egusphere-2022-1059

Mixing and air-sea buoyancy fluxes set the time-mean overturning circulation in the subpolar North Atlantic

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In this manuscript the water mass transformation by air-sea buoyancy fluxes and mixing in the subpolar North Atlantic and Nordic Seas is quantified. Observational, reanalysis, and numerical data are used in a comprehensive water mass transformation framework to determine where and how the dense water masses that supply the lower limb of the Atlantic Meridional Overturning Circulation at the OSNAP mooring array are formed.

I think this is a well-written and very interesting manuscript that significantly contributes to the understanding of water mass transformation and overturning in the subpolar North Atlantic and the Nordic Seas, in particular by emphasizing the importance of mixing. I have only a few comments and concerns, primarily related to uncertainties in the estimates and the occasional need for clarification elaborated on below, that I hope the authors will consider.

General comments:

The inability of coarse-resolution products such as the reanalyses and ECCO state estimate to resolve boundary currents is discussed. This consideration applies also to both of the observational data sets. Furthermore, the scarcity of data on the east Greenland shelf (e.g., Behrendt *et al.*, 2018) implies that the gridded products here primarily result from extrapolation unconstrained by direct observations. While the East Greenland Current is becoming ice-free in winter (Moore *et al.*, 2022), the same cannot be said for the shelf, so I am surprised to see air-sea interaction occurring along most or all of east Greenland despite the presence of sea ice in Figure 8a. I think these issues require more extensive consideration.

What is the magnitude of the error in your estimates? The mixing, in particular, is equated with the residual of the total and flux-driven transformations, and probably has substantial uncertainty.

I think some clarification regarding water mass products and the regional distribution of water masses is necessary. I concur that cooling by air-sea heat fluxes and freshening by mixing precondition the warm and salty Atlantic Water as it progresses northward. In the Iceland Basin and in the Irminger Sea this leads to the formation of subpolar mode water. In the Nordic Seas overflow water is formed, not subpolar mode water, which can be misunderstood from the abstract (line 8) and text (line 471). In the present climate deep or bottom water formation occurs at most to a very limited extent in the Nordic Seas (line 37). The dense water formed in the Greenland Sea, where the deepest and densest convection occurs, is not too dense to cross the Greenland-Scotland Ridge and contribute to the overflows (Brakstad *et al.*, 2019; Huang *et al.*, 2020). It is also not entirely clear in Figure 1 what you refer to as overflow water. Boxes 2 and 3 are too warm to represent the pure overflow water that crosses the Greenland-Scotland Ridge (see Figure 6 in Smedsrud *et al.*, 2022), so I suppose it must be the DSOW and NEADW found south of the ridge after mixing with and entrainment of subpolar water masses? In my opinion, adding a map to show the geographical distribution of the water masses in Figure 1 would have provided important clarification.

The water mass transformation framework is probably not familiar to most readers. I think that the narrative would benefit from occasionally summarizing key findings and recasting the explanations using more general terms, such as at the end of the data and methods section. Perhaps a schematic illustration would also be helpful.

I think that some sort of integrated measure of water mass transformation would have been very useful to include. Petit *et al.* (2020) found that the Iceland Basin and Irminger Sea were particularly important sources of dense water to the lower limb of the AMOC, but they did not account for mixing. How do your results reinforce or modify those of Petit *et al.* (2020) if you quantify the total transformation south and north of the Greenland-Scotland Ridge, considering also the preconditioning that occurs as the Atlantic Water flows northward and the regions of enhanced mixing downstream of the overflows across the Greenland-Scotland Ridge?

In this manuscript the time-mean overturning circulation is considered, while the water mass transformation by buoyancy loss from air-sea interaction occurs in winter. How would the results differ if you consider the water mass transformation that occurs in winter only? Without the seasonal cycle, Figure 8 would have been easier to interpret.

Specific comments:

Line 21:
There is substantial difference in density between LSW and the overflow waters formed in the Nordic Seas (e.g., Pacini *et al.*, 2020; Mastropole *et al.*, 2017; Smedsrud *et al.*, 2022).

Line 37:
In the present climate, only intermediate water masses are formed by gradual transformation of Atlantic Water (Mauritzen, 1996) and by open-ocean convection in the Greenland and Iceland Seas (Huang *et al.*, 2020). These intermediate water masses can contribute to the overflows across the Greenland-Scotland Ridge and are not confined to the Nordic Seas.

Line 135:
The transport through Bering Strait is on the order of 1 Sv (Woodgate, 2018). If you mean that this is negligible, you should write that instead.

Line 155:
How come a combination of ERA5, NCEP, and JRA55 is used for the fluxes in the observations, while only ERA5 is used for the fluxes in the reanalyses? This should be justified, in particular as the observational- and reanalysis-based results may be more directly compared if the only difference between the estimates are the oceanic parameters.

Line 205:
More importantly for the vertical structure of the subpolar North Atlantic, LSW is less dense than overflow water (e.g., Pacini *et al.*, 2020).

Lines 218 and elsewhere:
An estimate of the uncertainties, both in the magnitude of the overturning and in the density of maximum overturning, would have been very valuable to include. Without error bars, it is impossible to know how much confidence to place in these estimates.

Line 276:
Downstream of the overflows, where the mass transport approximately doubles by entrainment of ambient water masses (Dickson and Brown, 1994; Girton and Sanford, 2003), must be key locations for the mixing that leads to a convergence of volume within the density range of NADW. As discussed, the overflows are not well represented in the reanalyses and state estimate, but most likely not in the observational products either due to

the coarse resolution. What are the implications for your estimates of mixing?

Line 353:
How come the upper limit for the middle density class is 27.77 kg/m^3 rather than 27.8 kg/m^3?

Line 369 and elsewhere:
The region of negative transformation extends into the Iceland Sea, south of the Greenland Sea. Referring to the western part of the Nordic Seas exclusively as the Greenland Sea is not correct.

Line 405:
The region of most pronounced air-sea flux transformation is primarily the western Nordic Seas, i.e., the Greenland and Iceland Seas. The Greenland Sea is also where the deepest and densest convection occurs.

Line 521:
Intermediate water masses formed in the interior Greenland and Iceland Seas also contribute to the Denmark Strait overflow (Mastropole *et al.*, 2017; Semper *et al.*, 2019).

Line 527:
This paragraph highlighting processes that govern the mixing-driven water mass transformation is important. I think some of these processes could have been elaborated on (e.g., boundary current – interior exchange) and that the overflows, which are most likely key locations for the mixing that warms and freshens the coldest and densest water masses leading to the convergence of volume within the density range of NADW, should have been emphasized.

Figure 1:
I think you need to clarify the water masses and their geographical distribution in Figure 1. In particular, what exactly do you mean by overflow water (as discussed above, the "pure" overflow water at the Greenland-Scotland Ridge is different from the water masses you identify in boxes 2 and 3) and where is the NADW? I think that a map showing the geographical distribution of these water masses would be a very valuable inclusion.

Figure 5d:
I think Figure 5d requires a bit more explanation. It is not evident why overturning implies warming and salinification.

Figure 11:
Why is the water mass transformation due to air-sea fluxes an order of magnitude lower when comparing temperature classes (Figure 11) to density classes (Figure 8)?

Detailed comments:

Lines 9, 207, 504, and elsewhere:
Ridge, Seas, and Current should be capitalized.

Line 84:
There's an "in" too many.

Line 84:
He would be a more appropriate pronoun.

Line 166:
It should be “...each **has**...”

Lines 430 and 432:
Inconsistent use of hyphen in “mixing-driven cooling”.

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