parameterization will go deeper than the ED flux, but what fraction of the total is it, and is it deeper than in the EVD simulation? In examining KPP variants, we often find that the "deeper" schemes end up being similar to the "shallower" versions under the same surface forcing--it is quite hard to do this comparison fairly (see http://dx.doi.org/10.1175/JPO-D-22-0107.1 and http://dx.doi.org/10.1029/2019MS001810), especially so in a GCM with feedbacks present. Figure 9 does this comparison more effectively than the earlier figures.

We thank the reviewer for this suggestion. As the model outputs required to compute the diffusive and convective heat fluxes at hourly frequency, such as w_p shown in Fig. 2a, are not available, we instead computed the temperature trend from the divergence of the diffusive ($\partial z F_{diff}$), convective ($\partial z F_{conv}$), and total ($\partial z F_{tot}$) vertical heat fluxes from the daily model outputs. The fluxes were calculated at the model grid cell containing the mooring location and over the same time window as shown in Fig. 2a, as :

$$\partial_z F_{diff} = -\frac{\partial}{\partial z}\left(-K_z \frac{\partial T}{\partial z}\right),$$

$$\partial_z F_{conv} = -\frac{\partial}{\partial z}\left(\frac{\partial MF(T_p - T)}{\partial z}\right)$$

In the case of the EVD simulation: $\partial_z F_{tot} = \partial z F_{diff}$; whereas in the case of EDMF simulation: $\partial_z F_{tot} = \partial z F_{diff} + \partial_z F_{conv}$.

In the figure below we compare the contributions of the convective ($\partial z F_{conv}$) and diffusive ($\partial z F_{diff}$) components to the total flux divergence $\partial z F_{tot}$ in the EDMF simulation, and in terms of intensity and vertical extent for the three simulations, under identical surface forcing.

For the EDMF simulation, $\partial z F_{diff}$ is nearly negligible over most of the water column, except for a weak signal close to the surface during the summers. Consequently, the vertical structure of $\partial z F_{tot}$ is almost entirely determined by the convective contribution, $\partial z F_{conv}$. This confirms that, in the EDMF simulation, the deep response of the total vertical heat flux is primarily associated with the mass-flux component rather than with diffusive mixing. In terms of vertical extent, the EDMF $\partial z F_{tot}$ reaches greater depths than the diffusive signal in the TKE simulations during the strongest convective winters. This illustrates that the deeper penetration associated with EDMF results from the convective mass-flux contribution, rather than from an enhancement of the diffusive component.

The TKE+EVD and TKE+EVD+MLP simulations exhibit similar temporal variability in ∂zF_{tot} response, with the main convective events occurring during the same winters, but differ in the depth reached by the diffusive contribution: ∂zF_{diff}signal extends to greater depths in the TKE+EVD than in the TKE+EVD+MLP. This is consistent with the results presented in Fig. 9e, which shows deeper MLDs in the TKE+EVD simulation. This is due to a higher EVD triggering frequency in the TKE+EVD case than in the TKE+EVD+MLP case. Thus, the differences in the vertical extent of the diffusive heat-flux contribution are consistent with the differences in the simulated mixed-layer structure.

The interannual variability in the depth of ∂zF_{tot} is also consistent across the three simulations and agrees well with the variability identified in Figs.2a, 9e. In particular, the relatively shallow convective penetration during winter 2012/13 is apparent in all three simulations. The first winter shown here (2011/12), however, exhibits a deeper penetration of ∂zF_{tot} than that inferred from Fig. 2a. This difference is expected because the two figures do not represent exactly the same spatial sampling: Fig. 2a uses hourly model output at the specific mooring location, whereas the present analysis uses daily model output at the model grid cell encompassing the mooring location. Given the strong spatial variability of convection in the Labrador Sea, differences in the diagnosed penetration depth are therefore expected. This result further indicates that the different parameterizations respond consistently to the same atmospheric forcing while producing different vertical extents of the turbulent mixing response.

These results are now added and discussed in new Figs. 2b and S1, and lines **214-220, 316-339**.

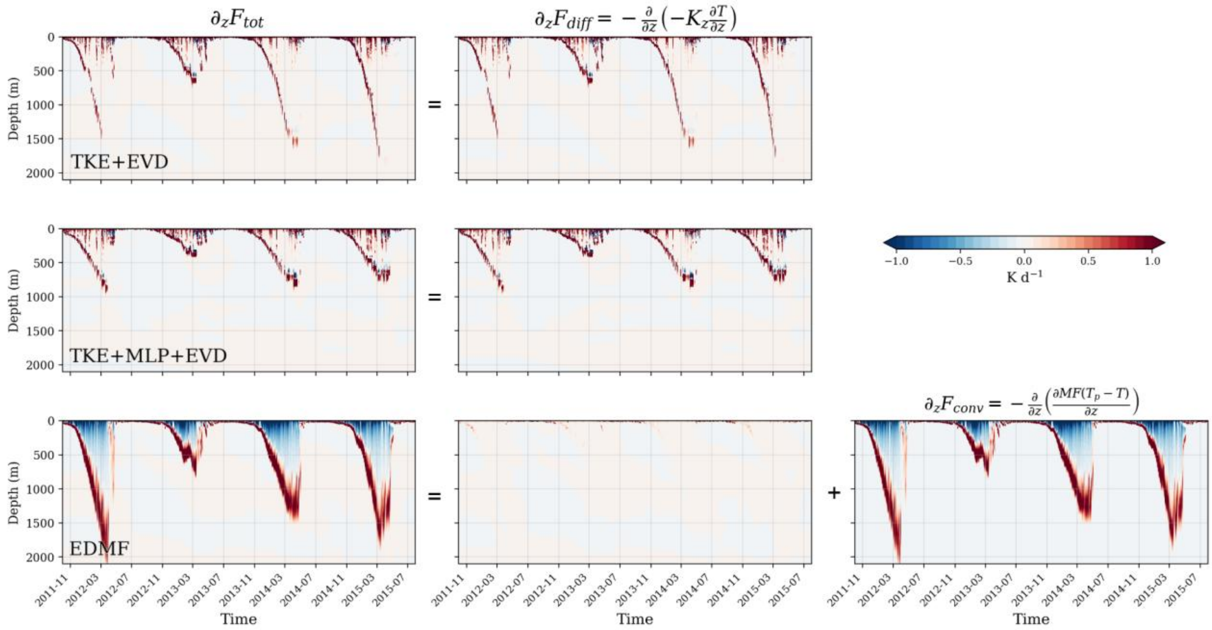

Figure: Vertical divergence (K day^{-1}) of the total (∂zF_{tot}), diffusive (∂zF_{diff}), and convective (∂zF_{conv}) vertical heat fluxes at the model grid cell containing the Labrador Sea mooring (56.53°, 52.65°W), over the same period as shown in Fig. 2a. Rows correspond from top to bottom to TKE+EVD, TKE+EVD+MLP, and EDMF. For the TKE-based simulations, $\partial_z F_{tot} = \partial zF_{diff}$, whereas for EDMF, $\partial_z F_{tot} = \partial zF_{diff} + \partial_z F_{conv}$.

Q1.D) Introduction: A paragraph on the dangers of over-interpreting bias reduction in global models as evidence for improved parameterization physics should be added. The key point is that because of compensating errors in global models, it is often the case that improved physics initially leads to increased bias rather than a reduction. In this case, because of past work on idealized models, care is taken to avoid overinterpretation by comparison to the conclusions drawn in those more controlled settings. Discussion of Figures 5 & 7 should also mention this context, because it is likely that if other parameterizations (e.g., GM) were retuned after implementation of the EDMF scheme, the bias and RMSD reduction might be greater than shown there. Also, you should revise the sentence "Overall, this first global-scale validation demonstrates that EDMF provides a more coherent and physically consistent representation of oceanic convection." correspondingly, as this GCM-bias reduction study does not show coherence nor physically consistent representation, it shows the impacts of those physical principles that are established in the process papers leading up to this one.

We agree with the reviewer that the reduction in biases obtained with EDMF should be interpreted with caution as they reflect the combined effect of EDMF, the other parameterizations, the surface forcing and their interactions. Indeed, the present EDMF simulation was not accompanied by a retuning of other parameterizations following the implementation of EDMF, such as the eddy-induced velocities parameterization (Gent and McWilliams,1990), the submesoscale mixed layer eddies parameterization (Fox-Kemper et al. 2008), or the vertical TKE closure scheme. Further improvements in the global mean state of temperature may therefore be possible through a joint retuning of the model components. We agree that our results should thus be viewed as an indication of the beneficial impact of EDMF formulation, rather than as a standalone demonstration of improved physical realism.

Following these recommendations, we have added a comment regarding the interpretation of bias reduction in global models lines **209-212**, and added/modified lines **744-753, 760-761**.

Q1.E) I'm confused by how large the JJASO bias in the global MLD is for the EDMF scheme vs de Boyer-Montegut, as it seems smaller than that in all of the 3 regions. In the global comparison only, the TKE+EVD seems to be closer to observations during JAS, while in all of the three regional panels the EDMF is closer. Also, you are showing the deB-M and Holte MLDs as though both are comparable to the model, but doesn't NEMO use the deB-M definition of MLD as suggested in Treguier et al. (2023; http://dx.doi.org/10.5194/gmd-16-3849-2023)?

Thank you for pointing this out. Regarding the first part of the comment, we carefully checked the MLD calculation and plotting procedures and found that the MLDs were not area-weighted. We have corrected this issue and produced a new **Fig. 8** using the correct are-weighting procedure for all MLD datasets. As a result, the previously observed large EDMF bias in JJASO relative to de Boyer-Montegut is substantially reduced.
Regarding the second part of the second part of the comment, we confirm that the MLD in NEMO is computed using the density threshold of 0.03 kg m^{-3} relative to 10 m depth, which is the criterion used in the de Boyer Montégut dataset (2004, 2024). We initially included the Holte et al. (2017) datasets to illustrate how the choice of the observational MLD reference dataset can affect the interpretation of the model results.
The "threshold MLD" provided by Holte et al (2017), is computed from individual profiles using the same density threshold proposed by de Boyer Montégut et al. (2004), here as "a density jump equivalent to a temperature difference of 0.2°C at the profile location". This ultimately leads to a smaller threshold for very cold, dense mixed layers. In addition, this Holte et al. (2017) dataset is

binned into 1°x1° grid cells, without applying a climatological interpolation to fill cells where the number of available profiles is insufficient. Finally, this dataset includes neither the Arctic, the Greenland Sea, the Baltic nor any ice-covered region. In light of these characteristics, and following the recommendations of Treguier et al (2023), we decided to remove the two Holte datasets from the comparison, as their non-global coverage makes them less suitable for comparison with global ocean models than objectively analyzed datasets such as that of de Boyer Montégut et al. (2024).
The text in lines **237-238**, and **526-535** has been revised accordingly.