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Interactive comment on "The coherence of the oceanic heat transport through the Nordic seas: oceanic heat budget and interannual variability" *by* Anna V. Vesman et al.

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General comments

Using observation-based datasets, Vesman et al. studied the connectivity of advective heat flux across a number of sections in the Norwegian Sea. They have further discussed the driving mechanisms for the heat flux variability, including NAO, AO, the meridional (C) and western (W) weather types. Results from this study have implications on the heat (and salt) transported to the Nordic and Artic Seas, which is important to understand the high latitude climate state and variability. The paper is overall clearly written and the focus on the heat flux connectivity is of interest to the community. However, throughout the paper, the authors computed heat flux with a reference temperature along a non-conserved section. This is actually a calculation of temperature flux instead of heat flux, and the difference between the two can be huge (see Forget and Ferreira, 2019). While the variability may not be significantly influenced, as the authors have suggested, the mean heat budget discussed in section 3.2 (Figure 6) is meaningless. I strongly suggest the authors to carefully address this issue before considering publication. One possible approach is to calculate heat flux along closed section and apply mass conservation. Another is to repeat calculations with different reference temperatures to test the sensitivity of the results.

Response: Thank you for your comments and suggestions, they helped to improve the quality of our work. Our study is focused on several closed upper ocean areas, limited from below by an isopycnal. The fluxes are estimated across all vertical sections, across the sea-surface and across the bottom isopycnal, thus closing the volumes studied. All water (warm or cold) passing through the boundaries of the selected water volume is taken into account. We also stress that the main goal of these computations was not estimating the heat balances over the selected areas (in fact, the tendencies in water temperature suggest misbalances), but deriving the main sources of the AW heat loss along its travel north. More detailed answers and corrections are provided below:

Detailed comments

[1]. Line 23: This sentence is hard to understand without reading the manuscript. Suggest to rewrite.

Response: Sentence was changed to: Line 20: “This is a result of different tendencies over the latest decades in the southern and the northern parts of the study region, as well as of a differential damping of the observed periodicities along the Atlantic Water path on its way north (the amplitude of 5–6 year oscillations drops significantly faster than that of 2–3 year oscillations).”

[2]. Line 48-49: For those without a knowledge on the current system (e.g. Yermak brach) or topography features (Yermak Plateau) in the Norwegian Sea, it is very difficult to navigate. I suggest labeling them in Figure 1.

Response: Authors agree that the map lacked important information and had some errors in the current directions. The map was modified and more information was added. Now Figure 1 includes: NwAFC - Norwegian Atlantic Front Current, NwCC – Norwegian Coastal Current, NCC – North Cape Current, WSC – West Spitsbergen Current, SB – Svalbard branch, YB – Yermak branch, EGC – East Greenland Current, EIC – East Icelandic Current, NIIC – North Icelandic Irminger Current, SIC – South Icelandic Current, FC – Faroe Current; VP – Voring plateau, LB – Lofoten basin, Sb – Spitsbergen, YP – Yermak plateau

Figure 1.Schematic map of oceanic circulation in the study region

[3]. Line 67: Where is the Norwegian Atlantic Coastal Current? Could you also label it in Figure 1?

Response:

Line 69: The phrase was changed to "The AW further enters the Barents Sea along the northern shelf of Scandinavia as the North Cape and the Norwegian Coastal (Murmansk) currents . . .." Norwegian Coastal Current was added to the map, previously erroneously named as the Norwegian Atlantic Coastal Current.

[4]. Line 87: I suggest adding a paragraph describing motivations of this work.

Response:

Line 90: The sentence was added: "In this paper we analyze the space-time variability in the advective heat fluxes along the AW pathways into the Arctic. The main motivation of this work was to understand to what extent the anomalies of the oceanic heat flux, entering the Nordic Seas from the south, are conducted into the Arctic. This shows whether the observations at the southern transects (i.e. Svinoy) are representative for evaluation of the variability of the ocean heat advection to the Arctic on the interannual time scales. We also aim to investigating mechanisms behind a possible coherence loss along the AW path."

[5]. Section 2.3: Estimates based on different atmospheric products could be quite different (Chavik and Rossby, 2019). I strongly suggest estimating with different products to derive an ensemble mean and a standard error.

Response:

Comparison between different reanalyzes models show very similar interannual variability. Example of heat fluxes, averaged over region, is presented in Supplementary material, Figure S2.

Figure S2. Ocean atmosphere heat fluxes for region A, calculated using different datasets

[6]. Section 2.5: To derive heat flux, it is necessary to have a closed basin (from coast to coast). While I understand the authors' focus is on heat carried by AW, such a calculation is only a temperature flux and should not be used to infer heat changes (heat changes are not only influenced by warm waters flowing northward but also by cold waters flowing southward at the section).

Response:

It is true that this work doesn't take a basin coast to coast, as, in this study, we are interested only in the northwards path of Atlantic water. Our study is focused on several closed upper ocean areas, limited from below by an isopycnal. The fluxes are estimated across all vertical sections, across the sea-surface and across the bottom isopycnal, thus closing the volumes studied. All water (warm or cold) passing through the boundaries of the selected water volume is taken into account. We also stress that the main goal of these computations was not estimating the heat balances over the selected areas (in fact, the tendencies in water temperature suggest misbalances), but deriving the main sources of the AW heat loss along its travel north. To further illustrate this complex problem of obtaining the heat balance, time series of the heat fluxes for different positions of the boundary transects, as well as for different reference temperatures were added to the Supplementary material. Important is that, with a single exception, the variations do not change the tendencies and the main patterns of the interannual variability of the heat fluxes. This suggest the robustness of the results obtained.

Lines 170-176 were changed to "The instability of the NwAFC, a relatively large (monthly) period of data averaging, the medium resolution of the available data, and anaccounted ageostrophic component can lead to a significant change in the integral flux through the section even with a relatively small change in the position of the transects. These uncertainties are taken into account when discussing the values of the ocean heat convergence in the subregions, limited by the transects: A (limited by the transects Svinoy and Jan–Mayen transects); B (between Jan-Mayen and Bear Island); C (between the transects Bear Island – Sorkapp); D (the transects Sorkapp and Fram strait). However, the trends and the interannual variability patterns are preserved (Fig. 3). More examples for different positions of the transects and variation of the reference temperature are presented in the Supplementary materials (Figure S1). Over the areas of the subregions A-D, the integral ocean-atmosphere and radiative heat-fluxes were also estimated. "

Figure S1. Examples of integral heat flux in AW layer depending on transects position and choice of reference temperature

[7]. Section 2.8: Vertical mixing or diapycnal mixing? Are you estimating the mixing at the base of the AW, which is along an isopycnal? If so, how robust is it to use vertical mixing coefficient Kz to estimate mixing across an isopycnal?

Response:

We estimate vertical mixing across the bottom isopycnal, so "diapycnal mixing" is the right term. Isopicnals locally are almost parallel to the horizontal, typically inclined to the horizontal only by a few degrees, so vertical or diapycnal mixing practically give the same values. Therefore, it is commonly accepted to use the vertical mixing coefficient for estimating a cross-isopycnal mixing in the ocean.

[8]. Line 238-239: The correlation seems to result from the trend. What is the correlation after detrending the time series?

Response:

After detrending the correlation decreases slightly: for water temperature from 0.70 to 0.63, for U component from 0.48 to 0.44, for V component it doesn't change (remaining 0.60).

Added a sentence: Line 250: "The monthly mean current velocities, derived from the mooring data, also show a significantly higher variability compared to altimetry based ARMOR3D data. For annual mean U and V components, which are of the main interest for this study, correlations between the data-sets increase (in the presented example, from 0.5 to 0.7 and from 0.6 to 0.7, respectively). Removing long-term trends from the time series results in slight decrease in the correlations for the cross-flow U component (to 0.4), while does not change that for the along-flow V component and for water temperature."

[9]. Figure 5: Suggesting adding error bars to the time series plot.

Response:

Error bars were added for seasonal data, however, for annual mean time series plot this doesn't seem necessary as they simply reflect the strong seasonal (and subseasonal) variability, while making the plots difficult to read.

Figure 5. Validation of ARMOR-3D (blue) against in situ data at mooring F5 (red) located in the WSC at 78,5° N 6° E: a – water temperature (oC), b – zonal current velocity U (cm s-1) and c – meridional current velocity V (cm s-1). Left -Taylor diagrams

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(ARMOR-3D is point B, in situ – point A), center – data time series, right - seasonal cycles. Data are averaged in 50-150 m layer.

[10]. Figure 6: Suggest adding uncertainties to the budget analysis. There is a clear difference of the mean meridional velocity between the ARMOR and the mooring (Figure 5), implying large uncertainties in the estimated advective heat flux. Again, the calculated heat flux is really a temperature flux, whose mean may be significantly modified with a different reference temperature.

Response:

Uncertainties of the means (in TW) were added to Figure 6.

Figure 6. Fluxes ± errors of the means (at the 95% confidence level).

[11]. Line 301: The correlation between Svinoy and Jan Mayen is as high as 0.7 according to Figure 7. Why is that a loss of correlation?

Response:

The correlation loss is due to atmosphere and eddies are removing heat from the Norwegian current and dispersing in across the Lofoten basin. The time variability of these processes do not necessarily correlate with that of the AW inflow across the Svinoy section. We are looking at the changes of the correlation coefficients between the transects as the AW progresses north, so "strong loss" of correlation refers to how fast correlation coefficient changes from transect to transect.

The description Lines 330-335 were changed to:

"The strongest correlation loss is found between Voring and Jan Mayen sections, while another one is between Isfjord and Fram sections. The correlation loss between Voring and Jan Mayen sections along the NwAC can be explained by an exceptionally high ocean eddy dynamics, which are effectively generated west of the Lofoten Islands (Isachsen, 2015) and redistributes the incoming heat over the area of the Lofoten basin, further released to the atmosphere (Dugstad et al., 2019; Raj and Halo, 2016). We may expect somewhat similar reasons for the correlation loss between Isfjord and Fram sections (von Appen et al., 2015, Bashmachnikov et al., 2020). "

[12]. Figure 9c: There seems to be an increase of the dominant period with time. For example, in months 192-288, there is a dominant period of >84 months. Is there an explanation for that?

Response:

The time change of the period is presumably related to the corresponding changes in the oceanic heat advection entering the study region (possibly linked to the variability of AMO, NAO or EA patterns). However, we concentrated here on the variability of the heat fluxes within the region (from south to north), and the mechanisms of variability of the fluxes entering the region is already out of the scope of the present analysis.

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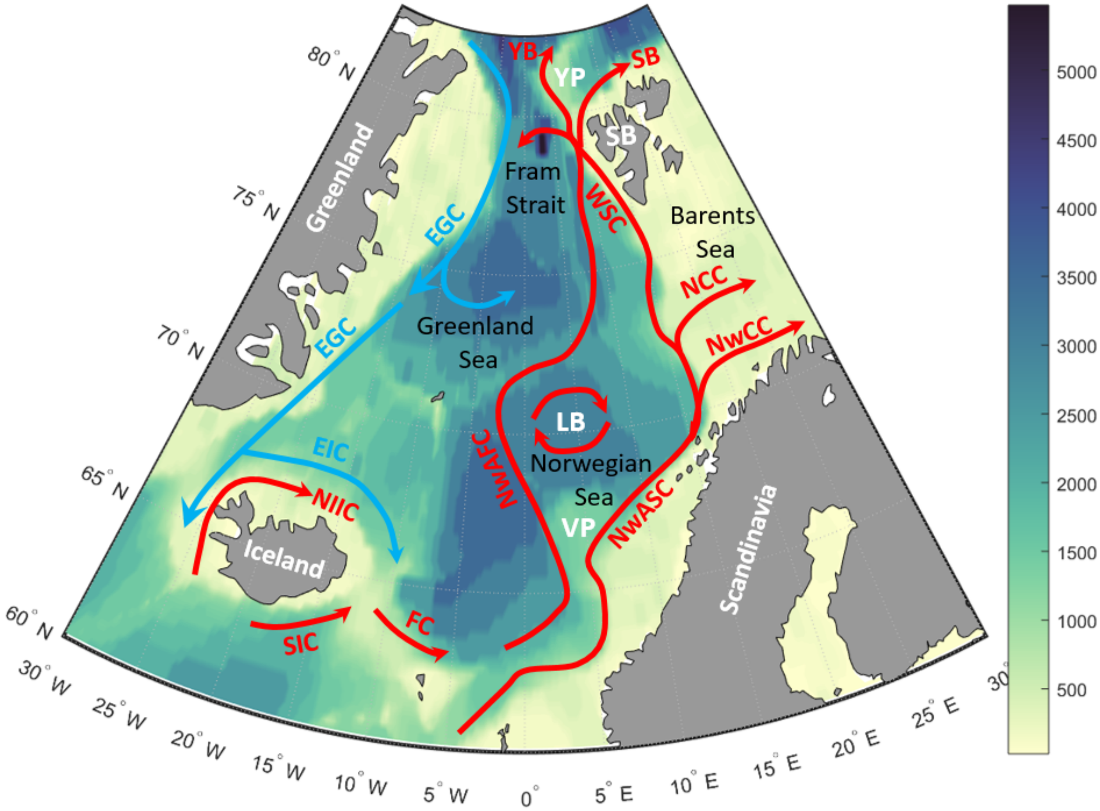


Fig. 1. Figure 1.Schematic map of oceanic circulation in the study region

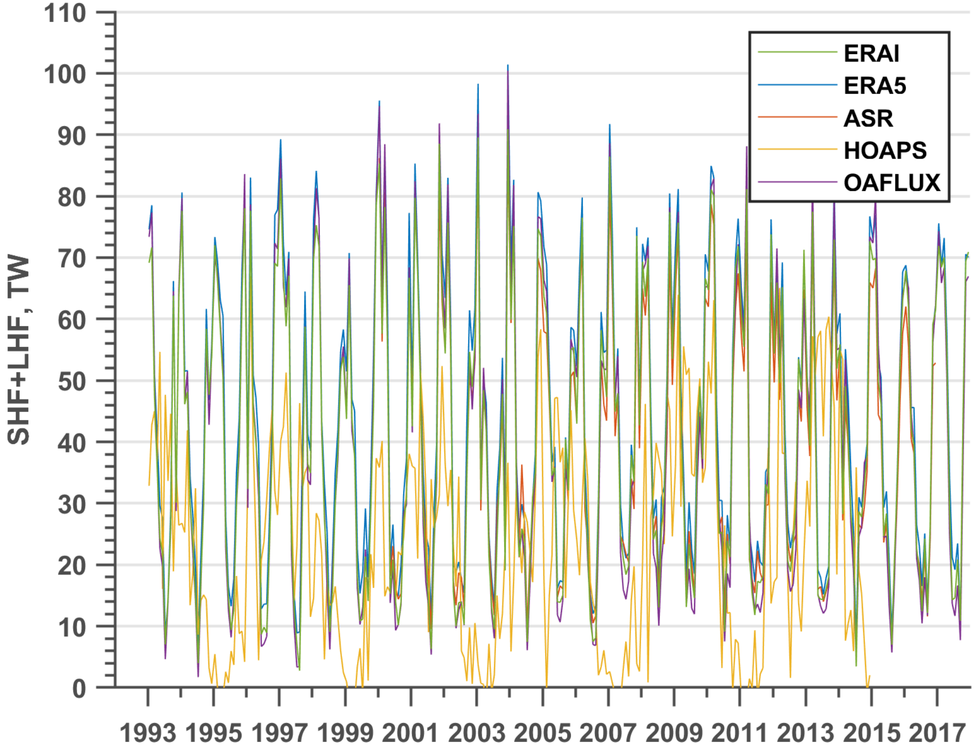


Fig. 2. Figure S2. Ocean atmosphere heat fluxes for region A, calculated using different datasets

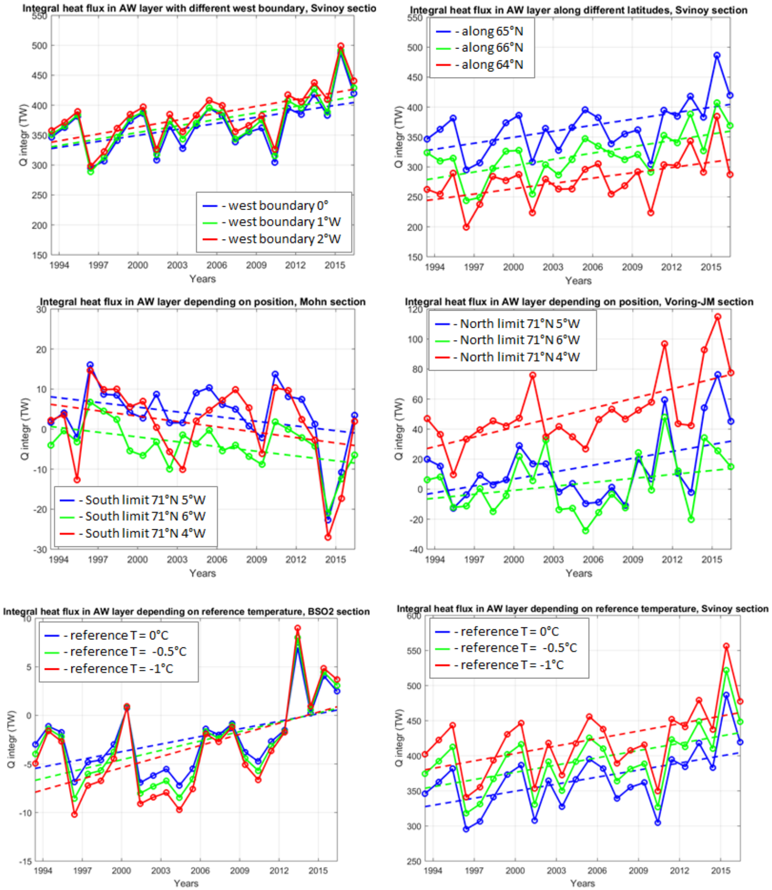
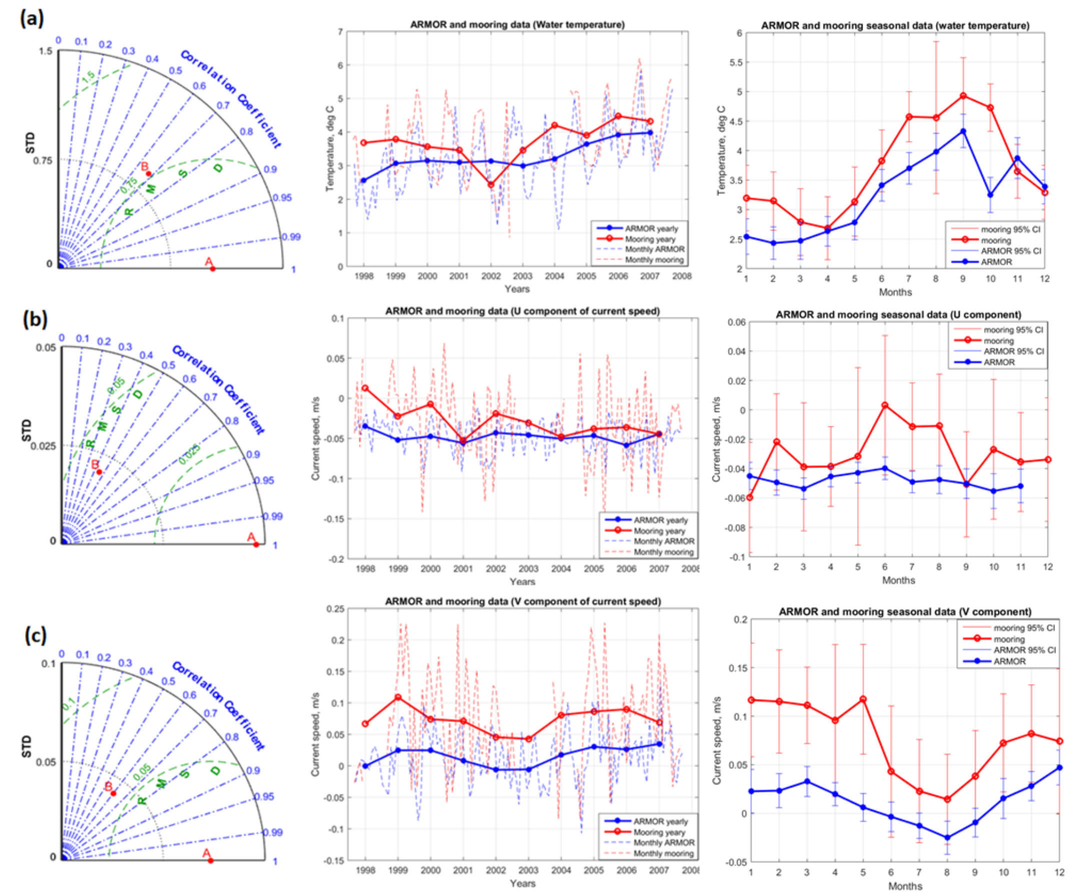


Fig. 3. Figure S1. Examples of integral heat flux in AW layer depending on transects position and choice of reference temperature



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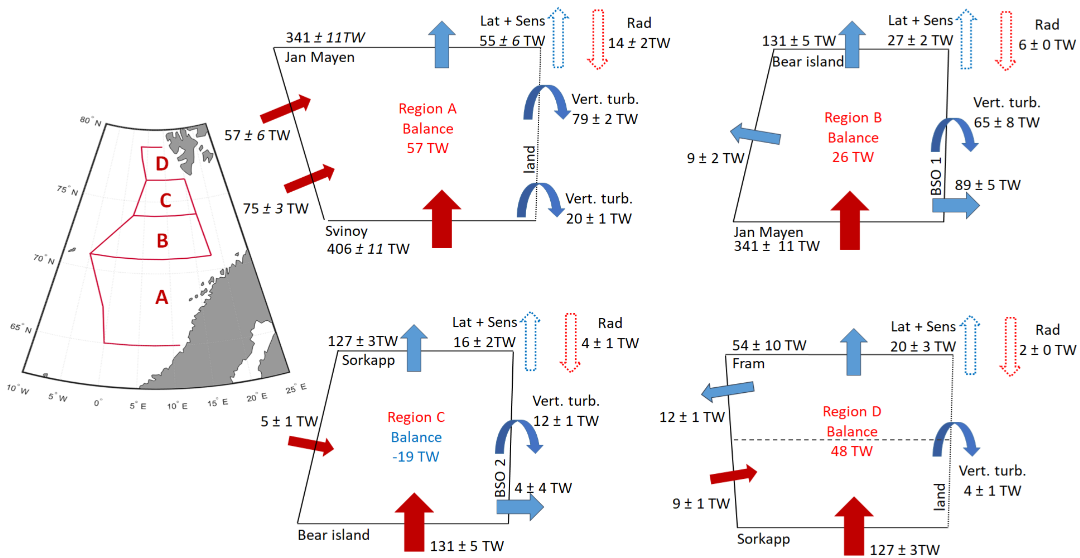

Fig. 5. Figure 6. Fluxes ± errors of the means (at the 95% confidence level).